Electrical cabinet fire extinguishment testing

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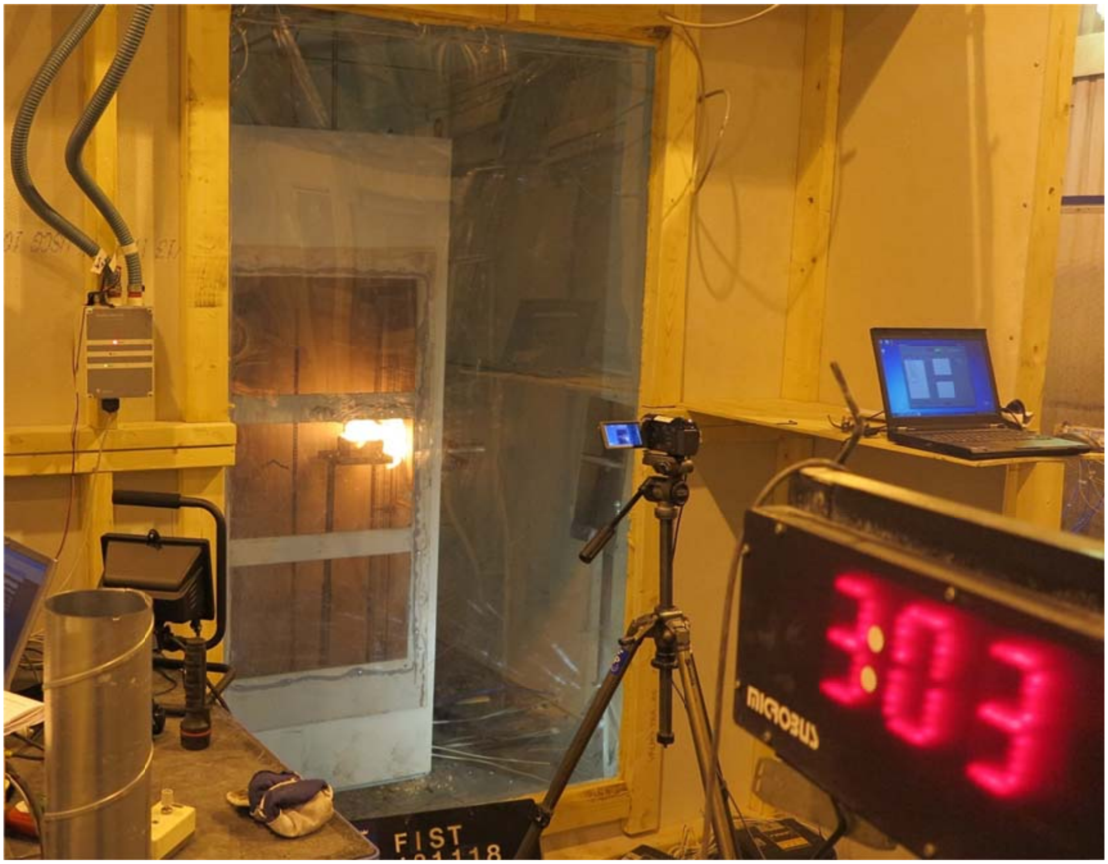

Abstract

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 fire fighting on navy ships. As part of this collaborative project, three gaseous fire suppression agents, NOVEC1230, nitrogen, and carbon dioxide, were evaluated to determine their efficacy in suppressing fires and preventing re-ignition in an electrical cabinet. The testing, carried out at SP Technical Research Institute of Sweden, Boras, Sweden in November/December 2013, also monitored the toxicity and corrosivity of degradation products arising from the suppressants and cooling of the space. The report presents and discusses the results of the testing.

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Introduction

A series of fire extinguishment tests in electrical cabinets were run at SP Technical Research Institute of Sweden during November 2013. The goal of the test series was to evaluate three gaseous fire suppressants/extinguishment systems with regards to extinguishment efficiency, protection against re-ignition, toxicity and corrosivity of degradation products, and cooling capacity.

The extinguishment systems evaluated were a fixed NOVEC 1230 system, a fixed nitrogen system and a system of portable CO_2 extinguishers with a NATO coupling that can be connected to the cabinet to allow discharge of CO_2 in the cabinet without opening the door.

The tests were performed in a cabinet with the dimensions 1.6 m x 0.4 m x 2.0 m (L x W x H). The cabinet was positioned in an air tight room where any gases escaping from the cabinet were collected and subsequently analysed.

Two different fire scenarios where evaluated;

- A 5 kW heptane fire to represent a fast growing fire. This scenario tested the system's ability to extinguish a fast growing fire before severe damage occurred
- An external radiation panel applying a thermal flux of approximately 40 kW/m^2 to the fuel source containing a cable bundle to represent a typical short circuit fire. The fuel (cable sheathing) is slowly heated until it ignites and the fire is continuously fed with external power from the electrical failure.

An aspirating fire detector was used in all tests.

Test compartment

The test compartment was 3.0 × 2.0 × 2.4m (L × W × H) with a door opening of 0.8 × 2.0 m (W × H). An electrical cabinet with the dimensions 1.6 x 0.4 x 2.0 (L x W x H) was positioned inside the compartment. The test compartment and electrical cabinet are shown in Figure 1. All tests were performed inside the cabinet and the larger compartment was used as a control volume where gases leaving the cabinet were collected.

The walls and the ceiling of the test compartment were constructed of an outer framework of 45mm x 90mm wood studs covered with calcium silica boards. In order to observe and record the tests a portion of the wall close to the cabinet door was replaced with an acrylic panel. A standard interior door was used in the door opening. All joints, gaps and penetrations in the test compartment were caulked with rubber sealant to make them as gas tight as possible.

The electrical cabinet was constructed from two Rittal TS 8804.500 cabinets achieving protection class IP55. All joints and the cabinet door was sealed with rubber strips. One cabinet door was equipped with fire resistant glass to enable the recording and observation of the tests. All penetrations in the cabinet were covered with rubber sealant. A Ø32 mm ventilation hole was drilled through the side wall of the cabinet.

Figure 1 shows an overview of set up of the test compartment and electrical cabinet.

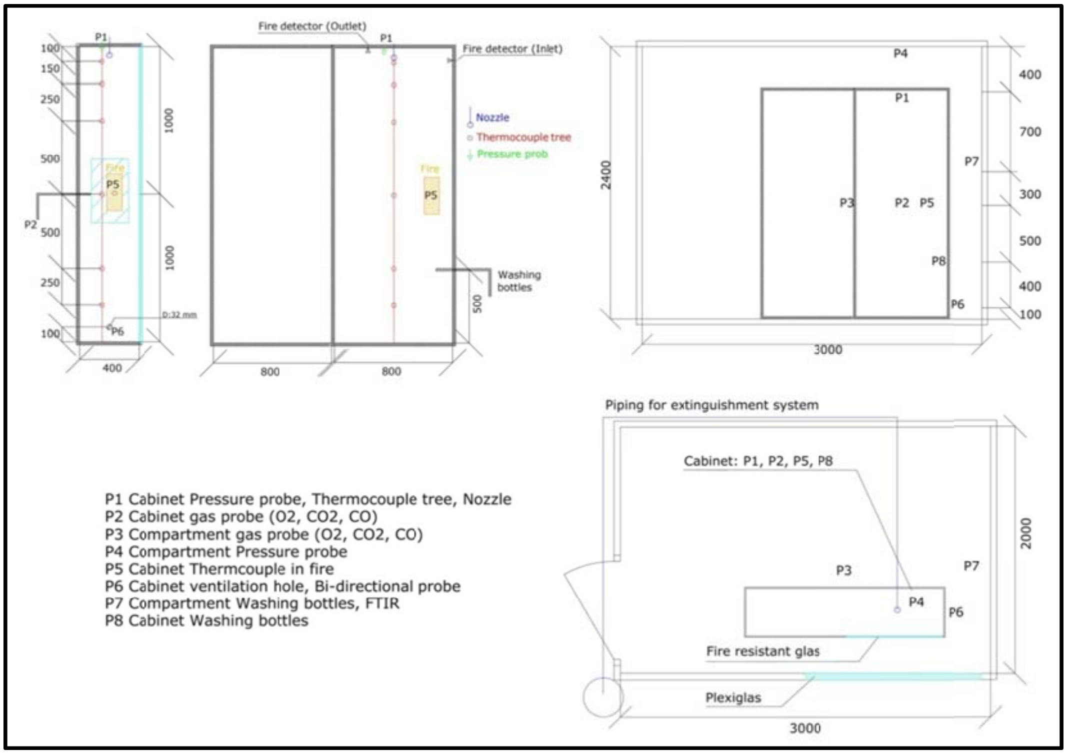

Figure 1. Schematic of the test compartment and electrical cabinet.

Instrumentation

The test compartment and electrical cabinet were equipped with thermocouples, gas measuring probes, pressure probes, and bi-directional probes. The measuring positions (P1-P8) are shown in Figure 1. The instrumentation at each position is described in detail below.

P1: A thermocouple tree with 0.5 mm type K thermocouples. The thermocouples were positioned 100, 250, 500, 1000 and 1750 mm below the ceiling. The pressure probe was placed 100 mm below the ceiling in the cabinet.

P2-P3: Oxygen, carbon monoxide and carbon dioxide measuring probes inside the compartment (P3) and cabinet (P2). Approximately 5 l gas per minute was pumped out from each measuring position for analysis. The probes were placed 1000 mm above the floor in cabinet and compartment.

P4: Pressure probe placed 100 mm below the ceiling of the compartment.

P5: A shielded 1 mm thermocouple placed just above the fuel surface or cable surface to register extinguishment and re-ignition times.

P6: Bi-directional probe with one 0.5 mm type K thermocouple placed in the cabinet ventilation hole (Ø 32 mm). Flow out of the cabinet was measured as positive flow.

P7-P8: Gas sampling with wash bottles (0.6 l/min) and FTIR spectrometer (3 l/min). In position P7 gas from the compartment was sampled with both wash bottles and FTIR. In position P8 gas from the cabinet was sampled with wash bottles. The objective of gas sampling was to measure hydrogen fluoride and hydrogen chloride in the cabinet and the compartment.

Fire scenarios

Two fire scenarios were used in this test series. Scenario 1 was a 5 kW heptane pool fire. Scenario 2 involved the exposure of ethylene-vinyl acetate sheathed cables wrapped with PVC to a heat flux of 40 kW/m^2 from a radiation panel. In fire scenario 1 the heptane pool was placed on a steel stand 1 m above the floor inside the cabinet. In fire scenario 2 the cables were placed in front of a window of fire resistant glass with the radiation panel placed outside the cabinet. The heptane pool and a cable ladder are shown in Figure 2.

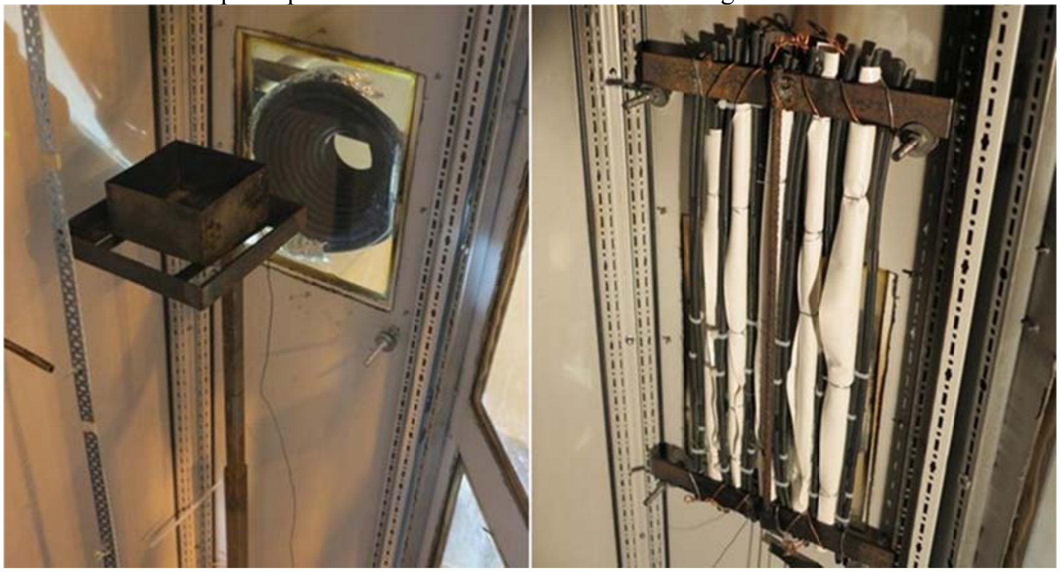

Figure 2. (Left) Position of heptane pool in fire scenario 1. An obstructing panel placed about 50 mm above the pan edge (see Figure 5). (Right) Cable ladder used in fire scenario 2.

Test equipment

FTIR (Fourier Transform Infrared) Spectroscopy

FTIR spectroscopy was used to continuously monitor gases in the electrical cabinet and test compartment during the fire testing. The major parts of the system are a spectrometer, a gas cell, a particle filter, a pump and sampling lines. The FTIR used in these tests was calibrated for several gases, e.g., carbon dioxide, carbon monoxide and hydrogen fluoride. An advantage of FTIR is that the IR spectra of the sampled gas allows the identification of all gases that have IR absorptions, not just the gases that the spectrometer was calibrated for. This allowed the detection of carbonyl fluoride in some of the tests (NOVEC 1230).

In these tests, gas was sampled at 3 l/min and the particle filter was changed before every test.

Wash bottle analysis

This technique used a suction pump, bottles, a basified solution (aqueous sodium hydroxide (20 mM)) and sampling pipe. Gases from the test compartment and the electrical cabinet was pulled through the solution in the wash bottles. Acid gases, for instance, hydrogen fluoride and hydrogen chloride, are soluble in the solution. The concentration of these ions arising from these soluble gases were then determined in an ion chromatograph and used to calculate the hydrogen fluoride content of the analysed gas. The measuring equipment is shown in Figure 3.

The gas from the compartment and the electrical cabinet was sampled at a flow rate of 0.6 l/min.

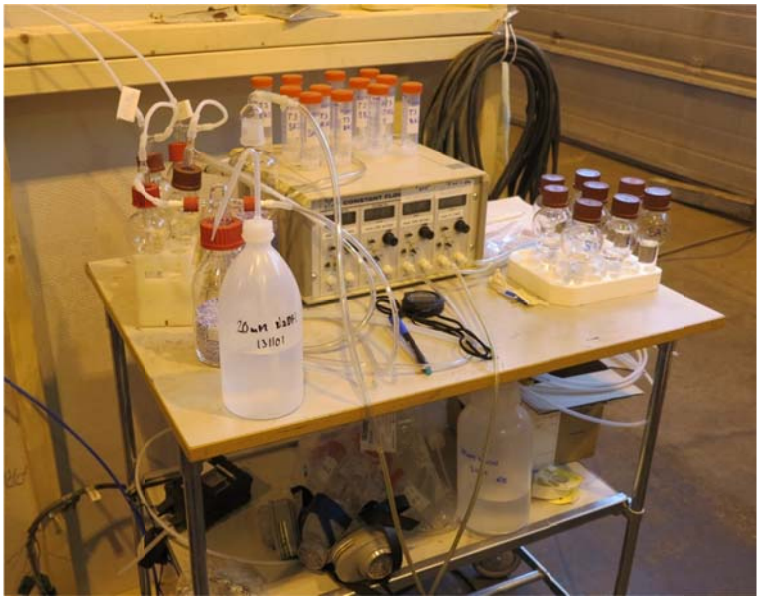

Figure 3. Wash bottle sampling apparatus.

Fuel pan

The fuel pan was a square steel pan with the dimensions 110 mm x 110 mm x 60 mm (L x W x H). An obstruction was placed 50 mm above the edge of the pan. The pan was filled with 1.1 dl of heptane for each test. This resulted in a 10 mm thick layer of fuel in the pan.

The heptane was ignited with a lighter. A pre-burn time of 60 seconds was used for the majority of the tests prior to activation of the fire suppression systems.

The results from a test of the heptane fuel in the Single Burning Item (SBI) [1] test apparatus are shown in Figure 4. The heat release rate (HRR) of the fuel reached approximately 5 kW one minute after ignition (240 s in Figure 4).

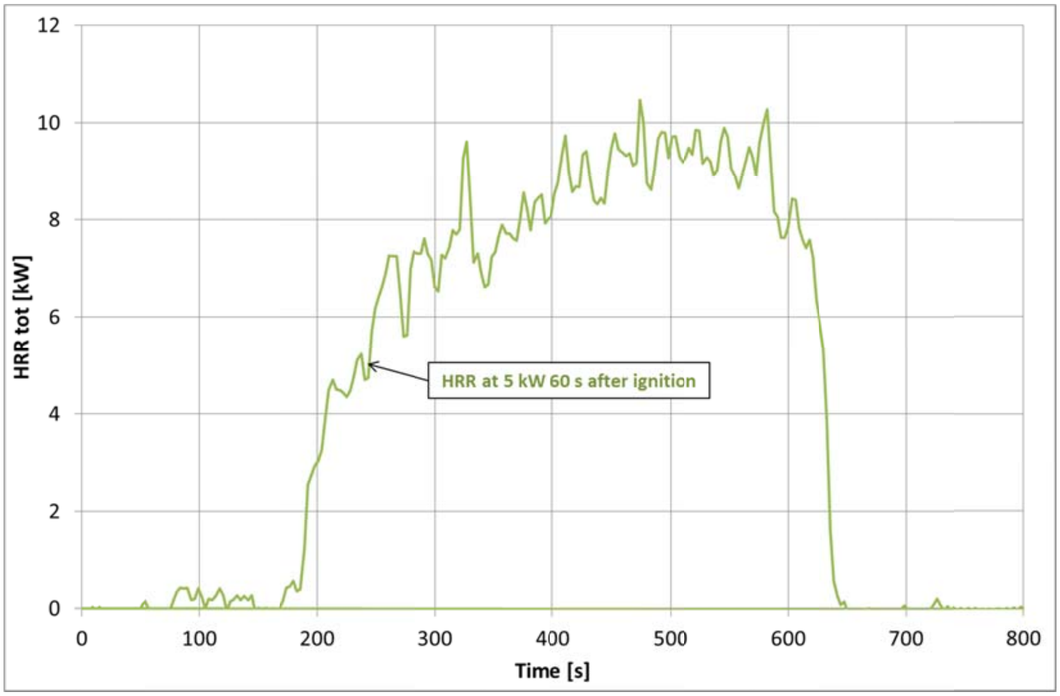

Figure 4 – Measured HRR as a function of time from test using the heptane pan in the SBI test rig.

Figure 5. (Left) Heptane fire in test 16. (Right) Picture of the fuel pan with obstructing panel approximately 50 mm above pan edge.

Radiation panel

The radiation panel consisted of an electrical heater rod tightly wound into the shape of a truncated cone. When the cone is powered it irradiates the material in front of it.. The intensity of the radiation (thermal flux) depends on the temperature of the heater rod, hence on the applied voltage.

The thermal flux of the of the radiation panel at 200V was tested using a plate thermometer. The plate thermometer and the radiation panel were positioned 20 mm from opposite sides of the fire resistant glass. This test setup (fire scenario 2) provided a radiant heat flux of approximately 40 kW/m^2.

Nozzle obstruction in the cabinet

In Test 8 an obstruction was placed under the extinguishment system nozzle to determine its effect on extinguishment time. The obstruction was placed approximately 100 mm below the nozzle and covered about half the length of the cabinet (800 mm). The obstruction is shown in Figure 6.

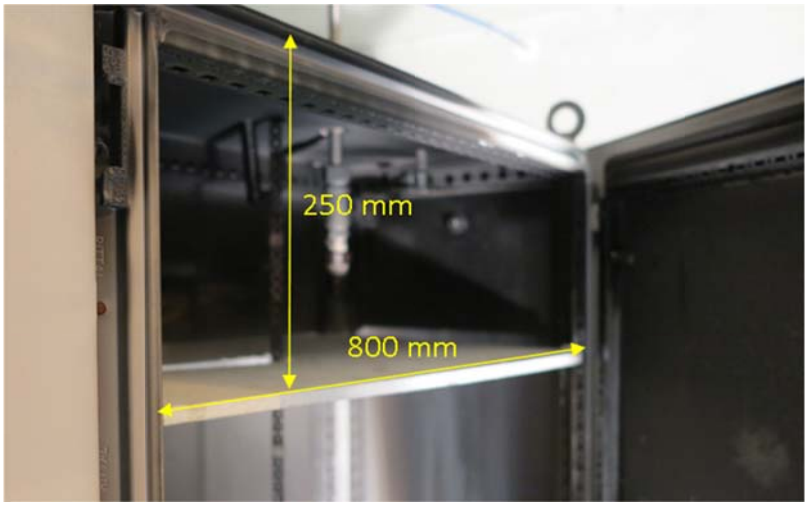

Figure 6. Cabinet equipped with nozzle obstruction (Test 8).

Throttle plate in extinguishment system piping

To simulate a damaged or malfunctioning extinguishment system where too little of the agent is released, a throttle plate was placed in the piping just prior the nozzle. The plate reduced the cross sectional area of the pipe to 25 % that of the open system.

Detection system

An aspirating fire detector (Stratos Micra 25 30760) was used in all tests. Both the detector inlet and outlet tubing was connected to the cabinet. The tubing leading to the detector inlet was placed approximately 100 mm below the cabinet ceiling and the tubing with the detector outlet (flow back into the cabinet) was placed in the ceiling of the cabinet. Their placements are shown in Figure 1. Both the inlet and outlet hoses were about approximately 4-5 m long. The detector measured smoke density (percent obscuration/m) in real time throughout the tests. Three fire alarm levels were set prior to the test series, Pre-alarm (16.5 %), Fire 1 (26.27 %) and Fire 2 (47.84%). The time until the smoke density reached each alarm level was recorded. Before any fire tests had been performed the detector registered a smoke density in the cabinet of 8 %.

Extinguishment system and agents

Three different extinguishing agents were used in the tests, Nitrogen, Carbon dioxide and NOVEC 1230. The piping and nozzle were designed for the NOVEC 1230 system but were also used, with minor modifications, for nitrogen testing. Carbon dioxide was released from a hand held CO_2 extinguisher through a NATO coupling. The coupling is shown in the cabinet wall in Figure 11.

Figure 7. (Left) Hand held CO_2 extinguisher (2 kg) connected to cabinet through NATO coupling. (Right) NOVEC 1230 (180°) nozzle used for all NOVEC 1230 and nitrogen fire suppression tests.

<u>NOVEC 1230:</u> The system consisted of one storage cylinder (5 L, 3kg), two nozzles and piping. Two nozzles were used because the storage cylinder contained about three times the agent necessary to achieve the effective concentration to suppress fires in the electrical cabinet. The nozzle with smaller orifice (see Figure 7) was placed inside the cabinet and the nozzle with larger orifice outside the test compartment. The release time was 4 s and the calculated gas concentration was 5.91 %.

<u>Carbon dioxide:</u> The system consisted of a 2 kg hand held CO_2 extinguisher and a NATO coupling. The inlet socket and hand applicator are shown in Figure 7. The extinguisher was fully opened at the time of release and the release time was approximately 50 – 60 s.

<u>Nitrogen:</u> The NOVEC 1230 cabinet piping and nozzle was used for the nitrogen testing. The second nozzle, outside the test compartment was plugged for these tests. A 20 l and 50 l, 250 bar, nitrogen cylinder with reducing valve was the source of the nitrogen gas. Nitrogen was released at the pressure of 12.5 bar for 60 s.

Performance indicators

The following performance indicators was identified as important in the selection of an extinguishment system to be installed in electrical cabinets.

Extinguishment/re-ignition time: Fast extinguishment and good protection against re-ignition can reduce the damage caused to the equipment in the cabinet. Extinguishment/re-ignition times were verified visually.

Pressure: Cabinet and compartment pressure was monitored during each test.

Toxic product release: A FTIR spectrometer was used to analyse smoke/decomposition gases from the compartment, primarily hydrogen fluorides (HF) released during the fire tests that used NOVEC 1230 as the extinguishing agent. In addition, smoke and gases were sampled from both the compartment and the cabinet in gas wash bottles filled with a sodium hydroxide solution. The water samples were analysed in an ion chromatograph to determine the concentrations of acid gases (hydrogen fluoride/hydrogen chloride).

Temperatures: Thermocouples were placed in the cabinet to evaluate the system's capacity to cool the gases in the cabinet.

Corrosion: During each of the extinguishment tests metallic coupons (copper, zinc and steel) were exposed to the atmosphere in the electrical cabinet. Mass loss of the coupons was measured and this mass loss was taken as a measure of the corrosivity of the environment in the cabinet.

Detection time: An aspirating fire detector (Stratos Micra 25 30760) was used to measure detection time for the different fire and gaseous fire suppression scenarios.

Test programme

The tests carried out in this study are listed in Table 1. The results of failed tests are not presented in this report, hence the missing test numbers in the table.

Table 1 – Test programme

Test no.	Scenario	Ext. system	Relative humidity [%]	Comment
2	Heptane	Free burning	Not recorded	
4	Heptane	Novec 1230	35	
7	Cable	Novec 1230	56	Increased humidity
8	Heptane	Novec 1230	31	Obstructed nozzle
9	Heptane	CO_2	41	
10	Cable	CO_2	56	
11	Heptane	Novec 1230	37	Slow flooding
12	Cable	Novec 1230	80	Increased humidity
13	Cable	Novec 1230	39	
16	Heptane	N_2	31	
18	Cable	N_2	31	
19	Cable	Novec 1230	42	No ventilation opening

Results

Extinguishment

Time to extinguishment and time to re-ignition results for the electrical cabinet fire suppression tests are presented in Table 2.

Table 2 – Extinguishment and re-ignition time

Test no.	Scenario	Ext. system	Comment	Time from activation to ext. [min:s]	Time from ext. to re-ignition [min:s]
4	Heptane	Novec 1230		0:05	-
7	Cable	Novec 1230	High humidity (56 %)	0:03	3:14
8	Heptane	Novec 1230	Obstructed nozzle	0:05	-
9	Heptane	CO_2		0:08	-
10	Cable	CO_2		0:09	7:27
11	Heptane	Novec 1230	Slow flooding	0:55	-
12	Cable	Novec 1230	High humidity (80 %)	0:02	-
13	Cable	Novec 1230		0:03	1:27
16	Heptane	N_2		0:59	-
18	Cable	N_2		0:10	-
19	Cable	Novec 1230	No ventilation opening	0:02	13:58

The extinguishment times for the NOVEC 1230 tests with unobstructed discharge varied between 2 and 5 seconds. For test 11 the extinguishment time was considerably longer (55 seconds) but the rate of discharge was reduced and therefore the time to establish the critical concentration of NOVEC 1230 in the cabinet was increased. The extinguishment time was not affected by varying humidity or by obstructing the nozzle. A slightly longer extinguishment time was observed for the heptane fire scenario (typically 5 seconds) than for the cable scenario (2-3 seconds). The estimated discharge time for the installed system (see Appendix 3) was 4.2 seconds which is just below the approved range of 5-10 seconds. Therefore in a real application the extinguishment time might be slightly longer compared to these results.

Re-ignition time in the cable scenario tests using NOVEC 1230 varied considerable; from 3:14 (min:s) to 1:27 (min:s) to no re-ignition. When the Ø32 mm ventilation opening in the cabinet was sealed the re-ignition time increased significantly to 13:58 [min:s]. This would result from the slower loss of NOVEC 1230 from the electrical cabinet and result in a longer time when the effective concentration of the agent necessary to prevent combustion was present in the cabinet.

The extinguishment times for CO_2 tests varied between 8 and 9 seconds. The re-ignition time in the cable scenario was 7:27 (min:s). In real applications the extinguishment time would be sensitive to the cabinet size since the same hose and NATO coupling is used regardless of CO_2 bottle size. This would result in an increase in the time to establish the critical extinguishing concentration of CO_2 in a larger cabinet.

For the N_2 system the extinguishment time was 59 seconds for the heptane fire scenario and 10 seconds for the cable fire scenario. The difference is likely due to differences in the extinguishment mechanisms of the heptane and cable bundle fires; cooling of the fuel in the cable fire and oxygen depletion for the heptane fire. In the cable fire scenario there was no re-ignition before the test was cancelled approximately 16 minutes after extinguishment.

One possible explanation for the re-ignition after extinguishment with CO_2 and NOVEC 1230 might be that these gases are significantly denser than air (CO_2: 1.98 kg/m^3 and NOVEC 1230

13.6 kg/m^3) and would accumulate (settle with time) in bottom of the electrical cabinet. As the fires where positioned at 1 m above the floor of the cabinet, the critical concentration of these gaseous agents at that level would decrease to the point where re-ignition was possible.

Toxicity – HF concentrations

Hydrogen fluoride (HF) testing was carried out for the NOVEC 1230 tests. HF levels were measured using two different methods; wash bottles where fluorides are dissolved in an aqueous sodium hydroxide solution and by FTIR (Fourier Transform Infrared Spectroscopy). The amount of fluorides found in the bottles and the calculated average HF concentrations during the sampling periods are shown in Table 3. Further, the sampling lines were washed, the wash water was collected and the amount of fluorides dissolved were analysed. The fluorides found in the sampling lines are presented as a mass of HF and as a percentage of the total amount of fluorides collected in the wash bottles.

Based on the fluoride mass found in the wash bottles the HF concentration in the sampled gas for each sampling period was calculated accordingly:

$$HF\ conc. = \frac{m_{F^-} * V_m}{V_{samp} * M_{F^-}} * \frac{M_{HF}}{M_{F-}} \qquad (1)\ \text{where;}$$

m_{F^-} is the mass of fluorides found in washing bottles

V_m is the molar volume of an ideal gas, 24.8 l/mol at 25°C and 1 atm.

M_{HF} is the molar mass of HF

M_{F^-} is the molar mass of F^-

V_{samp} is the sampled gas volume; 5 minutes of 0.6 l/min is 3 l.

Table 3 – Measured HF concentrations

Test no.	Scenario	Sampling periods	Fluoride in wash bottle, cabinet [mg]	Fluoride in wash bottle, room [mg]	Calc. HF conc. cabinet [PPM]	Calc. HF conc. room [PPM]	HF in sampling lines cabinet /percentage of total HF collected [mg]	HF in sampling lines room /percentage of total HF collected [mg]
4	Heptane	4:30 – 9:30	2.1	0.072	975	33	0.25 / 6%	-
		10:48 – 15:48	1.0	0.031	472	14		
		17:30 – 22:30	0.97	0.026	443	12		
7	Cable 56 % RH	12:30 – 17:30	0.31	0.044	144	20	0.53 = 12%	0.01 = 9%
		23:00 – 28:00	3.4	0.067	1554	31		
		38:00 – 43:00	0.71	0.040	326	18		
8	Heptane Obstr. nozzle	3:26 – 8:26	1.7	0.081	761	37	0.082 = 3%	0.004 = 3%
		10:00 – 15:00	0.68	0.042	313	19		
		16:30 – 21:30	0.40	0.023	184	11		
11	Heptane Slow flooding	4:00 – 9:00	31	0.14	14047*	66*	1.3 = 2%	0.015 = 2%
		11:30 – 16:30	18	0.31	8385*	144*		
		26:30 – 31:30	7.6	0.13	3468*	60*		
12	Cable 80 % RH	13:44 – 18:44	0.39	0.019	176	9	0.33 = 46%	0.10 = 152%
		23:44 – 28:44	0.17	0.026	76	12		
		38:44 – 43:44	0.18	0.023	80	10		
13	Cable	10:18 – 15:18	0.59	0.029	268	13	3.0 = 42%	0.014 = 5%
		20:18 – 25:18	5.2	0.15	2387	70		
		36:00 – 41:00	1.2	0.11	557	50		

*In test 11 a significant amount of Carbonyl fluoride (COF_2) was found in the FTIR analysis. It is, hence, reasonable to assume that a significant portion of the fluorides in the wash bottles originates from COF_2.

In Table 4 the results from the FTIR measurements are presented. After each test the FTIR filter was washed and the wash water was analysed for fluoride content. The fluorides found in the filter are presented as a mass of HF and as a percentage of the total amount of measured HF. The FTIR data was also analysed for carbonyl fluoride (COF_2). COF_2 was only detected in test 11.

Table 4 – Measured HF concentrations FTIR

Test no.	Scenario	Peak HF conc. room FTIR [PPM]	Peak COF_2 conc. room FTIR [PPM]	Measured fluorides in FTIR filter [µg]	Calculated HF in FTIR filter [µg] / % of measured HF
4	Heptane	<5	No COF_2 detected	82.4	86.7 / N/A
7	Cable	17	No COF_2 detected	188	198 / 22%
8	Heptane	7	No COF_2 detected	88.0	92.6 / 63%
11	Heptane	19	80*	163	172 / 17%
12	Cable	18	No COF_2 detected	175	184 / 15%
13	Cable	28	No COF_2 detected	71.6	75.4 / 3%

*FTIR equipment was not calibrated for COF_2. The value should only be considered as an indication of the formation of a significant amount of COF_2 in test 11.

In Figure 8 to Figure 13 the HF levels in the room both from wash bottle and FTIR analysis are presented.

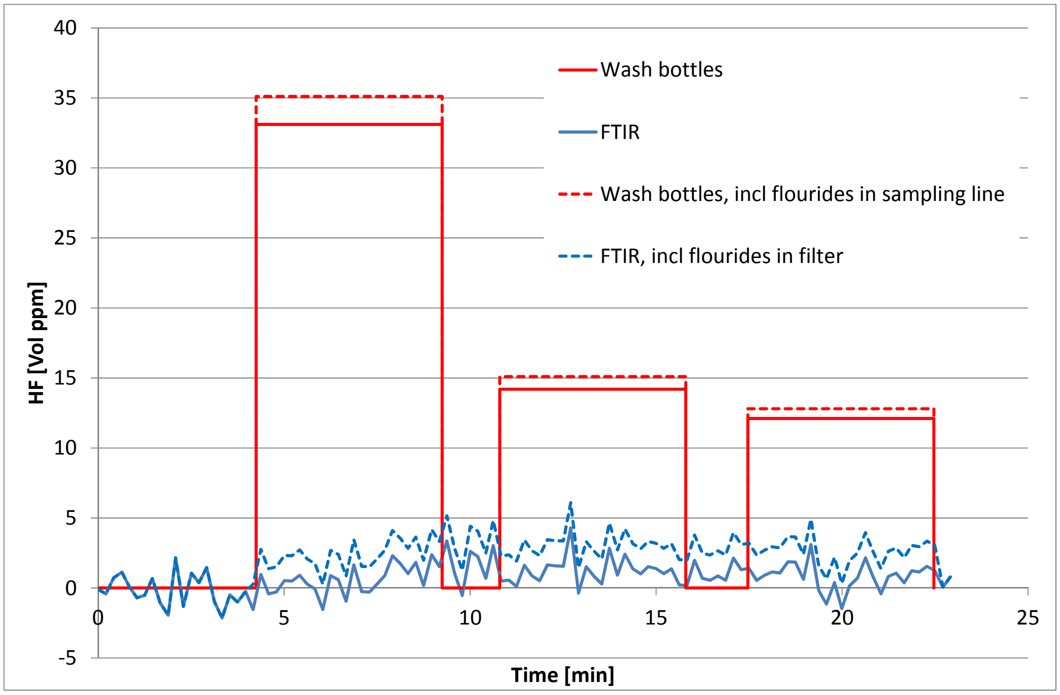

Figure 8 – HF levels in test 4

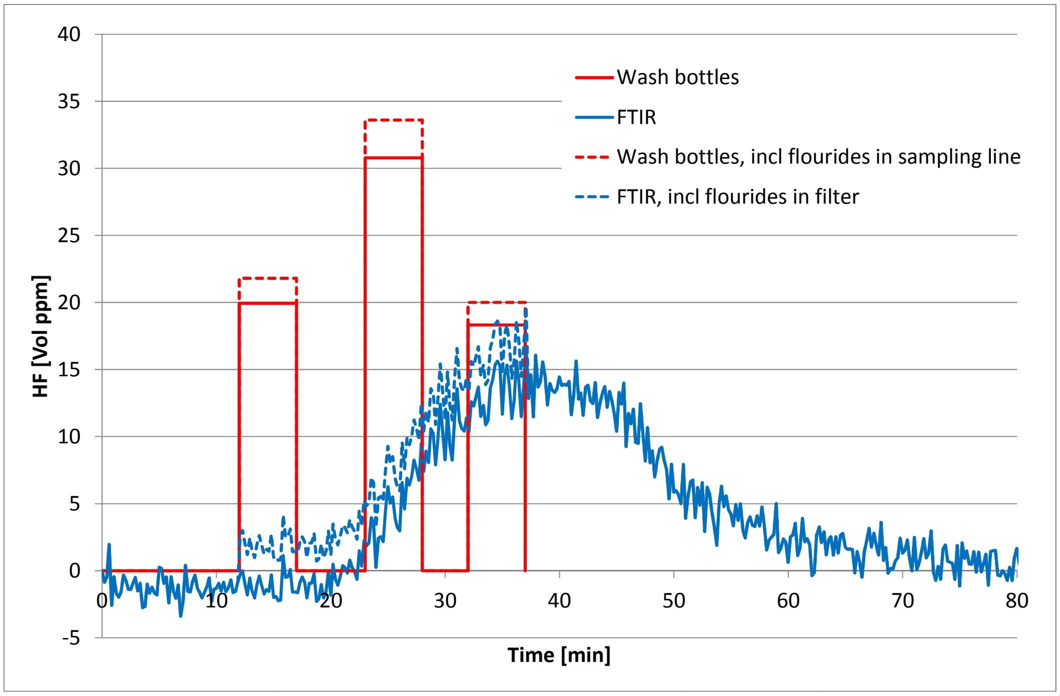

Figure 9 – HF levels in test 7

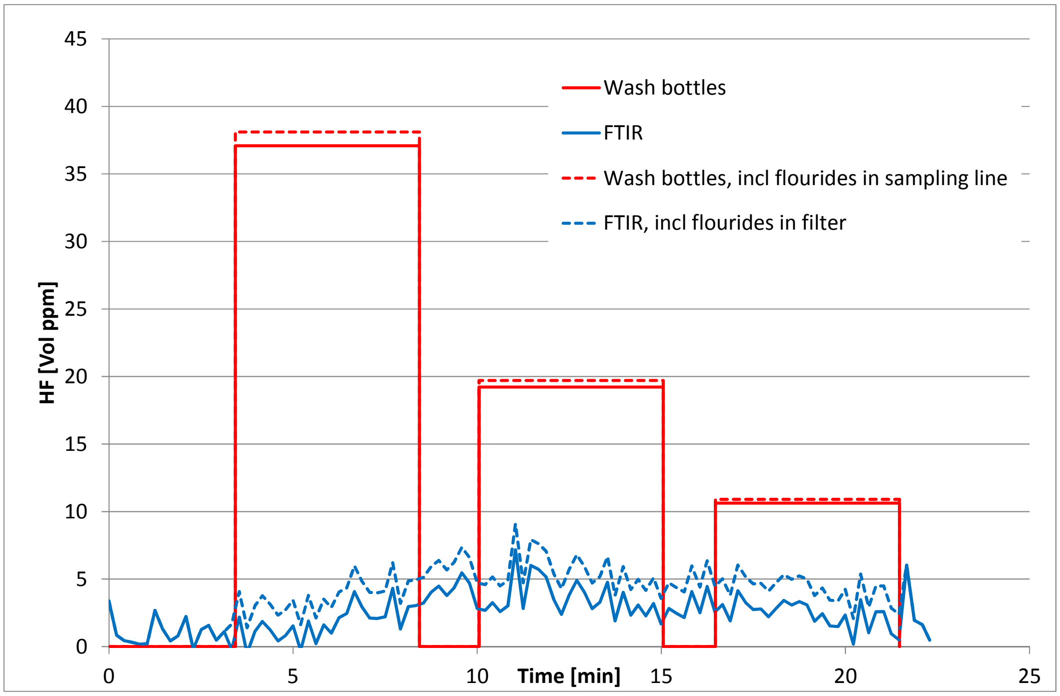

Figure 10 – HF levels in test 8

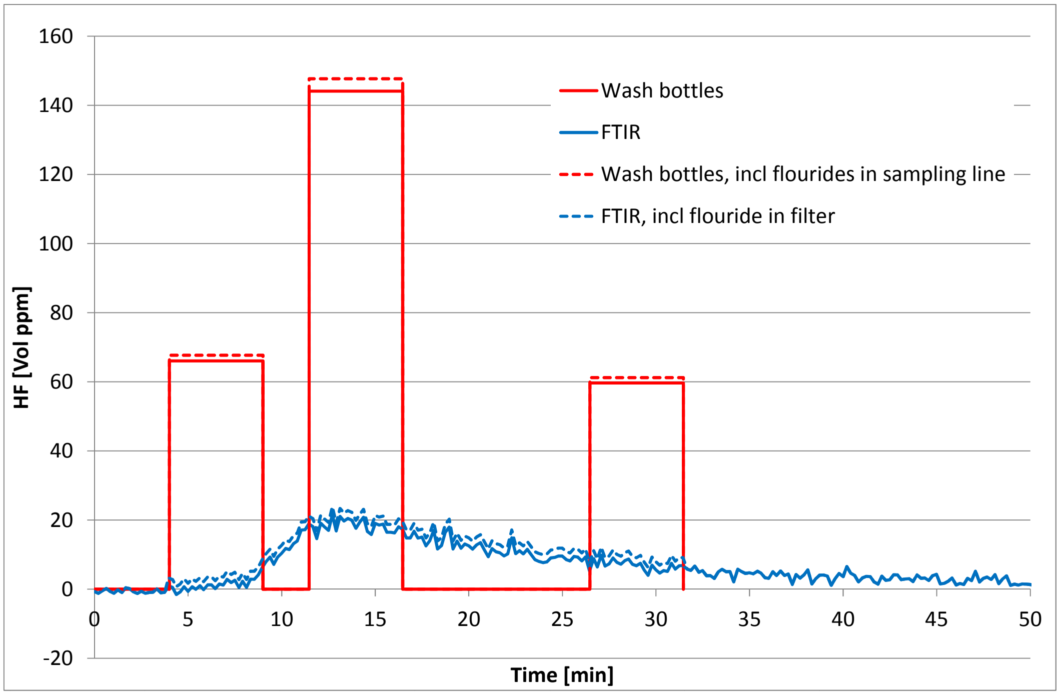

Figure 11 – HF levels in test 11, NOTE: in this test the FTIR measurement indicated a significant amount of COF_2, the fluorides from COF_2 are contributing to the wash bottle results above.

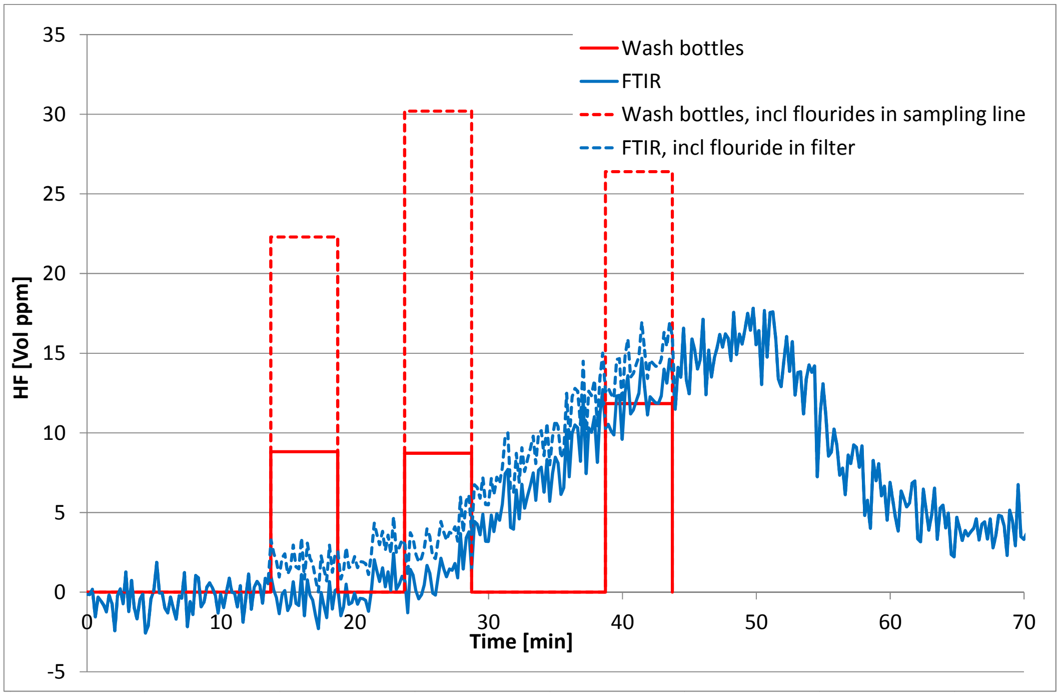

Figure 12 – HF levels in test 12

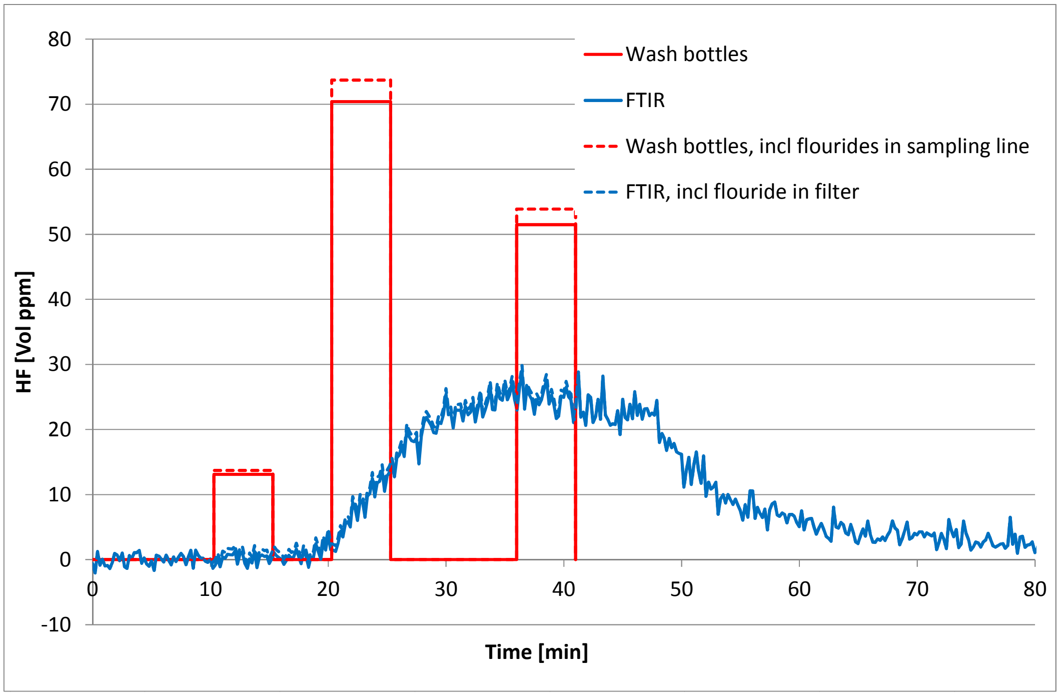

Figure 13 – HF levels in test 13

In Tests 4 and 8 (heptane fire scenario with normal discharge of NOVEC 1230 and extinguishment in 3-5 s), the peak HF levels in the cabinet varied between 761 ppm and 975 ppm (776 – 1035 ppm if fluorides in sampling lines are added) and the peak HF levels in the room varied between 33 ppm and 37 ppm (33 – 38 ppm if fluorides in sampling lines are added).

In Tests 7, 12, and 13 (cable fire scenario with normal discharge of NOVEC 1230 and extinguishment in 3-5 s), the peak HF levels in the cabinet varied between 176 ppm and 2387 ppm (257 – 3390 ppm if fluorides in sampling lines are added) and the peak HF levels in the room varied between 12 ppm and 70 ppm (30 – 74 ppm if fluorides in sampling lines are added).

In the cable fire tests the humidity was varied and a correlation between humidity and HF levels in the compartment was found; higher humidity resulted in a lower peak HF level.

In Test 11 (heptane fire scenario with failing discharge of NOVEC 1230 and extinguishment in 55 s), the peak HF level in the cabinet was 14047 ppm (14328 ppm if fluorides in sampling lines are added) and the peak HF level in the room was 144 ppm (147 ppm if fluorides in sampling lines are added). These values include fluorides from COF_2.

Low HF levels measured using FTIR method

As was seen above, the HF levels measured using FTIR were significantly lower than those measured using the wash bottle method. Several factors where identified that could have influenced the results. Inspection of the sampling line indicated that it was not heated 180 °C as expected. This temperature was chosen to minimize condensation in the line. During the tests, the temperature of the sampling line reached only 135 °C. In addition, HF gas could be absorbed on the sampling line and primary filter. This would reduce the amount of HF reaching the detector.

An additional series of tests were performed to determine if these factors affected the HF levels measured using the FTIR method. In these tests gas was sampled with a known concentration of HF and analysed by FTIR analysis. The HF concentration and the sampling line temperature were varied and tests were performed both with and without the primary and secondary filter in the FTIR. The measured HF concentration was logged and the response time was determined as the time it took for the FTIR to measure 90% of the known HF concentration (see Figure 14). In all tests except Test F, two measuring cycles were made. After the first cycle, the sampling line was detached from the HF flow and air sampled until the measured HF concentration returned to 0. The sampling line was reattached to the HF flow and HF concentration monitored again. A summary of the test conditions and results is shown in Table 5.

Table 5 – Summary of results from tests to determine FTIR response time.

Test	Conditions	Nominal HF concentration	Response time
A	Hose temperature: 180 °C No primary filter	56 ppm	Cycle 1: 32 min Cycle 2: 6 min
B	Hose temperature: 180 °C No primary filter Starting immediately after test 1*	186 ppm	Cycle 1: 1 min (from 56 ppm) Cycle 2: 2.5 min
C	Hose temperature: 135 °C No primary filter	56 ppm	Cycle 1: 12 min Cycle 2: 9 min
D	Hose temperature: 135 °C No primary filter Starting immediately after test 1*	186 ppm	Cycle 1: 1 min (from 56 ppm) Cycle 2: 2 min Cycle 3: 2 min
E	Hose temperature: 180 °C With primary filter	56 ppm	Cycle 1: 33 min Cycle 2: 19 min
F	Hose temperature: 180 °C With primary filter Starting immediately after test 1*	186 ppm	Cycle 1: 5 min
G	Hose temperature: 180 °C No primary filter No secondary filter**	56 ppm	Cycle 1: 3 min Cycle 2: 2 min
H	Hose temperature: 180 °C No primary filter No secondary filter** Starting immediately after test 1*	186 ppm	Cycle 1: 30 s Cycle 2: 45 s

*Sampling lines and filter are saturated with HF. This affects the response time in the first cycle.

**Test without a secondary filter is not possible when sampling from a fire exposed volume.

The response time in these tests varies between 0.5 and 33 minutes. It can be seen that the response time in conditions similar to those used in the electrical cabinet tests (cycle 1 in test E) is 33 minutes. Further, it can be seen that removing filters significantly reduces the response time and higher HF concentrations result in shorter response times. The reduced hose temperature does not obviously affect the response time.

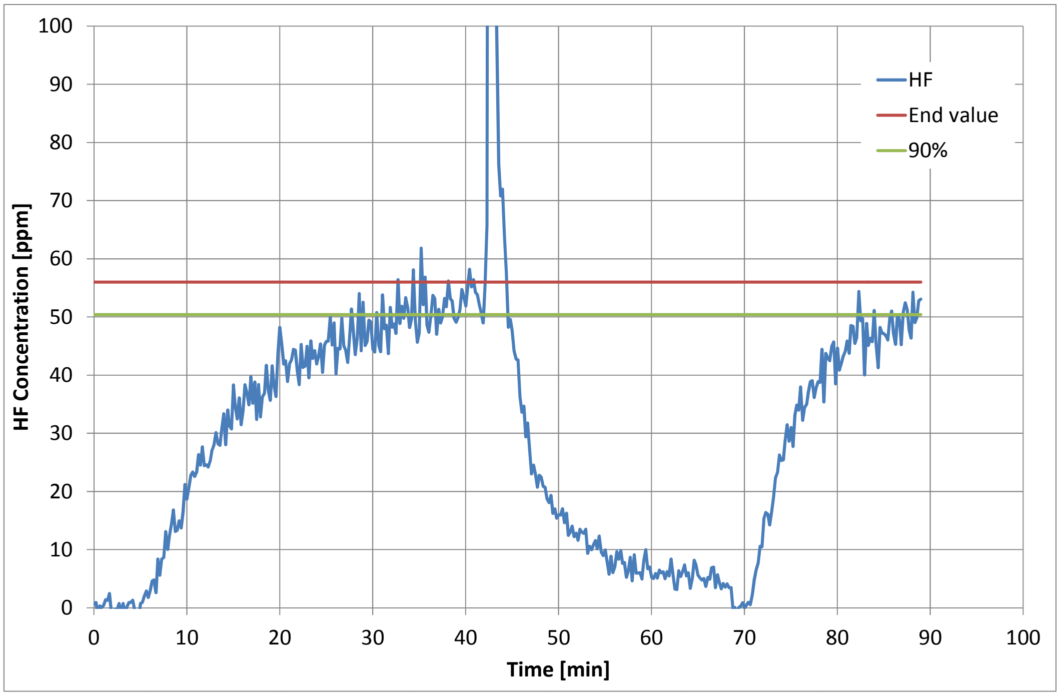

Figure 14 – Measured HF concentrations in test E. The end value (56 ppm) and the 90% value that indicates the response time level are included. When the sampling pipe was extracted from the HF-flow (at about 43 minutes) there was a value spike (276 ppm), possibly due to HF accumulated on the first cold section of the sampling line.

These long response times explains why peak HF values were not measured, or were underestimated, in the electrical cabinet tests where the peak HF levels occurred 0-15 minutes after the release of Novec 1230.

The tests with longer duration times showed good correspondence between FTIR and wash bottleresults after 40 minutes of sampling (approximately 30 minutes after release of Novec 1230), see Figure 9, Figure 12 and Figure 13.

Decay of HF

The decrease in the concentration of HF in the electrical cabinet can be assumed to be a first order process [2], i.e. it depends only on a decay speed constant and the concentration of HF (other reactants are always in an abundance). The concentration as a function of time, C(t), can be expressed as:

$C(t) = C_0 * e^{-kt}$ … (1) where

C_0 is the initial concentration, k is the decay speed constant and t is time.

When k is known the half-life ($t_{1/2}$) can be calculated accordingly:

$t_{1/2} = \frac{ln(2)}{k}$ … (2)

The results from Test 7 were used for HF half-life analysis due to the long duration of the test.

The HF concentration decrease in Test 7 was fitted to the following exponential function:

$C(t) = 797.6 * e^{-0.095t}$

Inserting the decay speed constant (0.095) in Eq. (2), the half-life of HF in the control volume surrounding the electrical cabinet was found to be approximately 7.3 minutes.

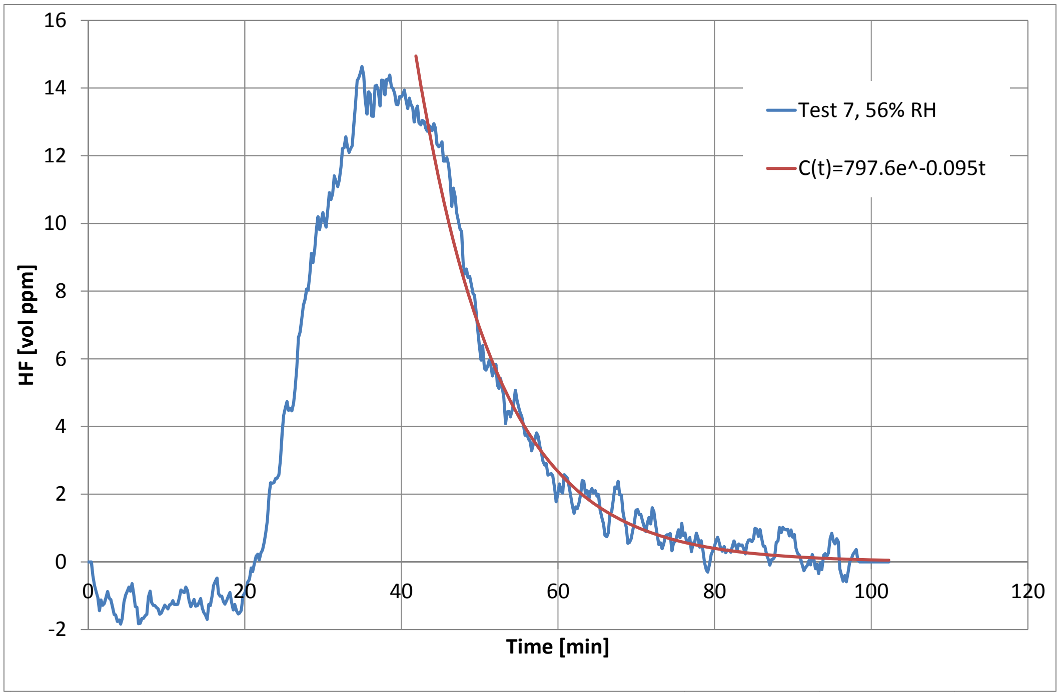

Figure 15 presents HF levels from the room measured with FTIR during test 7. It also shows the best fit exponential expression of the decay phase.

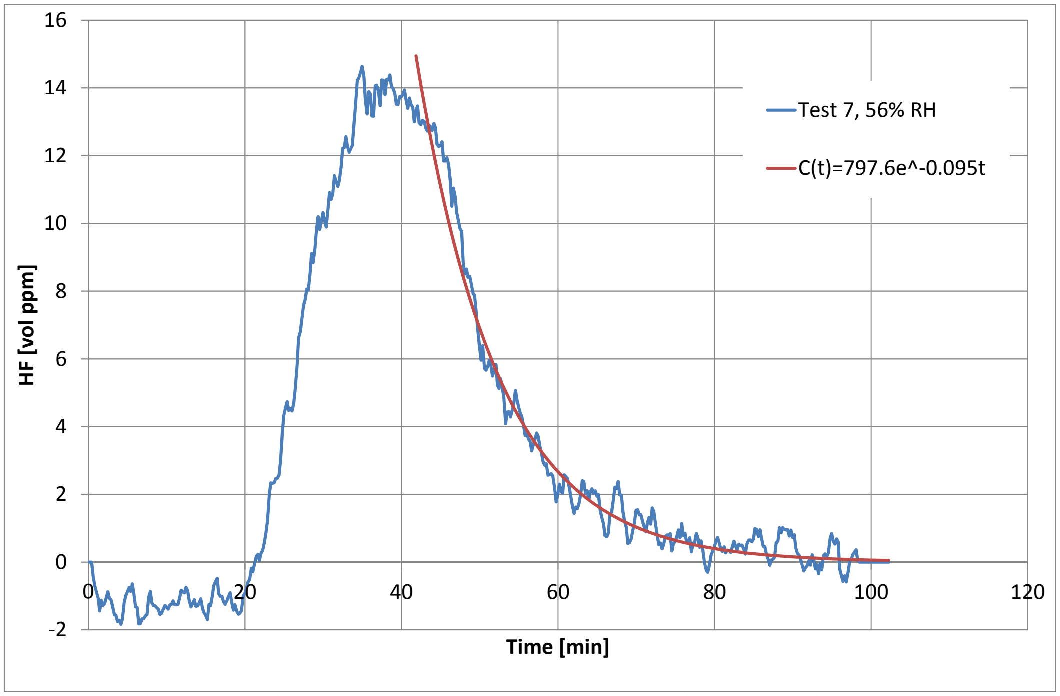

Figure 15 – HF levels in test 7.

A similar analysis was also performed on the decay of HF for tests 12 and 13. The half-life in both of these tests was found to be 6.9 minutes.

Temperatures

The temperatures inside the cabinet was monitored during the tests using a thermocouple tree. The average temperatures from the tests with the heptane fire scenario are plotted in Figure 16 and the average temperatures from the tests with cable fire scenario are plotted in Figure 17.

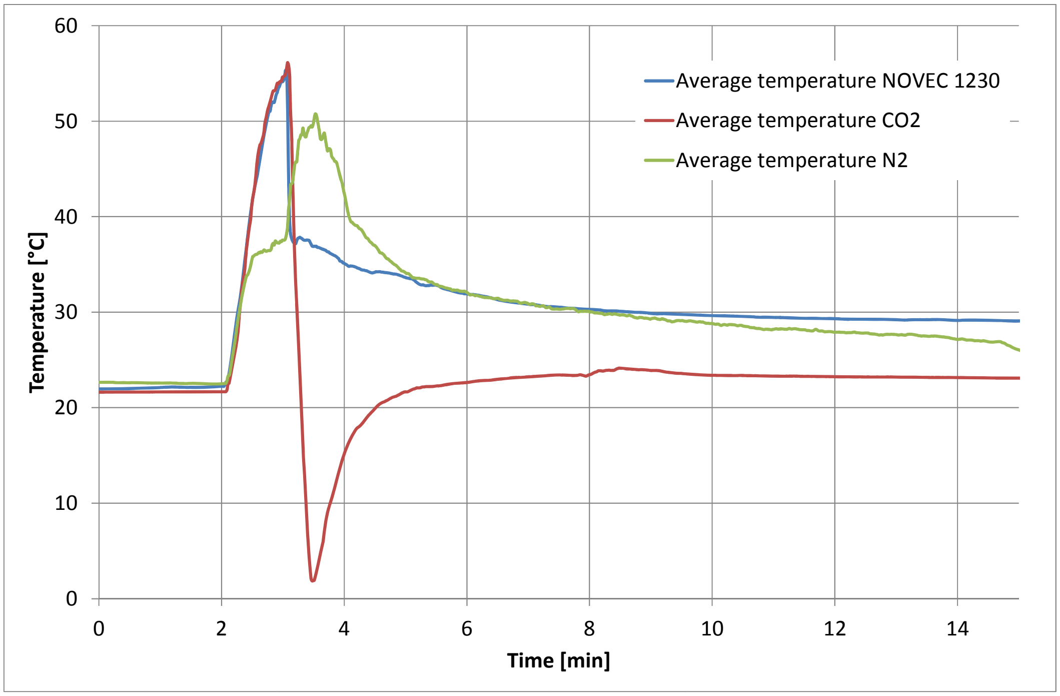

Figure 16 – Average cabinet temperature during extinguishment of the heptane fires.

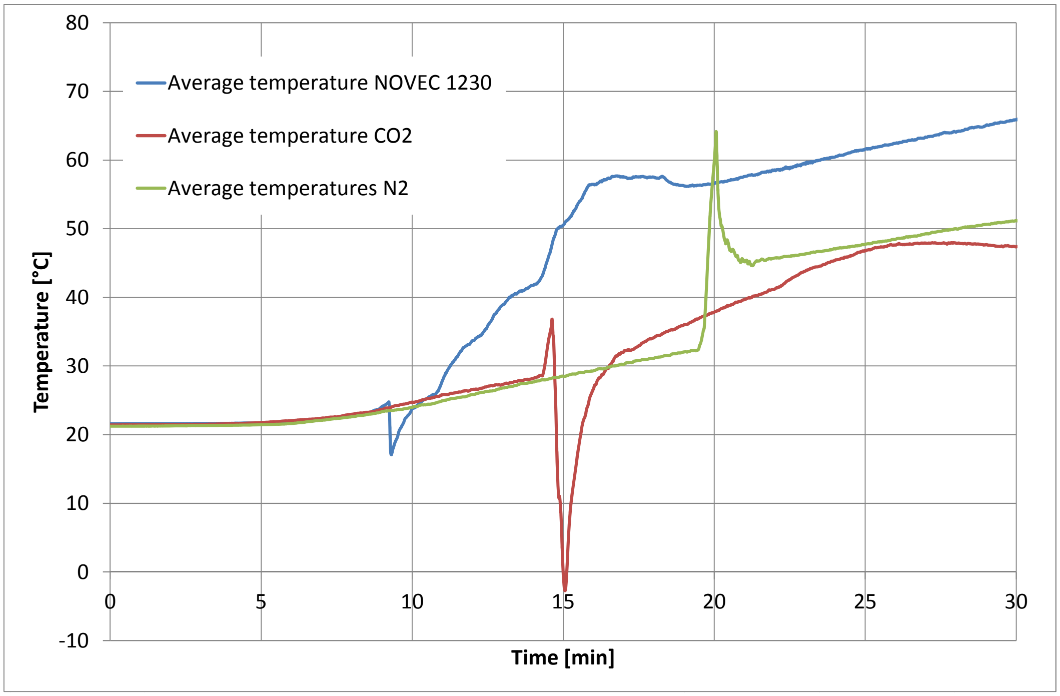

Figure 17 - Average cabinet temperatures during extinguishment of cable fire tests.

For the heptane fire scenario, all three gaseous suppressants resulted in cooling of the cabinet following activation of the system. Discharge of the CO_2 system resulted in an immediate cooling of the cabinet. It also produced in the most cooling, resulting in average temperatures close to 0 °C in both tests. Locally sub-zero temperatures occurred for short periods of times. In these CO_2 tests the coldest temperature measured by an individual thermocouple was -5 °C and the temperature did not stay below 0 °C for more than 10 seconds. Activation of the NOVEC 1230 system also resulted in an immediate decrease in the temperature of the cabinet. The N_2 systems was also effective in cooling the cabinet. However, the shorter discharge time of the NOVEC 1230 system results in a significantly faster cooling than was observed for the N_2 system.

Detection time

An aspirating fire detector (Stratos Micra 25 30760) was used in all tests. The time to alarm (at three levels) are presented in Table 6.

Table 6 – Detection time

Test no.	Scenario	Ext. system	Time to pre-alarm* [min:s]	Time to Alarm level 1* [min:s]	Time to Alarm level 2* [min:s]	Time to ignition Cable [min:s]
1	Cable	Free burning	Not recorded	9:51	13:21	Ignition failure
2	Heptane	Free burning	0:28	Not recorded	0:56	NA
3	Cable	Novec 1230	6:02	6:32	7:54	Ignition failure
4	Heptane	Novec 1230	0:50	Not recorded	1:18	NA
5	Cable	Novec 1230	5:38	5:54	6:30	Ignition failure
6	Cable	Novec 1230	4:54	5:07	5:28	Ignition failure
7	Cable	Novec 1230	8:40	8:58	9:21	9:28
8	Heptane	Novec 1230	Not recorded	0:22	0:31	N A
9	Heptane	CO_2	Not recorded	0:20	0:25	NA
10	Cable	CO_2	Not recorded	4:21	5:01	12:07
11	Heptane	Novec 1230	0:21	0:23	0:31	NA
12	Cable	Novec 1230	Not recorded	1:34	5:15	10:30
13	Cable	Novec 1230	4:29	4:25	6:01	6:25
15	Heptane	N_2	0:53	1:00	Not trigged	NA
16	Heptane	N_2	0:38	0:38	Not trigged	NA
17	Cable	N_2	4:41	4:47	6:52	Ignition failure
18	Cable	N_2	4:29	5:30	8:00	17:28

*Time from ignition in heptane fire scenario, time from radiation panel activation (i.e. start of heating phase) in cable scenario. NA – not applicable

For the heptane fires, the time to pre-alarm varied between 21 and 53 seconds, time to alarm level 1 varied between 20 and 60 seconds and time to alarm level 2 varied between 25 and 78 seconds. In two tests alarm level two was not trigged before activation of the extinguishment system.

In the cable fire scenario all three alarm levels was trigged before ignition. Pre-alarm was always trigged at least 48 seconds before ignition, alarm level 1 was always trigged at least 30 seconds before ignition and alarm level 2 was always trigged at least 7 seconds before ignition.

The Stratos Micra 25 detector is designed to automatically adjust to the environment it is monitoring. This is to minimize the number false alarms due to, for example, dust or other air pollutants. This feature together with the changes in the environment as fire testing continued resulted in drifting alarm levels and most likely a contamination of the detector. The default detector output smoke density was 8 % before the cabinet had been subjected to any fire test. Before the last test was conducted the detector output was 39.6 % even though the compartment and cabinet were ventilated between each test. The default alarm level settings were 16.5, 26.27 and 47. 84 % (Pre-Alarm: Fire 1 and Fire 2) at the start of testing and at the end of the test series these levels had increased to 48.6, 49.02 and 81.8 %. Possible explanations for the major differences in alarm level between test 1 and test 19 might be the accumulation of soot (although the detector filter was changed after every second or third test) or etching of lenses in the device from the exposure to hydrogen fluoride.

Corrosion

Coupons of carbon steel, copper and zinc (25 mm x 25 mm) were cleaned with ethanol and weighed before exposure to the environment in the electrical cabinet during the fire suppression tests.

Two coupons of each metal were exposed in each test. The coupons where placed at different heights in the cabinet (at 0.5 m and 1.5 m above the floor) to determine if the corrosivity of the atmosphere varied with height in the compartment. Test coupons with even numbers where placed at 0.5m above the floor in the cabinet and the test coupons with odd numbers were placed at 1.5m above the floor in the cabinet. The coupons where weighed after the fire tests.

The corrosion products were removed using different pickling liquors. The copper coupons where treated with a 5% solution of amidosulfuric acid, the steel coupons with a 50% solution of hydrochloric acid and the zinc coupons where pickled in a saturated glycine solution. The coupons where then reweighed and the mass loss calculated.

The coupons from test 1, 4, 10, 11, 12, 13 and 18 where selected for evaluation.

Table 7 – Mass loss from copper coupons.

Test no.	Coupon	Mass loss [mg/dm^2]	Average mass loss [g/m^2]	Comment	Rank
1	1	5.58	0.45	Almost unaffected	1
	2	3.44			
4	5	6.91	0.82	Mass loss evenly distributed on the surface	3
	6	9.37			
10	15	13.01	1.47	Unevenly affected. Heavily affected patches.	5
	16	16.24			
11	17	4.31	0.54	Mass loss evenly distributed on the surface	2
	18	6.45			
12	19	27.21	2.04	Mass loss unevenly distributed on the surface	7
	20	13.42			
13	21	13.08	1.56	Unevenly affected. Heavily affected patches.	6
	22	17.92			
18	23	16.58	1.14	Mass loss unevenly distributed on the surface	4
	24	6.18			

Observations:

- Test 12 (NOVEC, 80% RH) coupons had the highest level of corrosion.
- Test 11 (NOVEC, slow discharge) coupons had the second lowest corrosion levels despite being exposed to the highest fluoride levels.
- There was little difference in the average mass loss of the coupons for Test 10 (CO_2), Test 13 (NOVEC 1230) and Test 18 (N_2).

Table 8 – Mass loss from steel coupons.

Test no.	Coupon	Mass loss [mg/dm^2]	Average mass loss [g/m^2]	Rank
1	1	13.38	2.20	1
	2	30.48		
4	5	22.38	2.26	2
	6	22.75		
10	15	158.65	14.3	5
	16	127.2		
11	17	44.16	6.18	3
	18	79.33		
12	19	298.19	23.7	7
	20	175.45		
13	21	112.11	15.0	6
	22	186.38		
18	23	169.58	13.6	4
	24	102.07		

Observations:

- Test 12 (NOVEC, 80% RH) coupons had the highest level of corrosion.
- Test 11 (NOVEC, slow discharge) coupons had the third lowest corrosion levels despite being exposed to highest fluoride levels.
- There was little difference between average mass loss for coupons in Test 10 (CO_2), Test 13 (NOVEC 1230) and Test 18 (N_2).

Table 9 – Mass loss from zinc coupons.

Test no.	Coupon	Mass loss [mg/dm^2]	Average mass loss [g/m^2]	Rank
1	1	7.40	0.74	1
	2	7.27		
4	5	15.85	2.18	2
	6	27.7		
10	15	210.73	17.1	4
	16	130.58		
11	17	183.02	21.2	6
	18	239.78		
12	19	321.87	20.4	5
	20	84.39		
13	21	533.63	46.9	7
	22	403.92		
18	23	207.33	16.2	3
	24	116.7		

Observations:

- Test 13 (NOVEC, normal discharge) coupons had the highest level of corrosion
- In general, the mass loss of zinc coupons was greater in NOVEC 1230 tests. A possible explanation is that zinc is more sensitive to acidic conditions/low pH (see Appendix 2).

Comparison to outdoor environment according to ISO 9223

The metal mass loss of copper, steel and zinc coupons exposed in these tests are compared to those exposed to 1 year in a medium corrosive outdoor environment, C3 according to ISO 9223 [3], in Table 9.

Table 10 – Mass loss in test compared to 1 year in medium corrosive outdoor environment.

Metal	**Cu**	**Zn**	**Fe**
Mass loss (g/m2) C3 1 year	5<….≤12	5<….≤15	200<….≤400
Metal loss (g/m2) after fire tests	0.45 – 2.04	0.74 – 46.9	2.20 – 23.7

In the test that had the worst effect on copper (Test 12), the mass loss due to corrosion was equivalent to about 3 months in a C3 environment.

In the test that had the worst effect on zinc (Test 13), the mass loss due to corrosion was equivalent to about 4.5 years in a C3 environment.

In the test that had the worst effect on steel (Test 12), the mass loss due to corrosion was equivalent to about 1 month in a C3 environment.

When comparing the results from test 10, 13 and 18 (same fire scenario, different extinguishing agent), there is no obvious difference in corrosion damage to steel or copper coupons between the different system alternatives. The results seem to be more sensitive to the humidity in the compartment (compare test 12 and 13).

The corrosion damage to the zinc coupons was more severe for tests using NOVEC 1230 than for those using CO_2 and N_2.

Regardless of extinguishment system and fire scenario tested, it is likely that the cabinet will require cleaning (decontamination) after extinguishment of a fire to prevent corrosion of metals exposed to combustion gases and the gaseous agents and their degradation products.

Cabinet pressure

The pressure in the cabinet was monitored during the tests. The pressure for the tests with the heptane fire scenario are presented in Figure 18 and the pressure for the tests with cable fire scenario are presented in Figure 19.

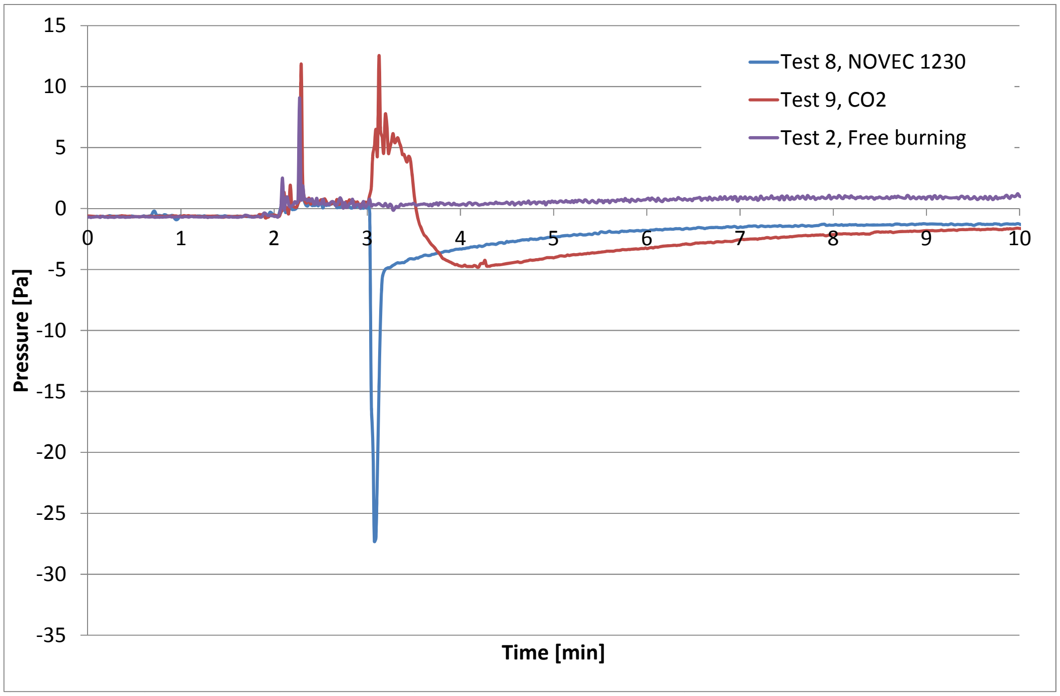

Figure 18 – Cabinet pressure measured in heptane fire tests. NOTE that Test 16 (N_2) is missing due to malfunctioning pressure sensor.

Several observations can be made concerning the results.

- The negative pressure in the electrical cabinet after activation of the NOVEC 1230 system probably reduced the amount of toxic gases leaving the cabinet.
- The pressure in the CO_2 test varied between 13 Pa and -5 Pa.
- The pressure in the NOVEC 1230 test varied between 0 and -27 Pa.
- During pre-burn, the fire caused a pressure rise of 12 Pa in the cabinet.

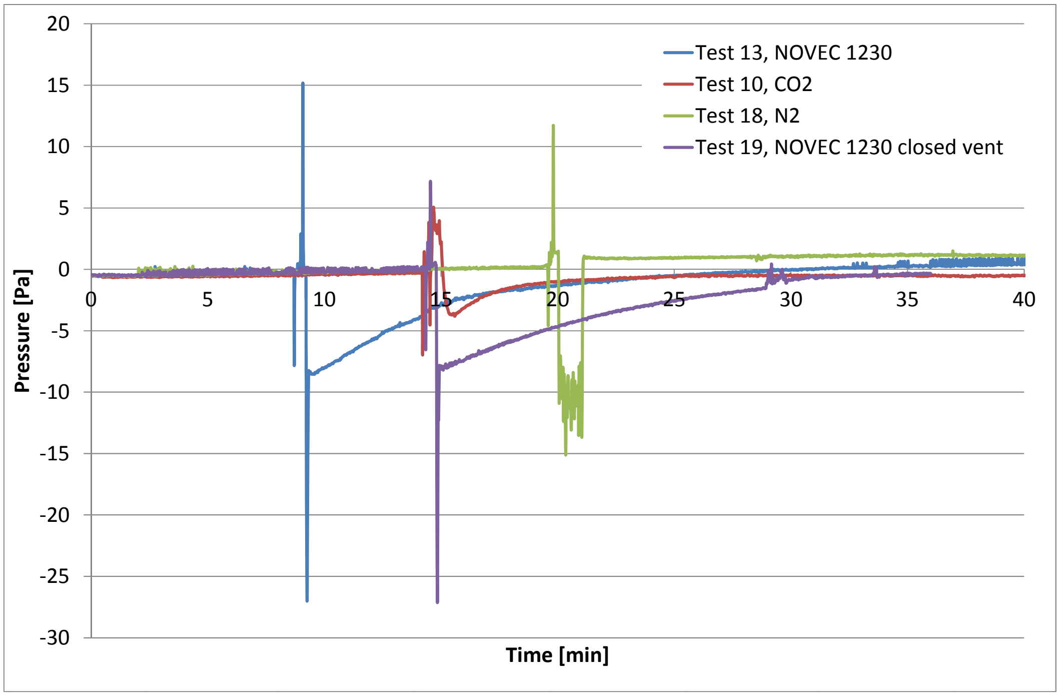

Figure 19 - Cabinet pressure measured in cable fire tests.

Observations:

- The negative pressure in the electrical cabinet after activation of the NOVEC 1230 system probably reduced the amount of toxic gases leaving the cabinet..
- The cabinet pressure in the CO_2 test varied between 5 Pa and -7 Pa.
- The cabinet pressure in the N2 test varied between 12 Pa and -15 Pa.
- The cabinet pressure in the NOVEC 1230 tests varied between 15 and -27 Pa.
- The pressure measured in the cabinet was not affected when the Ø32 mm vent opening was closed.
- During pre-burn, the fire caused a pressure rise in the cabinet of up to 15 Pa.

Oxygen concentration

The oxygen concentration in the cabinet was monitored during the tests. The oxygen concentrations for the heptane fire tests are presented in Figure 20 and the oxygen concentrations for the cable fire tests are presented in Figure 21.

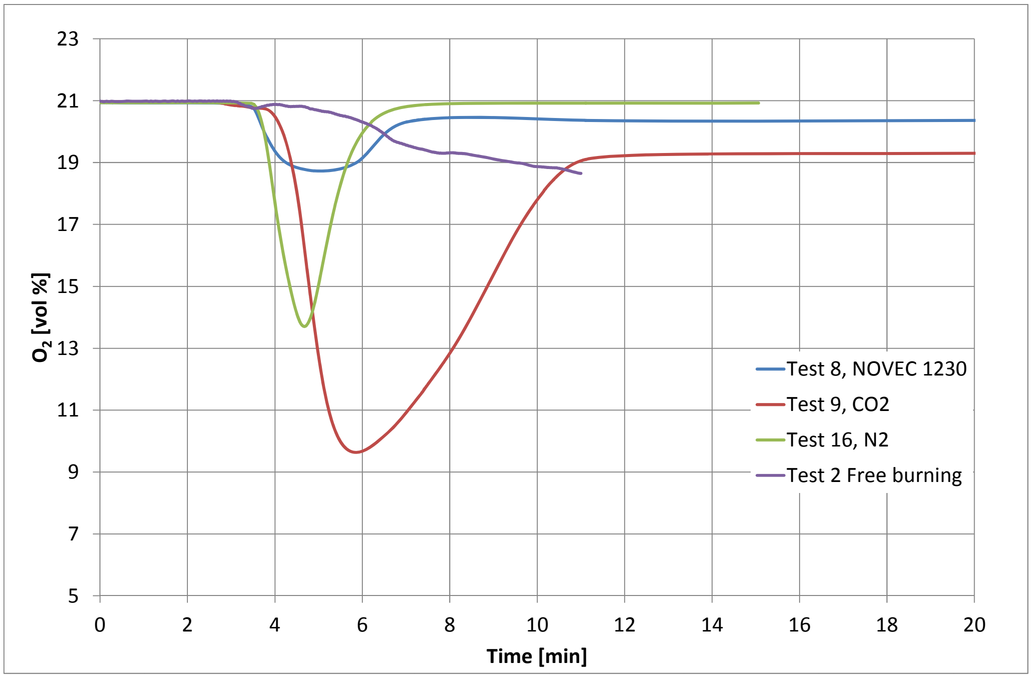

Figure 20 – Oxygen concentrations measured in heptane fire tests.

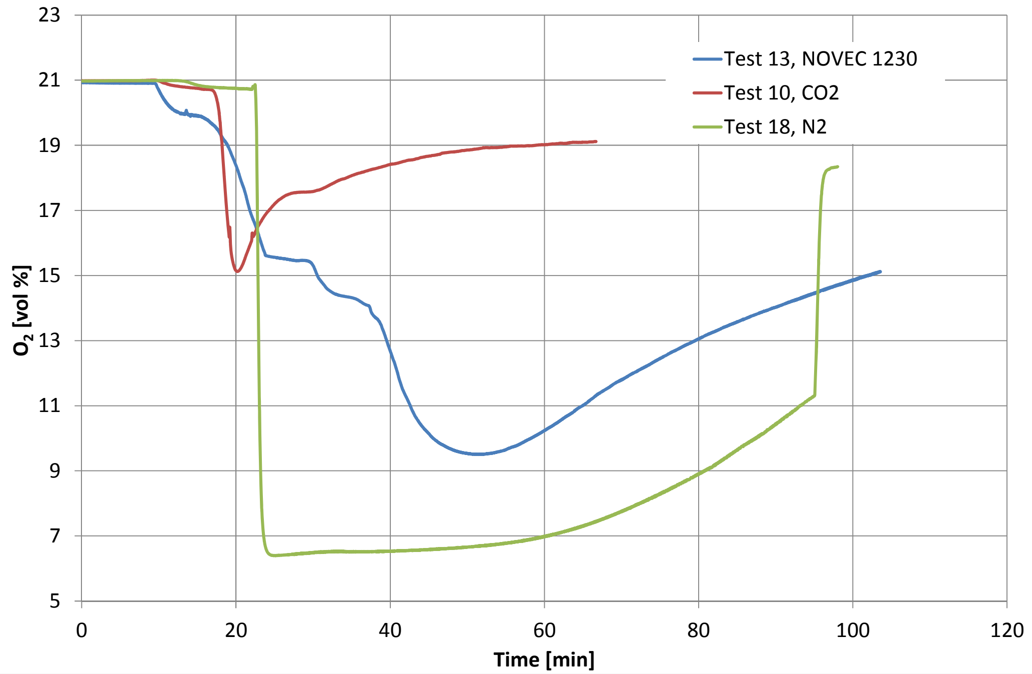

Figure 21 – Oxygen concentrations measured in cable fire tests.

The oxygen concentration appears to be over-estimated in the heptane fire scenario using NOVEC 1230. The oxygen concentration should be ≤15% (appr 6% NOVEC 1230 in the cabinet). It may be that the extinguishing agent was absorbed in the desiccant (Drierite) used in the humidity trap installed in the oxygen analyser.

In the CO_2 test, the oxygen level rises quite rapidly after discharge of the CO_2. This might be due to the relatively high density of CO_2. It accumulates in the bottom of the cabinet and displaces oxygen to the top of the cabinet. This may also be the reason for relatively fast re-ignition 7:27 [min:s] time for this test.

There was a large difference in oxygen concentrations after discharge of the agent in the two N_2 tests. In the cable tests the pyrolysis from the cables continues through the tests. This explains the low oxygen levels after extinguishment.

CO_2 extinguishment in a decommissioned electrical cabinet from a navy ship

A separate test was performed to analyze the effectiveness of a carbon dioxide fire extinguisher on a small pool fire in a decommissioned electrical cabinet from a Netherlands navy ship. The goal was to investigate if obstructions inside a ship board electrical cabinet will inhibit extinguishment of the fire. The cabinet was well ventilated through six ventilation openings on each side as shown in Figure 22. The carbon dioxide extinguisher (classification 89B, classified according to the SS-EN 3-7 standard [4]) was discharged through a NATO coupling on top of the cabinet. Classification 89B indicates that the extinguisher can extinguish a 2.80 m^2 pool fire containing 89 liters of industrial heptane and water.

Figure 22 – The electrical cabinet used in test 14.

The cabinet was heavily obstructed with electrical equipment and cables as shown inFigure 23. No further analyze was done on the equipment inside the cabinet.

Figure 23 – Obstructions in the electrical cabinet

A small heptane pool fire was used as the fire source. The fire was the same as that used in the other tests and the HHR curve is shown in Figure 4. The fuel pan was placed underneath the cabinet as shown in 24.

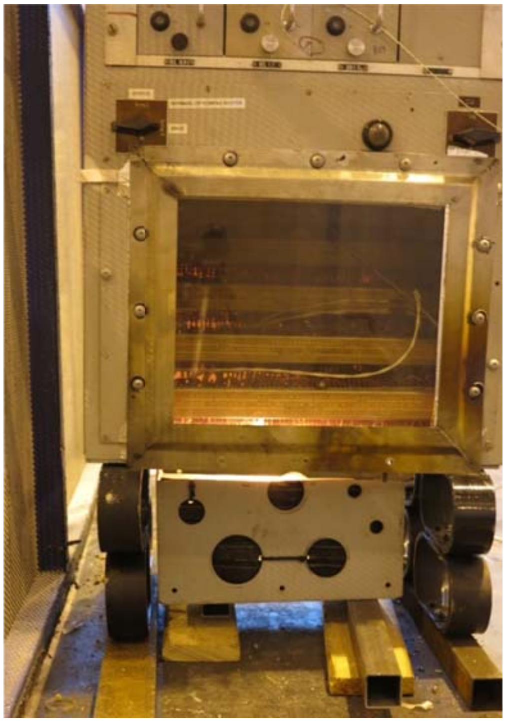

Figure 24 – Fire tray located under the cabinet.

Thermocouples were placed inside the electrical cabinet at 1/3 distance to the top of the cabinet, 2/3 distance to the top of the cabinet and at the top of the cabinet. The measured temperatures during the test are shown in **Error! Reference source not found.**. The carbon dioxide fire extinguisher was activated 3:30 (min:sec) which is 1:30 (min:sec) after ignition of the pool fire. There were problems with the thermocouple placed at top of the cabinet between 3:30 and 4:30. Due to this, the results from this thermocouple may be uncertain even after 4:30.

The results in Figure 25 how efficiently the carbon dioxide fire extinguisher cools the air inside the cabinet and keeps the temperature constant after activation even then though the cabinet was ventilated. The flames were extinguished 3-4 seconds after activation of the extinguisher. The temperature at the pool surface decreased from 600°C to 290°C before the extinguisher was activated. This temperature decrease was due to a lot of smoke inside the cabinet and oxygen depletion.

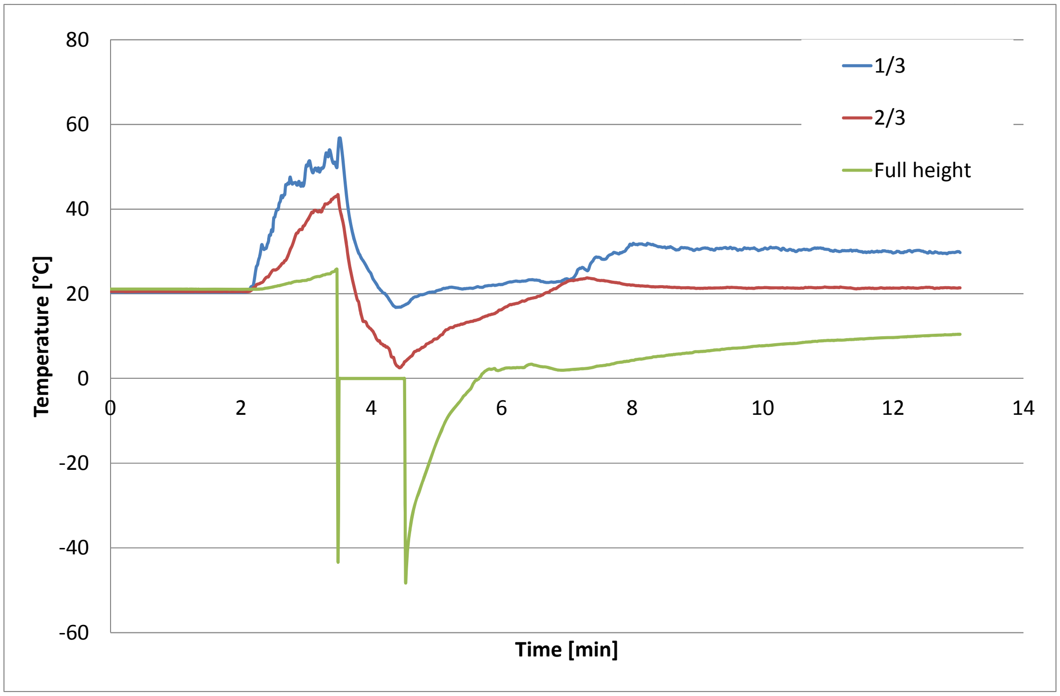

Figure 25 – Temperatures measured in the cabinet

Conclusions and comments

NOVEC 1230 extinguished the fire fastest in both the heptane and cable fire scenarios. Extinguishment time varied between 2 and 5 seconds. CO_2 extinguished the heptane and cable fires in 8 to 9 seconds while N_2 extinguished them in 10 to 59 seconds.

The N_2 system performed best in preventing re-ignition,; in the cable scenario test there was no re-ignition. In the test with the CO_2 system the cables re-ignited 7:27 [min:s] after extinguishment. Multiple cable scenario tests were performed with NOVEC 1230 and in one test the cables did not re-ignite, in the other two tests the times to re-ignition were 1:27 [min:s] and 3:14 [min:s] respectively. When the Ø32 mm ventilation opening in the cabinet was sealed the re-ignition time increased significantly to 13:58 [min:s].

The re-ignitions observed after extinguishment with CO_2 and NOVEC 1230 might be due to the density of these gases. They are significantly denser than air and are would tend to accumulate in the bottom of the cabinet and below the fires positioned at 1 m height.

Fire suppression testing with NOVEC 1230 resulted in the release of HF. The peak HF levels in the cabinet varied between 776 ppm and 1035 ppm for the heptane fire tests. For the same tests, the peak HF levels in the compartment varied between 33 ppm and 38 ppm. In the cable fire tests with the normal discharge of NOVEC 1230, the peak HF levels in the cabinet varied between 257 ppm and 3390 ppm and the peak HF levels in the compartment varied between 30 ppm and 74 ppm.

The rate of discharge of the NOVEC 1230 system was also found to have an effect on the levels of HF or fluorides produced. In the test with the heptane fire and a reduced rate of discharge of NOVEC 1230 into the cabinet, peak HF level (fluorides) in the cabinet was 14328 ppm and peak HF level (fluorides) in the room was 147 ppm. These values include fluorides from the production of COF_2 released by the thermal degradation of NOVEC 1230.

A correlation between humidity and HF levels in the compartment was found for the cable fire tests. As the humidity in the electrical cabinet was increased, the peak HF levels decreased.

The tests showed that the airborne HF levels in a contaminated, but not ventilated, compartment decline with time. An analysis of the HF levels in the room surrounding the cabinet indicated the decrease followed a first order exponential decay with a HF concentration half-life between 6.9 and 9.8 minutes.

The CO_2 system was the most efficient the cooling the cabinet with average cabinet temperatures following release of this suppressant close to 0 °C. Locally sub-zero temperatures occurred for short periods of times. The temperature reduction in the cabinet was similar for the tests using NOVEC 1230 and the N_2 systems. However, the shorter discharge time of the NOVEC 1230 system resulted in a significantly faster cooling rate.

The aspirating fire detector was very effective at detecting fires. In the heptane fire scenario the time to pre-alarm varied between 21 and 53 seconds, time to alarm level 1 varied between 20 and 60 seconds and time to alarm level 2 varied between 25 and 78 seconds. In two tests, the level two alarm did not trigger before the extinguishment system was activated (60 seconds after ignition).

In the cable fire tests, all three alarm levels were triggered before ignition of the cable bundle. Pre-alarm was triggered ≥ 48 seconds before, alarm level 1 was triggered ≥ 30 seconds before and alarm level 2 was triggered ≥ 7 seconds before cable bundle ignition.

The detector, Stratos Micra 25, was sensitive to repeated exposure to the gases from the tests. This could be seen in drifting pre-fire smoke density outputs and alarm level settings. A possible explanation for the major differences in alarm level between the first and the last test could be accumulation of soot (despite regular detector filter changes) or etching of lenses in the device caused by HF exposure.

In general, the difference in corrosion damage to steel or copper coupons by the three gaseous agents were small. The corrosion of steel and copper coupons was more sensitive to the humidity in the compartment than for the zinc coupons. The corrosion of zinc coupons was greater in tests with NOVEC 1230 than for those with CO_2 and N_2.

Regardless of extinguishment system and fire scenario tested it is likely that an electrical cabinet where any of these agents are discharged to extinguish a fire will have to be decontaminated to prevent corrosion to metallic materials in the cabinet.

The discharge of the extinguishment systems did cause an over pressure in the cabinet but it was no higher than the overpressure caused by fire during the pre-burning time. The highest measured over pressure in this test series was 15 Pa. During and after discharge the pressure in the cabinet dropped to a negative pressure.

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