DEVELOPMENT OF A LOW-PRESSURE FINE WATER SPRAY FIRE SUPPRESSION SYSTEM FOR THE ROYAL NAVY

INTERMEDIATE SCALE TESTING

BY

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Introduction

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 ship's 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 of the system. It is also hoped that the derived system will be suitable for retrospective installation into existing vessels.

This article 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:

1. That the constraints placed on the system by a war time role were very challenging (see below).
2. 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 watermist systems.

Likely fire scenarios	(*a*) Pool fires of marine diesel, aviation fuel, lubricating oils, and 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 (i.e. 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 and 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 watermist systems in a variety of sealed, 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 BRE.

Phase 1 & 2 – Baseline tests and literature studies

All tests at laboratory scale were conducted in a carefully controlled 96m^3 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 watermist 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 & 4 – Nozzle screening and water/additive tests

Phase 3 developed specialized 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 and four 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 & 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 $Dv_{0.9}$ 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 watermist 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 was 1 part AFFF to 99 parts seawater, giving 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. 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 additive while not detrimental to results, did not enhance knock down as with the pool fires, it did however 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 of the programme.

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 full-scale test. In particular the tests were to appraise system performance:

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

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 140m^3 volume and 4.9m height is shown in (FIGs.1a & b).

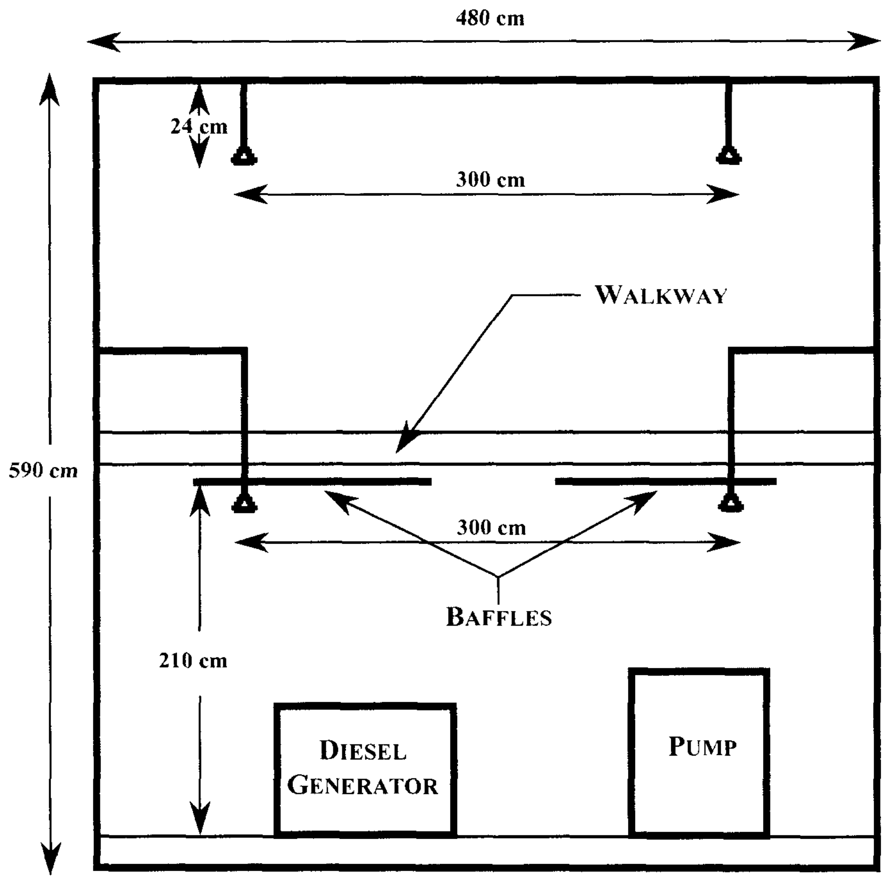


FIG. 1A – FWS INTERMEDIATE SCALE TEST RIG (ELEVATION)

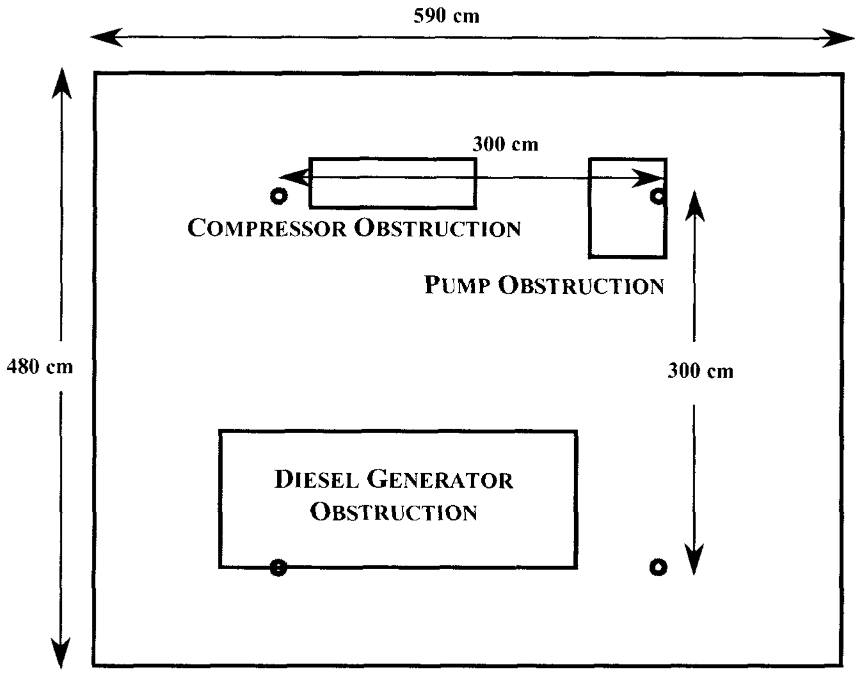
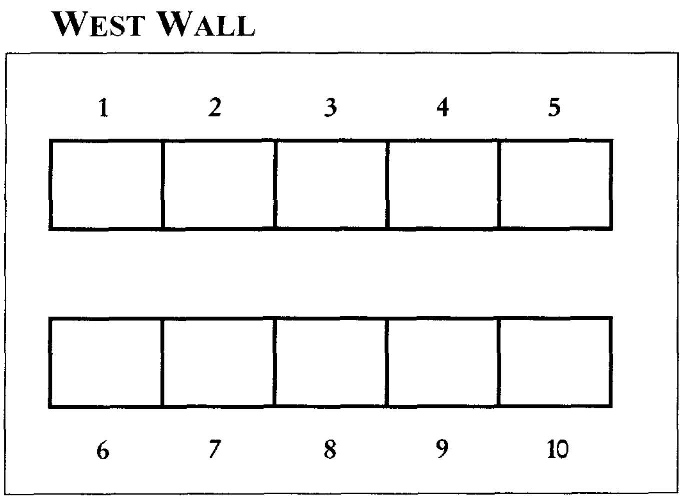


FIG.1B – FWS INTERMEDIATE SCALE TEST RIG (PLAN)

The rig was modified to allow different levels of symmetrical free ventilation or sealing to be achieved (with inlets and outlets high and low) as shown in (FIGs.2a & b).



* NOT TO SCALE

FIG. 2A- VENTILATION PANEL POSITIONS IN TEST RIG

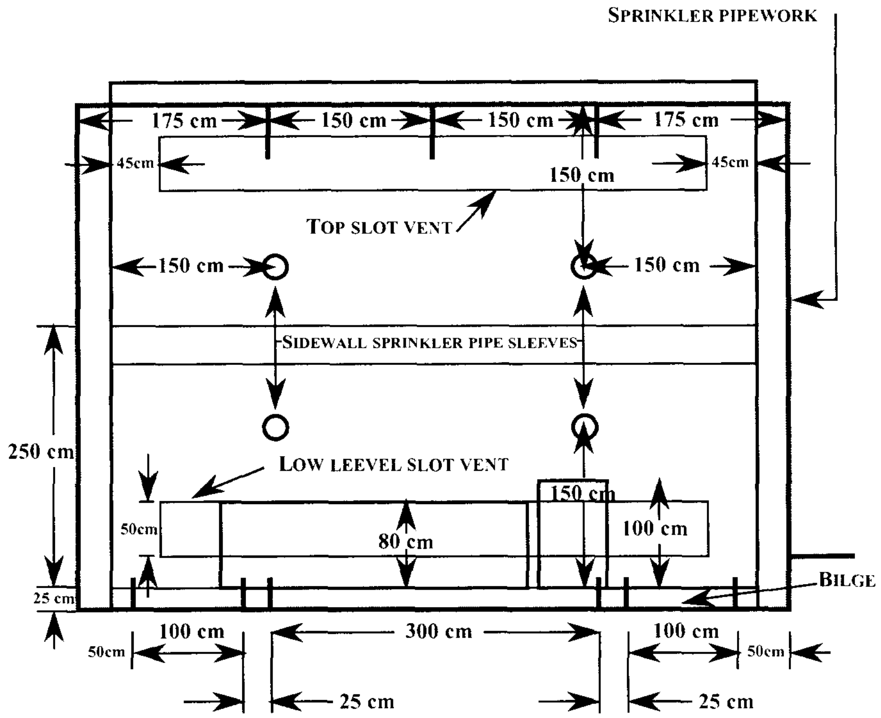


FIG.2B- VENTILATION PANEL POSITIONS IN TEST RIG (EACH PANEL 0.5 HIGH X 1.0M WIDE)

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 3m 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.
- 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.

RESULTS

Issues pertaining to extinguishing fires with FWS 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 FWS/water mist systems and, the enclosure size; amount of ventilation; fire size; and fire pre-burn times (detection).

With respect to extinguishing performance, the key parameters that are changed, prior to system operation, by any combination of these variables is:

- The mean oxygen content of the enclosure.

- The mean atmospheric temperature of the enclosure.
- The temperature of surfaces within the enclosure.

If atmospheric and surface temperatures are high then steam generation and therefore oxygen displacement is more prolific, and if oxygen content is already low then the extinguishing process is improved still further.

Thus 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 depleted by the fire, against the rate at which heat escapes and oxygen is replaced through ventilation.

Each of the parameters that influence the starting conditions tested in this study is tackled in turn below.

Fire pre-burn times

Table.1 shows the difference in starting conditions for fire pre-burn times of 3 and 7 ½ minutes respectively (all other experimental parameters identical).

TABLE 1 – *Influence of pre-burn times on extinguishment of the large and small spray fires*

Run number	Pre-burn time (minutes)	Mean enclosure Temperature prior to system operation (C)	Oxygen concentrations prior to system operation (%)		Extinguishing time (seconds)
			High	Low	
Large spray fire					
2	7 ½	295	8.34	15.19	10
10	3	258	10.04	17.23	45
Small spray fire					
1	10	202	14.58	16.48	22
11	3	131	17.83	19.88	Not extinguished

The benefits of an extended pre-burn time are clearly shown. During the extended pre-burn 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 seconds. The results are more pronounced when data from the small spray fire is compared. Here the difference in pre-burn times is the difference between satisfactory extinguishment, and failure.

Ventilation

Table.2 shows the difference in starting conditions for ventilation conditions of 2, 4, and 8 panels removed from the rig, respectively (all other experimental parameters identical).

TABLE.2 – *Influence of ventilation on extinguishment of the large and small spray fires*

Run number	Vent panels removed	Mean enclosure Temperature prior to system operation (C)	Oxygen concentrations prior to system operation (%)		Extinguishing time (seconds)
			High	Low	
Large spray fire					
25	2	238	11.64	17.08	14
39	4	175	15.75	20.81	27
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

For ventilated enclosure 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.

Fire size

The influence of fire size on the atmospheric conditions prior to extinguishing system operation is shown in Table.3 where data from the large and small spray fires operated under identical conditions are compared.

TABLE.3 – *Influence of fire size upon extinguishment by FWS*

Run number	Fire Size	Mean enclosure Temperature prior to system operation (C)	Oxygen concentrations prior to system operation (%)		Extinguishing time (seconds)
			High	Low	
38	Small spray	129	17.82	20.45	Not Extinguished
39	Large spray	175	15.75	20.81	31

In this example the small fire fails to produce the conditions for its own extinguishment, whilst the larger spray fire does.

Atmospheric cooling ability

A primary attribute of FWS is its ability to efficiently remove heat from its surroundings. 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.
- 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 FWS 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 number	Fire Size	Mean enclosure temperature prior to system operation (C)	Mean enclosure Temperature 3 minutes after system operation (C)	Extinguished
24	Large spray	147	59	No
39	Large spray	175	31	Yes
38	Small spray	129	43	No
31	Small spray	170	27	Yes
7	Single pool	109	49	No
6	Single pool	89	22	Yes

Generally the FWS 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.

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 FWS 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.
- 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 of the large spray, and double pools fires, respectively. Two large spray tests describe bulkhead cooling performance when the fire is extinguished successfully, and when it is not.

TABLE.5 – *Bulkhead cooling by FWS*

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	Large spray	147	500	71	10.5	86	27*	56	-5.8	No
27	Double pool	183	418	50	10	45	4.4*	63	1.4	Yes/No

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

Run 9 demonstrates clearly the difference in cooling rates of the 5mm 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 such a cable sheathing and insulation.

Table.6 shows egress smoke temperatures measured for the large and small spray fires respectively.

TABLE 6 – *Egress smoke cooling by FWSy*

Run No	Fire type	Mean temperature before and after system operation				Ext
		Enclosure		Smoke		
		Before	After	Before	After	
24	Large spray	148	60	231	66	No
39	Large spray	175	37	265	42	Yes
38	Small spray	129	45	201	63	No
31	Small spray	170	31	155	43	Yes
7	Single pool	110	49	34	28	No
6	Single pool	89	24	48	22	Yes

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 FWS.

Additive inclusion

Although under sealed enclosure conditions FWS performance may be perfectly satisfactory without the use of additive, it is likely that conditions will not be ideal or possible to guarantee. In determining the need for additive it is important to appreciate the differences in fire types and fuels, as its use is not always beneficial.

It is clear that 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 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 – *Summary differences for tackling of different fire types*

Fire type	Access	Class of fuel	AFFF benefits	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	Unobscured	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 guidelines for the envisaged system must ensure that the likelihood of significantly obscured fires occurring is zero.

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 optimizes 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 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 have been demonstrated that will be necessary in completing this study, namely:

- Nozzle numbers/spacings.
- Nozzle locations/obstructions.

Nozzle numbers

Pressure is a variable that influences the amount of water entering the enclosure, as is nozzle numbers. 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 nozzle numbers 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, respectively (all other parameters remaining the same).

TABLE.8 – *Summary data of tests using different numbers of nozzles*

Run	Nozzles	Fire size	Mean enclosure Temperature prior to system operation (C)	Oxygen concentrations prior to system operation (%)		Extinquishing time (seconds)
				High	Low	
11	4	Small spray	131	17.83	19.88	Not extinquished
14	6	Small spray	125	18	19.53	52
10	4	Large spray	258	10.04	17.23	45
15	6	Large spray	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. As stated above 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 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 quite simply 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. Of course the additive in water does 'flow' having impacted upon a surface and to this end was essential in the extinguishing of the pool burning portion of spray fires and even heavily obstructed bilge fires under the diesel generator.

Key therefore 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 metres.
- Nozzle to wall spacing 1.5 metres.
- Maximum nozzle operating height 3 metres.
- 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 metres two arrays of nozzles 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 (136m^3 volume) test enclosure, on a range of likely fuels and fire sizes, using conservative amounts of water. Further testing will establish if even greater economies of water usage are achievable without compromising the level of protection and 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 FWS system to be evaluated under some previously untested circumstances, namely, on larger fires, in a larger enclosure, 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 programme of work is given below.

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 additive is required to tackle problematic fire scenarios. Additive is beneficial for tackling unobscured surface burning fires such as wood crib and diesel pool fires, but 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 attempting to preserve key attributes of water mist and sprinkler systems low concentrations of additive have proved most favourable and the ability to accurately dose such quantities 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 optimized at the lower pressure.

This study has demonstrated how 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 metres was appropriate for tackling most unobscured fires (aside from spray fires) from a deckhead mounting point. With the introduction of obstructions an alternative installation criteria was successfully used whereby each nozzle protected a volume of size 3m x 3m x 3m that 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) 3 existing systems, namely:

- Fixed sprinkler system.
- Fixed 2 shot gas system.
- Manual fire fighting.

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 'new' system on each fire type in each condition. Table.9 compares 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*

		'IDEAL' enclosure condition Sealed/Small Low O_2 High T°C			'NON IDEAL' enclosure condition Ventilated/Large		
System		Pool	Spray	Class A	Pool	Spray	Class A
Established	Fixed sprinkler	✓	X	✓	✓	X	✓
Established	Fixed gas	✓	✓	✓	X	X	X
Established	Manual attack	✓	✓*	✓	✓	✓*	✓
Alternative	High pressure water mist	✓	✓	✓	X	X	X
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 such as 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.
- The need for relatively sealed enclosures.

The next stage in this development programme is a full scale, real geometry fire test programme. This 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 fulfil the design criteria for naval surface vessels.
- 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.

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