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A Review of Water Mist Technology for Fire Suppression

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The potential efficacy of water mist fire suppression systems has been demonstrated in a wide range of applications and by numerous experimental programs. These applications have included Class B spray and pool fires, aircraft cabins, shipboard machinery and engine room spaces, shipboard accommodation spaces, and computer and electronics applications. To summarize these experimental efforts, the efficacy of a particular water mist system is strongly dependent on the ability to not only generate sufficiently small droplet sizes but also distribute sufficient mist concentrations throughout the compartment. A widely accepted critical concentration of water droplets required to extinguish a fire is yet to be determined. Factors that contribute to the success or failure of a water mist system for a particular application include droplet size, velocity, the spray pattern geometry as well as the momentum and mixing characteristics of the spray jet, and the geometry and other characteristics of the protected area. At this time, the effect of these factors on system effectiveness is not well known. This will necessitate evaluation of water mist in context of a specific system for unique applications for the reasonable future unless breakthroughs in understanding of mist distribution and flame interaction occur through research.

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Nomenclature

C	vortex strength
c	jet momentum flux constant
C_D	drag coefficient
d_o	initial droplet diameter
F	drag force per unit mass of particle per unit velocity differential
g	gravitational acceleration
H	compartment height
I	droplet fallout rate per unit area
l_f	fluid mechanical length scale
l_g	particle aerodynamic length scale
$\dot{M}$	nozzle flow momentum
$\dot{M}''_{flame,max}$	maximum momentum flux of the flame
n	droplet number density
n_{ss}	steady state droplet number density
$\dot{n}''$	droplet generation rate per unit area
$\dot{Q}$	heat release rate
r	radial coordinate
r_p	particle radius
St	Stokes number
t	time
t_f	fluid mechanical time scale
t_v	evaporation time
U	velocity
U_o	gas velocity
U_p	particle velocity
U_t	terminal particle velocity due to gravity
α_g	gas thermal diffusivity
B	Spaulding B number
Δ	eddy size
λ	droplet evaporation constant
μ	viscosity
ρ	density
ρ_{air}	air density
ρ_g	gas density
ρ_l	liquid density
ρ_p	particle density (material density)
τ	aerodynamic response time

A REVIEW OF WATER MIST TECHNOLOGY FOR FIRE SUPPRESSION

1.0 WATER MIST AS A FIRE SUPPRESSION TECHNOLOGY

Water mist fire suppression systems have been studied for at least 50 years [1]. While no practical or commercially demonstrated systems had evolved until recently, the basis for use of fine liquid water droplets for gas-phase fire suppression is relatively old. Recent interest in water mist technology has been driven by two events. The need for low weight impact replacement sprinkler systems on commercial ships has been driven by International Maritime Organization (IMO) regulations requiring retrofit of fire suppression systems on most commercial marine vessels. This gave immediate impetus to the development of low water demand, high efficiency mist systems to replace sprinkler systems. The second is the phaseout of halons and the search for alternative technologies that preserve all or most of the benefits of a clean total flooding agent without adverse environmental impact.

The state of technology is such that the shipboard sprinkler replacement uses of water mist are relatively well developed and commercialized and the use of water mist as a Halon 1301 total flooding replacement agent is in its infancy. Nonetheless, as this review will demonstrate the underlying science and engineering methods needed for effective and reliable system design methods for these systems are largely lacking. Progress to date has been of a highly empirical and ad hoc nature.

Fine water mist has been an active area of research and development in recent years, and many commercial systems are available or in development. Fine water mist relies on relatively small (less than 200 μm) droplet sprays to extinguish fires. The mechanisms of extinguishment include gas phase cooling (evaporation and heat capacity), oxygen displacement by steam, wetting of fuel surfaces, and attenuation of radiative heat transfer.

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Water mist systems have attracted great interest for a number of reasons. These systems are perceived to have the following advantages:

(1) are inexpensive;
(2) are non-toxic and pose no environmental problems;
(3) suppress flammable liquid pool and spray fires as well as Class A fires;
(4) utilize water quantities a tenth or lower than sprinklers and hence have reduced collateral damage;
(5) can be made to perform functionally in some applications like total flooding gases (i.e., obstructed, enclosed fires) activated by a variety of means;
(6) may be non-electrically conductive; and
(7) may have application as inerting or explosion suppression systems.

Some of the potential perceived benefits have been demonstrated (items 3 and 4 above) while others remain to be proved.

1.1 Background

The potential efficacy of water mist fire suppression systems has been demonstrated in a wide range of applications and by numerous experimental programs. These applications have included Class B spray and pool fires [2-7], aircraft cabins [8-13], shipboard machinery and engine room spaces [14-25], shipboard accommodation spaces [20, 21, 26], and computer and electronics applications [9, 27-31].

To summarize these experimental efforts, the efficacy of a particular water mist system is strongly dependent on the ability to not only generate sufficiently small droplet sizes but also distribute sufficient mist concentrations throughout the compartment [7, 18, 32]. A widely accepted critical concentration of water droplets required to extinguish a fire is yet to be determined. Factors that contribute to the success or failure of a water mist system for a particular application include droplet size, velocity, the spray pattern geometry as well as the momentum and mixing characteristics of the spray jet, and the geometry and other characteristics of the protected area. At this time, the effect of these factors on system effectiveness is not well known. This will necessitate evaluation of water mist in context of a specific system for unique applications for the reasonable future unless breakthroughs in understanding of mist distribution and flame interaction occur through research.

It is also apparent that water mist systems when evaluated for fire extinction capability as opposed to fire suppression (an easier task) will be very sensitive to the details of the area being protected. It is, therefore, essential to develop worst case fire scenarios and hazard geometries to evaluate fire extinguishment capability.

There is no current theoretical basis for the selection of spray characteristics and other important water mist system parameters. At this time there are no engineering methods developed for the design and specification of water mist systems. All efforts to date have been on a trial and error empirical basis. While it is not unusual to have commercialized engineering systems which are not well understood from a science/engineering standpoint, the lack of a firm underpinning for this emerging technology is a serious impediment to the acceptance of water mist technologies. Further, the amount of full scale testing required to assure adequate system performance for all the different applications envisioned would require a prohibitive number of tests. Thousands of tests have been conducted to date. Based on the limited progress made in these thousands of tests, the vast majority of the needed testing remains to be done. An efficient mix of fundamental and applied approaches needs to be employed to reduce the time/expense of developing these technologies to the point where reliable system designs are possible.

1.2 Available Water Mist Technologies

The currently available atomization technologies include pressure atomizers, impingement atomizers, dual-fluid atomizers, effervescent atomizers, electrostatic atomizers, and ultrasonic atomizers. Two of these technologies are incorporated in water mist suppression systems under development and/or consideration: pressure atomizers and dual-fluid systems. Single-fluid systems (pressure atomizers) utilize water stored or pumped at high pressure (40-200 bar) and spray nozzles containing relatively small orifice sizes. Dual-fluid systems use air, nitrogen, or other gases to atomize water at a nozzle. Both types of systems have been shown to be effective fire suppression systems.

The single-fluid system nozzle incorporates two of the atomization techniques (pressure and simplex atomization). The fluid is transformed into a sheet through a flow chamber/pin (simplex-like) before it is forced through the relatively small orifice at high pressures (pressure-like). These nozzles are used in generic systems that utilize industrial specialty nozzles and proprietary systems.

The pressure atomizing nozzles have several advantages over dual fluid nozzles including low space and weight (no air compressor and gas storage cylinders), reduced piping requirements, easier system design, and easier installation. Disadvantages of these systems include relatively high operating pressure, high pressure pumps or water storage vessels, and potential for clogging problems due to small orifice nozzles.

The dual-fluid system nozzles can be classified into two basic groups: air-assisted and air atomized. The only air-assisted misting technology is used by Securiplex (BP) and Ginge-Kerr. The remaining systems can be classified as air atomized. The mechanism uses a gas (usually air) at high velocity to shear the water into small droplets. Air atomized nozzles use an order of magnitude more air to produce an order of magnitude smaller drops then air-assisted nozzles. These nozzles are used in generic systems that utilize modified industrial spray nozzles. Systems have been tested using water atomized by air, nitrogen, or gaseous extinguishing agents. These generic technologies include systems designed and developed by National Research Council Canada (NRCC) and the Naval Research Laboratory.

Advantages of the dual fluid systems include lower water supply pressures, larger orifice sizes which are less likely to clog, greater drop size flexibility, and the ability to substitute gaseous halon alternatives or inert gases for air as the atomizing fluid.

Disadvantages of these systems include the space and weight of an air compressor and/or cylinder bank and increased piping for gaseous fluid, difficult hydraulic design (may require regulators on each nozzle), difficult installation, and increased compartment pressure during system discharge.

2.0 TESTING AND EVALUATION OF AVAILABLE WATER MIST TECHNOLOGIES

There are currently at least eleven water mist system technologies available or under development using either dual-fluid (N_2/air and water) or single-fluid high-pressure systems. Table 1 summarizes the current manufacturers of water mist systems for fire suppression use. Some of these manufacturers are still in the R&D phase with their particular hardware.

Table 1. Water Mist Hardware Manufacturers

Company	Country	System Type
ADA Technologies	U.S.A.	Dual fluid, air atomized
Baumac International	U.S.A.	Single fluid, high pressure, low momentum
DAR CHEM	United Kingdom	Single fluid, low pressure
FSI/Kidde Graviner, Kidde Fenwal	United Kingdom, U.S.A	Dual fluid, air atomized
Ginge Kerr (BP)	United Kingdom, Denmark, Norway	Dual fluid, air assisted
Grinnell AquaMist	U.S.A	Single fluid, low pressure
Semco	USA/Denmark	Single fluid, high pressure, high momentum
HTC	Sweden	Single fluid, high pressure, high momentum
Marioff Hi-fog	Finland	Single fluid, high pressure, high momentum
Microguard-Unifog	Germany	Single fluid, high pressure, high momentum
Securiplex (BP)	Canada	Dual fluid, air assisted
Spraying Systems	U.S.A.	All
Bete Fog	U.S.A.	All

While some of the commercially-available systems have received limited acceptance from overseas approval authorities for limited applications, the approval testing and standardization effort is just getting underway in the United States. A newly formed NFPA committee, Water Mist Fire Suppression Systems Committee (NFPA 750), will not only face the task of developing performance criteria but also face the problem of evaluating the systems' adaptability to numerous fire protection applications. The committee has recently drafted an outline for the standardization of water mist technology. The intent of the committee is to have a draft specification by early 1995.

The number of commercial systems under development and the evolutionary nature of many of the systems makes descriptions of all the systems infeasible. However, it is useful to review one of each of the major types of systems. The system classifications which seem to be most useful in characterizing water mist systems are as follows:

System Type	Example
Single fluid, low pressure	Grinnell AquaMist
Single fluid, high pressure, high spray momentum	Marioff Hi-fog
Single fluid, high pressure, low spray momentum	Baumac MicroMist
Dual fluid, air assisted	Securiplex Fire Scope 2000
Dual fluid, air atomized	No example is yet commercially available

The following descriptions of the example systems is intended to give a sense of the wide range of system characteristics.

2.1 Single Fluid, Low Pressure: Grinnell AquaMist

Grinnell AquaMist is a low pressure system which operates in the range of 6.0 to 12.1 bar. At 6.0 bar, the nominal flow rate of a nozzle is 11.5 Lpm. System operations have been tested in the range of 4-30 bar and have been optimized to the 6.0-12.1 bar range. The Grinnell system is almost identical to a standard automatic sprinkler system in terms of system hardware and operating principles. The relatively low pressure AquaMist system trades off efficiency in producing small droplets (an advantage of high system pressure) against the cost and commercial advantages of using standard hardware.

2.1.1 System Characteristics

The AquaMist system operates with two nozzle types, the AM5 and AM6. Both types are automatically operated and differ only in the deflector design. All other nozzle components are identical. The two nozzles have been designed to perform optimally at the 6.0-12.1 bar operating pressure and the 11.5 Lpm flow rate. Grinnell nozzles have been calculated to operate at a nominal K-factor of 4.7 Lpm/bar$^{1/2}$. The nozzles will deliver a Sauter mean drop size of 60-150 microns depending on location in the spray. Spray patterns and droplet size have proved consistent in all tests in the normal operating range.

The heat sensitive element is a 3 mm bulb with a nominal Response Time Index (RTI) of 35 $m^{1/2} \times s^{1/2}$ and a nominal conductivity factor (C) of 0.65 $m^{1/2}/s^{1/2}$. The temperature rating is 68°C standard, with a minimum requirement of 30°C above ambient for higher ambient temperatures. Each nozzle is designed with a strainer with perforations of 2 mm for particle filtration to avoid clogging of the 2.7 mm diameter orifice within the nozzle.

The nozzle frame is manufactured using dezincified resistant brass. The nozzle waterway seal is composed of a beryllium nickel disc spring sealed on the interior and exterior edges with teflon gaskets. The seal ejection spring is made of stainless steel. All other components are fabricated from a salt water resistant phosphor bronze.

The system will work under normal pipe flow conditions. Pumps are required on a case by case application basis as with regular automatic sprinklers. A schematic representation is shown in Fig. 1.

2.1.2 Performance Tests

Extensive testing has been performed in evaluating the suppression and extinguishment capabilities of the AquaMist system for shipboard applications, such as, cabin, corridors, and public areas up to 5.0 meters in height (two decks).

The results of these fire tests, performed at the minimum specified design pressures, show that the AquaMist system controlled, suppressed or extinguished the fire, with reduced direct fire damage and relatively low ceiling gas temperatures.

Additional tests run on the AquaMist system show that it possesses the potential capability to suppress or extinguish concealed as well as exposed fires, arsonist fires, and residential scenarios involving combustible walls and furnishings. Testing has only recently begun on machinery space/flammable liquid hazards. The AquaMist system appears at this point to be a viable replacement for standard sprinkler systems in some applications. Its use as a total flooding replacement agent in highly obstructed geometries (e.g., computer facilities) has not been evaluated, but due to its relatively large droplet sizes total flooding behavior is not expected.

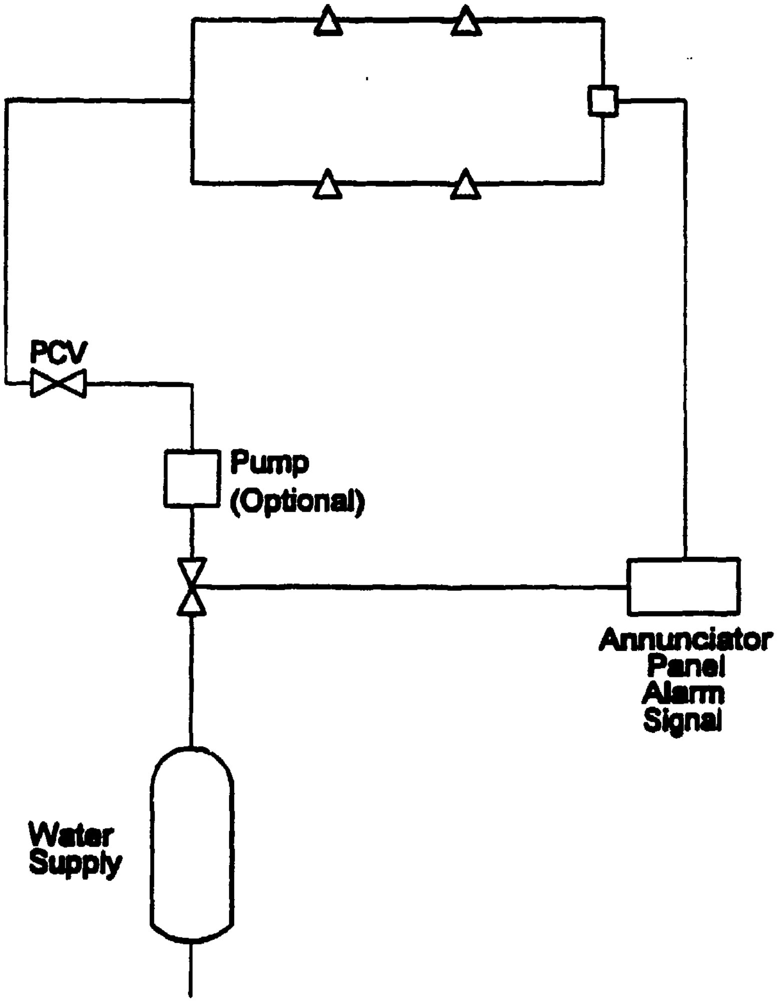


Figure 1. Typical Schematic of Grinnell AquaMist System (Low Pressure)

2.2 Single Fluid, High Pressure, High Momentum: Marioff Hi-fog Fire Extinguishing System

The Marioff system provides a light weight alternative to conventional sprinkler systems for shipboard applications. Testing to date and multiple system installations have brought acceptance to the fact that the Hi-fog system is a highly effective method of suppressing and extinguishing fires. It has shown the ability to penetrate plume gases, act as cooling agent, and extinguish.

The Marioff philosophy of water mist application is to provide a high momentum spray with droplet sizes on order of 60 microns in diameter. This has been empirically determined through Marioff's extensive work with shipboard installations. The major feature of the Marioff nozzle is its droplet size distribution. The droplet distribution is comprised of both large (~100 μm) and small (<50 μm) drops. The large droplets provide spray momentum which assists in penetration and mixing.

2.2.1 System Characteristics

The system is supplied by an array of one or more banks of pre-charged gas/water accumulators. The accumulators are installed with electrically driven low pressure water pumps and automatically activated electric and pneumatic recharge pumps. The ormal design procedure is to design for protection against a "worst case" 10 MW hydrocarbon fire. The accumulator design provides for 100% redundancy in a second bank, in the case of an accidental release in a wrong or non-fire area. The system is functional with both salt- and fresh water.

The system accumulators are always loaded with water pressurized to 280 bar. Non-return valves are supplied within the system heads to retain water within the piping. Recharge pumps will automatically engage if the accumulator pressure falls below 280 bar and will recharge until that pressure is reestablished. The recharge pump will recharge sufficiently to allow the system to have a high pressure release every 3 minutes until deactivation of the system.

Upon manual activation, low pressure pumps are activated, valves opened, and water is provided to all system heads at 16 bar. The theory is that this will give cooling to the pipework and heads prior to high pressure release which lasts approximately 45 seconds before decay. Low pressure mist remains to cool the space so that reignition does not occur.

The system can be manually or automatically actuated. Automatic actuation devices include frayable glass bulbs and heat or smoke detectors. Alarms are provided for all electrical and pump malfunctions or failures. The monitoring system will act accordingly to the situation. It also starts/stops pumps as necessary. All segments of the system are fitted with a manual override.

Marioff Hi-fog nozzles are designed to provide water droplets of 60 microns in diameter (average) with high spray momentum. The nozzles are designed in three basic styles. The first nozzle contains four outlets per nozzle and delivers 4.5 Lpm at 280 bar and 1.5 Lpm at 16 bar. The second design is a head which contains three central outlets with nine surrounding outlets capable of delivering 20 Lpm at 280 bar and 7 Lpm at 16 bar. The third arrangement allows for one central outlet surrounded by six perimeter outlets capable of delivering 8 Lpm at 280 bar and 2.5 Lpm at 16 bar. All nozzles are produced in stainless steel or bronze. Nozzle spacing varies with the ship hazard being addressed. Normal spacing is approximately 3 m between heads.

The Marioff water distribution systems are made solely of stainless steel conforming to AISI 304 or 316. The connection shall be of approved type DIN 2353. The piping system is installed to a minimum test pressure of 280 bar. All piping systems are designed on an individual case basis dependent on waterflow requirements, length and elevation considerations, and pressure losses. The piping systems are designed with a safety factor of 4:1 for minimum burst pressure. A system schematic is shown in Fig. 2.

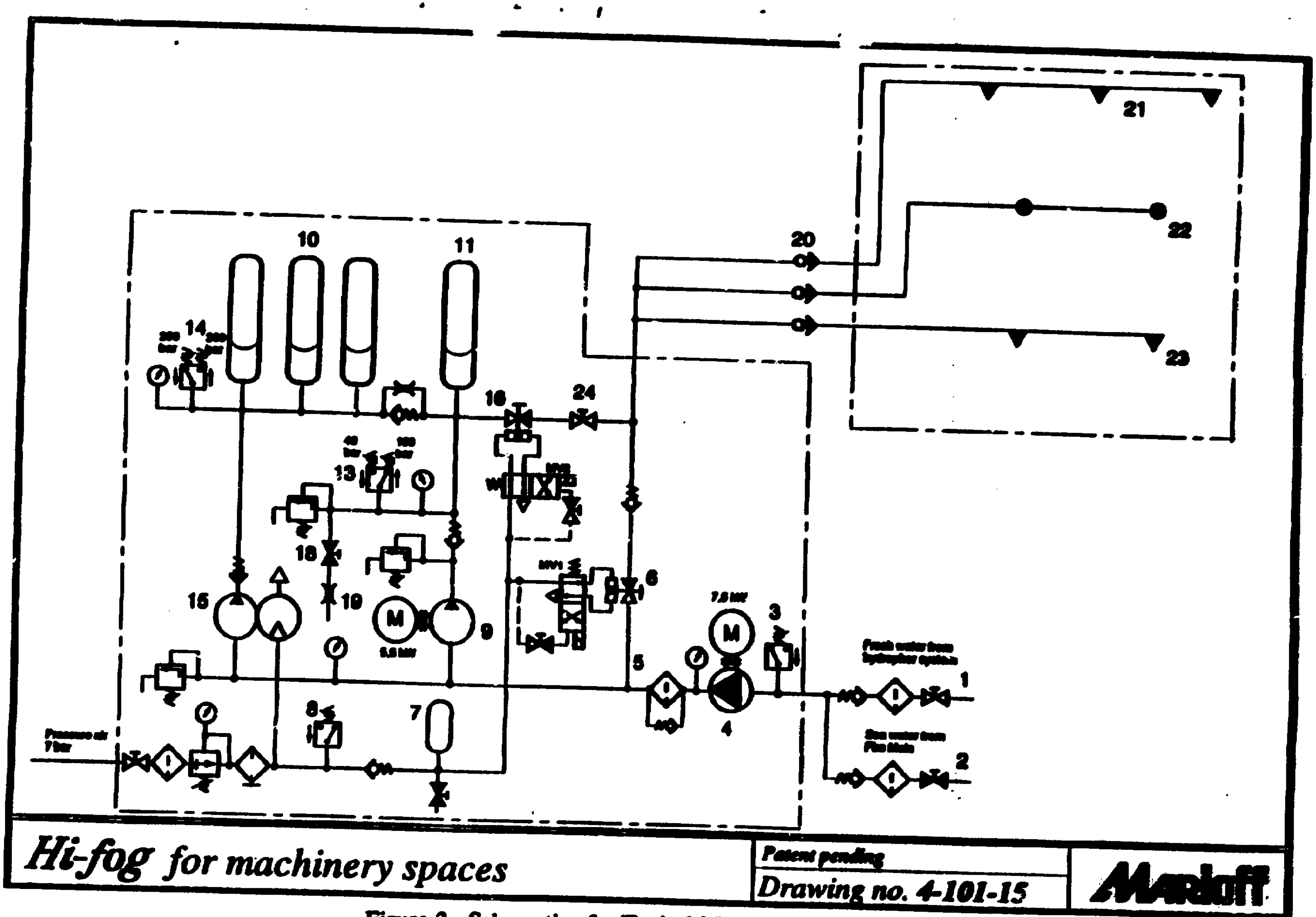


Figure 2. Schematic of a Typical Marioff Hi-fog System

Maricff also supplies an alternative to conventional automatic sprinkler heads. The heads have a reduced flow rate of 4.5 Lpm and operate in a similar way to the conventional heads. The head is activated by a release bulb. The difference from the conventional system is that the bulb is protected by a metal cover with small holes bored for heat flow to the bulb. When the bulb reaches its response temperature, it releases a valve spindle. The valve is released when a spring presses the spindle to the down position, water flow enters the nozzle, and is released as a high pressure (100 bar) fog. The design of the nozzle is shown in Fig. 3.

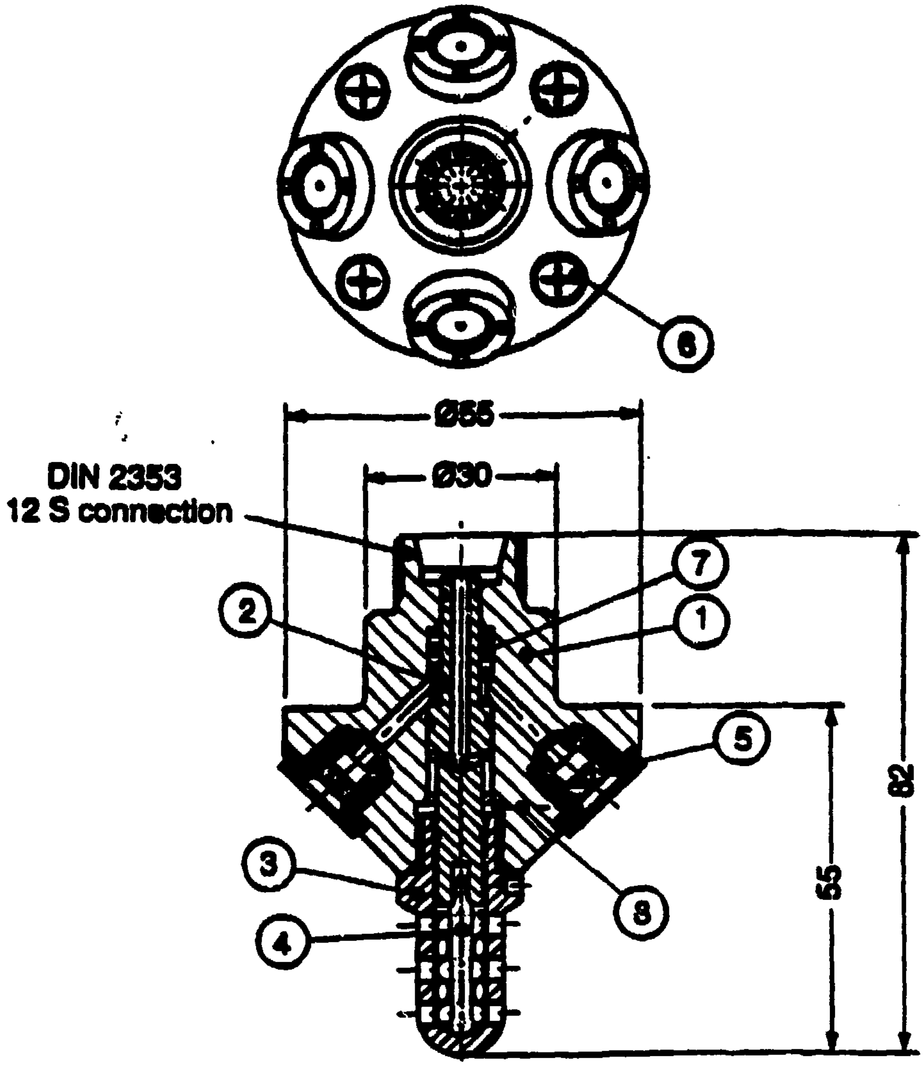
The head system is also available with an option of having the capability of two heads releasing when only one bulb reaches response temperature.

2.2.2 Performance Testing

Marioff has undergone extensive testing in many areas. Shipboard applications consisting of cabin, corridor, public area, engine room, pump room and bilge fires have shown Marioff's Hi Fog System to be very effective in controlling, suppressing, and extinguishing fires in these applications.

Testing and evaluation have been performed to test Marioff's systems ability to suppress deep seated fires (e.g., slow growth furniture fires), wood cribs, pool type fire scenarios, large room areas, and public areas. Testing indicates that water mist can be an effective alternative or replacement for automatic sprinkler systems.

The Marioff system exists in several variants, some explicitly designed to be used in total flooding replacement applications. Sufficient testing has not been performed to assess its capabilities against small, highly obstructed fire sources.



Type number: Hf - 104_ - 030

See drawing no. 4-100-64 for different variations

Part no.	Pcs.	Title	Drawing no.	Material, dimensions
8	1	Vent screw	DIN 916 M5 - 8: ø3	AISI 304
7	1	Spring		Stainless steel
6	4	Fixing screw		ø 3.5 x 19
5	4	Nozzle	4-100-02	
4	1	Release bulb	JOB BULB F3	temperature 68°C:RED
3	1	Cover		[illegible]
2	1	Valve spindle		[illegible]
1	1	Sprinkler body		[illegible]

Part of	Drawn by	Checked by	Date	Projection	
			18.06.-91		Hi-fog Marioff

Material, dimensions

Drawing no.	Title		
4-100-07	Sprinkler head	[illegible]	[illegible]

Figure 3. Marioff Hi-fog Sprinkler Head Diagram

2.3 Single Fluid, High Pressure, Low Momentum: Baumac International MicroMist System

Baumac International has developed the MicroMist System, a humidification/ evaporative cooling system adapted for use in fire protection applications. This system differs from the previously described systems.

The system consists of a water pumping station and provides for built-in particle filtration of 5 microns in diameter. The primary distinguishing factor is that the delivery system is a 0.5 inch diameter, thin wall stainless steel pipe with a large number of low flow nozzles. A patented nozzle installation process has been developed to minimize tube and nozzle installation failures or leaks. It may be produced and installed with almost limitless arrays of nozzle spacings and/or angles. The premise is to evenly produce and deliver a large quantity of small droplets over the protected area.

2.3.1 System Characteristics

The MicroMist System has been developed with four primary nozzle sizes MX-8, MX-12, MX-15, and MX-20. The number listed in the model description is representative of the nozzle orifice diameter in thousandths of an inch.

Test series run have been performed with nozzle flow rates as follows:

MX-8	0.10 Lpm @ 68 bar;
MX-12	0.21 Lpm @ 68 bar;
MX-15	0.28 Lpm @ 68 bar; and
MX-20	0.33 Lpm @ 68 bar.

Droplet sizes for the individual nozzles have been documented in extensive testing. The droplet diameters range from 10-120 microns. The smaller orifice heads tend to deliver a higher concentration in the range of 10-70 microns and the larger orifice outlets provide the contribution of the higher diameter droplets. An example of a typical nozzle layout scheme is shown in Fig. 4.

2.3.2 Performance Testing

Performance testing is currently ongoing to characterize the nozzle and its operating parameters. Tests have been run for a series of applications such as subfloors, computer rooms, computer cabinets, communications switchgear, public areas, and residential scenarios. Test results indicate that the Micromist system behaves the most like a total flooding system due primarily to the small drop sizes and the close nozzle spacing which minimizes the impact of obstructions.

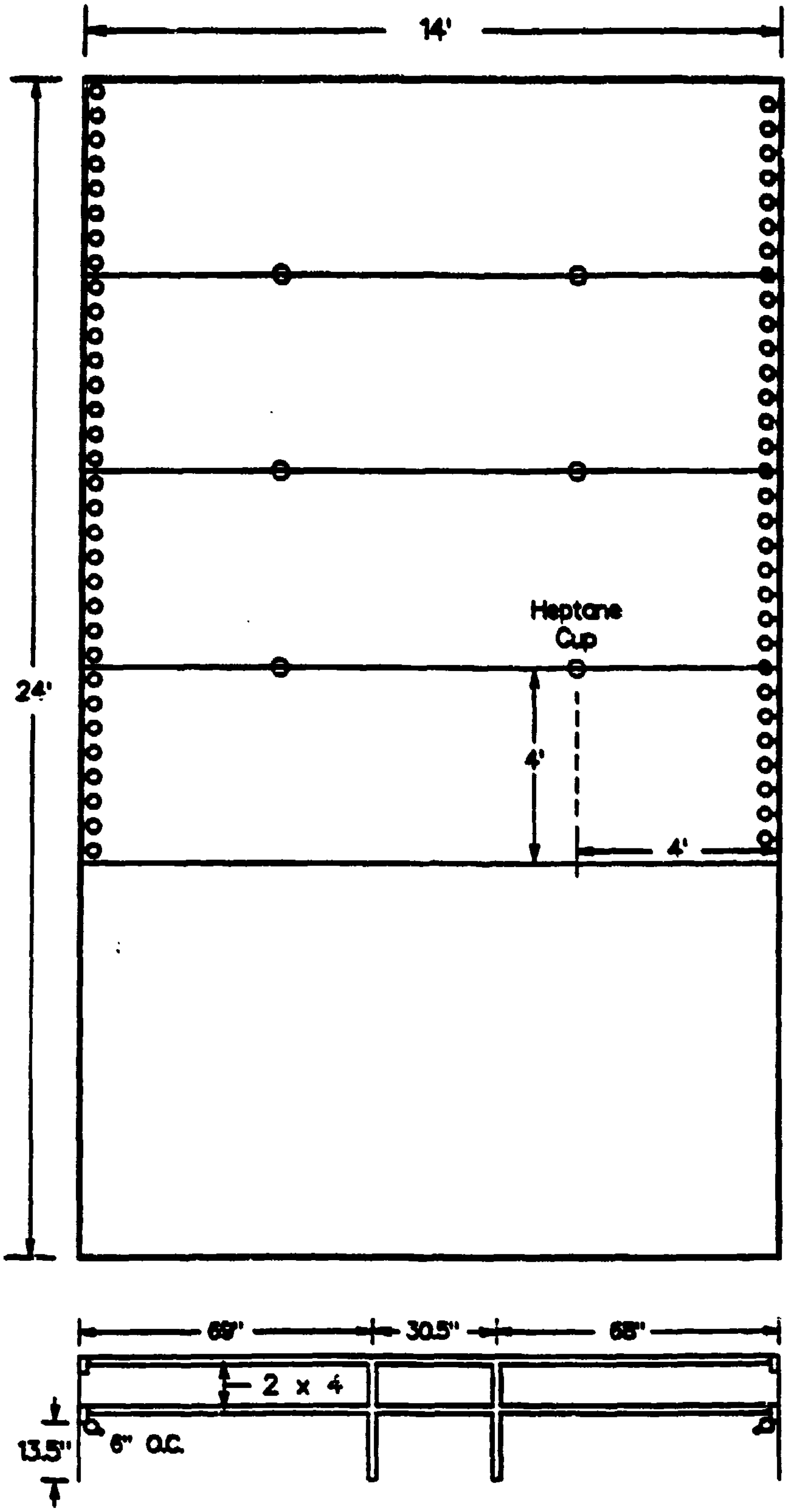
2.4 Dual Fluid, Air Assisted: Securiplex Fire-Scope 2000

2.4.1 General System Description

The Securiplex Fire-Scope 2000 system is an air pressure driven system. The driver is a 65 liter air cylinder, with a storage pressure of 150 bar. The water storage tanks are available in 200 liter increments, i.e., 200, 400, and 600 liters. One air cylinder is required for each 200 liters of water supply.

The delivery system is controlled by a series of regulators and control valves to assure proper water delivery and functionality of the system. The system may be actuated both manually or electronically and may be integrated with detection devices for increased fire protection effectiveness. A system schematic is shown in Fig. 5.

Securiplex operates these systems with two main dual fluid nozzle designs. The designs consist of nozzles that deliver flows of 10 Lpm or 20 Lpm. The two heads are designed to operate at a pressure of 5 bar. The spray angle of the heads may vary in angles of 45°, 60°, and 90° dependent on the fire suppression requirements of the protected area.



Sub-Floor Scenario

Figure 4. Typical Nozzle Array for Subfloor Test Scenario

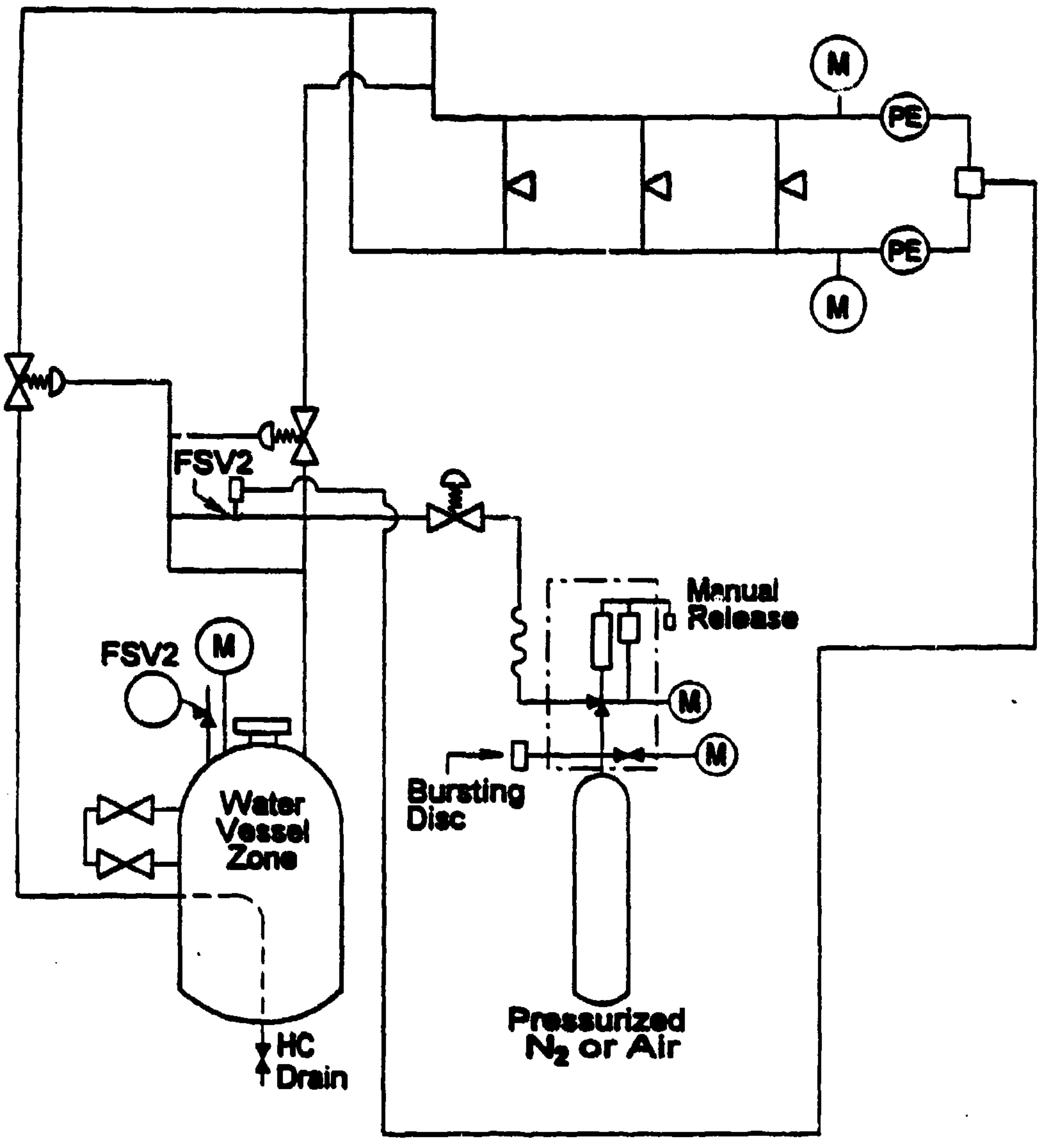


Figure 5. Schematic of a Typical Securiplex System

In total flooding applications, the protection volume of the 10 Lpm nozzles is approximately 5 m^3 per nozzle and the 20 Lpm nozzle will protect approximately 10 m^3 per nozzle. These quantities are subject to room configuration and fire risk assessment. The protection values are based on rooms with ceiling heights not exceeding 12 ft. For rooms exceeding the 12 ft height design, provisions for additional wall mounted heads must be included. The heads are manufactured in bronze. Piping for the Fire-Scope 2000 is standard mill ASTM A-179 steel tubing or galvanized steel pipe schedule 10 or better for conventional building applications.

2.4.2 Other Applications

Securiplex, in conjunction with Danish affiliate Ginge-Kerr A.S., is in the process of development, testing, and evaluation of systems for shipboard and gas turbine applications. The system under consideration is known as the Fine Water Spray (FWS) system.

The basic concept of this system is the same as the conventional building system. The water is stored in a tank and is driven by a gas, in this case, nitrogen. The concept of dual fluid delivery nozzles is consistent with the previous system. Nozzle delivery angles and flow rates also remain constant as with the previous system, but in the shipboard applications the water mist is delivered at lower pressures. This will allow for longer cooling periods in such applications as machinery or engine rooms.

2.4.3 Performance Testing

Extensive testing has been performed on various applications. An array of tests has been performed in simulated ship's engine room configurations. The water mist systems showed that oil spray and pool fuel fire conditions can be successfully controlled, suppressed or extinguished on a consistent basis. The testing was performed at Sintef (Norway) and is described in Section 3.6.

3.0 EXPERIMENTAL EVALUATION OF WATER MIST FIRE SUPPRESSION SYSTEMS

3.1 Overview

The efficacy of water mist fire suppression systems recently has been demonstrated for a range of applications through experimental programs. These applications have included the following:

- Class B spray and pool fires [2-7];
- Aircraft cabins [8-13];
- Shipboard machinery and engine room spaces [14-25];
- Shipboard accommodation spaces [20, 21, 26]; and
- Computer and electronics applications [9, 27-31].

In addition, Factory Mutual (FM) has developed an FM Data Sheet for water mist applications for turbine generator enclosures. International Standards Organization (ISO) is developing a water mist suppression test method [31, 33].

3.2 Naval Research Laboratory

Over 500 water mist system tests have been conducted by the Naval Research Laboratory. Many of these tests were part of an ongoing investigation into the use of water mist as a halon alternative in machinery space applications for the U.S. Navy [25]. These tests have included both generic systems utilizing modified industrial spray nozzles and commercially available fire protection misting hardware. The systems tested cover the spectrum of available technologies including dual-fluid fixed orifice; dual-fluid sheet/slit orifice; single-fluid, high-pressure multiple-orifice heads; and single-fluid high-pressure grid/matrix-type systems. It was not the intent of this investigation to judge one system against another, but rather to determine the capabilities and weaknesses of water mist technology.

The systems were evaluated in a 3 x 3 x 2.4 m (10 x 10 x 8 ft) compartment against a variety of fire conditions as shown in Fig. 6. These fire scenarios included both obstructed and unobstructed Class A wood crib fires and Class B spray and pool fires. Obstructions varied from shielded from above using various size plates to shielded on two sides and above. The average localized mist density, based on a combined total flow averaged over the entire compartment floor area, ranged from 0.5-1.5 Lpm/m^2 (0.01-0.03 gpm/ft^2) which corresponds to a volumetric density of 0.2-0.6 Lpm/m^3 (0.0015-0.0045 gpm/ft^2). This mist density is approximately one order of magnitude less than a conventional sprinkler system. Higher flux densities are currently being evaluated.

Each system was evaluated in a variety of configurations to achieve optimum results. The firefighting capabilities of these optimized systems varied only slightly for a given flux density. The results were primarily driven by the similarity in drop size distribution between the systems with the mass mean diameter of drops $D_{V0.5} \sim 75\ \mu m \pm 25\ \mu m$. An overview of the fire performance of three selected systems is shown in Table 2.

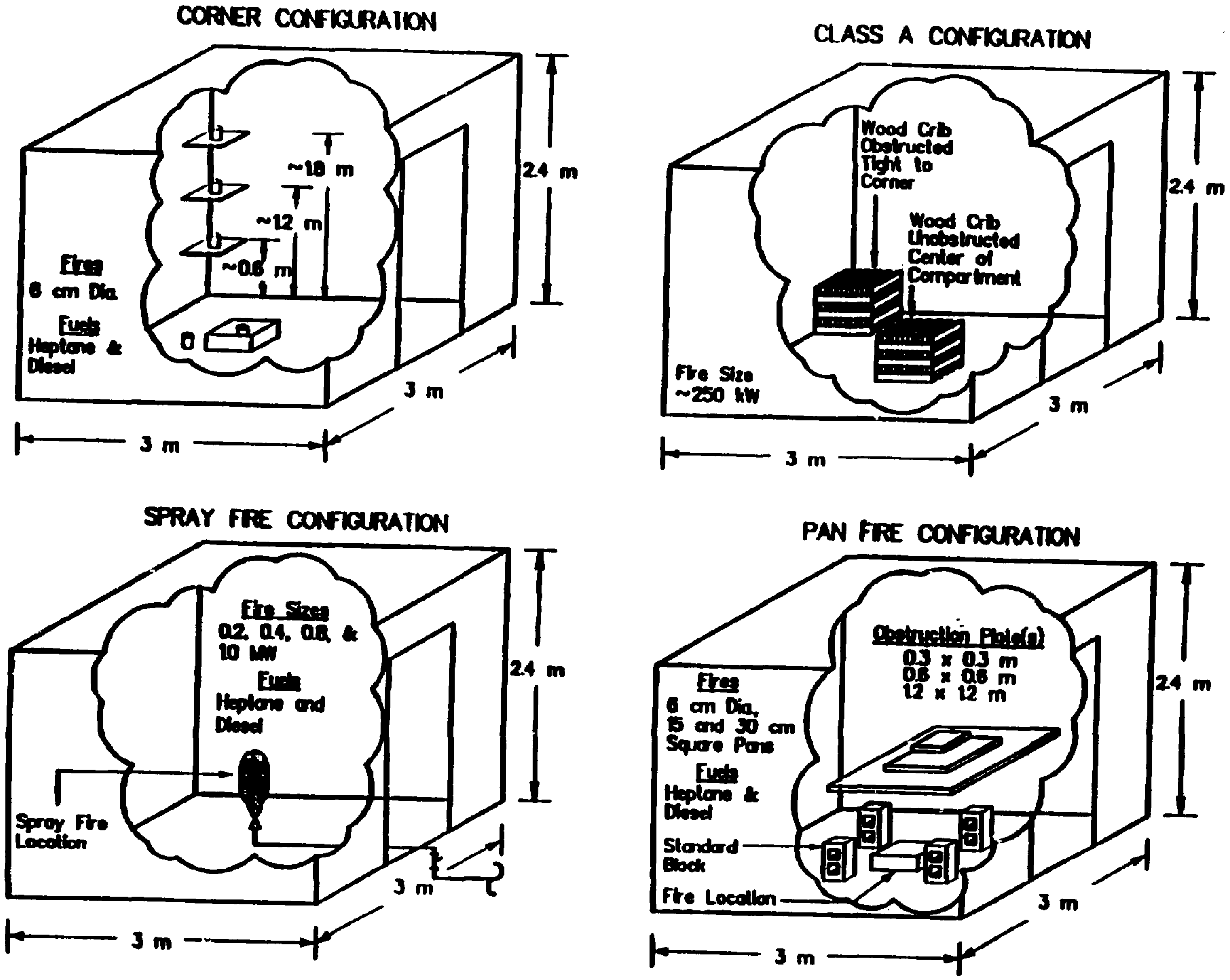


Figure 6. Test Fire Scenarios

Table 2. Firefighting Overview of Water Mist Systems — Probability of Success (%) as a Function of Fire Configuration

Test Configuration	System			
	Generic Dual-fluid	Marioff	Baumac	Modified Baumac
Corner Configuration				
Floor	80	90	95	95
0.6 m off deck	10	10	40	90
1.2 m off deck	10	10	20	60
1.8 m off deck	0	0	10	25
Pan Fires				
Unobstructed	85	90	97	98
Obstructed Plates				
0.3 m high	15	25	40	75
0.6 m high	0	10	10	40
1.2 m high	0	0	0	10
Class A Wood Cribs				
Center	80	80	90	95
Corner	10	10	10	10
Spray Fires	98	95	92	90

Notes: The values in Table 2 represent the percentage of test fires extinguished for a given fire/system configuration. Refer to Figure 6 for a better description of the fire scenarios. Class A wood crib fires were evaluated using a three-minute discharge time.

Some general observations of the firefighting performances of the water mist systems derived from this effort are listed as follows:

- All of the systems evaluated were able to extinguish unobstructed fires on the floor of the compartment with spray flux densities on the order of 1.0 Lpm/m^2;

- Many fires located at higher elevations in the compartment were extinguished with the remaining fires dramatically reduced in size;

- Large fires are easier to extinguish than small fires due to the displacement of oxygen by the expansion of the water mist to steam as well as higher plume entrainment rates associated with larger fires;

- The firefighting capabilities of the two-fluid systems were found to increase by substituting nitrogen and other inert gases for air as the second fluid; and

- Obstructed fires become more difficult to extinguish with increased horizontal drop travel distance (i.e., horizontal distance from the higher flux density region near the spray pattern to the fire source). Many fires were extinguished with distances on the order of 0.3 m (1 ft), but were not extinguished for greater distances. It is worthy to note that many of the highly obstructed fires, although not extinguished, were greatly reduced in size by the presence of the water mist.

The MicroMist system by Baumac and the Marioff system represent the extremes of design philosophy for single-fluid, high-pressure water mist systems. One relies on spray momentum for distribution and mixing of drops; the other utilizes many nozzles which produce small droplets with virtually no spray momentum.

The MicroMist system most closely approximates a "total flooding" system. The system was capable of effectively extinguishing a majority of the unobstructed fires and demonstrated superior firefighting capabilities (superior than the other systems tested) against the obstructed pan and corner fire scenarios. On a broader view, these extinguishment efficiencies are still dramatically less than the gaseous agent's extinguishment efficiencies and would be viewed as a failure in the context of a total flooding system.

Dual-fluid systems (air atomized) use air at 30-100 psi to atomize water supplied at 25-100 psi. The droplet size distribution can be varied across a wide range by changing the relative water/air flow rates, air pressure, and nozzle orifice design. There are several of these types of systems commercially available. They have been shown to be very effective in local application flammable liquid hazards.

The NRL testing has made it very clear that the most difficult fires to extinguish are small laminar flames. Based on droplet size distributions measured in some of the NRL testing, Leonard et al. [25] have developed correlations between the mist concentration and the probability of extinguishing small flammable liquid pool fires. These measurements indicate that the required extinguishment concentration is in range of 0.1-0.15 L/m^3 (see Fig. 7). Much additional work needs to be done to specifically determine the extinguishing concentrations required.

3.3 VTT Testing (Technical Research Institute of Finland)

Toumisarri [34] reviews an on-going project at the Fire Technology Laboratory of VTT that started in 1991 and will continue until the end of 1994. The project focuses on the water use efficiency in post flashover fire suppression of compartment fires. The tests compare commercially available fire hose nozzles and high pressure fog nozzles.

The test room is a 2.4 m x 3.5 m x 2.4 m enclosure with one ventilation opening. The fuel is eight wood cribs ignited with heptane pools under the cribs. Fires are allowed to burn for 3.5 minutes to a heat release rate of about 3.5 - 4.5 MW.

The results showed that the commercial nozzle on average, suppressed the burning gases in about 8 seconds with 11 L of water and fully extinguished the fires with 48 L of water. The mean drop size was 0.35 mm and the flow rate was 80 Lpm. The use of a fine mist nozzle resulted in a reduction in the quantity of water used to suppress the heated gases from 11 L to 2 L with an equivalent suppression time of 8 seconds. With the water fog the crib fires would not extinguish completely as they did with the commercial nozzles. The mean drop size for the fog nozzle was 0.1 mm at a flow rate of

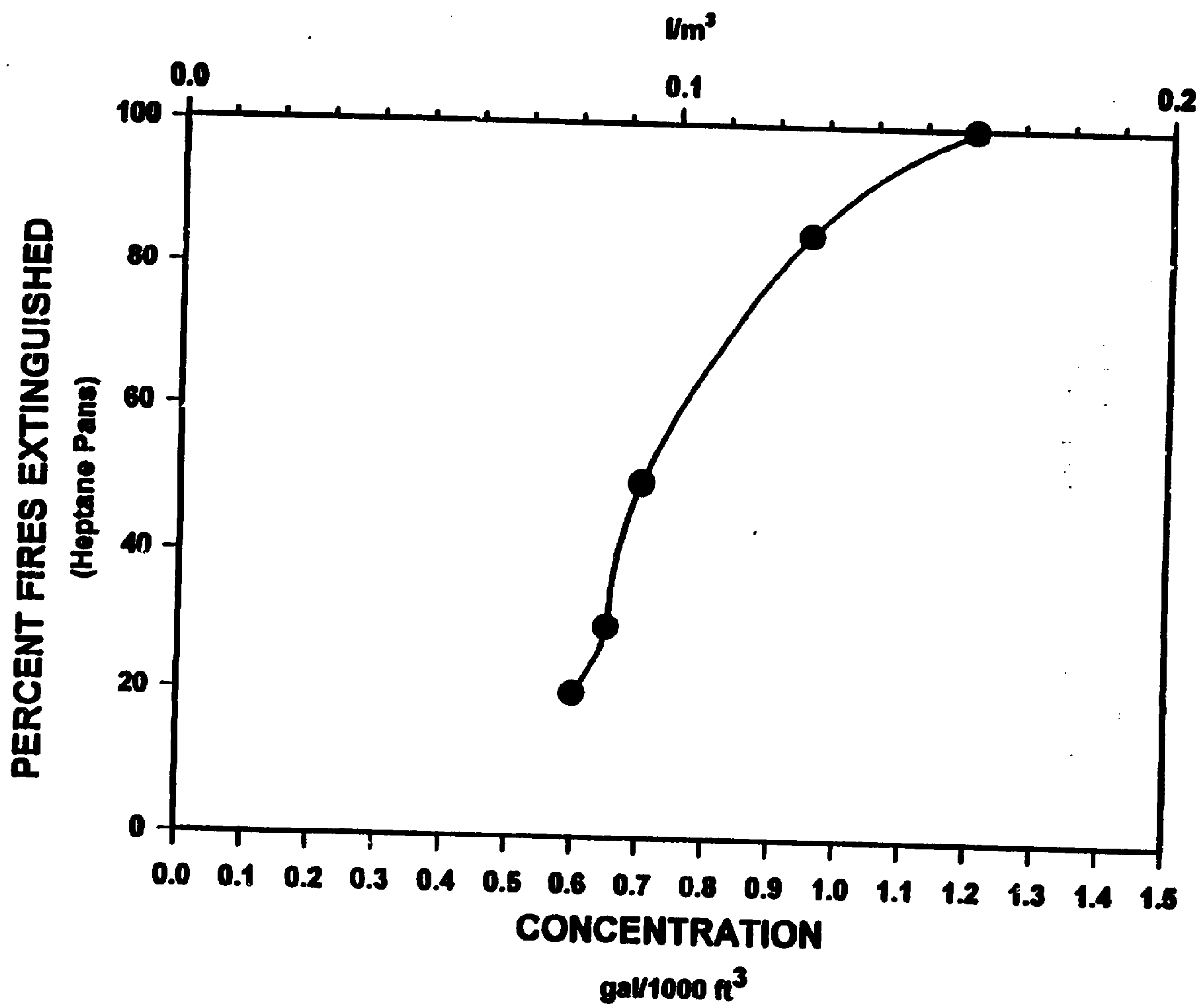


Figure 7. Required Extinguishment Concentrations

16 Lpm. Further studies and experimentation are being performed in order to realize the full potential of water fog for manual extinguishment.

3.4 Shipboard Engine Room Tests (SP-Sweden)

The International Maritime Organization (IMO) water sprinkler regulations had not been revised in over 25 years. To bring the regulations up to date, the IMO developed guidelines for new systems which would perform equivalent to the sprinklers specified in the old IMO regulation. The guidelines were adopted in 1992 and a working group was formed to develop sprinkler/water spray test methods for accommodations, public areas, and engine compartments.

Ryderman [33] first deals with the development of an engine compartment test method. The factors that must be considered in developing this method are as follows:

(1) types of fires - spray and pool;
(2) fuels - variable from high viscosity heavy oils to diesel;
(3) potential fire size - up to 30 MW
(4) ignition sources - e.g. heated engine block; and
(5) variation in compartment configurations.

A preliminary test method was developed which used three diesel fuel scenarios: a spray fire, a pool fire, and a combination spray and pool fire. The combination is presumed to be the "worst case". The test was designed with the premise of testing the reliability and quality of system components. Three typical volumes have been suggested as test method standards, 500 m^3, 3000 m^3, and >3000 m^3 for the various engine rooms in accordance with ship sizes.

Over 200 tests have been performed to validate this test method. The tests have shown the water mist systems to have the best performance in smaller rooms and have also shown that larger spaces could present installation practicality problems. Figure 8 shows the Engine Model.

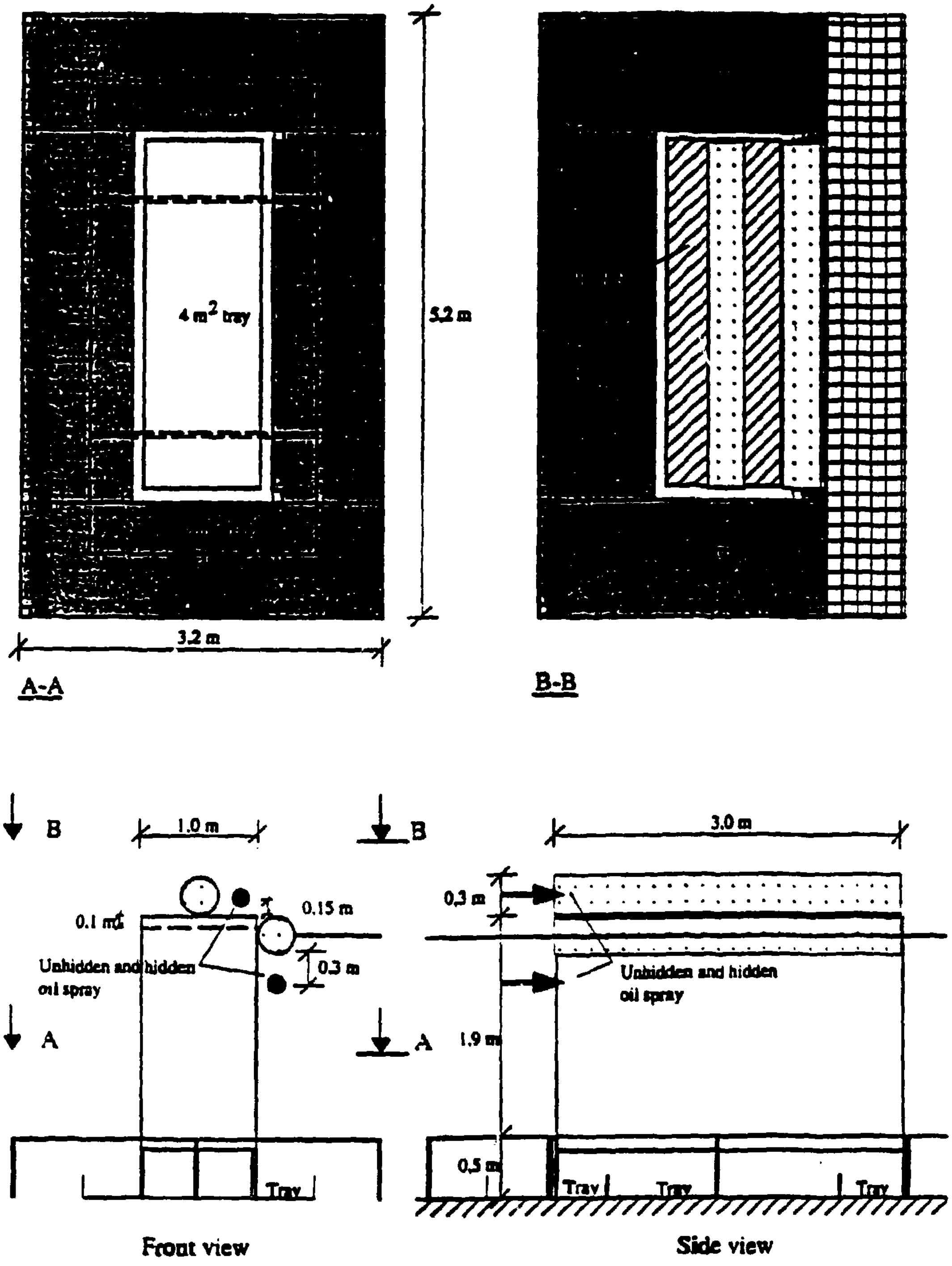


Figure 8. Engine Model

Also under consideration is the accommodation and public area standards. The Maritime Safety Committee (MSC) is currently reviewing a proposed sprinkler equivalency guidelines which would set the minimum requirements for water mist systems as follows:

(1) the sprinkler head shall be placed in an overhead position and spaced in a suitable pattern to maintain an average application rate of 5 Lpm/m^2;

(2) the pump and piping system shall be capable of maintaining that application rate for a simultaneous coverage of 280 m^2; and

(3) the sprinkler shall come into operation within the temperature range from 57°C to 79°C.

3.5 National Research Council of Canada (NRCC)

Mawhinney [17] describes engineering design criteria for machinery space water mist fire suppression systems based on Canadian Navy experiments conducted at the National Fire Laboratory in Canada.

Water mist fire suppressant key characteristics include drop size distribution, spray flux, and spray momentum, among others. Test results are based on a particular set of nozzles for a particular set of conditions. Based on NRC's results selecting one particular nozzle or system design for all application would not be appropriate until such time that all engineering constraints have been analyzed. System design must be based on fire suppression objectives and overall system economics in making the decisions on whether to use low pressure, intermediate pressure, high pressure, or twin fluid nozzles.

Based on Mawhinney's studies water mist does have total flooding limitations. His studies indicate that water mist is primarily useful for local applications systems where spray momentum can be relied upon to allow water penetration of the fire plume. For the Canadian Navy, compartments size limits of 200 m^3 maximum have been established based on economic and space/weight storage restrictions. Mawhinney concluded that water mist holds potential to be an effective fire suppressant for hydrocarbon liquid pool and spray fires depending on the geometry of the compartment.

The following table presents Mawhinney's results with respect to spray density and flow duration, depending on ventilation conditions and degree of compartment obstruction. These results apply only to the nozzle arrangement tested which is a generic industrial spray nozzle, not optimized for fire suppression.

Table 3. Design Application Densities and Durations for a Water Mist Total Flooding Fire Suppression System in Machinery Enclosures from [17]

Fire Category	Description	Ceiling Density (Lpm/m^2)		Under-deck Density (Lpm/m^2)		Duration of Spray (min.)	
Degree of Obstruction		Clear	Obstructed	Clear	Obstructed	Clea r	Obstructed
I	Large	2	4	1	3	1	3
II	Large (>1 MW) well-ventilated: pool and jet spray fires	4	6	1	3	2	4
III (a)	Medium size (0.4 - 1.0 MW), well-ventilated, hidden pool fires	2	4	3	3	2	4
III (b)	Small (<0.4 MW), well-ventilated pool fires	2	3	1	3	1	2
III (c)	Fires in insulation or rags soaked with oil	3	5	1	2	2	5
IV	Fires in electrical or electronic equipment including cable trays	Criteria not available		Criteria not available		Criteria not available	

3.6 Sintef (Norway)

Sintef has developed test procedures and empirical results for application of water mist to turbine hoods. The tests were performed in two different scales, 30 m^3 and 70 m^3 enclosures. Phase I work was to identify the extinguishing characteristics of various BP Sunbury Research Center nozzles and determine the efficiency of Ginge-Kerr Offshore's total fire suppression system. The suppression system consisted of dual fluid nozzle design using air and water at 5 bar. The nozzles produced a high velocity, small droplet water mist.

Phase II was to test and evaluate the efficiency of FWS nozzles in fighting various turbine hood fire scenarios in a full scale test enclosure. The enclosure consisted of an engine mock-up used to simulate hot engine surfaces, insulation mats, and piping as would be in a real condition engine hood. Diesel pool and spray fires, and diesel soaked insulation mat fires were performed under different air flow and nozzle position and flow conditions.

The tests results ran the full range of possibilities. Large underventilated gas, pool, and oil spray fires were extinguished with the addition of small amounts of water. This was due to near self- extinguishment caused by lack of oxygen being introduced into the hood.

The large well ventilated gas, pool, oil spray, and oil spray hitting hot metal surfaces had varying results. The fires were extinguished in the cases where the mist was able to reach the base of the fire, not when the droplets failed to do so. The oil spray on the hot metal surfaces was extinguished consistently when the water spray system covered the full area over which the oil spray hit the metal surface, even in the cases when the metal surface temperature remained high.

It was found that 1 m^2 (medium), well-ventilated pool fires, small pool fires (< 1 m^2), and fires in oil-soaked insulation mats were very difficult to extinguish. The droplets were not able to penetrate the fire to effectively evaporate the water in the flame zone nor reach the base of the fire.

The final condition, oil-soaked insulation mats with hot metal surfaces below the mat were partially successful. The fires were extinguished successfully but had a tendency toward reignition. The reignition can be curbed with sustained addition of the water mist to both displace oxygen and cool the metal surface. The effectiveness of water, in the form of a fine water spray and as an extinguishant has been recently demonstrated in full scale testing conducted at SINTEF laboratories in Trondeim, Norway. A full scale mockup of an enclosed ABB Stal GT-35 gas turbine was used for the purpose of these tests.

3.7 Federal Aviation Administration

The Federal Aviation Administration performed tests to evaluate and develop an on-board aircraft cabin water spray system against postcrash fires. Initial designs provided a system with an array of nozzles at the ceiling line, which would continuously discharge within the entire cabin for three minutes. Several fire scenarios were investigated inclusive of a wind driven external fuel fire adjacent to the fuselage opening and a quiescent fuel fire impinging upon the intact fuselage. Tests were performed for both narrow-body and wide-body aircraft. Hazard analysis assessments, using a dose fraction model, showed that the water spray system provided about two to three minutes of additional survival time in all conditions, except the worst case scenario.

From the results, a zoned water spray system was conceptualized, designed, and tested under full scale conditions. The results of the zoned system tests showed that the zoned systems can work as efficiently as the previously tested cabin system with ten percent of the water. This is crucial to space and weight constraints for aircraft.

3.8 Summary of Results of Testing Water Mist Suppression Systems

While there has been extensive testing of water mist systems by the system developers and independent laboratories, there has been relatively little progress in understanding the mechanisms of extinguishment and the distribution of mist throughout the compartment. As a result, little is also known about the effect of changes in spray characteristics, compartment characteristics, and fire size and type.

The available systems are extremely diverse and appear to perform quite differently. A wide range of required application rates have been measured depending on the system, the fuel source, and the compartment size and geometry. Some systems appear to rely on direct application of a high momentum spray directly to the fuel surface. Other systems have essentially no momentum and do not rely on nozzles directed at the fuel surface.

None of the testing to date has been designed to determine the momentum requirements for the local application type systems nor have criteria for total flooding system success been developed. The preliminary results of the NRL testing are the only available to begin a determination of the required mist concentration and droplet size distribution needed for reliable flame extinction.

4.0 FUNDAMENTAL STUDIES OF WATER-BASED SUPPRESSION AGENTS

4.1 Water Spray Extinguishment of Liquid Pool Fires

Water sprays as a means of fire protection has been in use at least since the 1930's. As such, water mist systems are in many ways not novel. The traditional use of water spray systems is as a local application extinguishing agent for high flashpoint liquid fires. The available research in water spray fire extinguishment was reviewed by Rasbash [1]. Rasbash was responsible for much of the available research up to that time [35-40].

He established that there are two basic mechanisms for extinguishment of liquid fuel fires, gas phase flame extinction and surface cooling. Gas phase extinction was observed to be very rapid while surface cooling was much slower due to the need for water reaching the liquid surface and cooling the liquid to below its firepoint temperature. Of course, low flashpoint fuels like gasoline cannot be extinguished by this mechanism. The work of Rasbash used mass mean droplet sizes of 200-500 μm. The research effort focused on water spray as a local application system and the effects of obstructions were not addressed. While the gas phase extinguishing mechanism was recognized in the 1950's, the idea of using water mist as a total flooding agent was clearly not envisioned at that time.

4.2 Water-Based Extinguishment of Solid Fuel Fires

There is a body of work relating to fundamental aspects of solid fuel fire extinction by water [41-46]. The work properly focuses on the effect of water application to the fuel surface. This body of research demonstrates that water application rates of only several g/m^2s are required to achieve extinction. This is, of course, several orders of magnitude less than typical water application rates via sprinklers or handheld fire hoses, indicating the gross inefficiency of traditional water based systems.

Beyler [47] developed an engineering theory of fire extinction derived from Rasbash's firepoint theory [1] which successfully explains these results in terms of fully independent fire property measurements. These results are directly applicable to water mist extinguishment in applications where cooling of the fuel surface is significant.

4.3 Water Spray Extinguishment of Liquid Spray or Gas Jet Flames

Extinguishment of jet diffusion flames by introduction of water sprays at the base of the flame has been studied by a number of investigators [48-54]. These flames can be extinguished very efficiently by this technique since the normal air entrainment process assures that all the water spray added adjacent to the flame is actually transported into the flame. The water required for extinguishment is reported in terms of the ratio of the water supply rate to the fuel supply rate at extinction. These ratios range from 1.5 to 10. While no systematic evaluation of droplet size on the water/fuel ratio at extinction has been performed, the available data indicate that the ratio is reduced with decreasing droplet size for laboratory flames. In full scale tests (150-220 MW) flames could be extinguished with a water/fuel ratio of as low as 1.6. Ratios of up to 10 were required depending on the orientation and geometry of the spray nozzles. These full scale studies were performed with conventional 100 psi spray nozzles. While drop size information was not given, such nozzles would be expected to produce droplets on the order of 1 mm diameter. To achieve similar water/fuel ratios at extinction of laboratory flames required droplet sizes of 15 μm [54, 55].

These studies also indicate the reductions in flame temperature which occur in flames with sub-extinguishing application rates of water. McCaffrey [50] observed in hydrogen flames that the maximum flame temperature per unit mass of water per unit mass of fuel was reduced from 150 to 50°C as the water/fuel ratio increased from 0 to 10. The degree of cooling was also a direct function of the drop size with higher cooling effects associated with smaller droplets. While McCaffrey [51] did not perform such systematic measurements for methane flames, the general trends are similar to hydrogen flames. Similarly, the radiation from the flames was directly reduced by water addition. Such reductions in flame radiation were directed correlated on the basis of the water/fuel ratio.

4.4 Gas Phase Extinguishment by Water Mist

There has been very little theoretical or experimental work to develop an understanding of gas phase extinguishment of fires. The earliest scientific study of the interaction of flames and water mist was performed by Seshadri [56]. He studied counterflow heptane and methanol flames with an oxidizer stream made up of O_2/N_2/water mist. This work was of a preliminary nature in that only a single water mist flow rate and drop size distribution was used. He simply added a fixed flow of water mist to the air stream and added nitrogen until the flame was extinguished. Based on extinction oxygen mass fractions as a function of strain rate, he deduced one step kinetic parameters for these systems. Based on the similarity of the kinetic parameters for O_2/N_2 and O_2/N_2/water mist, he concluded that the water had only a thermal effect. No detailed flame measurements were reported and droplet sizes were also not reported. More detailed work of this sort is needed.

There does not appear to have been any further fundamental work directly related to water mist gas phase extinction processes. There is, however, related experimental work with other particulate extinguishing agents known as dry chemical agents. Ewing et al. [55, 57-59] have been active in evaluating the role of thermal processes in the effectiveness of a wide range of extinguishing agents. Their work has included experimental investigations of dry chemical agents [57, 59].

In these evaluations they were able to identify a critical particle size below which the effectiveness of the dry chemical agent no longer increased. These critical particle sizes ranged from 20-50 μm for a number of dry chemical agents. The interpretation given for this behavior was that particle sizes below the critical size were fully decomposed in the flame while larger particles were less effective since they were not fully decomposed in the flame. There were no detailed measurements performed to confirm this interpretation, though the hypothesis appears to be quite reasonable. Based on the relative thermal stability of the dry chemicals relative to water, one might expect the critical droplet size for water to be somewhat larger.

The work of Ewing et al. [55, 57-59] makes it clear that dry chemicals are on a weight basis the most effective fire extinguishing agents available. In a forthcoming paper, Ewing et al. [60] develop an interpretation of a wide body of extinguishing agent evaluation data which indicate that condensed phase agents with large heats of gasification (evaporation or decomposition) would be expected to be very effective agents. Their hypothesis, which is consistent with correlations of a large body of data, is that heat extraction from the combustion region of the flame sheet is critical to flame extinction. They divide the flame into a preheat region and a combustion region as has historically been done in thermal analyses of flames. They argue that flame extinction is governed by heat extracted from the combustion region. Since dry chemical agents and water droplets can actually penetrate the preheat region and are largely decomposed or evaporated in the combustion region, these agents are more effective. Indeed, all condensed phase (evaporating or decomposing) extinguishing agents which have been evaluated are more effective than gaseous agents in that lower mass concentrations of agent are required for extinction. Holmstedt [54] has shown that the mass of dry chemical or fine water mist per unit mass of fuel is less than that required by Halon 1301 to extinguish a gaseous jet flame where the agent and fuel are mixed, and Ewing's correlation of a wide range of extinguishing agent testing demonstrates this trend as well.

While such results provide interesting and potentially fruitful directions for research and development, there is a definite need for additional detailed experimental and computational work to develop an understanding of the interaction of water mist droplets with a flame and the detailed processes involved in extinction.

4.5 Radiation Attenuation by Water Sprays

The value of water curtains in attenuating radiation from large fires has been recognized by firefighters for a very long time. The first scientific investigation of water spray attenuation of flame radiation was that of Thomas [61]. He examined theoretically the attenuation of radiation in the geometric optics limit and provided expressions for transmission through sprays. His results demonstrated that fine drops are most effective in attenuating radiation.

More recently, Ravigururagan and Beltran [62] and Coppalle, Nedelka, and Bauer [63] studied radiation attenuation by mists using Mie scattering theory and approximations to Mie scattering theory. These papers demonstrated that the most effective droplet size is approximately equal to the wavelength of the incident radiation. For fire sources this is roughly 2 μm. This is even smaller than most of the droplets in water mist sprays. Each of these investigators present methods for calculating attenuation from mists using approximations to the Mie scattering equations.

All of the work in the fire field relative to radiation attenuation by mist has its roots in the atmospheric and optical literature. There do not appear to be any experimental validation of the three models discussed above for actual fire conditions, though the models have roots in well established theories and rely on optical properties of water which are well known. Some experimental data for attenuation of radiation by water sprays are available [64], but the data are not suitable for model validation due to undocumented drop distributions and path lengths.

5.0 NONFIRE LITERATURE RELEVANT TO WATER MIST TECHNOLOGIES

5.1 Particulate Two-phase Flow

Applications of liquid/gas and solid/gas particulate, two-phase flows abound in engineering practice. As such there is extensive literature involving the prediction of the dynamics of these flows. While this is a very active area of research, the direct application of existing methods in this area to water mist fire suppression is not possible. The focus of most of the research in this field centers on spray dynamics and mixing in shear or duct flows, as well as particle collection. The dynamics of a spray contained in a compartment does not seem to have a focus in this field. The aspects of mist/flame interactions have also not been studied directly. Of course the evaporation of fuel droplets in a flame have been studied extensively, but some aspects of the water mist extinguishment problem are significantly different than fuel droplet burning and evaporation. Despite these differences, much can be learned about water mist fire suppression from the particulate two-phase flow literature.

It is useful to review some of the rudimentary concepts of particulate flows. The interaction of a particle with a gas flow is largely governed by the relaxation time of the particle, τ. The equation of motion for a particle in a gas flow is

$$\frac{dU_p}{dt} = F\,(U_o - U_p)$$

where F is the drag force per unit mass of particle per unit velocity differential which is given by

$$F = \frac{3}{8}\,C_D\,\frac{\rho_{air}}{\rho_p}\,\frac{|U - U_p|}{r_p}$$

Where the gas has a velocity, U_o, and the particle is initially at rest, the velocity of the particle, U_p, is given by Soo [65]

$$U_p = U_o\left(1 - \exp\left(\frac{-t}{\tau}\right)\right)$$

The aerodynamic response time, τ, is 1/F and is given by

$$\tau = 2r_p^2\,\frac{\rho_p}{9\mu}$$

in the Stokes regime. The aerodynamic response time is directly related to the terminal velocity of a particle in a gravitation field, U_t, [66].

$$U_t = g\tau$$

As we will see, the aerodynamic response time will be significant in a wide range of phenomena including particle settling losses, spray dynamics, and interactions of particles with obstructions and large scale turbulent structures.

The role of the aerodynamic response time in a wide range of particle dynamics phenomena is expressible in terms of the Stokes number, which is the ratio of the particle aerodynamic response time to the fluid mechanical time scale. The Stokes number has been used historically to define the collection efficiencies of impactors. The fluid mechanical time, t_f, is given by l_f/U, where l_f is the fluid mechanics length scale and U is a characteristic velocity. Alternately, the Stokes number can be interpreted in terms of lengths. The particle length, l_p, is U τ.

$$St = \frac{\tau}{t_f} = \tau\frac{U}{l_f} = \frac{l_p}{l_f}$$

For impactor/particle combinations with $St \tilde{>} 1$ the particle is deposited, while for $St \tilde{<} 1$ the particle remains in the flow. Of course the crossover from no collection to collection is not a step function due to the distribution of particles across the cross-section of the inlet. Similar treatment of flow around pipe bends leads to the same form of the Stokes number.

The interaction of particles with large scale turbulent structures can also be discussed in terms of a Stokes number [67]. Here the fluid mechanical time is related to the scale of the turbulent flow (eddy size), Δ, and the velocity difference across the shear layer, U, so that

$$St = \tau \frac{U}{\Delta}$$

For St<<1 the particles follow the flow. Similarly, for St>>1 the particle trajectory is unaffected by the turbulent structure. At St numbers of order one, the particle trajectory is strongly affected by the turbulence with the particle being centrifuged and further dispersed by the turbulence. These phenomena are very important in the extinguishment of turbulent flames by water mist where the flame exists at the boundary of the eddy. For droplets with St numbers of order one, the mist is effectively concentrated at the edge of the eddy, making the flame easier to extinguish. This will be discussed further later in this review.

The dynamics of droplet concentration at the edge of an eddy can be understood by examining particle motion in a vortex [65]. The flow is, of course, fully characterized by the vortex strength, C. The tangential velocity is simply given by C/r. The radial displacement of the particle is governed by the drag parameter, $r_o^2/(C\,\tau_o)$, where r_o is the initial radial position of the particle. For a drag parameter of zero, the particle is unaffected by the vortex. For a drag parameter of infinity, the particles are not radially displaced, being fully captured by the flow. Because the radial forces decay as 1/r, particles with intermediate drag parameters are effectively concentrated by the vortex motion. In this system the fluid mechanical time can be interpreted as r_o^2/C. This interpretation makes the drag parameter the inverse of a St number.

5.2 Mathematical Modeling of Sprays

There is ongoing interest in the research literature in the mathematical modeling of sprays and other dispersed flows. This work has involved a wide range of turbulence models including k-ϵ models and other closure models as well as direct simulation methods. Reviews of the modeling approaches used for sprays have been published by Faeth [68] and by Sirignano [69]. These reviewers each concentrate on their own approaches to the subject which differ considerably in focus. The Faeth review focuses on spray modeling and Sirignano focuses on droplet processes including heat transfer, internal circulation, and evaporation as well as droplet/droplet interactions.

Sirignano [69] demonstrates that while there is a rich variety of internal drop heating and flow dynamics, the particle lifetimes are quite independent of these differences. The shape of the evaporation curve is somewhat dependent on the internal drop processes. Nonetheless, the simple droplet evaporation models (see [70] for instance) are widely useful. The droplet evaporation time, t_v, is given by

$$t_v = \frac{\rho_l \, d_o^2}{8 \, \rho_g \, \alpha_g \ln(1 + B)} = \frac{d_o^2}{\lambda}$$

Based on typical flame conditions of about 1000°C, the B number for a water droplet is 1.5. Using typical air properties for the gas phase, this yields a λ of 240 $\mu m^2/ms$. For the range of droplet sizes normally associated with water mist systems (10-100 μm), this yields evaporation times of 0.5-50 ms. The fate of water droplets as they pass through a flame sheet has not been studied. With a typical flame thickness of about one millimeter, these evaporation times would require flow velocities through the flame sheet in the range 2-200 cm/s which are realizable.

Faeth [68] identifies three major classes of models for dispersed flows with regard to the gas/droplet interactions. The simplest is the locally homogeneous flow (LHF) analysis. In this class the gas and dispersed phase are assumed to have infinitely fast interphase transport rates. The gas and dispersed phase are in dynamic and thermodynamic equilibrium. As one might expect this class of models does not generally provide satisfactory results.

The remaining two classes of models do not assume interphase dynamic and thermodynamic equilibrium. The droplets are divided into samples or groups which are tracked through the flow field using a Lagrangian formulation. The gas phase flow is formulated in the usual Eulerian manner. Finite interphase transport is modeled via source terms in the gas phase and droplet equations. In the deterministic separated flow (DSF), interactions of the gas and droplets is only through the time-averaged drag terms so that no turbulence interactions are considered. In the stoichastic separated flow (SSF) analysis the turbulence interactions are included via random walk calculations for the motion of the droplets. Probability density functions (PDF) are required for turbulent velocity components and mixture fraction variables. Indications are that the results are relatively insensitive to the selection of a PDF form.

As a general observation the LHF models result in overpredictions of dispersion of the dispersed phase and result in overly rapid decay in jet velocity along the spray centerline. DSF models tend to result in the opposite trend, while SSF models tend to be both intermediate between the LHF and DSF result as well as closest to the experimental results. The success of the SSF models is quite remarkable when viewed in the context of the literature concerning the interaction of turbulence and particle flows. There is a wide body of literature that indicates that large scale turbulent structures are quite important in particle dispersion. Nonetheless, the k-ϵ/SSF models have been found to be quite successful despite the fact that the k-ϵ models do not have the ability to model large scale turbulent structures. Clearly, there are some issues to be resolved in this area.

5.3 Particle Loss Mechanisms and Mist Concentrations in Compartments

The mist is introduced as a spray and the momentum of the spray is responsible for mixing the mist within the compartment. The major loss mechanisms for mists in a compartment are gravitational settling and spray/boundary interactions. We will consider here some simple models for these loss mechanisms.

The conservation equation for a monodisperse mist including only the droplet fallout mechanism in a compartment under stirred conditions is given by

$$\frac{dn}{dt} = \frac{\dot{n}''}{H} - \frac{n\,U_t}{H}$$

where n is the droplet number density, $\dot{n}''$ is the droplet generation rate per unit floor area, H is the compartment height, and the droplet fallout losses per unit floor area, I, are given simply by $I = n\,U_t$. At steady state this yields a mist concentration of

$$n_{ss} = \frac{\dot{n}''}{U_t}$$

The buildup of the mist concentration is

$$n = \frac{\dot{n}''}{U_t}\left(1 - \exp\left(\frac{-U_t t}{H}\right)\right)$$

The decay of the mist concentration after water supply ends is given by

$$n(t) = n_{SS}\exp\frac{-U_t t}{H}$$

Of course, in a polydisperse mist there is a range of U_t and as such a range of the decay time constants, H/U_t. The time scale for the buildup and decay of mist number density is H/U_t. The time scales for these phenomena measured at NRL by Back et al. [71] and Leonard et al. [25] are generally consistent with the time constants indicated by the theory. The measured time scales were also found to be dependent on the elevation in the compartment. Since the model assumes perfect mixing variations with elevation are not predicted. Nonetheless, the variations in the time scale with elevation are consistent with the expected variation in average droplet size.

The loss of particles by spray/boundary interactions is more difficult. Sprays might be idealized to be omnidirectional with very low momentum such that boundary interactions are minor. Alteratively, the spray could be idealized as a single downward facing jet. In the latter, the jet radius increases linearly with distance, x, and the velocity goes as $M^{1/2}/x$, where M is the jet momentum. Thus, the Stokes number of the jet as it hits the floor follows the trend

$$St = \tau \frac{U}{r} \sim \tau \frac{\frac{M^{1/2}}{H}}{H} \sim \tau \frac{M^{1/2}}{H^2}$$

This indicates the role of jet momentum and ceiling height on spray/floor interactions. This assumes that gravity plays no role and that the differences in droplet and gas velocities in the jet may be ignored. The droplet size that yields St ~ 1 essentially defines the large particle limit of the droplet distribution and the fraction of the spray greater than this value will be lost directly and will not contribute to the mist concentration. Of course, if surface cooling is desired (local application type system), then the loss of a large fraction of the spray is desirable. If the system is to act as a total flooding agent, such losses are detrimental.

5.4 Water Mist Flame Extinguishment

Water mist fire suppression systems can be characterized as quasi-total flooding and local application systems. In the quasi-total flooding approach the goal is to generate a sufficiently high concentration of mist throughout the compartment such that flames anywhere in the compartment will be extinguished. The local application approach requires that potential fire locations be specifically identified and spray nozzles be directed at these surfaces. It is important to note that water mist system developers be directed at these surfaces. It is important to note that water mist system developers do not typically identify their system as being one or the other of these system types.

Mawhinney [72] has found in his work that the systems he studied were effective as local application systems. In order for these systems to be effective, he observed that the spray needed to have sufficient momentum to flatten and penetrate the buoyant flame. This can be expected to occur when the local momentum flux of the spray exceeds the local momentum flux of the buoyant flame over the full height of the flame. Based on the work of McCaffrey [73] and others (see Beyler [74] for a review of available data), the maximum local momentum flux of a buoyant flame occurs on the flame centerline at the flame tip height. The density at this location is approximately half normal air density and the velocity (m/s) is about 2 $\dot{Q}^{1/5}$ ($kW^{1/5}$). The flame momentum flux at the flame tip is given by

$$\dot{M}''_{flame,max} = \rho U^2 = \frac{\rho_{air}}{2}(2\dot{Q}^{1/5})^2 = 2\rho_{air}\dot{Q}^{2/5}$$

It is interesting to note that the flame height varies as $\dot{Q}^{2/5}$, so that the maximum local flame momentum flux scales directly with flame height. The full variation of the flame momentum flux can easily be represented using correlations available in [74]. The local momentum flux of the spray is given by

$$\dot{M}''_{spray} = \rho U^2 = \rho_{air}\left(\frac{c\dot{M}^{1/2}}{x}\right)^2 = \frac{\rho_{air}c^2\dot{M}}{x^2}$$

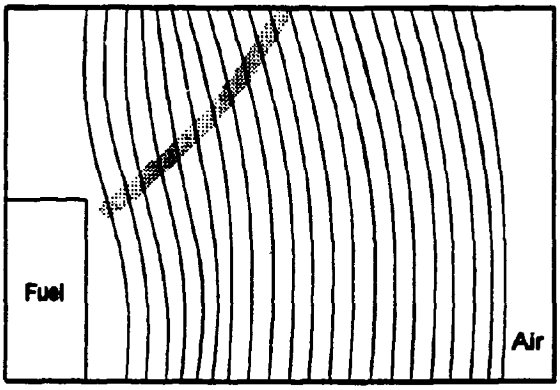
where $\dot{M}$ is the nozzle momentum.

At the very least the local spray momentum flux at the flame tip height must be greater than the local flame momentum flux in order to flatten the flame. Since the spray momentum flux decays as x^{-2} and the local flame momentum flux decreases less rapidly as one moves into the flame, the ratio of the local spray to flame momentum may decrease as one moves from the flame tip through the intermittent flame region.

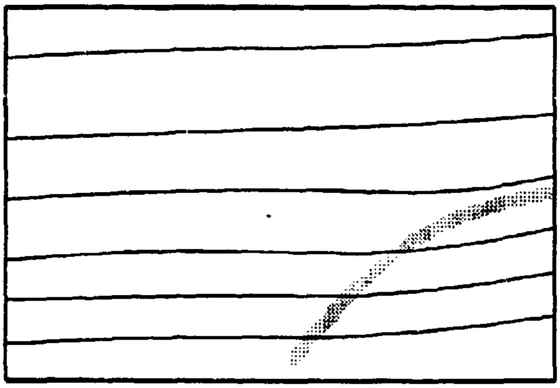
While the importance of this flame/spray interaction is well documented, no experimental investigations have been conducted in which the effect of the ratio of spray to flame momentum flux has been systematically studied. Such experiments are straightforward and should be pursued along with numerical modeling of this flow interaction.

In total flooding type systems the transport of water mist to the reaction zone is clearly dependent upon the gaseous flow fields within a flame, since as a first approximation the mist is carried to the flame by the gas flow. The extent to which streamlines cross from the air side of the flame into the interior of the flame, water mist will be carried convectively to the flame sheet. The general flow in a number of diffusion flames is illustrated in Fig. 9. For a boundary layer flame the streamlines pass from the air to the fuel side of the flame. The downstream direction of the streamline depends largely on whether the flame closes or not. Clearly if the flame closes, the streamlines cross out of the fuel side to the air side once again. In counterflow flames the stagnation point is always on the fuel side of the flame so that streamlines pass from the air side through the flame.

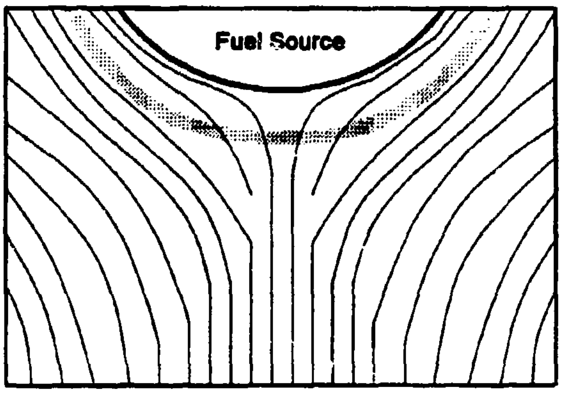
Since the streamlines cross the flame sheet, there is no need to transport droplets by diffusion to the flame or rely on droplet trajectories which do not follow the gas streamlines. As such there is no reason to expect that extinguishment of all flames is not possible if a sufficient concentration of droplets can be achieved at the flame location. Empirical observation that small flames are difficult or impossible to extinguish suggest that extinguishment may not be possible in all cases. It would appear that difficulties in extinguishment of small flames results from mist distribution problems. Further work is required in this area. There are two aspects of this problem which require further investigation.



Coflowing Diffusion Flame



Surface Flame



Counterflow Diffusion Flame

Figure 9. General flow in a number of diffusion flames

First, experimental and computational studies of simple laboratory flames interacting with mists need to be carried out to develop an understanding of the mist/flame interaction. From such work one would expect critical mist concentrations would be determined and the effect of droplet size on mist effectiveness would be established.

The second area of investigation is the distribution of mist within a compartment. This problem can largely be addressed without specific inclusion of the flame. It is simply a problem of mist transport and distribution within a compartment. This work would establish the effect of compartment size/geometry, nozzle location, drop size, and spray momentum on the distribution of mist within the compartment. Further, insights into the interaction of mists with obstructions could be studied to establish methods for avoiding shielded regions in which fires cannot be extinguished. These problems can best be addressed through a combination of experimental and theoretical (two-phase, computational fluid mechanics modeling) work.

5.5 Flame Turbulence/Mist Interactions

It has been empirically observed that large flames are easier to extinguish than are small flames. This observation holds for spray fires in compartments [25, 71] as well as spray/jet flames in the open [53]. Liquid fuel pan fires have been found to be easy to knock down, but it is difficult to extinguish the final flame remnants at the pool lip edge. In the compartment work there is no doubt that generation of steam by the large flame is significant in displacing oxygen and thus aiding in extinguishment. This effect does not readily explain the ease of extinguishment of flames in the open by water sprays. The interaction of droplets with large scale turbulent structures perhaps may be used to explain these results.

Since the large fires have prominent large scale turbulent structures with scales comparable to the flame diameter, the effect of these large scale turbulent structures can significantly concentrate the droplets at the outer edge of the turbulent structures where the flame sheet exists. Since the fluid mechanical times in these large flames are large, the droplet size which can be effectively centrifuged is also large. For very large flames length scales of ~10 m and flame velocities of ~20 m/s are not unusual. This results in time scales of about a second. The aerodynamic response time of a 3 mm drop is about 1 second, so that for large spray fires like those studied by Evans and Pfenning [53] ordinary low pressure spray nozzles which yield drops in the range 1-5 mm are very effective.

Smaller turbulent fires which have reduced fluid mechanical times would be expected to require commensurately lower droplet sizes to benefit from mist concentration effects due to turbulence. More importantly, small laminar flames would not benefit from this mechanism at all, thus requiring higher mist concentrations for extinguishment. This is consistent with the observed trends in experimental work. While this view of the interaction of turbulent structures is qualitatively consistent with the available experimental results, it must be considered a mere hypothesis which should be evaluated.

5.6 Combustion Interactions of Steam and Water Mist

The most studied multiphase flame is of course droplet combustion. These studies are not of direct interest in the present problem. However, some of the work done in the combustion literature also deals with the addition of water in the form of steam or mist.

Numerical studies with water mist in a premixed stagnation point methane/air flame have been reported by Chen and Rogg [75] using a 37 step chemical mechanism. Chen, Rogg and Bray[76] also presented numerical results for a counterflow methane/air diffusion flame with heptane droplets added to the fuel stream. While neither of these systems is the one of direct interest for our problem, together they include all the required elements of a model of water mist/flame interaction model. The premixed flame study with water mist was run for mist concentrations from zero to extinction concentrations. As expected the volume fraction of water mist at extinction is a function of the strain rate. The temperatures in the flame are a direct function of the mist concentration and the H atom concentration decreases with increasing mist concentration. Droplet evaporation times of about 15 ms are predicted.

These results are in agreement with recent results by Atreya [77] for nonluminous methane counterflow diffusion flames and with CHEMKIN calculations performed by Atreya. However, Atreya finds that when water is added to a sooty flame, the burning rate is enhanced at low water addition rates and is ultimately decreased and extinguished at higher application rates. This appears to result from the oxidation of soot, CO, and unburnt hydrocarbons due to the addition of water. While detailed species profiles needed to evaluate the detailed mechanism have not yet been made, the qualitative trend appears to be consistent with the water-gas reaction with subsequent oxidation of hydrogen.

In experiments conducted with steam replacement of nitrogen on the oxidizer stream (up to 30% H_2O), temperature profiles in the flame are only changed by about 20°C. Burning rates were enhanced in all experiments conducted and extinction was not observed. This was, of course, for constant oxygen concentrations. Had the water simply been added to the air so that the oxygen concentration was reduced flame extinction would be expected.

In experiments by Blevins and Roby [78] steam was added to the air side of a counterflow diffusion flame to reduce NO_x emissions. They observed that above a steam addition of more than 100 g/MJ of energy release neither the flame temperature nor the NOx emissions were further reduced beyond that obtained at 100 g/MJ. No flame extinction was observed and no oxygen concentrations were reported. These two experimental investigations clearly show that water addition can actually enhance combustion and may not in all cases act as an inert gas. This behavior was not observed in the early Seshadri study where detailed measurements were not made and only limited experimental conditions were investigated. The importance of combustion enhancement and non-inert behavior in water mist fire suppression remains to be assessed.

5.7 Transmission of Infectious Disease via Mists

The importance of aerosols in the transmission of infectious organisms was first established in the 1930's (see [79]). Concerns exist that water stored for use in water mist suppression systems may contain such organisms. Upon discharge, individuals may be exposed to these organisms. Droplets on the order of 1 μm are optimal for penetration and deposition in the lower respiratory tract [79, 80]. Since particle sizes of this order are included in water mists, aerodynamically there is a basis for this concern. The focus of the remaining issues is the ability for organisms to reach and survive in the stored water such that they are indeed available to be distributed by the mist. Such research is underway and results have not yet been reported. Methods for treating water to remove or kill organisms have not been studied in the context of water mist.

6.0 DISCUSSION

From this review of water mist technology for fire suppression, it is clear that to date most of the work has been highly empirical in nature. This strategy has been very effective in some regard, yet it is clear that there are major barriers to widespread use of water mist which do not seem to be addressable using the empirical approaches adopted to date. There are simply too many interacting variables to allow all relevant parameter combinations to be evaluated in an empirical fashion. The work would take many more years of effort and would still not yield the desired results. The introduction of more fundamental investigations into water mist technologies can serve to make the development process much more efficient and effective. There are a number of areas of investigation which appear to be potentially very fruitful based on the literature reviewed here.

Basic investigations into flame/mist interactions is essential in coming to an understanding of the extinction concentrations required for gas phase flame extinguishment. These investigations need to include the physical and chemical interactions between the water and the flame. Basic geometries like counterflow flames and laminar coflow flames are obvious choices for study. These flames have been well studied and detailed models are available for the flame itself. These flames are being used to study other detailed flame phenomena so that there are clear means for applying the results from these flames to more complex realistic flames. The investigations should include both experimental and theoretical work. From such work the mechanisms of extinction will be clarified and the design concentrations needed for effective water mist system designs will be firmly established.

It has been observed that large turbulent flames are more easily extinguished than small laminar flames. A hypothesis to explain this observation has been formulated in this review based on both fire and non-fire literature results. This hypothesis needs to be examined and formalized. If a model of the interaction of turbulent flames and water mist can be developed, this will provide needed information concerning the effectiveness of a given system against a range of fire sizes. In particular, if fire extinguishment is not needed, but rather suppression is only required to effectively reduce fire size, then lower mist concentrations are needed. The models would provide information concerning what fires could be suppressed and what fires could not be extinguished by a specific system. Systems which need only to deal with large jet flames would not need to be designed to the standard required to extinguish small laminar flames.

In local application type water mist systems there is a need to provide sufficient momentum to penetrate the fire plume. No systematic study of this spray/plume interaction has been undertaken. The simple concepts presented in this review form the basis for systematically investigating this phenomena. This can be done both experimentally and numerically, with the greatest benefit from a combination of the two approaches. The numerical modeling could be usefully employed simply to examine the fluid mechanical aspects of the interaction or could be further developed to include the extinction process itself.

Finally, the design of water mist systems involves the development of nozzle placements and characteristics which will assure that mist is effectively distributed. This task is well suited to a computational fluid mechanics (CFD) approach. While designs will not regularly be done using CFD, it can be used to develop design rules and simpler approaches as well as for direct application in especially challenging or critical applications. Of course some experimental validation of the CFD model would be required; this is an excellent application for these computational techniques. Similarly, the interaction of sprays and obstructions or decks can be studied to develop an understanding of the particle sizes required to allow the mist to remain in the gas phase and avoid the appearance of voids of mist concentrations around obstacles. This information is critical to effective water mist system designs.

In summary, this review has identified a number of areas of fundamental research into water mist fire extinguishment which would have great benefits to the development of water mist as a fire protection technology. The combined experimental/computation approach described here has the best chances of success. These efforts clearly have the potential for achieving results more rapidly than the current empirical methods and, in fact, have the capability of achieving results which would be wholly impractical if attacked solely on an empirical basis.

The water mist work which has been completed to date has shown the promise and potential capabilities of the technology. However, the current approaches have not and will not lead to wide acceptance of the technology for a broad range of applications. Without more fundamental efforts, the process of development of water mist will proceed in very narrow areas with very slow movement into new areas. This largely results from the limitations of the empirical approach taken to date. As in most areas of engineering development there has been an exploratory phase to water mist development. While the acute pressures for working systems in the short run will continue to require empirical testing, these efforts can be materially aided by more fundamental work. The fundamental work will also lay the groundwork for the important developments of the future. This is clearly the time for more analytical approaches to build on the existing base of knowledge to take the next important steps in the development of the technology.

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