DEVELOPMENT OF LOW PRESSURE FINE WATER SPRAY FOR THE ROYAL NAVY: RESULTS OF FULL SCALE TRIALS

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INTRODUCTION

Royal Navy (RN) machinery compartments have traditionally employed two types of fixed fire suppression system, a primary gaseous system (CO_2 or halon) and a secondary medium velocity water spray system with the option to induct Aqueous Film Forming Foam (AFFF) at a design concentration of 6%. The primary system is used to extinguish fires when manual attack has failed and the compartment has been shut-down. The secondary system is used for post-fire cooling, bilge protection (with AFFF added) or fire suppression in the event that the primary system fails, for example, due to loss of containment resulting from battle damage.

Fine Water Spray (FWS) offers the potential to be a suitable replacement for the secondary, medium velocity spray system and may also remove the requirement for a primary gaseous system in compartments containing non-sensitive equipment. Previous work [1, 2, 3, and 4] has demonstrated its suitability in a test enclosure 150 m^3 in volume against a range of typical machinery space fire scenarios. The developed system comprises the GW LoFlow K15 fine water spray head mounted in a 3m x 3m array and supplied with water at a nominal pressure of 7 Bar dosed with 1% of 6% AFFF concentrate. The use of AFFF is fundamental to the performance of the system and the concentration chosen was the most appropriate compromise between:

- large fire performance, where preservation of a small droplet fraction is important for the purposes of steam generation and atmospheric cooling (higher additive concentrations were demonstrated to enlarge the mean droplet size)
- small pool fire performance and bilge inerting (where higher additive concentrations are beneficial)

This paper documents findings from full scale trials of the system which included a sensitivity study into the operational limits of the system.

PERFORMANCE OBJECTIVES

The envisaged system, as part of a total fire management policy that includes for example, manual attack and fuel management techniques, shall enable the vessel and its crew to continue to discharge their primary functions until such time that full repairs may be affected.

The performance objectives for the FWS system are therefore:

Fire suppression – reliable extinguishment of fires. Some scenarios, where the fire is small or highly obscured may not be readily extinguished by the FWS system alone. The expectation of the system under these circumstances will be to suppress and control the fire to make possible extinguishment by manual attack or fuel management techniques.

Collateral damage and water consumption – in order to reduce collateral damage and free surface effects, water consumption is to be minimised through more efficient use of water in fire suppression and compartment cooling.

Ventilation – fire suppression performance must be tolerant of ventilation, which may occur through battle damage or operational necessity.

Cooling and post fire security - the system must provide effective cooling throughout the fire event to improve the tenability of escape, re-entry and recovery thus reducing the burden of external boundary cooling duties. The system must also be capable of delivering AFFF to the compartment's bilges.

SYSTEM DESIGN PARAMETERS

In the pursuit of these objectives, the FWS system has emerged with the following key design features:

Nozzle selection –Some water mist solutions, like gaseous systems require high enclosure integrity for robust performance. This cannot be guaranteed on a warship and it is therefore likely that small and ventilated fires will be problematic – more specifically – any situation where atmospheric temperatures are low, and 'global' oxygen concentrations are high, prior to system operation. To overcome these potential shortcomings the envisaged system shall use a low concentration of additive and therefore by definition, the nozzle must be capable of effective delivery of additive to the fire seat whilst maintaining a significant small droplet fraction for effective heat removal, mass transfer and radiation attenuation. The GW LoFlow K15 nozzle demonstrated good all-round performance and recognises significant water savings over the established medium velocity sprayer systems.

Additives – The suitability of a number of additives were evaluated during development and although some had equivalent or even slightly better performance, AFFF was selected as the most appropriate for FWS due to its existing widespread usage within the RN. The use of AFFF at 1% is an essential design feature in achieving the required performance.

Water source - whilst a fresh water source would be desirable to minimise collateral damage, the storage requirements to provide sufficient endurance would be prohibitive in most RN warships. Previous work [3] showed no clear pattern regarding the relative extinguishing performance of sea and fresh water supplies (with or without additives). However, other more conclusive studies [6, 7] have demonstrated some improvements in the extinguishing performance of synthetic seawater over fresh water. Seawater was selected for the RN application, due to its abundance and simplicity of integration with current ship's systems.

Delivery pressure – In order to reduce whole life costs and retain the potential for retro-fit, the system is required to operate from the ship's high pressure salt water (HPSW) system, typically with a nominal system pressure of 7 to 10 bar.

FULL SCALE TRIALS

TEST ARRANGEMENTS

The main machinery space of a CVS was taken as a suitable compartment to replicate for the design of the large-scale test facility. The primary components within the CVS's main machinery space are the diesel generators and gas turbines. The compartment was too large to construct in its entirety but for testing purposes, a compartment half the size was large enough to evaluate FWS for the spectrum of end use platforms.

The dimensions of the test facility and location of the GT and DG enclosures are shown in Figure 1 and Figure 2.

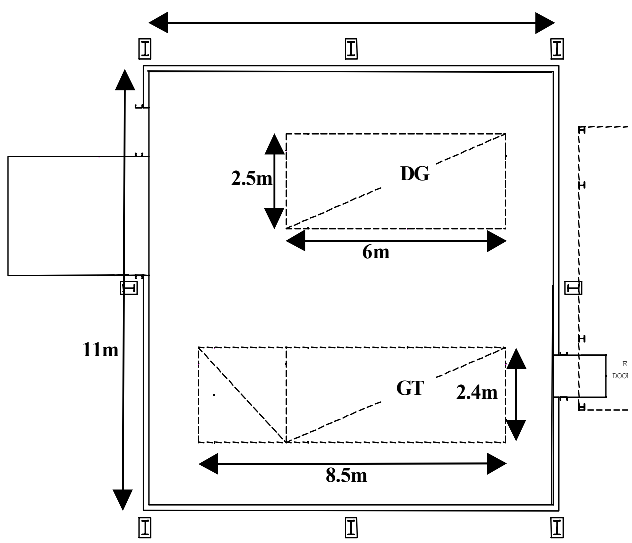

Figure 1 – Plan view of WSA's large scale test enclosure at Horsea Island

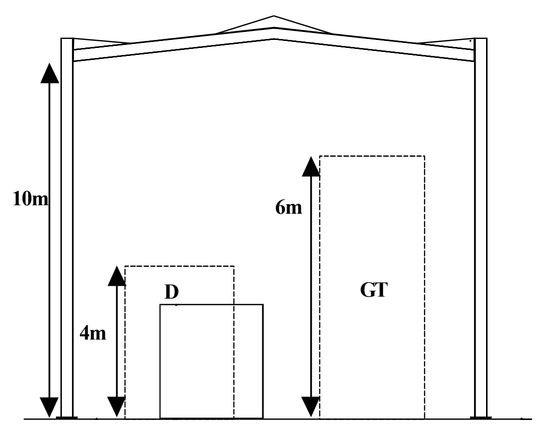

Figure 2 – Side view of WSA's large scale test enclosure at Horsea Island

The nozzles were installed into the test enclosure on a 3m x 3m array at three levels 3m apart as determined from the intermediate scale tests (each nozzle protecting a 3m x 3m x 3m 'cube') as shown in Figure 3 and Figure 4.

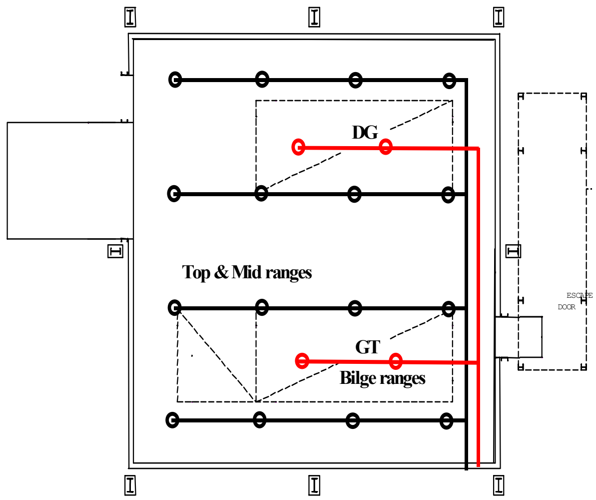

Figure 3 – Plan view of FWS pipe array in WSA's large scale test enclosure

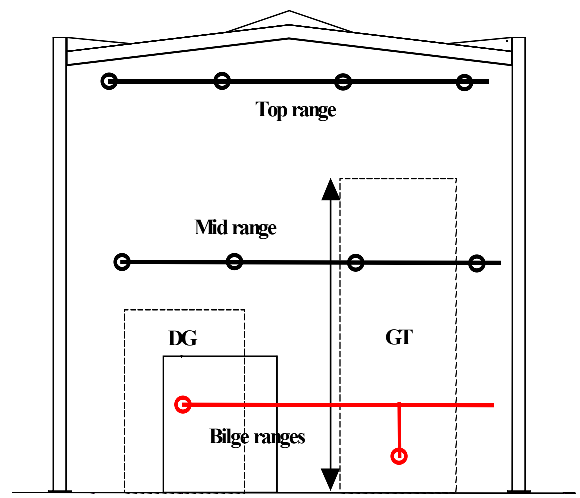

Figure 4 – Side view of FWS pipe array in WSA's large scale test enclosure

DESIGN FIRE & TESTING REGIME SPECIFICATION

The design fires were selected to accurately mimic realistic scenarios encountered onboard ship and operated to a regime that ensured repeatability for the duration of the test programme. Three fire types were selected for the testing

- spray fires of F-76 impacting onto metal objects
- pool fires of F-76
- combination spray and pool fires of F-76

Table 1 details the properties of the fires used in the research programme.

Type	Fuel	Fuel spray flow rate (l/min)	Fire tray size (m)	Heat output (MW)
Spray fire	F-76	6	None	3
Spray fire	F-76	3.5	None	1.75
Pool fire	F-76	0	1.22x2.44	4
Combination spray & pool	F-76	6	1.22x2.44	7
Combination spray & pool	F-76	3.5	1.22x2.44	5.75
Combination spray & pool	F-76	3.5	1.22x1.22	4

Table 1 – FWS design fire heat outputs

Note: All spray fires impacted onto a complex metal pump casing to better describe a typical fire scenario. This has been demonstrated to be a more onerous fire scenario; the hot target stabilising the fire and creating a permanent ignition source that must be managed prior to extinguishment. Likewise, the same pump was located within the fire tray for all pool fires for similar reasons.

For all testing, a ventilated pre-burn of 120 seconds was conducted prior to the test rig being sealed to the level required for the test. This was done to mitigate the potential performance enhancements that high temperatures and low initial oxygen content may recognise. At 135 seconds the FWS was actuated.

The FWS spray was evaluated initially in accordance with ideal design parameters against a range of fires. Upon completion of these tests the system sensitivities were appraised.

DESIGN PERFORMANCE

EXTINGUISHING PERFORMANCE

A series of spray fires were conducted to assess the impact of using different numbers of nozzles and water pressures for obscured and unobscured configurations. The results are shown in Table 2.

Configuration	Water pressure (bar)	Pipe ranges in use	Foam use	Extinguishing time[1] (mm:ss)	Comment
Unobscured	5.5	Top	No	9:13	
Unobscured	5.5	Top & Mid	No	4:10	Many re-flashes
Unobscured	7	Top	No	4:19	Many re-flashes
Unobscured	7	Top & Mid	No	2:17	
Obscured	7	Top	No	Not extinguished	
Obscured	7	Top & Mid	No	Not extinguished	Many re-flashes
Unobscured	5.5	Top	1%	3:50	Re-flash
Unobscured	7	Top	1%	1:51	

Table 2 – Spray fire test performance results

The testing demonstrated that spray fires could be managed using the FWS once the temperature of the impact object had been reduce to below the auto ignition temperature (AIT) of the fuel which, for F76, is around 200ºC. Not unsurprisingly, quicker extinguishment was achieved by increasing water usage either by increasing the water pressure, or the number of nozzles used.

The addition of the foam at 1% assisted the extinguishment process, possibly due to the increased wetting of the impact object increasing the cooling rate.

For scenarios where extinguishment was not achievable the conditions within the enclosure in respect of survivability and mitigation of consequential damage were very much improved. These fires were easily contained to a level where an alternative method of extinguishment, such as fuel management through the normal process of isolating fuel supplies and electrical power to the casualty compartment, would ensure extinguishment.

[1] After all re-flashes have stopped

Table 3 shows results from tests conducted using the 6 MW pool fire. Where foam was used, and could reach the seat of the fire, extinguishment was observed to be very rapid.

Configuration	Water pressure (bar)	Pipe ranges in use	Foam use	Extinguishing time[2] (mm:ss)	Comment
Unobscured	7	Top	No	Not extinguished	
Unobscured	7	Top & Mid	No	Not extinguished	Very close, burning limited to small areas in pump shadow
Obscured	5.5	Top	No	8:50	Many temporary reflashes
Obscured	7	Top & Mid	No	Not extinguished	
Unobscured	5.5	Top	1%	2:14	
Obscured	5.5	Top	1%	9:17	

Table 3 – Pool fire test performance results

Some fires conducted without additive were not extinguished by the FWS system. Whereas eventual extinguishment by oxygen depletion might be expected, the burning rate of the fire was reduced by the FWS to a level where this was not possible.

Tests conducted at reduced water pressures confirmed that the system could still be effective even with degraded supplies. The effect of increasing water pressure improved the potential to make up performance deficits on pool fires if foam was unavailable. Despite extinguishment not always being achieved the conditions within the enclosure in respect of survivability and mitigation of consequential damage are very much improved.

Table 4 shows results from tests conducted using the 5.75 MW combined spray and pool fire. This fire is of a size capable of self extinguishment by oxygen depletion within the enclosure, regardless of the application of the FWS system. The FWS spray is shown to have the effect of suppressing the fire and reducing the time taken for extinguishment.

Configuration	Water pressure (bar)	Pipe ranges in use	Foam use	Extinguishing time[3] (mm:ss)	Comment
Unobscured	5.5	Top	No	5:17	Many re-flashes
Unobscured	7	Top	No	8:05	Many re-flashes
Obscured	5.5	Top	No	4:47	Many re-flashes
Obscured	7	Top & mid	No	Not extinguished	
Unobscured	5.5	Top	1%	5:30	
Unobscured	5.5	Top	No	5:17	Many re-flashes

Table 4 – Combination spray/pool fire test performance results

During the extinguishing process all areas of the enclosure are sufficiently protected against consequential damage. These tests reiterated the excellent benefits realised by FWS in controlling the fire to a manageable level, improving survivability and mitigating consequential damage.

Most notable in these tests is the satisfactory performance recognised using the top range of heads only (10 m) thereby negating the need for an intermediate level array and providing further water savings over and above that originally envisaged for the system

[2] After all re-flashes have stopped
[3] After all re-flashes have stopped

DECKHEAD COOLING PERFORMANCE

A series of fires was conducted to threaten the deckhead of the enclosure to varying degrees. The fire was located centrally under a group of 4 heads at heights of 0m, 2m and 4m. Spray fires of 3, 6 and 7 l/min were used, the largest of which enabled flames to directly impinge on the deckhead. A nozzle was upturned centrally between the 3m grid to assess the merits of specific cooling. Only the top range of the FWS spray system was operated without foam at 7 bar pressure.

The temperature reached at the deckhead ranged from 118°C to 379°C without direct impingement of flames on the deckhead, this increased to 469°C with direct impingement. In all tests, the FWS system reduced the deckhead temperature to below 100°C. The use of upturned heads showed marginal benefit but does add greatly to the complexity of the installation. Whether this additional system complexity is worthwhile will depend upon other factors such as the risks within the deckhead of the compartment and adjacent compartments.

SPECIFIC ITEM PROTECTION PERFORMANCE

Having established the suitability of the system when used as a total flooding system an investigation was undertaken to evaluate the zoning potential of the system around items of known increased risk. Such items might include boilers and fuel separators. In the provision of installation rules there is a need to be able to accommodate intelligent approaches to specific hazard issues and the reduction of nozzle spacing is one way of achieving this.

A series of tests were conducted to assess whether additional protection could be offered to high risk items by additional nozzles in this area. The standard 3m grid (4 nozzles) was replaced by a 1.5m grid (9 nozzles) in one sector.

Reducing the nozzle spacing was demonstrated to increase the performance envelope of the system enabling fires to be extinguished that would not normally be possible. This should be limited to specific areas which contain high hazard items otherwise one of the key performance benefits is quickly lost: that being the low water requirement of the system.

BILGE PROTECTION PERFORMANCE

The GW LoFlow K15 nozzle did not give satisfactory performance in low height areas on large pool fires such as might be experienced in the bilge. The small droplet size is unable to overcome the repulsive forces of the fire and deliver foam effectively. An alternative small-bore medium velocity sprayer nozzle was found to be able to perform this function satisfactorily.

SYSTEM SENSITIVITY

PRESSURE SENSITIVITY EVALUATION

The water supply pressure to the FWS system cannot be guaranteed within a warship environment due to a variety of effects including its distance from the pump, frictional losses, height above the pump, other demands on the water supply system (fire hoses) and the rolling motion of the ship. Because of this it is essential to ensure that the end design is robust against reasonable water supply pressure excursions.

Using AFFF foam appropriately dosed to 1% for the water supply test pressure, experiments were conducted from 1.5 bar to 10 bar on each fire scenario. The results are shown in Table 5.

Fire type	Water pressure (Bar)	Result[4]
3MW spray	5	Many re-flashes, but not extinguished prior to fuel being exhausted
3MW spray	6	Many re-flashes, but not extinguished prior to fuel being exhausted
3MW spray	7	Extinguished at 2:22s
3MW spray	10	Extinguished at 6:59s
7MW spray/pool	1.5	Not extinguished
7MW spray/pool	3	Extinguished at 5:21s
7MW spray/pool	5	Extinguished at 1:06s
7MW spray/pool	7	Extinguished at 1:34s
7MW spray/pool	10	Extinguished at 0:26s
4MW Pool fire	1.5	Burning area dropped by 99% very quickly – Small flame approx. 15 cm in height remained inside pump coaming where foam was unable to reach
4MW Pool fire	3	Burning area dropped by 99% very quickly – Small flame approx. 15 cm in height remained inside pump coaming where foam was unable to reach
4MW Pool fire	5	Burning area dropped by 99% very quickly – Small flame approx. 15 cm in height remained inside pump coaming where foam was unable to reach
4MW Pool fire	7	Extinguished at 1:24
4MW Pool fire	10	Extinguished at 0:58s

Table 5 – FWS Performance pressure sensitivity on large pool fire

Where fires are not extinguished consideration must be given to the residual benefit of the system in terms of survivability and the mitigation of fire spread. In conclusion:

- Small spray fires (in relation to enclosure size) will be the most difficult to extinguish. Under these circumstances the role of the FWS system is to prevent fire spread and increase survivability within the enclosure until the fuel source can be managed or ceases. These test showed that below 7 bar, the design fire was not extinguished although its heat output was significantly reduced to the point where it became unstable, demonstrated by the considerable number of reflashes that were observed at 5 and 6 bar. The mean temperature within the enclosure was held to around 60°C within a very short period of time regardless of whether the fire was extinguished or not.

- Large fires (Combined spray and pool) which are able to drive the extinguishing process further by oxygen consumption and displacement by steam generation are observed to be tackled at lower pressure, only failing at 1.5 Bar.

[4] After all re-flashes have stopped

- Pool fires were managed at all pressures down to 1.5 bar, although in small areas of the pool shadowed by the pump flaming continued as foam failed to infiltrate the internals of the pump.

The system is seen to offer benefits on all fire types down to low operational pressures. Where extinguishment has not been achieved the fire size has been very significantly reduced and the enclosure conditions extensively modified in favour of preventing fire spread and increasing survivability. This demonstrates an encouraging degree of robustness to deviations from supply pressure.

VENTILATION SENSITIVITY PERFORMANCE

In an ideal situation the ship's crew will be able to isolate the fire compartment prior to operation of the extinguishing system as is currently done for Halon and CO_2 systems. Like a gas system, FWS will operate best if the integrity of the enclosure can be assured thus maximising the oxygen depleting effects of steam displacement and fire consumption. Unlike established gas systems, FWS has the potential to be more robust against failed or unsecured enclosures as many of the benefits will still be realised even if extinguishment of the fire is not achieved.

To evaluate the robustness of the system to uncontrolled ventilation, tests were conducted with each of the three fire scenarios with:

- no ventilation
- 1 m^2 low level ventilation
- 4m^2 balance ventilation (2m^2 high and 2m^2)

In confirmation of the suggested extinguishing mechanism for pool fires they are seen to be extinguished irrespective of ventilation conditions since their management depends only on foam delivery and this remains unaffected by enclosure ventilation.

The performance of the system on spray fires will be a function of fire size in relation to the size of the enclosure and the amount of applied ventilation. In these tests, the difference between the rates at which fresh air entered and oxygen depleted gas evacuated, enabled the extinguishment when ventilation was at low level only, but not at the more severe condition of balanced high and low ventilation.

Where the fires are not extinguished the benefits of FWS are maintained protecting the enclosure from fire spread and increased survivability.

NOZZLE BLOCKAGE / MALFUNCTION / MISPLACEMENT SENSITIVITY

The effect of reducing the nozzle spacing was assessed for specific item protection. The FWS system was also assessed in the event of a larger spacing than the designed 3m x 3m. There are a number of reasons why end use installation may differ from the design optimum, as outlined below:

- In the cluttered confines of the machinery space it will certainly not be possible to mount nozzles with absolute accuracy due to objects, such as beams and ventilation trunking hampering positioning. In this instance it my be preferable to leave nozzles out or move them to a more appropriate position.
- Nozzles may become blocked by corrosion, metal working chaff and even insect infestation
- Physical damage to the nozzles

Tests were conducted using each fire scenario with 2 or 4 nozzles blocked at the design pressure of 7 Bar with 1% AFFF.

Not unexpectedly, fires that were not extinguished by the system with all nozzles operational were not extinguishable when some or all local nozzles were blocked. Pool fires were generally managed as some foam still reached from more distant nozzles. Where extinguishment was not achieved, significant control was. The pool aspect of the combined fire was always managed; thereafter extinguishment being a function of spray fire size with smaller fires proving more problematic than larger ones. The larger fires were still managed even with the four closest nozzles blocked. The benefits in terms of reduction in enclosure temperature, mitigation of fire spread and increased survivability were still maintained.

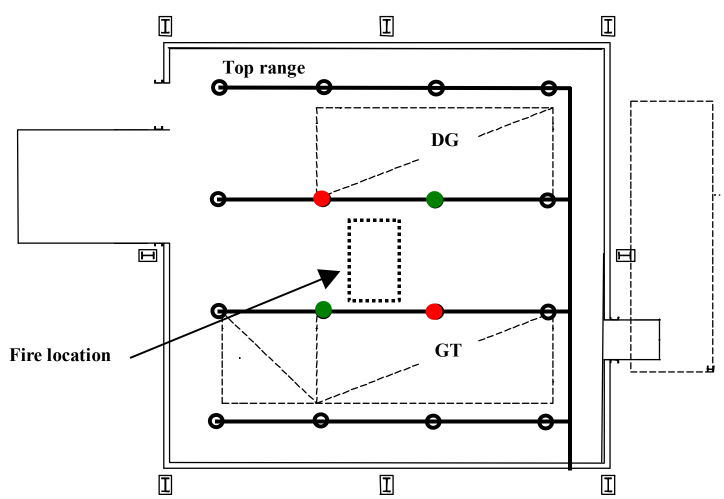

Figure 5 – Blocked nozzle locations

Run number	No. of nozzles blocked	Result
1.75MW Spray fire	0	Not extinguished
1.75MW Spray fire	2	Not extinguished
1.75MW Spray fire	4	Not extinguished
6MW Spray fire	0	Extinguished at 2:22s
6MW Spray fire	2	Extinguished at 5:35
6MW Spray fire	4	Not extinguished
5.75 MW spray/pool fire	1	Fire not extinguished – Pool quickly managed but spray fire remained
5.75 MW spray/pool fire	2	Fire not extinguished – Many re flashes
5.75 MW spray/pool fire	4	Fire not extinguished
7 MW spray/pool fire	0	Extinguished at 1:34s
7 MW spray/pool fire	4	Extinguished at 5:43
4MW pool fire	0	Extinguished at 1:24s
4MW pool fire	2	Extinguished (Video malfunction – no accurate timing)
4MW pool fire	4	Not extinguished but significantly controlled

Table 6 – FWS blocked nozzle performance

DISCUSSION

The described FWS system has largely exceeded expectations in terms of overall performance and degree of robustness and to this end the prime objectives of this study of evaluation, and optimisation at full-scale, have been met. In general terms the system can be expected to:

- Extinguish obscured spray and pool fires that are large in comparison to the enclosure size by oxygen depletion
- Extinguish some unobscured spray fires at high oxygen content by cooling of the objects onto which the fuel impacts
- Extinguish unobscured pool fires at high oxygen content by the application of foam additive
- Inert spilled fuel in the bilges
- Contain small obscured pool and spray fire
- Significantly improve the tenability and survivability of the protected space irrespective of whether the primary fire is extinguished or not
- Prevent fire spread and limit consequential damage to adjacent equipment
- Perform some or all aspects of boundary cooling

The next stage in its development will be the production of design guidance for its installation that covers all areas of system implementation, maintenance and operation. During preparation of this guidance the following outstanding issues will need to be addressed:

- Equipment robustness
- Required redundancy in specification
- Implications if used as the only ‘total-flooding’ option within a ship’s machinery space
- Mapping of failure modes if used as one of two systems within a ship machinery space

- Integration of operation with other fire management techniques and procedures
- Integration with the ship management system
- Foam injection techniques
- Operator awareness of performance capabilities

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