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Water Mist for Ship Machinery Spaces

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ABSTRACT

Fires in naval vessels may lead to a loss of capability, function, life and in extreme situations, the loss of the vessel. Machinery space fires are a particular concern because of the availability of fuel and ignition sources.

Suppressant systems employed in the machinery spaces of RAN vessels must have the capability to extinguish fires that result from ignition of these fuels. The fuel properties that affect extinguishing behaviour are examined in this paper and the suitability of water mist as the extinguishant of choice for these fuels examined. Extinguishing tests have shown that water mist systems are capable of extinguishing Class B fires and were successful in extinguishing fires of fuels with flash points from 60oC (diesel) to -4oC (heptane). Water mist is also able to thermally manage compartment temperatures improving habitability and reducing the risk of fire spread.

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Water Mist for Ship Machinery Spaces

Executive Summary

Fires occurring in naval vessels are a major concern because they may lead to a loss of capability, a loss of function, a loss of life or in extreme situations complete loss of the vessel. Fires in machinery rooms are particularly problematic because of the availability of fuel and ignition sources.

Protection against fires in high-risk areas such as machinery spaces requires an efficient, effective and safe extinguishant. The safety requirement is particularly important because many high-risk areas on board naval vessels are manned. The current halogenated hydrocarbon and inert gas systems require evacuation prior to the system discharge, which allows the fire to grow, possibly resulting in extended damage. A system that does not require immediate evacuation prior to actuation minimises the probability of fire growth. Water mist is a system that appears to meet these criteria for use in new Royal Australian Navy (RAN) vessels or as a replacement in the current fleet.

The principal fire threats in naval vessels are machinery spaces because of the presence of heat, fuel and ignition sources. Other areas such as power generation rooms, paint storage rooms, weapons storage rooms and flammable liquid storage rooms also have a high fire risk associated with them. Each of these areas is a source of fuel and therefore a fire risk. The most common fuels found in the machinery spaces of RAN vessels include marine diesel fuel, lube oils and hydraulic oils. Other stored fuels include aviation fuels, unleaded petrol and Otto fuel II (torpedo fuel). Suppressant systems employed in the machinery spaces must have the capability to extinguish fires that result from ignition of these fuels. The fuel properties that affect extinguishing behaviour are examined in this paper and the suitability of water mist for these fuels reviewed.

From the open literature, results from extinguishing tests on compartments ranging in sizes from $6m^3$ to $3000m^3$ are presented and show that water mist can be an effective medium to extinguish Class B fires. Water mist is also able to thermally manage compartment temperatures improving habitability and reducing the risk of fire spread. These extinguishing tests have shown that water based systems can be successful in extinguishing liquid fuel fires with flash points as diverse as diesel (60^oC) and heptane (-4^oC).

Water mist fire protection in machinery spaces is a viable alternative to the halogenated hydrocarbons currently in use in the machinery spaces of RAN vessels. Water mist is an effective suppressant against the wide range of fuels found in machinery spaces and does not require evacuation prior to release.

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Contents

1. Introduction

Fires occurring in naval vessels are a major concern because they may lead to a loss of capability, a loss of function or a loss of life. In extreme situations, fires may lead to complete loss of the vessel. Machinery spaces are particularly problematic because of the availability of fuel and ignition sources; in machinery spaces it is not uncommon for a fuel leak to spill or spray onto a hot manifold or engine surface resulting in a fire e.g. HMAS Westralia [1].

Leaks and spills result in a loss of fuel containment and an increased likelihood of fire spread in a compartment or bilges. Vapour build up in the bilges is a substantial fire risk and the location of the bilges makes these fires difficult to attack. In addition, burning fuels result in rapid temperature increases that may damage ancillary equipment or electrical systems. Heat convection through a compartment can result in flashover and conduction through decks and bulkheads increasing the likelihood of fires initiating in adjoining compartments.

Protection against fires in high-risk areas such as machinery spaces requires a fire extinguishant that is

- efficient (minimal hardware and extinguishant, low cost, easily replenished),
- effective (capable of extinguishing fires in a time comparable with current gaseous systems) and
- safe (minimal toxicity of both the extinguishant and thermal breakdown products).

The safety requirement is particularly important because many high-risk areas on board ships are manned. The current halogenated hydrocarbon and inert gas systems require evacuation prior to the system discharge, which allows a fire to grow, possibly resulting in extended damage. Water mist does not require evacuation prior to activation, minimising fire growth. It is a system that appears to meet the criterion described here for use in new Royal Australian Navy (RAN) vessels or as a replacement system in current fleet ships.

The principal fire threats to naval vessels in peacetime are machinery spaces because of the presence of heat, fuel and ignition sources. Other areas such as power generation rooms, paint stowage rooms, weapons stowage rooms, galleys and flammable liquid stowage rooms also have a high fire risk associated with them. Each of these areas has a source of fuel and therefore constitutes a fire risk. Machinery spaces are a major risk because the fuel and ignition source are available. The most common fuels found in the machinery spaces of RAN surface ships and submarines include:

a. Surface ships

1. F76 Marine diesel fuel
2. Lube oils
3. Hydraulic oils

b. Submarines

1. F76 Marine diesel fuel

Additionally, other hydrocarbon fuel sources are available onboard RAN surface ships and submarines and these include

c. Surface ships

1. JP4 (F44) Avgas helicopter fuel
2. F34 Army and Air Force aviation fuel
3. Unleaded petrol
4. Otto fuel II (torpedo fuel): this fuel has its own oxidant but has a low vapour pressure making it difficult to ignite; the flash point is approximately 127^{o}C. However once initiated it is extremely difficult to extinguish.

d. Submarines

1. Otto fuel II (torpedo fuel)

Suppressant systems employed in the machinery spaces of RAN vessels must have the capability to extinguish fires that result from ignition of these fuels. The fuel properties that affect extinguishing behaviour are examined in this paper and the suitability of water mist for these fuels estimated. The machinery space suppressant systems on board current RAN vessels are given in Table A1 in Appendix 1.

Table A1 shows that the RAN does not have a universal fire suppressant system for machinery space protection. The majority are halogen based (Halon 1301, HFC-227ea (also known as FM200) and NAF-S-III), which comprise one or more of the halogen elements; bromine, chlorine, fluorine or iodine and suppress fires by a combination of chemical and physical means. The chemical means is by interruption of the flame chemistry and the physical means is by cooling the flame zone to a point where combustion is suppressed. The cooling is achieved by the conduction of heat away from the flame front by the high thermal conductivity of the suppressant. The chemical processes that interrupt the flame chemistry also result in the production of hydrogen fluoride (HF), hydrogen chloride (HCl), hydrogen bromide (HBr), phosgene ($COCl_2$), carbon monoxide (CO) and carbon dioxide (CO_2), which are deleterious to health, even in small doses. The inert gas suppressants such as carbon dioxide extinguish by reducing the oxygen content to a level that will not support combustion. A 13% O_2 concentration will result in cessation of combustion for most hydrocarbon fuels [2]. However, between 12% and 16% O_2, humans experience increased heart rate, fatigue and rapid respiration; conditions that may be a concern if an evacuation is occurring. There is a conflict between the concentration necessary for suppression and the safe level for personnel, which can only be alleviated if personnel are evacuated prior to suppressant activation.

Halon 1301 has been the fire extinguishant of choice in ship machinery spaces since the mid-to-late 1960s because of its efficacy, however halons have been shown to be ozone depleting chemicals and their manufacture and use has been banned under the Montreal Protocol [3]. Although the RAN has exemptions through the Ozone Protection Act 1989 [4] enabling it to use Halon 1301, alternative extinguishing agents have been and are being sought to comply with the act. Alternatives to Halon 1301 are also being sought to overcome safety concerns resulting from the production of hydrogen fluoride. There is also a concern that stocks of Halon 1301 are depleting. Table A1 shows that Halon 1301 continues to be used as the principal fire suppressant system on RAN vessels, which will need to be addressed in the near future as stocks of Halon 1301 diminish. Non-ozone depleting halocarbon suppressants such as HFC-227ea and NAF-S-III have been introduced to replace Halon 1301. The introduction of these suppressants has by and large addressed the environmental concerns of halons, however like halons these halogenated hydrocarbons also break down under the influence of heat and produce hydrogen fluoride. A summary of hydrogen fluoride concerns, exposure levels and factors affecting HF concentration are presented in Appendix B.

The gaseous systems require the compartment to be evacuated prior to release otherwise personnel may be overcome by, a reduction in oxygen, the toxic gases produced during break down of the halogen suppressant or the toxicity of the suppressant itself. Elevated temperatures prior to the release of the suppressant can also cause severe injury to personnel as well as damage to cabling, electrical and mechanical systems.

If each of these concerns can be addressed by a single suppressant, the RAN can meet the Montreal Protocol [3] requirements, the safety requirements particularly the HF concerns and an extinguishing capability at least equal to Halon 1301. Water mist appears to fit these criteria and if its extinguishing capacity can match the chemical or gaseous suppressants' extinguishing attributes, it could replace Halon 1301, the halogenated hydrocarbons and inert gas systems.

The inert gas and halocarbon suppressants require a minimum concentration to extinguish a fire, if a compartment is breached, the effectiveness of the gaseous suppressants are diminished. A replacement suppressant will need to be effective in this situation.

2. Water Mist Extinguishing

Water mist is one of the preferred alternatives to Halon 1301 total flooding systems because it is toxicologically and physiologically inert. Water mist systems produce a drop size distribution with a range of drop sizes under 1000μm while the more conventional sprinkler systems produce much coarser particles. The smaller particle sizes have greater cooling efficiencies because evaporation and cooling are controlled by surface area and the surface area of a large number of small droplets is greater than that of a small number of large droplets of the same total volume. Coarse droplets from sprinkler systems are efficient at providing boundary cooling to large surfaces such as deck walls and floors and penetrating flames to get to the seat of a fire, but the large drop sizes that make up these sprays are not as effective on spilled fuel fires or in providing cooling to the regions around a flame. Mist systems also have lower water demands than sprinkler systems, which is beneficial in shipboard applications where prolonged sprinkler discharges may affect stability.

The International Maritime Organisation (IMO) allows water-based systems in machinery spaces and pump rooms [5]. However, the systems must be shown by test to be capable of extinguishing a range of fire scenarios that can occur in these spaces. The fire scenarios comprise low and high-pressure fuel spray fires, pan fires, obstructed fires and a wood crib fire. The method of acceptance of a water-based system differs from that of gaseous systems; the latter require a specific extinguishing concentration, dependant on the extinguishant employed, to be maintained for a specified period of time. Unlike water based systems, gaseous systems can be designed through calculation and are not required by the IMO to extinguish test fires to prove their capability.

3. Extinguishing Mechanisms

Fire extinguishment through water mist application is controlled by three mechanisms:

1. Flame cooling;

2. Reduced oxygen concentration by displacement of air by water vapour;

3. Radiant heat attenuation.

The mechanisms are illustrated in *Figure 1*.

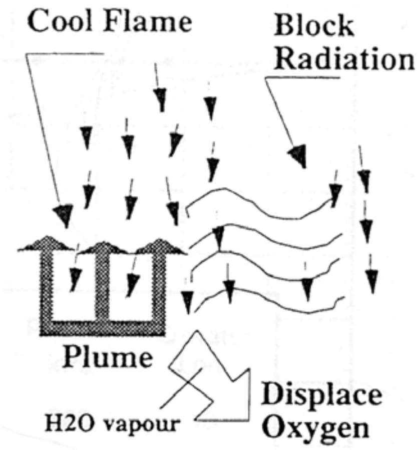

Figure 1 The three mechanisms of flame extinguishment by water mist [6]

Each of these mechanisms is essentially independent, but flame extinguishment generally occurs as a result of a combination of these effects. Each mechanism is described below.

3.1 Flame Cooling

Water is an efficient substance for removing heat from a system because of its high specific heat and latent heat of vaporization. The increased surface area of small drops for a given volume of water increases the evaporation rate via heat conduction from the flame, fire gases and hot surfaces. Flame cooling occurs when droplets of sufficient momentum penetrate the hot, buoyant gases and absorb heat directly from the flame environment. If the drops do not have sufficient momentum, they may evaporate or be removed by airflow currents before providing any significant flame cooling.

3.2 Oxygen Displacement

Some of the water introduced into a fire evaporates. When it does so, it expands to approximately 1500 times its initial volume, diluting the oxygen concentration around the flame by displacing the air. If the oxygen content is reduced from a typical 20.9% to around 13% for most Class B fuels, the fire will extinguish. A reduced oxygen concentration may become the dominant extinguishment mechanism when a compartment is sealed or poorly ventilated.

3.3 Radiant Heat Attenuation

Suspended water vapour may reduce radiant heat transfer between the flame and unburnt fuel. Radiant heat can cause unburned fuel to volatise resulting in flashover where all surrounding combustibles will begin to burn. Reducing radiant heat transfer may restrict fire growth and spread.

4. Water Mist Characterisation

Lefebvre [7] has identified three basic parameters that are important in characterising water mist behaviour and they are:

1. Flux density;
2. Spray momentum;
3. Drop size distribution.

Nozzle pressure, flow rate and the presence of obstructions influence these characteristics but do not themselves characterise the mist. The mist characteristics will also be affected by the presence of a fire but are initially measured in a non-fire environment.

4.1 Flux density

Reducing flame zone temperatures requires a sufficient volume of water droplets to interact with the fire. The greater the volume of water that interacts with the flames, the greater the heat absorption and the larger the reduction in flame zone temperature. Flux density is a measure of the volume of water available for flame cooling and is defined as the volume of water that passes through to the base of the spray cone per unit time. The total flow rate Q′ is a measure of the volume of water available for fire suppression, however some of the flow through the nozzle will be present as suspended mist droplets and some will evaporate, contributing to the other extinguishing mechanisms as described by *Eq. 1*.

$$Q' = Q'_{\text{spray cone base}} + Q'_{\text{evaporation}} + Q'_{\text{mist}} \qquad \textit{Eq. 1}$$

4.2 Spray momentum

Imparting sufficient momentum to some of the water particles is necessary for them to penetrate the flame before they evaporate or are transported away from the fire by the hot buoyant combustion gases. The velocities of the spray droplets exiting a nozzle are reduced by friction and drag.

4.3 The drop size distribution

Forcing liquid through a small diameter restriction such as a nozzle will result in a spray of droplets as it exits the restriction into air. The spray will not be made up of the same size droplets but a range of drop sizes referred to as the drop size distribution. The droplet size will be dependant on the nozzle type but will be controlled by viscosity, surface tension, the flow rate and pressure.

A number of representative drop size diameters [8] may be used to characterise sprays and the mean particle diameter is a convenient comparison. A mist of small diameter droplets (<50 μm) will exhibit gas like properties; the droplets following airflow patterns around obstructions and behaving like gaseous fire extinguishants. The main fire extinguishing mechanisms of the smaller water particles are radiant heat attenuation and oxygen displacement. Droplets over 50 μm diameter are projected into the fire zone because of their greater momentum.

The drop size distribution also varies throughout the protected volume. In a vertically downward spray, the larger particles (particles with greater momentum) will condense as they impact on objects in their path at a faster rate than the smaller particles. As the distance from the nozzle increases, interaction between falling particles will result in particles coalescing and the average particle size increasing. Interaction of sprays from adjoining nozzles will also result in a change in drop size distribution as will interaction with obstacles. These are all effects that occur without a fire present, however, when flames are present, evaporation rates and thermally induced air flows taking particles away or into a flame will have a significant input on the drop size distribution.

If the spray characteristics such as droplet velocity, drop size and flux are known at or near the nozzle, the spray behaviour at any point, particularly around the flame zone, can be modelled using a computational fluid dynamics package.

5. Entrainment

5.1 Air entrainment

The release of heat from a fire results in a column of hot gases and combustion products forming a plume above the fire. The high temperatures within the plume reduce the density of the hot gas resulting in buoyant motion of the plume. The buoyant flows within the plume causes the colder surrounding air to entrain into the flame zone and the plume, see *Figure 2*. Entrained air, because it is cold, will reduce the plume temperature and when the plume temperature and the surrounding air temperature are the same the plume stops rising. The fire gases may also be entrained into the flame zone through the eddy current motions, reducing the oxygen content and contributing to extinguishment.

Air entrainment into a fire varies with the fire's geometry (e.g. pool fires, wall fires, ceiling fires) and the degree of its confinement (e.g. pool fire against a wall). In a confined space the fire plume can be influenced by surrounding surfaces. If an item is burning against a wall or in a corner, the area through which air may be entrained is reduced. Similarly, if the fire plume impinges on a ceiling, it will be deflected horizontally to form a ceiling jet, again restricting entrainment.

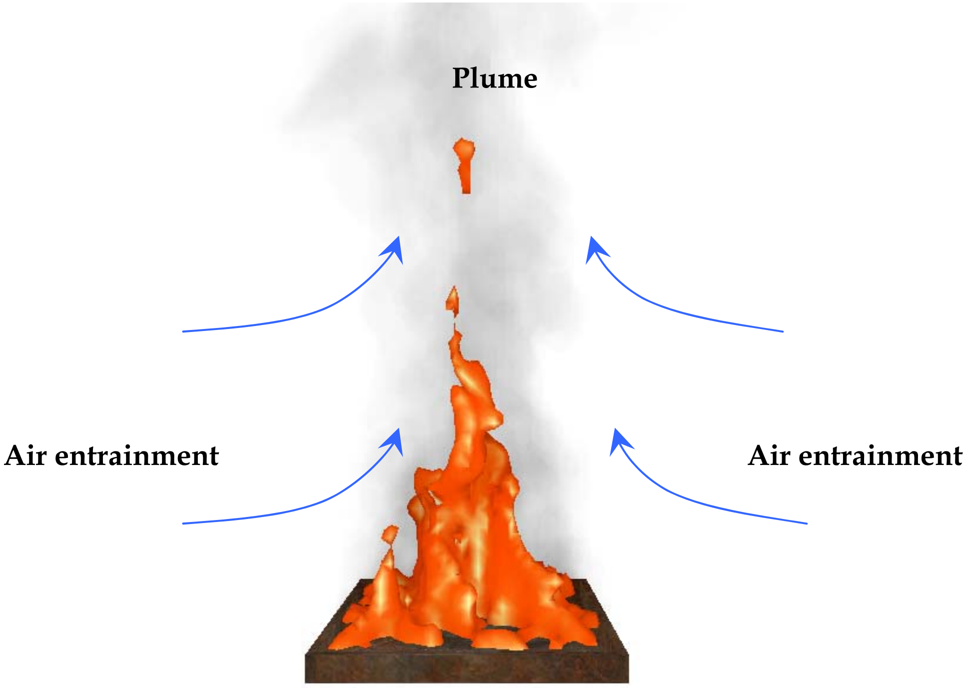

Figure 2 Air entrainment into an open atmosphere pool fire [9]

5.2 *Mist Entrainment*

Entrainment is also an important mechanism for directing mist into the flame zone and the region around the flame. The mist particles provide cooling that will slow down the reaction kinetics, which in the extreme will cool the liquid fuel to temperatures below the flashpoint. Entrainment of mist into the flame zone may also produce local dilution of the oxygen concentration to a level that will inhibit combustion.

Air is entrained into the fire from the environment surrounding the fire due to the density differences created by temperature differentials. Close to the flame the temperature is higher and the density lower; away from the flame, the temperature is lower and the density higher producing airflow into the flame to achieve an equilibrium condition. The mist particles are drawn into the flame by the exchange of momentum between the entrained air and the mist particles.

6. Droplet formation

Atomisation of a liquid can be achieved by the break-up of a jet emanating from an orifice. Turbulent flow occurs within the nozzle head producing disruptive forces on the jet on exiting the nozzle due to the lack of restriction imposed by the internal nozzle walls. When the disruptive forces reach critical levels, the jet will disintegrate into droplets. The break-up of the jet is only constrained by the surface tension of the liquid. When this is overcome, the jet breaks-up into a spray. An increasing liquid viscosity will however inhibit the disintegration of the liquid jet.

7. Extinguishing Class B liquid fires

The majority of fire threats in engine rooms, machinery rooms, pump rooms, paint storage rooms, weapons storage rooms and flammable liquid storage rooms are Class B (flammable and combustible) liquids. The properties of the fuels that will determine the ease of extinguishment are described below.

- *vapour pressure*: Vapour pressure is an indicator of volatility, a high vapour pressure resulting in a more volatile fuel. A volatile fuel is more likely to form a flammable mixture than a non or low volatility fuel and this generally increases with temperature.

- *ignition temperature*: The temperature at which the fuel air mixture must be heated before combustion occurs. A high ignition temperature indicates that the fuel is difficult to ignite; conversely a low ignition temperature means the fuel is easily ignited.

- *flash point*: The minimum temperature to which the fuel must be heated so that the vapour pressure results in a flammable fuel air mixture. High flash point fuels (temperatures that are well above room temperature) will not ignite when exposed to ignition sources at room temperature.

The values of each of these properties are peculiar to each fuel, however if the conditions are controlled and the properties do not reach critical levels for ignition, ignition will be suppressed. If ignition has already occurred, altering the external conditions so that the requirements for combustion are no longer met will result in extinguishment.

Water mist will provide cooling to liquid fuel (Class B) fires, which will affect ongoing combustion. Reducing the temperature of the fuel or the fuel-air mixture may move the fuel condition out of the range necessary for combustion.

Each of the fuels available to feed a fire held within in RAN vessels, with the exception of JP4 Avgas, has the benefit of a high flash point which makes them difficult to ignite, see *Table 1*. The application of water mist to a fire involving these fuels will dramatically reduce compartment temperatures and have a significant effect on extinguishment. The torpedo fuel Otto fuel II has its own oxygen supply which precludes the use of smothering agents but water mist can quickly reduce the temperature to below the flash point of the fuel, affecting extinguishment. Studies conducted on low flashpoint fuels such as heptane (flash point: -4°C) show that the application of water mist does not necessarily result in flame extinguishment because the temperature cannot be lowered below the flash point. Similar studies using diesel fuel (flash point 68-74°C) have been more successful in achieving flame extinguishment [10].

Table 1 The flash point of liquid fuels found onboard RAN vessels

Fuel	Flash point °C
F76: Marine diesel	68-74°C [11]
Lube oil	220°C [12]
Hydraulic oil	260°C [13]
F34 Army/Air Force aviation fuel	38°C [14]
JP4 (Avgas): helicopter fuel	-23°C [15]
Unleaded petrol	-40°C [16]
Otto fuel II	127°C [17]

8. Importance of mist parameters

To achieve extinguishment of liquid fuels by water mist, the particles must cool the flame, cool the fuel or provide a level of oxygen depletion that will alter the fuel/air ratio to one that cannot be ignited. The mist parameters (drop size distribution, flux density and momentum) will determine the water particle motion near the flame and throughout the compartment, therefore controlling the cooling and extinguishing behaviour. The priority when attempting to achieve flame cooling is to ensure the particles reach the flame. This requires a suitable droplet size distribution to provide the most efficient heat transfer, sufficient particle volume to absorb the heat generated by the fire and sufficient momentum to drive the particles through the plume.

Butz *et al* [18] compared the extinguishing behaviour of two water mist nozzle types on heptane fires. The nozzles produced different mist parameters, which were compared on extinguishing capability. The smaller high momentum particles were more effective at heat transfer from the flame than lower momentum particles (same particle size, lower velocity). To be effective in achieving flame cooling, the low velocity particles need to be large to achieve the momentum necessary to penetrate the combustion region. The flow rate is also important, providing a mist density that imparts sufficient heat transfer (not only to the combustion zone but also the compartment as a whole) to reduce the temperatures that allow combustion to continue.

The mist systems supplying the water have an effect on the extinguishing capability. The system pressure will control the particle velocity and size and therefore momentum. However, the benefits of a high supply pressure must be balanced with the weight, power and volume penalties of these systems. If the pressure from the ship's fire main is sufficient to produce the appropriate mist parameters for extinguishing, the system can be connected to the fire main without the need to install extra hardware.

9. Compartment ventilation

If extinguishing cannot be achieved through the removal of heat from the flame and combustion products, diluting the oxygen content to a level that will not support combustion is required. This occurs because the water particles do not reach the flame zone. The two factors contributing to this phenomenon are (i) the particles do not have sufficient momentum to penetrate the flame zone to directly reduce the flame temperature and (ii) they are too small to move through to the flames before evaporating prematurely. If the major contributing factor in extinguishment is oxygen dilution, ventilation due to breached decks, bulkheads or open doorways will result in airflow into compartment, disrupting the oxygen dilution and possibly delaying the conditions that could result in extinguishment.

10. The International Maritime Organisation (IMO) and Safety of Lives at Sea (SOLAS)

The International Maritime Organization (IMO) provides the regulations and practices for shipping engaged in international trade. These regulations concern maritime safety, efficiency of navigation and prevention and control of marine pollution from ships.

The International Convention for Safety of Life at Sea (SOLAS) deals with maritime safety and was initially adopted in 1960. A new SOLAS Convention was adopted in 1974, which has been updated and is referred to as SOLAS 1974, as amended.

Chapter II-2 of SOLAS 1974 [19] relates to fire protection, fire detection and fire suppression for passenger ships, cargo ships and tankers and incorporates water spray as one of the alternatives for fire suppression. Regulation 10 of Chapter II-2 states a fixed fire fighting system may comprise 'a fixed pressure water spray/mist fire-extinguishing system complying with the provisions of the Fire Safety Systems Code' [20]. The Code requires the system have an average water distribution rate of 5 litres/minute/metre^2 (lpm/m^2) in the spaces to be protected, and applies to ships whose keels were laid after July 1, 1998. Water mist nozzles shall be fitted above bilges, tank tops and other areas over which fuel is liable to spread and also above specific fire hazards. Water based systems should be shown by test to have the capability of extinguishing a variety of Class A and Class B fires in a specified mock up of a ships engine room [5]. These tests include spray and pan and obstructed and unobstructed fires.

The extinguishing test procedures have formed the basis for many water mist experimental investigations. The investigations typically use the standard extinguishing tests but implement variations to produce spray parameters that may be more effective in extinguishing situations.

11. Extinguishing behaviour of water mists during full scale fire tests on Class B fuels

A number of test programs examining water mist/water spray fire protection against Class B fuels in machinery spaces have been undertaken in recent times [21, 18, 22, 23]. These programs were conducted to assess the applicability of water based systems for protecting machinery spaces against Class B fires. The effects of variables such as fire size, ventilation, water discharge rate, particle size and compartment size on the extinguishing behaviour have been examined. Tests have been conducted in unventilated compartments, in forced ventilated conditions and with natural ventilation as described in the IMO water spray test protocol [19]. The protocol requires the test compartment have a specified ventilation opening, and that extinguishment occur within 15 minutes of the system activation with heptane and diesel used as fuels. Diesel is the most common fuel used in naval shipboard applications while heptane, although not used in shipboard applications, has a low flashpoint (-4^{o}C), which increases the extinguishing difficulty. A summary of the findings from the test programs is presented below.

11.1 Water spray protection in machinery spaces

Back *et al* [21] examined twelve water spray protection systems in a 500m^3 machinery space complete with engine mock-up. The engine mock-up simulates a shipboard environment, with obstructions between the fire and the nozzles increasing the extinguishing difficulty. Variations to the application rate and the system parameters were also employed to identify the affect of changes on extinguishing behaviour.

The program was divided into two phases, Phase 1 using the minimum water application rate of 5 lpm/m^2 and Phase 2 evaluating the effects of application rate, spray angle and system pressure on extinguishing behaviour. Phase 1 comprised five nozzles, each producing a 90^o cone spray with mean particle diameters between 300-1000 micron (Sauter mean diameter) [8]. Phase 2, comprised a further seven nozzles. The application rates during Phase 2 ranged from 0.9-17.1 lpm/m^2 with spray angles of 60^o, 90^o and 120^o. The mean particle size ranged from 250 to 850 micron (Sauter mean diameter).

The extinguishing times for the spray fires during the Phase 1 tests showed that larger fires were easier to extinguish than smaller fires irrespective of whether the fires were obstructed or not. This is due to oxygen consumption and water vapour generation. The capability to extinguish the fires reduced as the fire size decreased with an extinguishable fire size limit of approximately 1 MW.

The Phase 2 tests examined application rate, operating pressure and spray angle. Water application rates of 0.9, 2.7 and 5.0, 5.5, 8.5 and 17.0 lpm/m^2 showed that in general, as the application rate increased, the extinguishing times reduced. However, pressure increases while maintaining a constant or increased application rate resulted in a general increase in extinguishing times.

Increasing the water application rate while maintaining the drop size distribution resulted in greater flame cooling and mist evaporation contributing to suppression and extinguishment. The increase in pressure produces a reduction in the drop size distribution, which should enhance the extinguishing behaviour through water vapour generation. However, the results suggest that the reduced particle sizes may not have sufficient momentum to provide adequate flame cooling to reduce the extinguishment times.

The spray angle evaluations were conducted using a water application rate of 5 lpm/m^2. The narrow cone angles had difficulty extinguishing the 1 MW obstructed spray fires while the wider 120^o spray angle extinguished all fires. All of the spray systems were capable of reducing the compartment temperatures, after activation the temperatures were maintained between 50-70^{o}C. The temperature drop is associated with the energy absorbed by the water and the latent heat of vaporisation.

The capabilities of the spray systems against obstructed fires can be equated with how much saturated water vapour is produced and how well the airflow into the compartment is disrupted. These effects are associated with the drop size, momentum and temperature. Small drop sizes (<200 micron) extinguished fires when the dry oxygen concentration (oxygen concentration with water vapour removed) reduced to 16%, the medium drop size (200-800 micron) when the dry oxygen concentration reduced to 15% and the large drop sizes (>800 micron) when the dry oxygen concentration reduced to 13.5%. As the median drop size reduced, the greater the contribution that oxygen depletion provided to extinguishment. The larger drop size systems were relatively vapour free and relied on flame cooling to produce extinguishment.

When the compartment temperature increases, the flow of air into the compartment increases but the vapour production may be inadequate to saturate the air flowing in to reduce the oxygen content. Smaller drop size systems have higher evaporation rates than larger drop size systems but may also have difficulty in saturating the air in well-ventilated compartments. In closed compartments the saturated vapour concentration will increase allowing even the larger drop sizes to produce a reduction in oxygen concentration. The ability of a system to disrupt the flow of air through the ventilation space is a function of the water particle momentum. High spray momentum has an effect on the vent flow rate, producing turbulent conditions near the vent and reducing the impetus for gas flow through the vent. The smaller drop size system had superior extinguishing capabilities by producing high water vapour concentration but had minimal effect on the vent flow rate. The medium drop size had inadequate saturated vapour or vent flow reduction. The largest drop size performed similarly to the high momentum systems due to the reduced airflow through the venting.

When the water application rate was reduced below 10 lpm/m^2, the ability to produce water vapour was associated with a critical fire size. For application rates of 5 lpm/m^2, the critical fire size for a small water particle size system (<250 micron) was approximately 250 kW while for the larger particle size spray system (~1000 micron), the critical fire size was approximately 1MW. For tests conducted in the $500m^3$ compartment, 1 MW correlated with the fire size that was the most difficult to extinguish.

11.2 Fine water mists for suppression of Class B fuels

Butz *et al* [18] explored the effects of water flow rate and particle drop size on the ability of a mist system to extinguish Class B fires. The objective of this work was to determine the most efficient flow rate and drop size for extinguishing small and large fires in a $6m^3$ chamber. The fuel used was heptane and the chamber was force ventilated to provide a constant flow of air to enhance the extinguishing difficulty. The fires were unobstructed and the nozzle was located above the fires and directed vertically downward. The parameter used in this work for measuring the effectiveness or efficiency of the water mist systems was the time to extinguishment. Single and dual fluid nozzles were used to produce the sprays, with the dual fluid nozzle providing the spray with a smaller particle size and greater momentum (dual fluid nozzles use a low pressure air or nitrogen and a low pressure water supply to produce a small particle size distribution without the need for small orifices which are prone to clogging).

Of 85 tests performed, 18 fires were not able to be extinguished; the average extinguishing time was 12 seconds, the median time was 6 seconds and one third of the tests extinguished in 3 seconds or less. The test program is tabulated in *Table 2*.

The dual fluid atomisers were more effective at extinguishing at smaller droplet sizes while the single fluid nozzles were more effective at larger drop sizes. As water flow rates reduced, the single fluid nozzle extinguishing capability reduced, indicating that the mist density was inadequate to reduce the flame temperature or produce sufficient oxygen dilution. At flow rates below 3.8 lpm the single fluid nozzle did not successfully extinguish fires for water particle sizes of 40 and 80μm (nominal droplet diameter). However, the effectiveness improved at 100 μm due to increased momentum of the higher mass particles.

Table 2 Test configurations for Class B fuel extinguishing tests

Test parameter	Configuration	No. of tests
Nozzle	Dual fluid	45
	Single fluid	40
Flow rate	<1.5 lpm	5
	1.9-3.4 lpm	17
	3.8 lpm	52
	>3.8 lpm	11
Atomisation gas	Air	38
	Nitrogen	4
	Carbon Dioxide	3
Nominal droplet diameter	40μm	41
	80μm	32
	60μm	4
	90μm	4
	150μm	4
Fire pan size	7.6cm	2
	11.5cm	14
	23cm	69

At 40μm the dual fluid nozzle at 3.8 lpm produced an extinguishment in less than 3 seconds, reducing the water flow rate by a factor of 2 increased the extinguishing time by a factor of 2 and a further reduction to 1 lpm further extended the extinguishing times. At 0.6 lpm extinguishment did not always occur indicating that a limiting flow rate had been reached for heptane. For the single fluid nozzle at a flow rate of 3.8 lpm and a mean particle size of 40 μm, the extinguishing time was an average of 20 seconds while at a flow rate of 2 lpm, extinguishing did not occur. As the mean particle diameter increased to 80 μm, the single fluid nozzle performed better than the dual fluid nozzle. At a flow rate of 3.8 lpm, the single fluid nozzle produced extinguishment in 12 seconds, however as the flow rate decreased the extinguishing times increased and extinguishment did not occur when the flow rate reduced to 2.3 lpm.

The main requirement for extinguishing unobstructed Class B fuel fires is to ensure the water droplets reach the flame. The dual fluid nozzle provided velocity to the droplets via the atomising gas to project the droplets through the fire plume to the fire. Single fluid nozzles require significant droplet size and volume to provide sufficient mist concentration and momentum. The performance of equivalent droplet sizes is different for the two types of systems due to differences in momentum.

11.3 The capabilities and limitations of total flooding, water mist suppression systems in machinery space applications

Eight tests were conducted in machinery space volumes between 100-1000m^3 with varying levels of ventilation [22]. The tests were conducted using Class B fuels in simulated machinery spaces with closed, natural and forced ventilation. Machinery mock-ups were incorporated to simulate machinery space equipment, which provides obstructions to mist flow. The Class B fires comprised fuel spray and pan fires ranging from 0.1 to 10 MW using n-heptane and diesel.

During the investigations, some fires were extinguished by direct flame interaction while others were extinguished through oxygen dilution and depletion. Direct flame extinguishment is dependent on sufficient mist reaching the combustion zone, however the mist concentration reduced as the distance from the nozzle increased, reducing the effectiveness of the mist. This behaviour can be counteracted by using systems that impart high velocities to the spray particles to project them to the flames. Oxygen depletion and dilution can occur at a global or local scale, when it occurs within the flame zone the expansion of the steam disrupts the inflow of air into the flame reducing the oxygen concentration and enhancing extinguishment.

Unobstructed fires attacked with sprays with sufficient mist concentration and velocity were extinguished by direct flame interaction in less than 1 minute and were not affected by the fire size or the compartment size. The minimum mist concentration to extinguish by flame interaction was 0.3 lpm/m^3. Difficulties were experienced when the distance from the nozzle to the flame exceeded 3 metres.

Small droplets were more efficient at absorbing heat than the larger droplets due to their high surface area to volume ratio, but quickly lose energy (velocity) as the distance from the nozzle increases. As the distance increases, the ability to extinguish a fire through direct flame interaction also diminishes and a reduction in oxygen concentration is required to assist in the extinguishing process. If extinguishment through flame interaction does not occur, a steady state temperature condition is achieved until the flame is extinguished through oxygen depletion, although extinguishment may occur before the steady state conditions apply. Saturated water vapour in air above 80^{o}C will reduce the oxygen concentration below the limiting oxygen index (the oxygen concentration below which combustion will not occur) for most Class B fuels.

The level of oxygen depletion will be a function of fire size, compartment size, ventilation conditions and the amount of mist reaching the fire. For a given set of compartment conditions, extinguishment times will approach an infinite value as the critical fire size is reached. For a given fire scenario, the amount of mist reaching a fire will be a function of the spray characteristics, the location of the fire with respect to the nozzle and the degree of obstruction. As more mist acts directly on the flame, the dependency on oxygen depletion processes reduces and the fires are extinguished by cooling.

For obstructed fires, reduced oxygen concentrations are necessary for extinguishment because of the reduced effect of flame interaction by the mist. The limiting case for obstructed fires occurs when no mist reaches the fire and extinguishment is by consumption and/or by dilution of oxygen due to the saturated water vapour.

Measured extinguishment times for closed and ventilated compartments showed the ventilated condition marginally increased the critical fire size (below this fire size, extinguishing does not occur) due to the air flow into the compartment reducing the oxygen dilution.

Fire size to compartment volume ratios will also affect extinguishing times. For a given fire size and ventilation condition, increasing the compartment volume increases the extinguishment time without affecting the critical fire size. A doubling of compartment volume will typically double the extinguishment time; this is an oxygen dilution problem where the larger volume takes longer to dilute.

The extinguishing behaviour is summarised below

- Water mist systems will extinguish fires in minutes as opposed to seconds with gaseous halogen systems. The mechanisms that produce extinguishment require finite times to reach an extinguishing condition.

- After activation, all mist systems dramatically reduce compartment temperatures to a uniform 50-70^{o}C for the tests undertaken. The reduction in temperature will help with manual intervention, minimise thermal damage and reduce fire spread within and to other compartments.

- In closed compartments, larger fires were easier to extinguish than smaller fires.

- Lower flashpoint fuels were more difficult to extinguish than higher flash point fuels. This is attributed to the energy required to drive and maintain the temperature below the flash point of the fuel.

- Obstructed fires were more difficult to extinguish than unobstructed fires. Obstructions usually result in areas of low mist concentration and require oxygen depletion to aid extinguishment.

- Systems producing small drops with high momentum had superior extinguishing capabilities against obstructed and unobstructed Class B fires.

- Larger vent openings reduce the extinguishing capabilities of mist systems, this is related to mist loss through the vents resulting in reduced saturated vapour production and decreased oxygen depletion.

- Increased water discharge rates reduced the extinguishing times of unobstructed fires but had little effect on obstructed fires.

- Pan fires were more difficult to extinguish than spray fires. The heat release rate reduced as the oxygen was consumed, allowing the fire to approach the critical fire size.

- For obstructed fires there is a relationship between the time to extinguishment and the fire size, which is a function of the time required to reduce the oxygen concentration below a critical value. This concentration is dependent on the spray characteristics (particle size and momentum).

Water mist reduces the temperature of protected spaces, which reduces airflow through ventilation openings. These systems are less affected by ventilation due to compartment breaches than total flooding gaseous systems. Water mist has difficulty in extinguishing small obstructed fires due to low mist concentrations around the flame; this behaviour occurs primarily with low momentum sprays that are not turbulent, do not mix thoroughly and 'plate-out' on surfaces before their heat transfer properties can be utilised. In this case, extinguishment needs to be achieved by oxygen depletion.

11.4 Water mist protection requirements for very large machinery spaces

Back *et al* [23] evaluated the fire suppression capabilities of a water mist in large (~3000m^3) machinery spaces, the machinery space equating to Class 3 (>3000m^3) of the test protocol for water spray fire protection [19]. The nozzles used were industrial spray nozzles; two high-pressure, one normal and one low flow (3450 kPa+), an intermediate pressure nozzle (1200-3450 kPa) and a low-pressure nozzle (<1200 kPa). The normal flow, high pressure system produced a 0-400 micron spray, the low flow, high-pressure nozzle produced a 0-200 micron spray, the intermediate pressure nozzle produced a 200-400 micron spray and the low-pressure nozzle produced a 200-1000 micron spray. Total protection and zoned protection tests, ventilated and unventilated, obstructed spray and pan fire scenarios were examined using heptane (flash point – 4^{o}C) as the fuel.

The compartment comprised 3 levels with openings between the levels. The total protection system comprised 3 grids (each with 36 nozzles at 3m spacing) on each of the 3 levels while the zoned system was a compact version of the total protection configuration comprising 30 nozzles at 1.5m spacing. The zoned system comprised a single layer of uniformly spaced nozzles located below the uppermost deck. The evaluation comprised three spray fires (2.5, 5 and 10MW) and one pan fire ($2m^2$ area) similar to the test protocol for obstructed fires [19].

For the total protection system, spray fires located on the upper level of the space were difficult to extinguish because of minimal direct action by the mist on the flames and low mist concentration. Without ventilation, 5 and 10MW spray fires were extinguished, on average, in 5 and 8 minutes respectively while the smaller fires (2.5MW and $2m^2$) were not extinguished. 10MW fires with ventilation were also extinguished, however extinguishing times ranged between 7 and 14 minutes.

The extinguishing times for the zoned spray protection systems were at least equivalent to the total protection systems. The extinguishment times for the 10MW non-ventilated spray fires ranged from 2 to 5 minutes and the 5MW spray, 5 to 10 minutes. For the ventilated condition, the extinguishing times were approximately double. Some of the smaller fires, unable to be extinguished with the total protection system, were extinguished with the zoned system. The high-pressure zoned system was capable of extinguishing the smaller pan and 2.5kW spray fires, where the other zoned systems could not.

The limitations of water mist are associated with extinguishing small obstructed fires by direct flame interaction. This is due to mist fall out due to gravity which reduces the flame/mist interaction. However, many obstructed fires can be extinguished by reduced oxygen concentration. If the fire size is above the critical size, the fire can be extinguished without any mist reaching the fire.

12. Summary

The results of water mist extinguishing tests on a range of compartment sizes from $6m^3$ up to $3000m^3$ show that water mist can be an effective medium to extinguish fires provided that the limitations of these systems are acknowledged. Water mist is also able to thermally control compartment temperatures that not only improves habitability but also reduces the risk of fire spread. Extinguishing tests showed that water based systems extinguished larger Class B fires more easily than smaller fires and were successful in extinguishing fires using fuels with flash points as diverse as diesel (60^oC) and heptane (-4^oC).

The capability of water mist/spray systems will be dependent on a number of factors; the compartment size, the fire size, temperature and the presence of obstructions. The level of obstruction will determine which mechanism contributes to extinguishment. The presence of obstructions between the nozzles and the fire will inhibit water particle movement to the flame and reduces the contribution of the flame cooling as an extinguishing mechanism. The existence of a critical fire size below which fires will not be extinguished cannot be overlooked. However, with the temperature reduction provided by the mist, smaller fires not extinguished by the mist or spray could be extinguished with manual intervention. Compartment size will also affect extinguishing times, if oxygen dilution is the predominant mechanism, larger compartments will take longer to dilute the oxygen concentration for the same size fires and the compartment temperature will determine the level of water vapour saturation possible. If the temperature is not sufficient to produce an acceptable level of oxygen dilution, this mechanism will not produce an extinguishment.

The mist parameters important in producing a spray that will result in an extinguishing event are the water application rate, the particle size and particle momentum. In general, an increase in the water application rate increases the cooling effects and reduces the extinguishment times. For unobstructed fires, the extinguishing effects are direct flame cooling or oxygen dilution around the flame zone. The drop size and momentum will determine particle behaviour; for unobstructed fires, momentum is required to project the mist particles into the flame zone. The smaller drop size particles have higher evaporation rates that provide dilution of the oxygen and this is important for extinguishing obstructed fires.

Another important aspect of extinguishing behaviour is the effect of ventilation. Ventilation will increase extinguishing times and may inhibit extinguishment altogether.

The common liquid hydrocarbons found in quantity in machinery spaces have been listed in Table 1 with their respective flash points. Each has a flash point above 68^{o}C and are conducive to extinguishment by water mist suppression systems. Water mist is capable of lowering compartment temperatures in a matter of seconds after activation leading to extinguishment by lowering the fuel temperature. Low flash point fuels such as JP4 (-23^{o}C) will not be extinguished by flame cooling but will require a reduction in oxygen concentration. Obstructed fires will also be difficult to extinguish by cooling and will also depend on oxygen depletion.

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Appendix A: Fire Extinguishing Systems on RAN Ships

Table A1 RAN Ships and their principal fire extinguishing systems

Surface Combat		**Identifcation**	**Principal suppression system**
FFG			
	HMAS Adelaide	FFG01	Halon 1301
	HMAS Canberra	FFG02	Halon 1301
	HMAS Sydney	FFG03	Halon 1301
	HMAS Darwin	FFG04	NAF-S-III
	HMAS Melbourne	FFG05	Halon 1301
	HMAS Newcastle	FFG06	Halon 1301
ANZAC			
	HMAS Anzac	FFH150	Halon 1301
	HMAS Arunta	FFH151	Halon 1301
	HMAS Warramunga	FFH152	Halon 1301
	HMAS Stuart	FFH153	Halon 1301
	HMAS Parramatta	FFH154	Halon 1301
	HMAS Ballarat	FFH155	Halon 1301
	HMAS Toowoomba	FFH156	Halon 1301
	HMAS Perth	FFH157	Halon 1301
Submarine			
	HMAS Collins	SSK73	Halon 1301
	HMAS Farncomb	SSK74	Halon 1301
	HMAS Waller	SSK75	Halon 1301
	HMAS Dechaineux	SSK76	Halon 1301
	HMAS Sheean	SSK77	Halon 1301
	HMAS Rankin	SSK78	Halon 1301
Ampibious and Afloat Support			
	HMAS Tobruk	LSH50	FM-200
	HMAS Kanimbla	LPA51	FM-200
	HMAS Manoora	LPA52	FM-200
	HMAS Balikpapan	LCH126	CO2
	HMAS Brunei	LCH127	CO2
	HMAS Labuan	LCH128	CO2
	HMAS Tarakan	LCH129	CO2
	HMAS Wewak	LCH130	CO2
	HMAS Betano	LCH133	CO2
	HMAS Success	OR304	FM-200
	HMAS Westralia	O195	CO2 (with local water mist system)
Patrol Boat			
	HMAS Warrnambool	FCPB204	NAF-S-III
	HMAS Townsville	FCPB205	NAF-S-III
	HMAS Wollongong	FCPB206	NAF-S-III
	HMAS Launceston	FCPB207	NAF-S-III
	HMAS Whyalla	FCPB208	NAF-S-III
	HMAS Ipswich	FCPB209	NAF-S-III
	HMAS Cessnock	FCPB210	NAF-S-III

HMAS Bendigo	FCPB211	NAF-S-III
HMAS Gawler	FCPB212	NAF-S-III
HMAS Geraldton	FCPB213	NAF-S-III
HMAS Dubbo	FCPB214	NAF-S-III
HMAS Geelong	FCPB215	NAF-S-III
HMAS Gladstone	FCPB216	NAF-S-III
HMAS Bunbury	FCPB217	NAF-S-III

Hydrographic

HMAS Leeuwin	HSS245	FM-200
HMAS Melville	HSS246	FM-200
HMAS Paluma	SML01	FM-200
HMAS Mermaid	SML02	FM-200
HMAS Shepparton	AGSC03	FM-200
HMAS Benalla	SML04	FM-200

Mine Warfare

HMAS Rushcutter	MHI80	
HMAS Shoalwater	MHI81	
HMAS Huon	MHC82	NAF-S-III
HMAS Hawkesbury	MHC83	NAF-S-III
HMAS Norman	MHC84	NAF-S-III
HMAS Gascoyne	MHC85	NAF-S-III
HMAS Diamantina	MHC86	NAF-S-III
HMAS Yarra	MHC87	NAF-S-III

Sail Training Ship

Young Endeavour	STSYE	CO2

Appendix B: Hydrogen Fluoride Concerns

The resurgence of water in fire protection applications has been driven by concerns about hydrogen fluoride production from halocarbon extinguishants. The halogenated hydrocarbons such as Halon 1301, HFC-227ea and NAF-S-III used by the RAN in total flooding applications, all contain fluorine. When these substances are released onto a fire, the portion of the gas in contact with a hot surface or flame will decompose. The decomposition product of greatest concern is gaseous hydrogen fluoride (HF) which presents a health risk through skin (dermal) exposure and inhalation. Dermal exposure causes damage through fluoride ion action while inhalation results in damage to the mucous membranes through hydrogen ion attack. The toxicity levels and Occupational Health and Safety Exposure levels are listed below and these can be compared with levels produced during extinguishment using halogenated hydrocarbons. The factors influencing the level of HF formation are also described.

B.1. Toxicity levels

The short term or acute exposure levels for HF [B1] are

Inhalation (human): 50 parts per million/30 minutes (LClo)
Inhalation (man): 100milligram/metre^3/minute (TClo)
Inhalation (rat): 1276 parts per million /hour (LC_{50})
IDLH (immediate danger to life and health): 30 parts per million

Where LClo is the lowest observed lethal concentration of HF in air, TClo is the lowest toxic concentration and LC_{50} is the concentration that results in the death of half of a sample population. The IDLH level is self-explanatory.

B.2. Exposure standards

Workplace Exposure levels defines levels that will not result in adverse health effects. Compliance with the designated value does not, however, guarantee protection from discomfort or possible ill-health outcomes. The range of individual susceptibility is wide and it is possible that some people will experience discomfort or develop occupational illness from exposure to substances at levels below the exposure standard.

For HF, the workplace exposure levels [B1] are

Threshold Limit Value: 3 parts per million

Threshold limit value (TLV)**:** The concentration in air of a substance that most workers can be exposed to daily without adverse effect (the threshold between safe and dangerous concentrations). These values are time-weighted concentrations for a 7 or 8 hour workday and a 40 hour workweek. For most substances the value may be exceeded, to a certain extent, provided there are compensatory periods of exposure below the value during the workday (or in some cases the week). For some substances (mainly those that produce a rapid response) the limit is given as a ceiling concentration, a maximum permissible concentration - designated TLVC, which should never be exceeded.

8hr time weighted average: 3 parts per million

Time-weighted average exposure (TWAE) or concentration (TWAC)**:** The concentration in the exposure medium at each measured time interval multiplied by that time interval and divided by the total time of observation: for occupational exposure a working shift of eight hours is commonly used as the averaging time.

Short term exposure limit: 3 parts per million

Short term exposure limit (STEL): The 15 minute time weighted average exposure that should not be exceeded at any time during a work day.

The level of hydrogen fluoride can be reduced by minimising the amount of extinguishant that is allowed to decompose. This can be achieved in three ways

- Using the most efficient suppressant i.e. one that has a low extinguishing concentration. The fluorine available for hydrogen fluoride generation will come from the suppressant and minimising the volume of suppressant available will minimise the generation of hydrogen fluoride.

- Rapid extinguishant of the fire to reduce the build up in temperature within the compartment and remove the direct heat source of the flame to decompose the extinguishant. Delaying the time to extinguishment extends the periods that the decomposition reactions can occur resulting in increased hydrogen fluoride concentrations.

- Cooling the compartment reduces the decomposition reaction rates and may bring the temperature down to a level that will halt the decomposition.

`

B.3. Factors influencing HF formation

B.3.1 Fire size/room volume

Halocarbon suppressant agents decompose when in contact with a flame or hot surface. The more intense and physically larger fire will produce greater concentrations of HF. More intense fires provide greater energy to decompose the suppressant while the larger flame area provides a greater surface area for the decomposition reactions to occur.

The HF concentration from a given fire scenario will be inversely proportional to the room size. The same amount of HF produced in room sizes of increasing volume will result in lower concentrations.

B.3.2 Suppressant concentration

The suppressant agent concentration relative to the extinguishing concentration will influence fire suppression. Higher concentrations result in faster extinguishment, which halts HF formation. Lower agent concentrations will struggle to extinguish a fire allowing the agent to continue to decompose, increasing the concentration of HF.

B.3.3 Compartment geometry

The compartment geometry can affect the flow of oxygen to the fuel. A reduction in the oxygen available will reduce the fire intensity and the rate at which the suppressant will break down.

B.3.4 Flame contact time

The time that the flame is in contact with the agent will be directly proportional to the amount of HF formed.

B.3.5 Discharge time

Rapid discharge of the fire suppressant produces the necessary extinguishing concentrations of the suppressant agent in short time frames. This may promote extinguishment before the fire intensity increases and or spreads. The faster the suppressant concentration reaches the extinguishing concentration the shorter the period over which the suppressant can be broken down.

B.3.6 Nature of the agent

The production of HF is dependent of the availability of hydrogen and fluorine atoms. Fluorine is only available from the suppressant agent while hydrogen can be supplied by the fuel, the agent and moisture, therefore the HF concentration is primarily dependent on the type and concentration of the suppressant.

B.4. Re-ventilating after extinguishment

The HF concentration in post fire atmospheres will decay as a result of the high reactivity of the HF with materials in the compartment but will reduce at a faster rate once the ventilation system is activated. However, if post fire ventilation results in re-ignition the suppressant agent decomposition will continue, increasing the HF concentration. The dilution equation [B2] describes the change in concentration of a particular gas over time by a diluting gas supplied at a particular rate. The equation allows calculation of the time taken to reach the threshold limit value for a particular diluting gas exchange rate.

The loss of power to drive the ventilation system will result in the natural decay of the HF, this will significantly increase the time to reduce the concentration to the threshold limit value. The rate of HF decay will be dependent on the initial concentration and the rate of reaction of the HF with materials within the compartment.

The surest way to eliminate hydrogen fluoride formation during a fire is to eliminate the halogenated suppressants. However, this can only be achieved using non-fluorine based suppressants such as the inert gas suppressants or water.

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19. ABSTRACT

Fires in naval vessels may lead to a loss of capability, function, life and in extreme situations, the loss of the vessel. Machinery space fires are a particular concern because of the availability of fuel and ignition sources.

Suppressant systems employed in the machinery spaces of RAN vessels must have the capability to extinguish fires that result from ignition of these fuels. The fuel properties that affect extinguishing behaviour are examined in this paper and the suitability of water mist as the extinguishant of choice for these fuels examined. Extinguishing tests have shown that water mist systems are capable of extinguishing Class B fires and were successful in extinguishing fires of fuels with flash points from 60oC (diesel) to -4oC (heptane). Water mist is also able to thermally manage compartment temperatures improving habitability and reducing the risk of fire spread.

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