DEVELOPMENT OF A LOW-PRESSURE FINE WATER SPRAY FIRE SUPPRESSION SYSTEM FOR THE ROYAL NAW: INTERMEDIATE-SCALE TESTING

James L.D. Glockling
BRE, FRS, CF&ST

Mike Edwards and Steve Watkins
Warship Support Agency

INTRODUCTION

The United Kingdom Ministry of Defence Warship Support Agency (MoD/WSA) is the engineering support authority for the Royal Navy (RN). Under the Directorate of Operations Equipment, one of MFFM5's responsibilities is the research and development of halon alternatives for the RN. The fire protection design policy for Royal Navy surface ships has in the past relied heavily upon halon drench systems, fixed sprinkler systems and extensive manual attack ability. Halon is not permitted on future ships and with the envisaged reductions in ships complement there may not be the manpower available to immediately tackle a fire manually, particularly during action. Extinguishment of all fires by a halon replacement system is therefore of primary importance. Other gaseous alternative systems have been considered. Currently the preferred alternative is carbon dioxide, although its inherent dangers make this far from an ideal solution. For this reason, water-based replacement technologies are being investigated that will be able to operate within these and many other constraints that have a profound impact upon the selection and implementation ofthe system. It is also hoped that the derived system will be suitable for retrospective installation into existing vessels.

This paper details results of the "intermediate-scale test phase" of an ongoing project funded by the Warship Support Agency and conducted by the Special Projects Group of the Building Research Establishment (BRE), formerly the Loss Prevention Council (LPC). The selection of a water-based system was made after a review of RN fire protection requirements and an assessment of a wide range of halon alternatives. When conducting the assessment, two points became clear: first, that the constraints placed on the system by a war time role were very challenging (see below), and second, that any gaseous system, including halon, was unlikely to satisfy all of these requirements. In particular the ability to extinguish a fire in a battle damaged and therefore ventilated compartment, whilst creating an acceptable environment suitable for immediate re-entry and recovery, was a key requirement. Examination of the potential benefits of improved spray systems led to an initial project conducted in 1997 comparing typical commercially available water mist systems.

Likely fire scenarios:
- (a) Pool fires of marine diesel, aviation fuel, lubricating & hydraulic oils
- (b) Spray fires of diesel, aviation fuel, and oils
- (c) Combination fires of all fuels soaked into sound and thermal mineral insulation materials
- (d) Electric cable fires

Fire configuration: High degree of clutter in machinery spaces, fires may be obscured

Enclosure configuration: Sealing of the enclosure cannot be guaranteed (Le., missile strike), therefore
- (a) Degree of ventilation is unknown
- (b) Number of ventilation paths is unknown
- (c) Location of ventilation paths is unknown

Enclosure temperatures: Enclosures are usually metal constructions capable of achieving and storing much heat.

Water supply pressures: Present sprinkler systems have a nominal design pressure of 7 bar. Depending on fire main system configuration and demand, supply pressure may be as low as **3.5** bar.

Water source & quality:
- (a) Seawater preferred option
- (b) Capability to tolerate low water quality (some solids content)
- (c) Capability to use additives

Enclosure occupancy:	Machinery spaces are likely to be unmanned, but not unattended
Manual attack ability:	Reduced crew sizes mean manual attack may not be possible
System ability:	All fire sizes and types must be extinguished

PROGRESS

Starting in **1997,** the project has been undertaken in a number of logical research phases, the results of which are briefly outlined below.

LABORATORY-BASED RESEARCH PROGRAMME

These preliminary tests compared typical high and low pressure water mist systems in a variety of scaled, ventilated, obscured and unobscured scenarios with a range of **Class** A and B fuels. The results showed the potential for a low-pressure system to work at existing navy seawater main pressures of 7 bar and to provide better performance in ventilated conditions than high-pressure systems. Considering the system goals it was determined that this approach should be pursued via a phased development programme. **All** research has been conducted by the UK Building Research Establishment (formerly the LPC).

Phase **1** and **2 –** Baseline Tests and Literature Studies: **All** tests at laboratory scale were conducted in a carefully controlled **96m³** 8m x 4m **x** 3m high test compartment. Phase 1 tested existing RN systems (Halon 1301, CO_2, and traditional sprinklers) **as** a baseline to compare with water mist systems. Phase 2 conducted a literature study on commercially available low-pressure mist nozzles and potential additives. **A** range of promising nozzles and additives were then selected for assessment in the next phase.

Phase **3 and 4 –** Nozzle Screening **and Water/Additive** Tests: Phase **3** developed specialised calorimetry and distribution tests to enable initial comparison of nozzle performance without the expense of live fire testing. The selected nozzles were then screened using these techniques; four were assessed **as** having the performance characteristics required. These would be taken forward to full fire performance testing later in Phase **5;** however, Phase **4** deviated *to* assess water source and additive performance using one of the new nozzles **as** well **as** an existing ship-fitted sprinkler for comparison. The results showed little significant difference between sea and fresh water in extinguishing terms. The best additives improved knock down and gave varying degrees of post fire security (burn back) performance. The best all round were AFFF and FFFP; the foams claiming to be more environmentally friendly did not perform **as** well. At this stage the additives were used at the manufacturers' normal recommended concentrations.

Phase 5A and 5B – Small-Scale Fire Testing **and** Nozzle Characterization: Phase **5A** returned **to** the main theme by fully fire testing the four best low-pressure mist nozzles. Small difficult fires of diesel, avtur, heptane, wood cribs, cable and fuel soaked insulation were used to stretch the systems abilities. These small fires reduced the effect of global oxygen depletion, demonstrating each systems true capability. A GW Low Flow K15-C nozzle with a K factor of 15 gave the best all-round performance with impressive extinguishing performance particularly using additive. Phase 5B progressed to analyse the droplet characteristics of this nozzle using laser phase Doppler anemometry. It was shown that the nozzle produced a range of droplet sizes from 100 *to* 400 microns with a Dv_{90} of **322** microns. This indicated that the nozzle was able to provide larger droplets capable of delivering additive *to* the fire whilst maintaining a floating mist fraction. With the majority of droplets in the fine spray range as opposed to true water mist, the term Fine Water Spray (FWS) was used for the system from then on. The nominal flow rate of **39** l/min at **7** bar, while higher than many true mist nozzles, still allows significant water consumption savings compared to existing RN sprinklers, which typically have a **K** factor of **59.** It had **also** been hoped to size droplets doped with additive, but the high rejection rate **as** a result of the droplets losing their spherical shape when doped made this technique inaccurate. **Other** techniques were also tried, which indicated that the lower the additive concentration the better the quality of mist. More surprisingly, when further fire testing was conducted varying the **ratio** of water/AFFF from the normal **94/6** down to **99.5/0.5** (using **6%** AFFF concentrate), the system extinguishing performance improved and the burn back protection suffered only slightly. It was observed that the optimum ratio of 1 part AFFF to **99** parts seawater gave the best balance between these aspects of performance.

Phase 6 – Spray Fire Tests: Phase 6 followed with an examination of the performance of the system against diesel spray fires impinging on to a simulated array of pipes. This deliberately created a re-ignition source. Phase 6 testing was again conducted in the LPC test compartment but with varying degrees of free ventilation that proved to be a particularly significant factor with this type of fire. While the system could tackle larger spray fires successfully regardless of ventilation state, the smaller fires proved difficult to extinguish until the ventilation was limited. The use of an additive, while not detrimental to the results, did not enhance knock down as with the pool fires; however, it did help tackle fuel that pooled having hit the pipe array. These results proved the most challenging and would be duplicated to some extent in the intermediate-scale test programme undertaken as Phase 7.

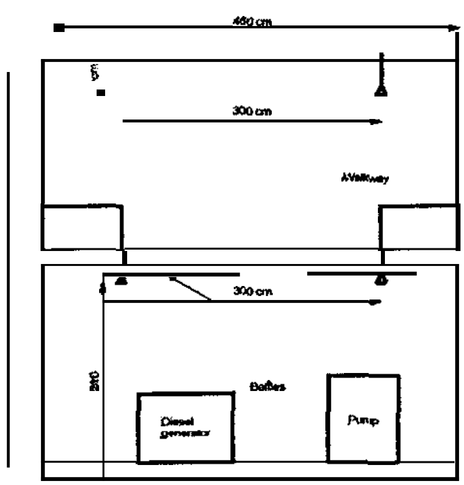
INTERMEDIATE-SCALE TESTS

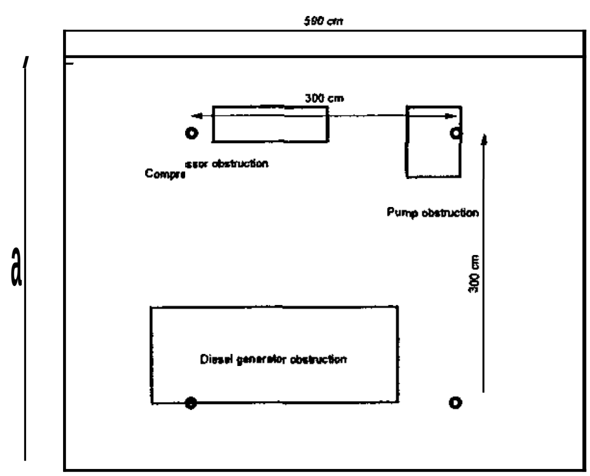
Having developed a system and operating philosophy at the laboratory scale there was a need to evaluate its performance on a larger scale with some hitherto untested scenario parameters prior to conducting a full-scale test. In particular, the tests were to appraise system performance:

- On larger fires
- In an enclosure with heat retaining surfaces
- In an enclosure with a more complex internal geometry
- On obstructed fires
- In an enclosure with greater deckhead height

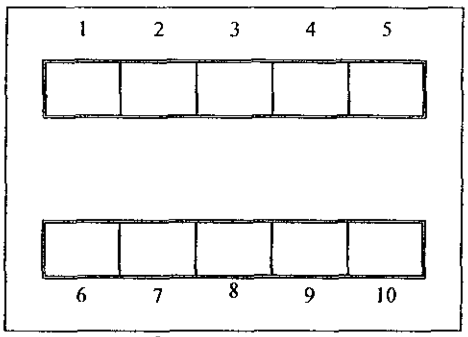
The tests were conducted using one of MFFM's existing facilities at the Naval Fire Training School on Horsea Island, Portsmouth. A schematic of the rig of 140 m³ volume and 4.9 m height is shown in Figure 1. The rig was modified to allow different levels of symmetrical free ventilation or sealing to be achieved (with inlets and outlets high and low) (Figure 2).

The rig contained a false bilge, a walkway at half height, a ladder, pipe obstructions, and several pieces of machinery at deck level. Tests were conducted initially using four Low Flow K15 nozzles on 3 m spacing at the overhead, then later adding another four nozzles at mid height. A wide range of fire types were tested including Class A cribs and insulation material, Class B diesel pan fires of around 800 kW, and two sizes of diesel spray fire, 1.5 and 3.0 MW impinging on an engine block. All fires were operated in open and obstructed locations.





WEST WALL



*Not to scale

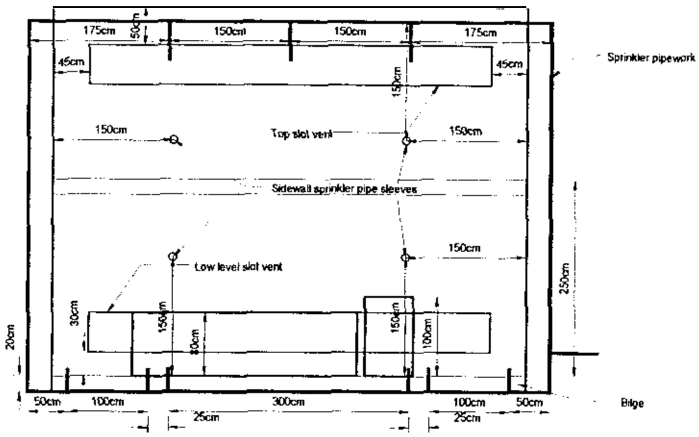


Figure 2. Ventilation panel positions in test rig (each **panel** 0.5 m high x 1.0 m wide),

RESULTS

Issues pertaining to extinguishing fires with Fine Water Spray systems with respect to performance and installation criteria are discussed below.

PERFORMANCE

Implications of Enclosure Conditions Prior to Extinguishing System Operation

Much has been written regarding the relationships that exist between the performance of fine water spray/ water mist systems and, the enclosure size; amount of ventilation; fire size; and fire preburn times (detection). With respect to extinguishing performance, the key parameters that are changed by any combination of these variables are the following: the mean oxygen content of the enclosure prior to system operation; the mean atmospheric temperature of the enclosure prior to system operation; and the temperature of surfaces within the enclosure prior to system operation. If atmospheric and surface temperatures are high, then steam generation and therefore oxygen displacement are more prolific; if oxygen content is already low, then the extinguishing process is improved still further.

Favourable conditions for operation might be a large fire in a small enclosure with zero, or little ventilation, and an unfavourable condition might be a small fire in a large ventilated enclosure. The ability to tackle fires between these limits depends upon the rates at which heat is generated and oxygen is depleted by the fire, against the rate at which heat escapes and oxygen is replaced through ventilation. Each of the parameters that influences the starting conditions tested in this study is discussed in turn below.

Fire Preburn Times: Table 1 shows the difference in starting conditions for fire preburn times of **3** and 7 1/2 min, respectively **(all** other experimental parameters identical).

TABLE 1. INFLUENCE OF PREBURN TIMES ON EXTINGUISHMENT OF THE LARGE **AND SMALL SPRAY** FIRES.

Run No.	Preburn Time (min)	Mean Enclosure Temperature Prior to System Operation ("C)	Oxygen Concentrations Prior to System Operation (%)		Extinguishing Time (sec)
			High	**Low**	
Large spray fire					
2	7 %	295	8.34	15.19	10
10	3	258	10.04	17.23	45
Small spray tire					
1	10	202	14.58	16.48	22
11	3	131	17.83	19.88	Not extinguished

The benefits of an extended preburn time are clearly shown. During the extended preburn period, the mean temperature of the enclosure is increased by an additional 37 °C and the oxygen lowered by a mean of 1.87%. The result is an extinguishing time difference of 35 sec. The results are more pronounced when data from the small spray fire are compared. Here the difference in pre-burn times is the difference between satisfactory extinguishment and failure.

Ventilation: In this example, the small fire fails to produce the conditions for its own extinguishment, whilst the larger spray fire does. Table 2 shows the difference in starting conditions for ventilation conditions of 2, 4, and 8 panels removed from the rig (all other experimental parameters identical). For ventilated enclosures the benefits of reduced ventilation on extinguishing performance are clearly shown. Operating with only 2 panels removed as opposed to 8, the enclosure temperatures at the time of system operation are 91 °C higher and the mean oxygen concentration is 5% lower.

TABLE 2. INFLUENCE OF VENTILATION ON EXTINGUISHMENT OF THE LARGE AND SMALL SPRAY FIRES.

Run No.	Vent Panels Removed	Mean Enclosure Temperature Prior to System Operation (°C)	Oxygen Concentrations Prior to System Operation (%)		Extinguishing Time (sec)
			High	Low	
Large spray fire					
25	2	238	11.64	17.08	14
39	4	175	15.75	20.81	21
47	8	165	17.65	20.84	35
24	8	147	18.06	20.83	Not extinguished
Small spray fire					
31	2	170	16.53	19.34	16
38	4	129	17.82	20.45	Not extinguished
20	8	112	19.08	20.82	195

Fire Size: The influence of fire size on the atmospheric conditions prior to extinguishing system operation where data from the large and small spray fires operated under identical conditions are compared (Table 3). In this example, the small fire fails to produce the conditions for its own extinguishment, whilst the larger spray fire does.

TABLE 3. INFLUENCE OF FIRE SIZE UPON EXTINGUISHMENT BY FINE WATER SPRAY.

Run No.	Fire Size	Mean Enclosure Temperature Prior to system Operation (°C)	Oxygen Concentrations Prior to System Operation (%)		Extinguishing Time (sec)
			High	Low	
38	Small spray	129	17.82	20.45	Not extinguished
39	Large spray	175	15.75	20.81	31

Atmospheric Cooling Ability

A primary attribute of fine water spray is its ability to remove heat from its surroundings efficiently. The rapidity with which it can do this is a function of the thermodynamic properties of water, the temperature and vapour concentration gradients existing between droplet and atmosphere, and the surface area over which heat and mass transfer can take place (heat absorption by the droplets and steam generation from the droplet). The finer the mist, the more efficiently and rapidly this can take place.

Even in the event of the fine water spray system not extinguishing the fire, the environment may be cooled sufficiently to make re-entry possible for manual tackling of the fire. Table 4 shows mean enclosure temperatures measured during successful and unsuccessful extinguishment of all fires.

TABLE **4.** INFLUENCE OF FWS ON ATMOSPHERIC TEMPERATURES

Run No.	Fire Type	Mean Enclosure Temperature Prior to System Operation (°C)	Mean Enclosure Temperature 3 min after System Operation (°C)	Ext.
24	Largespray	147	59	No
39	Large spray	175	31	**Yes**
38	Small spray	129	43	No
31	Small spray	170	21	Yes
7	Single pool	109	49	No
6	Single pool	89	22	Yes

Generally the fine water spray system is capable of maintaining atmospheric temperatures to within 40 °C of the ambient value. This has far reaching considerations for rapid entry into the enclosure (with suitable breathing apparatus) and for bulkhead cooling (see Bulkhead Cooling Ability).

Bulkhead Cooling Ability

Bulkhead cooling external to the fire enclosure is required to preserve the structural integrity of the vessel and prevent damage and spread to other areas. The use of fine water spray has the potential to replace the need for bulkhead cooling by:

- rapidly reducing enclosure temperatures
- putting limited amounts **of** water directly onto the internal bulkhead surfaces
- attenuating thermal radiation to the bulkhead
- producing all the above benefits regardless of whether the fire is extinguished or not

The rate at which cooling occurs will be a function of the enclosure temperature, amount of water impacting upon the bulkheads, aerosol properties, and the thermal inertia possessed by the structure. The use of wetting agents will also influence the efficiency with which water coating of surfaces occurs. Table *5* shows the bulkhead cooling during tackling ofthe large spray, and double-pool fires. Two large spray tests describe bulkhead cooling performance when the fire is extinguished successfully, and when it is not

TABLE 5. BULKHEAD COOLING BY **FINE** WATER SPRAY.

Run No.	Fire Type	Mean Temperature Prior to System Operation and Cooling Rate Shortly After								Ext.
		Enclosure		Unobscured bulkhead		Obscured bulkhead		Deckhead		
		T°C	T°C/min	T°C	T°C/min	T°C	T°C/min	T°C	T°C/min	
9	Large spray	251	418	106	45	130	12	--	--	Yes
24	Largespray	147	500	71	10.5	86	27'	56	-5.8	No
27	Doublepool	183	418	50	**10**	45	4.4*	63	1.4	Yes/No

* Bulkhead location not actually obscured from direct water impingement when 8 nozzles are used instead of 4, as in Runs 24 and 27

Run **9** demonstrates clearly the difference in cooling rates of the 5 mm thick bulkhead resulting from atmospheric cooling with and without direct surface water impingement. Unobscured surfaces (where direct drop impingement is possible) are seen to cool at the faster rate of 45 °C/min **as** opposed to 12 °C/min on obscured surfaces. Even when the fire is not extinguished significant bulkhead cooling is induced.

Egress Smoke Temperatures

In a fire scenario, there is often scope for extensive consequential damage as a result of hot gases escaping from the fire zone to sensitive areas. This damage may take the form of:

- heat damage to other areas and possible fire spread
- toxicity hazard as combustion products escape to manned areas
- chemical hazard to personnel and systems in adjoining spaces by corrosive/irritant gases

As with the measured cooling of the fire enclosure, escaping fire products are likewise cooled and most likely scrubbed of soluble corrosive and irritant gases, such as hydrogen chloride, hydrogen cyanide, and hydrogen fluoride that may be produced by the burning of plastic products (e.g., cable sheathing and insulation). Table 6 shows egress smoke temperatures measured for the large and small spray fires. Regardless of whether the fire is extinguished or not, it is highly likely that consequential damage resulting from leakage of hot and corrosive gases to other areas of the ship may be significantly reduced by the use of a Fine Water Spray.

TABLE 6. EGRESS SMOKE COOLING BY FINE WATER SPRAY.

24	Large spray	148	60	231	66	No
39	Largespray	175	37	265	42	Yes
38	Small spray	129	45	201	63	No
31	Small spray	170	31	155	43	Yes
7	Singlepool	110	49	34	28	No
6	Singlepool	89	24	48	22	Yes

Additive Inclusion

Although under sealed enclosure conditions (or circumstances that promote FWS function [see Implications of Enclosure Conditions Prior to Extinguishing System Operation]), FWS performance may be perfectly satisfactory without the use of an additive, it is likely that conditions will not be ideal or possible to guarantee. In determining the need for an additive, it is important to appreciate the differences in fire types and fuels, as its use is not always beneficial.

It is clear that an additive enhances/makes possible the tackling of the unobscured Class A wood crib, Class A PVC cable, and Class B liquid fuel fires. It is obviously also beneficial in tackling floor burning fuel from the spray fires (a very important part in their extinguishing process). It has been demonstrated previously that an additive increases the drop size distribution of the FWS. To this end it is likely that it will have a negative impact upon the tackling of obscured fires (larger drops are less mobile and less likely to 'flow' to fill volume). The increased drop size has already been demonstrated to have a negative effect upon the tackling of spray fires as the extinguishing process is a surface area-based issue (as opposed to putting a layer of additive onto of the top of a liquid pool). However, normal procedures in tackling spray fires would be to isolate the source of fuel.

In summary, the following is probably true and this will be a factor in determining the installation criteria of the system (Table 7). Installation guidelines for the envisaged system must ensure that the likelihood of significantly obscured fires occurring is zero.

TABLE 7. SUMMARY DIFFERENCES FOR TACKLING OF DIFFERENT FIRE TYPES.

FireType	Access	Class of Fuel	AFFF Benefit	Ideal Extinguishing Means
Wood crib	Unobscured	A	Good	AFFF
Wood crib	Obscured	A	No benefit unless capable of ultimately 'flowing' onto fuel under gravity resulting in 'Good' benefit'	AFFF and nozzle mounted under obstruction
Cable	Unohscured	A	Good	AFFF
Cable	Obscured	A	No benefit unless capable of ultimately 'flowing' onto fuel under gravity resulting in 'Good' benefit	AFFF and nozzle mounted under obstruction
Liquid pool	Unobscured	B	Good	AFFF
Liquid pool	Obscured	B	No benefit unless capable of ultimately 'flowing' onto fuel under gravity resulting in 'Good' benefit	AFFF and nozzle mounted under obstruction
Spray	Unobscured	B	Detrimental unless capable of ultimately 'flowing' onto resulting pool fires under gravity	Increased aerosol density and/or fuel isolation (AFFF to tackle **spilled** fuel)
Spray	Obscured	B	Detrimental unless capable of ultimately 'flowing' onto resulting pool fires under gravity	Nozzle mounted under obstruction and increased aerosol density and/or fuel isolation (AFFF to tackle spilled fuel)

INSTALLATION

Ultimately a design manual for the derived system must be developed. The design manual must ensure that for each probable scenario the system is installed in a manner that optimises its performance in terms of extinguishing ability and reliability. Circumstances will arise where a degree of compromise in terms of over-design is evident, but this is offset against negating the need for a real-scale evaluation of **all** installations and the implementation of simple rules that are robust and easy to use. The installation rules for the envisaged system will be appropriate for areas with a certain level of risk. Where specific risks are identified **as** presenting a special hazard in terms of likelihood or scale of potential damage, a separate system or different rules may apply. From these tests, the importance of a number of installation criteria necessary to complete this study has been demonstrated, namely, nozzle numbers/spacings and nozzle locations/obstructions.

Nozzle Numbers

Pressure is **a** variable that influences the amount of water entering the enclosure, **as** is the number of nozzels. Extra nozzles may be introduced to **a** volume by either decreasing the spacing or introducing more nozzles at various heights within the enclosure **on** the same spacing. Unlike modifying the operating pressure, changing the number of nozzle does not influence the drop size of the FWS. Table **8** shows the mean temperature and oxygen values measured whilst tackling small and large spray fires with 4 and ***6*** deckhead mounted nozzles, (all other parameters remain the same).

TABLE **8.** SUMMARY DATA OF TESTS USING DIFFERENT NUMBERS OF NOZZLES.

Run No.	Nozzles	Fire Size	Mean Enclosure Temperature Prior to System Operation (°C)	Oxygen Concentrations Prior to System Operation (%)		Extinguishing Time (sec)
				High	Low	
11	4	Small spray	131	17.83	19.88	Not extinguished
14	6	Small spray	125	18.00	19.53	52
10	4	Largespray	258	10.04	17.23	45
15	6	Largespray	241	11.33	17.72	17

By increasing the amount of water supplied to the enclosure in this way, the extinguishing time of the large spray fire is reduced and the small fire is extinguished where previously it was not. We have already seen in the Additive Inclusion section that spray fires differ significantly from pool or Class A fires in the way a system tackles them. For a given spray fire, an air aerosol loading will exist that will extinguish a fire by local oxygen depletion and cooling. As smaller fires are attempted, greater efficiency of heat removal/steam generation is required, which would generally require higher operating pressure or decreased nozzle spacings to achieve. Fuel isolation remains the best form of tackling spray fires, and it should be a key requirement when possible to do so.

Nozzle Locations/Obstructions

In all but a few isolated cases (generally where ventilation was minimal) Class A and Class B pool fires were not tackled by the system when obscured from the direct line-of-fire of the FWS nozzle. Relying so heavily on its good performance on these small fires (from the additive in the water supply) means that where the water does not go, fires are not extinguished. High-pressure systems attempt to do this by producing high momentum systems that force aerosol into all parts of the enclosure although again they can be easily defeated (as is a gas system) by even limited ventilation. The additive in water does "flow" after impacting the surface and to this end it was essential in the extinguishment of the pool burning portion of spray fires and of even heavily obstructed bilge fires under the diesel generator.

Consequently, the key to the design of such systems is that significant obstructions like walkways are not tolerated and extra nozzles are installed to tackle the obstacle.

The most appropriate installation philosophy for these tests involved the allocation of each nozzle to protect a given volume with a few basic rules, for example:

- Nozzle to nozzle spacing 3 m
- Max. nozzle operating height 3 ms
- Nozzle to wall spacing 1.5 m
- Nominal operating pressure 7 bar
- Maximum additive supply 1%
- Minimum additive supply 0.5%

Using these rules explains why for an enclosure height in excess of 5 m two nozzle arrays were required —one suspended from the deckhead, the other at a lower deck height. Further investigation on a larger scale will establish whether other nozzles, probably with a larger K-factor, could be used where greater unobstructed deckhead heights exist to avoid the inconvenience of intermediate level nozzles. What has been demonstrated is that with these few simple rules, a very promising level of protection has been established in this sizeable (136 m^3 volume) test enclosure, on a range of likely fuels and fire sizes, using conservative amounts of water. Further testing will establish (1) if even greater economies of water usage are achievable without compromising the level of protection and (2) whether performance may be increased in the light of renewed information concerning future ship pumping capacities.

CONCLUSIONS

This series of tests has enabled the performance of the derived Fine Water Spray system to be evaluated under some previously untested circumstances, namely, on larger fires, in a larger enclosure, and with realistic obstructions, and to evaluate other parameters, such as bulkhead cooling. The results presented herein will aid in the definition of the envisaged large-scale test rig, and ultimately the system design and associated installation manual. A brief summary of key factors studied in this work programme follows.

The ability of water mist to tackle fires has been demonstrated to be closely linked to environmental conditions prior to operation. Due to the operational requirements of a fighting ship, potentially beneficial environmental conditions cannot be guaranteed, so an additive is required to tackle problematic fire scenarios. Although an additive is beneficial for tackling unobscured surface burning fires such as wood crib and diesel pool fires, it is detrimental to the extinguishment of sprayed liquid fires and hidden surface fires (except where the fuel is located at low level where the additive will ultimately reach by gravity, such as a bilge). Spray fires can be tackled by increasing local aerosol densities, which may be achieved by increasing water supply pressure, reducing nozzle spacings, or selecting specialist nozzles, but are best handled by isolation **of** the fuel supply. Robust management of severely obscured fires with this low-pressure system can only be achieved by placement of nozzles to tackle the risk directly.

In adopting this approach, nozzle selection and additive usage must be considered together if optimum performance is to be achieved. In an attempt to preserve key attributes ofwater mist and sprinkler systems, low concentrations of additive have proven most favourable and the ability to dose such quantities accurately will be paramount. Testing to date has only considered water supply pressures up to 7 bar. It is possible that future ship designs will allow for operational pressures above this, which may offer significant performance enhancements to the FWS system. Similarly, operation at lower pressures has been shown to be detrimental to system performance unless the nozzles are optimised at the lower pressure.

This study has demonstrated how the FWS quickly induces very rapid and extensive environmental cooling that should accelerate re-entry and subsequent re-commissioning of the enclosure. The level of cooling and personnel protection is such that re-entry may well be possible with the fire still burning enabling manual attack to be considered where previously it might have been impossible. Cooling of the atmosphere and attenuation of thermal radiation additionally offers the potential of replacing/ reducing the need for bulkhead cooling. Smoke escaping from the enclosure is similarly cooled and potentially scrubbed of soluble toxic/irritant gases such as hydrogen chloride, hydrogen fluoride, and hydrogen cyanide, which will limit consequential damage and aid evacuation.

With respect to the enclosure in which these tests were conducted, a nozzle spacing of **3** m was appropriate for tackling most unobscured fires (aside from spray fires) from a deckhead mounting point. With the introduction of obstructions, an alternative installation criterion was successfully used whereby each nozzle protected a volume of size **3** x 3 x **3** m, which required a secondary water main mounted at a lower level. The water consumption for this installation (320 l $\min^{-1}$) represents a significant saving of resources when considering that it must replace (partially or wholly) three existing systems, namely, (1) fixed sprinkler system, **(2)** fixed 2-shot gas system, and **(3)** manual firetighting, and be capable of functioning in sealed and ventilated conditions. A fair comparison can only be made by consideration of the abilities of the established and 'hew" system on each fire type in each condition. Table 9 compares the performance of these systems and includes high-pressure water mist for further information.

TABLE 9. COMPARISON OF ALTERNATIVE SYSTEM ABILITIES ON A RANGE OF FIRE FOR EACH ENCLOSURE CONDITION.

	System	**"IDEAL"** Enclosure Condition, Sealed/Small Low **O,** High T °C			"NON-IDEAL" Enclosure Condition, Ventilated/Large High **O,** Low T°C		
		Pool	Spray	Class A	Pool	Spray	Class A
Established	Fixed sprinkler	✓	—	✓	✓	—	✓
Established	Fixed gas	✓	✓	✓	—	—	—
Established	Manual attack	✓	✓*	✓	✓	✓*	✓
Alternative	High pressure water mist	✓	✓	✓	—	—	—
Envisaged	**FWS** with **AFFF**	✓	✓	✓	✓	?+	✓

* - by shutting off the fuel supply
\+ - should be possible without having to shut off the fuel supply

Overall, the envisaged system continues to offer the prospect of satisfying economic replacement of existing onboard extinguishing systems for the total volume protection **of** open areas, e.g., machinery spaces. Fundamental to its development is its robustness of operation to function under a range of scenarios without some of the detrimental aspects of other systems, such as fire re-flash, excessive water usage, the need for bulkhead cooling, and the need for relatively sealed enclosures.

The next stage in this development programme is a full-scale, real geometry fire test programme, which will demonstrate the effectiveness of the design in larger volumes with more realistic clutter and enable the development of an understanding of the implications of nozzle placement and spray pattern requirement to achieve the degrees of surface covering and volume filling desired. Design and installation rules will be derived for future implementation of the system.

SUMMARY OF THE DERIVED METHODOLOGY FOR MACHINERY SPACE PROTECTION OF ROYAL NAVY SURFACE SHIPS

A summary of the conclusions drawn from the work to date is given below. Ongoing and future work may impact upon these at a later date.

- A FWS system may be best suited to fulfill the design criteria for naval surface vessels.
- AFFF (Mil. Spec.) additive shall be used to enhance the ability of the system to extinguish small fires and inert liquid fuels thereafter.
- Location of nozzles will reflect the need to project water and additive onto surfaces, and fill volumes with floating mist.
- A range of nozzles will probably be required to enable correct implementation of the system suitable for horizontal and vertical mounting with a selection of spray angles, patterns, and drop distributions.
- Hidden fires will be tackled by "design"; no 3-dimensional performance is inferred especially on small fires.
- Where possible, enclosures shall maintain their integrity, preventing ingress of oxygen and leakage of oxygen-depleted fire products and aerosol.

ACKNOWLEDGMENTS

Recognition is given to Kelvin Annable, Building Research Establishment, and WOMEA Paul Winton for their extensive input into the experimental content of this work. (British Crown Copyright 2001 / MOD; Published with the permission of the Controller of Her Britannic Majesty's Stationary Office)

NOTE

Further information may be found in the following reports, most of which are on file with the author.

C. Buckley, and D. Rush, "Development of Water Mist for the Royal Navy," published MoD paper 1996.

M. Edwards, and S. Watkins, "Further Development of Water Mist for the Royal Navy," published MoD paper, 1997

J.L.D. Glockling, M. Edwards, and S. Watkins, "Development of a Water Based Fire Suppression System for Naval Fighting Ships," published MoD paper, 1999

Unpublished MoD reports:

J.L.D. Glockling, K. Annable, "Comparative Performance Testing of Water Mist Systems," 1997.

J.L.D. Glockling, K. Annable, "Water Mist Development Phase 1 Results," 1998.

J.L.D. Glockling, K. Annable, "Water Mist Development Phase 2 Results," 1998.

J.L.D. Glockling, K. Annable, "Water Mist Development Phase 3 Results," 1998.

J.L.D. Glockling, K. Annable, "Water Mist Development Phase 4 Results," 1999.

J.L.D. Glockling, K. Annable, "Water Mist Development Phase 5 Results," 1999.

J.L.D. Glockling, K. Annable, "Fine Water Spray Development Phase 6 Results," 1999.

J.L.D. Glockling, K. Annable, "Fine Water Spray Development Phase 7 Results," 2000.