REPORT

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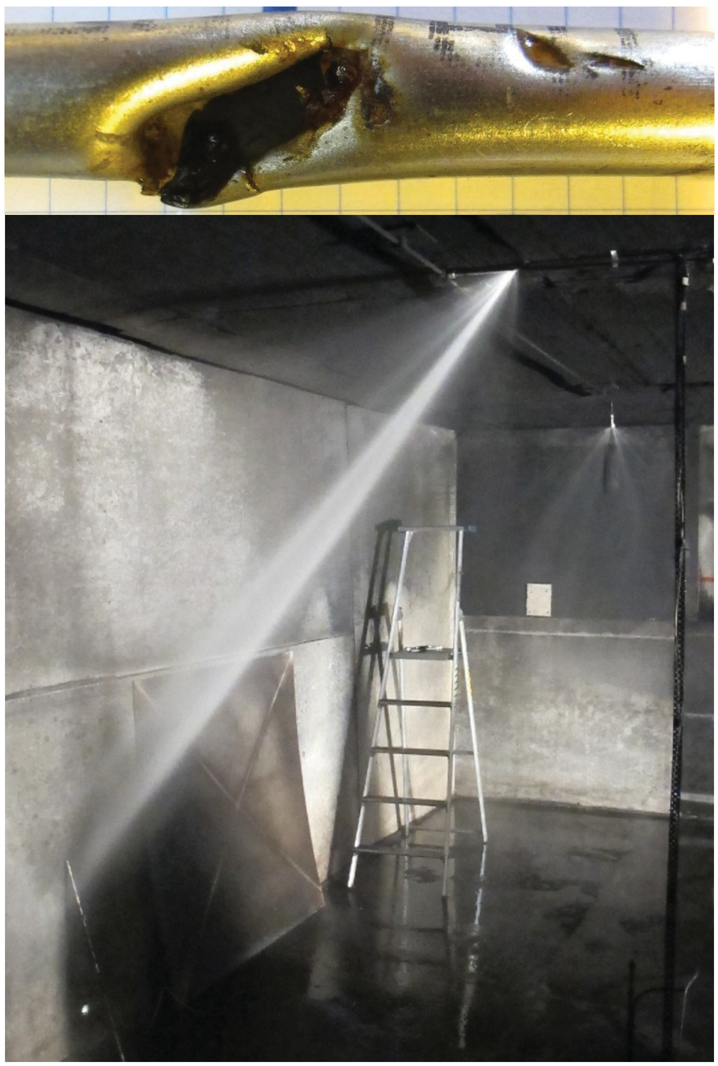
Tests of fire suppression effectiveness of damaged water mist systems



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Abstract

The FiST-project “New Technologies for Fire Suppression On Board Naval Craft”, is a tri-lateral (Canada, the Netherlands, Sweden) research project under the CAN/NLD/SWE Cooperative Science and Technology MOU. The focus of the project is active firefighting on navy ships. One important task is the investigation and identification of methods to introduce redundancy in active firefighting on naval vessels.

In this report, the results of a number of full scale fire tests run at the SP Technical Research Institute of Sweden, in January - February 2013, are presented. The objectives of the tests were to evaluate the residual capacity of a damaged high pressure water mist system and investigate how redundancies might be introduced or effect fire suppression systems.

In addition to these tests, the effectiveness of a high pressure water mist system was also evaluated as an alternative to the deluge system requirements (NSC (24 mm/min) or Class DNV (32 mm/min)) for weapon storage fire protection.

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Introduction

An series of full scale fire suppression tests were run at SP Technical Research Institute of Sweden during late January and February 2013. Two series of tests were completed.

The goal of the first series of tests was to evaluate residual firefighting capacity in a damaged high pressure water mist system. System damage was simulated in two ways; first by reducing the system water pressure in a physically intact water mist system and secondly by installing damaged sections of pipe in the system. The resulting leakage led to a reduction in system pressure depending on the size of the hole(s) in the damaged pipe and the capacity of the pump.

In the second series of tests the use of a high pressure water mist system as an alternative to the deluge spray systems requirements for shipboard ammunition storage spaces (e.g., found in the Naval Ship Code (NSC) or in Class DNV regulations) was investigated. This investigation used a “torpedo dummy”, a geometrical object that in shape and mass resembled a torpedo. The dummy was placed in, or close to, the hydrocarbon fire and temperatures were measured.

A possible redundancy solution for active firefighting on board navy ships was also considered in the testing. The redundancy investigated was one where a two pump system is used to supply water to the nozzles in a space. Each pump supplies half the nozzles. If one pump is destroyed, each compartment still has 50 % of the firefighting system left.

All tests were conducted in a ~135 m^3 enclosure with an 0.8 m x 2.0 m door opening using high pressure water mist nozzles (202-2,09-O) that complied with MSC/Circ.1165. A hydrocarbon fire was used as the design fire. Such a fire could result from a weapon impact that resulted in leakage and ignition of combustible fluids used on the ship. A water mist system approved according to MSC/Circ.1165 is generally optimized to suppress and extinguish fires in a large space with available ventilation openings. This implies that such a system can be expected to perform well in a situation where decks and bulkheads are partially damaged due to an explosion.

An important part of the FiST project is also to collect data to be used in later analyses. As part of this water mist droplet size distribution data as a function of pressure was collected using an optical based laser measurement technique called Global Sizing Velocimetry (GSV).

Test compartment

The test compartment was 7.5 × 7.5 × 2.4m (L × W × H) with an opening of 0.8 × 2.0 m (W × H). The walls of the test compartment had an outer framework of 45mm x 90mm wood studs covered with Promatect sheets (calcium silicate). The ceiling was constructed of steel beams covered with Promatect sheets that were lined with insulation boards.

Figure 1 shows an overview of set up of the test compartment for the damaged water mist system tests and Figure 2 shows an overview of the set up for the torpedo dummy tests.

When equipment and measuring devices are described with compass directions, south is towards the door, as shown in Figure 1.

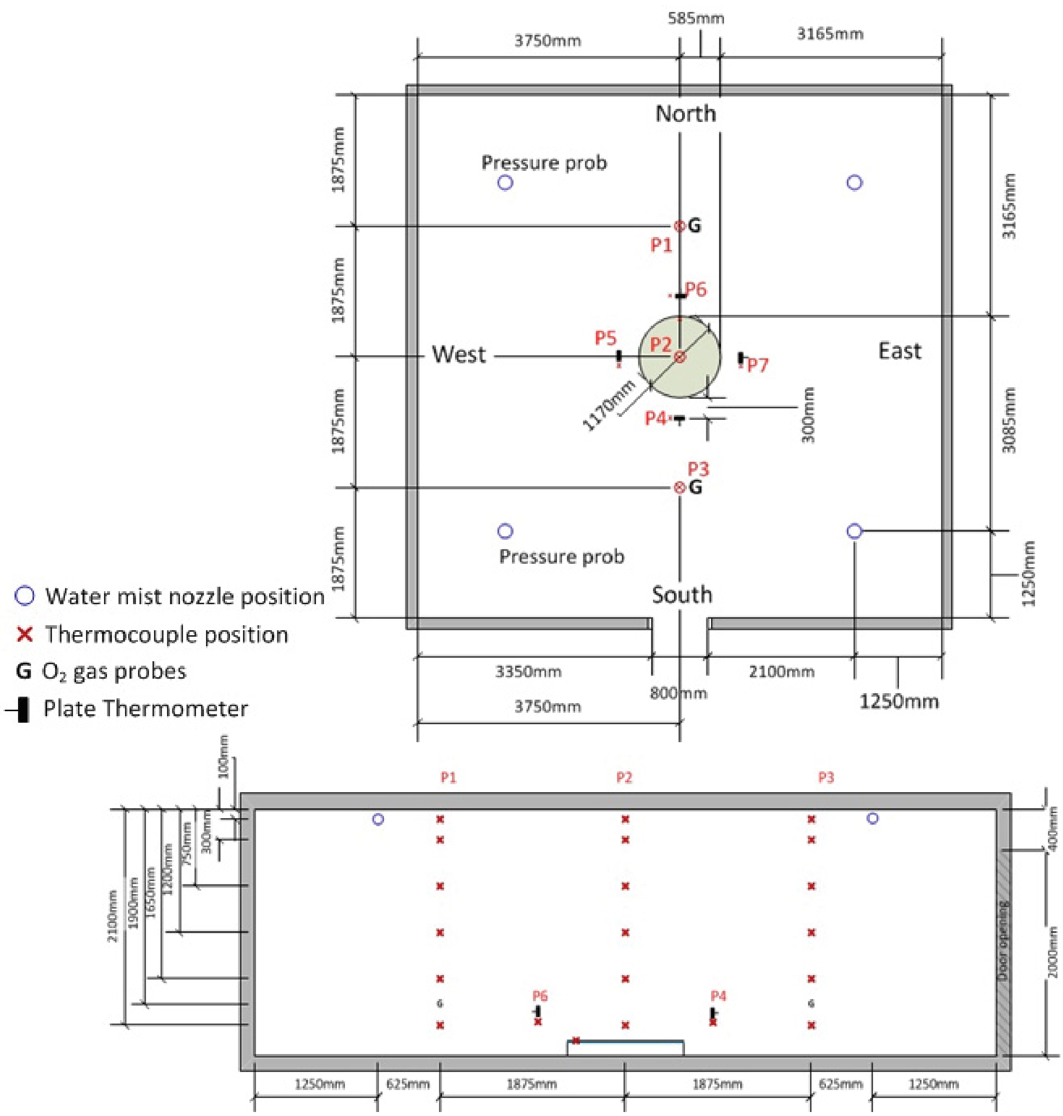


Figure 1. Schematic of test compartment used for the damaged water mist tests.

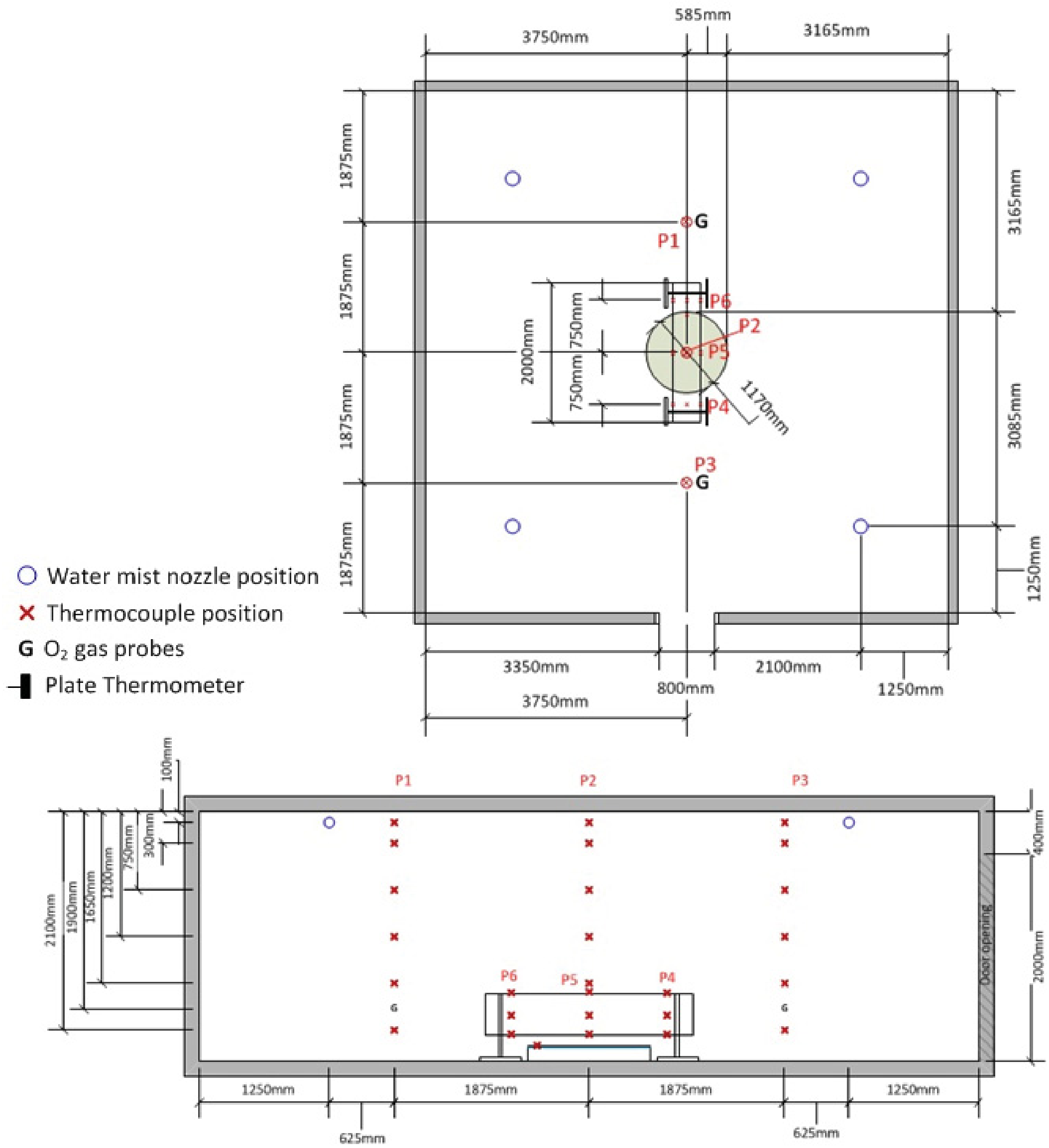


Figure 2. Schematic of test compartment used for the torpedo dummy tests.

Instrumentation

The test compartment for the damaged water mist system testing was equipped with thermocouple trees (P1, P2 and P3), oxygen measuring probes (G) and plate thermometers (P4, P5, P6 and P7) . The positions of the thermocouple trees and oxygen measuring probes were the same for the damaged water mist system tests and the torpedo dummy tests and are shown in Figure 1 and Figure 2. During the torpedo dummy tests the plate thermometers were removed from the test space. However, the torpedo was rigged with thermocouples to monitor the surface temperature of the torpedo at positions P3, P4 and P5 The instrumentation is described in detail in the following two sub sections.

Instrumentation - damaged water mist systems tests

P1: A thermocouple tree with 0.5 mm type K thermocouples. The thermocouples were positioned 100, 300,750, 1200, 1650 and 2100 mm below the ceiling. An oxygen probe (G) was positioned 500 mm from the floor.

P2: A thermocouple tree with 0.5 mm type K thermocouples. The thermocouples were positioned 100, 300,7500, 1200, 1650 and 2100 mm below the ceiling.

P3: A thermocouple tree with 0.5 mm type K thermocouples. The thermocouples were positioned 100, 300,7500, 1200, 1650 and 2100 mm below the ceiling. An oxygen probe (G) was positioned 500 mm from the floor.

P4-P7: Plate thermometers were placed around the pool fire at a horizontal distance of 300 mm and a vertical distance of 500 mm from the fuel surface.

In addition to the measuring devices in positions P1-P7, the following measuring devices were used in the test series:

- Water pressure sensors were placed on the two water mist nozzles furthest from the system pump. These nozzles were marked with “Pressure probe” in Figure 1.
- A water flow sensor was placed at the water pump to monitor water flow (l/min) during each test.
- A shielded 1 mm thermocouple was placed just above the fuel surface to register time of extinguishment

Instrumentation - torpedo dummy tests

P1-P3: See the description of instrumentation used in the damaged water mist system tests.

P4-P6: Four 0.5 mm type K thermocouples were welded onto the outside of the dummy torpedo at locations P4-P6. Viewed from the door opening the thermocouples were placed on the top of the tube (12 o´clock), on the right side of the tube (3 o´clock), underneath the tube (6 o´clock) and on the left side of the tube (9 o´clock).

Additional measuring devices were:

- Water pressure sensors, as described for the instrumentation used in the damaged water mist tests

- Water flow sensor, as described for the instrumentation used in the damaged water mist tests
- A shielded 1 mm thermocouple above fuel surface.

Fire scenarios

A diesel pool fire was used as the design fire scenario.

Test equipment

Fuel pan

The fuel pan was a circular steel pan (Ø=1170 mm (A=1.08 m^2) and 150 mm edge height). It was filled with water and 16 l of fuel was added for each test. This resulted in a 15 mm thick layer of fuel on top of the water. The water bed under the fuel layer was used for two reasons; to provide a flat, horizontal surface under the fuel and to achieve the desired freeboard in the pan. The pan was equipped with an overflow device to keep the freeboard constant at 25 mm. This prevented water from the fire protection system accumulating in the pan and causing it to overflow and spread the fuel on the floor. Previous tests at SP Fire Technology indicated that the maximum heat release rate of a fully exposed diesel pool fire, with A=1.08 m^2, is approximately 1.3 MW.

Fuel

Diesel fuel (Shell city diesel) with a flashpoint of ~ 74°C was used for the fire tests. To aid in starting the fire, approximately 0.5 l of heptane was gently pored over the diesel surface and ignited with a gas burner. The fire was allowed to burn for 30 seconds prior to activation of the fire suppression systems.

Obstructions

The fires were run without obstruction , with 100% obstruction, and with 50% obstruction. To achieve 100 % obstruction of the circular fuel pan, a Promatect sheet was placed 250 mm above the fuel surface as shown in Figure 3.

Figure 3 Experimental set-up for the 100% obstructed fuel pan fire.

To achieve a 50 % obstruction of the circular fuel pan, six spiro pipes (100 mm outside diameter) were placed 250 mm above the fuel surface as shown in Figure 4.

Figure 4 Experimental set-up for the 50% obstructed fuel pan fire.

Water mist system

A high pressure (100 bar) water mist system with Ultrafog nozzles (202-2,09-O), complying with MSC/Circ.1165, was used for this test series.

High pressure water mist system

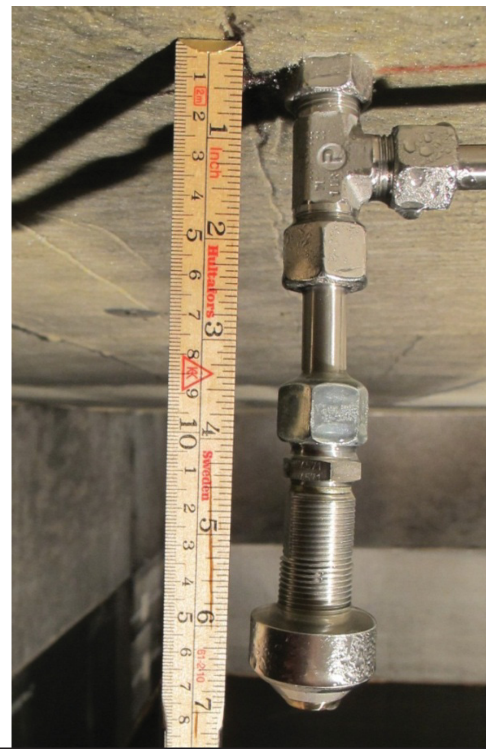
Nozzles: UltraFog 202-2,09-O

K-factor: 2.09 l/min*bar$^{1/2}$

Pressure: 100 bar

Nozzles - MSC/Circ.1165 certification requirements

- Spacing: maximum 5 m
- Maximum distance from bulkhead: 2.5 m
- Maximum ceiling height: 10.1 m



Four nozzles were installed in the compartment as required by the certificate (MSC/Circ.1165). The nozzles were installed with the maximum allowed spacing, according to the certificate, and not in a way that was optimized for the compartment. The same nozzle configuration would be acceptable for a significantly larger compartment; up to 10 m x 10 m x 10 m (L x W x H).

The actual nozzle configuration in this test series results in a higher water discharge density than would be the case if the compartment had the maximum allowed dimensions according to the certificate. The discharge rate per m^2 and per m^3 of the installed system are compared to those for a space with the maximum area and volume in **Error! Not a valid bookmark self-reference.**.

Table 1 – comparison of water flow per unit floor area and room volume.

	Discharge per floor area [l/m^2*min]	**Discharge per room volume [l/m^3*min]**
Installed configuration	1.5	0.6
Largest allowed compartment	0.8	0.08

A piston pump with a capacity of supplying slightly over 100 l/min at up to 120 bar was used for the test series. A mechanical pressure regulator was used to set the pressure.

Performance indicators

The average compartment temperature was used as a measure of how efficiently the water mist system cooled gases in the compartment. It was calculated as the average of the temperature from all the thermocouples at P1 and P3 in Figure 1. In the result Tables, the time to reduce the average gas temperature in the test space to less than 80°C is listed.

The time to extinguishment was a second performance indicator for a fire suppression system.

Average plate thermometer (PT) temperature is an indication on how well the system protects a target. A PT is affected by incident radiation to a much higher extent than a 0.5 mm thermocouple and is a good way to measure thermal exposure of an object close to the fire.

The ability a water mist system to mix water droplets, water vapour and combustion products within a compartment is a measure of how well the system will perform in fire scenarios or for geometries other than those used in the fire tests. In order to determine and quantify the temperature uniformity arising from the use of the tested systems, a Temperature Uniformity Factor (TUF) was used [1]. It is based on equations (2) to (4), which are the equations used for S*tandard deviation*, *Variance* and *Mean value*. The Temperature Uniformity Factor is measure of the temperature uniformity inside the test compartment as a function of time. The lower the value, the more uniform the temperature.

$$TUF(t) = \sqrt{Var(T_1 ... T_N)} \quad (2)$$

$$Var(T_1 ... T_N) = \frac{1}{N-1}\sum_{j=1}^{N}(T_j(t) - \overline{T}(t))^2 \quad (3)$$

$$\overline{T}(t) = \frac{1}{N}\sum_{j=1}^{N} T_j \quad (4)$$

where,

$TUF(t)$ = Temperature Uniformity Factor at time t (°C)

$T_k(t)$ = Temperature measured at thermocouple *k* at time t (°C)

$\overline{T}(t)$ = The average temperature at time t (°C)

The following performance criteria were used to evaluate the water mist systems performance for weapon protection.

- Maximum surface temperature of dummy torpedo must not exceed 200 °C.
- 60 seconds after activation of the system, the maximum surface temperature of the dummy torpedo must not exceed 150 °C.

This was based on the assumption that 200 °C is the critical temperature for a fast heating phase and that 150 °C is the critical temperature for a slow heating phase of the torpedo with respect to cook off of ordnance in afire. The criteria were assumed to be conservative since the surface temperature was measured. In a real scenario the critical temperature is the temperature of the high explosive inside the steel shell.

Test program

The tests carried out in this study are listed in Table 2.

Table 2 – Test program

Test no.	Description
1	WMS* at 100% of operating pressure, non-obstructed pool fire
2	WMS at 75% of operating pressure, non-obstructed pool fire
3	WMS at 50% of operating pressure, non-obstructed pool fire
4	WMS at 25% of operating pressure, non-obstructed pool fire
5	WMS at 5 bar (fire-main pressure), non-obstructed pool fire
6	WMS at 100% of operating pressure, 100 % obstructed pool fire
7	WMS at 75% of operating pressure, 100 %obstructed pool fire
8	WMS at 50% of operating pressure, 100 % obstructed pool fire
17	WMS at 25% of operating pressure, 100 %obstructed pool fire
9	WMS at 100% of operating pressure, 50 % obstructed pool fire
10	WMS at 75% of operating pressure, 50 % obstructed pool fire
11	WMS at 50% of operating pressure, 50 % obstructed pool fire
12	WMS at 25% of operating pressure, 50 %obstructed pool fire
28	WMS at 5% of operating pressure, 50 %obstructed pool fire
13	WMS at 100% of operating pressure, 50 % of nozzles
14	WMS at 50% of operating pressure, 50 % of nozzles
15	Torpedo test with Ultrafog system, 30 s pre-burning time, position 1
16	Torpedo test with Ultrafog system, 30 s pre-burning time, position 2
18	WMS at 100 %, Damage scenario 1 (Punctured pipe 1)
19	WMS at 100 %, Damage scenario 2 (Punctured pipe 2)
20	WMS at 100 %, Damage scenario 3 (Punctured pipe 4)
21	W WMS at 100 %, Damage scenario 4 (Punctured pipe 7)
22	WMS at 100 %, Damage scenario 5 (Punctured pipe 8)
23	WMS at 100 %, Damage scenario 6 (Punctured pipe 3)
24	WMS at 100 %, Damage scenario 7 (Punctured pipe 5)
25	WMS at 100 %, Damage scenario 8 (Punctured pipe 6)
26	WMS at 100 %, Damage scenario 9 (Punctured pipe 5 and 4)
27	WMS at 100 %, Damage scenario 10 (Punctured pipe 4 (changed location)
29	Free burning test

- WMS - Water mist system

Results

Reduced operating pressure

Many types of damage, such as leakage, buckled pipes, and malfunctioning pump(s), can result in reduced operating pressure at the nozzles in a water mist system.

To evaluate the performance of the high pressure water mist system at reduced operating pressure, the pressure in the system was varied between 5% and 100% of normal operating pressure. The efficacy of the water mist system was evaluated on pool fires with no obstruction, 50% obstruction and 100% obstruction.

The diesel pool fire was allowed to burn for 30 seconds prior to the activation of the system. Average gas temperatures in the compartment were calculated as an average of the temperatures of thermocouples in the thermocouple trees at P1 and P3 in Figure 1. The results are presented in Figure 5, Figure 9 and Figure 13.

Average plate thermometer temperatures were calculated by averaging the temperatures of the four plate thermocouples in positions P4, P5, P6, and P7 in Figure 1 and are presented in Figure 8, Figure 12 and

Figure 16.

Oxygen concentrations were calculated by averaging the output of two oxygen concentration analysers. The sampling locations for the analysers are marked G in Figure 1. The results are presented in Figure 6, Figure 10 and Figure 14. The sampled gas was dried before it was analysed, hence the water vapour content is not shown in the oxygen concentration versus time plots.

A summary of the results of the tests is presented in Table 3.

Table 3 – Summary of results for tests with reduced operating pressures.

Test no	Description of setup	Water discharge rate into test space [l/min]	Time (after activation) to temp <80°C [min:s]	Time (after activation) to temp <60°C [min:s]	Time (after activation) to extinguishment [min:s]	O_2 concentration at extinguishment [vol%]
1	100 % pressure No obstruction	83.6	1:57	6:01	Did not extinguish	- (lowest measured value: 14.5)
2	75 % pressure No obstruction	72.4	2:22	7:46	Did not extinguish	- (lowest measured value: 14.3)
3	50 % pressure No obstruction	59.1	2:27	2:56	2:45	15.1 (lowest measured value: 15.0)
4	25 % pressure No obstruction	41.8	3:46	4:19	4:00	15.3 (lowest measured value: 15.2)
5	5 bar No obstruction	18.7	-*	-*	Did not extinguish	- (lowest measured value: 16.2)
6	100 % pressure 100 % obstr.	83.6	3:08	3:44	3:30	15.7 (lowest measured value: 15.3)
8	75 % pressure 100 % obstr.	72.4	4:16	4:41	4:20	15.7 (lowest measured value: 15.4)
7	50 % pressure 100 % obstr.	59.1	2:50	3:14	2:58	16.9 (lowest measured value: 15.7)
17	25 % pressure 100 % obstr.	41.8	5:53	7:00	5:49	14.5 (lowest measured value: 14.5)
9	100 % pressure 50 % obstr.	83.6	2:38	4:40	Did not extinguish	- (lowest measured value: 14.0)
10	75 % pressure 50 % obstr.	72.4	2:37	8:55	Did not extinguish	- (lowest measured value: 14.7)**
11	50 % pressure 50 % obstr.	59.1	2:43	3:09	2:50	15.3 (lowest measured value: 14.7)
12	25 % pressure 50 % obstr.	41.8	3:41	5:08	3:20	15.9 (lowest measured value: 15.7)
28	5 bar 50 % obstr.	18.7	-*	-*	Did not extinguish	- (lowest measured value: 17.4)

*Temperature did not go below critical temperature before the test was cancelled or the fuel was consumed.
**Problem with O_2 measurement

Non-obstructed fire

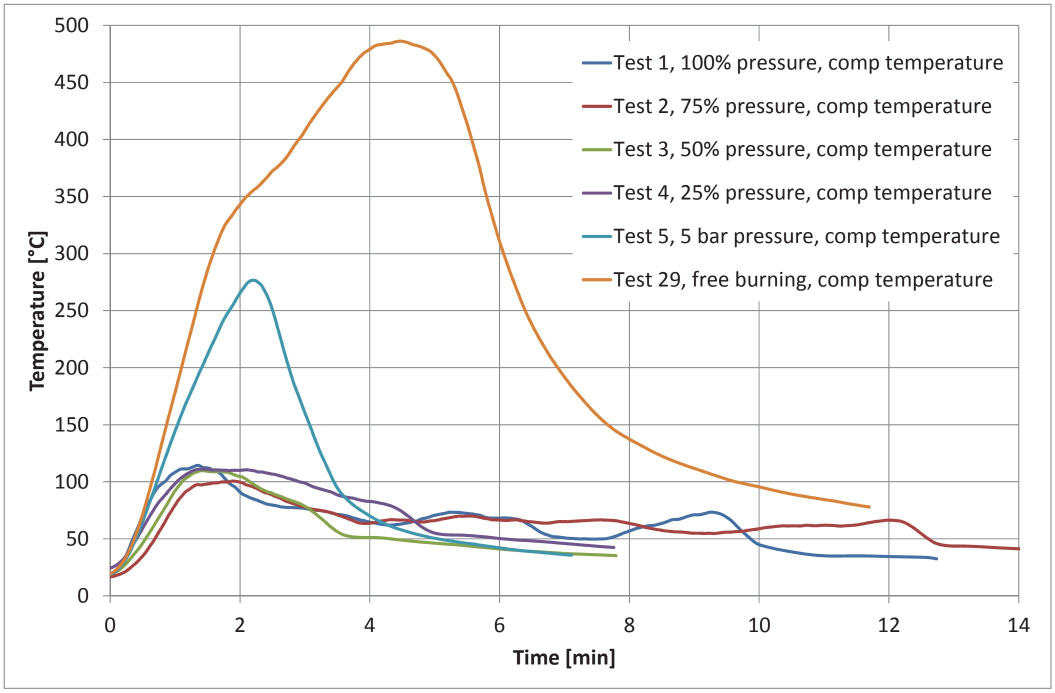


Figure 5 – Average compartment temperatures versus time for non-obstructed pool fire water mist suppression tests.

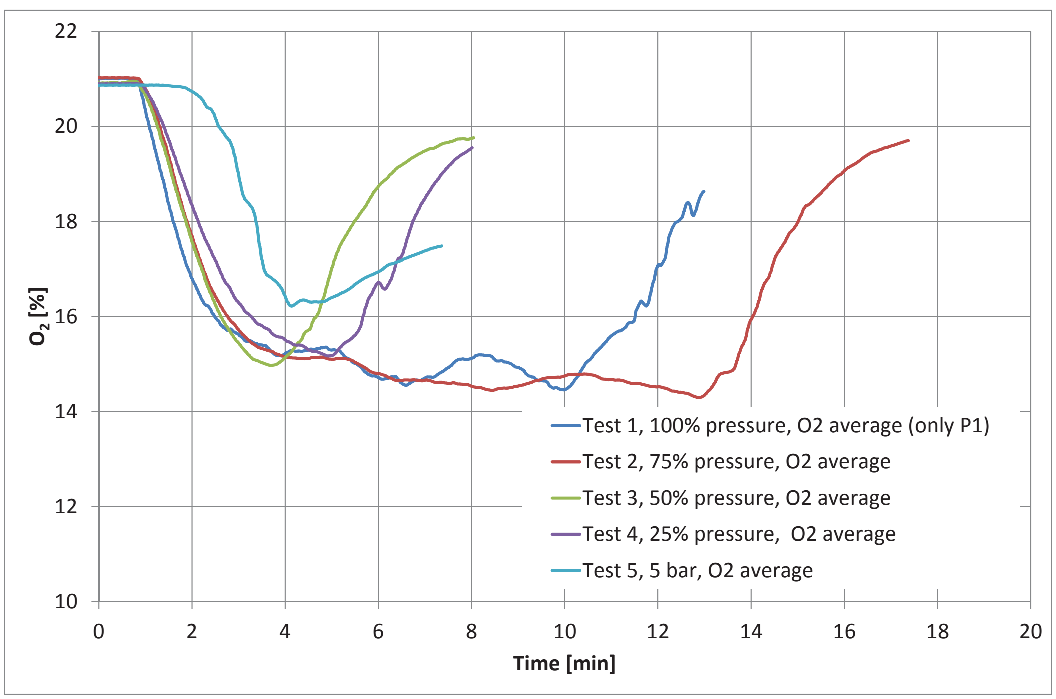


Figure 6 – Average oxygen concentrations versus time for non-obstructed tests.

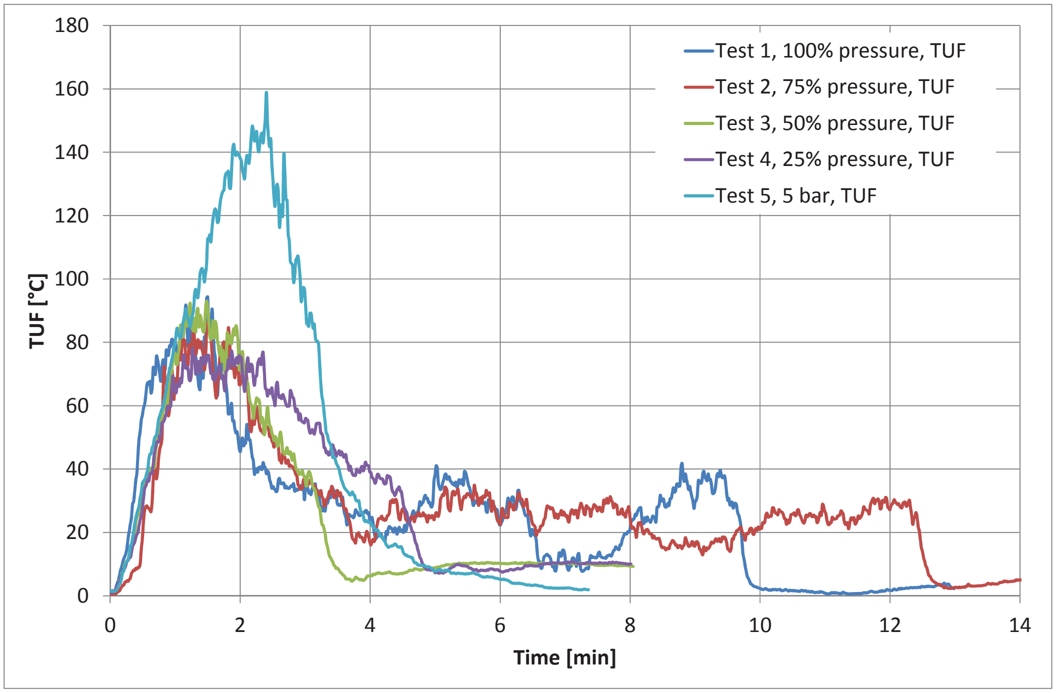


Figure 7 – Temperature Uniformity Factors versus time for non-obstructed tests.

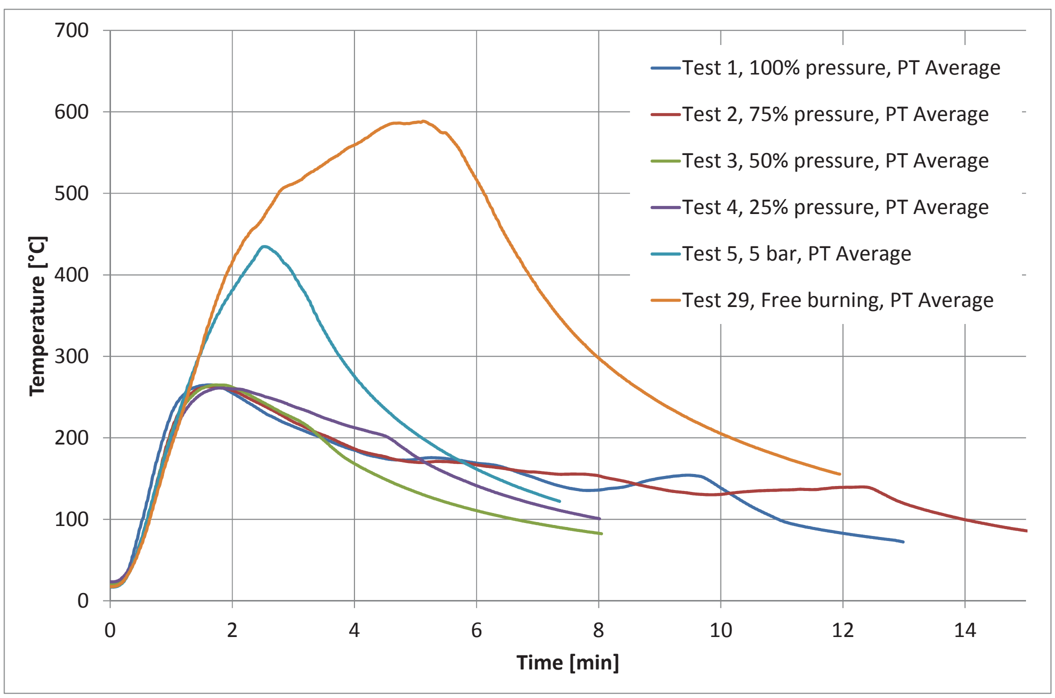


Figure 8 – Average PT (plate thermometer) temperatures versus time for non-obstructed tests.

Observations for non-obstructed fire tests (Tests 1-5)	
Gas temperatures	For Tests 1-4 (100%, 75%, 50% and 25 % of design pressure respectively), the water mist system cooled the compartment efficiently. A higher pressure (resulting in a higher water discharge density and an improved atomization) results in a more efficient cooling of the gases. Test 5 (at 5 bar) was aborted 2:15 min after ignition. It is difficult to say what effect the water mist system had on the gas temperatures in Test 5.
PT temperatures	The maximum average PT temperature was similar (between 261 and 265°C) for Tests 1-4. The temperature was reduced slightly faster at higher system pressures. In Test 5 the average PT temperature increased until the test was aborted and the fire was extinguished with foam.
Extinguishment	In Tests 1 and 2 the fire was not extinguished before the fuel was consumed. In Tests 3 and 4 the fire was extinguished quite rapidly (2:45 min and 4:00 min after water mist system activation respectively). In Test 5 the fire was not extinguished before the test was aborted. Extinguishment with a high pressure water mist system in a ventilated compartment is a scenario dependent performance indicator. In Tests 1 and 2 the fire was probably not extinguished because the system cooled the compartment too efficiently. This is discussed further in the Discussion section.
TUF	In Tests 1 and 2 the TUF value peaked at about 80-90 °C when the average temperature in the compartment was about 120 °C and was reduced to about 30°C three and a half minute after activation of the water mist system when the average temperature in the compartment was about 60 °C. It stayed at this level until the fuel was consumed. In Tests 3 and 4 the TUF value also peaked at about 80-90 °C and decreased until the fire was extinguished. In Test 5 the TUF value increased until the test was aborted and peaked at about 160 °C. The results indicated that the gases in the compartment were not very well-mixed in any of the tests.

100% obstructed fire

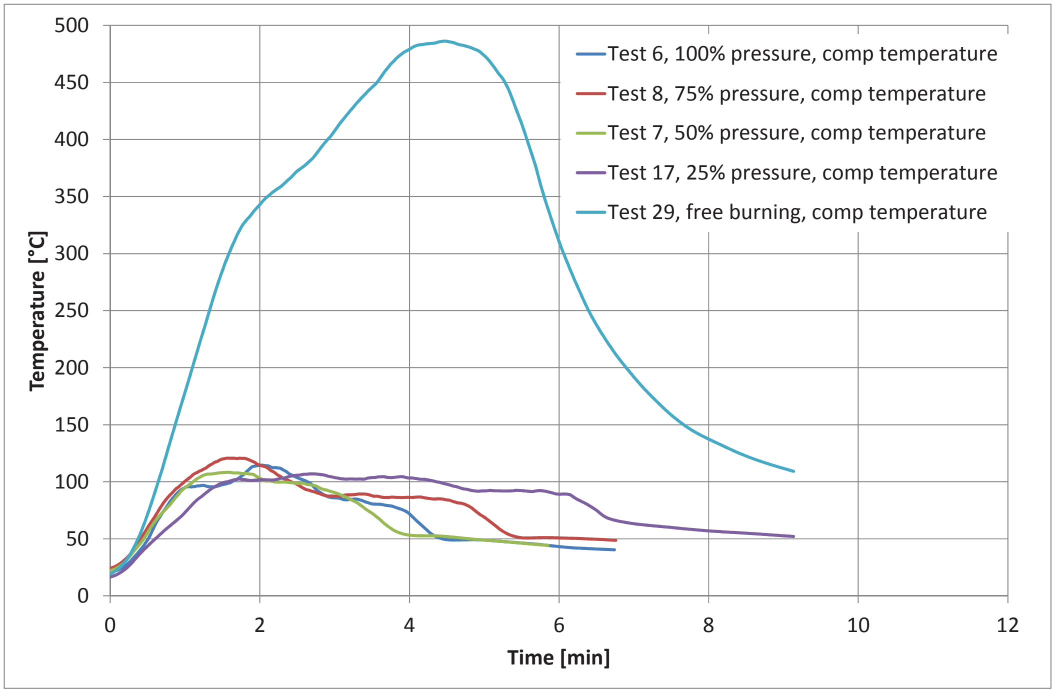


Figure 9 – Average compartment temperatures versus time for 100% obstructed fire tests.

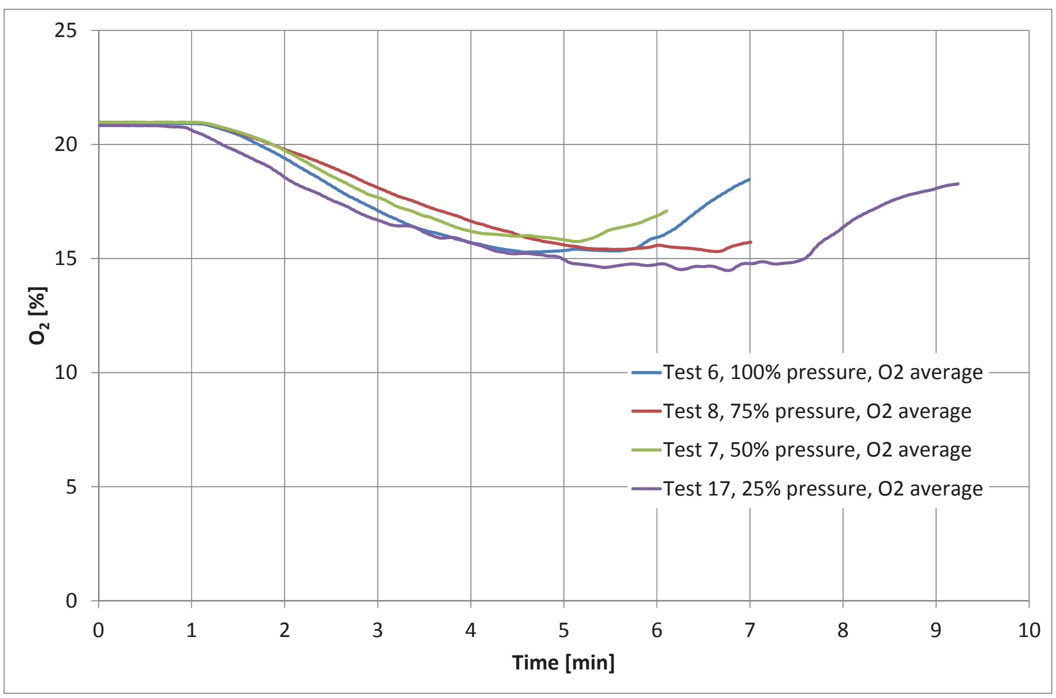


Figure 10 – Average oxygen concentrations versus time for 100% obstructed fire tests.

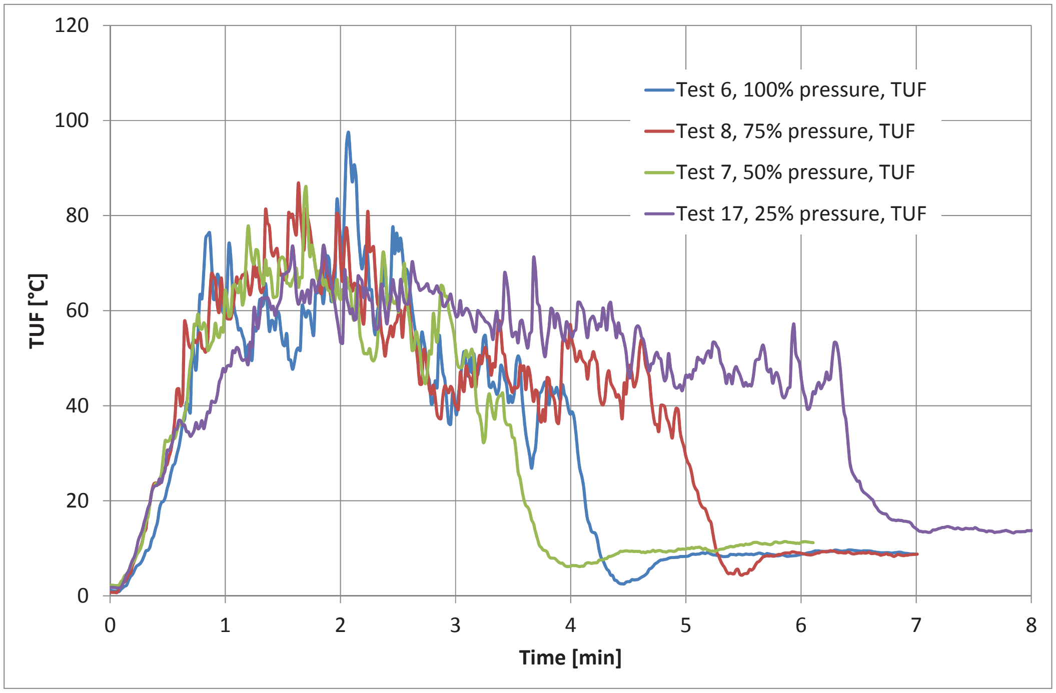


Figure 11 – Temperature Uniformity Factors versus time for 100% obstructed fire tests.

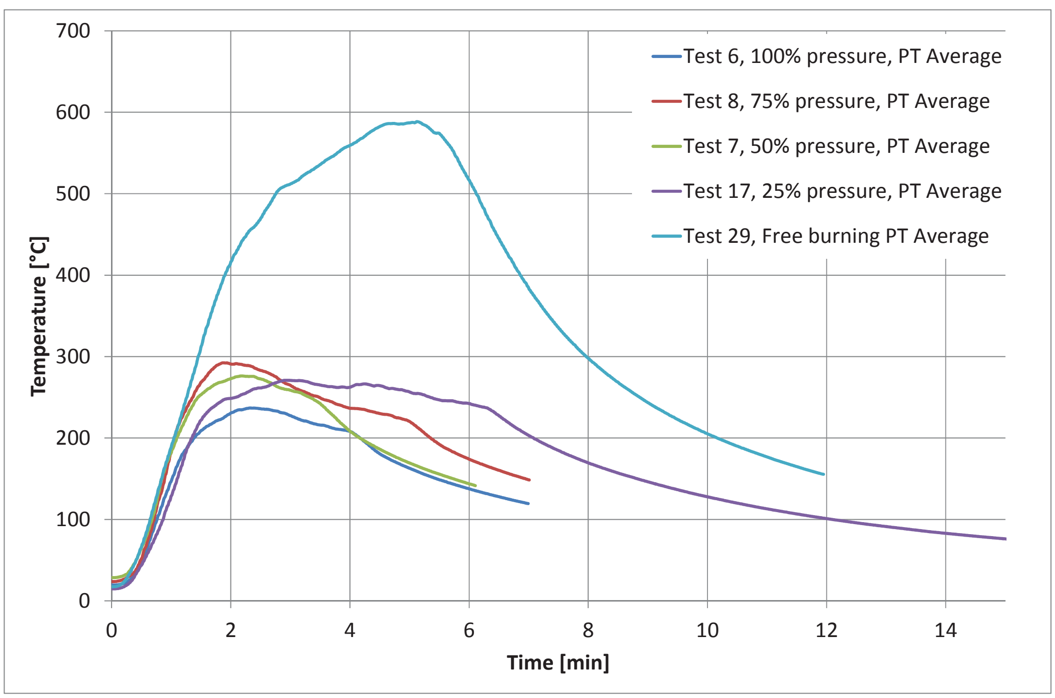


Figure 12 - Average PT (plate thermometer) temperatures versus time for 100% obstructed fire tests.

Observations for 100% obstructed fire tests (Test 6-8, 17)	
Gas temperatures	In all tests (100%, 75%, 50% and 25 % of design pressure) the water mist system cooled the compartment efficiently. Compared to the non-obstructed tests, the decrease in temperature was slower.
PT temperatures	The maximum average PT temperature (between 237 and 292°C) varied more than in the non-obstructed fires. There was no obvious correlation with the system pressure. This is probably an effect of the fluctuating behaviour of the flames coming out from under the obstruction.
Extinguishment	The fire was extinguished (time to extinguishment varied between 2:58 min and 5:49 min after activation) for tests at all pressures. The reduction of compartment temperatures was slower than for the unobstructed tests. This might be one reason why the fires were extinguished in the obstructed tests using 100% and 75% of design pressure of the water mist system and not in the unobstructed tests. This is discussed further in the Discussions section.
TUF	The TUF value peaked between 70 and 90 °C when the average temperature in the compartment was about 100 - 120 °C. The TUF was reduced to about 50°C before extinguishment occurred when the average temperature in the compartment was about 90 °C. This indicates that the gases in the compartment were not well-mixed in any of these tests.

50% obstructed fires

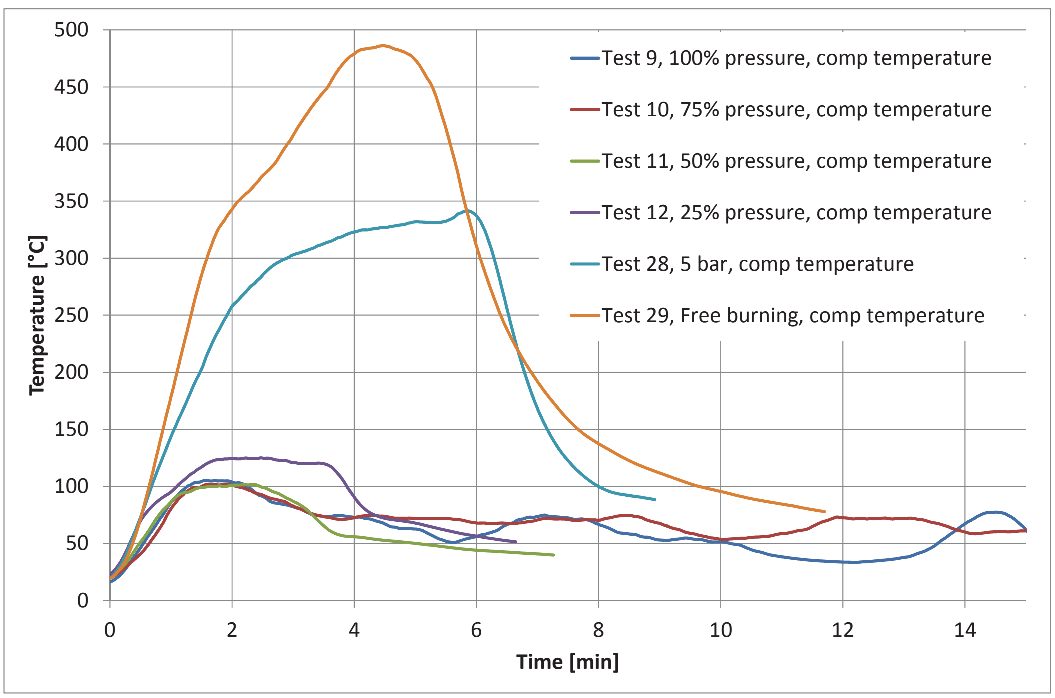


Figure 13 – Average compartment temperatures versus time for 50% obstructed fire tests.

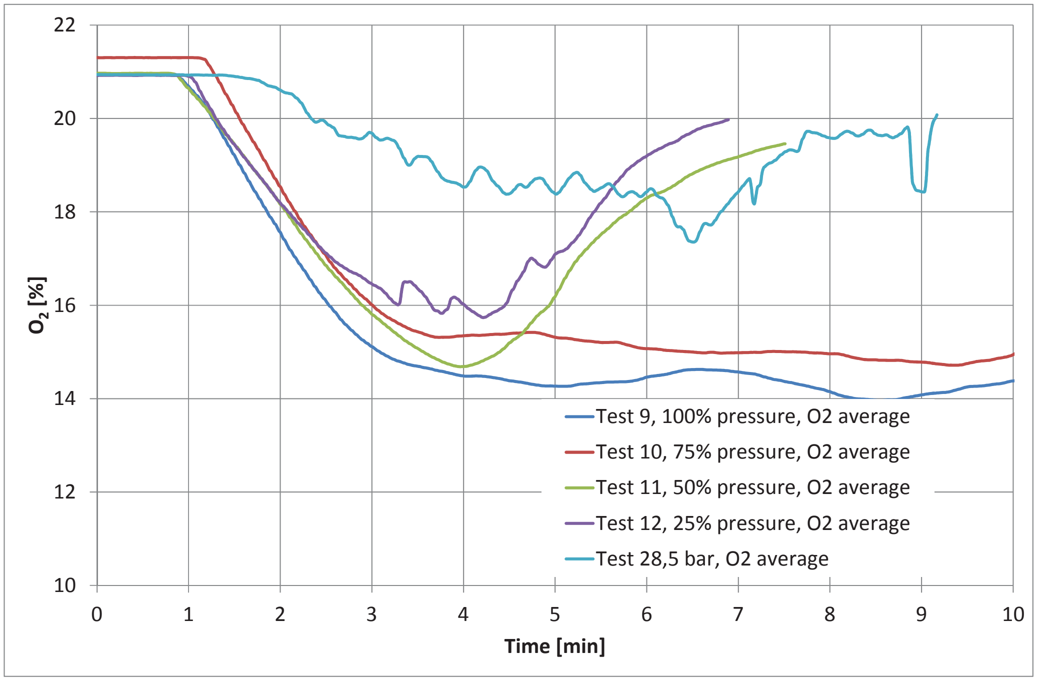


Figure 14 -– Average oxygen concentrations versus time for 50% obstructed fire tests.

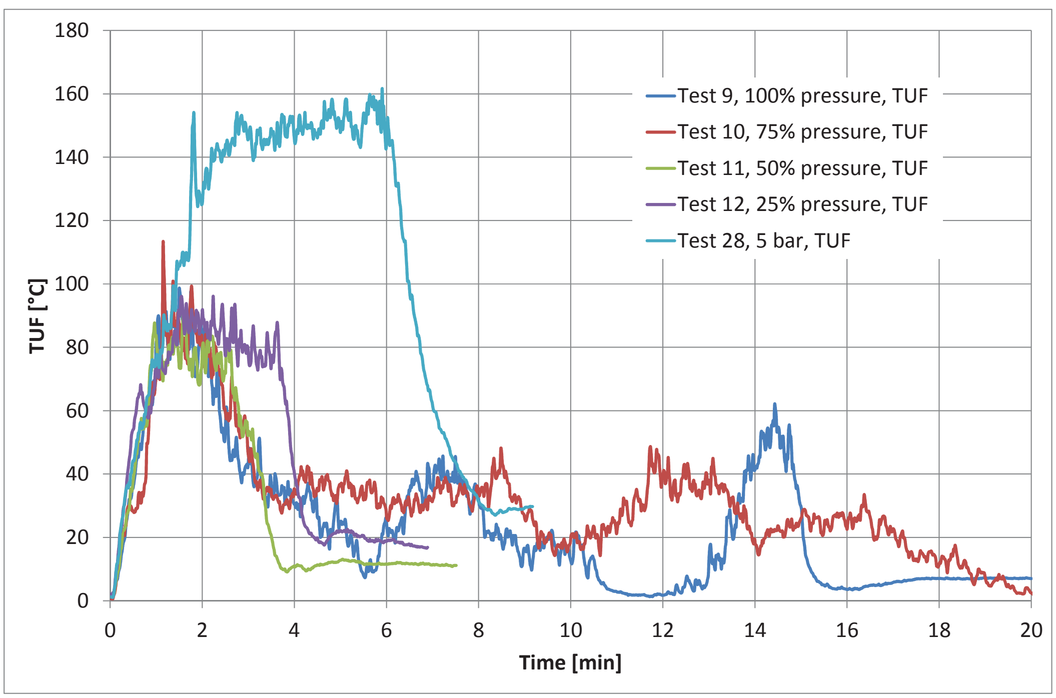


Figure 15 – Temperature Uniformity Factors versus time for 50% obstructed fire tests.

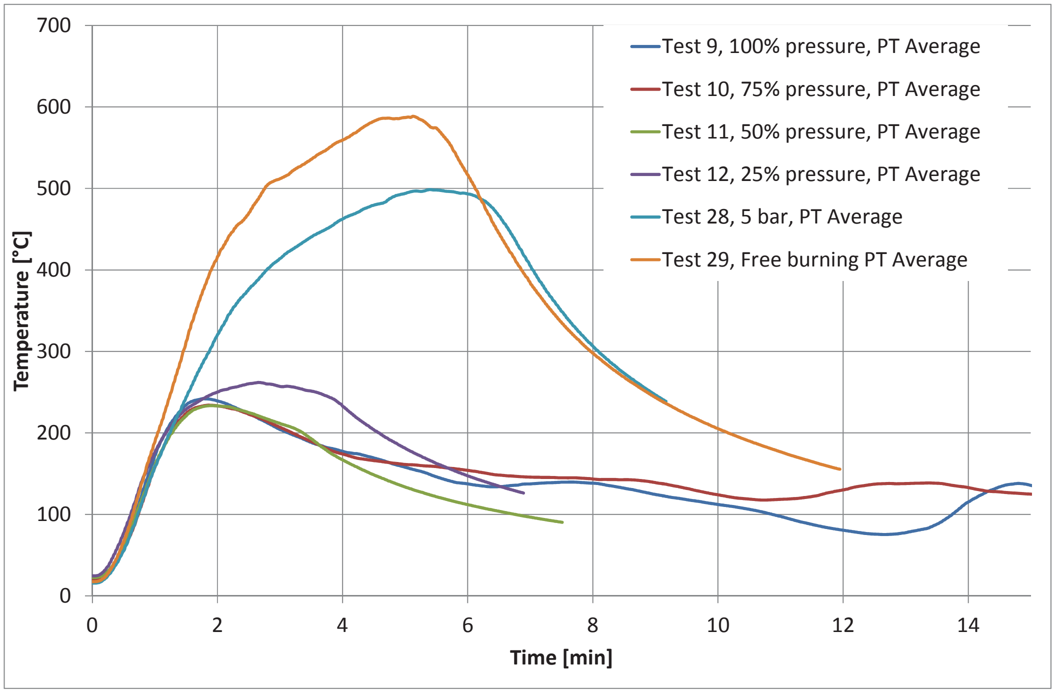


Figure 16 - Average PT (plate thermometer) temperatures versus time for 50% obstructed fire tests.

Observations for 50% obstructed fire tests (Tests 9-12, 28)	
Gas temperatures	For Tests 9-12 (100%, 75%, 50% and 25 % of design pressure respectively) the water mist system cooled the compartment efficiently. As was observed for the unobstructed fire tests, there was a correlation between applied pressure and system efficiency in cooling the space. Test 28 (at 5 bar) continued until all the fuel was consumed. If the gas temperatures in Test 28 (5 bar pressure) are compared to those for Test 29 (free burning), it can be seen that a small amount of water in the fire compartment is sufficient to significantly reduce the average compartment temperature (from 490 °C to 340 °C). Since the radiation to the floor is proportional to the gas temperature [K] to the power of 4, the emitted radiation from the gas volume in Test 28 is reduced to less than 50% that in Test 29. Since a flashover typically occurs when the compartment temperature is between 500 – 600 °C and the radiation level to the floor is 15 – 20 kW/m^2 [2] it is obvious that, even at fire main pressure (5-10 bar) the high pressure water mist system can significantly reduce the probability of flashover. This, in combination with the fact that lower compartment temperatures delay failures of surrounding divisions, will significantly improve the probability of a fire being contained in the original compartment even if a door etc. is left open.
PT temperatures	For Tests 9 - 11 , the maximum average PT-temperature was about the same (all between 234 and 242°C). In Test 12 the maximum average PT-temperature was 262°C. In Test 28, the average PT temperature increased until the fuel was consumed. It peaked at about 500 °C.
Extinguishment	In Tests 9 and 10 the fire was not extinguished before the fuel was consumed. In Tests 11 and 12 the fire was extinguished quite rapidly (2:50 min and 3:20 min after activation). In Test 28 the fire was not extinguished until the fuel was consumed. As was observed for the unobstructed Tests 1 and 2, in Tests 9 and 10 the fire was probably not extinguished because the water mist system cooled the compartment to efficiently. This is discussed further in the Discussions section.
TUF	In Tests 9 and 10 the TUF value peaked at about 80-90 °C when the average temperature in the compartment was about 100 °C and was reduced to about 30°C three and a half minute after activation when the average temperature in the compartment was about 60 °C. It stayed at this level until the fuel was consumed. In Tests 11 and 12 the TUF value also peaked at about 80-90 °C and decreased slowly until the fire was extinguished. In Test 28 the TUF value increased until the fuel was consumed and peaked at about 160 °C. This indicates that the gases in the compartment were not very well-mixed in any of the tests.

Damaged nozzles

Water mist nozzles can malfunction for a number of reasons, for example, due to clogging or damage resulting from an explosion. One possible approach to increasing redundancy and therefore survivability of a water mist system would be to supply water to half of the nozzles in a compartment from one pump and delivery lines and the other nozzles from a second pump and delivery lines. Therefore if one of the pumps or lines feeding the space is damaged or closed, 50% of the nozzles in a compartment would still function in case of fire.

Two tests were carried out to evaluate the performance of a high pressure water mist system with 50% of the nozzles malfunctioning. In the first, the system was operated at 100% pressure, and in the second at 50% of the normal operating pressure. No obstructions were used in these tests scenarios.

A pre-burn time of 30 seconds was used.

Average gas temperatures in the compartment were calculated as an average temperature of thermocouples in column P1 and P3 (see Figure 1). The results are presented in Figure 17.

Average plate thermometer temperatures were calculated by averaging the temperatures of the four plate thermocouples in positions P4, P5, P6, and P7 in Figure 1 and are presented in Figure 20.

Oxygen concentrations were calculated by averaging the output of two oxygen concentration analysers. The sampling locations for the analysers are marked G in Figure 1. The results are presented in Figure 18. The sampled gas was dried before it is analysed, hence the water vapour content is not shown in the oxygen concentration versus time plots.

A summary of the results of the tests is presented in Table 4.

Table 4 - Summary of results from tests with reduced number of nozzles

Tes t no	Description of setup	Water discharge rate into space [l/min]	Time (after activation) to temp <80°C [min:s]	Time (after activation) to temp <60°C [min:s]	Time (after activation) to extinguishment [min:s]	O_2 concentration at extinguishment [vol%]
13	100 % pressure 2 nozzles (50%) No obstruction	41.8	8:45	11:07	10:36	15.3 (lowest measured value: 15.3)
14	50 % pressure 2 nozzles (50%) No obstruction	29.6	11:53	16:08	Did not extinguish	- (lowest measured value: 14.8)

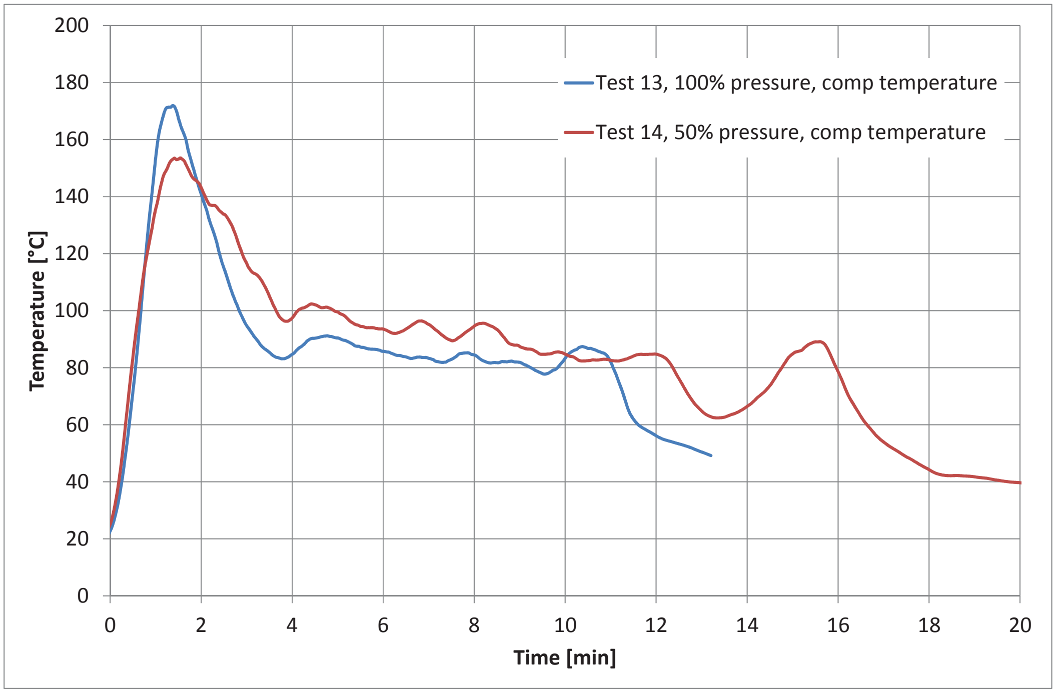


Figure 17 - Average compartment temperatures versus time for tests with 2 nozzles.

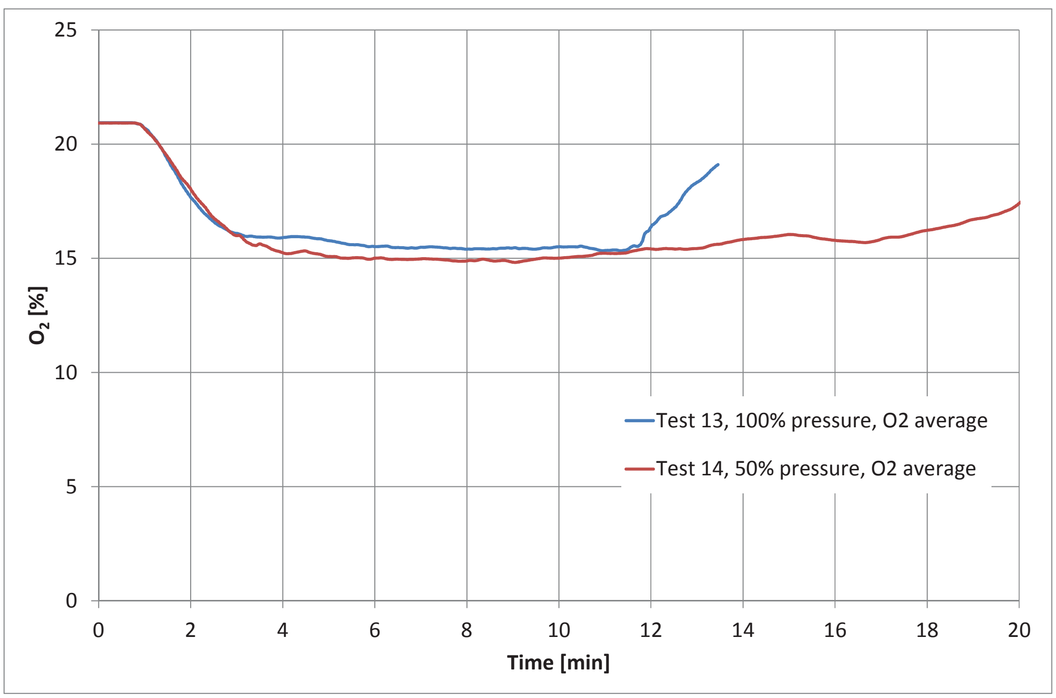


Figure 18 - Average oxygen concentrations versus time for tests with 2 nozzles.

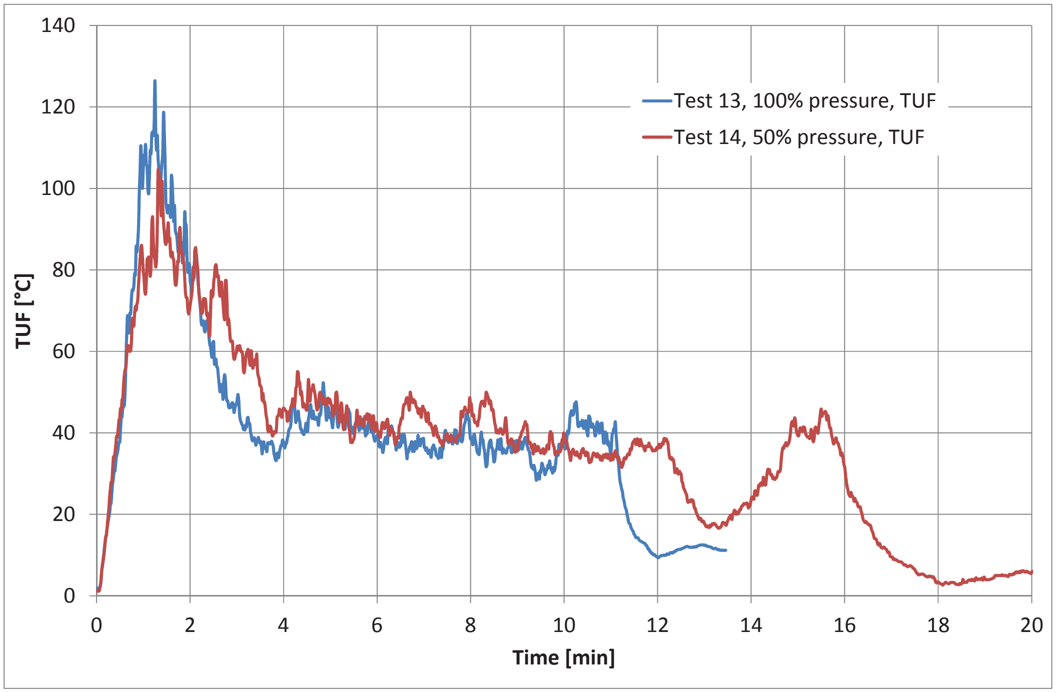


Figure 19 - Temperature Uniformity Factors versus time for tests with 2 nozzles.

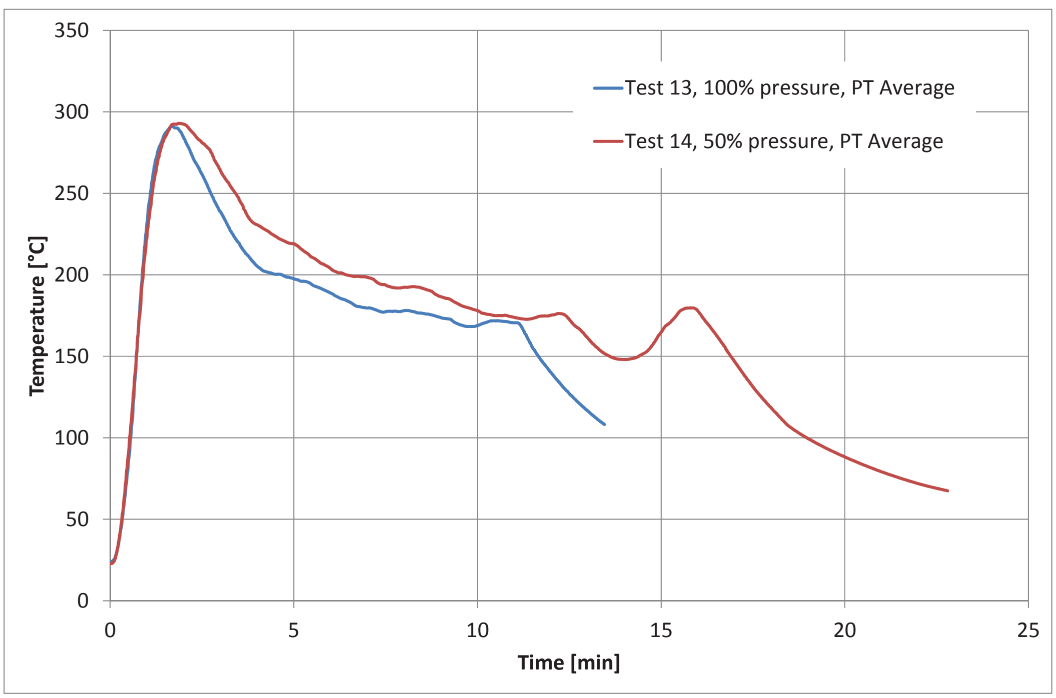


Figure 20 - Average PT (plate thermometer) temperatures versus time for tests with 2 nozzles.

Observations for tests with reduced number of nozzles	
Gas temperatures	In Tests 13 and 14 (100% and 50% of design pressure respectively) the water mist system cooled the compartment efficiently. There was a correlation between applied pressure and system efficiency in cooling the gases.
PT temperatures	The maximum average PT-temperature was similar for Test 13 and Test 14 (291°C and 293°C respectively). The temperature was reduced faster in Test 13 (100% design pressure).
Extinguishment	In Test 14, the fire was not extinguished before the fuel was consumed. In Test 13, the fire was extinguished 10:36 min after activation of the water mist system.
TUF	In Test 13, the TUF value peaked at about 120 °C when the average temperature in the compartment was about 170 °C. In Test 14, the TUF value peaked at about 100 °C when the average temperature in the compartment was about 150 °C. In both tests, the TUF value was reduced to about 40°C three and a half minutes after activation when the average temperature in the compartment was about 90-100 °C. It stayed at this level until the fire was extinguished or the fuel was consumed. The TUF indicates that the gases in the compartment were not very well-mixed in either test.

Damaged piping

An obvious damage scenario for a naval ship is weapon induced damage. A hit from a projectiles such as a grenade might bend and buckle pipes and fragments might puncture pipes resulting in leakage and, depending on the available pump capacity, reduced system pressure.

Before this series of tests, pipes of relevant dimensions and qualities for use in a high pressure water mist system were installed in a blast chamber at TNO and a grenade was detonated. Two racks of pipes (see Figure 21) were placed 2 meters and 3 meters away from the grenade. The caliber and type of grenade cannot be revealed because of classification. The grenade in the photographs is a dummy and is not the grenade that was used in the trials. This resulted in damage to the pipes; some of the pipes were severed while others suffered punctures of various sizes. A number of damaged pipe sections were selected for use in the fire testing described in this section. The damage scenarios are documented in Appendix 1.

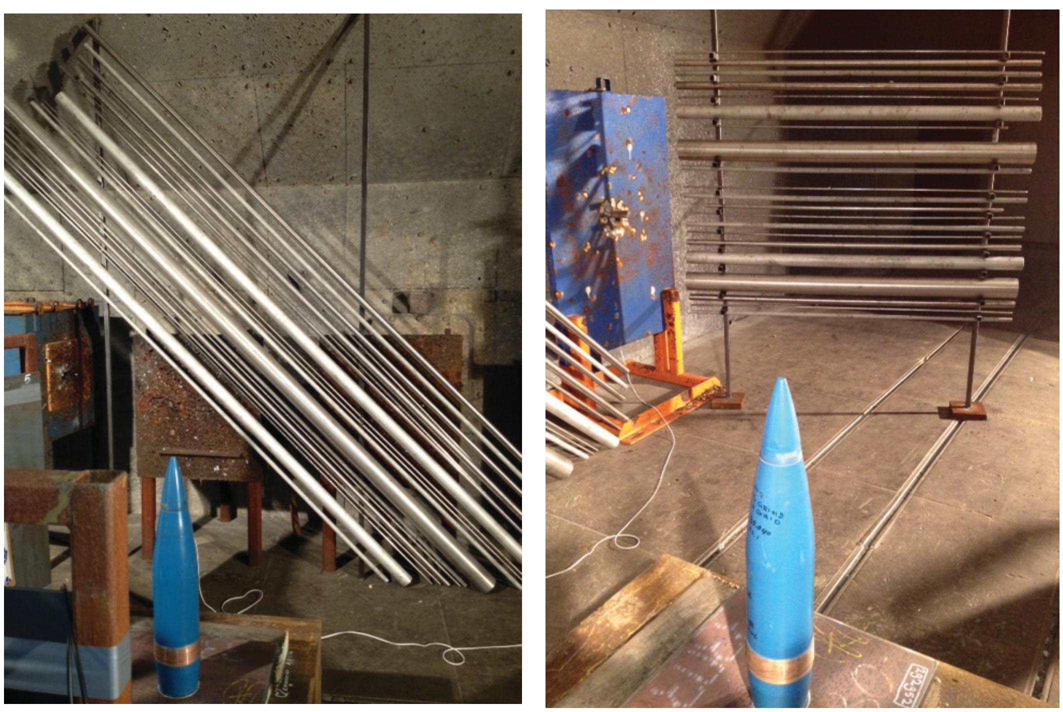


Figure 21 – Photo of setup prior to grenade test to damage piping segments.

To evaluate a high pressure systems performance with damaged pipe sections, a series of 10 tests were performed with damaged pipe sections installed in the water mist system inside the test compartment. The leakage flow resulting from the damaged pipe sections caused a pressure drop in the system. Since the damaged pipe sections were installed in the fire compartment the leakage spray also affected the fire and the conditions in the compartment.

This test series was done with pool fires with no obstructions. A pre-burn time of 30 seconds was used.

Average temperatures in the compartment were calculated by averaging the temperature of thermocouples in column P1 and P3 (see Figure 1). They are plotted against time in Figure 25 for the scenarios with pressures between 50% and 75% of normal operating pressure, in Figure 29 for the scenarios with pressures between 25% and 50% of normal operating pressure and in Figure 33 for the scenarios with pressures between 0% and 25% of normal operating pressure. These figures also show the compartment temperatures for the tests with intact piping in the same pressure range.

Average plate thermometer temperatures were calculated by averaging the temperatures of the four plate thermocouples in positions P4, P5, P6, and P7 in Figure 1and are presented in Figure 26 for the scenarios with pressures between 50% and 75% of normal operating pressure, in Figure 30 for the scenarios with pressures between 25% and 50% of normal operating pressure and in Figure 34 for the scenarios with pressures between 0% and 25% of normal operating pressure. These figures also contains the PT temperatures for the tests with intact piping in the same pressure range.

Oxygen concentrations were calculated by averaging the output of two oxygen concentration analysers. The sampling locations for the analysers are marked G in Figure 1. The results are presented in Figure 22 for the scenarios with pressures between 50% and 75% of normal operating pressure, in Figure 27 for the scenarios with pressures between 25% and 50% of normal operating pressure and in Figure 31 for the scenarios with pressures between 0% and 25% of normal operating pressure. These figures also contains the oxygen concentrations from the tests with intact piping in the same pressure range. The sampled gas is dried before it is analysed, hence the water vapour content is not shown in these oxygen concentration versus time plots.

A summary of the results of the tests is presented in 5.

Table 5 - Summary of results from tests with damaged pipes

Test no	Description of setup**	Average system pressure [% of design pressure]	Water discharge rate nozzles* [l/min]	Total water discharge ** [l/min]	Time (after activation) to temp <80°C [min:s]	Time (after activation) to temp <60°C [min:s]	Time (after activation) to extinguish-ment [min:s]	O_2 conc. at extinguish-ment [vol%]
18	Damage scenario 1	68.9	69.4	103.4	1:19	1:40	1:30	17.1 (lowest measured value: 16.7)
19	Damage scenario 2	34.3	49.0	104.6	1:52	6:55	Did not extinguish	- (lowest measured value: 14.4)
20	Damage scenario 3	28.8	44.9	104.9	1:57	2:11	2:00	16.3 (lowest measured value: 15.8)
21	Damage scenario 4	22.0	39.2	105.0	1:22	2:00	2:49	16.6 (lowest measured value: 16.3)
22	Damage scenario 5	16.8	34.3	105.5	Never over 80°C	3:09	6:43	14.6 (lowest measured value: 14.5)
23	Damage scenario 6	64.8	67.3	103.4	0:57	1:14	1:25	16.9 (lowest measured value: 16.6)
24	Damage scenario 7	35.8	50.0	105.0	1:25	4:49	4:50	15.2 (lowest measured value: 15.0)
25	Damage scenario 8	2.9	14.2	106.5	-	-	Did not extinguish	- (lowest measured value: 14.3)
26	Damage scenario 9	13.7	30.9	105.8	1:40	5:28	Did not extinguish	- (lowest measured value: 14.3)
27	Damage scenario 10	29.7	45.6	105.0	5:44	11:09	10:59	15.1 (lowest measured value: 14.5)

*Flow through nozzles (flow through pipe puncture(s) excluded)
**Flow through nozzles plus pipe puncture(s)

Water mist system at 50% - 75% of normal operating pressure

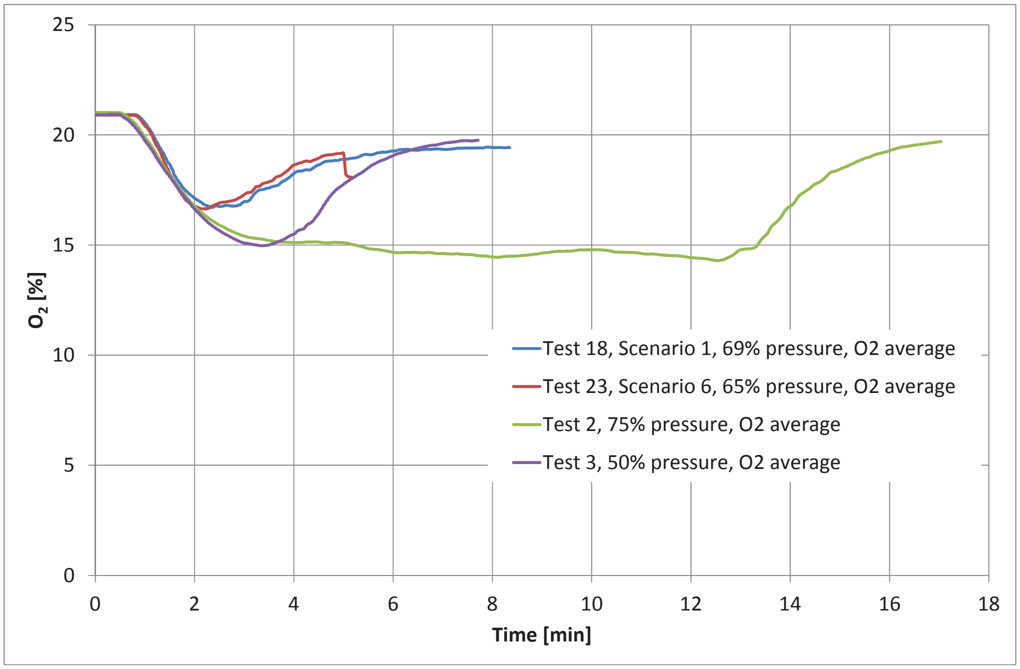


Figure 22 - Figure 23 - Average oxygen concentrations versus time for tests with damaged pipes and pressures between 50% and 75% of normal operating pressure. Damage scenarios (Tests 18 and 23) are compared with intact system with reduced pressure (Tests 2 and 3).

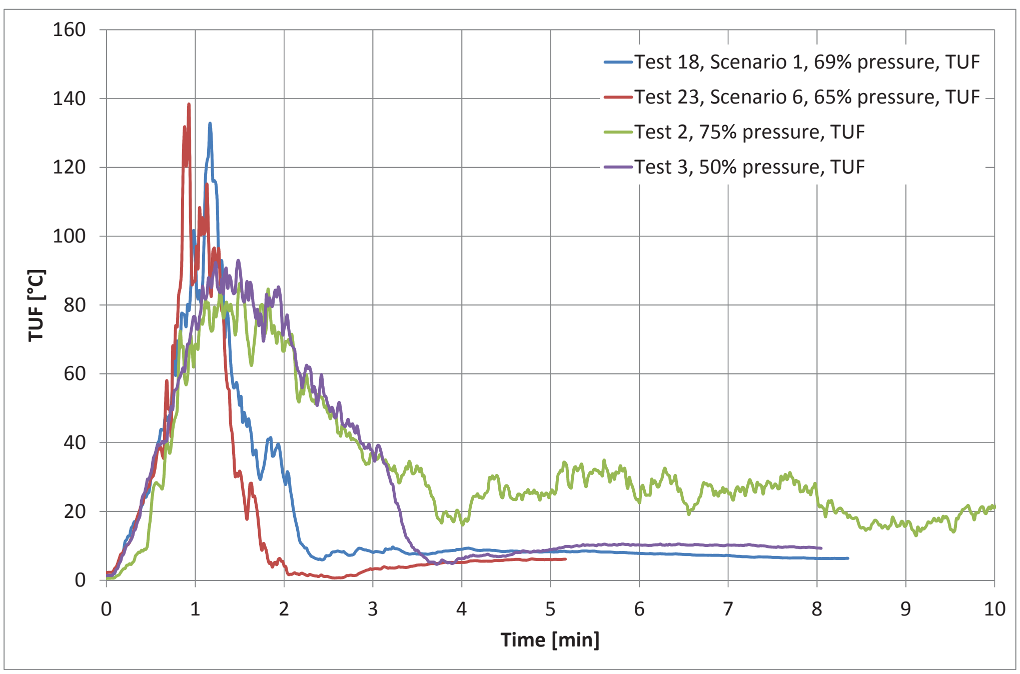


Figure 24 - Temperature Uniformity Factors versus time for tests with damaged pipes and pressures between 50% and 75% of normal operating pressure. Damage scenarios (Tests 18 and 23) are compared with intact system with reduced pressure (Tests 2 and 3).

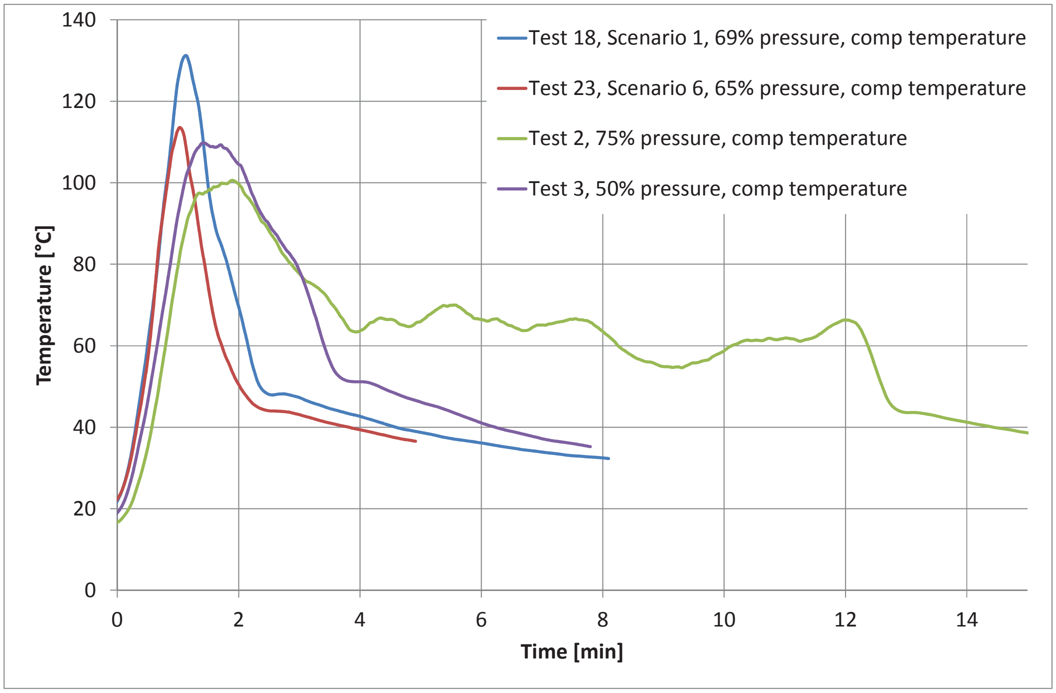


Figure 25 - Average compartment temperatures versus time for tests with damaged pipes and pressures between 50% and 75% of normal operating pressure. Damage scenarios (Tests 18 and 23) are compared with intact system with reduced pressure (Tests 2 and 3).

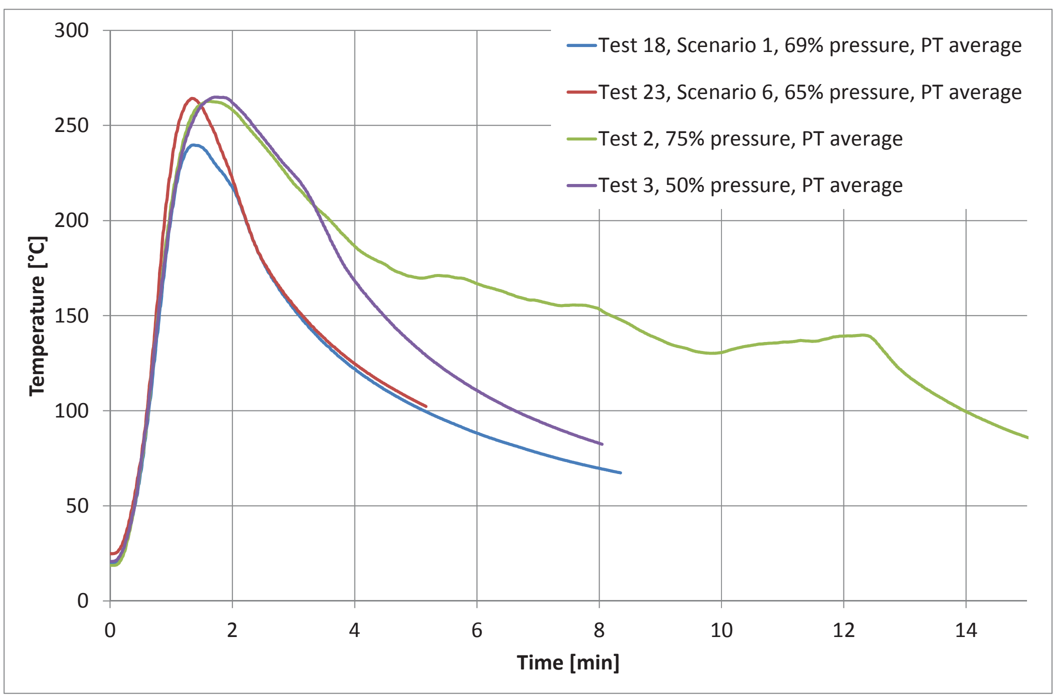


Figure 26 - Average PT (plate thermometer) temperatures versus time for tests with damaged pipes and pressures between 50% and 75% of normal operating pressure. Damage scenarios (Tests 18 and 23) are compared with intact system with reduced pressure (Test 2 and 3).

Observations for damage scenario tests with 50% - 75% of normal operation pressure	
Gas temperatures	The damaged water mist system reduced the compartment temperatures faster than was observed for the tests with intact piping and comparable system pressure. This is most likely due to the increased water discharged density in the compartment.
PT temperatures	In Test 23 the maximum average PT temperature was about the same as in Tests 2 and 3 (264°C). In Test 18 the maximum PT-temperature is slightly lower (240°C). The temperature was reduced faster in the tests with damaged piping.
Extinguishment	In both Tests 18 and 23 the fire was extinguished rapidly, in Test 18 1:30 min after activation and in Test 23 1:25 min after activation of the water mist system.
TUF	In Tests 18 and 23 the TUF value peaked at about 130 °C – 140 °C when the average temperature in the compartment was about 110 °C – 130 °C. In both tests the TUF value was rapidly reduced following activation of the water mist system, more rapidly than observed in Tests 2 and 3. This indicated that the gases in the compartment were quite well-mixed in these two damage scenarios (Tests 18 and 23).

Water mist system at 25% - 50% of normal operating pressure

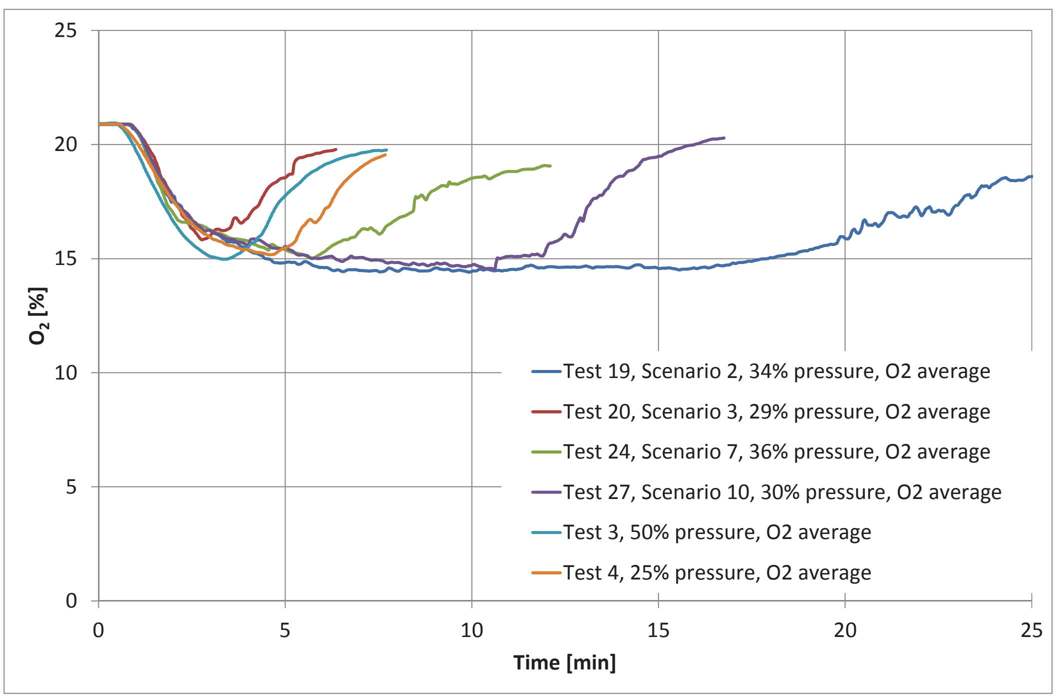


Figure 27 - Average oxygen concentrations versus time for tests with damaged pipes and pressures between 25% and 50% of normal operating pressure. Damage scenarios (Tests 19, 20, 24 and 27) are compared with intact system with reduced pressure (Tests 3 and 4).

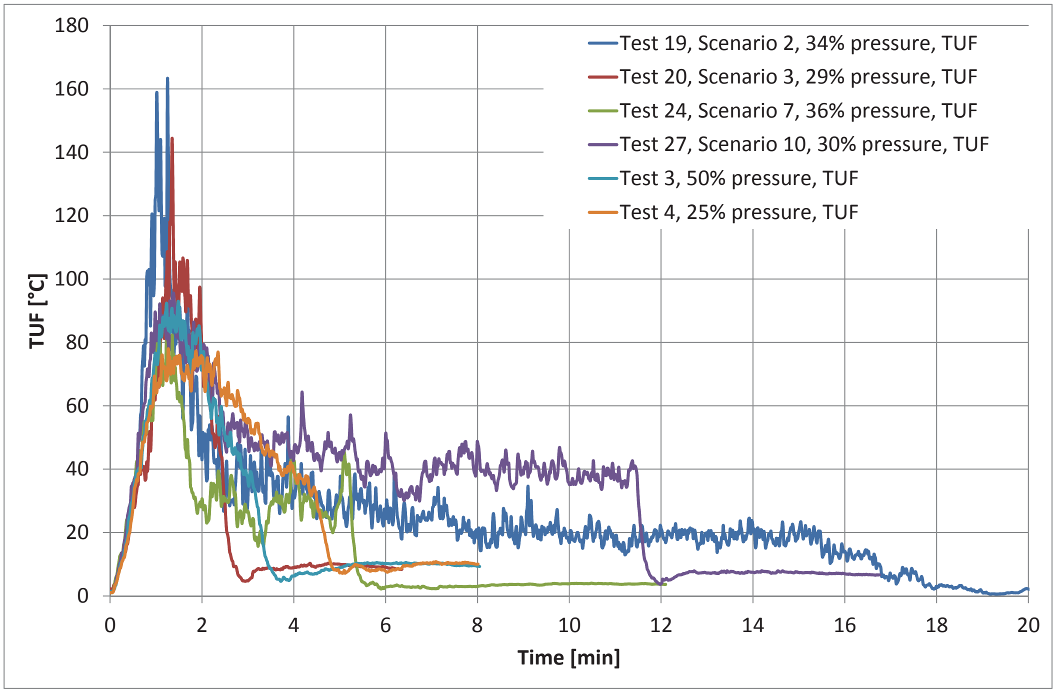


Figure 28 - Temperature Uniformity Factors versus time for tests with damaged pipes and pressures between 25% and 50% of normal operating pressure. Damage scenarios (Tests 19, 20, 24 and 27) are compared with intact system with reduced pressure (Tests 3 and 4).

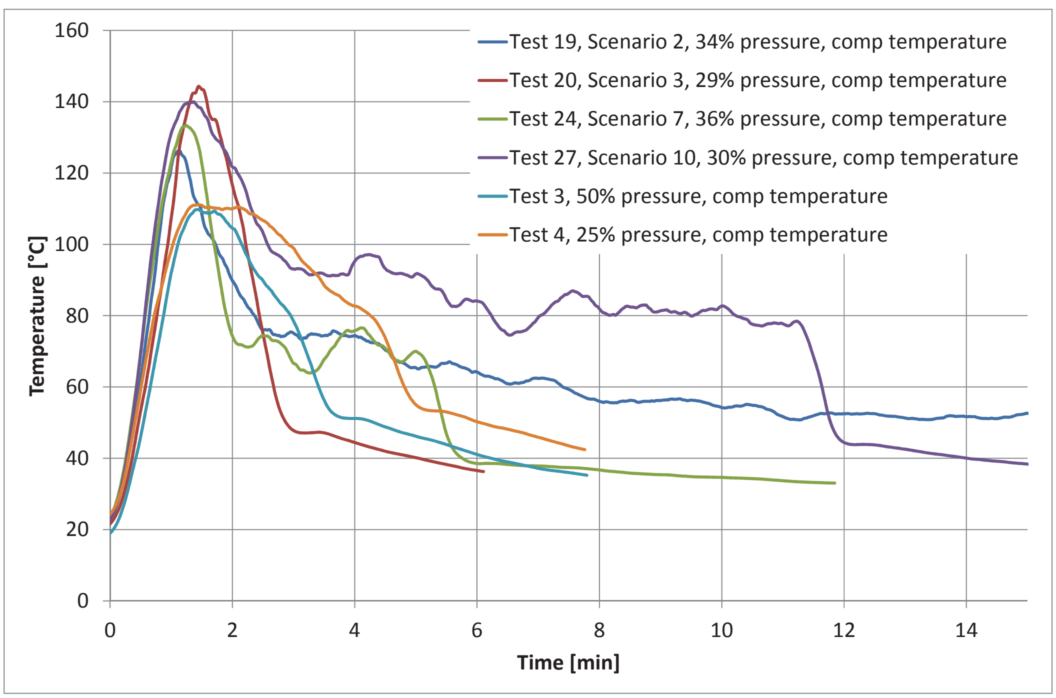


Figure 29 - Average compartment temperatures versus time in tests with damaged pipes and pressures between 25% and 50% of normal operating pressure. Damage scenarios (Tests 19, 20, 24 and 27) are compared with intact system with reduced pressure (Tests 3 and 4).

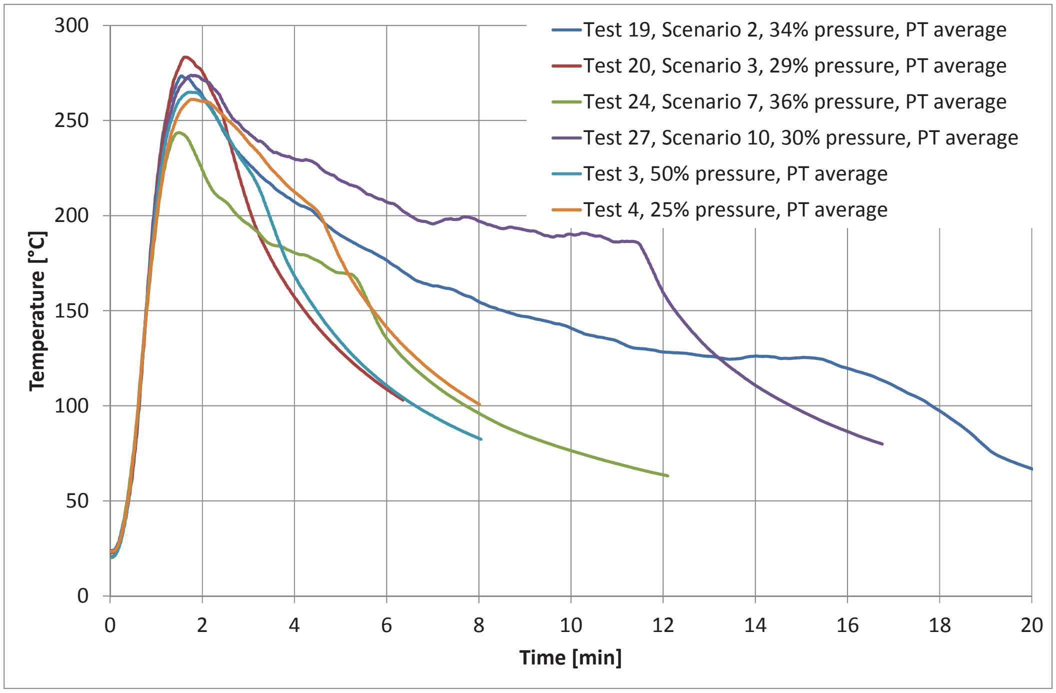


Figure 30 - Average PT (plate thermometer) temperatures versus time for tests with damaged pipes and pressures between 25% and 50% of normal operating pressure. Damage scenarios (Tests 19, 20, 24 and 27) are compared with intact system with reduced pressure (Tests 3 and 4).

Observations for damage scenario tests with 25% - 50% of normal operation pressure	
Gas temperatures	The water mist system with damaged piping reduced the compartment temperatures faster the system with intact piping and comparable system pressure. The initial peak temperature was higher in the tests with the damaged water mist system.
PT temperatures	The maximum average PT-temperature varied between 244°C and 283°C. No obvious difference between the performance of damaged systems and intact systems with comparable pressures was observed.
Extinguishment	Even though the system pressure in these damage scenarios only varied between 29 and 36 % of normal operating pressure, the time to extinguishment varied considerably. In Test 19 the fire was not extinguished before the fuel was consumed. In Test 20 the fire was extinguished 2:00 min after activation, in Test 24 4:50 min after activation and in Test 27 10:59 min after activation of the water mist system.
TUF	In Tests 19 and 20 the TUF value peaked at approximately 140 °C – 160 °C when the average temperature in the compartment was approximately 120 °C – 140 °C. In Test 19 the TUF value rapidly decreased to about 20°C after the water mist was activated, in Test 20 the TUF value decreased rapidly after the water mist system was activated prior to the extinguishment of the fire. In Tests 24 and 27 the TUF value peaked at about 80 °C – 90 °C when the average temperature in the compartment was about 130 °C – 140 °C. In Test 24 the TUF value rapidly decreased to about 30°C prior to the extinguishment of the fire, in Test 27 the TUF value decreased to about 50°C prior to the extinguishment of the fire. This indicated that the gases in the compartment were not very well-mixed in these extinguishment experiments.

Water mist system at 0% - 25% of normal operating pressure

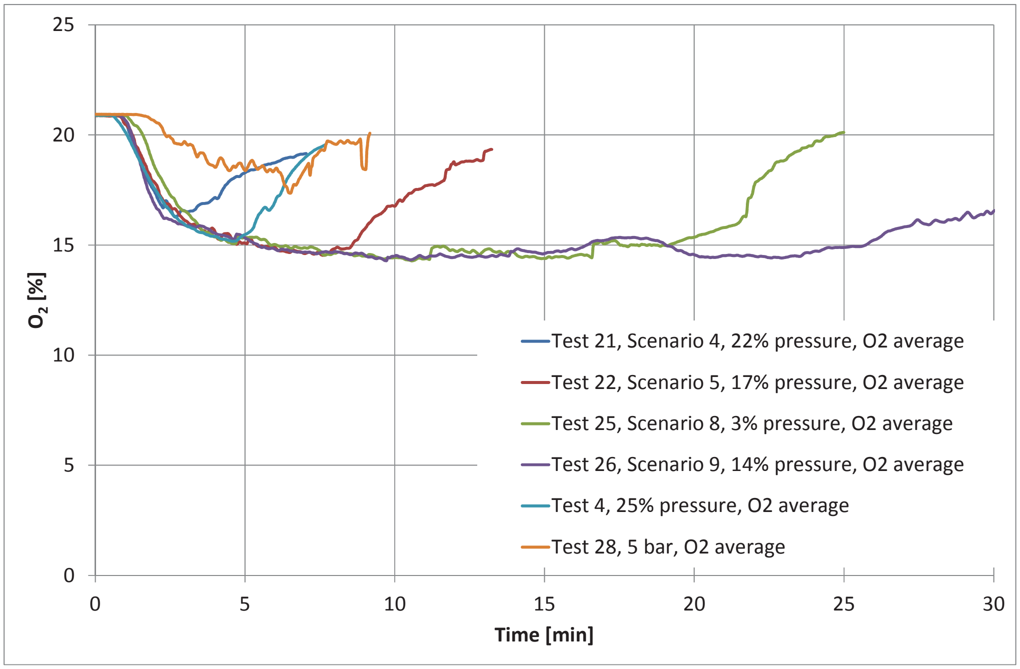


Figure 31 - Average oxygen concentrations versus time for tests with damaged pipes and pressures between 0% and 25% of normal operating pressure. Damage scenarios (Tests 21, 22, 25 and 26) are compared with intact system with reduced pressure (Tests 4 and 28).

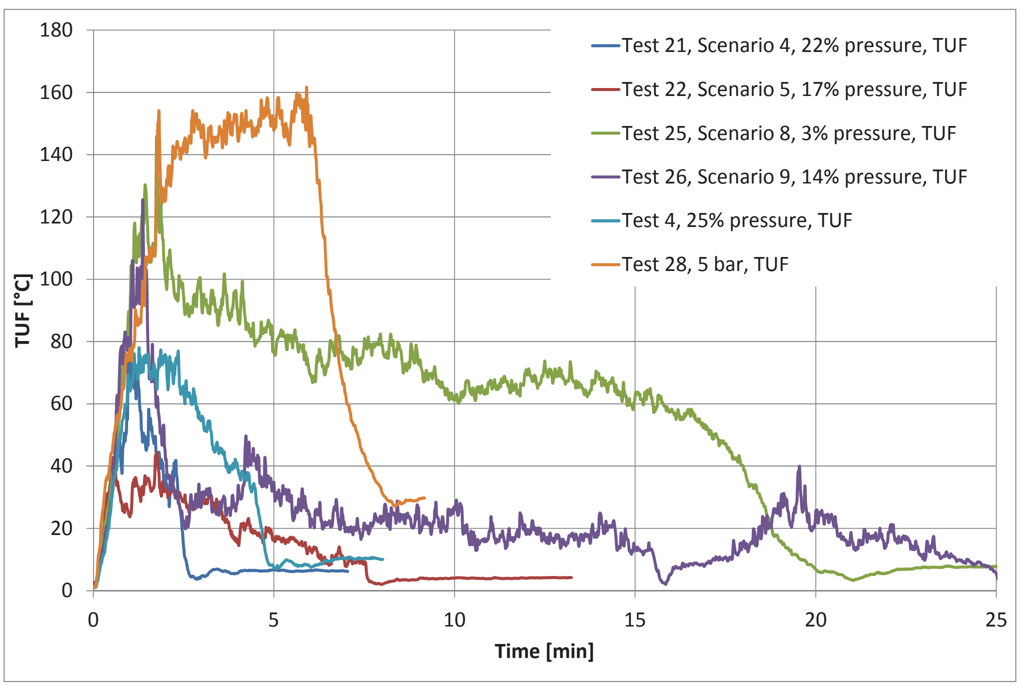


Figure 32 - Temperature Uniformity Factors versus time for tests with damaged pipes and pressures between 0% and 25% of normal operating pressure. Damage scenarios (Tests 21, 22, 25 and 26) are compared with intact system with reduced pressure (Tests 4 and 28).

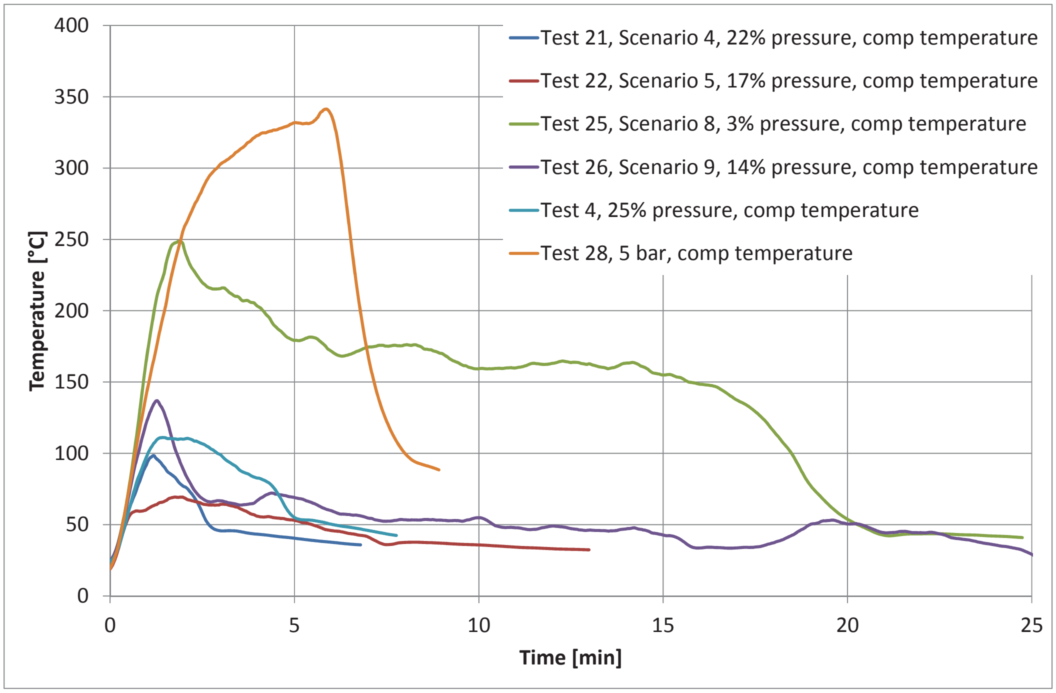


Figure 33 - Average compartment temperatures versus time for tests with damaged pipes and pressures between 0% and 25% of normal operating pressure. Damage scenarios (Tests 21, 22, 25 and 26) are compared with intact system with reduced pressure (Tests 4 and 28).

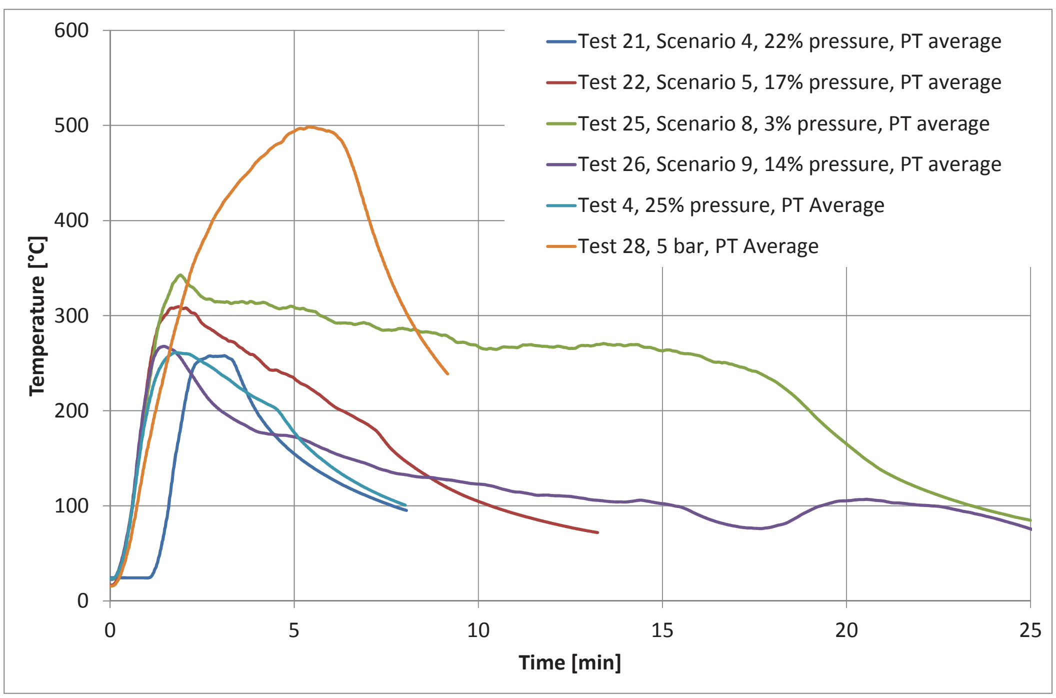


Figure 34 - Average PT (plate thermometer) temperatures versus time for tests with damaged pipes and pressures between 0% and 25% of normal operating pressure. Damage scenarios (Tests 21, 22, 25 and 26) are compared with intact system with reduced pressure (Tests 4 and 28).

Observations for damage scenario tests with 0% - 25% of normal operation pressure	
Gas temperatures	The damaged water mist system reduced compartment temperatures faster than was observed for the test with intact piping at 25% of normal operation pressure. The damaged water mist system used in Test 25 (3% of operating pressure) performed much better than the intact system at 5 bar. The testing indicated the system with a large puncture (16 x 6 mm, k-factor of 52) in one of the supply lines that resulted in an almost complete loss of pressure was capable of reducing gas temperatures from 500°C (free burning) to about 150°C - 170°C.
PT temperatures	The maximum average PT-temperature varied between 258°C and 309°C. The difference between the performance of damaged systems and intact systems with comparable pressures were small. In Test 25 (3% of normal operation pressure) the maximum average PT-temperature was 343°C and decreased slowly until the fuel was consumed.
Extinguishment	In Tests 25 and 26 the fire was not extinguished prior to the consumption of the fuel. In Test 21 the fire was extinguished 2:49 min after activation of the water mist system and in Test 22 the fire was extinguished 6:43 min after activation of the water mist system.
TUF	In Test 25 the TUF value peaked at about 140 °C and decreased to 60 °C after about 15 min. In Test 21 the TUF value peaked at about 80°C and rapidly decreased to about 5°C prior to the extinguishment of the fire. In Test 22 the TUF value peaked at about 40°C and decreased to about 10°C prior to the extinguishment of the fire. In Test 26 the TUF value peaked at about 130°C and decreased to about 20°C before the fuel was consumed. This indicates that the gases in the compartment were well-mixed in Tests 21 and 22.

Weapon protection

A series of tests were performed to evaluate the amount of water needed to prevent a weapon like a missile or a torpedo from heating to the point of cook-off during a fire in a magazine space. Two fuel pan positions were used during the testing.

- Position 1 - The fuel pan was directly below the dummy torpedo with a vertical distance of 50 mm between steel shell and fuel surface.
- Position 2 - The fuel pan was beside the dummy torpedo with a vertical distance of 50 mm between steel shell and fuel surface.

A summary of the results is presented in 6 and the maximum steel surface temperatures are plotted Figure 35 and Figure 36.

The water mist system did not fulfil the performance criteria for cooling the dummy torpedo.

Table 6 - Summary of results for tests with the torpedo dummy.

Test no	Description of setup	Peak surface temperature [°C]	Peak surface temperature > 1 min after activation [°C]	Time (after activation) to extinguishment [min:s]
15	100% system pressure Fuel pan in position 1	456	456	Did not extinguish
16	100% system pressure Fuel pan in position 2	268	268	5:20

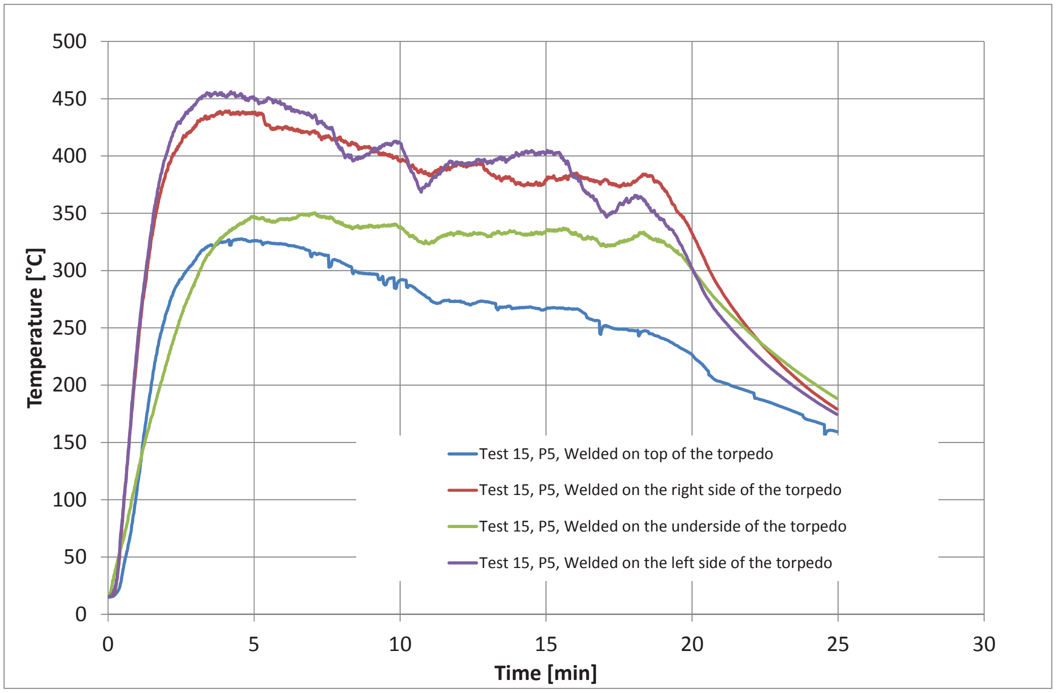


Figure 35 – Torpedo dummy temperatures versus time for Test 15 with fuel pan in position 1.

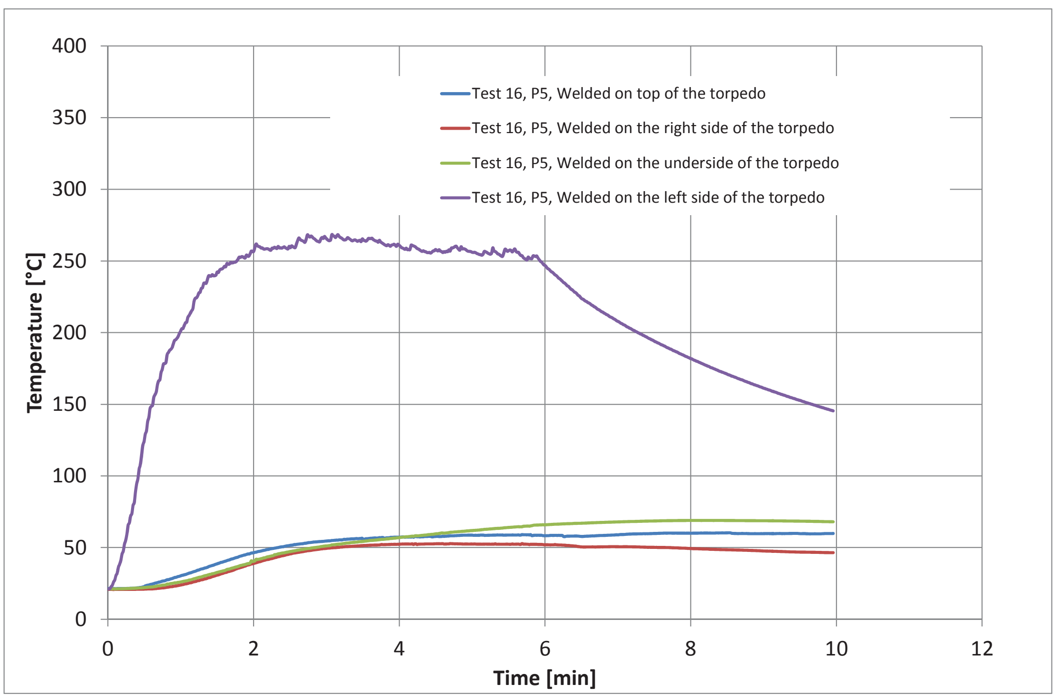


Figure 36 - Torpedo dummy temperatures versus time for Test 16 with fuel pan in position 2.

Droplet size measurements

Definitions

Small droplets (< 2 mm) are in general close to spherical in shape and can therefore be described using a single parameter [3]. Larger droplets are typically distorted by gravity. Different parameters can be used to characterize the droplets depending on the application. The parameters used in this report is presented below.

Length Mean Diameter or Arithmetic Mean Diameter (d_{10})

The length mean diameter (d_{10}) is defined in equation 1,

$$d_{10} = \frac{\int_0^\infty d f_d \, dd}{\int_0^\infty f_d \, dd} \qquad (1)$$

where f_d is the distribution of droplets in a spray.

Sauter Mean Diameter (d_{32})

The Sauter mean diameter is defined in equation 2,

$$d_{32} = \frac{\int_0^\infty d^3 f_d \, dd}{\int_0^\infty d^2 f_d \, dd} \qquad (2)$$

where d_{32} is the diameter of a droplet whose volume to surface ratio is the same as the volume to surface ratio of the entire spray. d_{32} is particularly important when mass transfer and the active area per volume are important [4, 5]. Therefore d_{32} is an appropriate parameter for the characterization of water mist since the purpose with the small droplets in water mist is to achieve large surface related effects, such as cooling and evaporation, while using small volumes of water.

Materials and methods

The size of the droplets produced by the water mist system was measured using optical based laser measurements. The technique employed in this report was Global Sizing Velocimetry (GSV) which infers the size of the droplets by analyzing their light interference pattern. Measurements of size are taken across the entire measuring volume.

The droplet diameter limit for GSV is set by the ability of the software to detect and characterize the interference patterns in the images. The detection range is typically between 10 and 1000 µm.

Figure 37 shows a schematic overview of the experimental setup for drop sizing using GSV.

The diameter limit for GSV is set by the ability of the software to detect and characterize the interference patterns in the images. The detection range is typically 10 – 1000 µm.

Figure 37 shows a schematic overview of the experimental setup for drop sizing using GSV.

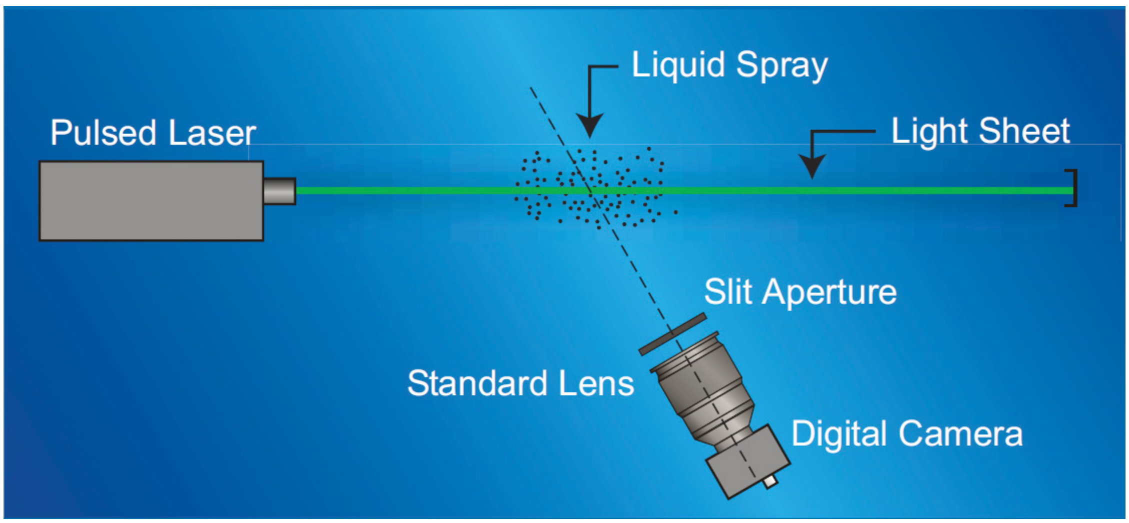


Figure 37 Schematic of the Global Sizing Velocimetry apparatus [4].

Measurements were made using the experimental set-up shown in Figure 38, where the main components of the acquisition and water mist equipment are shown. The acquisition equipment consisted of (A) a frequency doubled (532 nm) double pulsed Nd:YAG laser with cylindrical optics to form a thin laser sheet; (B) a double exposure non-intensified CCD camera with achromatic capturing optics, an interferometric filter centred at 532 nm with a FWHM of 10 nm and a slit for filtering spurious light; and (C) a control unit. The water mist system was fed by a positive displacement pump coupled to a pressure regulator which could be adjusted on demand. The pressure and flow upstream the nozzle was continuously controlled and logged.

As the nozzles used in this ttesting produced hollow cone sprays, the measuring volume was located 1000 mm vertically downstream of the nozzle and at a radial distance of 556 mm from the spray axis. Measurements were performed in the center of the spray plume and in the recirculation zone between two plumes. There were eight holes/plumes in the nozzle and consequently the nozzle was rotated 22.5° when shifting from measurements in the center of the plume to measurements between the centers of the plumes. In order to measure an undisturbed spray the nozzle was fixed two meters above ground level. Measurements were done at eight different pressures: 100, 75, 50, 25, 12.5, 6.2, 3.0, 1.5 bar.

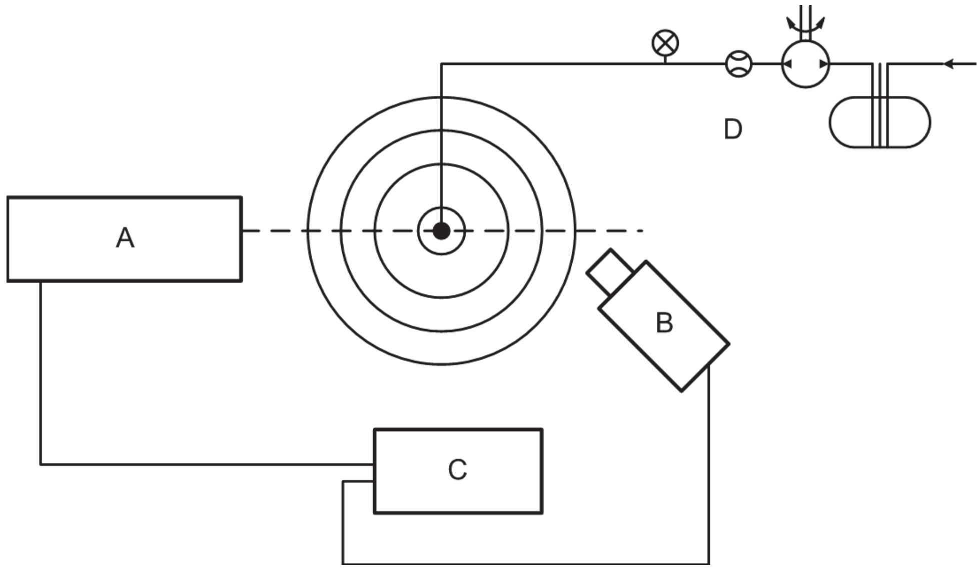


Figure 38: Schematic of the experimental set-up. A: laser and beam expanding optics, B: camera and acquiring optics, C: control unit, D: hydraulics and control systems for the water mist system.

For illustrative purposes, Figure 39 and Figure 40 show a photograph of the experimental setup and a photograph captured at the instant when measurements were being made respectively.

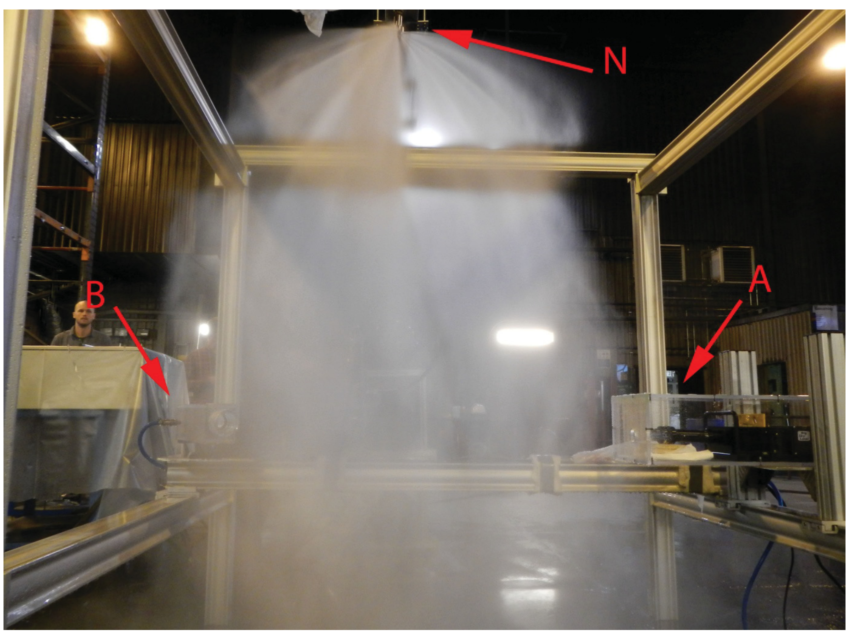


Figure 39: Photograph of the experimental set-up depicting some of the employed equipment and components. A: laser and beam expanding optics, B: camera and acquiring optics, N: nozzle.

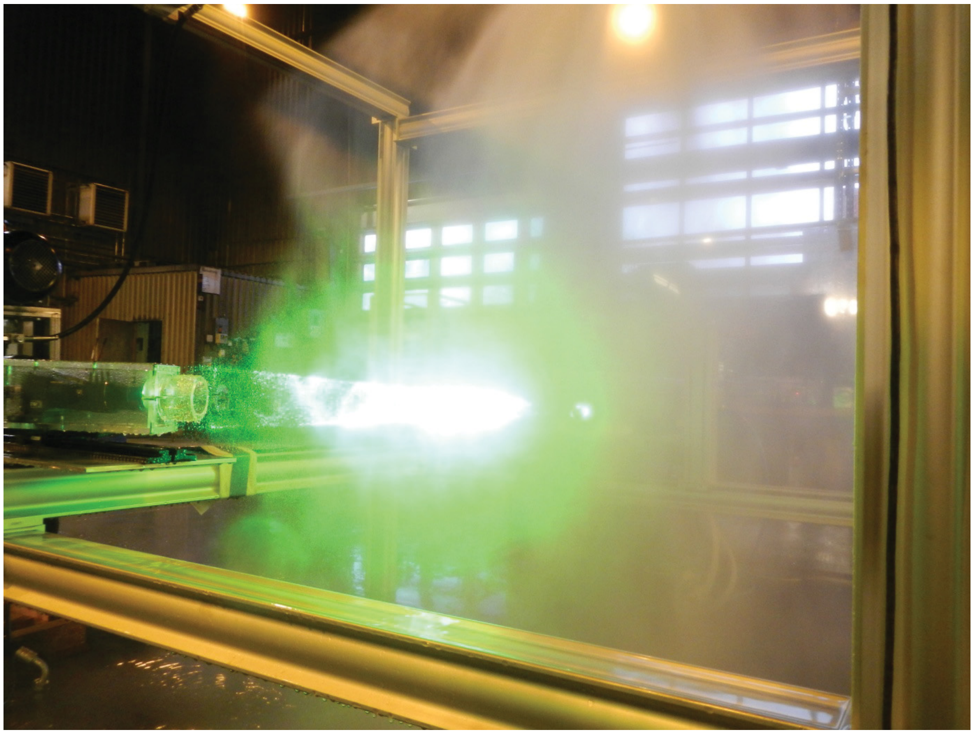


Figure 40: Photograph captured at the instant when measurements were being conducted. The photograph shows a laser pulse being fired through the spray and the front of the camera and its collecting optics.

Results

The size distribution of the mist droplets in the center of the spray/plume decreased monotonically as the system pressure was increased. An exception was at 50 bar. The reason for this deviation is not clear but could simply be a statistical artifact, indicating that more droplets should be sampled.

The size distributions are presented in Figure 41 to Figure 55 and the calculated Length Mean Diameter (d_{10}) and Sauter Mean Diameter (d_{32}) of the water mist droplets are presented in 7.

The position between two sprays/plumes was subjected to unstable conditions since the transport to this position was not determined by a single spray/plume but by the interaction of two sprays/plumes. This is also seen in the results where it droplets diameters do not monotonically decrease as pressure is increased. This could be due to the fact that the size distributions at this position are not primarily determined by the breakup characteristics of the individual sprays/plumes but rather are determined by the transport from the sprays/plumes to this position, which depends on the injection pressure in a complex way.

Table 7 – Results for droplet size measurements

Position	Pressure [bar]	d10 [µm]	d32 [[µm]
In spray	100	110.5	137.2
	75	124.4	157.5
	50	119.2	149.6
	25	125.1	166.4
	12	125	172
	6	145.2	190.0
	3	194.0	234.2
	1.5	235.4	273.5
Between sprays/plumes	100	120.0	146.9
	75	123.2	154.0
	50	126.4	163.1
	25	121.1	153.0
	12	111.4	144.7
	6	125.8	162.7
	3	176.1	219.6
	1.5	Too few droplets	Too few droplets

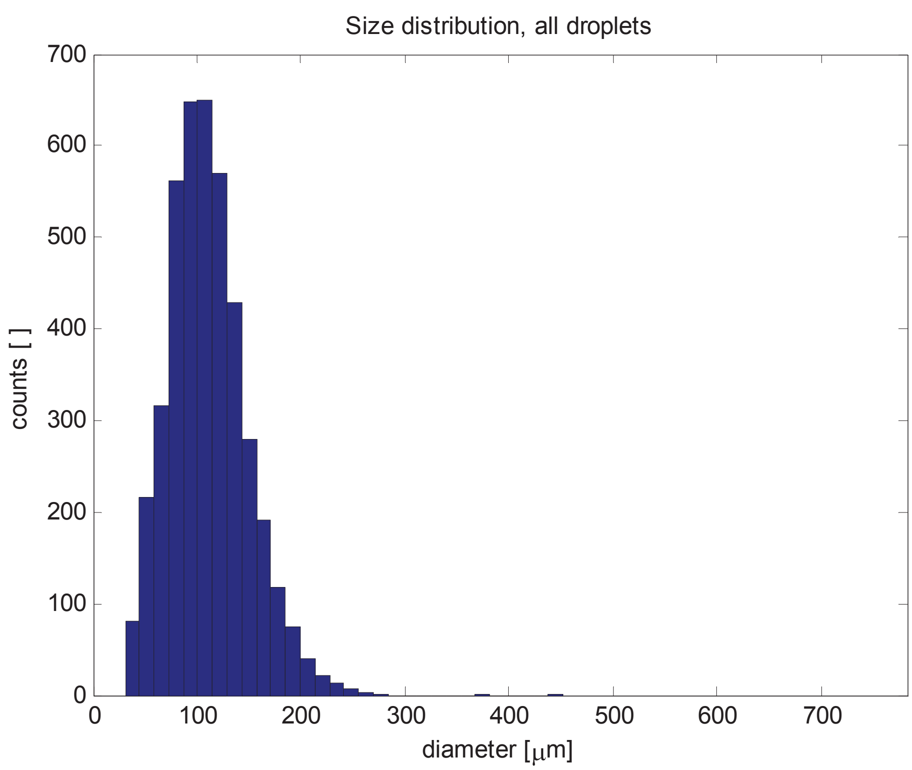


Figure 41. Size distribution in spray/plume, injection pressure 100 bar.

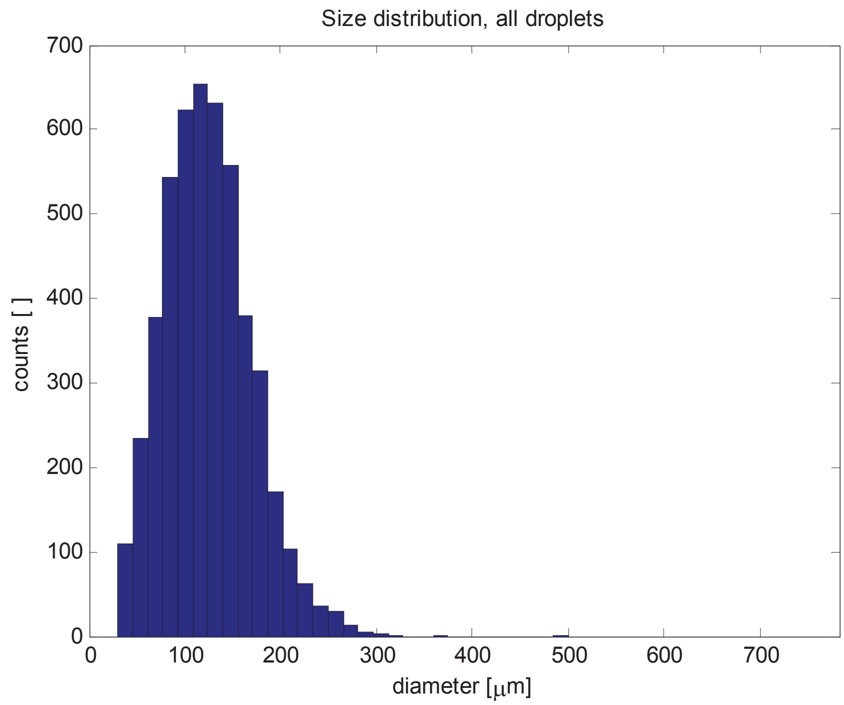


Figure 42. Size distribution in spray/plume, injection pressure 75 bar.

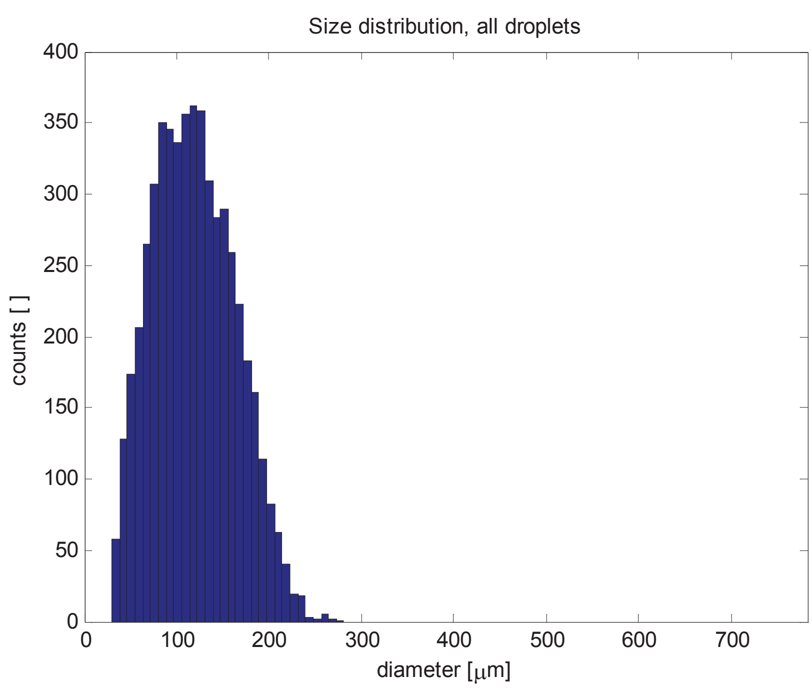


Figure 43. Size distribution in spray/plume, injection pressure 50 bar.

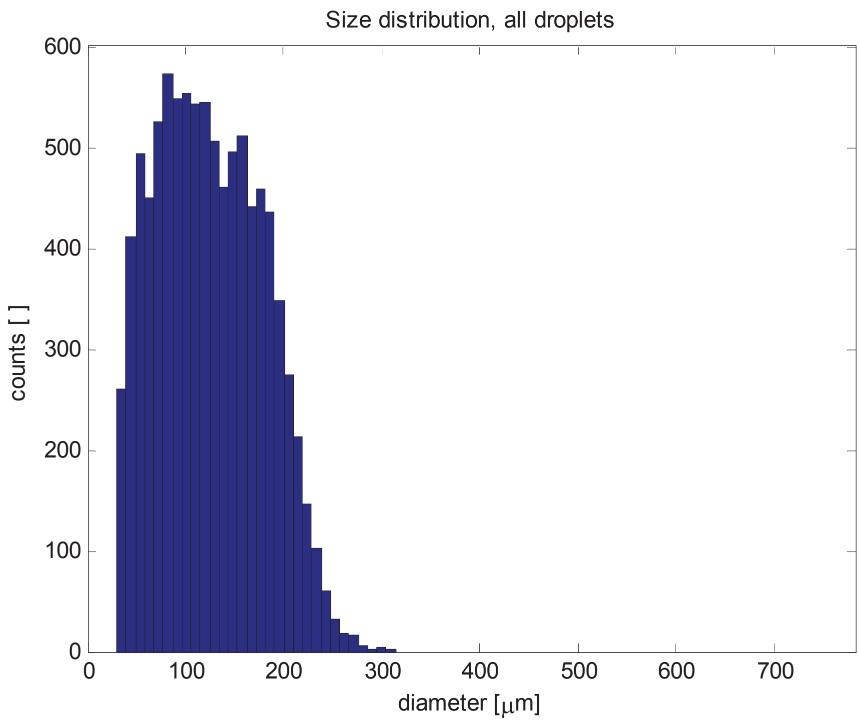


Figure 44. Size distribution in spray/plume, injection pressure 25 bar.

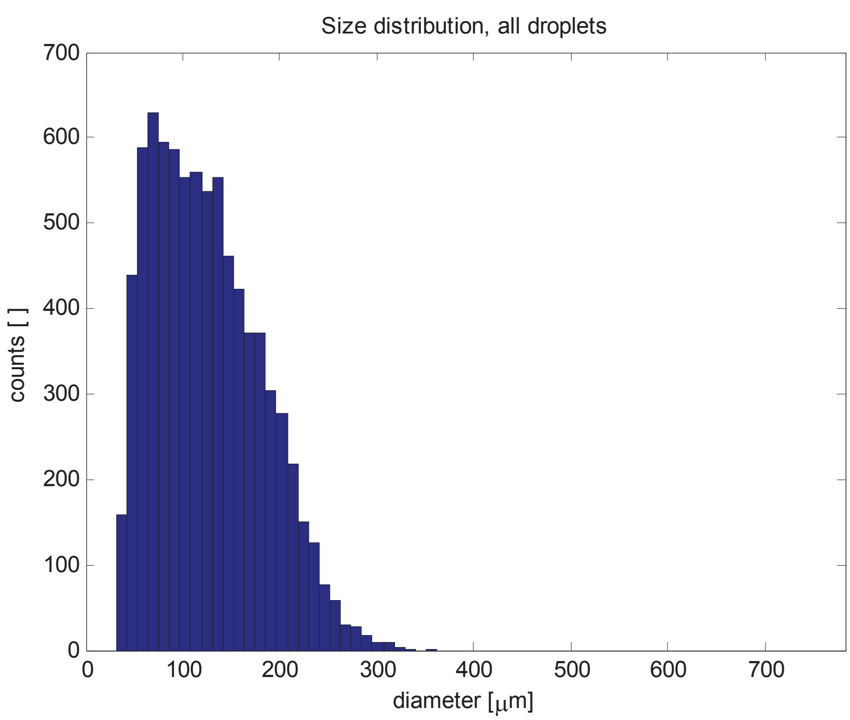


Figure 45. Size distribution in spray/plume, injection pressure 12 bar.

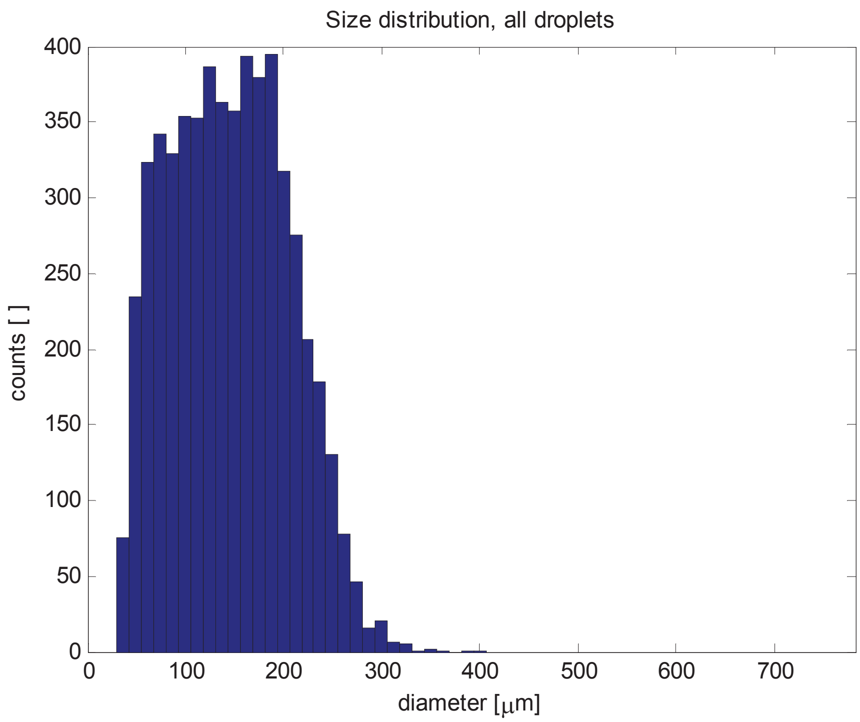


Figure 46. Size distribution in spray/plume, injection pressure 6 bar.

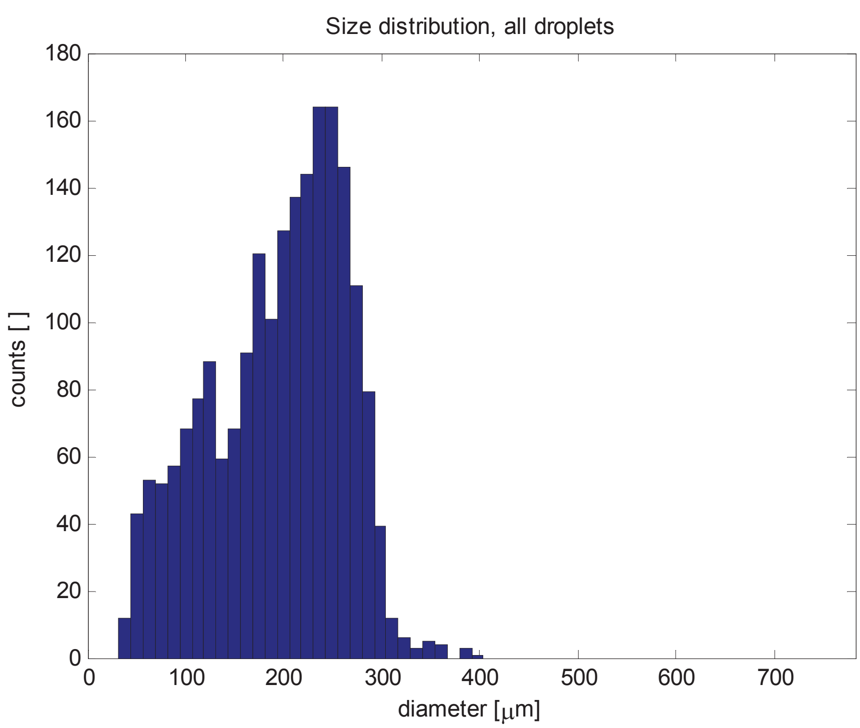


Figure 47. Size distribution in spray/plume, injection pressure 3 bar.

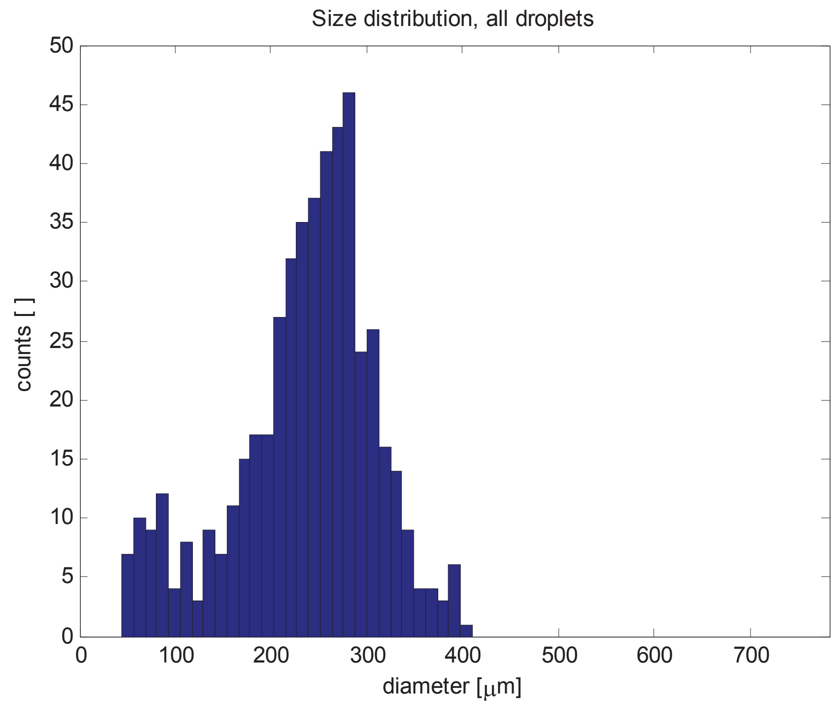


Figure 48. Size distribution in spray/plume, injection pressure 1.5 bar.

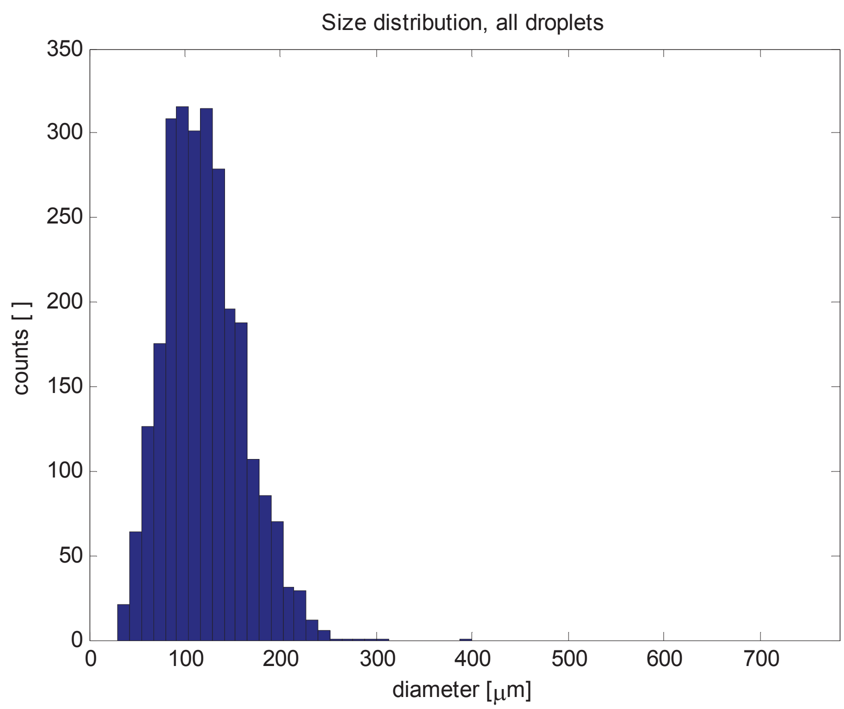


Figure 49. Size distribution between sprays/plumes, injection pressure 100 bar.

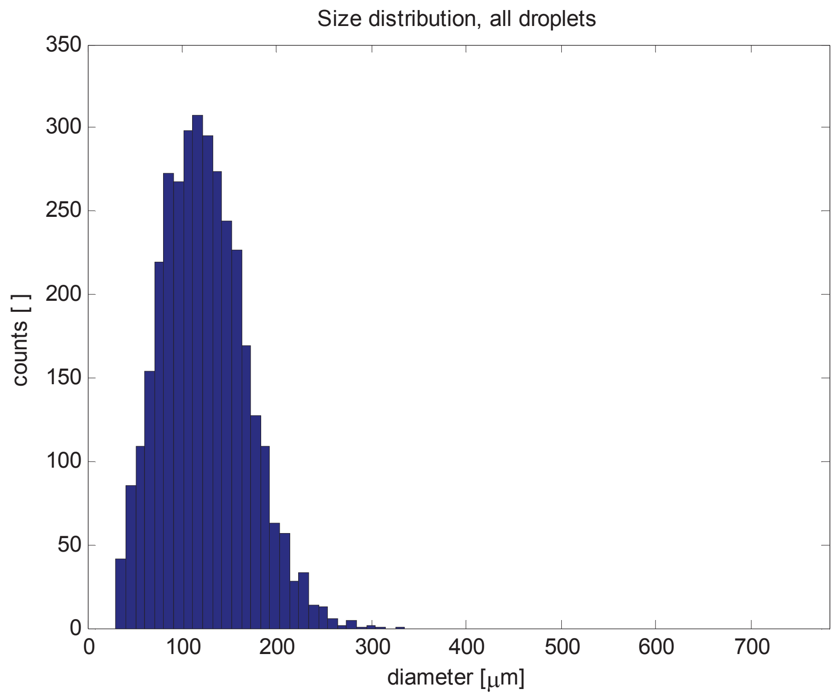


Figure 50. Size distribution between sprays/plumes, injection pressure 75 bar.

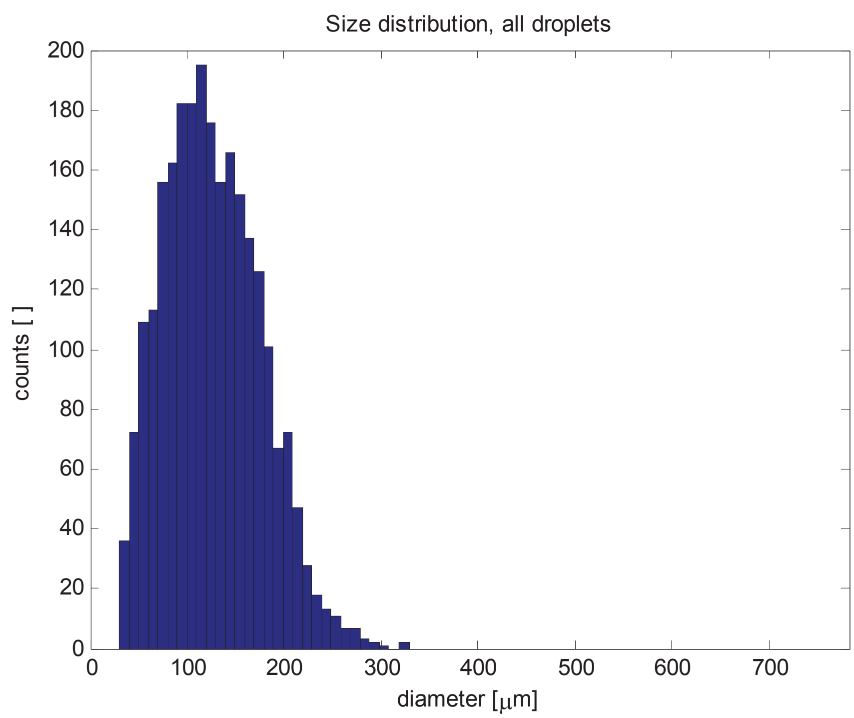


Figure 51. Size distribution between sprays/plumes, injection pressure 50 bar.

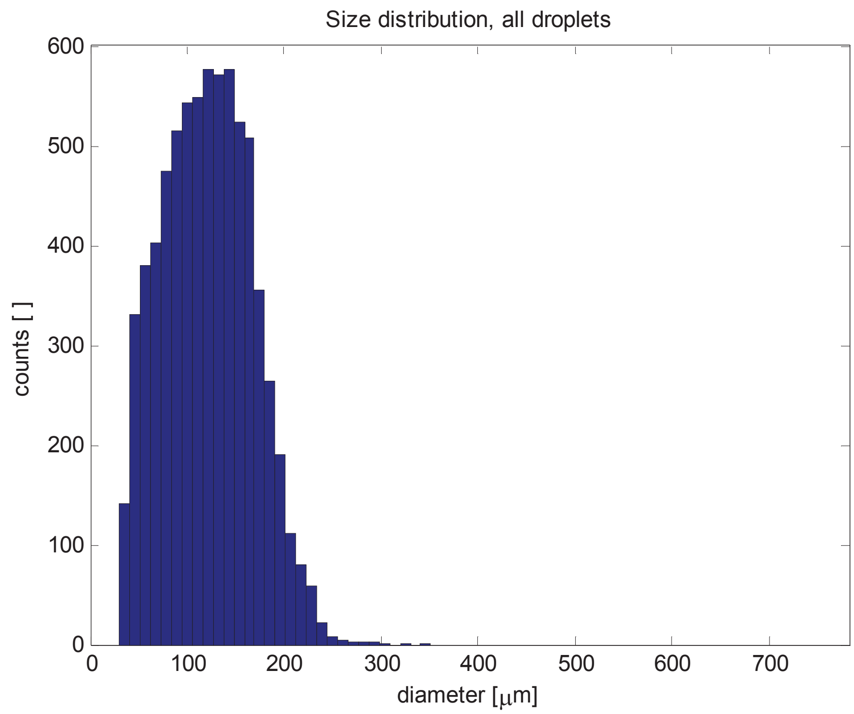


Figure 52. Size distribution between sprays/plumes, injection pressure 25 bar.

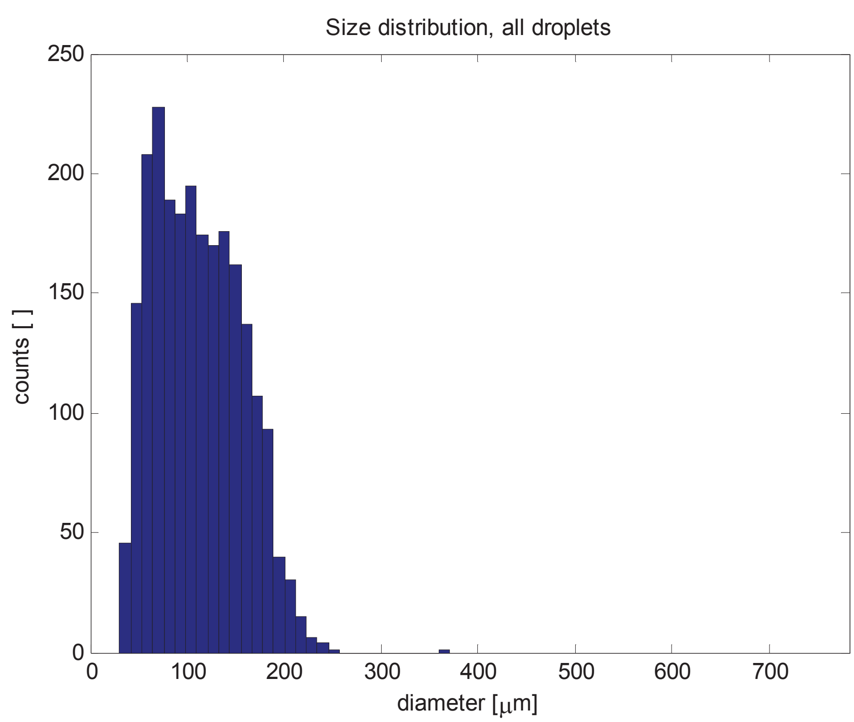


Figure 53. Size distribution between sprays/plumes, injection pressure 12 bar.

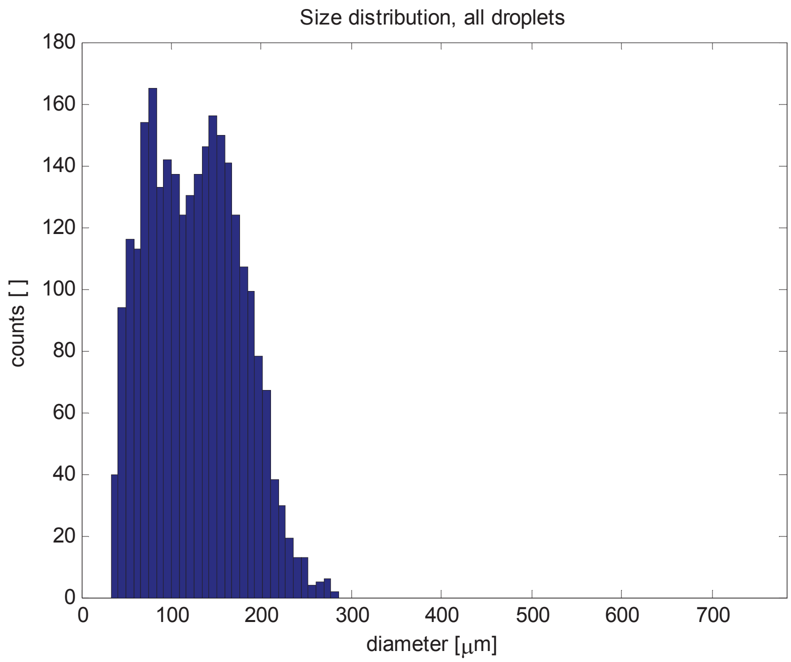


Figure 54. Size distribution between sprays/plumes, injection pressure 6 bar.

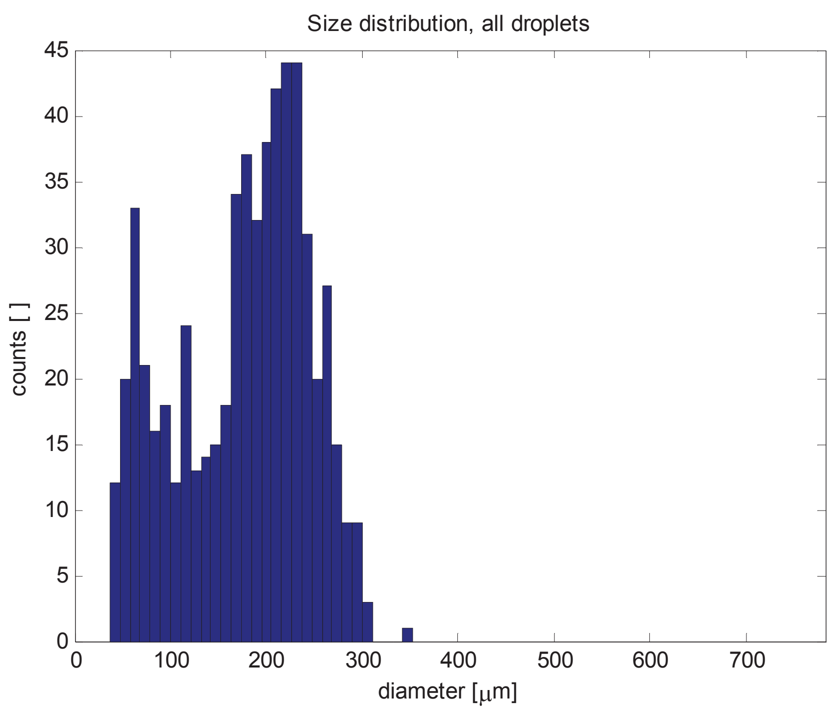


Figure 55. Size distribution between sprays/plumes, injection pressure 3 bar.

Discussion

Extinguishment

Extinguishment or time to extinguishment are, especially in the ventilated conditions used in this test series, very uncertain measures of performance for a water mist system. Small changes in conditions can result in large differences in time to extinguishment.

In the fire tests described in this report, extinguishment was not achieved when compartment temperatures were reduced too rapidly. One possible explanation for this is that the maximum partial pressure of water was reduced with reduced temperature and the total reduction of oxygen in the compartment depends on both accumulated combustion products and water vapour content. Further, when the temperature in the compartment is reduced the pressure in the compartment is reduced allowing for inlet of air through the ventilation opening.

As a result of this, temperature reduction in the test space and extinguishment (or time to extinguishment) can be contradictory. This was apparent in the tests with non-obstructed fires when the water mist system was at 100% and 75% of normal operating pressure. In these tests the system reduced the temperatures in the compartment very efficiently but the fire was not extinguished until the fuel was consumed.

Mixing performance

The Temperature Uniformity Factor (TUF) was calculated to evaluate the system's ability to create turbulence and mix the gases in the test compartment. The tests with intact systems at various pressures and for different fire scenarios all had TUF values that indicated that the water mist system was not very efficient in mixing the gases in the test space.

Other tests [1] have shown that high pressure water mist systems were efficient in mixing the gases in a compartment, that is, low TUF values were achieved. However, these tests were performed with smaller fires (250 – 500 kW pool fires) in a larger compartments (250 – 500 m^3) with no ventilation. In the tests performed in this project the fire was relatively large (1.3 MW), the compartment was smaller (135 m^3) and was ventilated by a 2 m x 0.8 m door opening. The airflow through the door opening was promoted by 1.3 MW pool fire. The kinetic energy in the high pressure water mist is probably not enough to disturb this airflow and efficiently mix the gas in the test space.

In Figure 56 the TUF values for two tests with the high pressure system are compared to TUF values for tests performed with a water spray system with significantly higher water discharge densities and lower pressures [7]. The low pressure water spray system mixed the gases more efficiently than the water mist system and the decrease in TUF values were achieved rapidly after the system was activated. This is likely due to the higher kinetic energy of the water spray.

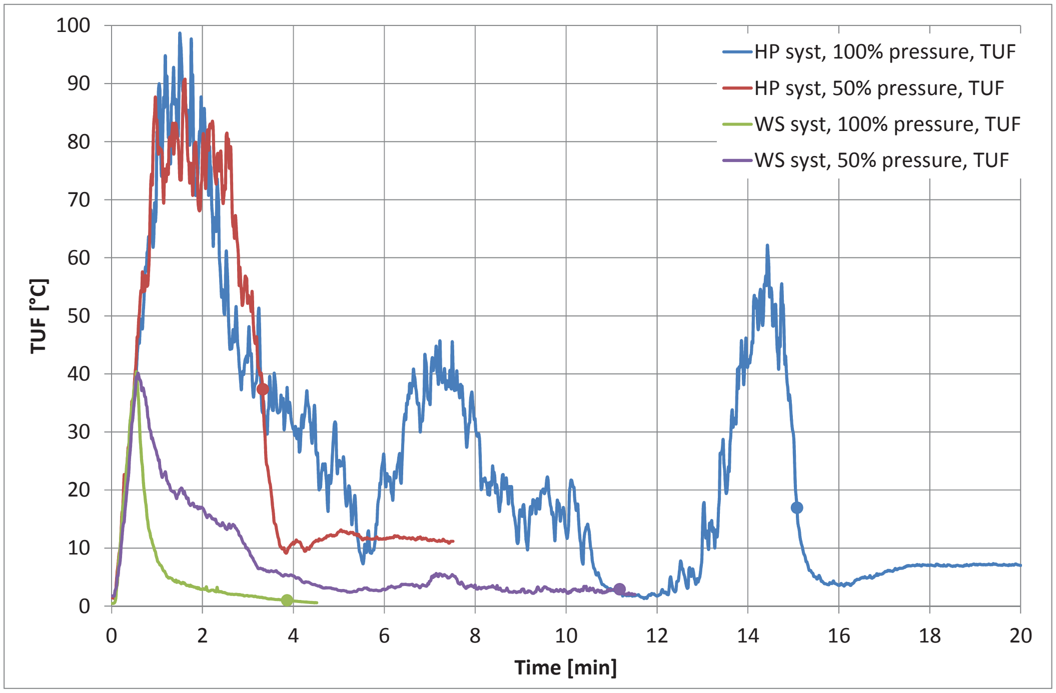


Figure 56 – Comparison of variation of TUFs with time of the high pressure (HP) water mist system in this test series and a water spray (WS) system. The time of extinguishment is marked with a dot.

In some of the tests using 'damaged systems', the damaged water mist system was quite efficient in mixing the gases in the compartment. This was seen in Tests 18, 21, 22 and 23. This could be an effect of asymmetry in the water discharge resulting from the punctures in the piping system creating turbulence in the compartment or simply an effect of the increased water discharge density in certain areas of the test space. Since the tests using a damaged system are a bit "uncontrolled" with regards to the direction of the spray from the punctures in the damaged pipes, the water might have in some cases (possibly in Tests 22 and 23, but not in Tests 18 and 21) hit the thermocouples directly and affected the calculated TUF values.

Effects of obstructions

The time to reduce the temperature to below 80°C increased with increased obstruction of the fire. The results are shown in Table 7. A possible explanation for this is that water mist cannot reach the fire and less of it is vaporized. Alternatively the obstruction increases the radiation/heat flux to the fuel surface and increases the heat release rate and therefore temperature in the space.

The fact that the compartment temperature was higher for the 100% obstructed fires might be a reason why the 100% obstructed fires were extinguished by the water mist system at 100% and 75% of normal operating pressure while the unobstructed fires at 100% and 75% of normal operating pressure were not extinguished.

Table 8 – Gas temperatures at varying obstruction conditions

Pressure [% of operating pressure]	Time (after activation) to temp <80°C [min:s] Non-obstructed	Time (after activation) to temp <80°C [min:s] 50% obstruction	Time (after activation) to temp <80°C [min:s] 100% obstruction
100	1:57	2:38	3:08
75	2:22	2:37	4:16
50	2:27	2:43	2:58
25	3:46	3:41	5:53

Conclusions

The results of a series of fire suppression tests using a dry pipe high pressure water mist in both the undamaged and damaged state have been reported. The tests were carried out in a compartment with the dimensions 7.5 m x 7.5 m x 2.4 m (L x W x H) in which a 1.3 MW fire was burning. The damage was simulated in three ways; by reducing system pressure to simulate leakage or a malfunctioning pump; by reducing the number of operational nozzles, and by using damaged sections of pipe in the water mist system.

The tests showed that a high pressure water mist system qualified according to MSC/Circ.1165 was capable of reducing the compartment temperatures to levels where human lives could be saved even when the system pressure was reduced to 25% of normal operating pressure. The reduced temperatures would also prevent division (bulkhead) failure and eliminate the risk of flashover so that the fire could most likely be contained in the compartment of origin. Even at pressures as low as 5 bar, i.e., a typical fire main pressure, the compartment temperatures were reduced such that the probability of flashover was significantly reduced and a division failure would be delayed or avoided.

The tests with a reduced number of nozzles indicated that the average temperature in the space peaked at 150 °C – 170 °C and decreased to about 80°C after 10 minutes. Temperatures were controlled to the degree that the chance of flashover was eliminated and a division failure was prevented. This implies that the suggested redundancy design using two separate water pump systems, each supplying 50 % of the nozzles in an enclosure with water, would be an efficient fire risk control measure.

For the conditions used in this test series, extinguishment was achieved when the water mist system did not cool the compartment too efficiently and when the water discharge density was high enough. However, extinguishment was found to be very scenario dependent. Changing test conditions, such as pre burning time, ventilation and compartment size might result in a very different performance of the water mist system

Comparison of the results for tests using damaged pipe sections with the results of tests with intact (undamaged) piping but at reduced operating pressure indicated that the spray from the punctures in the damaged pipe generally improved the performance of the system as measured by average gas temperatures, the mixing of gases (reduced TUF value) and time to extinguishment.. This implied that a damaged system generally performs at least as well as an intact system with reduced operating pressure. This knowledge can be an important factor in decision making progress on whether or not to shut off a damaged system.

In general the tested high pressure system was not very efficient in reducing the TUF values (mixing the gases) in the compartment. In some damage scenarios the mixing was improved by the spray from the punctures in the damaged pipes.

The tested high pressure system did not fulfil the performance criteria for cooling the dummy torpedo. Thus, such a system cannot, without further development, be recommended as an alternative to the high water density requirements for ammunition storage found in e.g. the Naval Ship Code (NSC), or in Class regulations.

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Appendices

Appendix 1 – Damage scenarios

Appendix 1

Damage scenarios

Damage scenario 1 - Pipe 1

Figure 57. Picture of pipe 1. In the left picture we see one puncture (approx. 2 mm) and one gash (approx. 6 mm). To the right is a picture of the spray from the puncture and gash when the pipe is installed in the test compartment. The pipe diameter is 12 mm.

The k-factor of the puncture and gash is approx. 4.1

Table 9 Pressure drop over nozzles when the damage pipe is installed in the test compartment,

Damage pipe no.	Total flow [L/min]	Pressure at north nozzle [bar]	Pressure at south nozzle [bar]	Average pressure [bar]	Calculated leak flow [L/min]
Pipe 1	103.6	65.8	72.0	68.9	34

Appendix 1

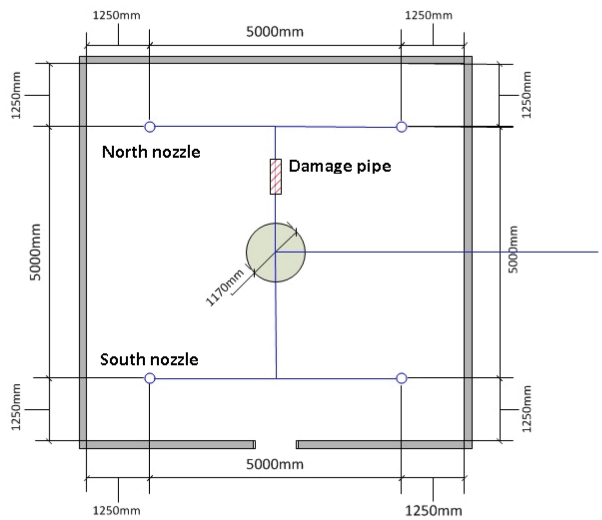

Figure 58. Overview of test compartment and placement of damaged pipes in tests 1-6.

Appendix 1

Damage scenario 2 - Pipe 2

Figure 59. Picture of pipe 2. The pipe is punctured in two places, hole 1 (approx. 3×4 mm) to the left and hole 2 (approx. 4×2 mm) to the right. The pipe diameter is 12 mm.

Figure 60. Picture of the spray from the punctures when the pipe is installed in the test compartment.

The overall k-factor of the punctures is approx. 9.8

Table 10. Pressure drop over nozzles when the damage pipe is installed in the test compartment, see Figure 58.

Damage pipe no.	Total flow [L/min]	Pressure at north nozzle [bar]	Pressure at south nozzle [bar]	Average pressure [bar]	Calculated leak flow [L/min]
Pipe 2	104.1	30.0	38.5	34.3	57.4

Appendix 1

Damage scenario 3 - Pipe 4

Figure 61. Picture of pipe 4, puncture is approx. 5×6 mm. To the right is a picture of the spray from the punctures when the pipe is installed in the test compartment. The pipe diameter is 12 mm.

The k-factor of the puncture is approx. 12.2

Table 11. Pressure drop over nozzles when the damage pipe is installed in the test compartment, see Figure 58.

Damage pipe no.	Total flow [L/min]	Pressure at north nozzle [bar]	Pressure at south nozzle [bar]	Average pressure [bar]	Calculated leak flow [L/min]
Pipe 4	104.8	24.0	33.6	28.8	65.5

Damage scenario 4 - Pipe 7

Figure 62. Picture of pipe 7,puncture approx. 16× 12 mm. To the right is a picture of the spray from the punctures when the pipe is installed in the test compartment. The pipe diameter is 12 mm

The k-factor of the puncture is approx. 36.9

Table 12. Pressure drop over nozzles when the damage pipe is installed in the test compartment, see Figure 58

Damage pipe no.	Total flow [L/min]	Pressure at north nozzle [bar]	Pressure at south nozzle [bar]	Average pressure [bar]	Calculated leak flow [L/min]
Pipe 7	104.9	12.9	31.0	22.0	132.5*

*Calculated leak flow not realistic. The reason for this in unknown.

Damage scenario 5 - Pipe 8

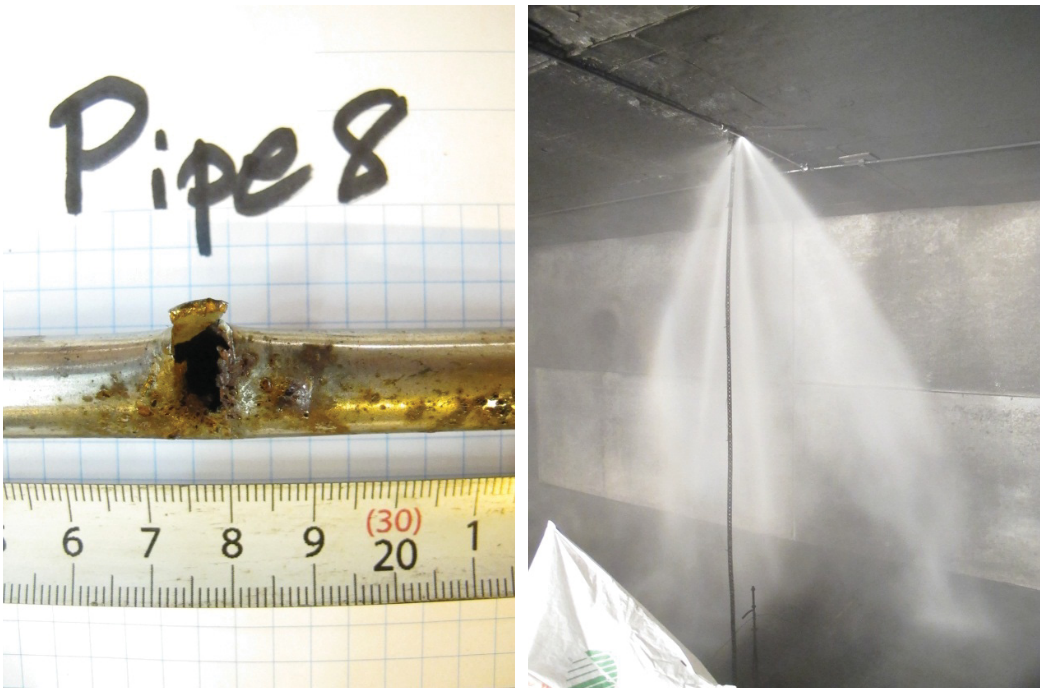

Figure 63. Picture of pipe 8,puncture approx. (not measured yet). To the right is a picture of the spray from the punctures when the pipe is installed in the test compartment. The pipe diameter is 12 mm

The k-factor of the puncture is approx. 19.4

Table 13. Pressure drop over nozzles when the damage pipe is installed in the test compartment, see Figure 58.

Damage pipe no.	Total flow [L/min]	Pressure at north nozzle [bar]	Pressure at south nozzle [bar]	Average pressure [bar]	Calculated leak flow [L/min]
Pipe 8	105.5	11.7	21.8	16.8	79.5

Damage scenario 6 - Pipe 3

Figure 64. Picture of pipe 3, puncture is approx. 5×2 mm. To the right is a picture of the spray from the punctures when the pipe is installed in the test compartment. The pipe diameter is 12 mm.

The k-factor of the puncture is approx. 4.4

Table 14. Pressure drop over nozzles when the damage pipe is installed in the test compartment, see Figure 58.

Damage pipe no.	Total flow [L/min]	Pressure at north nozzle [bar]	Pressure at south nozzle [bar]	Average pressure [bar]	Calculated leak flow [L/min]
Pipe 3	103.4	62.0	67.6	64.8	35.4

Damage scenario 7 - Pipe 5

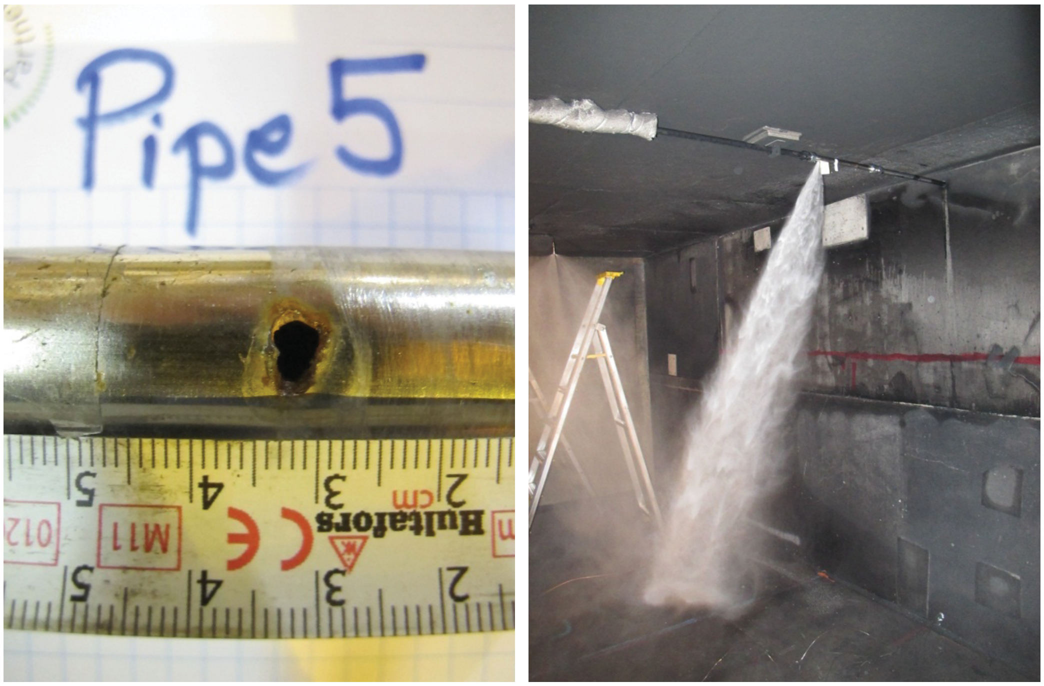

Figure 65. Picture of pipe 5, one puncture approx. 4×5 mm and one buckle approx. 5 mm. To the right is a picture of the spray from the punctures when the pipe is installed in the test compartment. The pipe diameter is 22 mm

The k-factor of the puncture is approx. 8.7

Table 15. Pressure drop over nozzles when the damage pipe is installed in the test compartment, see Figure 58

Damage pipe no.	Total flow [L/min]	Pressure at north nozzle [bar]	Pressure at south nozzle [bar]	Average pressure [bar]	Calculated leak flow [L/min]
Pipe 5	104.9	35.5	36.1	35.8	52.1

Appendix 1

Damage scenario 8 - Pipe 6

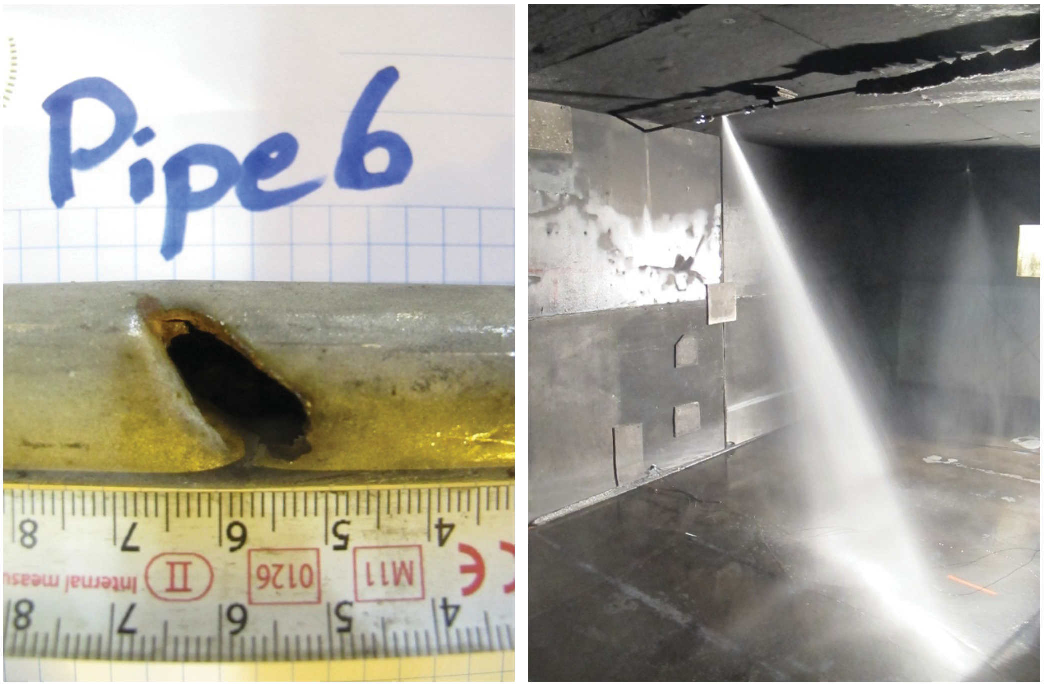

Figure 66. Picture of pipe 6, puncture approx. 16 × 6 mm. To the right is a picture of the spray from the punctures when the pipe is installed in the test compartment. The pipe diameter is 22 mm

The k-factor of the puncture is approx. 51.8

Table 16. Pressure drop over nozzles when the damage pipe is installed in the test compartment, seeFigure 58.

Damage pipe no.	Total flow [L/min]	Pressure at north nozzle [bar]	Pressure at south nozzle [bar]	Average pressure [bar]	Calculated leak flow [L/min]
Pipe 6	106.6	2.8	2.9	2.9	88.2

Damage scenario 9 - Pipe 4 and 5

For test 26 two damage pipes were installed in the piping system, pipe 5 in the feeding pipe and pipe 4 in the branch pipe, see Figure 67.Data on pipe 4 and 5 can be seen in this appendix on page 4 and 8.

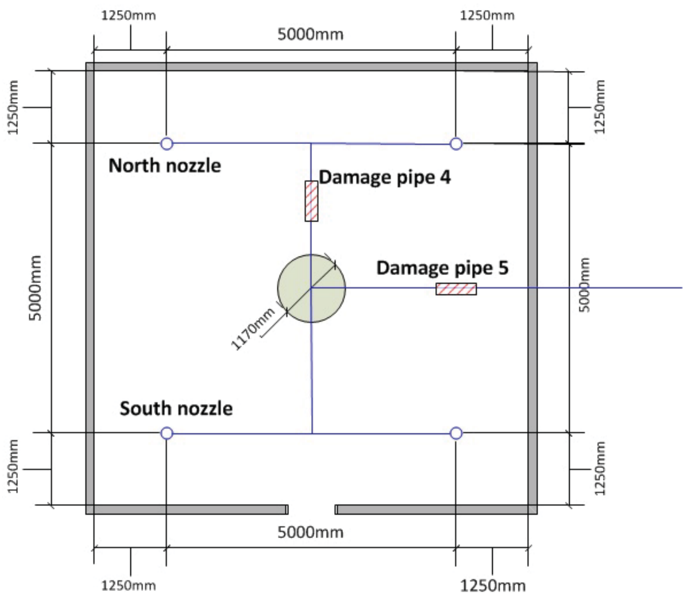

Figure 67. Overview of the test compartment with damage pipe 4 and 5 installed in the piping.

Table 17. Pressure drop over nozzles when the damage pipe is installed in the test compartment, see Figure 67.

Damage pipe no.	Total flow [L/min]	Pressure at north nozzle [bar]	Pressure at south nozzle [bar]	Average pressure [bar]	Calculated leak flow [L/min]
Pipe 4 and 5	105.8	11.6	15.8	13.7	77.4

Damage scenario 10 – Pipe 4

For test 27 the already tested damage pipe 4 was placed in a different location in the piping, see Figure 67. Data on pipe 4 can be seen in this appendix on page 4.

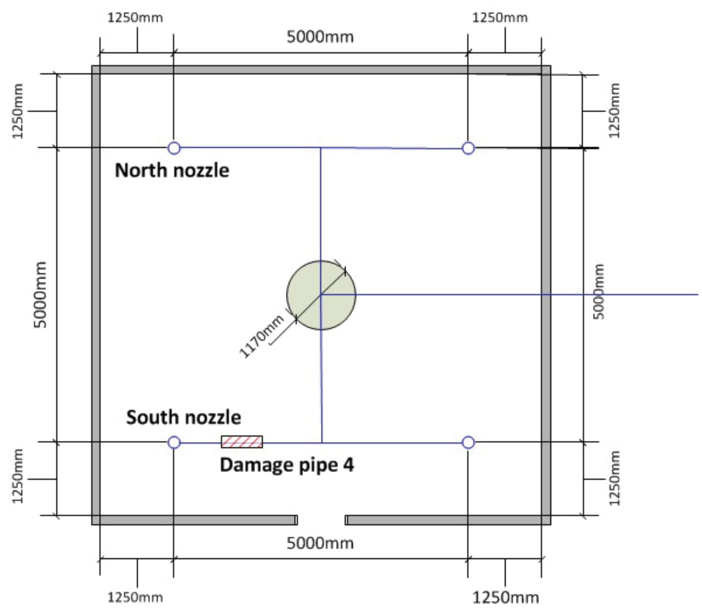

Figure 68. Overview of the test compartment when damage pipe 4 was moved to a different location in the piping.

Table 18. Pressure drop over nozzles when the damage pipe is installed in the test compartment, see Figure 68

Damage pipe no.	Total flow [L/min]	Pressure at north nozzle [bar]	Pressure at south nozzle [bar]	Average pressure [bar]	Calculated leak flow [L/min]
Pipe 4	104.9	35.6	23.8	29.7	66.5

Appendix 2