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Arvidsson, Magnus

2020

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Arvidsson, M. (2020). *Water mist fire protection systems: The development of testing procedures for marine and heritage applications*. [Licentiate Thesis, Division of Fire Safety Engineering]. Lund University.

Total number of authors:
1

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

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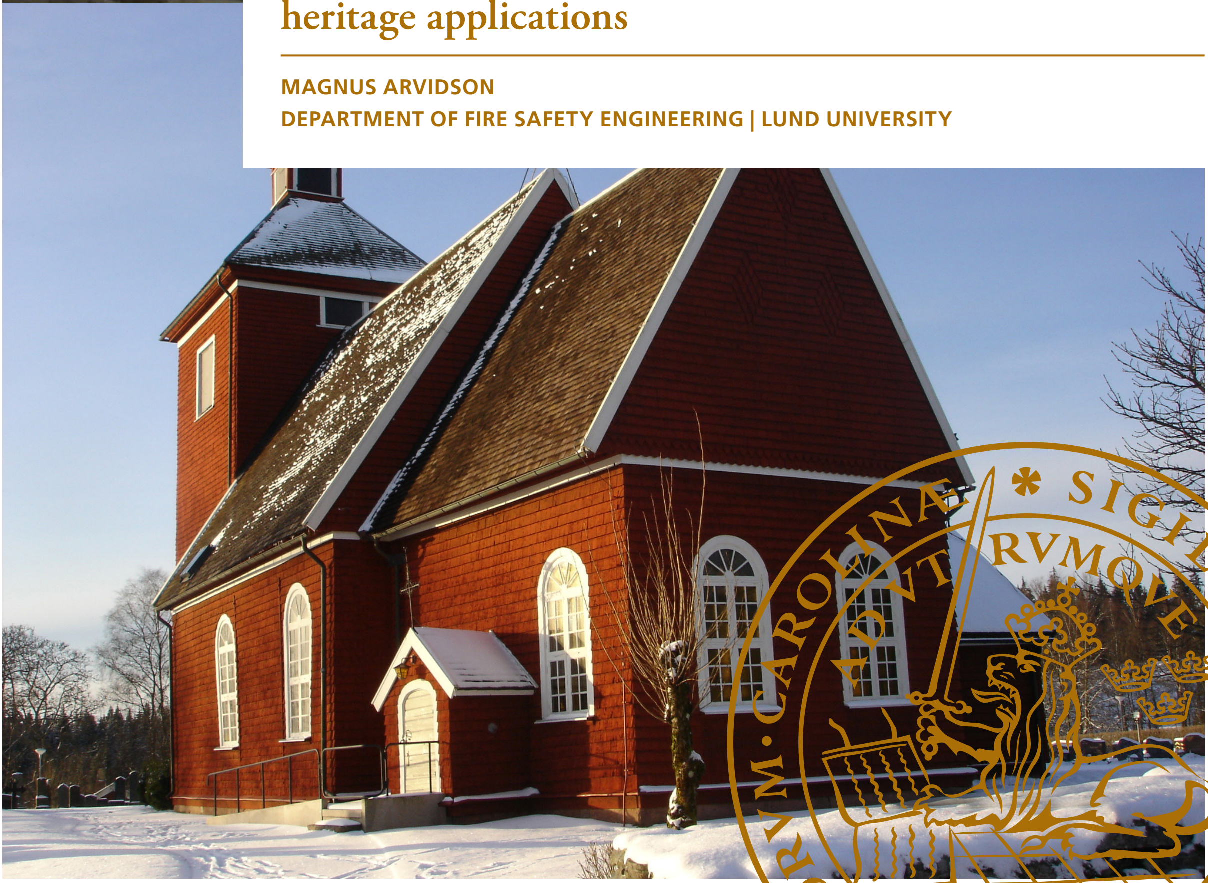
MAGNUS ARVIDSON

DEPARTMENT OF FIRE SAFETY ENGINEERING | LUND UNIVERSITY



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LICENTIATE DISSERTATION

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To be defended on September 9, 2020 at 09.00 in room V:B,V-huset, John Ericssons väg 1, Lund.

Faculty opponent
Dr. Jukka Vaari
VTT Technical Research Centre of Finland Ltd

Organization
LUND UNIVERSITY
Faculty of Engineering, Department of Fire Safety Engineering

Document name
LICENTIATE THESIS

Date of issue
2020-09-09

Author(s)
Magnus Arvidson

Sponsoring organization
RISE Research Institutes of Sweden

Title and subtitle
Water mist fire protection systems: The development of testing procedures for marine and heritage applications

Abstract

Modern, commercial water mist fire protection system technology evolved at the beginning of the 1990s due a need to replace halon fire-extinguishing systems and improve fire safety on passenger ships. This thesis documents the unknown water mist system development work by two Swedish companies during the 1970s and 1980s. It also documents the development of the first international installation recommendations and fire test procedures for marine applications.

Several of these fire test procedures needed revisions. A research project in the thesis showed that those for machinery space protection can be significantly improved by using simple and inexpensive measurements and performance measurement parameters. In another research project, tests simulating fire on a ro-ro cargo space of a ship was conducted. The results indicate that large water droplets are required for fire suppression, but smaller water droplets cool the fire gases well.

For the protection of heritage buildings, a field study suggests that functional testing is essential to maintain the function of a system. Testing using commercial nozzles indicate that exposure of sensitive wall paintings to water spray could cause significant damage under real-life conditions, even if the flow rate is low.

Future research should focus on improving fire test procedures based on experience as well on a theoretical understanding of the mechanisms of water mist. Long-term field experience is also desired for continual improvements of the performance and reliability of systems. In order to convince authorities, insurers, fire protection consultants and end-users on using water mist, these issues need to be dealt with in a systematic manner.

Key words
Water mist, fire protection, fire test procedures, ships, marine applications, heritage buildings

Classification system and/or index terms (if any)

Supplementary bibliographical information

Language
English

ISSN and key title
1402-3504 Water mist fire protection systems

ISBN
978-91-7895-553-4 (print)
978-91-7895-554-1 (pdf)

Recipient's notes

Number of pages 89

Price

Security classification

Signature Magnus Arv

Date 2020-09-09

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LUND
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Cover photos Magnus Arvidson

RISE Research Institutes of Sweden and Department of Fire Safety Engineering,
Faculty of Engineering, Lund University, Sweden

ISBN 978-91-7895-553-4 (print), 978-91-7895-554-1 (pdf)
ISSN 1402-3504

Printed in Sweden by Media-Tryck, Lund University
Lund 2020

Printed matter
3041 0903

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MADE IN SWEDEN

“In the future a liquid, e.g. water, atomized to drops smaller than powder grains will be the most important extinguishing agent against flames indoor, so-called fine mist.”

Krister Giselsson and Mats Rosander from the lecture book “The fundamentals of fire”, published by GIRO-Brand AB, first edition 1978

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Acknowledgements

The material presented in this licentiate thesis is the result of many years of work and summarises some of my projects related to water mist fire protection technology. I was introduced to the technology in 1992 when Göran Sundholm, the founder of Marioff Corporation Oy approached RISE (then SP) for fire testing of the HI-FOG water mist fire protection system that he was developing for marine applications. At that time, the terminology "water fog" was commonly used, however, this term was later changed. One might claim that the development of the specific system and the required fire test procedures for the water mist fire protection systems went hand in hand. Soon thereafter I was involved as a technical advisor for the Swedish Maritime Administration during the annual Fire Protection Sub-Committee meetings at the International Maritime Organization (IMO). During these meetings, the first international installation guidelines and fire test procedures for water mist fire protection systems were developed. In 1994, I was elected in the technical committee at the National Fire Protection Association (NFPA) that worked with the first edition of NFPA 750 under the chairmanship of Jack R. Mawhinney. The first edition of the standard was published in 1996. In 1998, CEN standardization work on water mist fire protection systems started and I was involved in the working group. In 1998 the International Water Mist Association (IWMA) was also formed and a few years later I joined its Scientific Council.

Firstly, I would like to thank the funding organizations enabling the project that forms this thesis, the Swedish Fire Research Board (Brandforsk), VINNOVA, Sweden's innovation agency, the Swedish Mercantile Marine Foundation, the Swedish National Heritage Board, the National Property Board of Sweden and the Directorate for Cultural Heritage (Norway). Part of the work was financed by commercial companies; FOGTEC Brandschutz GmbH & Co. kg and Ultra Fog AB which is gratefully acknowledged.

Secondly, I would like to thank my supervisor Professor Patrick van Hees at Lund University and my co-supervisor Adj. Professor Björn Sundström at Luleå University of Technology. The input and advice from other colleagues at RISE have also been instrumental for the work, especially the help from Tommy Hertzberg but also Haukur Ingason and Henry Persson. The review and input from Margaret McNamee and Francine Amon on several of the papers is also gratefully acknowledged.

Thirdly, I would like to thank the people at the Swedish Maritime Administration that was part of the Swedish delegation at the IMO meetings; Krister Ingvarson, Bengt Lyderson and Johan Wikman. These people saw the potential with water mist technology and encouraged my involvement at the meetings.

Contacts, discussions and projects with the water mist manufacturers have also been important; Göran Sundholm, Maarit Tuomisaari, Didrik Tollander, Anders

Kjellberg, Leif Hanje, Erik Christensen, the late Jerry Pepi, David LeBlanc, Max Lakkonen, Carsten Palle, Jens Toft Jensen, Henrik Bygbjerg, Erling Mengshoel and many more are gratefully acknowledged. Contacts with staff at other fire test laboratories, especially Ragnar Wighus and Are Wendelborg Brandt at RISE in Norway as well as Gerard G. (Jerry) Back and Jack R. Mawhinney at Jensen Hughes has been imperative. Another important person was Jan G. Andersson at Elplanering Väst AB for his comprehensive knowledge about heritage buildings.

I conclude by acknowledging the love of my life, Gerd Sundström for her inspiration and valuable input. Finally, I would like to thank our daughter Tove, simply for her positive attitude, charm and inspiration.

Magnus Arvidson, Hudiksvall, 2020

Populärvetenskaplig sammanfattning

Även om man redan under 1930- och 40-talen förstod att små vattendroppar under vissa förutsättningar kan förbättra släckeffektiviteten för vatten jämfört med större vattendroppar och slutna vattenstrålar, så var det inte förrän på 1990-talet som tekniken med fasta system med ”vattendimma” kommersialiserades. Incitamentet var i första hand det så kallade Montrealprotokollet och branden ombord på passagerarfärjan Scandinavian Star. Montrealprotokollet är en internationell överenskommelse som reglerar produktionen och användningen av ett antal substanser som tros påverka jordens ozonskikt. Avtalet trädde i kraft den 1 januari 1989 och inkluderar bromerade brandsläckningsgaser (’haloner’). Branden på Scandinavian Star den 7 april 1990, där 158 personer omkom, resulterade i betydligt högre brandsäkerhetskrav på passagerarfartyg i internationell trafik, däribland krav på sprinkler i passagerar- och publika utrymmen. Fasta vattendimsystem kom därför att lanseras som ett alternativ till halongaser i maskinrum på fartyg och som ett alternativ till traditionella sprinklersystem på passagerarfartyg.

Denna avhandling sammanfattar resultaten från några av de projekt som författaren drivit under många års arbete med vattendimsystem. Avhandlingen dokumenterar den tidiga utvecklingen av kommersiella så kallade högtrycksystem som bedrevs (oberoende men med viss samverkan) av två svenska företag under 1970- och 1980-talen. Inget av de båda företagen hade dock någon större kommersiell framgång, delvis beroende på att marknaden för tekniken var alltför begränsad. Avhandlingen dokumenterar även utvecklingen av de allra första internationella (IMO) installationsrekommendationerna och standardiserade brandprovningsmetoderna. Dessa dokument kom att ha stort inflytande för acceptansen av vattendimsystem.

Några de brandprovningsmetoder som togs fram av IMO hade flera brister, vilket bidrog till att vattendimsystem avsedda för fartygsmaskinrum bland annat kunde dimensioneras med mycket låga vattenflöden. Detta uppmärksammades av sjöfartsmyndigheter och klassningssällskap som önskade bättre brandprovningsmetoder. I ett forskningsprojekt utvecklades en metodik som mäter systemens förmåga att dämpa en spillbrand, kyla brandgaser och fördela vattendroppar och vattenånga i försöksrummet. Metodiken ger, tillsammans med tiden till släckning, en bättre bild av det provade systemets prestanda. Delar av metodiken implementerades av IMO i den relevanta brandprovningsmetoden. I ett annat forskningsprojekt jämfördes prestandan för traditionella vattenspraysystem och vattendimma i ett scenario som simulerar en brand i en lastbilstrailer i ett ro-ro lastutrymme på ett fartyg. Resultaten indikerar att stora vattendroppar krävs för att dämpa brandeffekten från en brand. Däremot kyler mindre vattendroppar brandgaserna väl. Slutsatserna kom att ligga till grund för de reviderade dimensioneringsreglerna för sprinkler- och vattenspraysystem på ro-ro lastutrymmen.

Kulturbyggnader är en tillämpning där vattendimsystem passar bra. I ett projekt sammanställdes erfarenheter från nio svenska kyrkor där sprinkler installerades åren 2004–2006, samt erfarenheter från Norge där sprinklersystem har installerats i ett större antal kyrkor. Studien visar att installationerna är diskreta och väl utförda, den normale kyrkobesökaren lägger troligen inte märke till dem överhuvudtaget. Men systeminstallationerna är relativt komplexa. En erfarenhet från Norge är att sofistikerade lösningar och ”modern” teknik ställer höga krav på underhåll och att de ofta är dyra. Enkla lösningar är därför eftersträvansvärda. Regelbunden kontroll, provning och underhåll är nyckeln till hög tillförlitlighet och flera fall där system inte fungerat vid funktionskontroll dokumenterades. Men kontroll och provning kräver tid, utbildning och engagemang från anläggningsskötaren. Flera anläggningsskötare utryckte att underhållet krävt mer tid och varit dyrare än man förväntat sig.

Många träkyrkor har mer eller mindre heltäckande vägg- och takmålningar som troligen är mycket känsliga för vattenbegjutning. Påverkan på känsliga målningar av vattensprayen från både traditionell sprinkler och vattendimma undersöktes med försök. Resultaten pekar mot att även mycket små vattenmängder kan skada känsliga ytor, även om ett högre vattenflöde förstås bidrar till större påverkan. En annan slutsats är att faktorer som sprickbildning och andra ytdefekter i färglagren och antal färglager har stor betydelse för hur stor skadan blir. Försöken visar också att takytan i närområdet ovanför en nedåtriktad sprinkler kan utsättas för kraftig vattenbegjutning. Det dock bör understrykas att man i varje enskilt fall bör ställa sig frågan om man kan acceptera risken för en mindre vattenskada (vid en oavsiktlig aktivering) för att förhindra att en hel byggnad totalförstörs vid en brand.

Summary

Although it was already understood during the 1930s and 1940s that small water droplets could, under certain conditions, improve fire-fighting efficiency compared to larger water droplets and solid streams of water, it was not until the 1990s that the technology with fixed with “water mist” fire protection systems was commercialized. The incentive was primarily the so-called Montreal Protocol and the fire on-board the Scandinavian Star passenger ferry. Water mist fire protection systems were launched as an alternative to halon gases in engine rooms on ships and to traditional sprinkler systems on passenger ships.

This thesis summarizes the results of some of the projects that the author has conducted during many years of work with water mist fire protection systems. The thesis documents the early development of commercial high-pressure systems by two Swedish companies (independently but with some cooperation) during the 1970s and 1980s. Neither of the two companies had any major commercial success, partly because the technology market was too limited. The thesis also documents the development of the very first international (by IMO) standardized installation recommendations and fire test procedures. These documents came to have a great influence on the acceptance of water mist technology. Some of the fire test procedures developed by the IMO had shortcomings, which was noted by maritime authorities and classification societies. In a research project, a methodology was developed that measure the fire suppression capability, the temperature reduction capability and the ability to mix water vapor, water droplets and combustion gases within the protected compartment. The methodology, together with the time to extinguishment, gives a better understanding of the performance of the tested system. Parts of the methodology were implemented by the IMO in the relevant fire procedures. In another research project, the performance of traditional water spray and water mist fire protection systems was compared in a scenario that simulates a fire in a freight truck trailer on a ro-ro cargo space of a ship. The results indicate that larger water droplets are required for fire suppression, but, smaller water droplets cool the fire gases well. The conclusions formed the basis for the revised design and installation guidelines for traditional sprinklers and water spray systems in ro-ro cargo spaces.

The protection of heritage buildings is an application where water mist systems may fit well. A field study summarizes experiences from nine Swedish churches where sprinklers were installed in the years 2004-2006, as well as experiences from Norway where sprinkler systems have been installed in a larger number of churches. The study shows that the installations are unobtrusive and well done, the normal church visitor probably does not notice them at all. But the system installations are relatively complex. One experience from Norway is that sophisticated solutions and “modern” technology place high demands on maintenance and that they are often expensive. Simple solutions are therefore desirable. Regular inspection, testing and

maintenance is the key to high reliability and several cases where systems have not functioned during functional testes were documented. But this require time, training and commitment from the staff. Several staff members expressed that it required more time and was more expensive than expected.

Walls and ceilings inside many old churches and other heritage buildings are often decorated with invaluable paintings, artefacts and décor. The paint may be water-soluble and therefore very sensitive to water. The influence of the water sprays from commercial nozzles were tested: a traditional spray sprinkler, a low-pressure and a high-pressure water mist nozzle was investigated. In summary, the results indicate that the water spray could cause significant damage under real-life conditions, even if the flow rate is low. Another conclusion is that factors such as cracking and other surface defects in the paint layers and the number of paint layers are of great importance for the extent of the damage. The tests also show that the ceiling surface in the immediate area above a pendent sprinkler can be exposed to heavy water spraying. In an actual case one should ask the question whether one can accept the probability of minor water damage (inadvertent activation) to prevent the entire building from being destroyed in the event of a fire.

List of abbreviations

Terms that are used recurrently in the thesis are explained below. The terms are either considered to be unfamiliar about the subject or needing an explanation in the context of this thesis.

CEN	European Committee for Standardization
DNV	Det Norske Veritas
ESFR	Early Suppression Fast Response (sprinklers)
FP	Fire-Protection Sub-Committee (at IMO)
HP	High-pressure water mist system
HPLF	High-pressure low flow water mist system
HRR	Heat release rate
IWMA	International Water Mist Association
IWMC	International Water Mist Conference
IMO	International Maritime Organization
LFL	The lower flammability limit of a fuel
LP	Low-pressure water mist system
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
Ro-ro	Roll-on roll-off cargo space on ships
RISE	RISE Research Institutes of Sweden (the company name in use from 2016)
SMD	Sauter mean diameter
SP	SP Swedish National Testing and Research Institute (the company name that was used up until 2016)
THR	Total heat release
TUF	Temperature uniformity factor
UL	Underwriters Laboratories, Inc.
VdS	VdS Schadenverhütung
VINNOVA	Sweden’s innovation agency
VTT	Technical Research Centre of Finland
WS	Water spray system

List of symbols

A	Total surface area of all water droplets in a monodispersed spray (m^2)
a	Surface area of an individual water droplet (m^2)
m_{vapor}	Mass of water vapor (kg)
m_{air}	Mass of air (kg)
N	Number of water droplets in a monodispersed spray
P	Atmospheric pressure (kPa)
P_i	Partial pressure (kPa) of an individual gas i
P_{O_2}	Partial pressure of oxygen in air (kPa)
$P_{sat,t}$	Saturation vapor pressure (kPa) at the actual temperature t (°C)
P_{vapor}	Partial pressure of water vapor in air (kPa)
r	Radius of an individual water droplet in a monodispersed spray (m)
V	Volume of water (m^3)
W	Humidity ratio
W_{sat}	Humidity ratio at saturation for the same temperature and pressure as those of the actual state

Greek

μ	Degree of saturation
$\emptyset$	Relative humidity
x_{vapor}	Mole fraction of water vapor in a mixture of water vapor and air
$x_{vapor,sat}$	Mole fraction of water vapor for the same temperature and pressure as those of the actual state.
$x_{w,sat}$	Mole fraction of water vapor for the same temperature and pressure as those of the actual state

1 Introduction

1.1 The early development and use of water mist technology

The use of water atomised to fine water droplets has been recognized as a fire-fighting agent for long time. Lakkonen (2008) has summarised some parts of the history of the development, marketing and use of water mist technology. As an example, one company in USA was marketing a back-bag system with a lance producing small water droplets to fight small forest fires as early as in 1880. At the beginning of the 1900s, pumping equipment and new sealing materials were developed which allowed higher pressure levels. The efficiency of smaller water droplet sprays was recognized. In the 1930s there were several companies offering systems that applied finely atomized water in form of mist or fog, i.e. the terminologies fog and mist were used early. The key benefits of water mist utilized today, as cooling effects, oxygen displacement and reduced water damage potential was used as arguments for the technology.

A considerable amount of research on fire extinguishment using water sprays were conducted at the Fire Research Station in United Kingdom during the 1950s. Some of the work is summarised below.

Rasbash and Rogowski (1953) conducted a series of tests to investigate the effect of water sprays on a kerosene fire in a circular 30 cm diameter fire tray. It was possible to study the effect of droplet sizes and the flow rate at pressures between 0.35 and 5.9 bar, while maintaining a fairly uniform spray pattern over the fire area. At low pressures (between 0.7 bar and 2.1 bar), the fire was extinguished mainly as the kerosene was cooled to and below the fire point. At a higher pressure (5.9 bar) fire extinguishment was achieved without cooling the liquid to the fire point and there was evidence that the flame itself was extinguished. The efficiency increased with an increase in pressure. This was shown by a reduction of the minimum flow rate required to extinguish the fire and by a reduction in the time which was required for fire extinguishment at a given flow rate. There was no indication that the formation of an oil in water emulsion played any part in the extinction process.

An additional study was made by Rasbash and Rogowski (1955) to determine the effect of three water sprays providing different droplet sizes on six liquid fuel fires. The liquids were alcohol, benzol, petrol, kerosene, gas oil and transformer oil. The sprays had a flow rate over the fire area of 1.6 g/cm^2 (16 kg/m^2) per minute and the mean droplet sizes were 280 µm, 390 µm and 490 µm. It was found that the smallest droplet spray was the best for the extinguishment of the more volatile liquids, but the coarsest spray was best for the less volatile liquids. The results suggest that the main fire extinguishment mechanisms were 1) cooling of the liquid to below the fire point, 2) smothering the flame by formation of steam at the hot burning liquid, 3) extinction of the flame either by formation of steam in the flame or cooling, and 4) for alcohol, by dilution. From a practical perspective, it was determined essential that the water spray pattern is sufficiently large to cover the whole area of the fire.

Another series of fire tests by Rasbash and Rogowski (1955) focused on the fire extinguishment of a petrol fire in a circular 30 cm diameter fire tray with several water sprays. The drop sizes of the sprays varied between 200 µm and 600 µm, the entrained air velocities between 0.2 m/s and 0.5 m/s and the water flow rates between 6 kg/m^2 and 40 kg/m^2 per minute. It was found that the time to extinguishment was noticeably reduced by an increase in the rate of flow and the entrained air velocity and by a decrease in the droplet size. From a practical perspective, it was argued that the water spray pattern needs to be sufficiently large to cover the whole area of the fire and that the water flow rates need to be significantly higher than 1 gallons/ft^2 (41 kg/m^2) per minute. This would result in very high flow rate demands for a petrol fire of a practical size.

As early as in 1955, Rasbash (1955) discusses the relative merits of high- and low-pressure water sprays used for fire extinguishment of flammable liquid fires. The relative effect of increasing the pressure in a high-pressure spray range (56 bar to 103 bar) and a low-pressure spray range (up to 7 bar) for the extinguishment of these fires is discussed. After considering practical aspects, it is concluded that it is not in general worthwhile increasing the pressure in the high-pressure region.

Sönnerberg (1952) is the principal editor of a comprehensive encyclopaedia that documents the history of fire-fighting and the organisation of modern fire services as well as equipment, agents, methods and tactics. The focus of the book is Sweden; however, one part covers fire services in other countries. The use of the (then) newer types of hand-held water mist nozzles for manual fire-fighting is described. It is told that these nozzles have been used for about ten years and that the technology has its origin in the USA. High-pressure nozzles, defined as having an operating pressure of between 40 to 50 bars, and low-pressure nozzles used at between 7 to 10 bars are mentioned. The drawbacks of the nozzles are the limited throws and flow rates, which prevents their use for large, open fires as it is required that the operator can advance close to the fire. It is, however, concluded that water mist is effective for fires in enclosed spaces and for final extinguishment. Water mist is superior a solid stream of water or other extinguishants for certain fires. The examples include fires in cutter shavings, peat litter, charcoal dust and similar fires where the material swirls up by a solid water stream. Another example is premises for spray painting with cellulose paint where dried paint waste has ignited. A finely atomized water spray is usually more effective than a solid water stream. The third example is fires in heavy oils, as lubrication oil, machine oil and fuel oil or melting combustible substances as asphalt, pitch, resin, paraffin, stearin, rubber and grease. Fires in these materials are more rapidly extinguished with water mist than with foam. The burning surfaces are cooled below the auto-ignition temperature, resulting in reduced pyrolyzing and fire extinguishment. A solid water stream penetrates the oil (or equivalent) and the vaporization could lead to boil over. The book does also reveal that fire-fighting using water mist was introduced in the USA for aircraft crash fires, in contrary to Swedish and European fire services that is using foam for these types of fires. The reason is believed to be that chemically generated foam have been used in USA, which have limited the foam generating capacities. Finally, it is concluded that water mist is ineffective for fires in gasoline, unless the conditions are very favourable, such as small fuel quantities, enclosed spaces, etc.

Fixed installed water mist systems have traditionally not been used on-board ships. Stålemo and Hultqvist (1966) describes the former installation requirements of water spray systems in machinery spaces, probably based on rules by Det Norske Veritas (DNV). The system shall consist of a pump, a pressure tank, section control valves, the system pipe-work and the water spray nozzles. The water spray nozzles shall be positioned to provide a uniform discharge in the space to be protected and in particular above fire hazard areas as the tank top and other areas to where oil can spread, as above scuppers and below bilges. For a machinery space, no more than 5 sections are allowed and for boiler rooms, no more than 2 sections. The emergency pump shall have a capacity sufficient for all nozzles within the largest protected space. Nozzles should be of an approved type and have a single orifice that is larger than 7 mm in diameter. The nozzle flow rate should be no less than 40 litres/min but should not exceed 100 litres/min at the actual operating pressure. The system shall be controlled from outside of the protected space with section control valves that are clearly marked. Regarding equipment for manual fire-fighting, where the essential fire hazard is flammable liquid fires, it is described that hand-held nozzles intended to be used in machinery spaces should be designed to provide "best possible atomization" and a shape of the water spray cone that offers the user the best protection. The nozzles can also be equipped with an extension such that the fire fighter can operate from a certain distance from the fire. It is, however, mentioned that water vapor ('steam') has been used as a fire extinguishant on-board older ships, with the intent to reduce the oxygen concentration. This requires large amount of steam that need to be continuously discharged into the space to compensate for the fact that it condenses to water. The steam is generated using boilers. It is stated that the water vapor decomposes when getting in contact with glowing metal, especially if the metal is pulverized. The water vapor also decompose in contact with glowing coke or charcoal. The decomposition products are combustible, primarily hydrogen.

Nash and Young (1991) does also describe the former use of sprinklers and water spray systems on-board ships. Automatic sprinkler systems for accommodation and public spaces were not specifically required, but the SOLAS convention from 1960 provides three optional basic principles for protecting ships and their occupants:

Method I: The use of internal divisional class 'B' bulkheads, but not fire detection or sprinkler systems.
Method II: The use of an automatic fire alarm and sprinkler system without any restriction on the type of internal divisional bulkheads.
Method III: The use of an automatic fire alarm system and an appropriate series of class 'A' or 'B' bulkheads, but no sprinkler system.

A class 'A' bulkhead should have a 60 minutes fire rating and a class 'B' bulkhead either a 15- or 30-minutes fire rating. As observed, Method II was the only where an automatic sprinkler system was required. This was the fire protection method that was most favoured in United Kingdom and Method I the most favoured in United States. Therefore, the UK Department of Trade developed detailed requirements on the design and installation of automatic sprinkler systems on ships, that was published as Statutory Instrument No. 1103 in 1965. These requirements were adopted in the 1974 SOLAS Convention, Regulation 12, Chapter II 2, with few changes. The main requirements include the use of either wet- or dry-pipe (in areas where freezing may be a concern) systems using automatic sprinklers, sections that include no more than 200 sprinklers, the use of ordinary temperature rated sprinklers, a nominal discharge density of 5 mm/min and an operating area of 280 m^2.

1.2 The modern development and commercialisation of water mist technology

As described above, water mist was primarily used for manual fire-fighting applications and was not widely adopted for use in fixed fire protection systems. Reasons included the problems of delivering smaller droplets from fixed nozzles to the seat of the fire through the fire plume and the cost of the increased pressures and pipe friction losses compared to standard sprinklers (Mawhinney and Richardson 1997).

The major commercial establishment of 'modern' water mist fire protection systems occurred during the early 1990s. The incentive was primarily the so-called Montreal Protocol and the fire on-board the passenger ferry Scandinavian Star. The Montreal Protocol is an international agreement that regulates the production and use of a number of substances that are believed to affect the earth's ozone layer (www.unenvironment.org 2019). The agreement entered into force on January 1, 1989 and includes brominated fire extinguishing gases ('halons'). The Scandinavian Star fire on April 7, 1990 (Almersjö et al. 1998), resulted in significantly higher fire safety requirements for passenger ships in international traffic, including requirements for sprinklers in accommodation and public spaces (www.imo.org 2019).

When automatic fire sprinkler systems became mandatory on-board passenger ships, IMO decided to allow the use of ‘equivalent’ fire sprinkler systems. The development and commercialisation of water mist technology at Marioff KY, later Marioff Corporation Oy, is an essential part of the modern history of water mist technology as the company was the first to obtain maritime approvals for fixed high-pressure water mist fire protection systems. The company was founded by Göran Sundholm in 1985 in Vantaa, Finland. The company began by providing specialized hydraulics services and products, mainly to the marine and offshore markets. In January 1991, the HI-FOG system was started to be developed and the system was presented to the market at the Cruise and Ferry exhibition in April 1991. At that time, the company had 14 employees. Fire testing was undertaken at the Swedish National Testing and Research Institute (SP) and later at the Technical Research Centre of Finland (VTT). The first machinery space system was installed in 1992. The millionth nozzle was manufactured in 2000 and in 2002, the number of employees had increased to 307, of which approximately 100 were working abroad (Sandberg 2005).

In 1993, National Institute of Standards and Technology (NIST) organised a workshop on water mist fire suppression (Jason and Notarianni 1993) and in 1994, SP organised and international conference on water mist fire protection systems (SP 1994).

Mawhinney and Richardson (1997) conducted a comprehensive review of water mist fire suppression research and development in 1996. The material lists agencies, universities, users, consultants and manufacturers world-wide undertaking relevant work and contains 48 parties. The large number of parties and the amount of work and projects done and planned indicate a vast interest in water mist technology.

1.3 The development of international installation guidelines and fire test procedures

The shipping market and the maritime authorities were the first to implement water mist technology. The IMO is the United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine pollution by ships. In 1993 IMO adopted the first guidelines for the approval of alternative sprinkler systems for passenger ships, Resolution A.755(18). With these requirements as the basis, fire test procedures and a component manufacturing standard for nozzles were developed and published in IMO Resolution A.800(19) in 1995. Several other installations guidelines and fire test procedures for water mist fire protection systems followed; MSC/Circ. 668 (1994) for total compartment systems intended for machinery spaces, MSC/Circ. 913 (1999) for local application systems in machinery spaces as well as MSC/Circ.914 (1999) and MSC.1/Circ.1272 (2008) for ro-ro cargo spaces.

Acceptance for use in land-based applications took longer time. In 1996, the National Fire Protection Association (NFPA) published the first edition of NFPA 750, the Standard on Water Mist Fire Protection Systems. The standard contains the minimum requirements for the design, installation, maintenance and testing of systems. But it does not provide definitive fire performance criteria or specific guidance on how to design a system to control, suppress or extinguish a fire. Instead, reliance is placed on the obtaining and installation of water mist equipment or systems that have demonstrated performance in fire tests as part of a listing (approval) process. In 2002, Underwriters Laboratories Inc. (UL) published UL 2167 for the testing of water mist nozzles. The standard contains both nozzle component tests and fire tests for different applications.

The first edition of FM Global Property Loss Prevention Data Sheets 4-2 (2006) provides information on installation criteria for water mist systems presently FM Approved for the protection of enclosures with specific hazards containing limited amounts of ignitable liquids and process equipment, such as; combustion turbine(s), industrial oil cookers, continuous wood board presses, machinery in enclosures, computer room subfloors, indoor transformers, wet benches in cleanrooms and light hazard occupancies. FM Class Number 5560 contains fire test procedures for the specific hazards and was published in its first edition in 2005.

CEN/TS 14972:2008 is a Technical Specification and was published in its first edition in 2008 by the European Committee for Standardization (CEN). The work with the document was initiated in 1998. It specifies the minimum requirements and information on design, installation and testing and gives criteria for the acceptance of fixed land-based water mist systems for specific hazards and provides fire test protocols for a variety of hazard groups.

Other organisations that have published installation requirements and fire test procedures for water mist fire protection systems are VdS Schadenverhütung in Germany and BRE Global in United Kingdom.

Several of the fire test procedures for light hazard applications and protection of machinery spaces from the organisations listed above has been based or at least influenced by the fire test procedures published by IMO.

1.4 Fire testing with inappropriate fire test procedures

The early fire test procedures were developed with little practical experience and scientific background. There was a great need for authorities, insurers and end users to find suitable alternatives for the replacement of halons and the system manufacturers were eager entering the marketplace. One example where this resulted in the development of poor system technologies was systems intended for machinery spaces on-board ships. The fire test procedures by IMO specified that the tests were supposed to be conducted in a fire test compartment having a certain volume and being naturally ventilated through a large doorway opening positioned at one of the walls. The fire test scenarios were chosen to reflect fires that may occur in a machinery space: oil spill fires, cascading fires and oil spray fires at different oil mass flow rates and pressures. However, fire testing at different fire test laboratories revealed complications with the fire test procedures. The most problematic being that potentially inadequate system concepts had entered the market, for example systems with very low water flow rates and limited cooling capabilities. Other systems passed the tests with ‘doorway screening nozzles’ that were horizontally directed towards the centre of the test compartment. The intent of these nozzles was to enhance the burning rate of the smallest pool fire scenarios used, thereby increasing the gas temperatures inside the test compartment and reducing the oxygen level faster. This approach will indeed reduce the time to extinguishment and the system may pass the test. But the performance of the system is strongly linked to the specific test conditions, such as the exact test compartment geometry and the location of the fire. Therefore, the system performance may be different in actual use (Vaari 2002).

Another example is the development of fire test procedures for ro-ro spaces on ships. Since the mid-1990s, several projects have been conducted (Arvidson et al. 1997, Larsson et al. 2002, Arvidson and Torstensson 2002) aiming at investigating the fire hazards in ro-ro and cargo spaces, the consequences of such fires, and the most appropriate fire protection systems. These projects showed that a fire in a ro-ro space can be very large before it becomes ventilation controlled, due to the large volumes and a virtually unlimited availability of air. A fire during loading or unloading may be critical as a fire potentially could become very large before being controlled by ventilation conditions.

MSC/Circ. 914 was adopted by IMO in 1999 and contains guidelines for the approval of alternative fixed water-based fire-fighting systems for ‘special category spaces’, defined as ro-ro spaces to where vehicles can be driven and to which passengers have access. The performance criteria of these guidelines were set higher than expected from a system designed in accordance with Resolution A.123(V) from 1967 and automatic activation was envisioned. With the introduction of MSC.1/Circ. 1272 in 2008, alternative systems, i.e. typically water mist fire protection systems, were allowed to be automatically activated utilizing automatic nozzles. These guidelines provided a performance-based fire test method for the approval of “fixed water-based fire-fighting systems for ro-ro spaces and special category spaces equivalent to that referred to in Resolution A.123(V)”. The intent of the fire test procedures was to demonstrate similar performance compared to the water spray systems designed in accordance with Resolution A.123(V).

The fire test procedures, including the fire test set ups and acceptance criteria, were established in a project conducted at VTT Technical Research Centre of Finland. Benchmark fire suppression tests were conducted with a water spray system designed in accordance with Resolution A.123(V), but the acceptance criteria were chosen such that they were somewhat higher than established with the benchmark system. In addition, the approach of installing automatic sprinkler systems in ro-ro spaces was investigated (Vaari 2006).

At the IMO, questions were raised by Member States, based on an assessment by Shipp et al. (2006), as to whether a water spray system in accordance with Resolution A.123(V) can control or suppress a fire in the ro-ro space of a ship with modern cars, coaches and heavy goods vehicles, due the high fire load, the potential shielding of a fire and the fact that the systems are manually operated. It was therefore a need for revising the installation guidelines for fixed water-based fire-fighting systems for ro-ro spaces.

1.5 The installation and field experience with water mist fire protection systems

Water mist fire protection systems were early considered as an alternative to gaseous fire protection systems for Class B fire hazards as well as an alternative to traditional fire sprinkler systems for light and ordinary hazard applications.

The use of small-bore piping and the potential for a reduction of the water flow rates made the technology especially interesting for heritage buildings. Around 2005, several water mist fire protection system installations were made in old wood churches in Sweden. Some of these installations were inherently complex, combining not only water mist with traditional sprinkler technology but did also use different system types for the same church. Claims were also raised by system installers that the potential for water damage to wall- and ceiling paintings was negligible when using water mist fire protection systems, however, this claim was not supported by any evidence.

Traditional fire sprinkler system technology was documented very early (Dana 1914) and the historic development of the sprinkler standard is well documented (Jensen 1985). The former reference is considered as being culturally important and is part of the knowledge base of civilization as we know it. System development work and improvements of traditional fire sprinklers have been documented on an ongoing basis, for example by Coleman (1985), Fleming (1985), Yao (1988) and Croce et al. (2020). The performance and reliability of traditional sprinkler systems have also been documented over the years; the most outstanding documentation is probably by Maryatt (1988). The performance and reliability have been improved continually through field experience and the efforts of manufacturers and testing organisations (Isman 2008).

For water mist system technology, much less field experience is available. FM Global indicates that field experience has been a rationale for the revision of certain requirements, for example that corrosion deposits found in system piping resulted in the exclusion of the use of galvanized steel piping (FM DS 4-2 2013). Problems associated with the performance of automatic water mist nozzles have been documented by maritime classification societies (Det Norske Veritas AS 2012) and flag state administrations (MSC 94/20/2 2014). Field experience from Swedish installations have also been documented that indicates that clogging of nozzles and filters is one of the practical concerns with maintaining system operability (Arvidson 2014).

1.6 The research objectives of the thesis

The material presented in this licentiate thesis is the result of many years of work and summarises some of the projects related to water mist fire protection system technology, from 1992 to present, where the author has served as the project leader and the main provider. The research objectives of the underlying projects were to:

RO1: Document the previously unknown history of the development of modern, fixed-installed high-pressure systems in Sweden and acknowledge the true pioneers that never earned any commercial success in the marketplace.

RO2: Document the development of the very first (by IMO) international installation guidelines and fire test procedures as well the rationales and background behind the fire test scenarios and acceptance criteria of the fire test procedures.

RO3: Improve the IMO fire test procedures for machinery spaces on ships by using additional measurement parameters.

RO4: Explore the possibilities of using water mist fire protection systems for high fire hazards, i.e. ro-ro spaces on ships and revise the existing installation guidelines for fixed water-based fire-fighting systems for these spaces.

RO5: Document lessons learned from actual water mist fire protection system installations in wood churches.

RO6: Study the influence of water sprays on sensitive building surfaces such as wall and ceiling paintings in heritage buildings.

All the projects covering these research objectives are associated with each other; the development of system technology, the development, use and improvements of fire test procedures, utilization for new fire hazards and finally the application and practical use of water mist technology. A common denominator is that all projects have been initiated due to a specific question or request from market actors.

1.7 List of publications

1.7.1 Papers included in the thesis

This thesis is based on six papers that are included in Annex A. Three of the papers (papers III, IV and V have been peer-reviewed and published in Journal of Fire Protection Engineering and Fire Technology, respectively. The other three papers were presented at the annual International Water Mist Conference.

Two papers represent literature reviews (papers I and II), one a field study (paper V) and three papers are experimental studies (papers III, IV and VI). The papers are listed below:

Paper I: Arvidson, Magnus, “The history of the development of modern water mist system technology in Sweden”, presented at the International Water Mist Conference, Denmark, September 17 – 19, 2008.

Paper II: Arvidson, Magnus, “The background and the development of the guidelines in IMO Resolution A.800(19)”, presented at the International Water Mist Conference, Istanbul, October 21-22, 2014.

Paper III: Arvidson, Magnus, “A novel method to evaluate fire test performance of water mist and water spray total compartment protection”, Journal of Fire Protection Engineering, Volume 23, Issue 4, November 2013, pages 277-299 (DOI: 10.1177/1042391513485954).

Paper IV: Arvidson, Magnus, “Large-scale water spray and water mist fire suppression system tests for the protection of ro-ro cargo decks on ships”, Fire Technology, Vol. 50, 2014, pages 589-610 (DOI 10.1007/s10694-012-0312-7).

Paper V: Arvidson, Magnus, ”Experience with fire suppression installations for wood churches in Sweden”, Journal of Fire Protection Engineering”, Volume 18, Issue 2, May 2008, pages 141-159 (DOI: 10.1177/1042391507086431).

Paper VI: Arvidson, Magnus, "The influence of water from sprinkler sprays on invaluable wall- and ceiling paintings in heritage buildings", presented at the International Water Mist Conference, Paris, November 28-30, 2007.

1.7.2 The author's contributions

The author's contributions to each of the papers were:

Paper I: A water mist system manufacturer requested a documentation of the development of high-pressure water mist system technology in Sweden. The author undertook a literature review, searched the archives of RISE, conducted interviews with the key people still alive and summarized the outcome in a conference paper.

Paper II: A water mist system manufacturer requested a literature review of the development of the installation requirements and fire test procedures for 'equivalent' sprinkler systems for passenger ships published by the International Maritime Organization (IMO) in 1995. The author participated in the work at IMO when this standard was developed. He made a summary of the discussions, the rationales, the fire tests, and other efforts that formed the base for the IMO requirements. Input to the work was based on documentation from IMO as well as own notes, documents and reports. The work was presented in a conference paper.

Paper III: A concern was raised among maritime authorities that the fire test procedures developed by IMO for 'equivalent' (to halon) fire-fighting systems in machinery spaces were inadequate. In response to this concern, the author planned and conducted a series of fire tests with colleagues at RISE. The data was analyzed by the author and Tommy Hertzberg and published in two SP Reports. The experience from the tests resulted in a proposed revision of the IMO fire test procedures that was partly accepted. Later, the results were summarized and published in a peer-reviewed paper by the author.

Paper IV: The performance of water spray and water mist systems intended for the protection of ro-ro spaces on-board ships had not been documented using a representative freight truck trailer fire load. The author planned and conducted a series of fire tests with colleagues at RISE. The data was analysed by the author and published in two SP Reports and was later presented at several conferences and published in a peer-reviewed paper. The project resulted in a revision of relevant IMO requirements.

Paper V:	During the beginning of the 2000s, fixed fire suppression systems (primarily water mist systems) were installed in several old wood churches in Sweden. Upon a request by the Swedish National Heritage Board, the author conducted a field study of selected installations that included visits and interviews with the fire protection consultants, installers and end-users. The study was published in an SP Report by the author, was presented at several conferences and later summarized and published in a peer-reviewed paper.
Paper VI:	The influence of water from sprinkler sprays (including water mist sprays) on valuable wall and ceiling paintings in heritage buildings was investigated in a series of tests upon a request by the Swedish National Heritage Board. The tests were planned and conducted by the author in co-operation with colleagues at RISE. The test samples were prepared by Hans-Peter Hedlund from the Swedish National Heritage Board. The data was analysed by the author, Anna Bäckman and Sofia Källqvist at SP and published in an SP Report. Later, the results were summarized and presented in a conference paper by the author.

1.7.3 List of publications not included in the thesis

Publications that are not included in the thesis but relevant for the subject and published by the author during his time as a PhD student, are presented below. Some of the publications may provide additional information on the performance of water mist fire protection systems.

Peer-reviewed papers

Arvidson, Magnus, “Flammability of antifreeze agents for automatic sprinkler systems”, Journal of Fire Protection Engineering”, Volume 21, Issue 2, May 2011, pages 115-132.

Arvidson, Magnus, “The response time of different sprinkler glass bulbs in a residential room fire scenario”, Fire Technology, published online May 22, 2018 (DOI: 10.1007/s10694-018-0729-8) and printed in Fire Technology, ISSN 0015-2684, Volume 54, Number 5, September 2018, pages 1265-1282.

Non peer-reviewed international conference papers

Arvidson, Magnus, “Testing of residential sprinklers and water mist nozzles in residential area fire scenarios”, Fire Sprinkler International 2018, Stockholm, June 13-14, 2018. Organizer: European Fire Sprinkler Network.

Arvidson, Magnus, “The response time of different sprinkler glass bulbs in a living room scenario”, Fire Sprinkler International 2016, Munich, April 19-20, 2016.

Arvidson, Magnus, “Practical experience from the installation of water mist systems. What can be learnt?”, International Water Mist Conference 2015, Amsterdam, October 28-29, 2015.

Arvidson, Magnus, “Keynote presentation: Fixed water-based fire-fighting systems for road tunnels: Performance objectives and the features of a standardized fire test protocol”, The 6th International Symposium on Tunnel Safety and Security, Marseille, March 12-14, 2014 (with paper).

2 Theoretical background

2.1 Different techniques for the atomisation of water

There are many industrial applications that involve atomising of liquids into smaller droplets. Examples include spray painting, application of glue over a surface, cooling and cleaning of gases, washing, humidification, combustion, dust control, etc. Fire suppression is in other words just one area where different types of nozzles and atomising techniques are used. The increased surface area per litre of water associated with smaller droplets dramatically increases the rate of heat transfer from the fire to the water droplets, with corresponding increased cooling of the flame and combustion gases combined with dilution of the oxygen concentration and generation of water vapor. There are several principles of atomising water into smaller droplets, as described below.

2.1.1 Hydraulic atomisation

This involves discharging the water through one or more relatively small nozzle orifices, the shape of which determines the spray pattern. This process normally works at a higher pressure, with a low flow rate. At some distance from the nozzle, depending on the various designs and operating parameters, the spray changes to a fine mist. A higher water pressure usually produces smaller droplets. Water pressures of up to 100 bar that are often used for such water mist fire protection systems which produce droplet sizes that are comparable with those produced by pneumatic atomisation (see below).

Another way of atomising the water is to make two or more jets impinge in the opening of a nozzle. There are commercial water mist nozzles that uses this principle of atomisation.

2.1.2 Pneumatic atomisation

This involves the use of compressed air or Nitrogen, which is supplied to the nozzle in a separate tube. Working pressures of both the water and the gas are normally low (less than about 10 bar). This principle normally produces the smallest water droplets of the most common techniques. If Nitrogen gas is used, the oxygen concentration inside a protected compartment may be reduced both by the gas and due to the formation of water vapor.

2.1.3 Mechanical atomisation

A water jet from a nozzle strikes a spreader plate that breaks up the jet and distributes the water as a spray. This method of atomising water produces the relatively largest water droplets of the three main principles and is typical for standard sprinklers where rather low water pressures, in the range from 0.5 bar to 5 bar are used. The design of the spreader plate (i.e. the deflector) can vary, to produce different spray patterns, although a flat, circular arrangement with slots is often used. Another variant is a cone shaped spiral.

Several other methods of atomising water have been developed, primarily for fire-fighting. The following are a few examples:

2.1.4 Atomisation by expanding gas

This uses compressed air or Nitrogen, connected directly into the water pipe system. The gas expands at the nozzle and helps to atomise the water. It produces very small water droplets, particularly if the gas flow volume is large in proportion to the water flow volume.

2.1.5 Ultrasonic atomization

New technology on the market includes systems where the water droplets are generated in a generator with a patented technology consisting of, among other things, an oscillating plate. Compared with a system using hydraulic atomization, the water droplets are significantly smaller, in the order of less than 10 µm compared to 50 µm to 150 µm. This means that the water droplets obtain physical properties similar to a gas, i.e. they are transported with air currents and can be distributed around obstructions. A similar technique is commonly used for humidification but at much lesser water flow rates.

2.1.6 Hybrid, dual agent supersonic nozzles

These nozzles atomize water using compressed air or Nitrogen into very small droplets. The droplets are carried by the gas stream that creates a high momentum that spread droplets several meters. The nozzles are designed to accelerate the gas flow to a supersonic velocity.

2.1.7 Superheated water

This method is based on heating of water in a pressure vessel to a temperature above its boiling point. However, as the water is not allowed to expand, it remains in the liquid phase. A control valve is opened and the pressure in the vessel drives the water into a pipe system. When it expands through a distribution nozzle to atmospheric pressure and room temperature, some of the water turns to steam, forming a cloud that consists of a mix of water vapor and small water droplets. The technique was specifically developed for fire suppression but as far it is known there is no commercial system on the marketplace.

2.2 Describing water droplet sizes

If a volume V of water is atomized into a monodispersed spray (droplets of uniform size) of N droplets, each droplet has a volume given by:

$$\frac{V}{N} = \frac{4}{3}\pi r^3 \qquad (1)$$

Where r is the radius of an individual droplet. For a monodispersed water spray, having N droplets with a surface area a, the total surface area A of the droplets are:

$$A = Na = \left(\frac{3V}{4\pi r^3}\right)(4\pi r^3) = \frac{3V}{r} \quad (2)$$

If the intent is to expose a maximum surface area of droplets to the surroundings, it requires droplets as small as possible. For any given volume of water, the total surface area is inversely proportional to the droplet size. In other words, if the droplet diameter is halved, the total surface area is doubled. A decrease of the droplet diameter by a factor of ten increases the number of droplets by a factor of 1000. Table 1 shows the calculated number of droplets and the total surface area of the droplets for 1 litre of water in a monodispersed water spray having selected water droplets diameters.

Table 1 The total number of droplets and the total surface area of the droplets for 1 litre of water in a monodispersed water spray having selected water droplets diameters.

Droplet diameter [µm]	Total number of droplets	Total surface area [m^2]
1000	1.91E+06	6
500	1.53E+07	12
250	1.22E+08	24
100	1.91E+09	60
50	3.06E+10	240
10	1.91E+12	600
1	1.91E+15	6000

A water spray from a nozzle contains a range of droplet sizes (polydisperse spray), often referred to as the droplet size distribution. The droplet size distribution is dependent on the nozzle type and can vary considerably from one nozzle type to another. Other factors such as the liquid properties, the water pressure and spray angle can also affect droplet sizes. It should also be understood that the droplet size measurement techniques, type of droplet size analyser and data analysis and reporting methods all have a strong influence on the results for a specific nozzle.

To compare the droplet sizes generated by one nozzle with another nozzle, the same characteristic diameters, which are extracted from the droplet size distribution, must be used. Figure 1 shows a typical droplet size distribution. Given below is a list of the most popular mean and characteristic diameters, definitions and most appropriate use as described by Schick (2008):

DV0.5: Volume Median Diameter (also known as VMD or MVD). The value where 50 % of the total volume (or mass) of the liquid spray is made up of droplets with diameters larger than the median value and 50 % smaller than the median value. This value is best used for comparing the average droplet sizes from various analysers.

DV0.1: A value where 10 % of the total volume (or mass) of the liquid spray is made up of droplets with diameters smaller or equal to this value. This diameter is best suited to evaluate drift potential of individual droplets.

DV0.9: A value where 90 % of the total volume (or mass) of the liquid spray is made up of droplets with diameters smaller or equal to this value. This measurement is best suited when complete evaporation of the spray is required.

D32: The Sauter Mean Diameter (also known as SMD) is the diameter of a droplet having the same volume to surface area ratio as the total volume of all the droplets to the total surface area of all the droplets. This diameter is best suited to calculate the efficiency and mass transfer rates in chemical reactions.

There are many other characteristic diameters, however, the ones listed above are stated in NFPA 750 (1996) and associated with water mist fire protection systems. This first edition of NFPA 750 from 1996 defined “water mist” as “A water spray for which the DV0.99, for the flow-weighted cumulative volumetric distribution of water droplets is less than 1000 µm within the nozzle operating pressure range." This characteristic diameter was chosen to intentionally include virtually all droplets of a water spray when determining whether a nozzle generated water mist. The definition used in CEN/TS 14972:2008 is similar, however, DV0.9 is used as the characteristic diameter of the water spray.

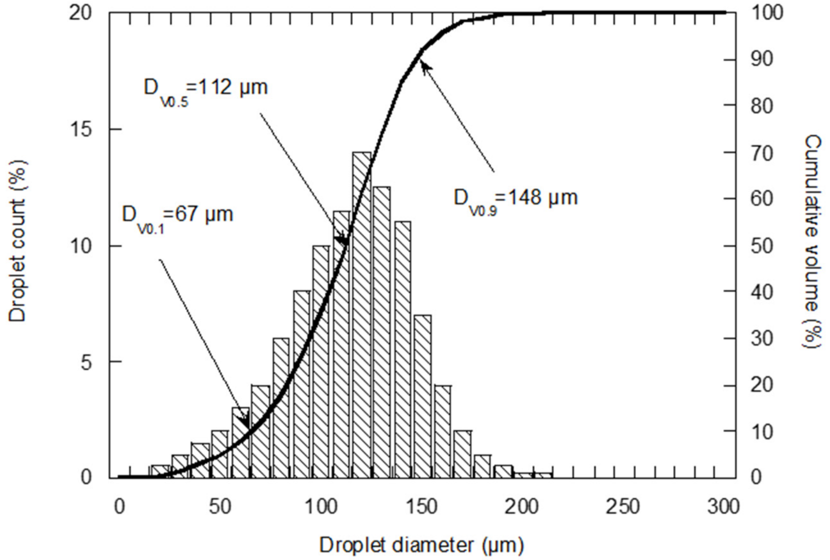

Figure 1 **A typical droplet size distribution, where some of the characteristics diameters that are commonly used are indicated. Illustration: Magnus Arvidson.**

2.3 Extinguishing mechanisms

The physical properties of water are probably well known but still worthwhile to mention:

- Freezing point 0 °C and boiling point approximately 100 °C.
- Density, approximately 1000 kg/m^3 at 25 °C.
- Heat of fusion of ice, 2.09 kJ/kg.
- Specific heat capacity in liquid phase, 4.18 kJ/kg °C, specific heat capacity in gas phase, 2.01 kJ/kg °C.
- Heat of vaporization at 100 °C, 2 260 kJ/kg.
- Expansion at the transition from liquid to gas phase at normal atmospheric pressure, approximately 1700 times.

Water is a very effective extinguishant, primarily due to its ability of absorbing heat in the liquid phase but specifically in connection with the phase change from liquid to gas. The extinguishing mechanisms can be said to consist of five main elements according to Mawhinney and Back (2016):

- Gas-phase cooling as the water is heated and converted into water vapor.
- Oxygen depletion by the formation of water vapor and flammable vapor dilution.
- Wetting and cooling of the fuel surface.
- Blocking of the transfer of radiant heat.
- Kinetic effects.

The two first points are the most important fire-fighting mechanisms when tackling flammable liquid fires in enclosed spaces with a low degree of ventilation. Absorption of thermal radiation is most effective if the water is applied to the fire in the form of (small) water droplets.

The fire extinguishing mechanisms listed above are relevant for both flammable liquid (Class B) spill and spray fires as well as ordinary combustible (Class A) fires. However, the importance of the mechanisms is different depending on for example the type of fuel, whether the fire is inside an enclosure or not, the ventilation conditions, etc. The influence of the mechanisms may also vary over time during the fire suppression or fire extinguishing process. So which is better, nozzles that produce relatively small droplets, or those that produce somewhat larger droplets? This is a question that is often asked, and to which there is no clear answer, although the results from trials indicate that smaller water droplets improve the ability to extinguish smaller, hidden fires in enclosed spaces (Arvidson and Hertzberg 2001).

Each of the mechanisms listed above are briefly discussed below based on the information by Mawhinney and Back (2016) but extended with information from other references.

2.3.1 Gas phase cooling

Gas phase cooling is the elimination of heat from the combustion zone as liquid water is heated, evaporates and water vapor continues to be heated. Figure 2 illustrates thermal energy of one litre of water when heated (Grant et al. 2000).

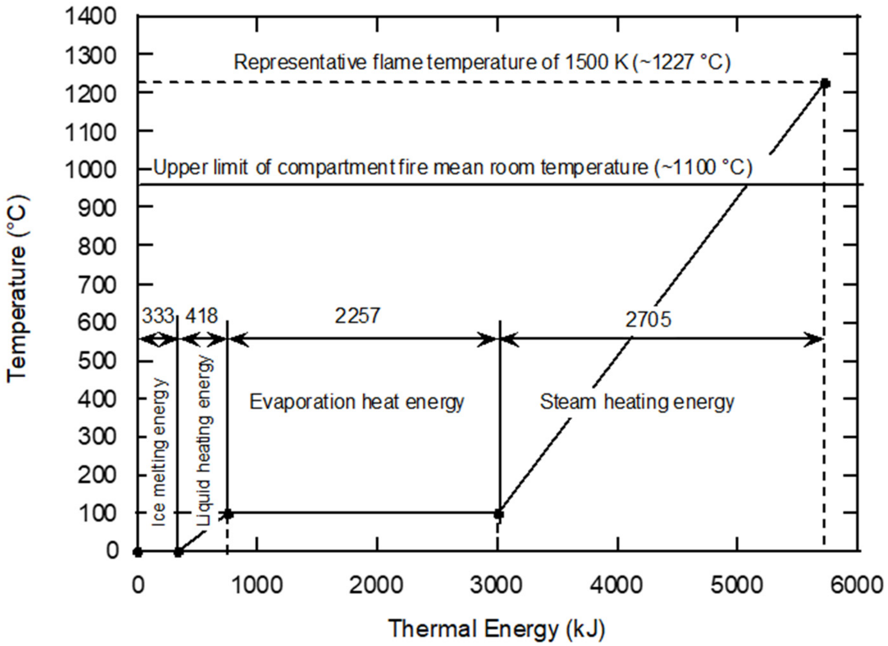

Figure 2 **The thermal energy of one litre of water that is heated, evaporates and where the water vapor is continuously heated. Reproduced from Grant et al. (2000).**

If the flame temperature of a fire is reduced below the limiting adiabatic temperature, the flame will be extinguished. The limiting adiabatic flame temperature is approximately 1600 K (1327 °C). The cooling of the flame also reduces the radiation (thermal feedback) to the fuel surface, which will reduce the rate of gasification or pyrolysis.

In general, cooling due to evaporation of the water proceeds more rapidly if a greater surface area of droplets is available and if the velocity of the droplets is higher, with as high a temperature difference as possible between the droplets and the ambient gas temperature. If the velocity of the droplets relative to the surrounding gas is too low, an insulating layer is created around each droplet, consisting of gas with a high concentration of water and at a (relatively) low temperature – relative to the ambient temperature of the surroundings. This prevents full use of the energy transfer potential (i.e. the difference in energy content of the gas and the liquid), and so evaporation occurs more slowly (Arvidson and Hertzberg 2001).

The rate of evaporation is directly proportional to the surface area of the droplet exposed to the heat, which in turn depends on the size of the droplets. As the total droplet surface area is inversely proportional to the size of the droplets, the rate of evaporation increases rapidly as the size of the droplets decreases. Hertzberg et al. (2004) have calculated the 'lifetime' of small water droplets in hot environments.

Table 2 shows the time to evaporation for different sized water droplets in environments having a temperature ranging from 150 °C to 600 °C.

Table 2 **The time to evaporation for different sized water droplets in environments having a temperature ranging from 150 °C to 600 °C (Hertzberg et al. 2004). Note that the time is given in milliseconds (ms) as well as in seconds (s).**

Water droplet diameter [µm]	**Temperature [°C]**				
	150	200	300	400	600
5	3.9 ms	1.8 ms	0.8 ms	0.5 ms	0.2 ms
10	15.6 ms	7.2 ms	3.1 ms	1.8 ms	0.8 ms
50	391 ms	179 ms	77 ms	45 ms	22 ms
100	1565 ms	716 ms	307 ms	181 ms	89 ms
300	29.7 s				
400	39.7 s				
500	49.6 s				

As illustrated, the time to evaporation is very short for smaller droplets, in the order of a few milliseconds to fractions of a second. For larger water droplets, the time to evaporation is significantly longer, i.e. several tens of seconds. Nozzles generating larger droplets are therefore preferable for applications where wetting and cooling of the fuel surfaces are desired and where droplets need to pass through the fire plume and the flame to reach the seat of the fire. Early Suppression Fast Response (ESFR) sprinklers is an example of a sprinkler for warehouse protection that is specifically designed to achieve this. These sprinklers are located at the ceiling as with conventional sprinklers but incorporates larger K-factors that delivers large, high-momentum water droplets to penetrate the fire plume. With fire suppression should be understood that the fire does not necessarily will be extinguished, the fire is rather “knocked” back down to its original point of origin (Yao, 1988).

2.3.2 Oxygen depletion and flammable vapor dilution

The vaporisation of water inside a flame and the volume expansion of the water droplets can interrupt the entrainment of air (oxygen gas) to the flame. This can be regarded as a local dilution effect. Inside an enclosure, the vaporisation of water reduces the oxygen concentration as a more global effect. For larger fires inside an enclosure, the oxygen depletion by the fire itself is an important effect. If the combined effects of oxygen depletion due to the fire and due to the water vapor can reduce the oxygen concentration below a critical value, the fire will be extinguished. For hydrocarbon fires, the minimum oxygen concentration is typically 13-vol% (Mawhinney and Back 2016).

Dry air constitutes of the following gases (ASHRAE 55, 2017), refer to Table 3.

Table 3 **Composition (per definition) of dry air (ASHRAE 55, 2017).**

Substance	Molecular weight		Mole fraction composition in dry air		Partial molecular weight in dry air
Oxygen (O_2)	32.000	×	0.2095	=	6.704
Nitrogen (N_2)	28.016	×	0.7809	=	21.878
Argon (Ar)	39.944	×	0.0093	=	0.371
Carbon dioxide (CO_2)	44.01	×	0.0003	=	0.013
Water vapor	18.016	×	-	=	-
			1,0000		28.966

This composition of dry air is per definition regarded as exact, but in reality, small amounts of other substances as Neon, Methane and Helium are present in the atmosphere. The amount of water vapor in air varies according to the temperature and density of air. Moist air may contain variable amounts of water vapor, from zero (dry air) to that of saturated moist air. The humidity ratio, W, is defined as the mass of water vapor per unit mass of dry air in a moist air mixture.

$$W = \frac{m_{vapor}}{m_{air}} \qquad (3)$$

Two measures of humidity relative to the saturation conditions are commonly used. The degree of saturation, μ, is defined as the relation:

$$\mu = \frac{W}{W_{sat}} \qquad (4)$$

Where W_{sat} is the humidity ratio at saturation for the same temperature and pressure as those of the actual state. The relative humidity, $\emptyset$, is defined as:

$$\emptyset = \frac{x_{vapor}}{x_{vapor,sat}} \qquad (5)$$

Where x_{vapor} is the mole fraction of the water vapor in the mixture and $x_{vapor,\ sat}$ is the mole fraction of water vapor for the same temperature and pressure as those of the actual state. The relative humidity is usually expressed as percentage rather than as fraction. If the air is fully saturated ($\emptyset$=1), W can be expressed as based on the Ideal gas law:

$$W = 0.622 \frac{P_{sat,t}}{P - P_{sat,t}} \qquad (6)$$

Where 0.622 is the ratio of the molecular weight of water (18.016) divided by the molecular weight of dry air (28.966), $Psat,\ t$ is the saturation vapor pressure at the actual temperature t and P is the atmospheric pressure (1 atm = 101.3 kPa).

Neither $\emptyset$ nor μ are defined when the temperature of moist air exceeds the saturation temperature of pure water corresponding to the moist air pressure. Thus for 1 atm (101.3 kPa), $\emptyset$ nor μ are undefined for temperatures higher than 100 °C.

There are several empirical equations to express the water vapor saturation pressure to sufficient accuracy. The following equation is valid in a range from approximately 0 °C and up to 95 °C:

$$P_{sat,t} = e^{\left(16.64 - \frac{4026}{t+235}\right)} \quad (6)$$

Where $P_{sat,\,t}$ is the water vapor saturation pressure in kPa and t is the temperature in °C. Table 4 shows the calculated water vapor saturation pressure and the humidity ratio at 1 atm (101.3 kPa) at selected temperatures up to 95 °C.

Table 4 **The calculated water vapor saturation pressure and humidity ratio at 1 atm (101.3 kPa) at selected temperatures up to 95 °C.**

Air temperature (°C)	Psat,t, saturation pressure (kPa)	W, humidity ratio at 1 atm (g/kg)
0	0.61	3.8
10	1.23	7.6
20	2.34	14.7
30	4.25	27.3
40	7.39	48.9
50	12.35	86.4
60	19.94	152.4
70	31.19	276.7
80	47.42	547.4
90	70.27	1408.4
95	84.77	3190.9

When the water vapor content increases in moist air, the relative amount of the other gases decreases per unit volume and the density of the mix decreases since water vapor is lighter than air.

The partial pressure is defined as the pressure of a single gas component in a mixture of gases. It corresponds to the total pressure which the single gas component would apply if it alone occupied the whole volume. The partial oxygen pressure can be calculated given the relative humidity, the ambient temperature and the total atmospheric pressure. The partial oxygen pressure then equates to:

$$P_{O_2} = \left(P - P_{vapor}\right) \times 0.2095 \quad (7)$$

Where P_{O2} is the partial pressure of oxygen in kPa, P is the atmospheric pressure in kPa and P_{vapor} is the partial pressure of water vapor in air in kPa. Given the partial oxygen pressure and the atmospheric pressure P the volumetric content of oxygen can be calculated as:

$$Vol\%(O_2) = \frac{P_{O2}}{P} \times 100 \quad (8)$$

The effect of humidity on reducing the partial oxygen pressure and therefore the volumetric content of oxygen, if the air is fully saturated (Ø=1) and the atmospheric pressure remains at 1 atm (101.3 kPa), is exemplified in Figure 3.

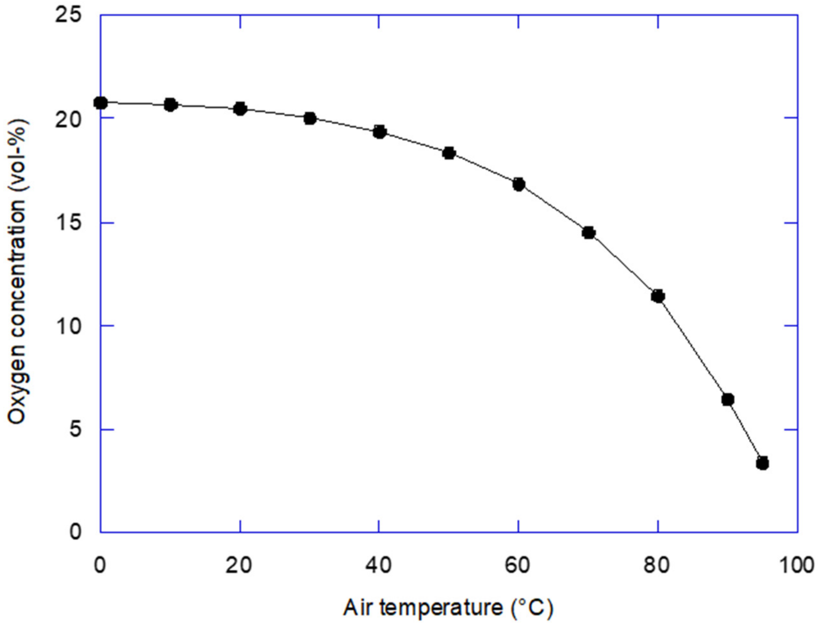

Figure 3 **The effect of humidity on reducing the volumetric content of oxygen if the air is fully saturated (Ø=1) and the atmospheric pressure remains at 1 atm (101.3 kPa).**

From this graph it appears that the oxygen concentration is around 13 vol-%, i.e. sufficiently low for the extinguishment of a hydrocarbon fire inside an enclosure at an air temperature of around 75 °C if the air is fully saturated.

2.3.3 Wetting and cooling of the fuel surface

Wetting and cooling of the fuel surface is a mechanism associated with ordinary combustibles, i.e. solid fuels, and flammable liquids with a flashpoint above normal ambient temperature as high flashpoint hydrocarbon liquids. Naturally, it requires that the water droplets can penetrate the fire plume and reach to the burning surface. Water droplets (or run off water) that reach burning surfaces is heated, evaporates and cools the surface. This cooling will reduce the pyrolysis or gasification rate of the fuel (Mawhinney and Back 2016).

If the pyrolysis rate of solid fuels become small enough, equivalent to a heat release rate of in the order of 50 kW to 75 kW per square meter, flames cannot exist above the surface. Theory and experiments show that approximately 2 g/s per square meter of water is required for fire extinguishment of wood (where the rate of pyrolysis is less than approximately 5 g/s per square meter). If the surface is exposed to a heat flux of for example 25 kW/m^2, the water amount needs to be increased to 10 g/s per square meter (Hertzberg et al. 2004).

If the vapor-air mixture above the fuel surface is reduced below the lower flammability limit (LFL) of the fuel, the flame will be extinguished.

2.3.4 Blocking of the transfer of radiant heat

Water mist and water vapor reduce radiant heat flux from a fire to nearby objects, which can limit or prevent fire spread to combustible material or fuel or limit or prevent thermal damage to critical objects. Within the combustion zone, radiation attenuation is the result of gas phase cooling and an increase in the amount of water vapor between the fuel and the flame. The main mechanisms of radiation attenuation by a water spray is absorption and scattering by water droplets and absorption by water vapor (Mawhinney and Back 2016).

Dombrovsky et al. (2016) have developed a simplified theoretical model for the attenuation of heat radiation by water mist. The model is based on the calculation of the absorption and scattering characteristics of water droplets, local 1-D solutions for radiative heat transfer through the mist layer, and a transient heat transfer model considering heating and evaporation of the droplets. A case study using the simplified theoretical model shows that a water mist spray containing relatively small droplets is efficient in heat radiation attenuation due to a large value of the attenuation parameter of smaller droplets. However, the volumetric absorption of the incident radiation near the irradiated surface of the mist and low velocities of the falling droplets will lead to a high rate evaporation of droplets. For very large droplets, the radiation is not practically reflected from the mist because of low scattering properties of larger droplets. If a water spray with large droplets are used, a considerable attenuation of the fire radiation require a geometrically thick mist layer with a high flow rate of water.

Försth and Möller (2011) have used Mie theory to study the interaction between radiation from fires and single water droplets. It was found that a reduction of the droplet diameter, down to 1 µm – 10 µm, improves the volumetric radiation absorption efficiency. Decreasing the diameter further does not lead to improved volumetric absorption since the Rayleigh limit is reached, where the volumetric absorption is independent of the diameter. Fact is that there was a maximum in volumetric absorption occurring for droplets with 1 µm – 10 µm diameter.

2.3.5 Kinetic effects

Kinetic effects may contribute either to flame intensification or to fire extinguishment. It is likely that entrainment and turbulence generated by the mist may result in flare up of a flame and for flammable liquid spill fires, intensification of a fire could be caused by splattering of droplets in heated oil. But kinetic effect may also contribute to flame suppression as water droplets, water vapor and combustion gases are added to the combustion reaction (Mawhinney and Back 2016). Flame intensification was observed when testing a high-pressure water mist system for residential area applications. Visually, it was judged that the water mist nozzles entrained air to the flame that made the fire burn more intensely. The effect was not noted with traditional residential sprinklers (Arvidson and Larsson, 2001).

2.4 The application of water mist fire protection systems

Water mist fire protection systems have been suggested, tested and are used for a broad range of applications and fire hazards. The following section summarises some of these application and experience from fire testing.

Marine engine rooms and gas turbine enclosures belong to the applications for which a great number of fire tests have been carried out. A common feature of these applications is that the primary fire risk consists of leaks of fuel, lubricating oil or hydraulic oil coming into contact with hot surfaces and catching fire. This could create fuel or oil spray or spill fires. Most of the investigations that have been carried out come to much the same conclusions; 1) large fires are rapidly extinguished, 2) smaller fires take longer to put out, and 3) it is difficult to extinguish smaller fires that are ‘hidden’ by obstructions from the direct application of water (Back et al., 2000).

Electronic equipment, electrical equipment and computer rooms have traditionally been protected by gas extinguishing systems, such as halon or carbon dioxide systems. Fires in such environments generally spread relatively slowly, and it tends to be the smoke, rather than the heat from the fire, that is the major problem. In the mid-1990s, a number of fire tests using water mist for applications such as these were carried out. The fires are usually far too small to evaporate any water droplets outside of the flame, and therefore direct application of the water to the burning surface is required to suppress or extinguish a fire. This means that the nozzles must be installed inside the computer or electrical cubicles to be effective. However, systems are available on the marketplace that have been developed to wash the smoke and to extinguish fires, but they require a certain input of inert gas (usually Nitrogen) for fire extinguishment (Arvidson and Hertzberg 2001).

Water mist fire protection systems are also used in applications where traditional fire sprinklers are common, and particularly in areas that are lightly or moderately loaded non storage and non-manufacturing areas with ordinary combustibles where an expected fire will develop relatively slowly. Typical examples are residential areas, hotels, office spaces and heritage buildings. Arvidson (2017) have compared the performance of residential fire sprinklers with automatic commercial low- and high-pressure water mist nozzles. For most of the tests, the flow rate of the residential sprinkler was 30.3 litres/min (corresponding to the minimum design density of 2.05 mm/min as per the recommendations in NFPA 13D and 13R). Additional tests were conducted at 60.6 litres/min which equals the minimum design density of 4.1 mm/min as per NFPA 13.The flow rates of the water mist nozzles ranged from 17.2 litres/min to 36.7 litres/min. Roughly, it could be concluded that the performance of the water mist nozzles was comparable or better than the residential sprinklers at approximately half the water flow rate for the tested fire scenarios.

Protection of prison cells represents another application where mist may be a good fit, both in terms of permanently installed automatic systems and for manual fire-fighting. The fuel loading in prisons cells is limited and the compartment volume is small, however, many fires are intentionally started. Large-scale fire sprinkler and water mist fire protection system tests were conducted at BRE Global using an authentic fire loading that was partly shielded from the direct application of water. A free-burn fire tests showed that the environment inside the cell is hazardous after about 10 minutes due to high temperatures and toxic gases. The automatic fire sprinkler that was tested activated after about 7 minutes and controlled the fire. The performance of the sprinkler was relatively the worst compared with the tested water mist fire protection systems, but the environment was survivable. The fixed water mist fire protection systems provided at least fire control, but the performance varied significantly, both in terms of fire suppression performance and in terms of the environmental conditions inside the cell. The gas temperatures were generally low and four of these tests were specifically interesting as the water distribution tests (without fire) showed that very little water reached the fire loading. However, during the fire tests the fire size increased but was suddenly suppressed or extinguished within a few minutes, even though the measured oxygen concentration was relatively high and theoretically sufficient to maintain a fire. The reason for the phenomena was likely that the amount of water vapor increased with the temperature which suppressed the fire. This indicates that a fire inside a small and reasonably enclosed room cannot reach a certain level in the presence of water mist and water vapor. The water flow rates of the water mist nozzles were between 9 % to 70 % of the fire sprinkler. The effectiveness did not necessarily improve with a higher flow rate but the nozzle with the lowest flow rate was not the most efficient either (Annable and Shipp 2008).

Attempts are made to expand the application of water mist fire protection systems from light to ordinary hazard occupancies. Yu et al. (2019) have conducted large scale fire tests comparing standard orifice sprinklers and low-pressure water mist nozzles. All fire tests were conducted under a large-scale calorimeter and water discharge was initiated at a designated heat release rate. Two fuel arrays were used, a 2.74 m high rack arrangement involving three layers of double wall cardboard cartons with non-combustible content and a 1.20 m high palletized configuration with single wall cardboard cartons with polystyrene meat trays. For the tests using the former fuel array, a grid of four open sprinklers or nozzles were positioned 4.42 m above floor and was discharging 6.1 mm/min. For the latter fuel array, the nozzle grid was positioned 2.90 m above floor and was discharging 8.1 mm/min. The vertical distance from the top of the fuel array was thereby maintained at about 1.7 m in both test series. The operating pressure of the water mist nozzles ranged from 16.5 bar to 100 bar. The performance of the tested systems is influenced by the amount of water that can reach the top of a burning fuel array. This amount depends on the droplets’ fire plume penetration capability and the droplet volume preservation during the passage through the fire plume. For the same discharge rate, the spray thrust force increases as the nozzle orifice size decreases due to the higher discharge velocity. But this will also generate smaller droplets. The test results showed that the droplet penetration capability of the fire plume and the droplet lifetimes are reduced with smaller droplets. Therefore, for the same discharge density and nozzle distance above the fire, a water spray with a higher starting thrust force may not necessarily project a greater water flux to the top of fuel array through the fire plume. In order to provide comparable fire suppression results to a traditional sprinkler system (in an open environment), a water mist fire protection system require comparable application densities.

Road tunnels are an application where fire sprinkler systems are not particularly common. Increased traffic on the road network, increasing numbers of tunnels and especially several serious tunnel fires have pioneered sprinklers in road tunnels. Water mist fire protection systems have been promoted as an alternative to traditional sprinkler or water spray systems and in recent years several extensive large-scale fire tests have been conducted. The tests show that the systems' advantages are primarily the cooling of hot gases, which limits the thermal exposure to the tunnel construction, and the prevention of spread of fire to nearby vehicles. A similar application is the protection of the parking garages for cars. Several test series show that water mist is comparable in performance to traditional sprinkler systems, although the distance between the nozzles is often higher and water flow rates lower (Arvidson 2014).

3 Research results

In this chapter, the objectives and key findings for each of the six appended papers are presented. It can be concluded, based on the description in Chapter 1, that there is a need for documenting the development of modern water mist technology and the associated fire test procedures, new or revised methodologies for fire testing need to be established and experience from actual installations need to be documented.

A common denominator is that all papers have been initiated due to a specific question or request from market actors. Text, figures and the conclusions in this section are, to a large extent, reproduced from the papers. A more comprehensive understanding of the conducted research can be obtained by reading the detailed papers.

3.1 Paper I: The history of the development of modern water mist system technology in Sweden

For Paper I, the overall objective was to document the history of the development of water mist system technology in Sweden, with a focus on fixed installed systems. This history was untold and very few knew that the development of commercial systems started as early as the 1970s. Another motivation for the study was to give credit to the people that pioneered the technology and were able to 'think outside of the box' long before the commercial break through of water mist technology in the beginning of the 1990s. The final objective was to inspire others to document the history of water mist technology in other parts of the world. The work is based on a literature review, a search in the archives of RISE and by interviews with the key people still alive.

The study showed that the very first commercial, fixed high-pressure water mist systems were developed in Sweden during the late 1970s and early 1980s by people like Omar Vestli and Håkan Ungerth from the companies Electrolux Euroclean AB and (later) HTC i Åmål AB as well as Krister Giselsson and Mats Rosander from the companies GIRO Brand AB and (later) ULTRA FOG AB. These companies independently, and to some extent in collaboration, developed systems for the protection of hotels, passenger ship cabins and flammable liquid hazards. Very early, these people saw the potential and benefits of water mist technology.

During the late 1970s, Electrolux Euroclean AB, situated in Åmål in Sweden, marketed high-pressure cleaning equipment. Market penetration was quite broad, and one application involved small fast food kiosks, where the cleaning equipment was used to wash the cooking equipment and the floor. On one occasion, a fire started in a deep fat fryer and the personnel used – in lieu of other suitable equipment – the high-pressure cleaner to tackle the fire. Surprisingly, the fire was instantaneously extinguished. Soon after this, the company decided to develop a high-pressure water mist system for fire protection purposes. The primary application was the protection of deep fat fryers and similar equipment, although the next step in the development process involved flammable liquid fires in enclosed machinery spaces. According to participants in these first investigations, fire tests were conducted in the backyard of the company in a test compartment, to explore the possibilities of the technology, but it has not been possible to locate documentation of these tests. There is, however, documentation available from fire tests conducted at the Norwegian Fire Protection Training Institute in September 1981.

In April 1983, the company approached SP Technical Research Institute of Sweden to conduct third party tests of the system. During these tests, multiple orifice nozzles supplied by Spraying Systems Co. were used. However, in 1984 or 1985 Electrolux Euroclean AB began to manufacture nozzles designed within the company. This facilitated experimentation with different micro nozzles and spray angles. The micro nozzles that were used as a basis for this developmental work were purchased from Monarch Manufacturing Works, Inc. and originally used as oil burner nozzles.

Figure 4 shows a high-pressure automatic (i.e. with a glass bulb) multi-orifice type nozzle, with a nozzle body having five micro nozzles developed by HTC i Åmål AB in the late 1980s or early 1990s. The system operating pressure was 100 bar and the measured flow rate was 6.0 litres/minute. The nozzle was fitted with a standard response glass bulb, having a nominal operating temperature of 68 °C.

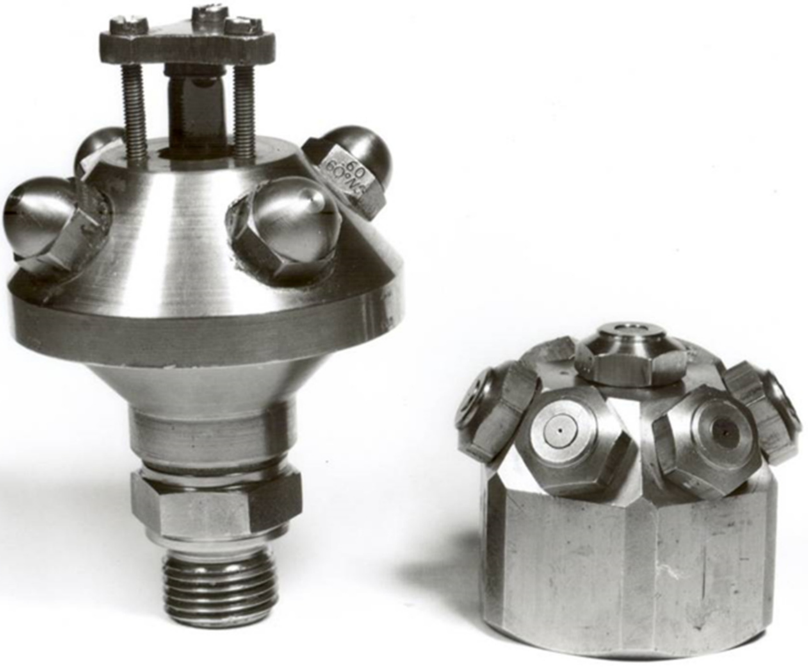

Figure 4 **A very early automatic (with glass bulb) multi-orifice nozzle developed by HTC i Åmål AB along with a "1 7N2 Fogjet" nozzle from Spraying Systems Co. (to the right) that was tested at SP in 1983. Photo: Håkan Ungerth.**

Krister Giselsson graduated as a fire protection engineer in 1969 and after a number of years at the fire departments of Sollentuna and Helsingborg, he was given a position as a teacher at the Swedish Fire School in Stockholm in 1974. In the early 1970s, while working as a fire protection engineer, Giselsson carried out numerous test burns in derelict buildings which were scheduled to be demolished to make way for new constructions. This provided the opportunity to gain experience of fire spread and fire phenomena under a variety of conditions. One observation was that fire behaved very differently in rooms that were completely dried out as compared to rooms that had been unoccupied for some time and had broken windows. Probably as small amount of moisture absorbed in the building material of the walls and the ceiling of rooms which had been exposed to the elements affected the development of the fire.

In 1975, Giselsson was given the job of investigating flashover and fire spread phenomena and found that part of the explanation for these earlier observations, i.e. that a small quantity of water reduces the temperature of the combustion gases and lowers the flammability in the compartment. This is enough to delay or prevent flashover. In many cases less than one litres of water is needed. The use of finely atomized water is an application based on this knowledge. Small water droplets are suspended in the air and prevent flashover. The smallest amount of water recorded to show this effect inside an otherwise dry room in a wood building with 30 m^2 floor area, was 0.8 litres/min. This corresponds to 0.027 litres/m^3 per minute.

In 1976, fire tests were undertaken at the Fire Department of Lidingö, where outdoor gasoline pool fires, sized approximately 4 m^2, were extinguished with a hand-held nozzle that produced finely dispersed water droplets at 300 bar.

Mats Rosander graduated as a fire protection engineer in 1977 and established collaboration with Giselsson in the company GIRO Brand AB that was started in 1978. Rosander also received employment as a teacher at the Swedish Fire School in Stockholm, responsible for active fire-fighting.

In 1980, Krister Giselsson and Mats Rosander began to experiment with extremely fine water droplets in compartment fires and for this reason they established collaboration with Electrolux Euroclean AB who provided the high-pressure pump units. Later, they were also supported by Kjell Rognmo, a fire protection engineer (graduated in 1979) from the fire department in Stockholm. The same year, the work by Giselsson and Rosander was recognized by "Styrelsen för teknisk utveckling (STU)", the governmental institution responsible for financing industrial research in the 1970s and 1980s, in a compilation that discusses the needs for technical improvements of the equipment used by the fire services. The compilation lists three optional nozzles for manual fire-fighting able to replace the traditional type of nozzle. The list includes the use of high-pressure water mist nozzles and reflects on the possibility of using the technology for sprinkler systems.

Several documented fire test series were conducted as part of this development, some for invited audiences. In May 1982, Krister Giselsson and Mats Rosander organised fire tests in a derelict house in Rotebro, Sollentuna, north west of Stockholm. The tests were conducted on the bottom storey of a two-storey domestic dwelling, refer to Figure 5. The system that was tested consisted of a high-pressure pump unit supplied by Electrolux Euroclean AB. The pump unit had a maximum capacity of 13 litres/min at 175 bar, however, the pressure could be adjusted through a pressure regulation valve. The power generator that was available could reach a maximum pressure of 150 bar.

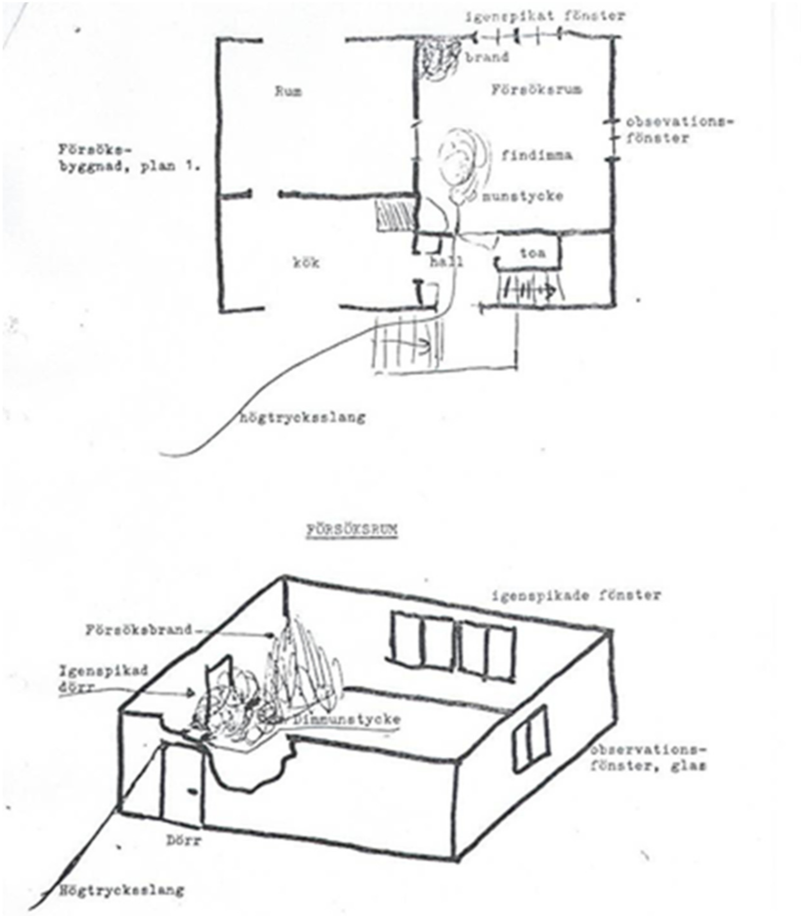

Figure 5 A sketch from the fire tests conducted in Sollentuna in May 1982. Illustration: Krister Giselsson.

The report from the tests concludes that fixed sprinkler systems with finely atomized water are useful in different types of buildings. A typical domestic dwelling with five living rooms, a hallway, a bathroom and five additional rooms could be protected with about 15 nozzles and a total flow rate of 60 litres/min. If activated simultaneously, the electrical power demand of around 15 kW could, however, be a practical problem. An alternative solution could be that the system is activated in sections, thus reducing the power demand to about 5 kW.

Unfortunately, these companies and the people that pioneered the high-pressure water mist technology had limited commercial success due to low initial returns on high investments. Their ideas and knowledge, however, have formed the basis for commercialisation of the systems by other companies that were ultimately more successful on the marketplace.

An obvious limitation of the study was that several of the people that participated in the worked had passed away. This underlines the importance of the time factor in a study like this.

3.2 Paper II: The background and the development of the guidelines in IMO Resolution A.800(19)

Paper II contains a chronological description of the background and the development process of IMO Resolution A.800(19). This IMO standard contains installation guidelines and fire test procedures for 'equivalent' sprinkler systems used as an alternative to traditional sprinkler systems for accommodation and public spaces on-board passenger ships. The history is especially interesting as it was the starting point for the development and the commercialization of the water mist fire protection system technology. Several other internationally recognized fire test procedures and installation standards for water mist fire protection systems have been based or at least inspired by IMO Resolution A.800(19). The author participated in the work at IMO when the standard was developed, and the compilation was based on documentation from IMO as well as own notes, documents and reports.

The work at IMO was initiated in May 1991 at the 59th session of the Maritime Safety Committee that instructed the Sub Committee on Fire Protection to develop guidelines for the approval of equivalent sprinkler systems. The work was finalised in May 1992 at FP37 and IMO adopted Resolution A.755(18), containing guidelines for the approval of sprinkler systems equivalent to that referred to in SOLAS Regulation II 2/12, in 1993. The guidelines are the very first international installation guidelines for water mist fire protection systems.

With these requirements as the basis, the process of developing fire test procedures and a component manufacturing standard for nozzles started at FP38 in 1993. The fire test procedures were required to cover the wide variety of fire load, fuel arrangements, room geometries and ventilation conditions typically found on-board passenger ships. This is reflected by the fact that several different fire scenarios are included:

- Cabin fire tests.
- Corridor fire tests.
- Luxury cabin fire tests.
- Open and corner public space fire tests.
- Shopping & Storage area fire tests.

The acceptance criteria, in terms of maximum allowed ceiling surface or ceiling gas temperatures and maximum allowed fire damage for all the fire scenarios listed above are directly or indirectly based on the performance of standard sprinklers. The acceptance criteria for the cabin, corridor and public space fire tests were establish based on reference sprinkler tests conducted at the fire test laboratories of SP and VTT in 1995. The fire source of the Luxury cabin fire tests was taken directly from the residential sprinkler fire tests used by Underwriters Laboratories Inc. and FM Global, respectively. Therefore, the acceptance criteria were adopted directly from these standards. For the Shopping & Storage area fire tests, no reference sprinkler tests were conducted. The fuel package for the tests was implemented from a series of sprinkler tests at FM Global in 1989. However, these tests were conducted with a ceiling height of 6.1 m and the vertical distance measured from the top of the commodity stacks to the ceiling was 3.7 m. For the Shopping & Storage area fire tests, the vertical distance measured from the top of the commodity stacks to the ceiling is only 1.0 m, reflecting actual conditions on-board a ship. As a result, no ceiling gas temperature requirements are given, the performance of the tested is system is based on the fire loss of the main array and the potential for fire spread to target arrays.

In some respects, it can be argued that the performance requirements for alternative systems is set higher compared to the expected performance of traditional sprinkler systems, for example since a certain performance is expected even when a nozzle is disabled. This is usually not required for traditional sprinklers. On the other hand, the efficiency and reliability of traditional sprinkler technology has been proven over more than 100 years and it should be recognised that some of the requirements reflect concerns with introducing new technologies.

The study was based on documentation from IMO as well as own notes, documents and reports. No other people from the working group at IMO was involved, which to some extent make the description of the development work biased. A delegate from Finland (Maarit Tuomisaari) that also was involved in the work was, however, given the opportunity to read and comment on the paper before it was published.

3.3 Paper III: A novel method to evaluate fire test performance of water mist and water spray total compartment protection

Paper III contains an experimental study where the performance of total compartment water mist and water spray fire protection systems intended for machinery space protection was compared. The paper does also suggest how fire test procedures can be improved by simple and inexpensive measurements and performance measurement parameters.

Two series of tests were conducted: the first inside a 500 m^3 test compartment, the second inside a 250 m^3 test compartment. The ceiling heights were identical at 5.0 m. The walls and the ceiling were constructed from nominally 2 mm thick steel sheets.

Diesel oil and heptane pool fires having nominal HRRs of 250 kW, 500 kW, 1 MW and 2 MW, respectively, were used and the pool fire trays were either fully exposed to the water spray (unobstructed) or completely shielded by a horizontal steel plate obstruction measuring 2.0 m by 2.0 m. The vertical distance measured from the rim of the fire tray to the bottom of the steel plate was 0.7 m. In order to be able to calculate the HRRs of the fires, the weight loss of the fire tray was measured using a load cell. These measurements were only valid for the cases where the pool fires were completely shielded by the horizontal steel plate obstruction since direct droplet impingement on the fuel surface would influence the reading. Figure 6 shows one of the pool fire trays when positioned on the load cell under the obstruction steel plate.

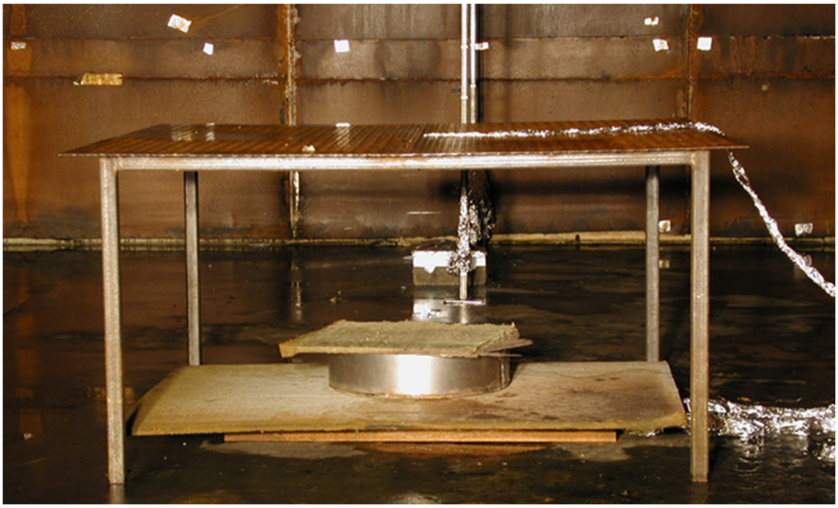

Figure 6 One of the pool fire trays when positioned on the load cell under the obstruction steel plate. Photo: Magnus Arvidson.

In addition, the test compartments were instrumented to measure the gas, wall and ceiling temperatures, the radiant heat flux from the fires, the compartment pressure and the gas concentrations of O_2, CO and CO_2.

Some of the findings and suggestions of the paper are summarised here. The following system denotations are used; WS: water spray system; LP: low-pressure water mist system; HP: high-pressure water mist system; HPLF: high-pressure low flow water mist system.

Instead of using the time to extinguishment, which is used in most standardized fire test procedures as the single parameter to evaluate the test results, additional parameters were studied. During the tests, the fire suppression capability of the systems, their temperature reduction capability and their ability to mix water vapor, water droplets and combustion gases within the compartment were determined. These parameters provided a more complete picture of system performance. Figure 7 shows the Total Heat Release (THR) for five system tests inside the 250 m^3 test compartment with the obstructed 250 kW heptane pool fire. The ranking of the tested systems is identical with the ranking obtained in the tests inside the large test compartment. In addition, it can be observed that the WS and HPLF systems shows the least fire suppression capability of the tested systems.

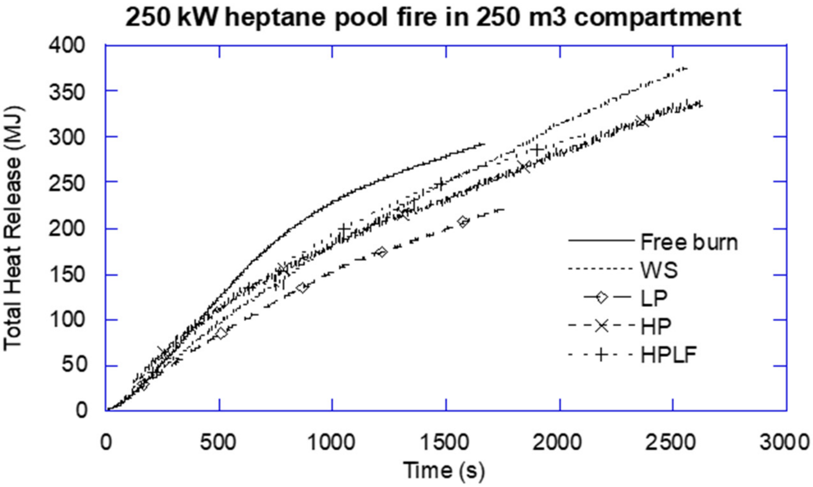

Figure 7 **The THR for the tests with the obstructed 250 kW heptane pool fire inside the 250 m^3 test compartment. The lines of the graph are cut at the extinguishment of the fire. Adapted from Paper III.**

Figure 8 shows the average gas temperatures inside the 250 m^3 test compartment with the obstructed 250 kW heptane pool fire. For these tests, the HPLF system provides the least cooling, which is consistent with its low water flow rate. The other systems are ranked in the same order as the tests conducted in the 500 m^3 test compartment with the 500 kW fire source. Furthermore, it was observed that the temperature levels were comparable for both test compartment volumes.

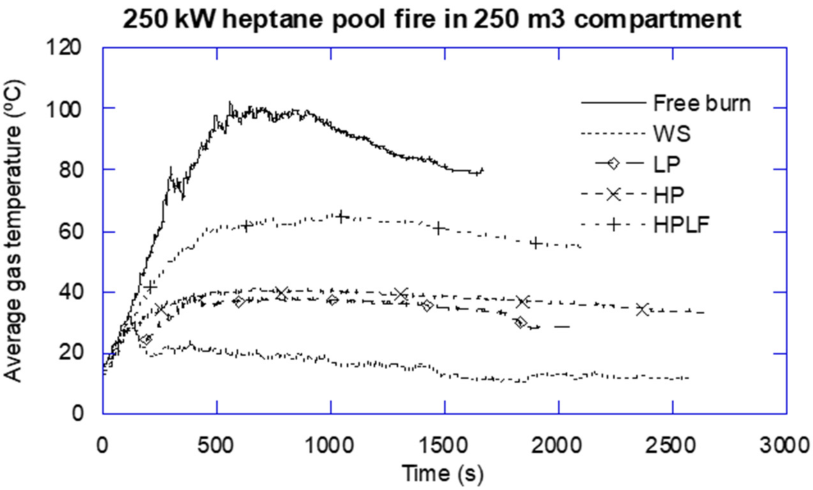

Figure 8 **The average gas temperature for the tests with the obstructed 250 kW heptane pool fire inside the 250 m^3 test compartment. The lines of the graph are cut at the extinguishment of the fire. Adapted from Paper III.**

In order to determine and quantify the temperature uniformity of the tested systems, a Temperature Uniformity Factor (TUF) was introduced. This factor expresses the temperature uniformity inside the test compartment, as a function of time. The lower the value, the more uniform the temperature.

Figure 9 shows the TUF for the obstructed 250 kW heptane pool fire tests inside the 250 m^3 test compartment.

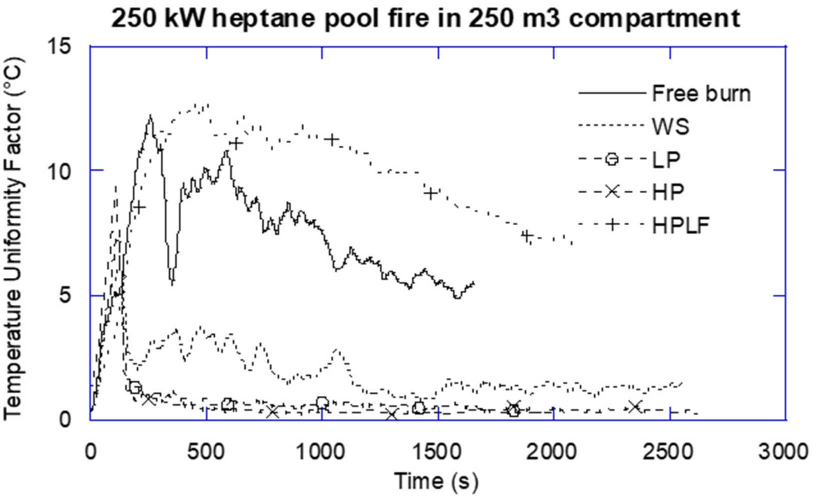

Figure 9 **The TUF for the tests using the obstructed 250 kW heptane pool fire inside the 250 m^3 test compartment. The lines of the graph are cut at the extinguishment of the fire. Adapted from Paper III.**

The HPLF system provides, by far, the poorest mixing for all fire scenarios in the 250 m^3 test compartment. This is no doubt due to the low momentum of the water spray and the low water flow rate.

Typically, the times to extinguishment ranged from around 2 minutes for the largest fires to between 30 and 40 minutes for the smallest fires. It was also observed that gas temperatures were significantly reduced upon system activation and larger fires were easier and faster to extinguish than smaller fires.

However, in addition, there were other findings of interest. The time to extinguishment was not repeatable, even under identical test conditions. The tests that were repeated in the 500 m^3 test compartment show a 20 % to 80 % variation in time to extinguishment. Repeatability was better for the tests in the 250 m^3 test compartment; however, the variation was between 30 % and 40 % for several of these tests. In several different cases it was also observed that the free burning fires self-extinguished, due to oxygen depletion, at least as fast as the fires were extinguished by the tested systems.

The tests and the test results show that ‘time to extinguishment’ should not be the only parameter considered when the performance of a water mist or water spray fire protection system is evaluated. Extinguishment is naturally desirable but focus on this parameter alone can lead to misinterpretation of test results with subsequent reliance on ineffective systems. As an example, the performance of the HPLF system would be judged as comparable or even superior to the HP system when judged exclusively on time to extinguishment, for a specific fire scenario. In fact, the HPLF system does not provide fire suppression capability, gas phase cooling and temperature uniformity nearly as well as the HP system or any of the other tested systems.

If supplemented by other relevant parameters, the understanding of system performance is enhanced, and the performance of the system can be related to such objectives as fire suppression capability, the probability for fire spreading inside the protected compartment, fire spreading to adjacent compartments, as well as accessibility for manual fire fighting. The three suggested parameters are not independent of each other; for example, if the fire size is reduced, the gas temperature is also reduced. Moreover, there is a relationship between these parameters and the time to extinguishment. The water vapor concentration increases significantly as the temperature rises, and an increase in gas temperature could therefore potentially reduce time to extinguishment. Despite these relationships, the use of the additional parameters gives a broader understanding of system performance during testing.

As with any large-scale fire testing, the inclusion of relevant system technologies is a matter of cost and therefore a limitation. Preferably, additional types of systems should have been included and additional tests would have made a statistical evaluation approach possible.

3.4 Paper IV: Large-scale water spray and water mist fire suppression system tests for the protection of ro-ro cargo spaces on ships

Paper IV summarises a series of large-scale fire suppression tests conducted to simulate a fire in the trailer of a heavy goods freight truck in a roll-on roll-off (ro-ro) cargo space. These large open spaces make it possible for fire to spread over a large area, the fire loading is very high, and a fire is potentially fully shielded by the body of a vehicle coupled to a reduced ability for egress and manual intervention.

The fire suppression tests were conducted using a freight truck trailer mock-up with authentic geometry. The tests were designed to vary the following parameters; the system technology, i.e. both a traditional water spray system and high-pressure water mist system was tested, the water discharge density, the water pressure (water spray system only) while maintaining the water discharge density, thereby varying the droplet size and the momentum of the water spray and finally the exposure of the fire was varied by using or not using a roof on the trailer mock-up.

The mock-up was constructed from square iron rods and the bottom and the roof of the platform of the mock-up was constructed from steel plates. Six rows of commodity were positioned on the platform such that longitudinal and transversal gaps of 100 mm were created between the stacks of commodity. For the tests using a roof over the trailer mock-up the number of commodity pallets was reduced to two rows, i.e. one third of the amount of commodity used for the tests without the roof. Figure 10 shows the test set ups during fire testing.

Figure 10. An illustration of the arrangement of the commodity on the trailer mock-up with and without the roof. Steel sheet screens instrumented with thermocouples were positioned on either of the long sides. Note that less amount of commodity was used for the latter tests. Photos: Magnus Arvidson.

A steel sheet (nominally 0.8 mm thick) screen was positioned parallel with the long sides of the trailer mock-up. The screens had a height (2.8 m) that corresponded to the height of the 'cargo space' of the mock-up. The tops of the screens were levelled with the top level of the roof over the trailer mock-up, i.e. 4.0 m above floor level. The length of 2.7 m was shorter than the overall length of the mock-up but covered the two central stacks of commodity and extended halfway along the length (on either side) of the adjacent stacks. The surface temperatures of the steel screens were measured at 18 different measurement points.

A standardized commodity, the EUR Std Plastic commodity, was used as the fire load. It consists of empty Polystyrene (PP) cups without lids, placed upside down (i.e. open end down), in compartmented cartons, 120 cups per carton. The cartons are made from single-wall, corrugated cardboard. Each wood pallet in the tests contained a total of eight commodity cartons.

Table 5 summarizes the water spray and high-pressure water mist nozzles used in the tests, their K-factor, the nominal water discharge density, the system operating pressure and the estimated median droplet size.

Table 5. **The water spray and high-pressure water mist nozzles used in the tests.**

System	Nominal discharge density [mm/min]	Nozzle K-factor [metric]	Minimum orifice diameter [mm]	System operating pressure [bar]	Water flow rate per nozzle [L/min]	Estimated median droplet size [µm]
Water spray	5	43.2	8.3	1.2	48	889
Water spray	10	80.6	11.1	1.4	96	1028
Water spray	10	43.2	8.3	4.9	96	559
Water spray	15	103.7	12.7	1.9	144	1014
Water mist	3.75	3.6	-	100	36	~150
Water mist	4.6	4.4	-	100	45	~150
Water mist	5.8	6.1	-	84	56	~150

For both types of systems, piping system consisted of four branch lines with nozzle connections for eight nozzles at a 3.2 m by 3.0 m nozzle spacing, i.e. a coverage area of 9.6 m² per nozzle. The vertical distance measured from the nozzles to the roof (when used) of the trailer mock-up was 0.5 m and the vertical distance to the top of the stacks of commodity approximately 1.0 m.

The tests were conducted under an Industrial Calorimeter, a large hood connected to an evacuation system capable of collecting all the combustion gases produced by the fire in order to measure the heat release rate. The fire suppression system was manually activated at a convective heat release rate of 3 MW, which equalled a total heat release rate of approximately 5 MW.

Figure 11 shows the heat release rate histories for the exposed as well as the shielded fire scenario.

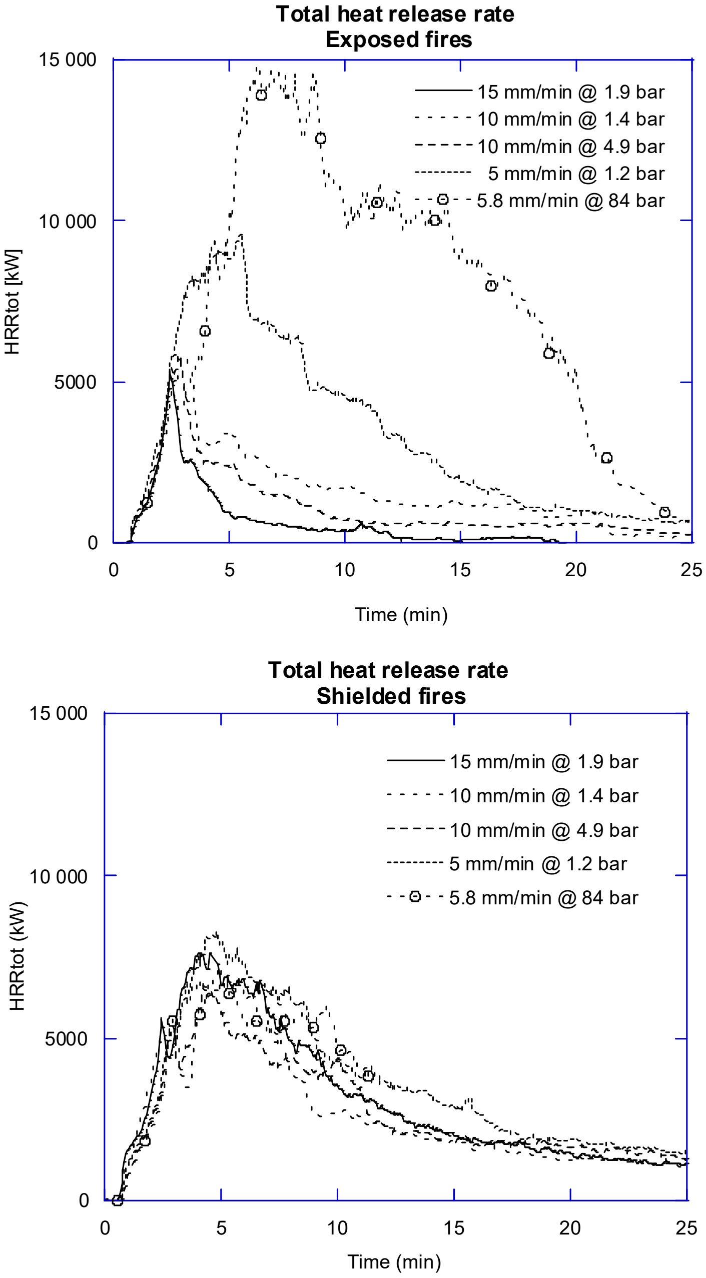

Figure 11. **The total heat release rate histories for the exposed (top) and the shielded fires on the simulated freight truck trailer. Adapted from Paper IV.**

The tests where the fires were fully exposed to the water spray shows that there is a clear relationship between the level of performance and the water application rate. A discharge density of 15 mm/min provided immediate fire suppression, 10 mm/min fire suppression, and 5 mm/min fire control. The high-pressure water mist system provided fire control at a discharge density of 5.8 mm/min. However, the tests at 3.75 and 4.6 mm/min, respectively, went out of control and are therefore not illustrated in the graphs as the tests were manually terminated.

For the final test (not shown in the heat release rate graphs), the activation of the water spray system (10 mm/min at 4.9 bar) was intentionally delayed until the fire size was twice as large as in the other tests. Despite this, the fire was almost immediately suppressed.

Based on the heat release rate measurements, the total and convective energy generated during the duration of the tests can be calculated. Figure 12 shows this data. For the fires where the fire was shielded from direct water application, the tested systems had a limited effect on the total energy generated, as almost all combustible material was consumed. The most efficient reduction of the convective energy of the water spray systems were demonstrated with 10 mm/min at the higher system operating pressure of 4.9 bar.

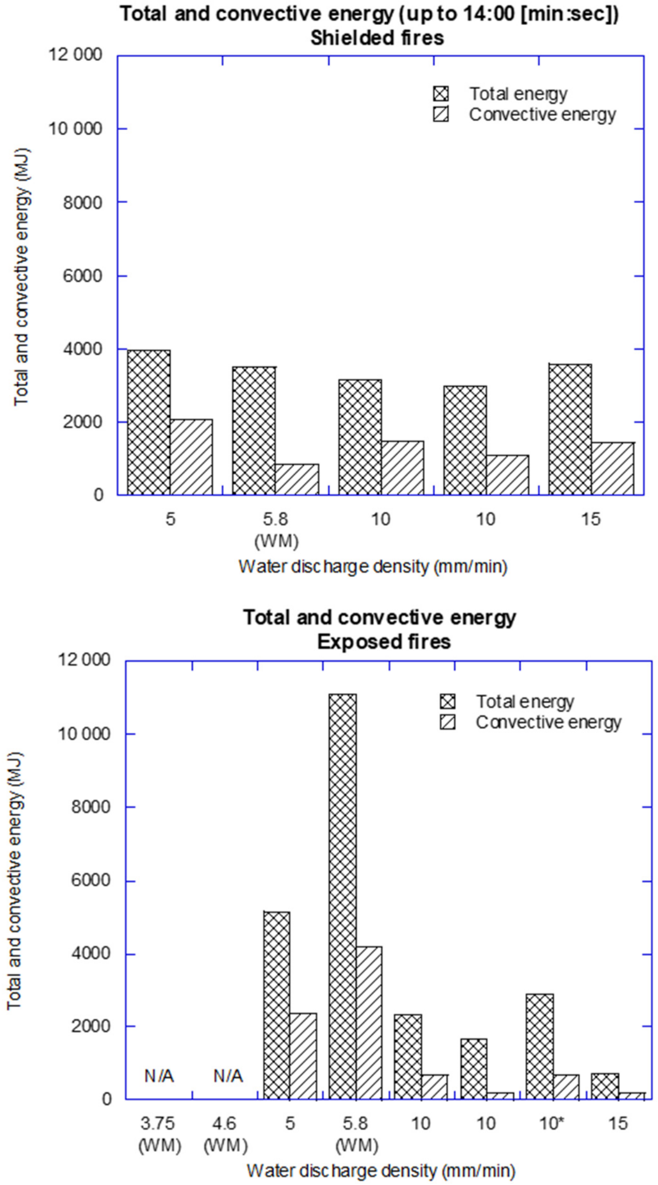

Figure 12. The total and convective energy for the exposed (top) and the shielded fire (right) scenarios. The terminology “WM” denotes Water Mist and the “*” indicates the water spray system test with delayed activation. Adapted from Paper IV.

The high-pressure water mist system reduced the total convective energy to a level that was less than all water spray system tests which underlines the improved cooling efficiency of the smaller water droplets.

The surface temperatures of the steel sheet plates positioned along both long sides of the trailer mock-up were measured at eighteen (18) different measurement points, on each of the steel sheet plates. Three of the measurement points were positioned on the horizontal top surface of the steel plate and the remaining fifteen measurement points on the vertical surface facing the trailer mock-up. Figure 13 shows the mean temperature for the exposed as well as the shielded fire scenario.

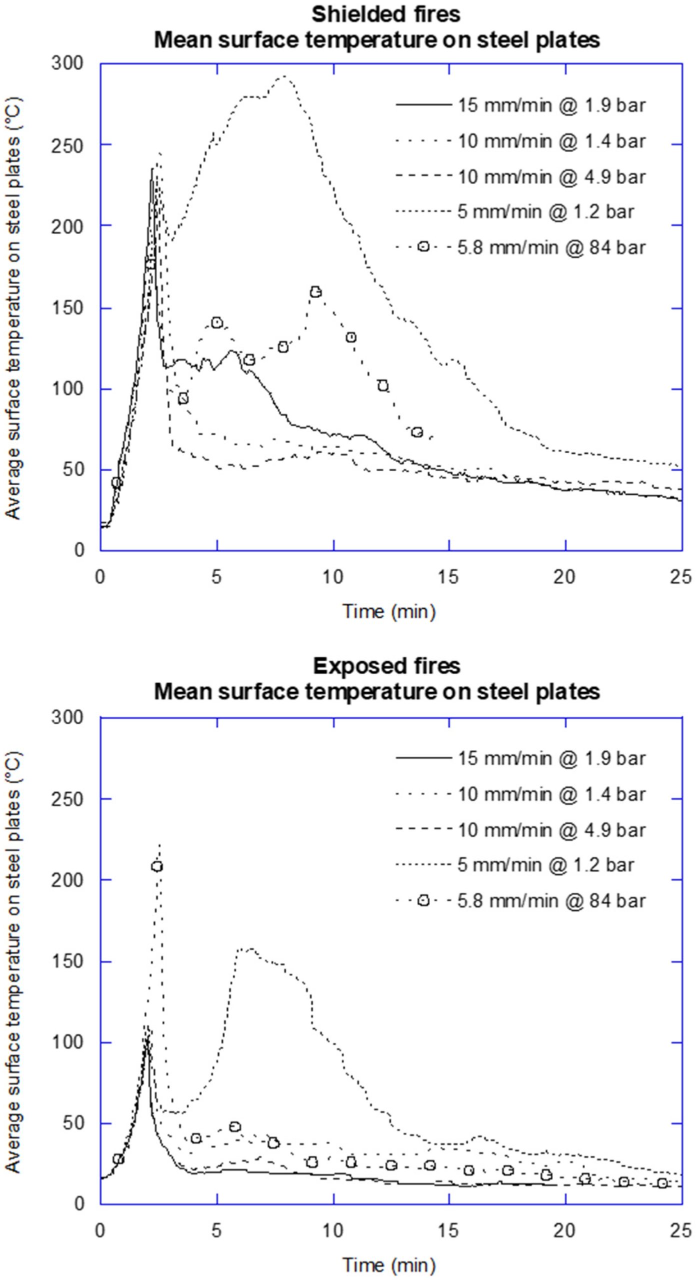

Figure 13. **The mean temperature of the steel sheet plates for the exposed (top) and the shielded fire scenarios. Adapted from Paper IV.**

For the exposed fire scenario, the reduction of the mean steel sheet temperatures correlates reasonably well with the suppression ability of the tested systems. However, the high-pressure water mist system reduced the temperatures better than it provided fire suppression. For the shielded fires, a higher discharge density generally reduced the mean steel sheet temperature better, although the reduction was better at the 10 mm/min density as compared to the 15 mm/min density. The high-pressure water mist system, discharging 5.8 mm/min reduced the mean temperature better than did the water spray system with a discharge rate of 5 mm/min.

In conclusion, the fire test results indicate that a water discharge density of at least 10 mm/min is necessary to provide fire suppression of a fire in a heavy goods freight truck, which is twice as high as the prescriptive requirements. Furthermore, the test results indicate that a high-pressure water mist system would require higher flow rates as compared to a traditional water spray system in order to provide fire control. The reason is probably that the smaller droplets did reach the seat of the fire due to insufficient momentum and/or because they evaporated in the hot fire plume.

From a practical perspective, the project resulted in a revision of the installation guidelines for fixed water-based fire-fighting systems for ro-ro spaces on ships. The outcome of the project was presented at IMO FP55 in 2011 and the relevant Working Group at FP55 concluded that the proposed installation guidelines resulting from the project should be combined with the performance guidelines in MSC.1/Circ.1272 for alternative systems, to provide for a prescriptive as well as a performance-based option. The working group considered that existing fixed fire protection systems for special category spaces, approved and installed based on Resolution A.123(V), should be permitted to remain in service if they are serviceable. In May 2012, MSC 90 adopted the revised guidelines as MSC.1/Circ.1430.

As with any large-scale fire testing, the inclusion of relevant system technologies is a matter of cost and therefore a limitation. Preferably, additional types of water mist system nozzles (a broader range of water spray nozzles were used) should have been included in the tests. The momentum of the water spray and the droplet sizes, which are key parameters in these fire scenarios, differs with the design of the nozzle. Another limitation was that the tests were conducted under a calorimeter. This is obviously essential for the measurement of the heat release rate, however, tests under a ceiling construction may have improved the performance of (in particular) the water mist nozzles, as smaller droplets are more likely to be carried away by the air flow generated by the calorimeter.

3.5 Paper V: Experience with fire protection installations for wood churches in Sweden

Paper V summarizes lessons learned and practical experience from nine fire suppression installations made in small or intermediate sized wood churches in Sweden between 2004 and 2007. This study is probably the first ever to document such experience.

Nine wood churches protected with fire protection systems were included in the study. Six of the nine churches were visited and are shown in Figure 14. The other three churches are not explicitly described in the report, by request of the owners. However, all relevant experience from the installations was included in the analysis.

For seven of the nine churches in the study, high-pressure water mist systems were installed and for the remaining two churches traditional sprinkler systems were installed. For two of the churches with water mist system installations, the exterior facades were protected with a traditional deluge sprinkler system.

Hedareds stave church

Frödinge church

Älgarås church

Habo church

Fröskog church

Skålleruds church

Figure 14 **The churches that were described in detail in the project. Photos: Magnus Arvidson.**

The main impression from the study is that all the system installations are very discreet and carefully done, without interfering with the demands of fire protection or those of the building itself. Figure 15 shows an example of an almost unnoticeable installation of system piping in Habo church. However, in some cases it can be concluded that the level of system complexity is very high, especially for the churches where different system technologies have been used for the protection of the interior and the exterior. A high complexity may translate to reduced reliability and increased demand for proper inspection, testing, and maintenance.

Figure 15 **Sometimes, system piping cannot be concealed, but with the smaller diameter pipe associated with water mist fire protection systems, the installation can be made much less noticeable, as in Habo church. Photo: Magnus Arvidson.**

Six cases of unintentional system activations were documented, an alarmingly high number relative to the small number of system installations. The reason for all these activations can be traced back to the fire detection system. Fortunately, little or very limited water damage has been reported, probably because all cases involved the accidental activation of deluge sections on the outside of the buildings.

A number of unintentional fire alarms, for miscellaneous reasons, were documented. Some are ‘typical’ for fire detection system installations, some are not. Functional tests are exceptionally important in order to uncover any functional problems associated with the system and several cases where systems failed to operate during testing were documented. This illustrates that functional tests should be conducted regularly.

The cold climate in the Nordic countries almost always requires that parts of the fire protection system used for the protection of heritage buildings are of the dry-pipe or deluge system type or that an antifreeze solution is used. Several of the churches that were studied utilize the possibility to manually flush the system piping with compressed air after the water is turned off. There is no actual field experience with the concept as the installations are so new and future experience will show whether the concept will prevent problems associated with freezing or not. The use of an antifreeze solution increases the complexity of the system and the required maintenance work. Another drawback is that antifreeze solutions may leak and damage interior and inventories, as was documented from one of the installations.

The field study was limited to a few objects (nine churches) and no statistically significant conclusions can be made. These installations where also among the first of its kind, at least in Sweden but probably in broader perspective. Therefore, it is likely that the fire protection consultants and installers were in experienced, which could explain some of the problems that were documented.

3.6 Paper VI: The influence of water from sprinkler sprays on invaluable wall- and ceiling paintings in heritage buildings

The objective of Paper VI was a result of a general claim by water mist system suppliers that water mist would not harm the wall and ceiling paintings, artefacts and décor found inside many old churches and other heritage buildings. No independent testing had been conducted to show whether this was the case or not.

The basic set-up for the tests was relatively simple, it consisted of a vertical plywood panel, nominally 12 mm thick. The front surface of the panel was painted, and its structure prevented any water absorption. A water collector tray was installed at the bottom part of the panel, with the intention of collecting the water that flooded down the wall. A similar plywood panel formed a ‘ceiling’ at a 90° angle to the wall panel where the tested sprinkler or water mist nozzles were installed.

Test samples were installed at two different heights on the wall, measured from the underside of the ceiling: 0.5 m and 1.5 m, respectively. New test samples were made from wood with the dimensions 40 mm (H) × 70 mm (W), with a thickness of 20 mm. The test samples were painted with three different paints on a thin layer of primer: 1) distemper, made from animal heat-setting glue, 2) egg tempera, and 3) oil paint. Authentic test samples were taken from a decorated wall from a dismantled heritage building. The paintings were probably from the early 1700s. It is also believed that they were made using distemper on a water-soluble primer. The test samples were made from wood and had the dimensions 140 mm (H) × 70 mm (W) with a thickness of approximately 25 mm. Figure 16 shows the test samples when installed at the wall.

Figure 16 **The newly made (left) and authentic test samples when installed at the wall. Photos: Magnus Arvidson.**

A standard sprinkler and low- and high-pressure water mist nozzles, respectively, was tested. In addition to the different water pressures and water flow rates, spray patterns were different, with different wall and ceiling wetting capabilities.

In contrast to the authentic test samples, the newly made test samples probably had characteristics that were homogenous. A strict comparison of the influence of the water spray on different types of paint is probably best for these tests. Based on the test results, it can be questioned how representative the newly made test samples were compared to the actual, old paint work. There are uncertainties concerning how time and environment affects the paint, etc. Additionally, the newly made test samples did not have any cracks or damage in the paint surface that seems to have influenced the results of the authentic test samples quite a lot. It is therefore difficult – not to say impossible to translate the results obtained from the new test samples to actual conditions.

The newly made test samples were not damaged so severely that the numbering that was painted on them had been affected, in any of the tests. Visually, there was no difference between the three systems tested with regard to the damage of the test samples. However, it was important not to touch a wet surface, as this could cause permanent damage.

The authentic test samples were more or less affected by the water spray. The damage was most severe when using the standard sprinkler, where 16.0 litres/minute hit the wall, corresponding to 480 litres during the 30-minute discharge duration time. After the test, both the underlying layer of paint and the pure wood surface were visible over large parts of the samples.

It is clear from the tests that there was a significant individual difference between the different test samples, due to factors like cracks and other defects on the layers of paint. It was, however, verified that even a very small amount of water will harm sensitive surfaces. During the tests with the low-pressure and high-pressure water mist nozzles, only 1.0 litres/minute and 2.2 litres/minute, respectively, hit the wall. This corresponds to a total amount of water of 30 litres and 66 litres, respectively, during the 30-minute discharge duration time. In practice, one would expect that a direct hit will cause more damage than an indirect hit, due to the mechanical influence. However, this theory could not be verified due to the large individual difference in sensitivity of the authentic test samples. Regarding the wetting of the ceiling surface, it is likely that a standard sprinkler or a water nozzle with a narrower spray angle will wet the ceiling less compared to a wider spray angle. In practice, the ceiling wetting of a standard sprinkler or water mist nozzle intended for a building with sensitive ceiling paintings would need to be investigated on a case-by-case basis. It is also important to keep in mind that there are technical solutions to limit the risk for water damage due to unintentional system activation, as pre action systems.

4 Discussion

This thesis contains six papers (Papers I – VI), each of them focused on a specific research objective. A common denominator is that all projects have been initiated due to a specific question or request from market actors.

Although the fundamentals of water use and water sprays evolved as early as in the 1930s to 1950s, primarily for manual fire-fighting using handheld nozzles, it was not until the late 1980s and early 1990s that fixed water mist fire protection systems were developed and commercialised, initially for the shipboard market. There were principally two incentives for the regained interest in water mist technology; the Montreal Protocol on Substances that Deplete the Ozone Layer signed in 1987 and effective 1989 (www.unenvironment.org 2019) and the fire on-board Scandinavian Star in 1990 (Almersjö, et al. 1998). Based on these incentives, authorities, researchers, testing agencies and system manufacturers made a much more determined effort to develop alternative fire suppression systems. With the adoption by IMO of installation guidelines and fire test procedures for accommodation areas and machinery spaces, respectively, water mist fire protection systems were recognized as a factual alternative (IMO is using the term 'equivalent' systems) to traditional fire sprinkler systems and halon fire extinguishing systems. Paper II describes the development of the installation requirements and fire test procedures for equivalent sprinkler systems for accommodation areas and public spaces on passenger ships that was published by IMO as Resolution A.755(18) in 1993 and Resolution A.800(19) in 1995.

But the early history of water mist fire protection system development has been untold. Paper I describe the development of fixed high-pressure water mist fire protection systems in Sweden during the late 1970s and early 1980s. Two companies independently, and to some extent in collaboration, developed systems for the protection of hotels, passenger cabins and flammable liquid hazards. What is interesting with this study is how early these people saw the potential and benefits of water mist technology. Unfortunately, these companies and the people that pioneered the high-pressure water mist technology had limited commercial success. The motivations for alternatives to traditional fire sprinkler systems and halon fire extinguishing systems were simply too limited at that time.

There was an emerging need for alternatives to traditional fire sprinklers and halon agents. This limited the opportunities for pre-normative research and testing. In many cases, fire test procedures were established based on round table discussions where few of the participants had practical experience and theoretical competence. As a result, the first fire test procedures that were adopted needed to be revised in a few years' time, both to correct regular errors but also to expand their scopes and field of applications, for example related to the maximum sized spaces allowed to be protected. Other problems included concerns that potentially poor system concepts entered the market. For example, systems with very low water flow rates and limited cooling capabilities or systems where the performance was strongly linked to the specific test conditions, such as the exact test compartment geometry and the location of the fire relative to water mist nozzles. Paper III describe an attempt to improve the fire test procedures for total compartment water mist and water spray fire protection systems intended for machinery space protection. This can be made by using fairly simple and inexpensive measurements and performance measurement parameters. The three parameters suggested in the paper measure the fire suppression capability, the temperature reduction capability and the ability to mix water vapor, water droplets and combustion gases within the protected compartment. These parameters provide a more complete picture of system performance and can be used as a complement to the time to fire extinguishment requirement. If used, these parameters could prevent poor system concepts from being developed. From a practical perspective, the project resulted in a revision of the fire test procedures for water mist fire protection systems for machinery spaces that was published in MSC/Circ. 1165 (2005).

When having water mist concepts for both accommodation areas and public spaces on passenger ships as well as for machinery spaces, the water mist manufacturers looked for possibilities of expanding the field of application to also include ro-ro spaces. Traditionally, manually operated deluge water spray systems are being used in ro-ro spaces where personnel safety is a concern and gaseous agents and high expansion systems are not allowed to be used. There are several fire protection challenges associated with ro-ro spaces; they are very large, the fire load is very high, a fire may be shielded from direct application of water from over-head sprinklers or nozzles, there are limited possibilities for pre-wetting, etc. Due to these challenges, water mist fire protection systems are not an obvious system alternative. Paper IV summarises a series of large-scale fire suppression tests conducted to simulate a fire in the trailer of a heavy goods freight truck in a ro-ro space. The tests were designed to vary the system technology (water spray or water mist), the water discharge density, the exposure of the fire to the water spray, etc. In conclusion, the fire test results indicate that a water discharge density of at least 10 mm/min is necessary to provide fire suppression of a fire in a heavy goods freight truck, which is twice as high as the (then) prescriptive requirements by IMO. The test results also indicate that a high-pressure water mist system would require higher flow rates as compared to a traditional water spray system in order to provide fire control. The reason is probably that the smaller droplets did not reach the seat of the fire due to insufficient momentum and/or because they evaporated in the hot fire plume. From a practical perspective, the project resulted in a revision of the installation guidelines for fixed water-based fire-fighting systems for ro-ro spaces that was published in MSC.1/Circ.1430 (2012).

Paper V summarizes lessons learned and practical experience from nine fire suppression installations made in small or intermediate sized wood churches in Sweden between 2004 and 2007. Most of the installations included water mist fire protection systems. This study is probably the first ever to document such experience. The main impression from the study is that all the system installations are very discreet and carefully done, without interfering with the demands of fire protection or those of the building itself. However, in some cases it can be concluded that the level of system complexity is very high, especially for the churches where different system technologies have been used for the protection of the interior and the exterior. A high complexity may translate to reduced reliability and increased demand for proper inspection, testing, and maintenance. The latter observation suggests that functional testing is essential to maintain the function of a system.

Paper VI describe an experimental study on the influence of water from sprinkler sprays on invaluable wall- and ceiling paintings in heritage buildings. The tests indicate that even small amounts of water could damage sensitive surfaces. But it is likely that the lower water flow rates associated with water mist systems have less potential for water damage as compared to traditional sprinklers.

5 Conclusion

The research objectives for this licentiate thesis were to:

RO1:	Document the previously unknown history of the development of modern, fixed-installed high-pressure systems in Sweden.
RO2:	Document the development of the very first (by IMO) international installation guidelines and fire test procedures as well the rationales and background behind the fire test scenarios and acceptance criteria of the fire test procedures.
RO3:	Improve the IMO fire test procedures for machinery spaces on ships by using additional measurement parameters.
RO4:	Explore the possibilities of using water mist fire protection systems for high fire hazards, i.e. ro-ro spaces on ships and revise the existing installation guidelines for fixed water-based fire-fighting systems for these spaces.
RO5:	Document lessons learned from actual water mist fire protection system installations in wood churches.
RO6:	Study the influence of water sprays on sensitive building surfaces such as wall and ceiling paintings in heritage buildings.

It is concluded (RO1) that modern fixed high-pressure water mist fire protection systems were developed in Sweden during the late 1970s and early 1980s by two independent companies. The companies had limited commercial success, but it is no doubt that their efforts inspired their followers on the marketplace. The very first installation requirements and fire test procedures for water mist fire protection systems were published by IMO in the early 1990s. The procedures were developed to address a demand for ‘equivalent’ sprinkler systems for accommodation and public spaces on-board passenger ships. This work was documented (RO2) in detail. The work by IMO influenced other international fire test procedures.

The fire test procedures for machinery spaces on ships developed by IMO needed to be improved. A novel methodology for the measurement of the performance of water mist fire protection systems was established based on fire tests to address RO3. The measurement parameters give a broader understanding of system performance and are repeatable. The parameters measures fire suppression performance, cooling capability and the ability of the system to mix water vapor, water droplets and combustion gases within the test compartment. The project resulted in a revision of the IMO fire test procedures.

A series of large-scale fire tests were conducted to address RO4. The fire tests results indicate that a high-pressure water mist system would require higher flow rates as compared to a traditional water spray system in order to provide fire control of a freight truck trailer fire in a ro-ro space. The reason is probably that the (small) droplets did not reach the seat of the fire as they had insufficient momentum and/or because they evaporated in the hot fire plume. However, the high-pressure water mist system reduced the total convective energy to a level that was less than the tested water spray systems, which illustrates improved cooling capabilities of smaller droplets. This work resulted in a revision of IMO regulations.

Water mist fire protection systems may offer several benefits for the protection of heritage buildings. A field study documented (RO5) system installations and noted several cases of unintentional system activations and fire alarms. This experience suggests that functional testing is essential to maintain the function of a system.

A series of water spray tests were conducted to address RO6. These tests indicate that even small amounts of water could damage sensitive building surfaces as wall and ceiling paintings. But it is likely that the lower water flow rates associated with water mist systems have less potential for water damage as compared to traditional sprinklers.

6 Future research

Parts of this thesis are considered to provide a contribution to why, when and how water mist fire protection systems as we know them today and the associated fire test procedures evolved. This documentation is perhaps more important than it may appear, valuable historical information will be lost with the people that participated in that work. Hopefully, this part of the thesis will encourage others to document the history and the continuing evolvement of water mist technology.

One of the learnings from this work is that pre-normative research is essential to develop proper fire test procedures. Since the issuing of the very first installation recommendations and fire test procedures by IMO, many national and international organizations have developed their own standards. Some of them are unique, other share many similarities with the ones originally developed by IMO. Future research should focus on aligning these fire test procedures and revise them based on experience as well on a theoretical understanding of the mechanisms of water mist. It may well be that some fire test procedures could be simplified and improved if applying a more theoretical approach. One such example is given by Yu et al. (2017), where psychical scaling is used to translate model-scale fire test results to large-scale. A better understanding of the performance during testing would also allow for the extrapolation of test results. The repeatability and the reproducibility of large-scale fire test procedures should also be explored further. There are likewise many possible applications not yet addressed by proper fire test procedures. The everchanging world and new technologies will undoubtedly introduce new fire hazards where water mist may be applied.

Additional long-term field experience is desired for continual improvements of the performance and reliability of systems. As for traditional sprinkler technology, component test procedures, fire test procedures, installation practices as well as control, inspection and maintenance routines need to be constantly reviewed and updated based on field experience. The greatest resistance against water mist technology among authorities, insurers, fire protection consultants and end users are currently the concern about system performance and system reliability. In order to convince these parties about the benefits of water mist fire protection systems, these issues need to be dealt with in a systematic manner.

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Water mist fire protection systems

The major commercial establishment of ‘modern’ water mist fire protection systems occurred during the early 1990s. The incentive was primarily the so-called Montreal Protocol and the fire on-board the passenger ferry Scandinavian Star.

The Montreal Protocol is an international agreement that regulates the production and use of several substances that are believed to affect the earth’s ozone layer. The agreement entered into force in 1989 and includes brominated fire extinguishing gases (‘halons’). Water mist fire protection systems were developed to replace systems using these banned gases.

The Scandinavian Star fire in 1990 resulted in significantly higher fire safety requirements for passenger ships in international traffic, including requirements for sprinklers in accommodation and public spaces. Water mist fire protection systems turned out to be a desirable alternative to standard sprinkler systems for these applications.

The material presented in this licentiate thesis is the result of almost 30 years of work and summarises some of my projects related to water mist fire protection technology. During these years, a promising technology has evolved into a commercial technology with many applications. Being a part of this development has been very stimulating and interesting. I trust that the technology will continue to evolve with the changing demands of the future.

Printed by Media-Tryck, Lund 2020 NORDIC SWAN ECOLABEL 3041 0903

ISBN 978-91-7895-553-4
ISSN 1402-3504
ISRN LUTVDG/TVBB--1064—SE
Report 1064
Fire Safety Engineering
Lund University