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The VINNOVA water mist research project: A description of the 500 m^3 machinery space tests

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Abstract

This report describes water mist and water spray system tests inside a simulated machinery space. The tests were conducted inside a compartment measuring 8,0 m by 12,5 m with a ceiling height of 5,0 m. The corresponding volume was 500 m^3. The walls and the ceiling were constructed from steel plates. The test compartment replicates an intermediate size machinery space compartment onboard a ship.

Either diesel oil or heptane pool fires were used as the fire source. The fires had nominal heat release rates of 500 kW, 1 MW and 2 MW, respectively and were either fully exposed to the water spray or completely shielded by a horizontal obstruction steel plate measuring 2 m by 2 m.

Three different systems were tested; (1) a water spray system flowing 500 L/min at 2 bar (this system was designed according to the SOLAS convention), (2) a low-pressure system flowing 97 L/min at 12 bar and (3) a high-pressure system flowing 60 L/min at 70 bar. In addition to the tests using these three systems, free burn tests were conducted inside the compartment.

This report contains a description of the test set-up, its instrumentation, the fire test procedures and a limited presentation of the results. A more thorough analysis of the test results will be made in subsequent reports, articles and papers.

Key words: Water mist, water sprays, machinery spaces, fire, fire tests, halon alternative.

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Preface

About two-thirds of all fires on board ships start in the machinery space. An estimation made by Det Norske Veritas indicates that the direct cost for a fire is of the order of 1 – 4 million USD for a cargo vessel - and much more for a passenger vessel. Obviously, a fire in the machinery space also represents a hazard for the crew members and fire fighters and may lead to a situation where passengers need to be evacuated from the vessel.

Traditionally, Halon and Carbon Dioxide (CO_2) gas extinguishing systems are those most commonly used in machinery spaces. With the phase-out of Halon and the increasing safety concerns regarding the use of CO_2, the need for alternative extinguishing agents has emerged. The developments during the 1990s have shown that water mist has the potential to replace, or to provide an alternative to, traditional fire protection systems. Water has many advantages as a fire extinguishant; it is inexpensive, non-toxic, safe for personnel and does not represent a risk to the external environment.

The primary objective of the project is to investigate and demonstrate the potential use of water mist in large machinery spaces on board ships. To reach this goal, several full-scale tests need to be conducted and sufficient scaling rules need to be developed. The following parts are included in this project:

- Full scale machinery space water mist system tests in three different volumes,
- The development of scaling rules,
- Formulation of the requirements for water mist systems for large machinery spaces,
- Provision of input for the forthcoming revision of IMO MSC/Circ.668 and 728.
- Preparation of an implementation of the international SOLAS requirements.

This report contains a description of the test set-up, its instrumentation, the fire test procedures and a limited presentation of the results. A more thorough analysis of the test results will be made in subsequent reports, articles and papers.

The project was financed by VINNOVA, the Swedish Agency for Innovation Systems, project no. 20851-1 together with Marioff Corporation Oy (Finland) and Tyco Fire Products (USA). The input and help from these partners is gratefully acknowledged.

The internal project no. was BRs 6081.

1 The test compartment

The test compartment measured 8,0 m by 12,5 m and had a ceiling height of 5,0 m. The walls and the ceiling were constructed from nominally 2 mm thick steel plates. The compartment was fitted with one doorway opening at floor level. The doorway opening had a sliding steel door, measuring 2,5 m by 2,3 m. This door was open during the ignition of the tests fires, but was closed immediately thereafter.

The ceiling had three pressure relief vents, one large vent, positioned centric at the ceiling and two smaller vents, positioned close to the ceiling corners. All three vents had steel hatches.

The large vent measured 2,0 m by 2,9 m (5,8 m^2). The two smaller vents measured 0,75 m by 0,75 m each (0,56 m^2). During the majority of the tests, the hatches of the large, centric opening were sealed closed. The hatches of the two smaller vents at the ceiling corners were allowed to open and close during the tests to relief the over pressure inside the test compartment.

However, during a limited number of tests, either the hatches of the large opening or the two hatches of the smaller vents were open during the entire test. These tests were conducted in order to evaluate the performance of the tested systems during other ventilation conditions. Principle drawings of the test compartment are presented in enclosure 1.

The leakage integrity of the test compartment has previously been measured using the fan pressurisation method. Three tests were conducted, the first with all openings sealed closed (over pressure only) and the second and third allowing the two smaller vents at the corners to open (over pressure and under pressure). The results are summarized in the table below. The tests are documented in test report ETs P009428, dated 2001-07-09.

Table 1 The results from the integrity tests of the test compartment.

	Leakage flow [L/s]		
Pressure [Pa]	Test 1, all hatches sealed closed	Test 2, two smaller vents allowed to open	Test 3, two smaller vents allowed to open
-200	-	110	-
-150	-	95	-
-100	-	70	-
-50	-	50	-
0	0	0	0
50	85	-	112
100	165	-	255
150	285	-	N/D
200	N/D	-	N/D

N/D = Not Determined due to the limited capacity of the fan.

2 The fire scenarios

Either diesel oil or heptane pool fires were used. The fires had a nominal heat release rate of 500 kW, 1 MW and 2 MW, respectively and were either fully exposed to the water spray or completely shielded by a horizontal obstruction steel plate measuring 2 m by 2 m. The nominal thickness of the steel plate was 4 mm.

The pool fires were arranged in circular trays with diameters chosen to provide the desired heat release rate. The rim height of the trays was 150 mm and trays were filled with 50 mm of fuel. Additional water was added to provide a freeboard of 50 mm. The 500 kW trays were filled with 100 mm of fuel (only) from test 3. The following two tables provide information on the trays.

Table 2 The sizes of the diesel oil trays.

Nominal HRR	Diameter [cm]	Area [m^2]	Rim height [mm]	Amount of fuel [L]	Amount of water [L]
500 kW	79	0,49	150	49	-
1 MW	101	0,80	150	40	40
2 MW*	144	1,63	250	81,5	244

*) No tests were conducted using the 2 MW diesel pool fire. Size of pool fire tray given for reference purposes only.

Table 3 The sizes of the heptane trays.

Nominal HRR	Diameter [cm]	Area [m^2]	Rim height [mm]	Amount of fuel [L]	Amount of water [L]
500 kW	62	0,30	150	30	-
1 MW	79	0,49	150	24,5	24,5
2 MW	112	0,98	150	49	49

During the tests, the pool fire tray was placed on a load cell to determine the weight loss. The vertical distance measured from the rim of the trays to the bottom side of the horizontal obstruction steel plate was 700 mm.

The reason for choosing pool fires only, was twofold. Firstly, it is possible to determine the heat release rate of the fire by means of measuring the weight loss of the fire tray. Obviously, this is however, only possible for the cases where the pool fire was obstructed from direct impingement of the water spray. Secondly, pool fires are generally more difficult to extinguish for a given fire size, compared to spray fires.

3 The water spray and the water mist systems

3.1 Water spray system in accordance with Chapter 7 of the FSS Code

Under the test compartment ceiling, a piping arrangement was fabricated consisting of a single feed grided piping system, which was installed to minimise the difference between the flow rates of the nozzles. A supply hose was connected to one of the 40 mm mains located on opposite sides of the grid. Four 32 mm cross connections spaced 3,33 m apart were made between the mains to serve as the feed lines to the individual nozzles during the test. At 3,33 m spacing along the cross connections, 15 mm diameter pipe drops were installed down to the pendent nozzles. The ceiling to nozzle deflector distance was 250 mm. The system was fitted with a pressure transducer so that the operator could adjust the pump output and maintain the specific flowing pressure in response to any pressure changes.

The nozzles were made by Tyco Fire products and designated Protectospray D3 24-110. The nozzles had a K-factor of 43,2 (metric) and a spray angle of 110º.

No pump unit was necessary; the water was taken directly from the public water main.

A nominal flowing pressure of 2 bar was utilised throughout the tests, which provided for a flow rate per nozzle of about 62,5 L/min. The total flow rate was 500 L/min and the corresponding nominal discharge density 5 mm/min.

From the initiation of the water flow into the test compartment there was a 2 - 3 second delay before full pressure to the nozzle piping system was reached.

This system was designed according to the requirements of Chapter 7 of the FSS Code[1] (previously these requirements were found in SOLAS II-2, regulation 10).

3.2 Low-pressure water mist system (Tyco Fire Products)

The pipe-work for this system was identical with the pipe-work used for the water spray system. Eight *AquaMist* AM15 (K=3,6 metric) nozzles were fitted directly into 32 mm x 15 mm reducing tees. The nozzles were installed in an upright position (per manufacturers instructions) with a ceiling to nozzle diffuser distance of 250 mm.

The pump unit was connected to a 3 m^3 stainless steel tank that was continuously filled from the public water main with potable water.

A nominal flowing pressure of 12 bar was utilised throughout the tests, which provided for a flow rate per nozzle of about 12,1 L/min. The total flow rate was 97 L/min and the corresponding nominal discharge density 0,97 mm/min.

From the initiation of the water flow into the test compartment there was a 2 - 3 second delay before full pressure to the nozzle piping system was reached.

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[1] International Code for Fire Safety Systems (FSS Code), Resolution MSC.98(73), International Maritime Organization, London, UK, 2001

3.3 High-pressure water mist system (Marioff Corporation Oy)

Under the test compartment ceiling, a tree type piping arrangement was fabricated consisting of a 25 mm primary stainless steel main with pairs of 2,5 m long, 12 mm diameter branch lines running perpendicular to the main line at 5,0 m intervals. A total of four nozzles (K=1,9) were installed in the test compartment. A supply pipe was connected to one end of the 25 mm main, which were connected to the high-pressure pump unit.

The nozzles were designated Hi-Fog 4S 1MC 8MB 1000.

A nominal flowing pressure of 70 bar was utilised throughout the tests, which provided for a flow rate per nozzle of about 15 L/min. The total flow rate was 60 L/min and the corresponding nominal discharge density 0,60 mm/min.

During the tests, the flow meter was positioned on the low-pressure side of the pump. The water flow to the pump was approximately 84 L/min and 24 L/min were shunted off.

4 Instrumentation

The test compartment was instrumented to measure both the thermal conditions inside the space, the wall and ceiling surface temperatures, the radiant heat flux from the fires, the compartment pressure as well as the gas concentrations of O_2, CO and CO_2. Table 4 provides information on all measurement positions and associated channels.

The data was recorded at a rate of about one scan per second.

4.1 Temperature measurements

Two thermocouple trees were used to measure the gas temperatures inside the test compartment. Each tree consisted of 10 thermocouples positioned at the following distances below the ceiling; 250 mm, 500 mm, 1000 mm, 1500 mm, 2000 mm, 2500 mm, 3000 mm, 3500 mm, 4000 mm and 4500 mm. Small angle iron shields were positioned above each measurement point to minimize wetting of the thermocouples by direct water spray impingement. The ceiling gas temperature (25 mm below the ceiling surface) was measured centric at the ceiling, right above the position of the fire source.

All thermocouples were of type K (chromel-alumel) and made from 0,5 mm wire welded together. Pentronic AB manufactures the wires. The quality is class 1, according to the IEC 584-1 standard, which means an accuracy of ±1,5°C in the interval -40 to +375°C and 0,04% of measured value above 375°C.

The wall surface temperatures were measured with a type K thermocouple that was spot-welded to the walls (on the inside of the test compartment). The measurement points were positioned at the centreline of the short side wall and the long side wall, respectively, 500 mm, 2500 mm and 4500 mm below the ceiling. The ceiling surface temperature was measured centric at the ceiling, above the position of the fire source, using a thermocouple spot-welded to the ceiling.

4.2 Gas concentration measurements

4.2.1 Oxygen concentration measurements

For the measurements of the oxygen (O_2) concentration at the measurement position 4500 mm below ceiling, a Siemens Oxymat analyser having inventory number 700014 was used (channel 5). The instrument was calibrated prior to use for a span of 14,7 - 21 vol-% oxygen. The inaccuracy is less than ±0,1 vol-% oxygen.

For the measurements of the oxygen (O_2) concentration at the measurement position 1000 mm below ceiling, a M & C Instruments, PMA 10 analyser having inventory number 700173 was used (channel 80). The instrument was calibrated prior to use for a span of 0 – 21 vol-% oxygen. The inaccuracy is less than ±0,1 vol-% oxygen.

4.2.2 Carbon monoxide concentration measurements

The concentration of carbon monoxide (CO) was recorded at the measurement position 4500 mm below ceiling (channel 6) with a Rosemount Binos 100-2M analyser having inventory number 700394. The instrument was calibrated prior to the use for a span of 0 – 0,6 vol-% carbon monoxide. The inaccuracy is equal to, or less than ±2% of full scale.

The concentration of carbon monoxide (CO) was recorded at the measurement position 1000 mm below ceiling (channel 79) with a Siemens Ultramat 22P analyser having inventory number 700240. The instrument was calibrated prior to the use for a span of 0 – 3 vol-% carbon monoxide. The inaccuracy is equal to, or less than ±2% of full scale.

4.2.3 Carbon Dioxide concentration measurements

The concentration of carbon dioxide (CO_2) at the measurement position 4500 mm below ceiling was recorded (channel 7) with a Rosemount Binos 100-2M analyser having inventory number 700394. The instrument was calibrated prior to the use for a span of 0 – 6,0 vol-% carbon dioxide. The inaccuracy is equal to, or less than ±2% of full scale.

The concentration of carbon dioxide (CO_2) at the measurement position 1000 mm below ceiling was recorded (channel 78) with a Siemens Ultramat 22P analyser having inventory number 700240. The instrument was calibrated prior to the use for a span of 0 – 10 vol-% carbon dioxide. The inaccuracy is equal to, or less than ±2% of full scale.

4.3 Heat flux measurements

The radiant heat flux from the fires was recorded with a Schmidt Boelter transducer manufactured by Medtherm Co., positioned 4000 mm from the fire and 500 mm above floor. The instrument has a full-scale range of 0 – 20 kW/m^2. The transducer had serial number 56363.

4.4 Compartment pressure measurements

The compartment pressure was measured close to one of the corners of the test compartment using a Digima Premo 355 differential pressure transducer, having inventory number 700179. The instrument has an inaccuracy of less than 0,5% of measured value, and the response time from zero to full scale is less than one millisecond.

4.5 Humidity measurements

The humidity inside the test compartment was measured at three different positions, 1000 mm, 2500 mm and 4500 mm below the ceiling, respectively, using Testo Hygrotest 650 version 4 transmitters. The instruments have an external humidity and temperature probe. The accuracy of the instrument is ±1% RH.

4.6 System water pressure and water flow rate

The system water pressure was measured at two positions, at the pump, or, for the water spray system tests, at the public water supply and at the pipe-work grid, using Transinstrument 2000A pressure transducers.

The total water flow rate was measured using a Krohne 0 – 2000 L/min flow meter. The instrument has inventory number 701065. For the high-pressure system tests, it should be noted that the flow meter was positioned on the low-pressure side of the pump. The water flow to the pump was approximately 84 L/min and 24 L/min were shunted off. The latter value was determined by using collecting the water for one minute and weighing it.

4.7 The weight loss of the fire tray

The weight loss of the fire tray was determined using a load cell.

Table 4 Measurement positions and associated channels. Refer to drawings in enclosure for exact positions.

Channel No.	Channel name	Description and position
Ch 21	TC 1	Gas temperature, 250 mm below ceiling (pos. 1)
Ch 22	TC 2	Gas temperature, 500 mm below ceiling (pos. 1)
Ch 23	TC 3	Gas temperature, 1000 mm below ceiling (pos. 1)
Ch 24	TC 4	Gas temperature, 1500 mm below ceiling (pos. 1)
Ch 25	TC 5	Gas temperature, 2000 mm below ceiling (pos. 1)
Ch 26	TC 6	Gas temperature, 2500 mm below ceiling (pos. 1)
Ch 27	TC 7	Gas temperature, 3000 mm below ceiling (pos. 1)
Ch 28	TC 8	Gas temperature, 3500 mm below ceiling (pos. 1)
Ch 29	TC 9	Gas temperature, 4000 mm below ceiling (pos. 1)
Ch 30	TC 10	Gas temperature, 4500 mm below ceiling (pos. 1)
Ch 31	TC 11	Gas temperature, 250 mm below ceiling (pos. 2)
Ch 32	TC 12	Gas temperature, 500 mm below ceiling (pos. 2)
Ch 33	TC 13	Gas temperature, 1000 mm below ceiling (pos. 2)
Ch 34	TC 14	Gas temperature, 1500 mm below ceiling (pos. 2)
Ch 35	TC 15	Gas temperature, 2000 mm below ceiling (pos. 2)
Ch 36	TC 16	Gas temperature, 2500 mm below ceiling (pos. 2)
Ch 37	TC 17	Gas temperature, 3000 mm below ceiling (pos. 2)
Ch 38	TC 18	Gas temperature, 3500 mm below ceiling (pos. 2)
Ch 39	TC 19	Gas temperature, 4000 mm below ceiling (pos. 2)
Ch 40	TC 20	Gas temperature, 4500 mm below ceiling (pos. 2)
Ch 44	TC 24	Gas temperature, centric at corner ceiling opening (pos.4)
Ch 48	TC 28	Gas temperature, centric at corner ceiling opening (pos. 6)
Ch 52	TC 32	Flame temperature, close to pool fire (sheathed)
Ch 49	TC 29	Ceiling surface temp. centric at ceiling (spot-welded)
Ch 50	TC 30	Gas temperature, centric at ceiling, 25 mm below ceiling (sheathed)
Ch 41	TC 21	Wall surface temp. 500 mm below ceiling (short side wall)
Ch 42	TC 22	Wall surface temp. 2500 mm below ceiling (short side wall)
Ch 43	TC 23	Wall surface temp. 4500 mm below ceiling (short side wall)
Ch 45	TC 25	Wall surface temp. 500 mm below ceiling (long side wall)
Ch 46	TC 26	Wall surface temp. 2500 mm below ceiling (long side wall)
Ch 47	TC 27	Wall surface temp. 4500 mm below ceiling (long side wall)
Ch 51	TC 31	Surface temperature of obstruction steel plate (welded)
Ch 78	CO2	Oxygen concentration, 1000 mm below ceiling (pos. 1)
Ch 79	CO** (inaccurate)	Carbon monoxide concentration, 1000 mm below ceiling (pos. 1)
Ch 80	O2	Carbon dioxide concentration, 1000 mm below ceiling (pos. 1)
Ch 5	CO2	Oxygen concentration, 4500 mm below ceiling (pos. 1)
Ch 6	CO	Carbon monoxide concentration, 4500 mm below ceiling (pos. 1)
Ch 7	O2	Carbon dioxide concentration, 4500 mm below ceiling (pos. 1)
Ch 77*	Värmestrålning	Heat flux meter, 4500 mm below ceiling
Ch 61	Pumptryck	Water pressure (at pump)
Ch 63	Systemtryck	Water pressure (system pressure)
Ch 56	Rumstryck	Compartment pressure
Ch 55	Vattenflöde	System water flow rate
Ch 75/Ch 76	Luftfuktighet / Temperatur	Humidity meter / temp., 1000 mm below ceiling (pos. 1)*
Ch 73/Ch 74	Luftfuktighet / Temperatur	Humidity meter / temp., 2500 mm below ceiling (pos. 1)
Ch 71/Ch 72	Luftfuktighet / Temperatur	Humidity meter / temp., 4500 mm below ceiling (pos. 1)

*) The CO measurement equipment at the higher position probably shows higher values than actual concentration.

**) Heat flux meter installed 4000 mm below ceiling in tests 1 and 2.

5 Test procedures

5.1 Fire test procedures

The fires were ignited using a torch, and allowed to burn for 2 minutes (500 kW and 1 MW fires) or 30 seconds (2 MW fires) before the water flow was initiated. For the diesel pool fires, a small amount of heptane was used to obtain ignition.

From the temperature readings during the tests and from visual observations from the test compartment window it was possible to judge when the fires were extinguished. Water was left on for a couple of minutes after extinguishment to cool the test compartment. The measurements were continued for an additional period of time after the flow of water was shut off.

The level of fuel in the tray was observed after the end of the applicable tests to make sure that no limitation of fuel occurred during the test.

The data file identities were specified using the following principal code:

TestXSN(HRR)FTOF, where:

X = consecutive test number.
S = "system".
N = system type, was given either 1, 2 or 3 or FB for Free Burn.
HRR = nominal heat release rate, was given either 500 (kW), 1 (MW) or 2 (MW)
FT = Fire Type, was given P for Pool fire.
O = Obstruction, was given either E or O (Exposed or Obstructed)
F = Fuel, was given either H or D (Heptane or Diesel).

The name "Test10S1(500)POH" would therefore correspond to the 10th consecutive test, the first tested system (the low-pressure system), and an obstructed 500 kW heptane pool fire.

The fire test procedure was as follows:

00:00	Start of the measurement
01:00	Ignition of the fire
01:05	Closure of the steel door to the test compartment
01:30	Initiation of water (for the tests using fires with nominal HRR of 2 MW)
03:00	Initiation of the water (for all other fire sizes)

5.2 Water discharge test procedure

The water discharge densities of the three systems were measured at the center of the test compartment using 25 water collector trays under non-fire conditions. Each tray measured 500 mm by 500 mm. Each discharge test was conducted for two minutes and the amount of water in each tray was determined by weighing the water.

The steel door and all the ventilation openings were closed during the water discharge tests.

6 Test results and observations

This section provides a limited presentation of the test results and observations. A more thorough analysis of the test results will be made in subsequent reports, articles and papers.

6.1 Fire tests

All times to extinguishment given in the tables below are calculated from the ignition of the fire, not from the activation of the system, in order to provide comparable data irrespective of the pre-burn time.

During the first tests with the low-pressure system significant under pressure was created during the initial cooling of the hot atmosphere of the test compartment. This under pressure was of the order of -400 Pa and was judged to be crucial to the test compartment integrity. It was therefore judged to be necessary to reduce the pre-planned pre-burn time of the 2 MW fires from 2 minutes to only 30 seconds. In addition, the practice for all the following 1 MW and 2 MW size fires tests was to open one of the small ceiling vents just prior to the activation of the system, to deal with the initial under pressure, and close it 10 - 15 seconds later. An exception from this practice was made for test 30, in order to attain comparison test data for the high-pressure system with the obstructed 1 MW heptane pool fire.

The pressure vents of the test compartment, however, were able to compensate for the subsequent over pressure phase caused by the water vapour expansion.

Table 5 Test results and observations for the low-pressure system.

Test no.	**Fuel**	**HRR**	**Obstruction?**	**Ext. Time**	**Ventilation openings?**	**Remarks and observations**
1	Heptane	500 kW	Obstructed	N/E	None	Fuel consumed after approx. 22 minutes.
2	Heptane	1 MW	Obstructed	12:30	None	Critical under pressure inside test compartment upon activation of the system.
3	Heptane	500 kW	Obstructed	33:15	None	100 mm of fuel used in tray. Heat flux gauge moved to 4500 mm below ceiling. Thermocouple used in fire tray out of function.
5	Heptane	2 MW	Obstructed	03:12	None	Teflon filters installed on the humidity meters.
6	Heptane	2 MW	Exposed	04:21	None	-
7	Heptane	2 MW	Exposed	06:08	None	Repeat of test 6.
8	Heptane	1 MW	Exposed	15:50	None	-
9	Heptane	500 kW	Exposed	29:00	None	-
10	Diesel	500 kW	Exposed	N/E	None	Fire manually extinguished after 36 minutes from ignition.
11	Diesel	1 MW	Exposed	N/E	None	Fire manually extinguished 27 minutes after ignition.
12	Diesel	1 MW	Obstructed	17:10	None	Size of the insulation board protecting the load cell reduced.
13	Heptane	1 MW	Obstructed	22:55	Two small vents open	-
14	Heptane	1 MW	Obstructed	16:30	Two small vents open	Repeat of test 13
15	Heptane	1 MW	Obstructed	N/E	Large vent open	Fuel consumed after approx. 17 minutes after ignition.
16	Heptane	2 MW	Obstructed	11:34	Large vent open	Overload of the compartment pressure transducer

Table 6 Test results and observations for the water spray system installed in accordance with Chapter 7 of the FSS Code.

Test no.	**Fuel**	**HRR**	**Obstruction?**	**Ext. time**	**Ventilation openings?**	**Remarks and observations**
17	Heptane	500 kW	Obstructed	28:07	None	-
18	Heptane	1 MW	Obstructed	10:40	None	One small vent opening was opened prior to the initiation of the water to reduce the under pressure. Closed after 20 seconds.
19	Heptane	2 MW	Obstructed	07:10	None	-
20	Heptane	2 MW	Obstructed	05:55	None	Repeat of test 19.
21	Heptane	2 MW	Obstructed	N/E	Large vent opening	Very close to extinguishment after approximately 7 minutes, 10 minutes and 13 minutes. Fuel consumed after approx. 17 minutes.
22	Diesel	500 kW	Obstructed	29:00	None	-
23	Diesel	1 MW	Obstructed	10:05	None	-
24	Heptane	1 MW	Obstructed	14:50	Two small vents open	-
25	Heptane	1 MW	Obstructed	N/E	Large vent opening	-
26	Heptane	1 MW	Exposed	N/E	None	The system was shut off, 15:00 after ignition, due to the risk for overflowing the fire tray.
27	Diesel	500 kW	Exposed	N/E	None	The system was shut off, 11:00 after ignition, due to the risk for overflowing the fire tray.
28	Diesel	1 MW	Exposed	17:05	None	Very close to extinguishment after approx. 10 minutes.

Table 7 Test results and observations for the high-pressure system.

Test no.	**Fuel**	**HRR**	**Obstruction?**	**Ext. time**	**Ventilation openings?**	**Remarks and observations**
29	Heptane	500 kW	Obstructed	26:18	None	-
30	Heptane	1 MW	Obstructed	08:47	None	No provisions made to deal with the initial under pressure.
31	Heptane	1 MW	Obstructed	07:28	Two small vents open	-
32	Heptane	1 MW	Obstructed	13:22	Two small vents open	Repeat of test 31
33	Heptane	1 MW	Obstructed	N/E	Large vent opening	Fuel consumed after approx 39 minutes. Compartment pressure measurement uncertain.
34	Heptane	2 MW	Obstructed	06:23	Large vent opening	Compartment pressure transducer out of function
35	Heptane	2 MW	Obstructed	03:25	None	-
36	Heptane	2 MW	Exposed	03:55	None	-
37	Heptane	1 MW	Exposed	08:00	None	-
38	Diesel	1 MW	Exposed	05:12	None	-
39	Diesel	500 kW	Exposed	09:40	None	-
40	Diesel	1 MW	Obstructed	08:50	None	-

Table 8 Free-burn tests, conducted without the application of water.

Test no.	**Fuel**	**HRR**	**Obstruction?**	**Ext. time**	**Ventilation openings?**	**Remarks and observations**
4	Heptane	500 kW	Obstructed	19:25	None	-
41	Heptane	1 MW	Obstructed	09:03	None	-
42	Heptane	2 MW	Obstructed	03:40	None	Humidity meters not in use. T/C trees moved. The load cell was not used.
42	Heptane	1 MW	Obstructed	07:55	Two small vents open	Humidity meters not in use. T/C trees moved. The load cell was not used.

6.2 Water discharge tests

The tables below present the results from the water discharge density measurements. Each discharge test was conducted for two minutes and the amount of water in each tray was determined by weighing the water. The tables provide the results in mm/min (equal to L/m^2/min).

Table 9 Water discharge densities for the low-pressure system in mm/min.

0,32 21	**0,29** 22	**0,26** 23	**0,23** 24	**0,23** 25
0,33 16	**0,30** 17	**0,31** 18	**0,30** 19	**0,27** 20
0,33 11	**0,29** 12	**0,31** 13	**0,31** 14	**0,32** 15
0,30 6	**0,32** 7	**0,28** 8	**0,31** 9	**0,33** 10
0,24 1	**0,29** 2	**0,28** 3	**0,30** 4	**0,30** 5

It can be concluded that the water discharge density for the low-pressure system was very uniform between the four nozzles. The average discharge density measured 0,29 mm/min as compared to the nominal discharge density of 0,97 mm/min.

Table 10 Water discharge densities for the water spray system installed in accordance with Chapter 7 of the FSS Code in mm/min.

1,34 21	**1,78** 22	**1,86** 23	**1,42** 24	**1,15** 25
1,27 16	**1,41** 17	**1,43** 18	**1,38** 19	**1,41** 20
1,30 11	**1,23** 12	**1,17** 13	**1,32** 14	**1,67** 15
1,16 6	**1,18** 7	**1,22** 8	**1,25** 9	**1,49** 10
1,01 1	**1,03** 2	**1,28** 3	**1,55** 4	**1,27** 5

It can be concluded that the water discharge density for the water spray system was relatively uniform between the four nozzles. The average discharge density measured 1,34 mm/min as compared to the nominal discharge density of 5 mm/min.

Table 11 Water discharge densities for the high-pressure system in mm/min.

0,12 21	**0,13** 22	**0,19** 23	**0,38** 24	**0,54** 25
0,11 16	**0,14** 17	**0,17** 18	**0,24** 19	**0,27** 20
0,09 11	**0,11** 12	**0,13** 13	**0,15** 14	**0,15** 15
0,12 6	**0,16** 7	**0,18** 8	**0,16** 9	**0,15** 10
0,15 1	**0,18** 2	**0,21** 3	**0,19** 4	**0,18** 5

It can be concluded that the water discharge density for the high-pressure system was relatively uniform between the four nozzles. The average discharge density measured 0,18 mm/min as compared to the nominal discharge density of 0,60 mm/min.

7 Discussion of the test results

7.1 Times to extinguishment

Time to extinguishment is the traditional, and most simplistic, means of evaluating the performance of any fire protection system. For water spray and water mist systems, experience has shown that the time to extinguishment is primarily a function of the compartment volume, the fire size, the ventilation conditions, the fire type, the degree of obstruction of the fire and the characteristics of the system. All these parameters, except for the compartment volume, were studied in these tests.

All times to extinguishment given in the tables below are calculated from the ignition of the fire, not from the activation of the system, in order to provide comparable data irrespective of the pre-burn time.

7.2 The repeatability of the times to extinguishment

Several of the fire scenarios were repeated, at ‘identical’ conditions and these tests indicate that ‘time to extinguishment’ is not a very repeatable variable, refer to table 12.

One scenario was repeated using the water spray system and the obstructed 2 MW heptane fire. The difference in time to extinguishment, comparing tests 19 and 20, was over 20%.

Comparing tests 13 and 14, which were conducted under the same conditions, using the low-pressure system, indicates considerably different times to extinguishment for the obstructed 1 MW heptane pool fire, however, the oxygen level upon extinguishment was nearly identical. The difference in time to extinguishment is nearly 40%. For these two tests, the two small vents at the ceiling were open. The same trend is seen for the exposed 2 MW heptane fire, comparing tests 6 and 7. The difference in time to extinguishment is over 40%.

The most extreme variation in time to extinguishment was observed for the obstructed 1 MW heptane pool fire using the high-pressure system; refer to tests 31 and 32. The difference is nearly 80%. For these two tests the two small vents at the ceiling were open.

The measured “dry” oxygen concentrations were adjusted to include water vapour, assuming that the gases were saturated. These values are indicated as the “wet” oxygen concentrations in table 12. A test-to-test comparison of the minimum ”wet” oxygen concentrations indicates that they are reasonably similar.

Table 12 Comparison of times to extinguishment for the tests that were repeated

Test no.	**System**	**Fuel**	**HRR**	**Obstruction**	**Ventilation openings**	**Ext. time [min:sec]**	**Minimum (dry/wet) oxygen concentration [vol-%]**			
							1000 mm below ceiling		4500 mm below ceiling	
							Dry	Wet	Dry	Wet
19	WS	Heptane	2 MW	Obstructed	None	07:10	13,7	12,2	14,7*	13,8
20	WS	Heptane	2 MW	Obstructed	None	05:55	14,6	13,0	14,9	13,9
13	LP	Heptane	1 MW	Obstructed	Two small vents open	22:55	14,8	13,5	15,5	14,1
14	LP	Heptane	1 MW	Obstructed	Two small vents open	16:30	15,1	13,5	15,5	13,9
6	LP	Heptane	2 MW	Exposed	None	04:21	17,1	14,1	17,7	14,9
7	LP	Heptane	2 MW	Exposed	None	06:08	16,7	14,3	17,3	14,8
31	HP	Heptane	1 MW	Obstructed	Two small vents open	07:28	16,4	13,7	16,7	14,2
32	HP	Heptane	1 MW	Obstructed	Two small vents open	13:22	15,6	13,4	15,7	13,6

*) The minimum limit of the instrument.

7.3 Comparing times to extinguishment with the free burn tests

As pointed out above, the tests indicate that the time to extinguishment is not a very repeatable variable. However, the time to extinguishment could serve as an indication of the performance of a system, if it is followed by an analysis based on other measurements. As previously mentioned, free burn tests were conducted, in addition to the tests using the three systems. All the free burn tests were conducted with the test compartment sealed closed.

The tests indicate that the time to extinguishment for the obstructed 500 kW pool fire actually was shorter for the free burn test (no system activated) compared to the all three system tests. For the other free burn fire scenarios, i.e. the obstructed 1 MW and 2 MW heptane pool fires, the times to extinguishment for the free burn tests were comparable to the fastest times achieved with the systems. It should be pointed out that these observations were made with the test compartment sealed closed, but it highlights the fact that the benefit from a water spray or water mist system does not necessarily lie in the time to extinguishment of a fire. If a compartment is closed and sufficiently air tight and robust, a fire could self-extinguish as fast as it would be extinguished by a water spray or water mist system.

Table 13 Comparison of times to extinguishment for the free burn tests versus the tests that were conducted with the three systems. The test compartment was sealed closed.

Test no.	**System**	**Fuel**	**HRR**	**Ext. time [min:sec]**	**Minimum (dry/wet) oxygen concentration [vol-%]**			
					1000 mm below ceiling		4500 mm below ceiling	
					Dry	Wet	Dry	Wet
4	Free burn	Heptane	500 kW	19:25	13,3	-	14,7*	-
17	WS	Heptane	500 kW	28:07	13,8	13,5	14,7*	14,5
3	LP	Heptane	500 kW	33:15	14,3	13,6	14,9	14,1
29	HP	Heptane	500 kW	26:18	14,9	13,7	14,9	13,7
41	Free burn	Heptane	1 MW	09:03	14,3	-	15,3	-
18	WS	Heptane	1 MW	10:40	15,0	14,2	15,3	14,8
2	LP	Heptane	1 MW	12:30	15,4	13,7	16,2	14,4
30	HP	Heptane	1 MW	08:47	15,9	13,3	16,0	13,5
42	Free burn	Heptane	2 MW	03:40	11,4	-	14,7*	-
19	WS	Heptane	2 MW	07:10	13,7	12,2	14,7*	13,8
20	WS	Heptane	2 MW	05:55	14,6	13,0	14,9	13,9
5	LP	Heptane	2 MW	03:12	16,5	13,2	17,1	14,0
35	HP	Heptane	2 MW	03:25	16,3	12,2	16,7	13,5

*) The minimum limit of the instrument.

7.4 The influence of the obstruction steel plate

The influence of the horizontal obstruction steel plate on the ability for fire extinguishment is interesting to study. Different trials using both exposed and obstructed pool fires were made using all three systems. The results are presented in table 14.

Table 14 Comparison of times to extinguishment for obstructed versus exposed pool fires. The test compartment was sealed closed.

Test no.	**System**	**Fuel**	**HRR**	**Obstruction**	**Ventilation openings**	**Ext. time [min:sec]**	**Minimum (dry) oxygen concentration [vol-%]**	
							1000 mm below ceiling	4500 mm below ceiling
18	WS	Heptane	1 MW	Obstructed	None	10:40	15,0	15,3
26	WS	Heptane	1 MW	Exposed	None	N/E**	16,3	16,5
22	WS	Diesel	500 kW	Obstructed	None	29:00	13,3	14,7*
27	WS	Diesel	500 kW	Exposed	None	N/E***	19,2	19,3
23	WS	Diesel	1 MW	Obstructed	None	10:05	14,7	14,8
28	WS	Diesel	1 MW	Exposed	None	17:05	17,7	18,0
12	LP	Diesel	1 MW	Obstructed	None	17:10	14,6	15,4
11	LP	Diesel	1 MW	Exposed	None	N/E	16,8	17,2
2	LP	Heptane	1 MW	Obstructed	None	12:30	15,4	16,2
8	LP	Heptane	1 MW	Exposed	None	15:50	15,9	16,5
3	LP	Heptane	500 kW	Obstructed	None	33:15	14,3	14,9
9	LP	Heptane	500 kW	Exposed	None	29:00	15,5	16,1
5	LP	Heptane	2 MW	Obstructed	None	03:12	16,5	17,1
6	LP	Heptane	2 MW	Exposed	None	04:21	17,1	17,7
7	LP	Heptane	2 MW	Exposed	None	06:08	16,7	17,3
30	HP	Heptane	1 MW	Obstructed	None	08:47	15,9	16,0
37	HP	Heptane	1 MW	Exposed	None	08:00	17,0	17,4
40	HP	Diesel	1 MW	Obstructed	None	08:50	15,9	16,4
38	HP	Diesel	1 MW	Exposed	None	05:12	17,5	17,9

N/E = Not Extinguished.
*) Minimum limit of the instrument.
**) For test 26, the system was shut off, 15:00 after ignition, due to the risk for overflowing the fire tray. The minimum oxygen level is given after this time.
***) For test 27, the system was shut off, 11:00 after ignition, due to the risk for overflowing the fire tray. The minimum oxygen level is given after this time.

A common view is that exposed fires are easier to extinguish compared to obstructed fires. The results obtained during these tests indicate that this viewpoint may be true for system having small water droplets, but not true for systems having larger water droplets.

Test 18 (obstructed 1 MW heptane pool fire) and test 26 (exposed 1 MW heptane pool fire) were conducted using the water spray system. The obstructed fire was extinguished after 10:40 (min:sec). For the exposed fire, the water spray system was shut off, 15:00 (min:sec) after ignition, as there was an obvious risk for overflowing the fire tray. Both from the visual observations and from the oxygen concentration measurements, it can be determined that the exposed fire was suppressed by the water spray, which reduced the reduction of the oxygen level inside the test compartment. The trend is the same for test 22 (obstructed 500 kW diesel pool fire) and test 27 (exposed 500 kW diesel pool fire). The obstructed diesel pool fire was extinguished after 29:00 (min:sec), the exposed fire was suppressed until the fire tray nearly overflowed, and the water flow was shut off.

Further analysis of the tests using the water spray system shows that the time to extinguishment was prolonged for other exposed fires. The fire in test 23 (obstructed 1 MW diesel pool fire) was extinguished after 10:05 (min:sec), whilst the fire in test 28 (exposed 1 MW diesel pool fire) was extinguished after 17:05 (min:sec).

For the water spray system, it can be therefore be concluded that the interaction between the water droplets and the fuel surface reduces the heat release rate of the exposed pool fires such that the times to extinguishment is either prolonged or the fire is not extinguished relative to the same fires when obstructed.

The trend is to some extent observed with the low-pressure system, but it is not as pronounced. When the 1 MW diesel pool fire was obstructed in test 12, the fire was extinguished after 17:10 (min:sec), when it was exposed in test 11, the fire was not extinguished. The fire in test 2 (obstructed 1 MW heptane pool fire) was extinguished after 12:30 (min:sec), whilst the fire in test 8 (exposed 1 MW heptane pool fire) was extinguished after 15:50 (min:sec). The tendency is also observed for the 2 MW heptane fires, both tests conducted with the fire exposed, tests 6 and 7 experience longer times to extinguishment compared to the obstructed case in test 5. However, for the 500 kW heptane pool fire tests, the exposed fire was actually extinguished faster, after 29:00 (min:sec) in test 3, than when obstructed, after 33:15 (min:sec) in test 9.

For the high-pressure system, exposed fires seems to be extinguished faster compared to obstructed fires. Comparing test 30 (obstructed 1 MW heptane pool fire) with test 37 (exposed 1 MW heptane pool fire) shows that the exposed pool fire is extinguished slightly faster, 08:00 (min:sec) as compared to 08:47 (min:sec) for the obstructed fire. Comparing test 40 (obstructed 1 MW diesel pool fire) with test 38 (exposed 1 MW diesel pool fire) also shows that the exposed pool fire is extinguished faster than the obstructed fire, 05:12 (min:sec) relative to 08:50 (min:sec). For both these scenarios, the minimum (dry) oxygen concentration was lower for the obstructed fires. This may indicate that there is an interaction between the water droplets and the combustion processes taking place in the fire.

The conclusion may be formulated as follows: when water droplets are large enough to penetrate the fire plume and into the flames of the fire, to interact with the fuel surface, the extinguishment of exposed fires may be prolonged compared to obstructed fires of the same fire size. This was proven by the tests with the water spray system and to some extent the tests with the low-pressure system. Especially for the diesel pool fires, it could visually be determined that the larger droplets and relatively higher discharge densities of these two systems reduced the fire size (flames mainly around the rim of the fire tray) such that the reduction in oxygen concentration did not reach a level such that it assisted extinguishment. To illustrate this, the graphs of figure A-1 shows the (dry) oxygen concentrations and the average gas temperatures during tests 11 and 12.

When the water droplets are small enough to interact with the combustion processes in the fire, exposed fires are generally extinguished faster than obstructed fires. This was observed with the high-pressure system.

7.5 The influence of the fuel

The influence of the fuel was investigated in a limited number of tests. Table 15 summarises the test results for obstructed heptane and diesel pool fires. The test compartment was sealed closed for all of the tests.

Table 15 Comparison of times to extinguishment for the obstructed heptane versus the obstructed diesel pool fires. The test compartment was sealed closed.

Test no.	**System**	**Fuel**	**HRR**	**Obstruction**	**Ventilation openings**	**Ext. time [min:sec]**	**Minimum (dry) oxygen concentration [vol-%]**	
							1000 mm below ceiling	4500 mm below ceiling
17	WS	Heptane	500 kW	Obstructed	None	28:07	13,8	14,7*
22	WS	Diesel	500 kW	Obstructed	None	29:00	13,3	14,7*
18	WS	Heptane	1 MW	Obstructed	None	10:40	15,0	15,3
23	WS	Diesel	1 MW	Obstructed	None	10:05	14,7	14,8
2	LP	Heptane	1 MW	Obstructed	None	12:30	15,4	16,2
12	LP	Diesel	1 MW	Obstructed	None	17:10	14,6	15,4
30	HP	Heptane	1 MW	Obstructed	None	08:47	15,9	16,0
40	HP	Diesel	1 MW	Obstructed	None	08:50	15,9	16,4

*) The minimum limit of the instrument.

It can be concluded that the times to extinguishment is comparable for all pair of tests, except for tests 2 and 12, where the extinguishment time for the diesel pool fire is longer. It is also observed that the minimum (dry) oxygen level at extinguishment generally is lower for the diesel pool fires.

The test results for exposed heptane and diesel pool fires are presented in the table 16.

Table 16 Comparison of times to extinguishment for the exposed heptane versus the exposed diesel pool fires. The test compartment was sealed closed.

Test no.	**System**	**Fuel**	**HRR**	**Obstruction**	**Ventilation openings**	**Ext. time [min:sec]**	**Minimum (dry) oxygen concentration [vol-%]**	
							1000 mm below ceiling	4500 mm below ceil.
26	WS	Heptane	1 MW	Exposed	None	N/E*	16,3	16,5
28	WS	Diesel	1 MW	Exposed	None	17:05	17,7	18,0
9	LP	Heptane	500 kW	Exposed	None	29:00	15,5	16,1
10	LP	Diesel	500 kW	Exposed	None	N/E	17,1	17,4
8	LP	Heptane	1 MW	Exposed	None	15:50	15,9	16,5
11	LP	Diesel	1 MW	Exposed	None	N/E	16,8	17,2
37	HP	Heptane	1 MW	Exposed	None	08:00	17,0	17,4
38	HP	Diesel	1 MW	Exposed	None	05:12	17,5	17,9

*) For test 26, the system was shut off, 15:00 after ignition, due to the risk for overflowing the fire tray. The minimum oxygen level is given after this time.

These results are not as straightforward compared as those where the pool fire trays were obstructed. For the cases where the fire not was extinguished, it may be concluded that the fuel surface cooling counteracts extinguishment. This is especially noticeable for the low-pressure system, which was able to suppress the exposed 500 kW and 1 MW diesel pool fires to such a degree that extinguishment did not occurred. Both the heptane fires of the same size were extinguished.

For the high-pressure system, the exposed 1 MW diesel fire was extinguished faster compared to the same heptane fire.

7.6 The reduction of the gas temperatures

The graphs presented in figure A-2 show the calculated average gas temperatures inside the test compartment for the obstructed 500 kW, 1 MW and 2 MW heptane pool fires. The calculation is based on the readings of all the 20 thermocouples on the two thermocouple trees.

Not surprisingly, the peak temperatures for the free burn tests are dependent on the heat release rate of the fire, the larger the fire the higher the temperature. The peak temperature varies between 125°C to 225°C. The temperature is reduced as the heat release rate of the fires is reduced with the reduced oxygen level. Comparing the average temperature 10 minutes after the ignition, indicates approximately the same temperature level for all three free burn tests, i.e. approximately 110°C to 120°C.

Generally, the water spray system provided significantly better gas phase cooling than both the low-pressure and the high-pressure systems for the obstructed 500 kW and 1 MW fires. This is primarily attributed to the higher water flow rate of the water spray system. It is also noticeable that the gradual decrease in temperature is more significant for the water spray system tests compared to the other two systems. For the 2 MW fires, the difference in gas phase cooling for the three systems is not as significant, although it is clear that the water spray system provides the fastest cooling.

7.7 The reduction of wall surface temperatures

The graphs presented in figures A-3 through A-5 show the wall surface temperatures, as measured at the long sidewall (referred to as position 5), for the obstructed 500 kW, 1 MW and 2 MW heptane pool fires. In addition, the peak temperatures are listed in table 17.

The free burn tests shows that the wall surface temperatures increase until the fire size becomes influenced by the reduction of oxygen level inside the test compartment. These tests also indicate, as would be expected, that higher temperatures are measured at the highest thermocouple position, 500 mm below the ceiling. For the 500 kW and the 1 MW fires, the wall temperatures peaked at approximately 80˚C, for the 2 MW fire, the temperature peaked at approximately 130˚C.

For the system tests, the temperatures at the different positions converge. The water spray system provides the best wall surface cooling of the three systems tested. The wall cooling ability of the low-pressure and the high-pressure systems is generally comparable. The ‘peak’ temperatures given for the three systems are taken at the same time as the peak occurred for the corresponding free burn test. Usually, the ‘peak’ temperature was the maximum measured, however, there are three exceptions, tests 17 and 18, conducted with the water spray system and test 5 conducted with the low-pressure system. For the first two tests, slightly higher temperatures were recorded during the free burn phase.

It is worthwhile noticing that the highest temperatures were usually measured at the highest thermocouple position, 500 mm below the ceiling. However, for all three tests with the high-pressure system, higher temperatures (although the difference is minor) were measured at the two measurement points further down the wall.

Table 17 The peak wall surface temperatures at the long sidewall for the obstructed heptane pool fires. The test compartment was sealed closed.

Test no.	**System**	**HRR**	**Peak wall surface temperatures [˚C]**		
			500 mm below ceil.	2500 mm below ceil.	4500 mm below ceil.
4	Free burn	500 kW	79	73	60
17	WS	500 kW	21	20	19
3	LP	500 kW	37	36	35
29	HP	500 kW	39	40	42
41	Free burn	1 MW	84	72	62
18	WS	1 MW	28	28	27
2	LP	1 MW	44	42	41
30	HP	1 MW	43	48	45
42	Free burn	2 MW	130	113	88
19	WS	2 MW	36	35	33
5	LP	2 MW	52	46	45
35	HP	2 MW	46	50	50

7.8 The influence of the ventilation openings

Table 18 show the results for the tests conducted with the large ceiling hatch fully open, as compared to the same fire scenarios with the test compartment sealed closed. Only obstructed 1 MW and 2 MW heptane pool fires were used for this comparison, the 500 kW fires were judged to be too small to be extinguished under such ventilation conditions.

Table 18 The influence of the large ventilation opening for the obstructed heptane pool fires.

Test no.	**System**	**Fuel**	**HRR**	**Ventilation openings?**	**Ext. time [min:sec]**	**Minimum (dry) oxygen concentration [vol-%]**	
						1000 mm below ceiling	4500 mm below ceiling
18	WS	Heptane	1 MW	None	10:40	15,0	15,3
25	WS	Heptane	1 MW	Large vent.	N/E	15,2	15,6
2	LP	Heptane	1 MW	None	12:30	15,4	16,2
15	LP	Heptane	1 MW	Large vent.	N/E	17,4	17,5
30	HP	Heptane	1 MW	None	08:47	15,9	16,0
33	HP	Heptane	1 MW	Large vent.	N/E	16,8	17,2
19	WS	Heptane	2 MW	None	07:10	13,7	14,7*
20	WS	Heptane	2 MW	None	05:55	14,6	14,9
21	WS	Heptane	2 MW	Large vent.	N/E**	15,3	15,5
5	LP	Heptane	2 MW	None	03:12	16,5	17,1
16	LP	Heptane	2 MW	Large vent.	11:34	16,4	16,9
35	HP	Heptane	2 MW	None	03:25	16,3	16,7
34	HP	Heptane	2 MW	Large vent.	06:23	16,0	16,6

*) The minimum limit of the instrument.
**) Test 21 was close to extinguishment during several occasions.

It is obvious that the possibility for fire extinguishment and the time to extinguishment was influenced by the status of the large ceiling hatch, i.e. open or closed. The obstructed 1 MW fire was not extinguished by any of the systems when the large ceiling hatch was open. The 2 MW fire was extinguishment by both the low-pressure and the high-pressure systems with the large ceiling hatch open. However, the times to extinguishment were almost doubled (HP system) or three-doubled (LP system) that measured with the large ceiling hatch closed.

For the cases where the fire not was extinguished, the minimum (dry) oxygen concentrations were not reduced to the level of extinguishment found when the test compartment was sealed closed. For the cases where the fire was extinguished, the minimum (dry) oxygen concentrations were generally lower when the ceiling hatch was open. However, the difference is minor.

7.9 The production of carbon monoxide and carbon dioxide

The maximum measured carbon monoxide (CO) and carbon dioxide (CO2) concentration for the obstructed 500 kW, 1 MW and 2 MW heptane pool fires are given in table 19.

Table 19 Maximum concentrations of carbon monoxide and carbon dioxide for the free burn tests versus the tests that were conducted with the three systems. The test compartment was sealed closed.

Test no.	**System**	**Fuel**	**HRR**	**Ext. time [min:sec]**	**Maximum concentrations [vol-%]**			
					1000 mm below ceiling		4500 mm below ceiling	
					CO*	CO_2	CO	CO_2
4	Free burn	Heptane	500 kW	19:25	0,174	5,08	0,095	4,47
17	WS	Heptane	500 kW	28:07	0,138	4,72	0,056	4,54
3	LP	Heptane	500 kW	33:15	0,132	4,85	0,054	4,00
29	HP	Heptane	500 kW	26:18	0,148	4,00	0,066	4,08
41	Free burn	Heptane	1 MW	09:03	0,169	4,60	0,052	3,82
18	WS	Heptane	1 MW	10:40	0,160	4,02	0,056	3,80
2	LP	Heptane	1 MW	12:30	0,186	3,05	0,058	3,07
30	HP	Heptane	1 MW	08:47	0,171	3,30	0,055	3,27
42	Free burn	Heptane	2 MW	03:40	0,169	6,40	0,044	5,34
19	WS	Heptane	2 MW	07:10	0,214	4,94	0,077	4,59
20	WS	Heptane	2 MW	05:55	0,209	4,33	0,070	4,09
5	LP	Heptane	2 MW	03:12	0,117	2,95	0,036	2,53
35	HP	Heptane	2 MW	03:25	0,169	3,19	0,039	2,84

*) The instrument probably showed too high CO levels.

7.10 The ability to mix water droplets, water vapour and combustion products

The ability to mix water droplets, water vapour and combustion products within a compartment expresses a characteristic quality of a water mist or a water spray system. Mixing is a measure on how the initial momentum of the water droplets is transferred to the gas. A high degree of mixing may be obtained using a high system flow rate. Systems with higher flow rates typically have higher momentum sprays from the nozzles that result in better mixing due to the increased turbulence in the compartment. A high degree of mixing may also be obtained using large droplets, however, larger droplets provide less water/gas interface area per volume of water, compared to smaller droplets. This in turn means that the gas phase cooling will be less efficient.

The number of nozzles, their individual spacing and their position relative to the walls of the protected compartment as well as the ceiling-to-nozzle distance is also influential on the mixing functionality of the system. Moreover, the fire size is important, the larger the fire the higher the turbulence inside the protected compartment.

The measurements of the concentration of carbon dioxide (CO_2) were used for the comparison of the mixing ability of the three tested systems. The concentration of carbon dioxide (CO_2) was measured at two different positions of the test compartment, 1000 mm and 4500 mm below the ceiling, respectively. By dividing the measured concentration at the highest position with the measured concentration at the lowest position, a ratio indicating the mixing ability was achieved.

For the obstructed 500 kW heptane fires, the high-pressure system provided the best mixing inside the test compartment, see to figure A-6. The calculated carbon dioxide ratio is close to 1,00. The low-pressure system provided slightly better mixing than the water spray system. For both these systems the calculated carbon dioxide ratio varies between 1,05 and 1,10. For the free burn test it is clear that the mixing is less compared to all three systems, which would be expected.

For the obstructed 1 MW heptane fires, the trend is similar, the high-pressure system provided the best mixing inside the compartment, with a calculated carbon dioxide ratio approaching 1,00. The low-pressure system and the water spray system were comparable, but still slightly less efficient than the high-pressure system. For the obstructed 2 MW heptane fires, all three systems provide essentially similar mixing. As a matter of fact, the free burn test is comparable to the tests with the three systems, which illustrates the effect from turbulence generated by the fire itself on providing good mixing.

In addition to the conclusions given above, the tests allow a comparison of the mixing ability for the cases where the test compartment was sealed closed as compared to the cases where the large ceiling hatch was fully open. Only obstructed 1 MW and 2 MW heptane pool fires were used for this comparison, refer to figures A-7 through A-9. It can be concluded that the mixing ability of the low-pressure system is not influenced by the fact that the large ceiling hatch was fully open. The ability of the water spray system and the high-pressure system to provide mixing is reduced. However, it should be pointed out that the water spray system provides faster mixing compared to the other two systems. The fact that the high-pressure systems ability to provide mixing is influenced more by the ventilation opening at the ceiling compared to the water spray system can be explained by the larger droplets and the higher water flow rate of the water spray system. The fact that the low-pressure system performed better than the other two systems is more difficult to explain.

7.11 Cooling of the obstruction steel plate

The surface temperature of the horizontal obstruction steel plate used for the obstructed fires was measured using a spot-welded thermocouple at its centre point. The graphs presented in figure A-10 show this temperature for the obstructed 500 kW, 1 MW and 2 MW heptane pool fires, respectively.

It is clear that the water spray system, the system with the highest average water discharge density, provides the fastest and most efficient cooling of the obstruction steel plate. The steel plate was almost immediately cooled below 100°C upon the initiation of water for both the 500 kW and 1 MW fires. For the 2 MW fire, the temperature was kept at 100°C and below. It should be noted that the reduced, 30 seconds, free burn time for the 2 MW fires limited the pre-heating of the steel plate.

The low-pressure system seems to provide better surface cooling compared to the high-pressure system for the 500 kW and 1 MW fires. This is logical, as its average water discharge density is higher. However, for the 2 MW fire, the high-pressure system provided better cooling of the steel plate.

It should be pointed out that the measurement during test 41 (free burn test) and test 30 (high-pressure system test) to some degree seem to be affected by the fact that the top surface of the plate was not completely dry at the beginning of the test. In retrospect it can be concluded that a horizontal, cylindrical shaped obstruction would have been better when measuring the surface cooling ability of the systems.

7.12 Compartment pressures

During the first tests with the low-pressure system a significant under pressure was created during the initial cooling of the hot atmosphere of the test compartment. This under pressure was of the order of -400 Pa and was judged to be crucial to the test compartment integrity. It was therefore judged necessary to reduce the pre-planned pre-burn time of the 2 MW fires from 2 minutes to 30 seconds. In addition, the practice for all the following 1 MW and 2 MW size fires tests was to open one of the small ceiling vents just prior to the activation of the system, to deal with the initial under pressure, and close them 10 - 15 seconds later. An exception from this practice was made for test 30, in order to attain comparison test data for the high-pressure system with the obstructed 1 MW heptane pool fire. The subsequent over pressure phase caused by the water vapour expansion was not a problem, as the pressure vents of the test compartment were able to cope with it.

For some of the tests conducted with the test compartment sealed closed (over pressure vents only), a significant under pressure (in the order of -300 Pa to -500 Pa) was generated at the moment the fire was extinguished. This is illustrated by tests 19 and 20, both conducted with the water spray system and the obstructed 2 MW heptane fire. This phenomenon can be explained by the sudden cooling effect when the fire is out. The effect was also observed in tests 6 and 7 for the low-pressure system and the exposed 2 MW heptane fire as well as in tests 35 and 26 with the high-pressure system and the obstructed / exposed 2 MW heptane fire. The graphs of figure A-11 show the compartment pressure for the above-mentioned tests.

For these tests, it is also interesting to notice the over pressure generated by the formation of water vapour for the tests with the low-pressure and high-pressure systems. No significant over pressure was recorded during the tests with the water spray system, which indicates that the formation of water vapour was limited.

As mentioned above, the pressure vents of the test compartment reduced the over pressure caused by the water vapour expansion. It is therefore not possible to compare the maximum measured over pressure with the minimum measured under pressure in absolute numbers. It was, however, observed that the over pressure generated during the free burn phase (before activation of the system) generally was higher than the over pressure generated on and after the activation of the systems.

8 Conclusions

The following conclusions can be drawn based on the tests:

- The test show that ‘time to extinguishment’ is not a sufficient measure of the performance of a water mist or water spray system as:

1) Time to extinguishment is not a very repeatable variable. Tests that were repeated under the same conditions indicate a 20% to 80% variation.

2) Free burning pool fires (no system used) might self-extinguish faster, or as fast, as pool fires extinguished by a water mist or water spray system provided that the test compartment is sufficiently airtight.

3) Exposed pool fires may be suppressed to such an extent that they not will be extinguished until the fuel has been consumed. A ‘time to extinguishment’ measure could exclude such a system, although it is in fact very effective.

- A significant under pressure was created during the initial cooling of the hot atmosphere of the test compartment. This under pressure measured in the order of -400 Pa. The subsequent over pressure phase caused by the water vapour expansion was not problematic, as the pressure vents of the test compartment could cope. For some of the tests conducted with the test compartment sealed closed (over pressure vents only), quite a significant under pressure (in the order of -300 Pa to -500 Pa) was generated at the moment the fire was extinguished. This phenomenon can be explained by the sudden cooling effect when the fire is extinguished.

- For exposed pool fires, it is clear that an ‘efficient’ fuel surface cooling can counteract extinguishment. When water droplets are large enough to penetrate the fire plume and the flame of the fire, to interact with the fuel surface, the extinguishment of exposed fires may be prolonged compared to obstructed fires of the same fire size. This effect was primarily observed for the water spray system, but to some extent also with the low-pressure system. When the water droplets are small enough to interact with the combustion processes in the fire, exposed fires are generally extinguished faster than obstructed fires. This was observed with the high-pressure system.

- Generally, the water spray system provided significantly better gas phase cooling than both the low-pressure and the high-pressure systems for the obstructed 500 kW and 1 MW fires. This is primarily attributed to the higher water flow rate of the water spray system. It is also noticeable that the gradual decrease in temperature is more significant for the water spray systems tests compared to the other two systems. For the 2 MW fires, the difference in gas phase cooling for the three systems is not as great, although it is clear that the water spray system provides the fastest cooling.

- The water spray system provides the best wall surface cooling of the three tested systems. The wall cooling ability of the low-pressure and the high-pressure system is generally comparable.

- The water spray system, the system with the highest average water discharge density, provided the fastest and most efficient cooling of the obstruction steel plate. The steel plate was almost immediately cooled below 100°C upon the initiation of water for both the obstructed 500 kW and 1 MW heptane fires. For the obstructed 2 MW heptane fire, the temperature was kept at 100°C and below. It should be noted that the reduced, 30 seconds, free burn time for the 2 MW fires limited the pre-heating of the steel plate. The low-pressure system seems to provide better surface cooling compared to the high-pressure system for the 500 kW and 1 MW fires. This is logical, as its average water discharge density is higher. However, for the 2 MW fire, the high-pressure system provided better cooling of the steel plate.

- For obstructed pool fires of the same nominal fire size, the time to extinguishment and the associated minimum oxygen concentrations seem to be fairly independent of whether the fuel is heptane or diesel. For exposed fires, no general conclusion can be drawn regarding the influence of the fuel.

- The tests indicate that the high-pressure system provided slightly better mixing of water droplets, water vapour and combustion products within the compartment compared to the water spray system and the low-pressure system. However, for 2 MW fires, that induce a high turbulence inside the compartment, all three systems provided similar mixing efficiency. In fact, the free burn test is comparable to the tests with the three systems, which illustrates the effect from turbulence generated by the fire on providing good mixing.

- The mixing ability for the low-pressure system was not influenced by the fact that the large hatch at the ceiling was fully open, as compared to the cases where the test compartment was sealed closed. The ability of the water spray system and the high-pressure system to provide mixing was reduced.

Appendix A – selected graphs from the tests

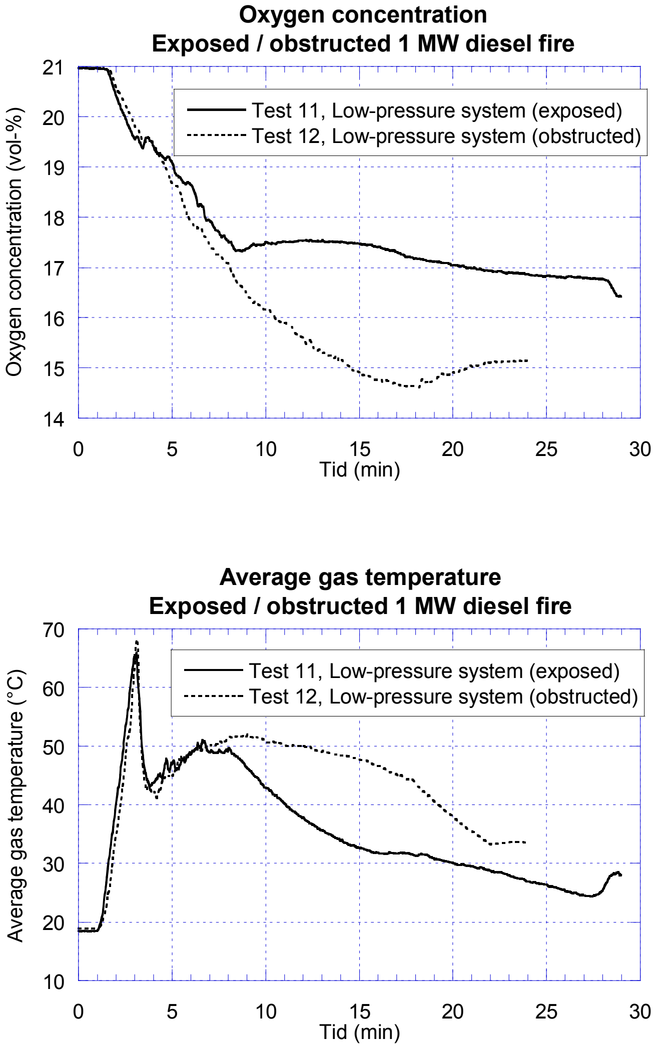
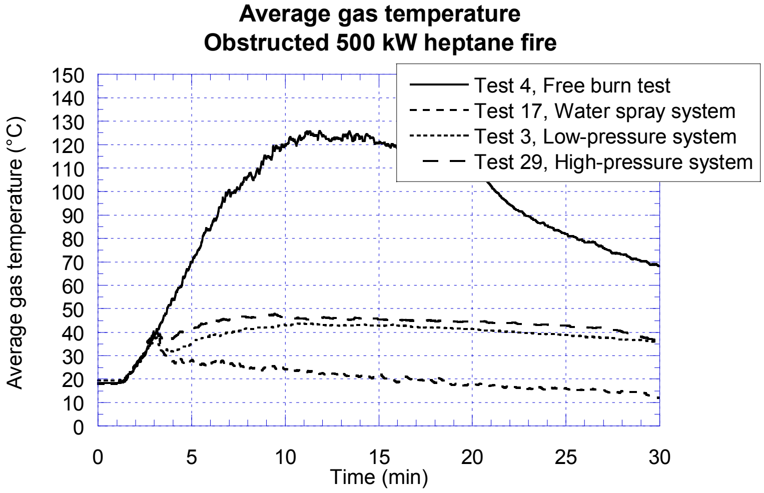
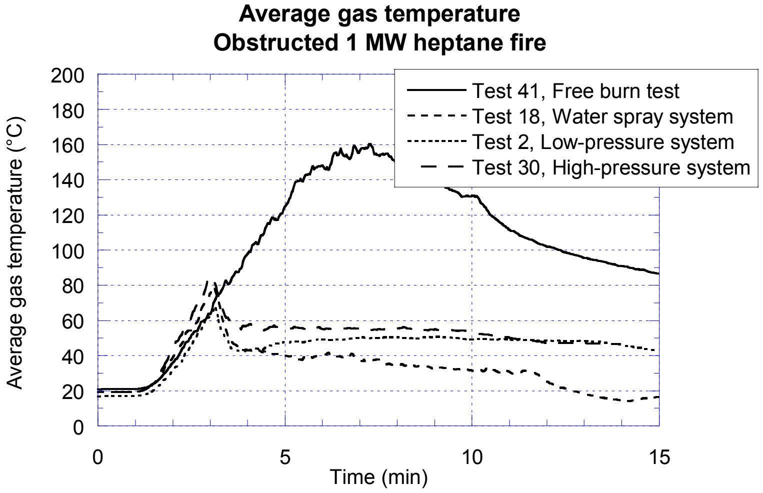


Figure A-1 The (dry) oxygen concentrations and the average gas temperatures during tests 11 and 12.





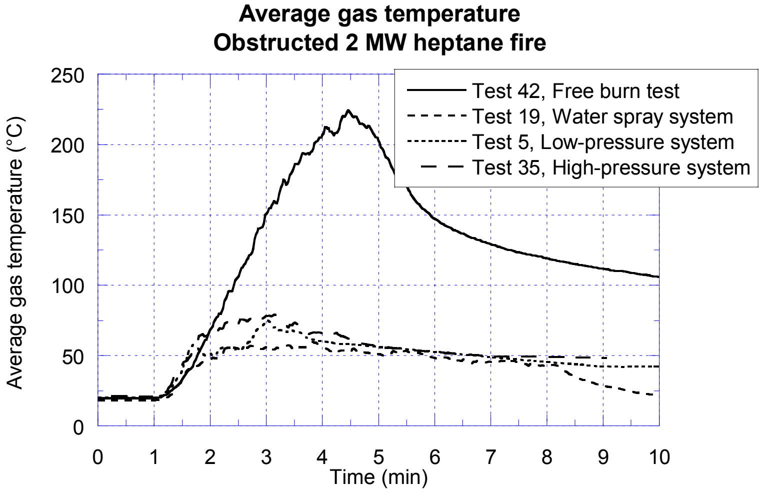
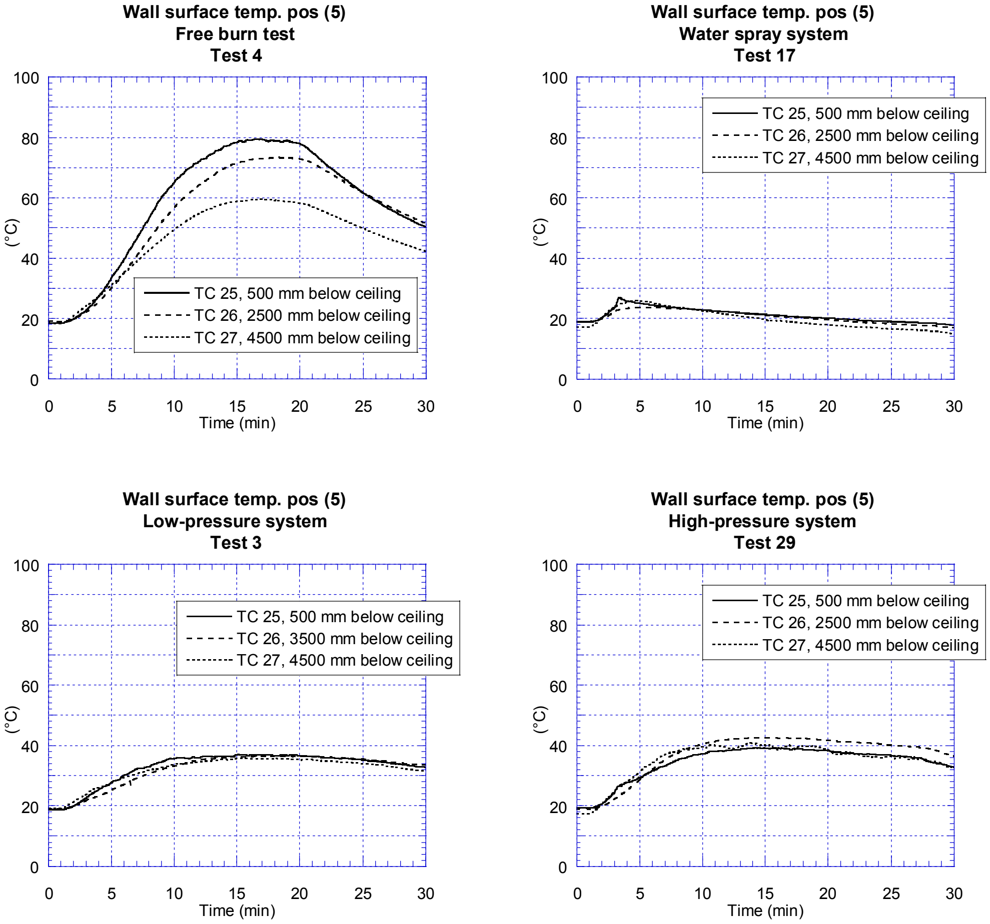


Figure A-2 The average gas temperature inside the test compartment, for the obstructed heptane pool fire scenarios. The test compartment was sealed closed.

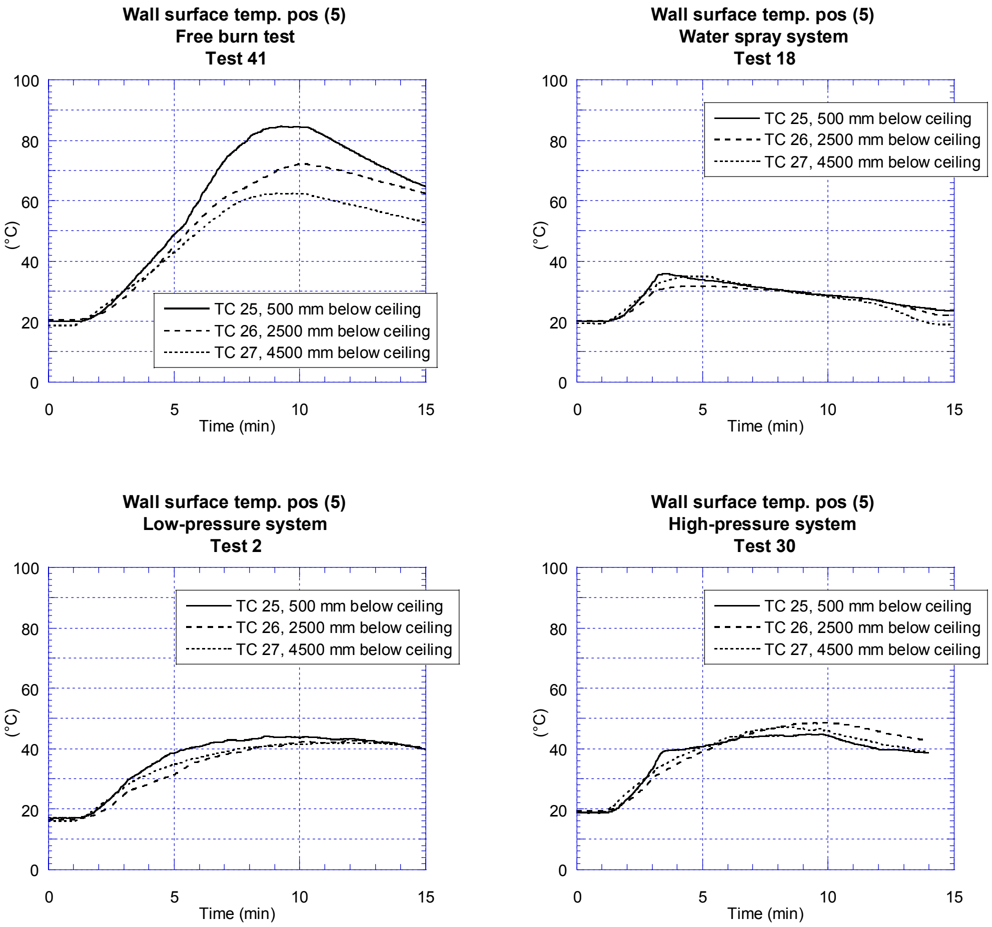

Wall surface temp. pos (5)
Free burn test
Test 4

Wall surface temp. pos (5)
Water spray system
Test 17

Wall surface temp. pos (5)
Low-pressure system
Test 3

Wall surface temp. pos (5)
High-pressure system
Test 29

Figure A-3 The wall surface temperatures for the tests with the obstructed 500 kW heptane pool fire scenario. The test compartment was sealed closed.



Wall surface temp. pos (5)
Free burn test
Test 41

Wall surface temp. pos (5)
Water spray system
Test 18

Wall surface temp. pos (5)
Low-pressure system
Test 2

Wall surface temp. pos (5)
High-pressure system
Test 30

Figure A-4 The wall surface temperatures for the tests with the obstructed 1 MW heptane pool fire scenario. The test compartment was sealed closed.

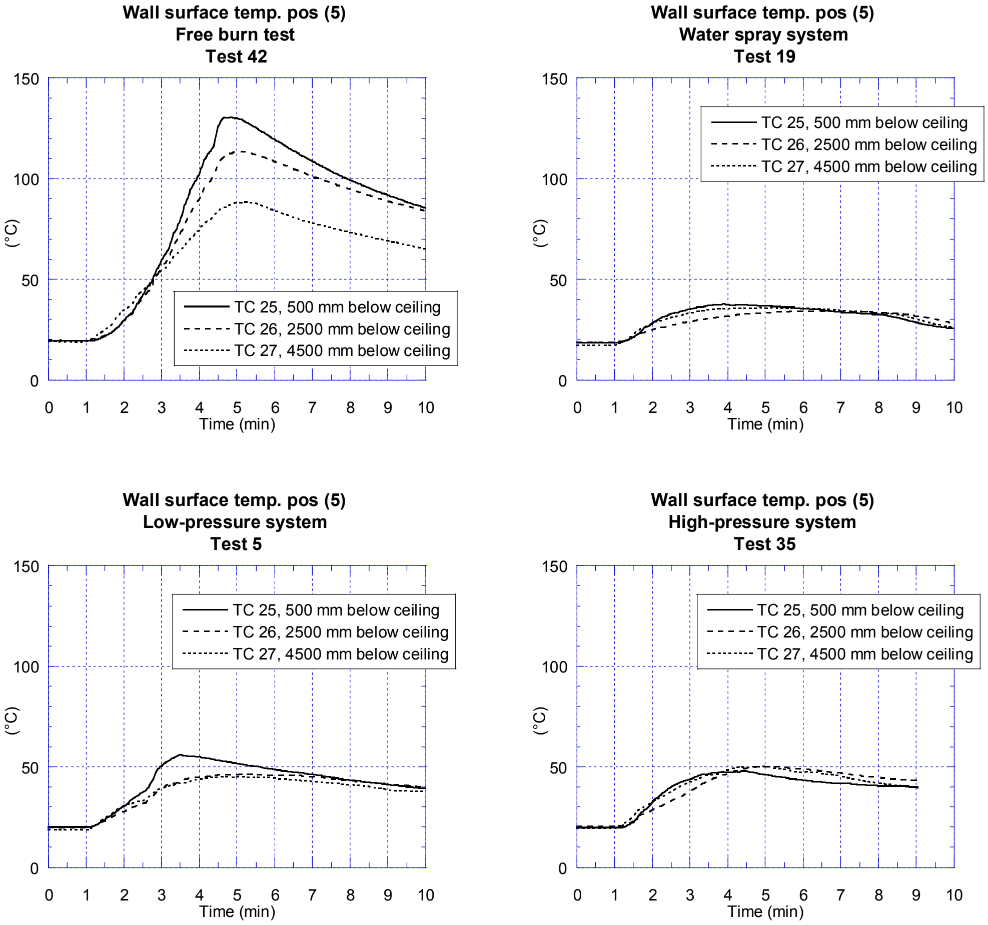


Figure A-5 The wall surface temperatures for the tests with the obstructed 2 MW heptane pool fire scenario. The test compartment was sealed closed.

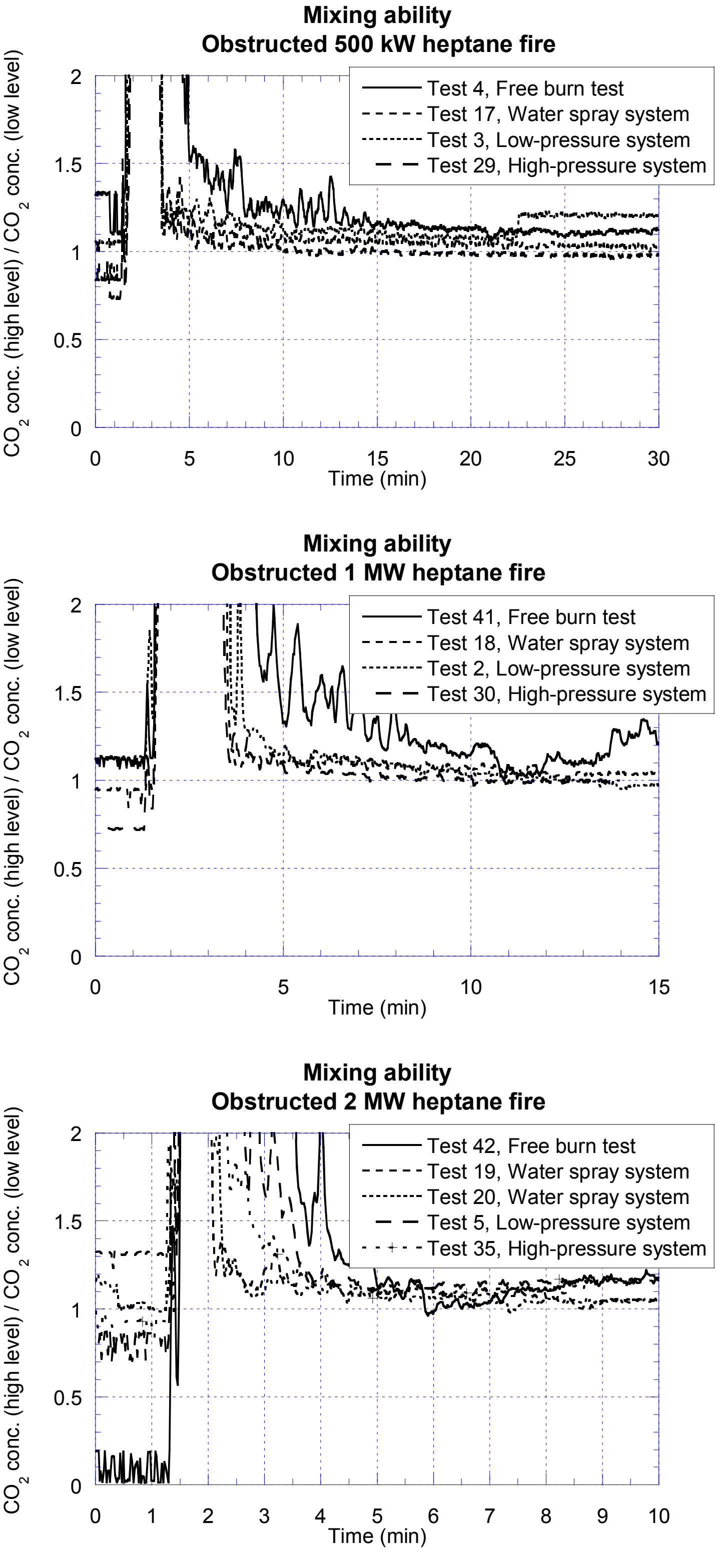
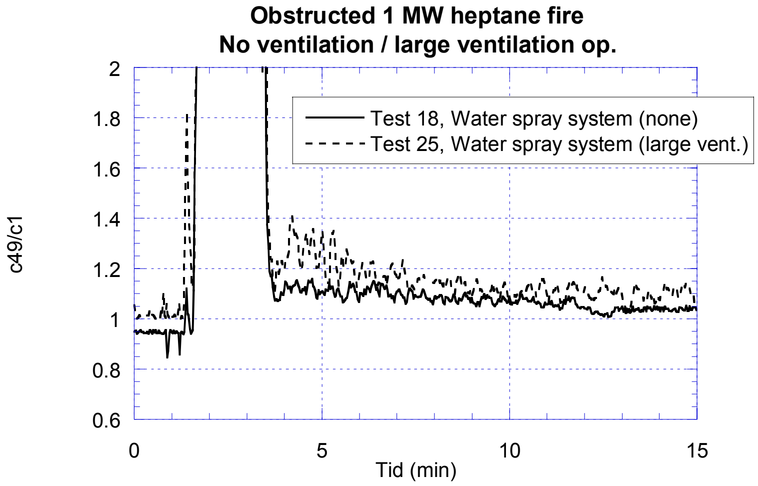


Figure A-6 The mixing ability for the three systems as compared to the free burn tests. The obstructed heptane pool fire scenarios were used and the test compartment was sealed closed.



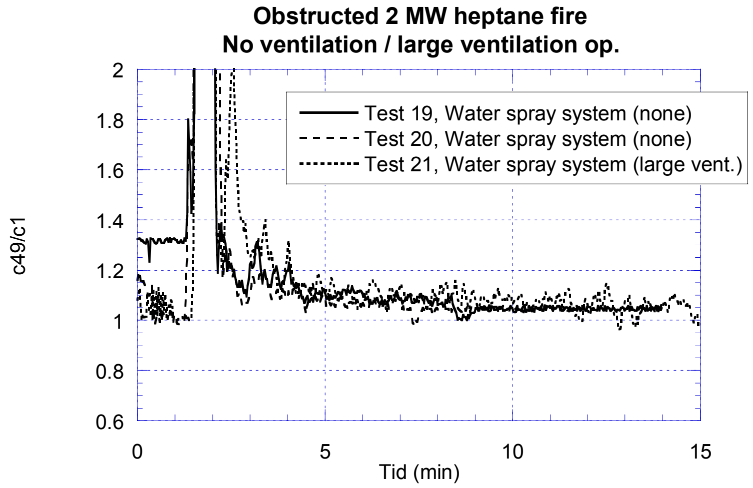


Figure A-7 The influence of the large ventilation opening on the mixing ability for the water spray system.

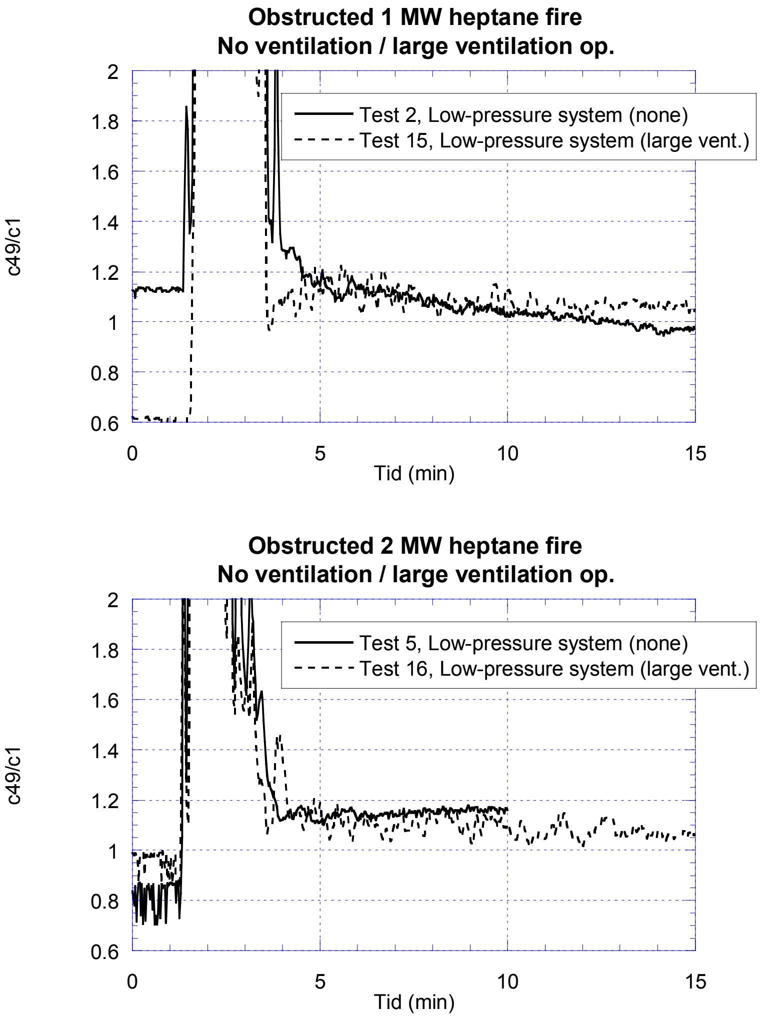
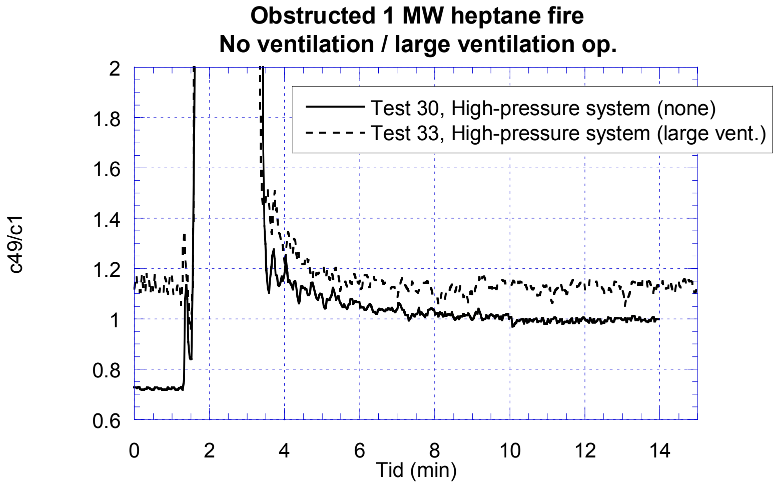


Figure A-8 The influence of the large ventilation opening on the mixing ability for the low-pressure system.



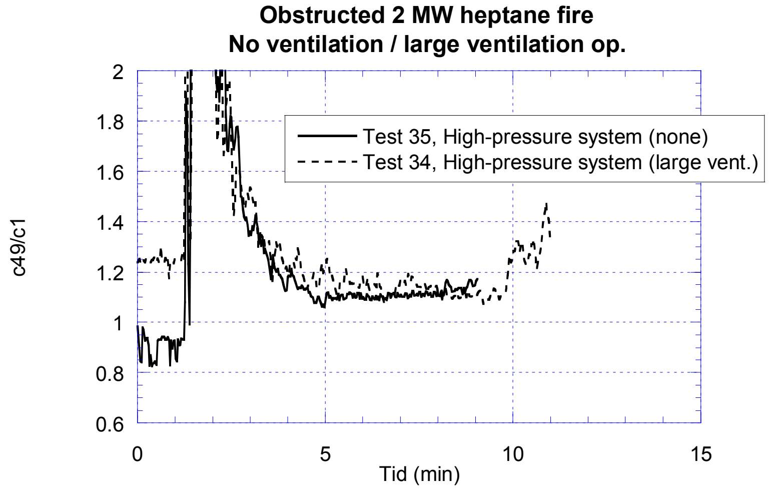
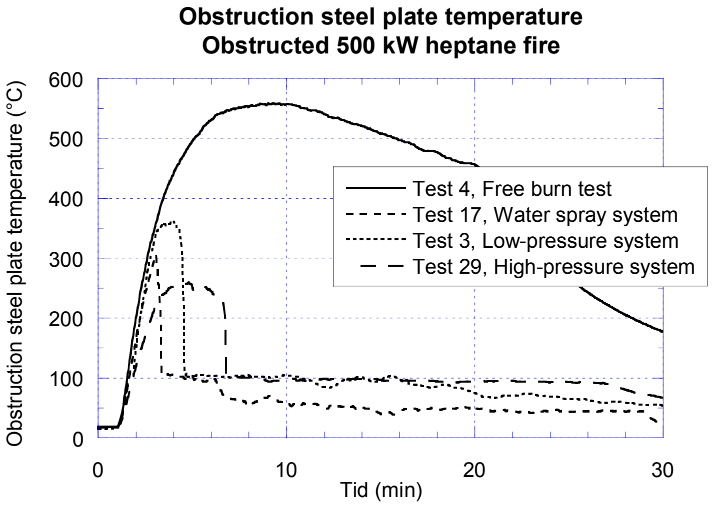
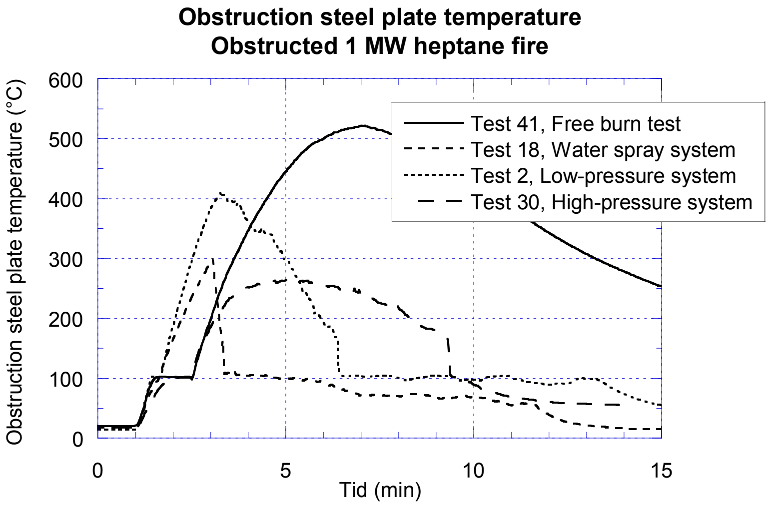


Figure A-9 The influence of the large ventilation opening on the mixing ability for the high-pressure system.





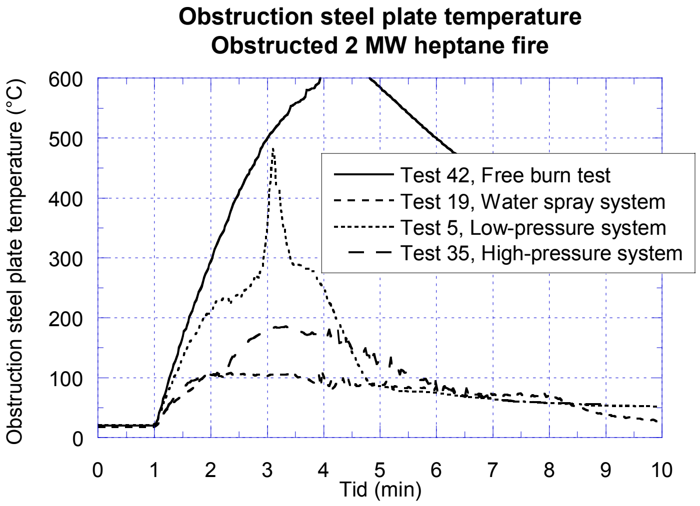
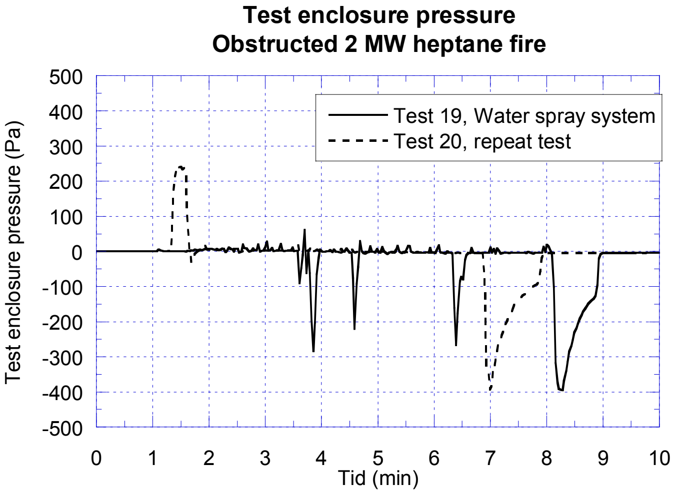


Figure A-10 Temperatures measured on the obstruction steel plate.



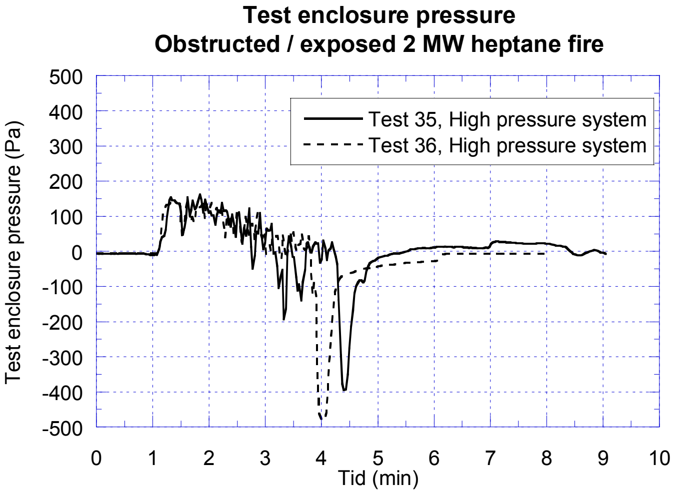


Figure A-11 For the tests conducted with the test compartment sealed closed, here exemplified with tests 6 and 7, tests 19 and 20 as well as tests 35 and 36, a significant under pressure was generated at the moment the fire was extinguished.

Appendix B – Selected photos from the tests

Photo B1 The 500 m^3 test compartment.

Photo B2 The pipe-work for the water spray and low-pressure water mist system. At the centre of the ceiling, the steel hatches for the large ventilation opening.

Photo B3 One (of the two) small over pressure vents at the ceiling.

Photo B4 One (of the two) small over pressure vents at the ceiling. Here showed sealed closed during the integrity test of the test compartment.

Photo B5 The horizontal obstruction steel plate, with the fire tray positioned on a load cell.

Photo B6 The size of the obstructed 500 kW heptane pool fire.

Steel module enclosure

Exterior, top view

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Rev. Date:

Scale: 1:75

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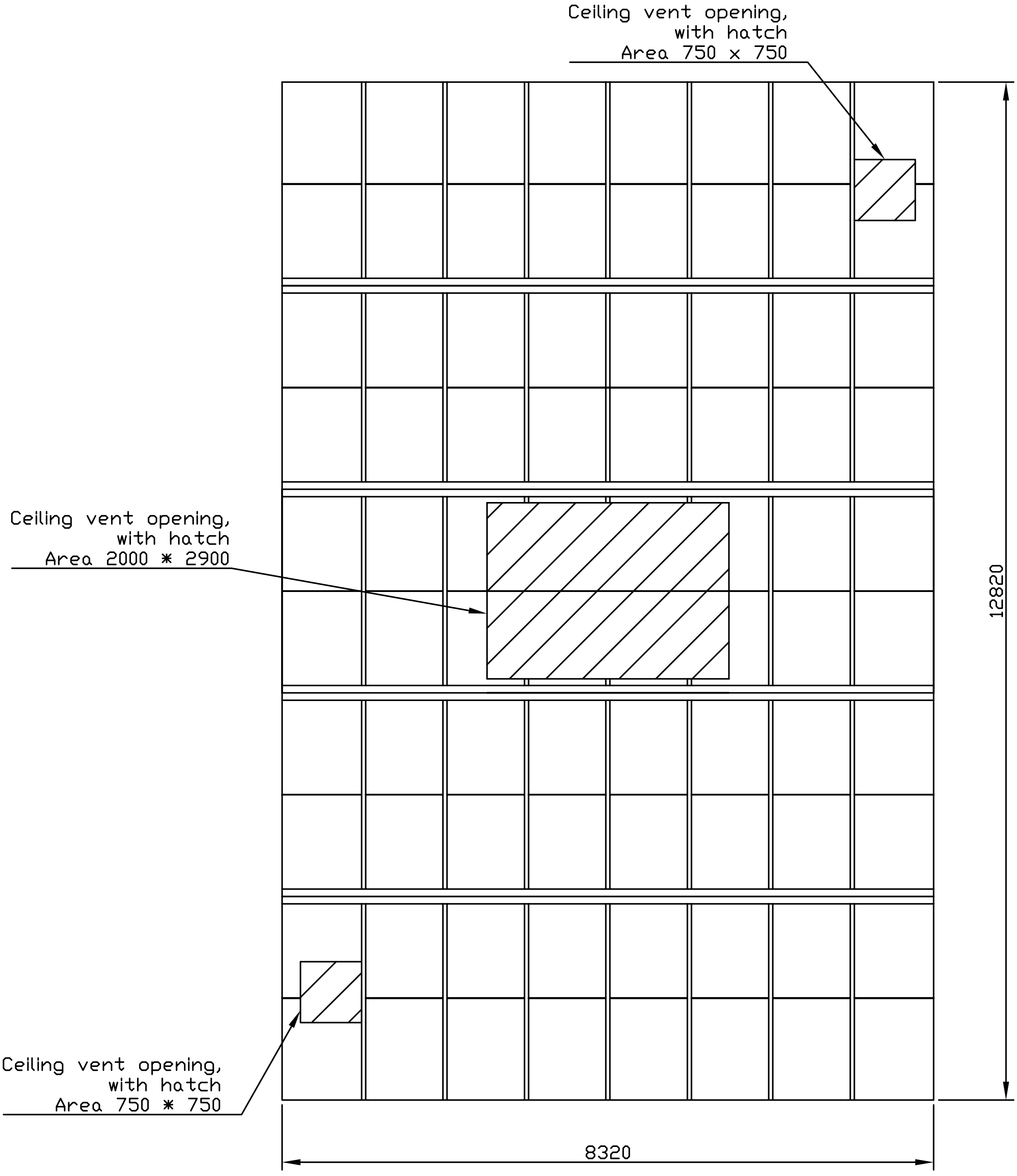

Steel module enclosure

Exterior side views

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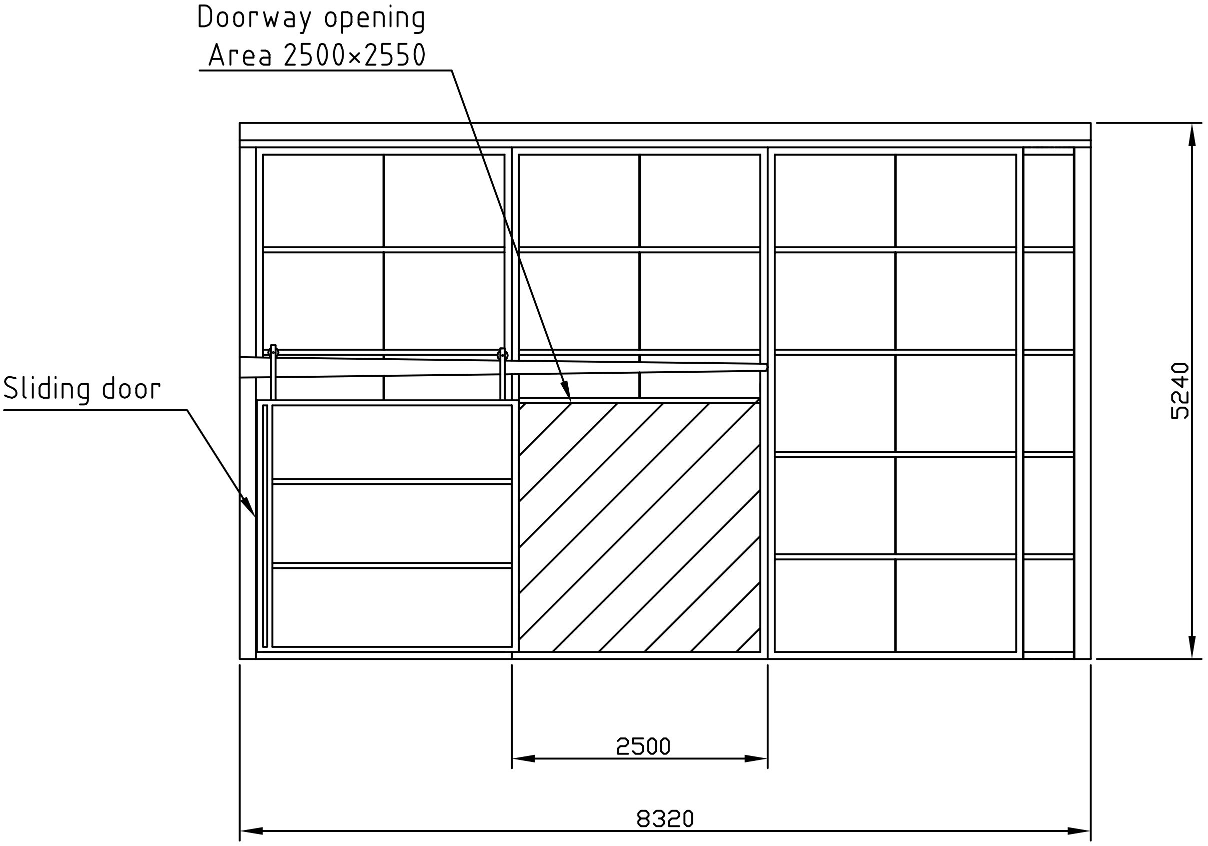
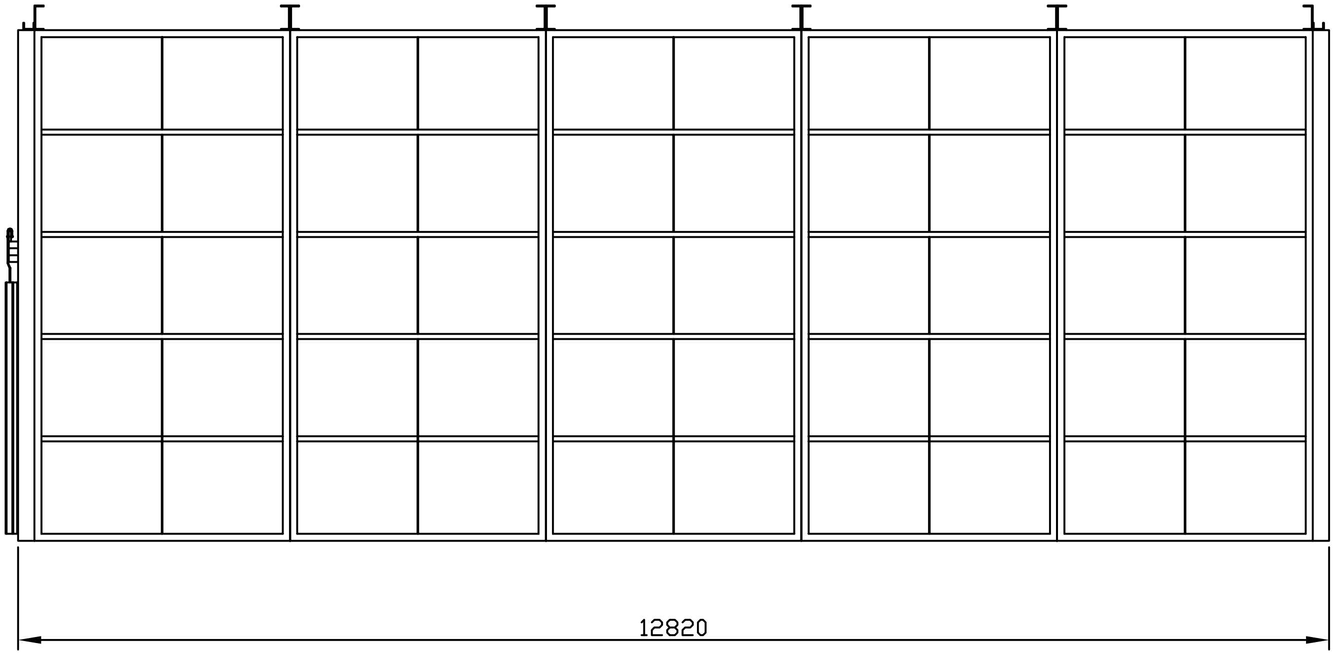


Short side view



Long side view

Steel module enclosure

Interior, top view

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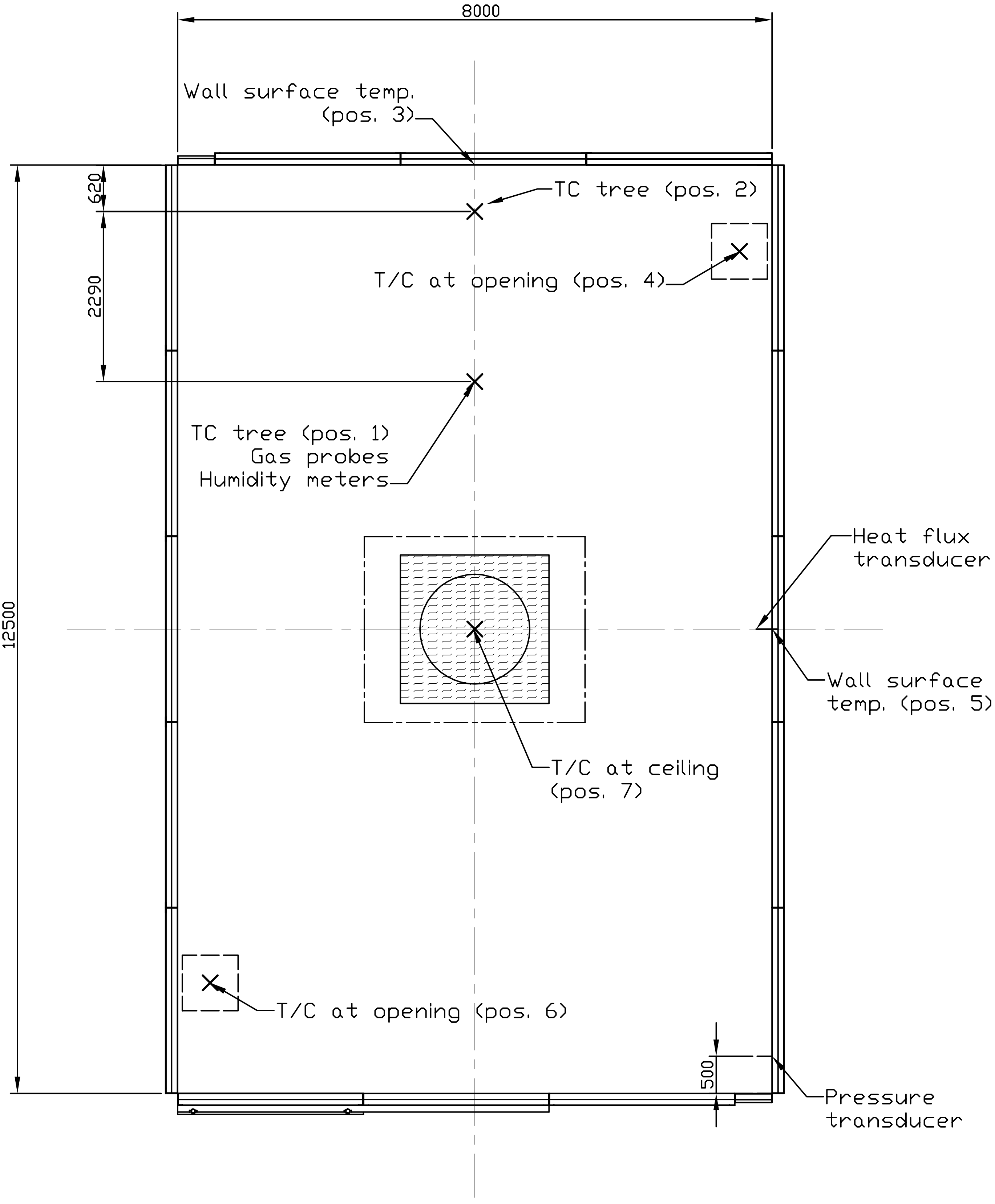

Steel module enclosure

Interior, rear view

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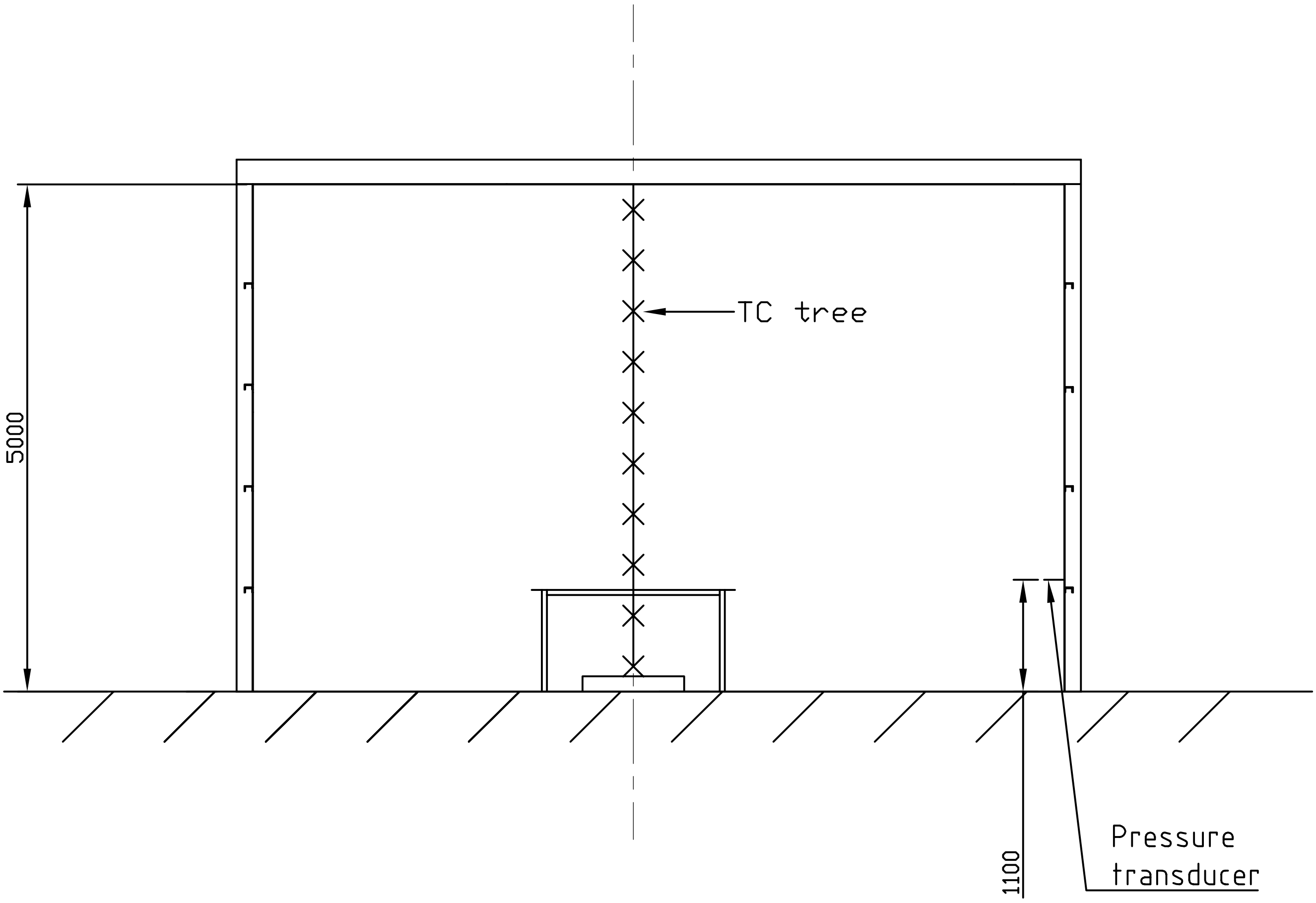

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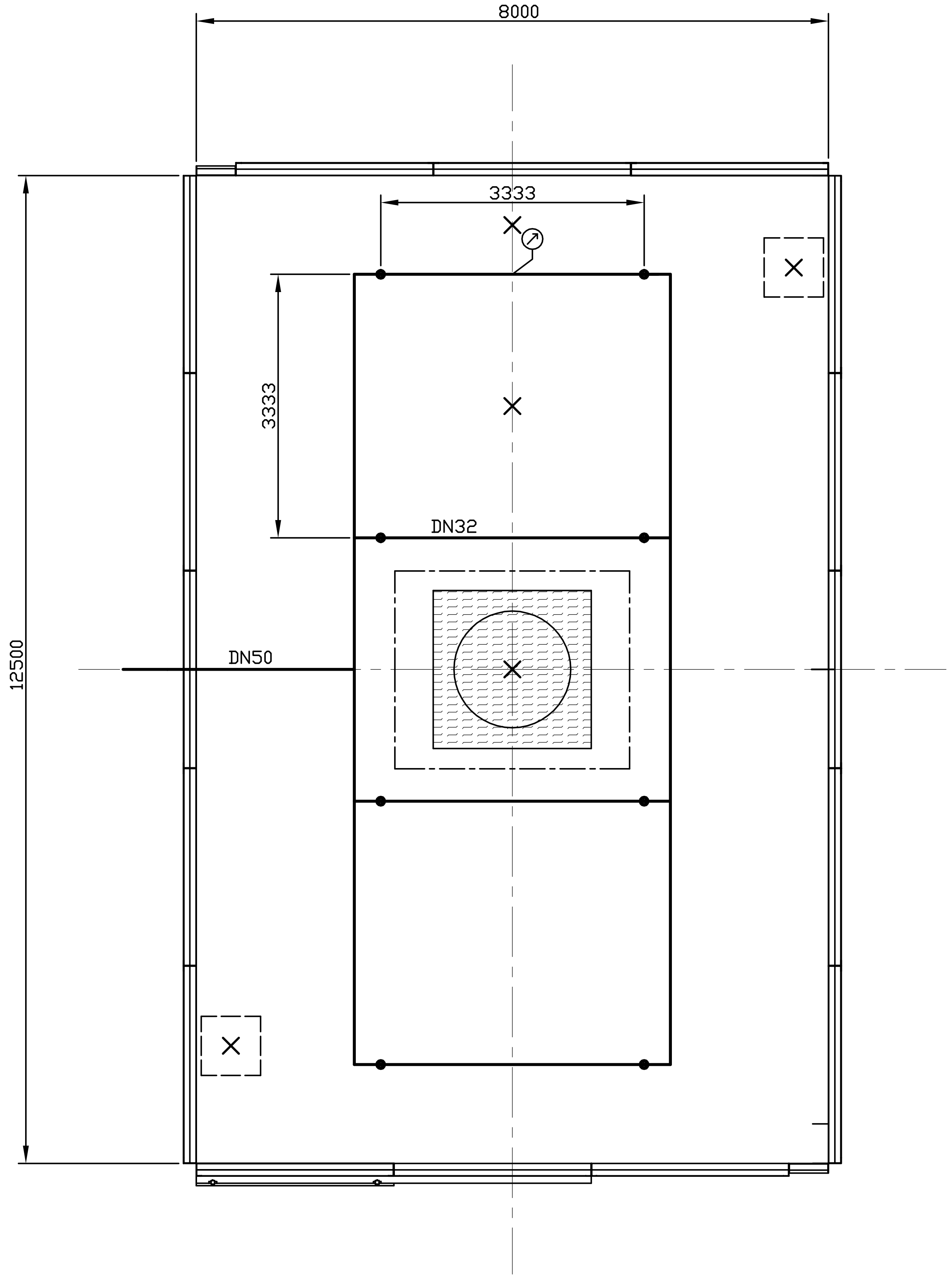

Steel module enclosure

Interior, top view

High-pressure system

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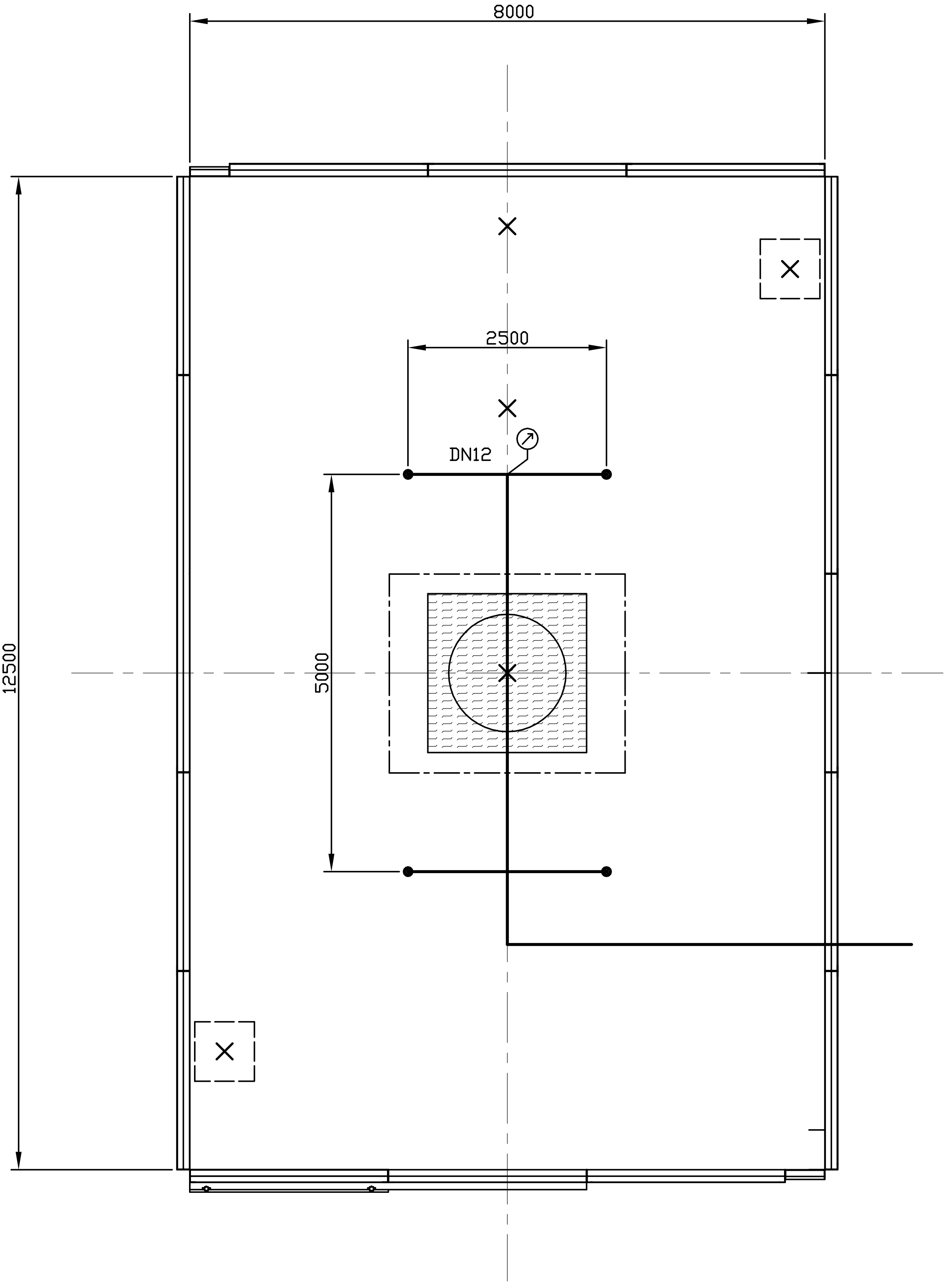

Steel module enclosure

Position of water collector trays

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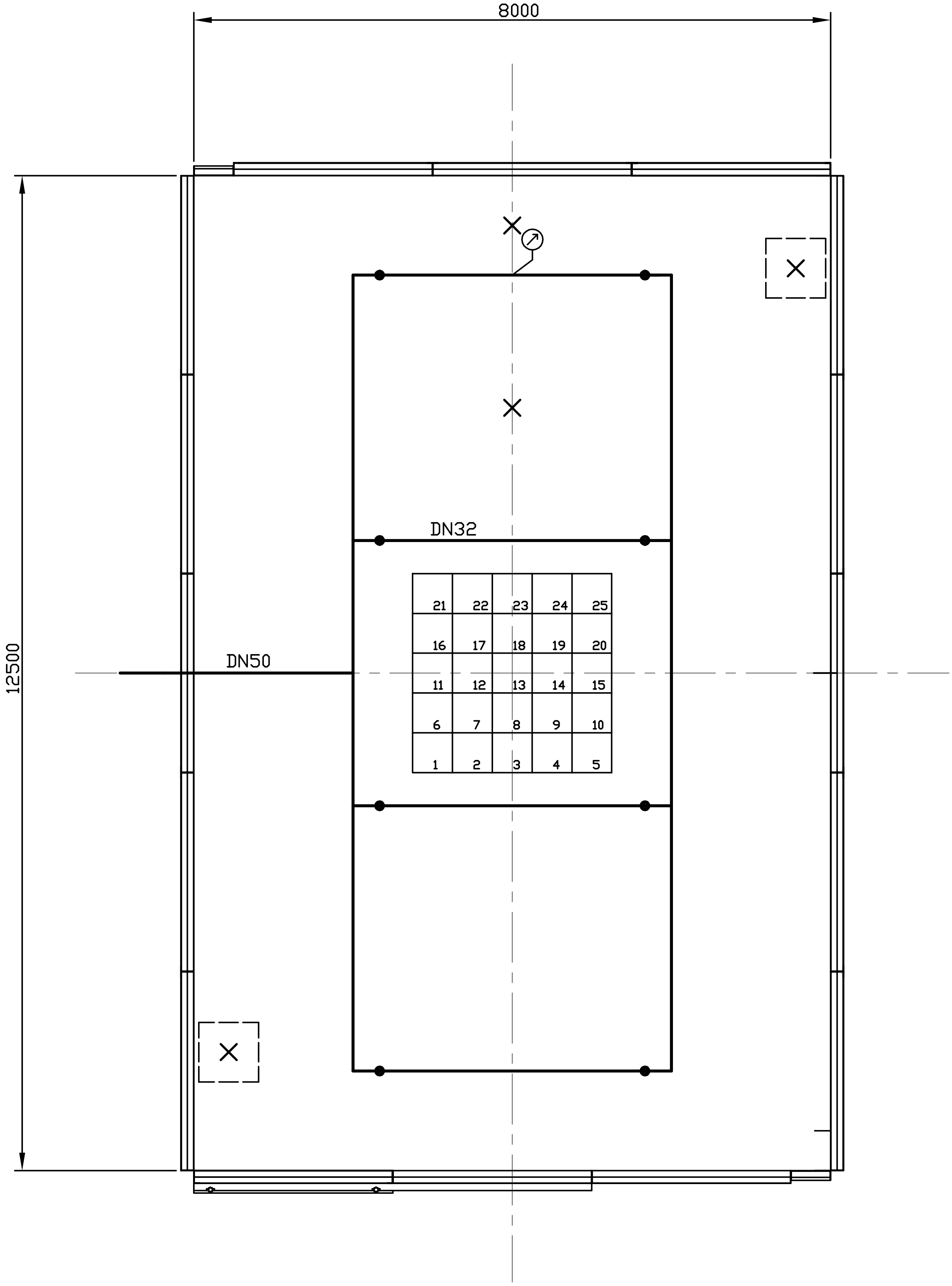

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