DEVELOPMENT OF LOW PRESSURE FINE WATER SPRAY FOR THE ROYAL NAVY: ADDITIVE RESEARCH AND PREPARATIONS FOR FULL SCALE TESTING

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INTRODUCTION

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 to extinguish a fire, for example, due to loss of containment resulting from battle damage.

Fine Water Spray (FWS), is a low pressure water mist which is emerging as a potential replacement for the secondary, medium velocity spray system and may also remove the requirement for a primary gaseous system in compartments containing non-sensitive equipments. Previous work[1,2,3] has led to successful intermediate scale trials[4] of FWS against a range of machinery space fires in a test rig enclosure of 150m^3.

One of the most notable findings of the work to date was the observed enhancement in extinguishing performance when using FWS with AFFF at 1% (1/6th normal design concentration) and laboratory studies have been undertaken to better understand the extinguishing mechanisms involved. Intermediate scale trials also identified areas for further work, pre-requisite to full scale trials of FWS, including nozzle scoping for high and low height areas, spray fire optimisation and deckhead space protection. This work has now been completed.

This paper describes in more detail the evolving performance objectives and design features of FWS, and updates the reader on additive studies and preparatory work for full scale trials.

FWS PERFORMANCE OBJECTIVES AND DESIGN FEATURES

As FWS is being developed against generic fire hazards likely to be experienced in most future warships, a priority for the project is to minimise, by the provision of design guidance, the requirement for further fire testing in real compartment geometries. Some of the key performance objectives which have evolved since the outset of the project are set out below:

Fire suppression – reliable extinguishment of all fires wherever feasible. Fires such as small highly obscured pool fires or impacting spray fires, which may not be feasibly extinguished by FWS, must be suppressed and controlled to make possible extinguishment by manual attack or fuel management.

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

Ventilation – fire suppression performance should be tolerant of ventilation which might be introduced through battle damage.

Cooling and post fire security - the system must provide effective cooling during and post fire to improve the tenability of escape, re-entry and recovery and reduce the burden of external boundary cooling duties. The system should also be capable of delivering AFFF to the fuel surfaces.

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

Nozzle selection – the LoFlow K15 nozzle has been identified as offering good potential for protection of heights between 3 and 5 metres. Comparative tests with a typical medium velocity spray nozzle also indicated that water savings of up to 40% may be achieved whilst at the same time improving Class B extinguishing performance.

Additives – in comparative tests of five candidate additives, a film forming fluoroprotein (FFFP) demonstrated the best overall performance, closely followed by two variants of AFFF. AFFF has been taken forward as the preferred additive for FWS due to its existing widespread usage within RN. Moreover, the use of AFFF at 1% has become an essential design feature in achieving the required performance against pool fires.

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 [5,6] have demonstrated some improvements in the extinguishing performance of synthetic sea water over fresh water.

Delivery pressure – In order to reduce whole life costs and retain the potential for retro-fit, the system must operate from the ship's high pressure salt water (HPSW) system, typically with a nominal system pressure of 7 to 10 bar. Nozzle delivery pressures of less than 7 bar have proved detrimental to the performance of the LoFlow K15 nozzle and therefore careful account must be taken of head, pipework and strainer losses within system design.

ADDITIVE STUDIES

FWS without additives is believed to operate by purely physical suppression mechanisms, primarily heat extraction, oxygen displacement and blocking of radiant heat[7]. By contrast, agents which operate by chemical mechanisms normally degrade in the combustion region to form highly reactive species which are believed to be efficient in the termination of the energetic reaction occurring within a fire[8].

As the long hydrocarbon chains in AFFF and FFFP are highly fluorinated, it was postulated at the outset that these suppression agents may act as fluorine radical providers and therefore contribute a chemical suppression mechanism. The use of these additives in FWS will also affect the physical interactions between (i) water supply and nozzle, (ii) droplets colliding with each other, (iii) droplets and gas phase flows, (iv) droplets and flames and (v) droplets and fuel surface.

INVESTIGATION OF CHEMICAL EFFECTS

Laboratory scale tests were performed on 7 AFFF and 1 FFFP agent to investigate the potential for chemical suppression mechanisms to occur. Initially these studies were performed using a 3m x 3m x 3m test chamber (figure 1), using agents premixed to $1/6^{th}$ of the design concentration. To allow the identification of any degradation products formed in the fire it was vital to have sustained periods of suppressed burning. This required a flowrate which was below the operating range of the LoFlow K15 nozzle and a Lechler 460.408.17.CA axial-flow cone nozzle was selected instead. During these tests, the gaseous combustion products were analysed using a Fourier Transform infrared spectrometer (FT-IR), fitted with a heated 5l gas cell. Samples of the premixed suppression agents and the waste waters produced by the tests were also analysed by ion chromatography to determine the concentrations of halides present. These waste water samples were also analysed by gas chromatography to detect any fluorocarbons present. During these tests the time to extinguishment of the fire was also recorded.

Further tests were then performed using a modified Meker pattern burner. Undiluted AFFF and FFFP were introduced directly into the flame to increase the concentration of any gaseous degradation products formed. The Meker burner flame was generated by premixing methane and air externally to the burner to ensure a consistent flame. The agent was then introduced through a hypodermic syringe and needle to a tip resting on the centre of the burner plate using a syringe pump to ensure an even flow. The gases produced by the burner were again analysed using the FT-IR to investigate the formation of fluorine containing degradation products.

The analysis performed during the 3m cube and Meker burner experiments failed to identify any fluorinated species in the gas phase during the application of the AFFF and FFFP agents tested.

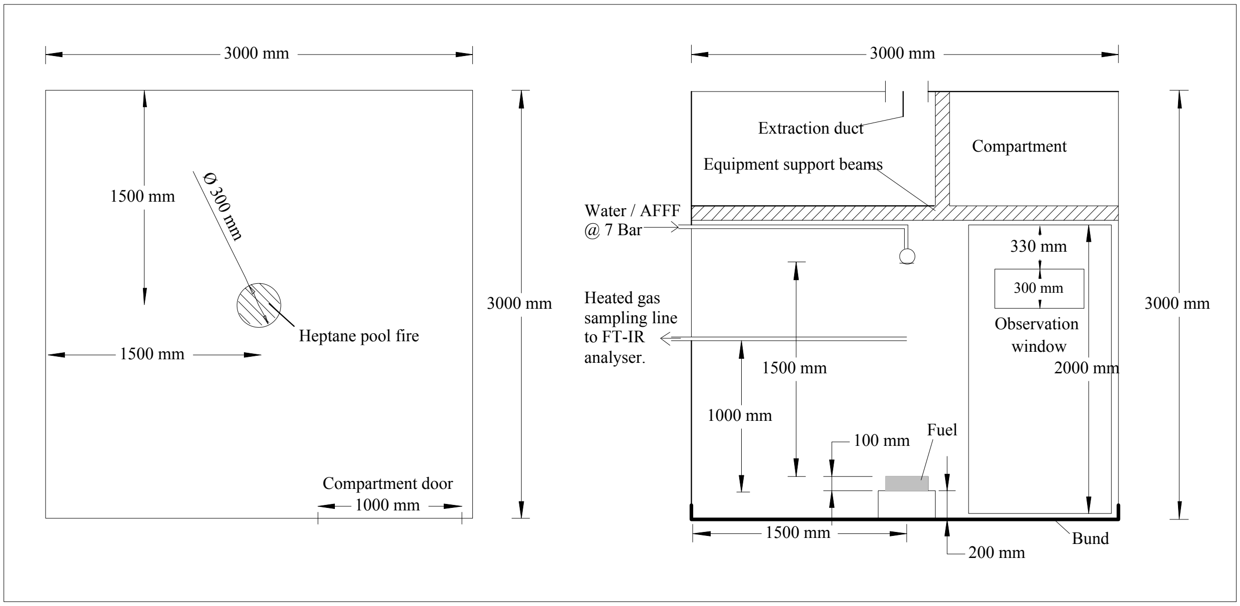

Figure 1. Schematic of 3m cube for determination of the degradation products of additives

The time to extinguishment for the test in the 3m cube varied considerably from those recorded during previous work[3]. Indexing of the suppression times however produced a very similar ranking of the suppression agents to that previously obtained. Gas chromatography analysis of the waste water samples taken from the 3m cube tests failed to detect any fluorocarbons but ion chromatography did show small increases in the concentrations of fluoride. However, these increases were less than 2ppm and would appear to be the result of the loss of water from the samples rather than the degradation of the agents used. The lack of any fluorocarbon degradation products in these tests suggests that it is unlikely that any chemical suppression mechanism occurs with the use of these agents in FWS.

INVESTIGATION OF PHYSICAL EFFECTS

Comparative high speed photography and droplet characterisation work was performed on the FWS generated from deionised water only and a dilute solution of an AFFF agent. The work was carried out using both Lechler 460.408.17CA and LoFlow K15 nozzles. In this study, the spray head was operated in a fume cupboard containing a cine camera and a 10W laser light source. The camera and light source were set up so that a small section of the spray cone, 0.25 m below the nozzle, was in the field of view of the camera with the droplets travelling across the plane of the camera. Using 10ns pulses at 10kHz from the laser and filming at 7000 frames per second it was possible to film the progress of individual droplets through the cameras field of view. The addition of a needle with a 310µm diameter into this area allowed the camera system to be focused and gave a reference for the measurement of the droplet sizes and trajectories. After filming a spray test, the cine films were then assessed using a Cortex IQ120 image analysing system. This allowed the diameters of all of the droplets in a frame of the film to be assessed. By analysing successive frames the velocities and trajectories of the droplets were also determined.

A range of droplet sizes (from 0-500μm) were apparent in the water only spray, however all of the droplets appeared to be close to spherical (figure 2). In contrast, for the water + 1% AFFF spray a wider range of droplet sizes was apparent, with a greater proportion of very large droplets (around 500μm). Many of these larger droplets appeared to be distinctly elongated, forming oval and other more irregular shapes (figure 3).

These differences were reflected in the analysis of droplet sizes: the surface, volume and Sauter mean diameters each showed an increase of the order of 50% for water + 1% AFFF as compared with the water only spray. The total volume of the droplets analysed was also distinctly greater for the water +1% AFFF spray.

Comparing the droplet diameter distributions for the two spray solutions (figure 4) highlights these differences further. With the addition of AFFF the number of droplets with diameters of 200-600μm increases significantly whilst there is a significant reduction in the number of droplets with diameters of 100-200μm. Although the majority of the droplets were numerically within the 100-200μm range in each case, it should be noted that a few larger droplets, as in the case of the water + 1% AFFF spray, may carry a large proportion of the volume of water delivered by the nozzle. These droplets are arguably the most important for transport of water to the base of the fire.

Comparing the velocity distributions (figure 5), a similar range of velocities between 1 and 26 ms^{-1} was seen in each case, however, a greater proportion of the droplets appeared to be travelling at higher velocities for the water + 1% AFFF spray, as compared to those for water alone. This probably reflects the greater proportion of larger droplets, since large droplets are likely to have more momentum and are generally observed to travel at higher velocities in sprinkler sprays.

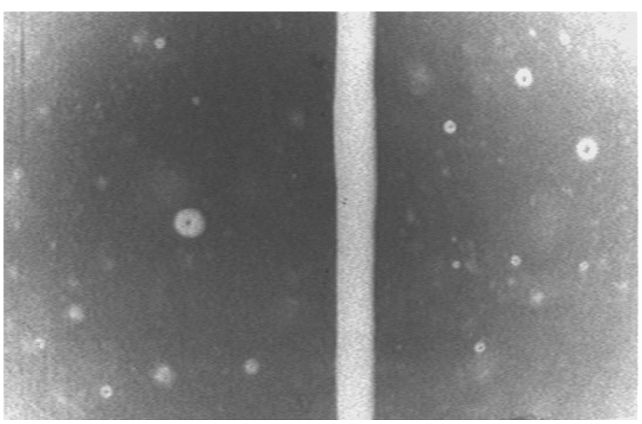

Figure 2. Photograph of droplets from Lechler 460.408.17CA nozzle with water only

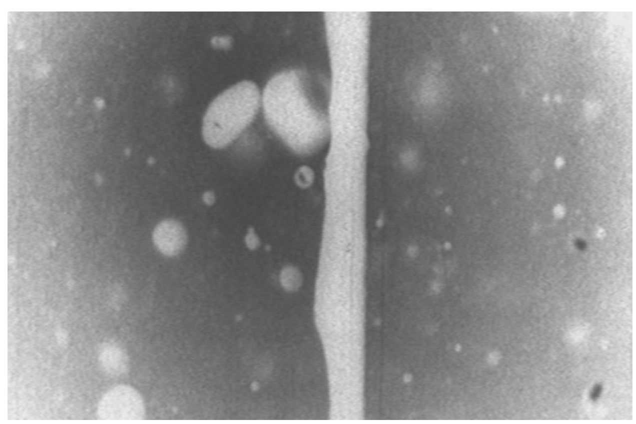

Figure 3. Photograph of a droplets from Lechler 460.408.17CA nozzle with water + 1% AFFF

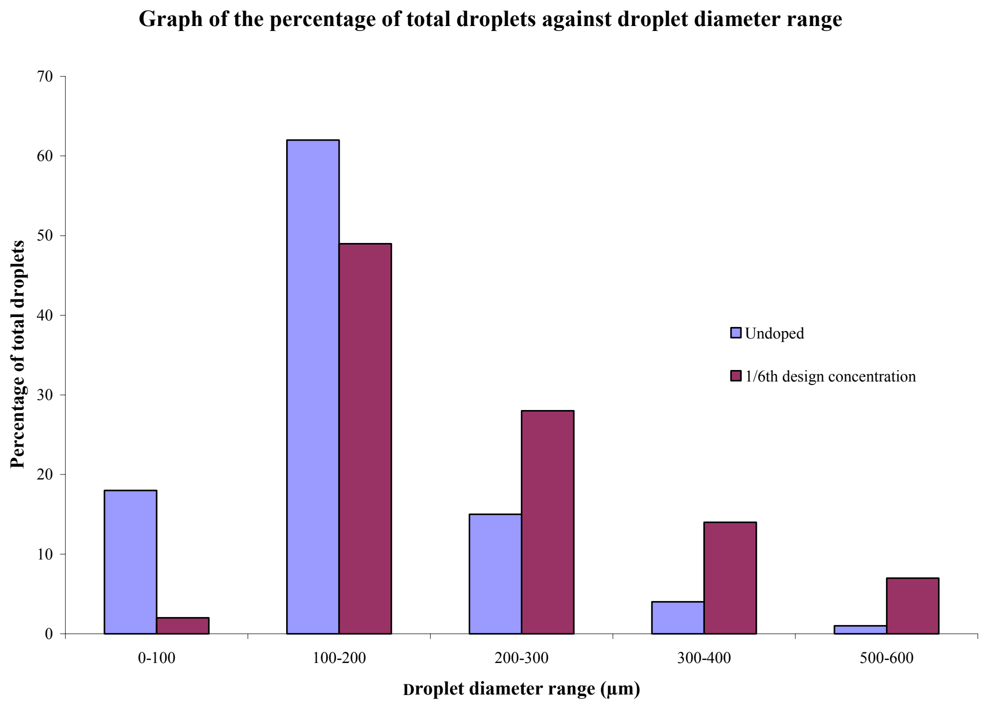

Figure 4. Droplet diameters for Lechler 460.408.17CA nozzle

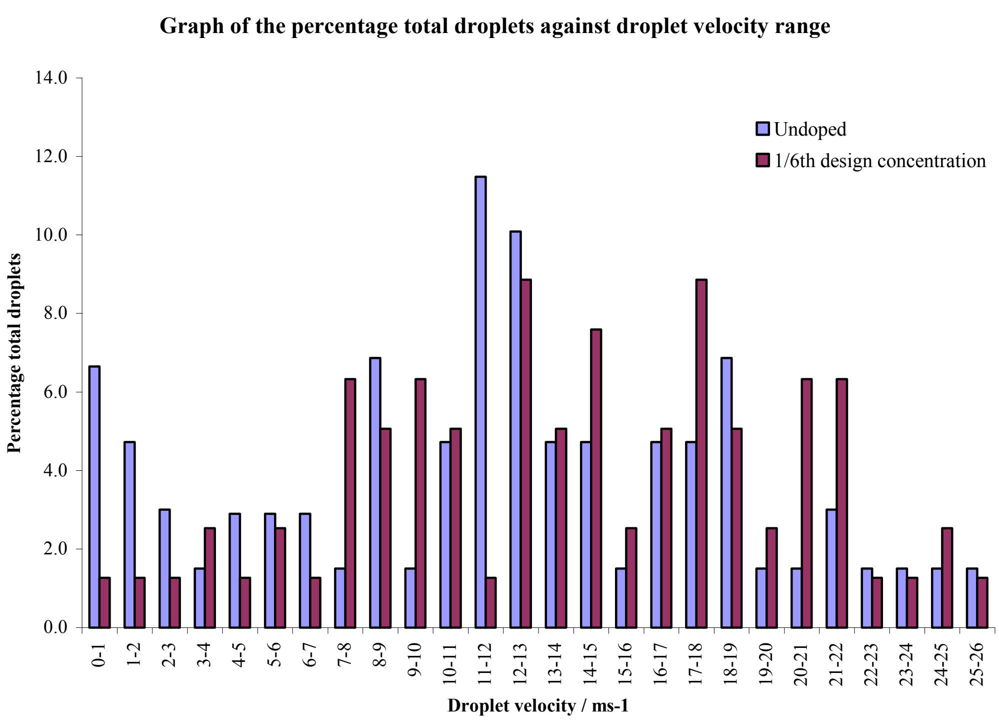

Figure 5. Droplet velocity for Lechler 460.408.17CA nozzle

The presence of larger deformed droplets and the increase in mean diameters in the water + 1% AFFF spray is counter intuitive and is not fully understood, given that AFFF significantly reduces the surface tension of water, but may be the result of increased viscosity or changes in droplet interactions occurring between the nozzle and the camera. The deformation of the larger droplets observed in the water + 1% AFFF spray suggests that these droplets might be more prone to break-up as the shear rate increases in a fire plume.

The LoFlow nozzle generally followed the same trends in droplet sizes, velocities and shapes with the addition of AFFF. However, there were significant differences, most notably for the nozzle, the percentage of total droplets in the 0-100μm fell from 17% to 14% with the addition of AFFF. By comparison, the same parameter for the Lechler nozzle, fell from 18% to 2%. Also, droplet mean diameters did not increase by the same extent for the nozzle (17% increase compared to 50% increase for the Lechler nozzle). This would tend to suggest that some nozzles will benefit more from the addition of AFFF, than others.

PREPARATIONS FOR FULL SCALE TRIALS

TEST ARRANGEMENTS

Nozzle scoping for high and low height areas, spray fire optimisation and deckhead space protection tests were conducted in an Actual Delivered Density (ADD) rig within a burn hall of volume in excess of 6,000m^3. The ADD rig consists of a 6 metre square non-combustible ceiling supported on hoists that allows for a variable height of up to 7 metres. The nozzle array was supported from the variable height ceiling and mountings allowed nozzle spacings to be varied.

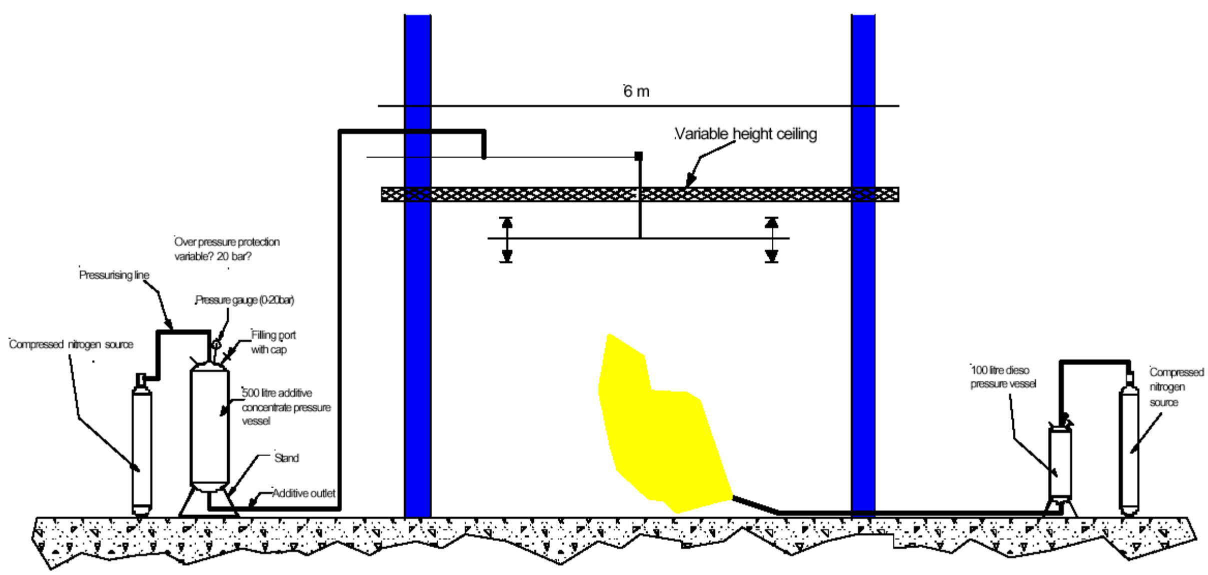

Figure 6. Elevation of ADD test rig

Two test fires were used for high and low height nozzle scoping: a dieso spray fire of 1.5MW and a dieso pool fire of tray dimensions (0.59m x 0.5m). These were selected as fires which could be extinguished by the LoFlow K15 nozzle in a 3 x 3 metre array at 3 metres ceiling height in the free ventilation conditions of the ADD rig. A third test fire was used for spray fire optimisation and deckhead cooling tests: a dieso spray fire of 1.5MW impacting upon an 8 inch steel pipe.

All tests were conducted using fresh water at a delivery pressure of 7 bar and with AFFF additive injected at 1% concentration.

NOZZLE SCOPING FOR HIGH AND LOW HEIGHT APPLICATIONS

To scope suitable nozzles with potential for high height applications, tests were conducted at 7 metres ceiling height with results shown in figure 7. Although more extensive test results supplied by the manufacturer indicate the S22 to be the more suitable for high height applications, under these experimental conditions the difference between the two nozzles was almost indistinguishable.

Nozzles for low height applications should have a lower k-factor than the LoFlow K15 and should ideally produce a finer mist capable of spreading within the confined space (large drop penetration being less important) at a spray angle of 180°. The Mistery K10 and AM25 K9 nozzles were tested in the ADD rig at 1 metre height and 7 bar water pressure with test results shown in table 1.

Table 1. Results From Nozzle Scoping Tests For High And Low Height Applications

	Fire	Nozzle	Result
7m ceiling tests	Spray	LoFlow K15	Extinguished on 13 seconds
	Pool	LoFlow K15	Extinguished on 11 seconds
	Spray	S22 K22	Extinguished on 10 seconds
	Pool	S22 K22	Extinguished on 16 seconds
1m ceiling tests	Pool	LoFlow K15	Not extinguished
	Pool	Mistery K10	Not extinguished
	Pool	AM25 K9	Extinguished on 65 seconds
	Spray	AM25 K9	Not extinguished

OPTIMISATION OF SPRAY FIRE PERFORMANCE

Intermediate scale testing[4] showed that a greater range of spray fires could be tackled by using more tiers of nozzles or by reducing the nozzle spacing. The purpose of these tests was to evaluate the performance of the above nozzles against the 1.5 MW spray fire impacting on an 8 inch steel pipe. An ADD rig ceiling height of 3 metres was used with nozzle spacings of 1.5, 2 and 3 metres. The impacting spray fire was not extinguished by any nozzles at any of these spacings (fuel supply shut off at 180 seconds). The limited performance against spray fires was due substantially to very challenging, free ventilation conditions in the burn hall. In previous FWS testing on spray fires[4], impacting spray fires ranging from 200 to 650kW were extinguished with much more restricted ventilation but it is accepted practise that spray fires in RN machinery spaces would be tackled by isolation of the fuel supply, rather than reliance upon the fire suppression system.

DECKHEAD AND HEAD SPACE PROTECTION

Deck head protection is necessary to preserve ship's structural integrity, prevent flashover and extinguish fires involving materials located in the deckhead space , particularly where these are above nozzle mountings.

To simulate the thermal properties of a deckhead, the ADD rig was augmented with a section of 5mm thick steel sheet with thermocouples on either side. Ceiling and smoke thermocouples were also installed at key locations. The impacting spray test fire was used, located directly beneath the simulated deckhead at a ceiling height of 3 metres. This was the worst case position of the

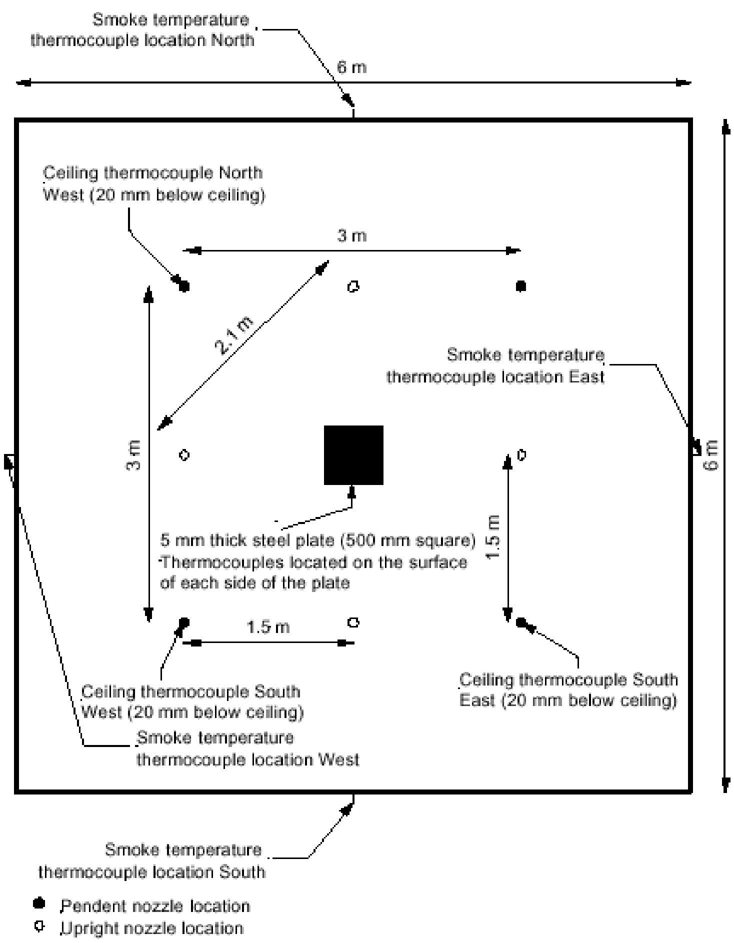

Figure 7. Plan of ADD rig ceiling for deckhead cooling tests

fire relative to the nozzles. After an initial free-burn test, tests were repeated for a number of nozzle combinations arranged as shown in figure 7. The time averaged results from these tests are shown in table 2. Time-temperature profiles for fire side of steel plate and mean ceiling temperatures are shown in figures 8 and 9 respectively.

Table 2. Results From Deckhead Cooling Tests

Pendent nozzle	Upright nozzle	Average* deckhead temp °C (fire side)	Average* deckhead temp. °C (non-fire side)	Average* temp. °C under ceiling	Average* spill smoke temp. °C
none	none	197	48	176	83
LoFlow K15	none	195	45	146	63
LoFlow K15	Mistery K5	176	42	52	29
AM25 K9	none	237	54	171	78
AM25 K9	Mistery K5	198	59	50	31

All tests: 30 seconds pre-burn, fuel shut off at 180 seconds, FWS shut off at 720 seconds.
*Temperatures time-averaged between t=0 and t=180 seconds.

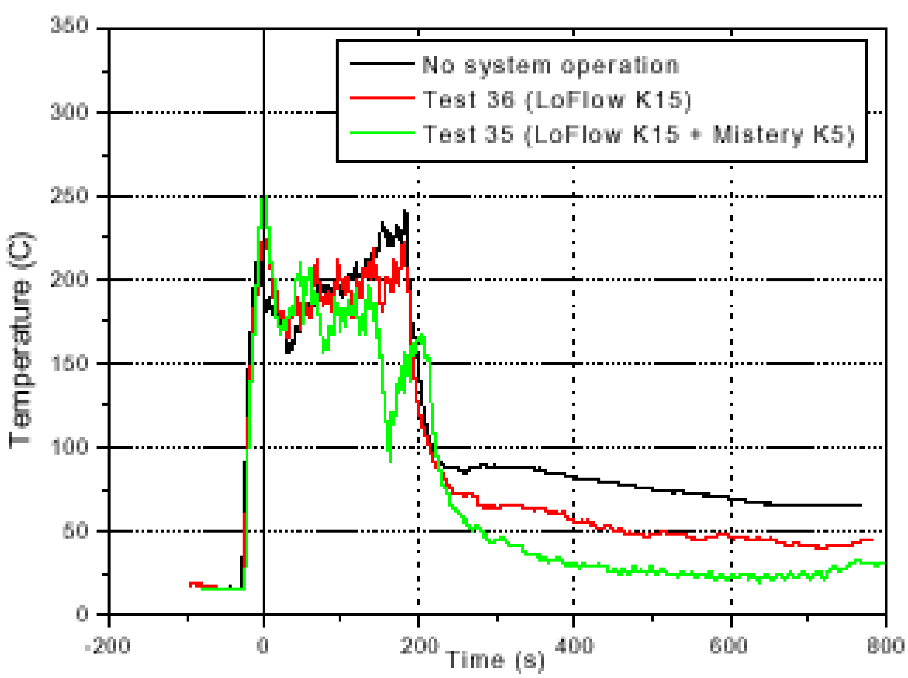

Figure 8. Steel plate temperatures on fire side

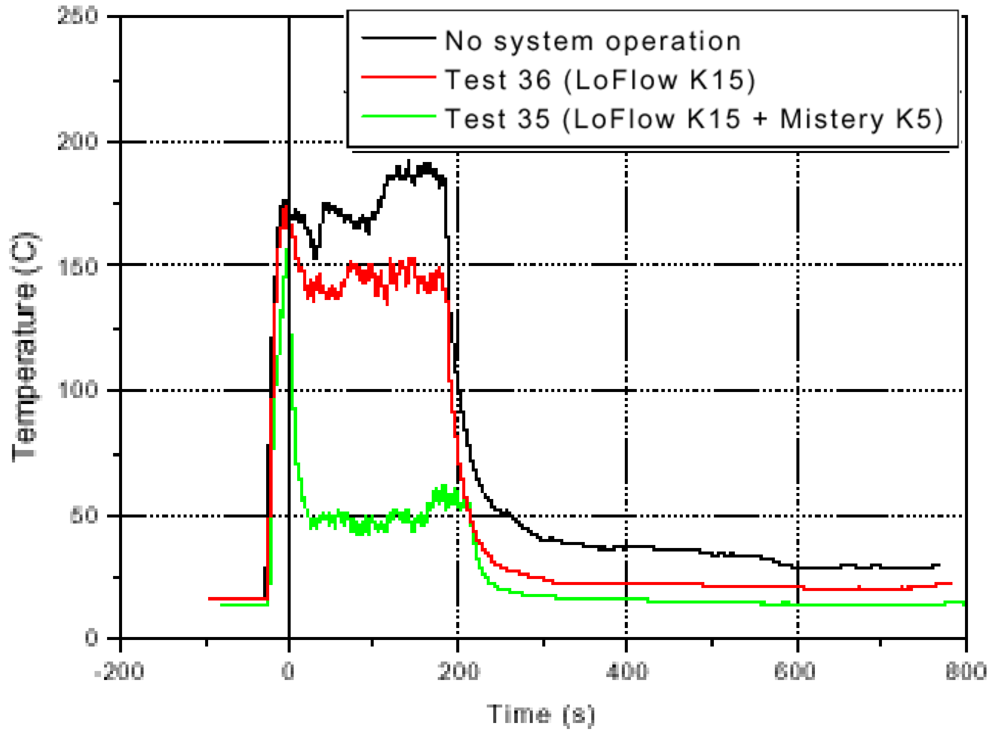

Figure 9. Average ceiling temperatures

CONCLUSIONS

ADDITIVE CHEMICAL EFFECTS

The lack of observable degradation products from the application of AFFF and FFFP agents in FWS and Meker Burner tests suggests that any chemical suppression mechanism is unlikely in this application

ADDITIVE PHYSICAL EFFECTS

The limited scope of these tests and the complexity of droplet interactions has, thus far, precluded a complete assessment of the physical mechanisms by which AFFF enhances FWS extinguishing performance. The film- forming effects of foam additives, in terms of cooling of the fuel surface and attenuation of radiative feedback, are well understood. This study suggests that the production of larger droplets and increase in droplet mean diameters, which results from the addition of AFFF, may also improve transport of droplets to the flame region and the fuel surface of unobscurred fires. Quantifying this effect would require observation of the fate of individual droplets under controlled temperature conditions at varying distances from the nozzle.

AFFF leads to a significant reduction in the surface tension of the spray solution. The effect of this upon coalescence during droplet collisions, droplet shape and break-up in the fire plume would also be an interesting area for further research.

NOZZLES FOR HIGH AND LOW HEIGHT APPLICATIONS

None of the nozzles tested showed clear performance enhancements over the LoFlow K15 (even those with higher flow rates). This nozzle will therefore be taken forward to full scale trials in heights of up to 7 metres.

None of the nozzles tested showed clear potential for low height applications (1 metre height). Nozzles with preferred cone angles and spray patterns have since been identified, but these have yet to be tested in full scale trials.

SPRAY FIRE OPTIMISATION

Like small highly obscured pool fires, the impacting spray fire appears to be a limiting case on FWS extinguishing performance. The impacting spray fire was particularly onerous in the free ventilation conditions of the ADD rig and better performance has been achieved in enclosed spaces during previous tests. In RN machinery spaces, such fires would be extinguished by isolation of the fuel supply with FWS providing suppression and containment of the spray fires and extinguishment of the residual pool fire.

PROTECTION OF DECKHEAD SPACE

Significant cooling of the hot gas layer could be achieved by the use of additional upward facing, low k-factor nozzles. This would preserve structural integrity, inhibit flashover and spread of fire to the deckhead, however, some fire hazards at deckhead level may warrant more dedicated protection.

The same cooling enhancements did not extend to deckhead surfaces for which only minor benefits were observed. The potential for FWS to reduce boundary cooling duties will need to be examined more closely in full scale trials.

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