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Fire protection in ammunition storage spaces on board naval craft: An evaluation of the water application rate

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Abstract

Ammunition storage spaces on naval vessels are commonly fitted with drencher systems that are designed to prevent ordnance reaching a temperature where it might explode due to fast or slow "cook-off". Many of these systems are traditional low pressure water spray systems that are required by the Naval Ship Code and class requirements to deliver water at a rate of between 24 ℓ/m^2/min and 32 ℓ/m^2/min. The origin of this requirement is not entirely clear. The high flow rates are a burden on system design and rapid flooding of the magazines decreases the stability of the ship due to free surface effects. The objective of this study was to evaluate the necessity of high flow rates. In addition, the feasibility of reducing them using a lower flow rate drencher system –if necessary in conjunction with a low pressure water mist system– was investigated. The experiments involved exposure of an instrumented steel tube, representing ordnance, to a diesel pool fire located beneath or beside it. The temperature of the tube was monitored prior to, during and after activation of the fire suppression to ensure that it did not exceed a threshold temperature of 200°C. Flow rates from the drencher system were varied and at lower flows the WMS was activated. For the fire scenarios studied, the results indicated that a flow rate of 32 ℓ/m^2/min exceeded that required to keep the temperature of the ordnance below 200 ^{o}C. At an application rate of 10 ℓ/m² per minute, the installed drencher system suppressed the fire and the kept the temperature of the ordnance below the threshold. A dual system of drencher combined with water mist system was effective at comparable flow rates. The fire however, although controlled, was not fully extinguished in all cases. This study is part of a trilateral research project between Canada, The Netherlands and Sweden designated FiST. Results contribute to defining the way ahead in the process of evaluation of national requirements for fixed fire fighting systems for magazines.

Keywords

Fixed fire fighting sprinkler system, Water mist system, Drencher system, Application rate, Weapon stowage, Naval craft, Navy Requirements

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Introduction

This paper is based on an extensive amount of full-scale tests that were run at SP Technical Research Institute of Sweden during late December 2011 and January-February 2012. The test series was carried out as a part of a collaborative project called New Technologies for Fire Suppression On Board Naval Craft (FiST). The objective of the FiST research project is to assess residual capacity of typical naval fire fighting systems after damage has been inflicted. Water mist systems (WMS) are being used more and more in modern day warships, hence the main focus of the project is on this type of fire fighting system. FiST is a four year (2011-2014) trilateral project involving participants from:

Sweden	FMV Swedish Defence Material Administration
	SP Technical Research Institute of Sweden
	FOI Swedish Defence Research Agency
	FireTech Engineering
Canada	Defence R&D Canada Atlantic
The Netherlands	Royal Netherlands Navy Defence Materiel Organisation
	TNO Defence Research

Goal

The goal of the tests was to evaluate the necessity of the high water discharge density requirements for explosive stowage magazines found in e.g. the ANEP-77 Naval Ship Code [1] and in Class regulations such as DNV [2]. The high flow rates are a burden on system design and rapid flooding of the magazines decreases the stability of the ship due to free surface effects. Furthermore, we want to assess the feasibility of reducing the flow rate using a lower flow rate drencher system – if necessary in conjunction with a low pressure water mist system.

Background

The military and civilian regulations and rules concerning water application rates for explosive storage magazines have requirements that vary between 24-40 ℓ/m^2 per minute for water spray systems. ANEP-77 and DNV regulations require application rates of 24-32 ℓ/m^2 per minute. The U.S. Navy's handbook on magazine sprinkling requires that ordnance shall be protected by a deluge-type sprinkling system that delivers a minimum of 0.80 gpm/ft^2 [3] or 32 $\ell/min/m^2$. However, the rationale for the flow rates specified by different countries or rules societies is difficult to find. In the United Kingdom Ministry of defence standard [4] it is concluded that presently the preferred system is the Rapid Reaction Spray System (RRSS), based on a series of trials during the 1980's. One can imagine that the state of the art in both sprinkler systems and ammunition sensitivity require a verification of these requirements, since nearly thirty years have passed and Navies are up for a next generation of warships.

Experimental set-up

For the test series that is presented in this paper a low pressure drencher system and WMS were chosen in favour of a high pressure WMS, mainly due to the possibility to use the ship's fire main, but also due to technical simplicity and lower cost. To evaluate the cooling effect of these systems on an ammunition item in a weapon stowage space, mock ups of an explosive storage magazine and ordnance dummy were built. The dummy was a geometrical object that in shape and mass resembled an authentic torpedo or missile. The dummy was placed in, or close to, a hydrocarbon fire and temperatures were measured on the exterior and on the interior of the steel tube. Temperatures and oxygen concentrations were monitored during the fire tests.

Test compartment

The fire test compartment was 4.8m × 4.8m × 2.4m (L × W × H) with an opening of 0.8m × 2.0m (W × H). Figure 1 shows a detailed drawing of the test compartment and the placement of the ordnance dummy and fuel pan positions 1 and 2. In Position 1, the fuel pan was situated directly beneath the ordnance dummy with a vertical distance of 50 mm between the steel shell and fuel surface. The dummy was positioned in the center of the room. In Position 2, the fuel pan was situated beside the ordnance dummy with a vertical distance of 50 mm between the steel shell and the fuel surface. There was a horizontal distance of 0 or 250 mm between the fuel pan and the ordnance dummy.

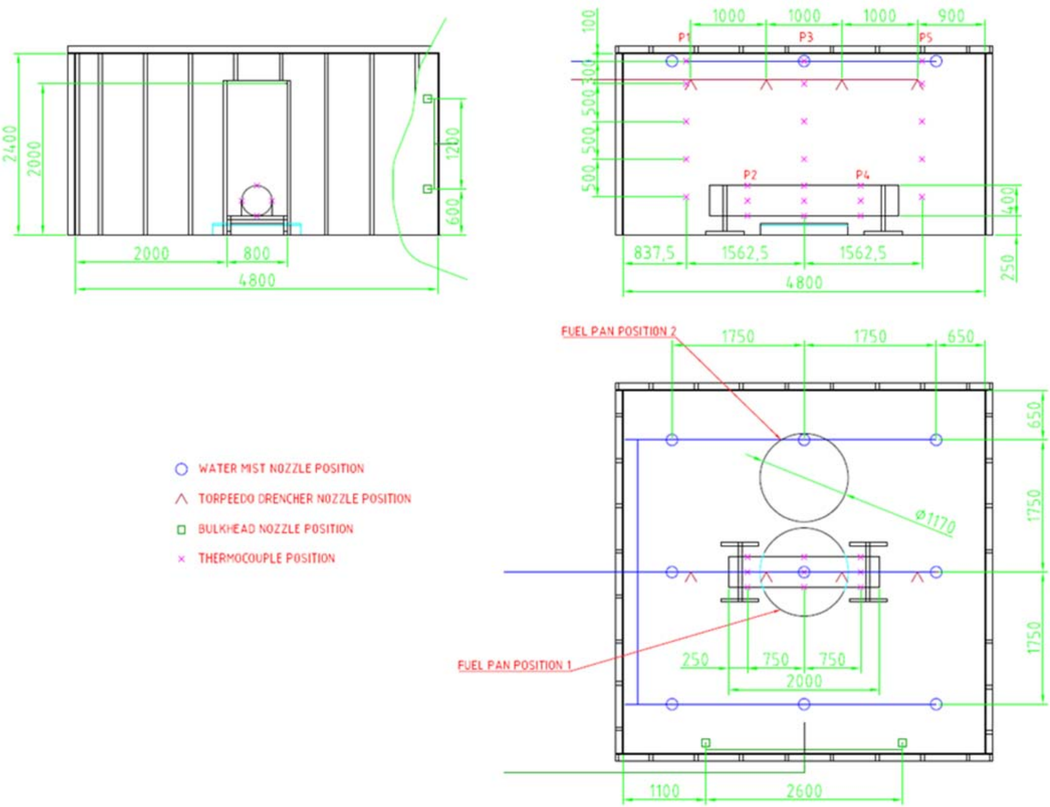

Figure 1 Test compartment

The test compartment walls had an outer framework of 45mm x 90mm wood studs. 12 mm Promatect boards (calcium silicate) were used to surface the walls of the room. The ceiling was constructed of steel beams, covered with Promatect boards and then with insulation boards.

Measurements and instrumentation

Figure 2 shows a side view of the test compartment. The five positions marked as P1-P5 in the view indicate the position of the measuring devices. All thermocouples were Type K.

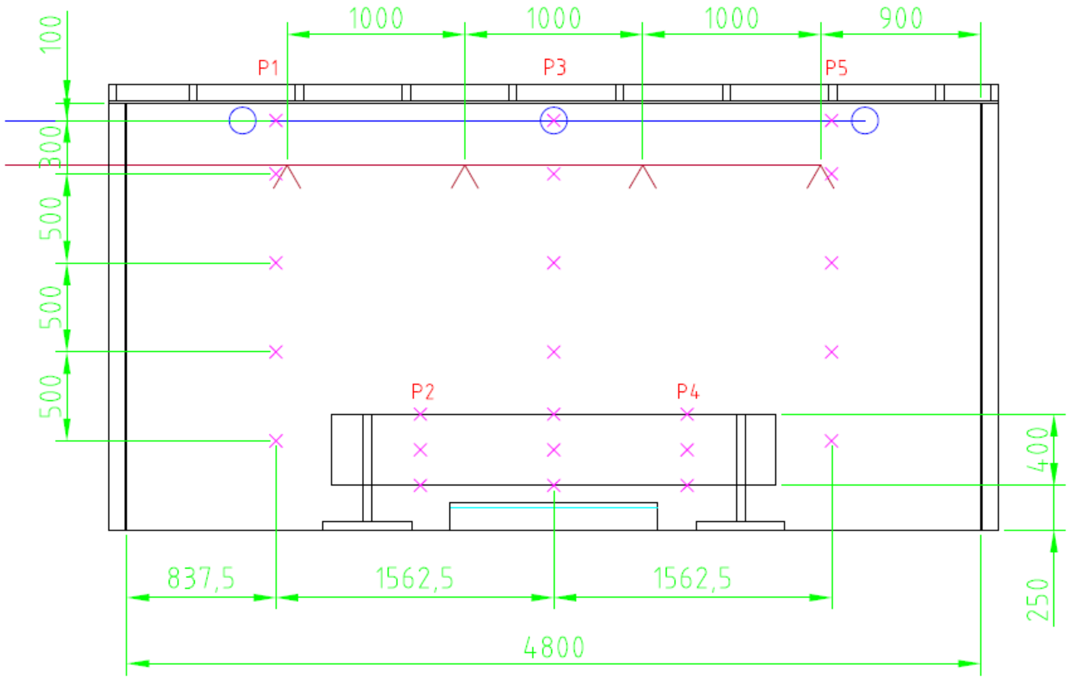

Figure 2 Side view of the test compartment, showing position P1-P5

In addition to the measuring devices in position P1-P5, the following measuring devices were used in the test series:

- 1 mm sheathed thermocouple placed above the fuel surface to indicate if burning was taking place.
- Two O_2 analyzers were placed close to P5 to monitor the oxygen level inside the compartment. The sampling pipes collected smoke at a distance of 900 mm and 1900 mm below the ceiling.
- A water pressure sensor was placed in the pipe system to monitor water pressure during each test.
- A water flow sensor was placed at the pump to monitor water flow (ℓ/min) during each test.

Measurements and film camera were started at reference time t=0 [s]. Ignition of the pool fire occurred at 60 s after that. The water mist / drencher system was activated at t=90 s. The table in the Results section lists the times for extinguishment using the same format. The pre-burning time was 30 seconds before the WMS and drencher were activated. This pre-burning time was selected based on 1) the free burning test indicated that the critical temperature was reached after approximately 40 seconds and 2) with a longer pre-burning time the fire is easier to extinguish with a water based extinguishment system so this would not represent worst case.

Fire source used in the test series

The fire source was a circular steel pan of Ø=1170 mm (A=1.08 m^2) with a 150 mm edge height that was filled with water and 16 litres of Shell city diesel. This resulted in a 15 mm thick layer of fuel on top of the water. There were two reasons for using a water bed under the fuel layer: to provide a flat, horizontal surface under the fuel and to achieve the desired freeboard. The pan was equipped with an overflow device to keep the freeboard constant at 25 mm. It prevented water from the fire protection system accumulating in the pan and causing it to overflow and spread the fuel on the surrounding floor surface. The overflow also prevents boil-over if the fuel or water starts to boil. Shell city diesel has a flashpoint of 74 °C. The maximum heat release rate of a fully exposed diesel pool fire with an area of 1.08 m^2 is 1.3 MW [5, 6]. To aid in starting the fire, approximately 0.5 litres of heptane was gently pored over the diesel surface and ignited with a gas burner.

Description of the dummy torpedo

One of the objectives of the tests is to assess the applicability of WMSs for ammunition stores. In order to design a representative of ordnance that can be stored in ammunition spaces we have studied missiles and torpedoes. Anti-ship missile generally have a fragmenting casing around the explosive, torpedoes just the body. When studying the heating effect of the explosive, the casing should be taken into account for the missiles and only the body thickness in case of the torpedo.

There are five parameters important for designing a mockup:

External material	Some torpedoes have an aluminium alloy body, some have an FRP shell, but commonly it is plain steel.
Diameter	Typical anti-ship missiles have diameters the order of 35 cm. Widely used torpedoes range from 35 to 50 cm in diameter.
Casing thickness	For the torpedoes numbers could not be found in literature, but experts state it is just a couple of mm. The worst case will be the lowest of these thicknesses as the explosive will start heating more quickly compared to the configuration with a large thickness. For anti-ship missiles casing thickness varies typically from 15 mm to 30 mm.
Length	This is not so terribly important as long as the top and bottom end don't heat too much and heat dissipation is mainly radially inward. Length must thus be significantly greater than the pan diameter.
Filling	The filling of the tube needs to be a good thermal representative of high explosive. Literature [7] suggests the use of glass beads with a polyurethane matrix. The thermal conductivity bandwidth of explosives range from 0.25 W/mK to 0.5 W/mK and depending on the mixing of glass beads/polyurethane it is possible to get within that range. However, dry sand has a thermal conductivity between 0.15 and 0.25 W/mK and is easier to use.

The dummy is shown in Figure 3. The steel cylinder is 200 cm long and 35 cm in diameter with a wall thickness of 3 mm and weighed 65 kg. The tube was filled with dry sand, making the total weight of the dummy 371 kg.

Figure 3 Dummy ordnance position directly over the fuel pan in Position 1.

Obstruction of the fuel pan

In some experiments obstructions were placed between the extinguishment system and the fire to mimic realistic situations with obscured fires. In tests where the fuel pan was in Position 1 the ordnance dummy acted as the obstruction. With the fuel pan in Position 2, several configurations of a Promatect sheet were used:

- Lined up with the ordnance dummy, i.e. no gap in between
- Spaced 250 mm away from the ordnance dummy
- Vertical obstruction (460 mm Promatect board) between ordnance dummy and fuel pan

Figure 4 Promatect calcium silica board obstruction used when the fuel pan was in Position 2, horizontal (left) and vertical (right).

Water mist system

A 10 bar low pressure water mist system was used for the fire suppression testing. The system is shown in Figure 1 and Figure 2 in blue lines. Figure 5 shows the system in the test compartment.

Incoming pipes were 1.5 inch in diameter and the three longitudinal pipes were 1 inch in diameter. Nine BETE TF8-170 nozzles were mounted with a spacing of 1.75 m (three on each longitudinal pipe). The nozzles had a K-factor of 5.93 ℓ/min/√bar.

Figure 5 Low pressure water mist system. Parts of two of the longitudinal pipes and four nozzles are shown. Close-up of the BETE TF8-170 nozzle is shown on the right.

A low pressure system has the advantage of being relatively cheap and simple (compared to high pressure systems). A low pressure system also provides the possibility of using the existing water sources on the vessel (fire main), possibly with the addition of small booster pumps, to supply the system. Uninterrupted water supply to the system may be ensured by built-in redundancy strategies in existing infrastructure like the fire main.

Geometries, ventilation conditions and pool fire sizes can significantly vary between ship types, operational conditions and fire scenarios. The extinguishment system used in this test series was selected based on the criteria that it should be able to quickly extinguish a non-obstructed diesel pool fire and suppress an obstructed diesel pool fire in a non-confined environment where oxygen depletion has no effect. This is representative for a small fire with a short pre-burning time in a large compartment.

The relatively high discharge density of the system selected for these tests was required to fulfill the criteria above.

Drencher system

A drencher system was used during the test series, in some tests in combination with the water mist system. In Figure 1 and Figure 2 the weapon drencher system is drawn in red lines. The system was mounted underneath the WMS centre line (see Figure 6). The system used 1 inch pipe and four LECHLER nozzles to deliver 32 ℓ/m^2, 10 ℓ /m^2 or 5 ℓ /m^2 per minute (measured discharge density over the ordnance dummy, the nominal discharge density was slightly higher). A LECHLER

460.928 nozzle was used for flows of 32 ℓ/m^2 per minute; a LECHLER 460.728 nozzle for flows of 10 ℓ/m^2 per minute; and a LECHLER 460.608 nozzle for flows of 5 ℓ/m^2 per minute.

Figure 6 Drencher system and LECHLER nozzles 460.928, 460.728 and 460.608 from top to bottom.

Experiments

The following configurations were tested:

- A WMS providing approximately 6 ℓ/m^2 per minute
- A dual system of water mist providing approximately 6 ℓ/m^2 per minute in conjunction with a drencher system providing 5 ℓ/m^2 per minute
- A drencher system providing 10 ℓ/m^2 per minute
- A drencher system providing 32 ℓ/m^2 per minute

Potential benefits of a dual system, water mist in conjunction with a drencher, are addressed in the Discussion section.

A list of the tests that were conducted in this investigation is shown in Table 1. The Table also includes a short description of the parameters used for each test.

Table 1 List of tests

Test	Goal	Drencher ℓ/m²/min	WMS ℓ/m²/min	Fuel pan position	Obstruction
14	Free-burning reference test	-	-	1	
15	WMS test		6	1	Torpedo
16	Drencher system test	32	-	1	Torpedo
17	Reduced drencher system test	10	-	1	Torpedo
18	Drencher in conjunction with WMS	5	6	1	Torpedo
19	Drencher in conjunction with WMS	5	6	2	Promatect lined up with torpedo
20	Drencher effectiveness on obstructed fire	32	-	2	Promatect lined up with torpedo
21	Drencher effectiveness on obstructed fire	32	-	2	Promatect spaced 250 mm from torpedo
22	Drencher effectiveness on open fire	32	-	2	No obstruction
23	Drencher effectiveness on obstructed fire	32	-	2	460 mm vertical Promatect sheet
24	Reduced drencher system test on open fire	10		2	No obstruction
25	Reduced drencher system test on obstructed fire	10		2	Promatect lined up with torpedo
26	Drencher in conjunction with WMS on obstructed fire	5	6	2	Promatect lined up with torpedo
27	Free-burning reference test	-	-	2	-

Performance criteria

Three criteria were used to evaluate the efficiency of the four fire suppression systems:

- The maximum outside surface temperature of the dummy torpedo must not exceed 200 °C.
- One minute after activation of the suppression system(s) the outside surface temperature must not exceed 150 °C.
- Temperature on the inside of the tube must not exceed 150 °C at any time.

These criteria are based on the assumption that 200 °C is the critical temperature for the fast heating phase and that 150 °C is the critical temperature for the slow heating phase of high explosives.

Extinguishment of the fire was not one of the performance criteria. We will get back to this in the *Discussion* section.

Results

A summary of the results of the fire tests is presented in Table 2.

Table 2 Summary of results

Test	Drencher ℓ/m²/min	WMS ℓ/m²/min	Fuel pan position	Obstruction	Peak surface T [°C]	Peak surface T > 1 min [°C]	Time to ext. [s]	O2 conc. at ext. [vol%]
14	-	-	1	-	550[1]	-	-	Data not available
15		6	1	Torpedo	203	203	—[2]	17.9[3]
16	32	-	1	Torpedo	128	39	24	20.2
17	10	-	1	Torpedo	138	89	45	19.9
18	5	6	1	Torpedo	148	92	53	19.7
19	5	6	2[4]	Promatect lined up with torpedo	150	81	—[2]	13.5[3]
20	32	-	2[4]	Promatect lined up with torpedo	113	35	27	20.3
21	32	-	2[5]	Promatect lined up with torpedo	77	30	7	20.5
22	32	-	2[5]	-	50	31	7	20.9
23	32	-	2[5]	Vertical 460 mm Prometect board	40	27	15	20.9
24	10	-	2[5]	-	65	38	160	19.2
25	10	-	2[4]	Promatect lined up with torpedo	162	82	—[2]	18.2[3]
26	5	6	2[4]	Promatect lined up with torpedo	151	105	—[2]	14.0[3]
27	-	-	2[4]	-	604[1]	-	-	15.5[3]

1 When the test was aborted, the temperature was still rising.

2 Did not extinguish

3 Lowest measured concentration.

4 The fuel pan was positioned edge to edge to the ordnance dummy

5 The fuel pan was positioned with a horizontal distance of 250 mm between ordnance dummy and fuel pan

In some of the tests the fire was not extinguished. The fire was however suppressed and under control, as demonstrated in the photos below.

Figure 7 Controlled fires in Test 15 (left) and Test 19 (right).

Maximum steel surface temperatures for selected tests are presented in Figure 8 and Figure 9.

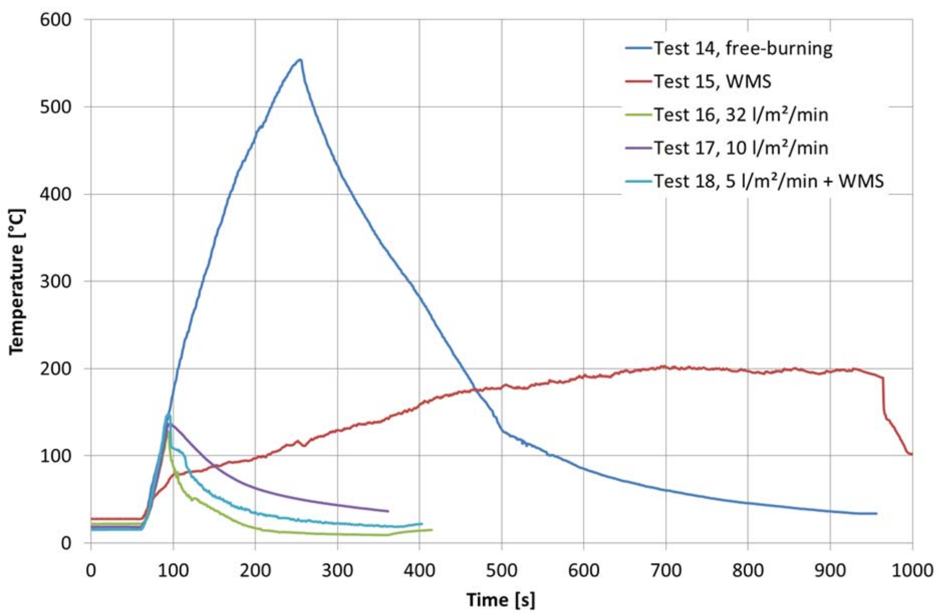

Figure 8 Dummy torpedo temperatures with fuel pan in Position 1 (under the ordnance dummy).

In Figure 8 the maximum ordnance dummy surface temperature profiles for a free burning fire (Test 14), and fires suppressed using the WMS (Test 15), and the drencher system using flows of 32 ℓ/m^2 per minute (Test 16), 10 ℓ/m^2 per minute (Test 17) and 5 ℓ/m^2 per minute with the WMS activated (Test 18) are shown. For these tests, the fuel pan was located in Position 1, directly beneath the ordnance dummy. The WMS did not extinguish the pan fire and the temperature of the exterior of the ordnance dummy continued to increase over the time that the fire burned and exceeded 200 ^{o}C after 700 seconds (12 minutes). The drencher system operated at 32 ℓ/m^2 per minute, at 10 ℓ /m^2 per minute and at 5 ℓ /m^2 per minute in conjunction with the WMS kept the temperature of the ordnance dummy below 200 ^{o}C and extinguished the fires. As the flow rate of the drencher system was decreased both the maximum temperature of the ordnance dummy and the peak temperature of the surface of the ordnance dummy one minute after activation of the system increased. When comparing the results of Test 17 and 18, it appears that the combined effect of drencher system and WMS is slightly more effective in decreasing the temperature than the drencher system alone. In both tests (combined) flow rates are comparable. As listed in Table 2, the peak temperature for Test 18 is slightly higher, but the rate of cooling of the surface of the ordnance dummy is more rapid. Note that all drencher configurations fulfil the performance requirements that the surface temperature not exceed 200 °C and that one minute after activation of the system the surface temperature be below 150 °C.

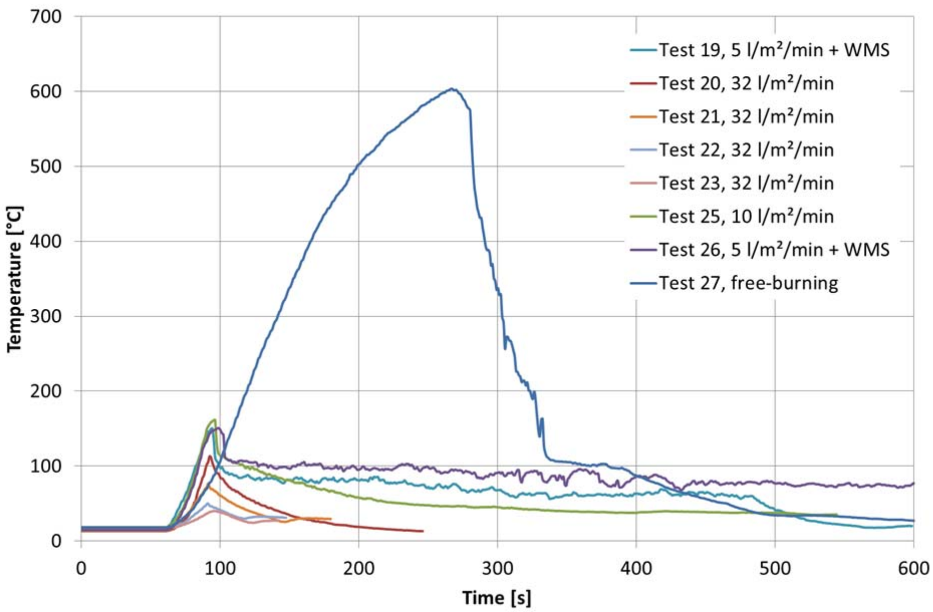

Figure 9 Dummy torpedo temperatures with fuel pan in Position 2 (beside the ordnance dummy).

In Figure 9, the maximum surface temperature profiles for a free burning fire (Test 27) and the drencher system using flows of 32 ℓ/m² per minute (Test 20), 10 ℓ/m² per minute (Test 25) and 5 ℓ/m² per minute with the WMS activated (Test 26) are shown. For these tests, the fuel pan was located in Position 2 (the ordnance dummy was located to the side of the fuel pan) and the fire was obstructed using a Promatect sheet. The drencher system operated at 32 ℓ/m² per minute, at 10 ℓ/m² per minute, and at 5 ℓ/m² per minute in conjunction with the WMS kept the temperature of the ordnance dummy below 200 ^{o}C. However, the drencher system at a flow rate of 10 ℓ/m² per minute and at 5 ℓ/m² per minute in conjunction with the WMS did not extinguish the pan fire. As the flow rate of the drencher system was decreased, the peak temperature of the surface of the ordnance dummy one minute after activation of the system increased. Test 19 and 26 are identical and the results show comparable temperature developments, indicating good reproducibility.

Again, it is interesting to compare Test 25 and 26, where water flow rates are comparable but use is made of a WMS in Test 26. A more or less steady state situation is reached earlier for Test 26 but that temperature is higher than that observed for the drencher system at 10 ℓ/m² per minute. This may be attributed to the higher local flow rate near the ordnance dummy. That is, the drencher system has a much smaller coverage area compared to the WMS. The increased amount of water delivered to the ordnance dummy surface would result in the observed temperature decrease.

Note that all drencher configurations fulfil the performance requirements that the surface temperature not exceed 200 °C and that one minute after activation of the system the surface temperature be below 150 °C.

When comparing Figure 8 and Figure 9 it can be seen that the steel surface temperature rises faster with the fuel pan in Position 2 than in Position 1. This result can be derived from the following simple equations. The total heat flux affecting a section of the steel surface can be written:

$$\dot{q}''_{tot} = \dot{q}''_{rad,inc} - \dot{q}''_{rad,emi} + \dot{q}''_{conv}$$

Where
$\dot{q}''_{rad,inc}$ is the incident radiant heat flux;
$\dot{q}''_{rad,emi}$ is the emitted radiation from the steel surface and;
$\dot{q}''_{conv}$ is the convective heat transfer

In these scenarios the incident radiant heat flux is expected to be a big part of the total heat flux. The incident radiation can be written:

$$\dot{q}''_{rad,inc} = \alpha \ \varepsilon \ \sigma \ T^4_{fire}$$

Where
α is the radiation absorption coefficient of the steel surface;
ε is the radiation emissivity coefficient of the flames;
σ is Stefan Boltzmann constant and
T_{fire} is the flame temperature

The radiation emissivity coefficient, ε, depends on the thickness of the flame (d) and the effective emission coefficient (K) accordingly [8]:

$$\varepsilon = 1 - e^{(-Kd)}$$

It is difficult to find reliable figures for K valid for diesel. For petrol K is 2.0 and for kerosene K is 2.6 [8]. Diesel can be assumed to be in the same region as kerosene.

In Figure 10 it can be seen that the thickness of the flame affecting the area where the peak surface temperature is measured is more than the pan diameter, say 1.2 m, with the fuel pan in Position 2 and significantly less, say 0.3 m, with the fuel pan in Position 1. Using K=2.6 and the estimated flame thicknesses above ε can be calculated to 0.96 with the fuel pan in Position 2 and 0.54 with the fuel pan in Position 1. Hence, the difference in flame thickness results in a significant difference in incident radiant heat flux.

Figure 10 Difference in effective flame thickness with the two different fuel pan positions

So far we have only considered outside surface temperatures of the ordnance dummy. The third performance criterion concerns the inside of the cylinder, which gives an indication of the actual temperature of the high explosive. Figure 11 shows plots of the inside and outside temperatures of the ordnance dummy for Test 14 through 18 with the fuel pan in Position 1.

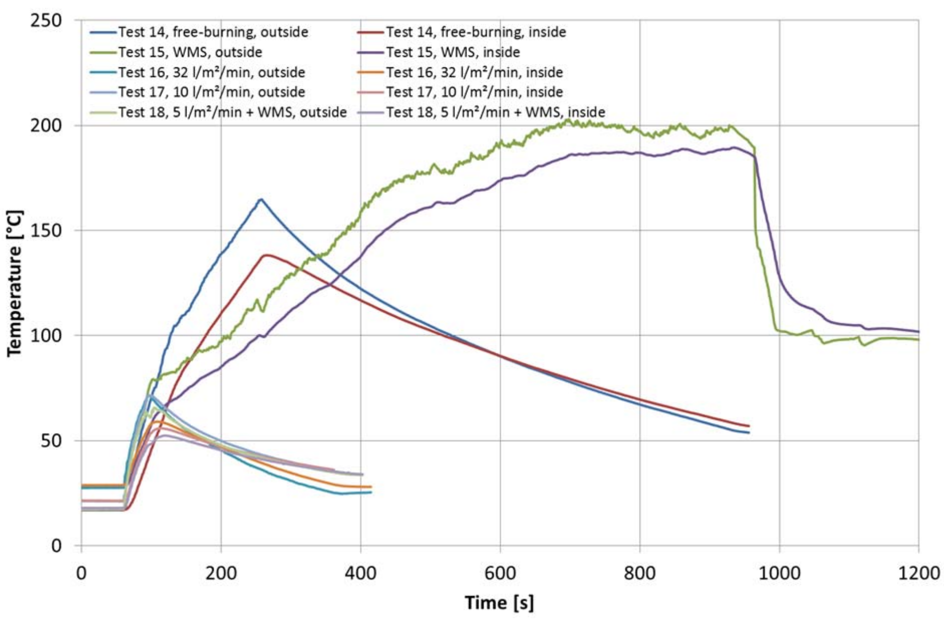

Figure 11 Dummy torpedo bottom side temperatures, outside and inside of the steel with fuel pan in Position 1

The temperatures plotted in Figure 11 are different from the maximum temperatures measured for the ordnance dummy. This has to do with the effective flame thickness. The thermocouple inside the cylinder was located in the bottom. At this position the flame thickness is only 50 mm. Apart from this thin flame the bottom surface of the torpedo only 'sees' the cold fuel surface. So, even if the gas temperature in the flame is high the incident radiant heat flux is low and therefore the total heat flux in this position is low.

From Figure 11 the difference between inside and outside temperature is in the order of 20-30 °C. We can use this knowledge to estimate inside temperatures at those positions where the peak temperatures were found, see Figure 8 and Figure 9. The difference between inside and outside temperature is bigger when the temperature rise is fast and smaller when the temperature rise is slow, therefore it would be conservative to assume the same temperature difference in positions with higher temperatures. When we assume a gradient of 20 °C across the thickness of the cylinder, this means that the outside temperature must not exceed 170 °C (this results in 150 °C on the inside). All drencher and drencher/WMS combinations fulfil this requirement. The WMS system at 6 ℓ/m² per minute flow rate does not.

As can be seen from Figure 9, the peak temperature measured on the cylinder registered 600 °C when the fuel pan was in Position 2 and no suppression system was used. The inside temperature at that position on the cylinder would have been in the order of 580 °C, well above the performance criterion. The high explosive inside the ordnance would have gone into an irreversible reaction leading to explosion or deflagration.

Oxygen concentrations at the height of the fire source were also measured. The development over time is given in Figure 12 and Figure 13 for fuel pan positions 1 and 2 respectively.

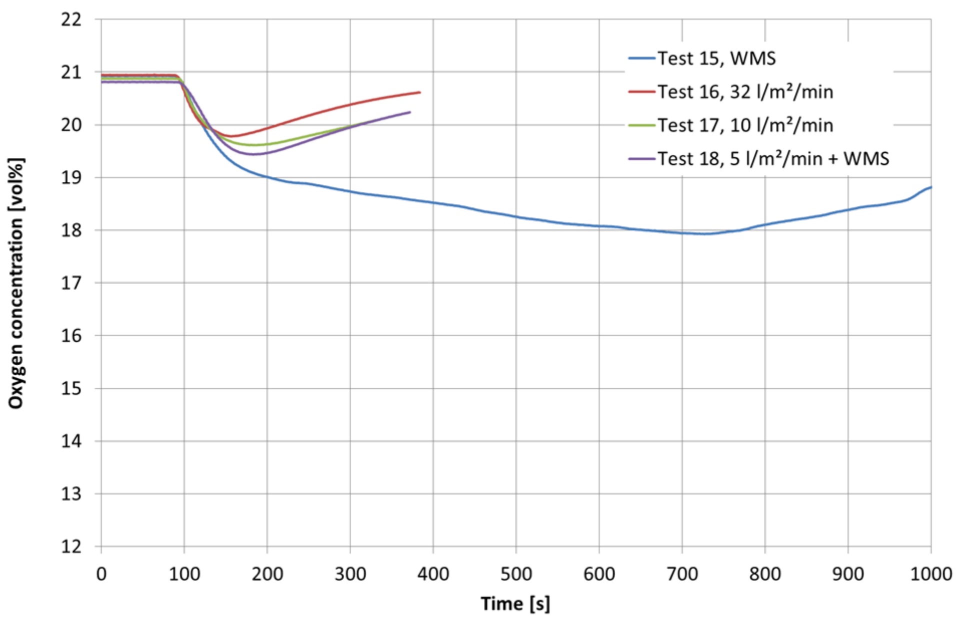

Figure 12 Oxygen concentration 0.5 meter over the floor, fuel pan in Position 1

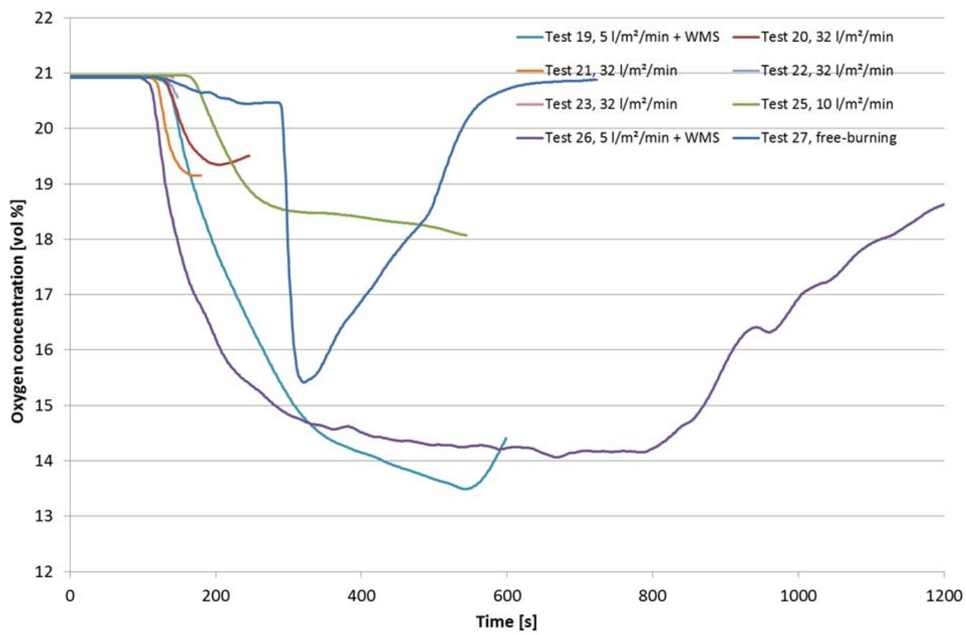

Figure 13 Oxygen concentration 0.5 meter over the floor, fuel pan in Position 2

It is interesting to see that when using a drencher system in conjunction with a WMS (Test 19 and 26), the oxygen concentration continues to decrease after the point where, when using the drencher system alone (Test 25), the concentration did not decrease below 18 %. This can be explained from the fact that when using the WMS more water is evaporated and oxygen is depleted inside the room. Expanding gases (including vaporized water) creates over pressure and reduces the amount of air that can enter the compartment. In the tests with the drencher the same effect can be seen initially but not after "steady state". The drencher system mainly has an effect in two dimensions on the surface of the ordnance and on the pool fire surface. The rapid decrease of the free burning Test 27 near 300 seconds has to do with extinction of the fire using the WMS.

While the oxygen levels in Test 19 and Test 26 dropped well below 15%, the fire did not extinguish. Commonly the range of 14-15% is regarded as insufficient to support a fire. Visual observations from the tests support the estimate that full fire extinction was very near. It is however not obvious that a higher flow rate of the WMS would result in more water evaporation and the oxygen level would be further reduced. The fire would probably be extinguished if the pre-burning time was longer or if the system is reconfigured to achieve improved cooling of flames and fuel (smaller droplets might have this effect, also more strategic nozzle positions).

Discussion

As stated in the section *Performance criteria* extinguishment of the fire was not one of the criteria considered necessary for prevention of damage escalation from exploding ordnance. This may be a somewhat uncomfortable thought. Extinguishment can be a performance criterion for well-defined scenarios where ventilation conditions, fire size, obstructions, pre-burning time and geometries are fixed. Then it is possible to design a system that will extinguish the fire. However, if conditions are changed from the test-scenario (additional obstructions, larger ventilation openings, shorter pre-burning time, smaller fire etc.) it is not obvious that the approved system will extinguish this fire. If the oxygen supply is not limited it is always possible to obstruct a fire so a water extinguishing system can't extinguish it. The scenario with a 100% obstructed fire in Position 2 is designed as a highly unlikely worst case scenario where we wanted to see that the system was capable of cooling the ordnance dummy although the fire under the obstruction was still burning. This scenario represents a situation with at least four failures: fuel is spilled, fuel is ignited, the door is not closed and a misplaced obstruction blocks the water from the suppression system. Still the system was able to keep the ordnance under the critical temperature. If any of these failures were removed the fire would be extinguished or avoided. The approved systems always extinguished the fire when the ordnance dummy is the only obstruction.

The benefit of the use of dual water mist/drencher system might be for fire scenarios where a WMS has obvious advantages, such as very large fires relative to the compartment size. Whether a dual system is beneficial depends on the specific situation and must be addressed on a case to case basis. Another positive aspect of a dual system is increased survivability due to its inherent redundancy. This is one of the research topics the FiST project will be addressing.

In 2008 TNO performed experiments proving the explosion suppressing effect of water mist [9]. A bare charge of 23 kg high explosive was detonated inside a bunker where a water mist system was installed. Results from a reference test without water mist present in the bunker were compared with tests where water mist was dispersed prior to the explosion. It showed that the presence of water mist could reduce the pressure effects from the explosion by 30-40%. Temperatures in the compartment shortly after the explosion were reduced from 600 °C to 100 °C when a WMS was used. The explosion reducing effect is a strong argument for the use of a dual system in ammunition storage spaces. The TNO research showed that the impact on system design in order to get the measured reduction in explosion effects is manageable. Similar research was done in the US [10].

Although potential benefits of a dual water mist-drencher system have been highlighted, the higher cost and increased complexity of dual systems may limit their installation on naval vessels.

It is emphasized that the results presented in this paper are only valid for the experimental conditions used in this test series. Factors such as time to activation of the suppression system, the type of fuel, compartment properties, other stowage and ventilation can have a large effect on the effectiveness of the system and its ability to keep the temperature of the stowed ordnance below the critical temperature.

Conclusion

Fire suppression system configurations with drencher flows well below 32 ℓ/m² per minute were sufficient to fulfil the performance requirements. At a drencher flow rate of 10 ℓ/m² per minute, the requirements were met, although the fire was not extinguished in all scenarios. Extinguishment of the fire was not considered a performance criterion as ordnance in a burning compartment may not react, as long as the temperature of the ordnance can be kept below that required for cook-off.

Results for a 5 ℓ/m² per minute drencher system in conjunction with a 6 ℓ/m² per minute WMS were comparable with those for a 10 ℓ/m² per minute drencher system.

The WMS at 6 ℓ/m² per minute is insufficient to fulfil the performance requirements. The peak surface temperature of the ordnance dummy exceeds 200 °C. It would be interesting to compare the effectiveness of a WMS at 10 ℓ/m² per minute with the drencher at 10 ℓ/m² per minute. We hope to address this in upcoming tests in the FiST project.

The results of this test programme contribute to defining the way ahead in the process of evaluation of national requirements for fixed fire fighting systems for magazines and review of the prescribed 32 ℓ/m² per minute flow rate. Through papers like this and presentations for stakeholders we will try to initiate a discussion on protection of ammunition storage spaces and aid in the new technical requirements to be specified.

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