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Cable Fires in Difficultly Accessible Areas

Brandforsk project 623-001

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Abstract

In power plants and underground constructions with difficultly accessible areas, cables are often mounted in separated rooms. These can be e.g. vertical shafts, horizontal galleries or corridors. Sometimes even large amounts of cables are hidden in so-called plenums above suspended ceiling or beneath sub floors. The consequences of a cable fire in these areas can be catastrophic taking into account the loss of power and communications, difficult rescue operations and loss of property. Normal ventilation is often used in the installations but it also occurs in case of a fire that a smoke extraction system is started with high ventilations rates. The effect of the ventilation on the flame spread for such scenarios has not been thoroughly studied and there is still a lacking know-how. Therefore a project sponsored by the Swedish Board of Fire research (Brandforsk) was initiated. In total 5 horizontal and 10 vertical tests were performed with different ventilation conditions and loadings. Both high and less performing cables were used in both set-ups. Heat release rate, Smoke production rate, flame spread and content of the smoke gases (e.g. HCl, HF), were measured. At the same time a specific scenario was selected to simulate the flame propagation by means of a flame spread model incorporated in the CFD code SOFIE.

From the test results and simulations the following conclusions could be drawn:

1. Positive or negative ventilation effect on flame spread depends mainly on direction and magnitude of the ventilation, the size of the initial fire and the geometry of the compartment. For each situation there exists an “optimum” ventilation rate where the flame spread is extremely fast compared to e.g. the non-ventilated case.

2. CFD calculations can provide an excellent tool for determining hazardous situations or as a complement to one or two experiments.

3. Use of improved cables reduces the risk of flame spread but the selection of the type of cables should be considered. It was shown that the highest performing cables produced large amounts of halogens per gram of combusted material when involved in a fully developed fire.

Use of active systems should be considered in high-risk areas as a trade-off for using the highest performing cables.

Key words: flame spread, cables, toxicity, ventilation, full-scale tests, simulations, CFD

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Preface

The Swedish Board for Fire Research (Brandforsk) sponsored this project with reference number 623-001. For the project a reference group was established with the following members: Bo Hedberg, Birka Energi, Stockholm; Olle Jarvid, Nexans, Grimsås; Leif Olsson, Göteborgs Energi; Örjan Thorné, Räddningstjänsten, Svedala; Jesper Axelsson, SP; Patrick Van Hees, SP; Haukur Ingason, SP and Per Blomqvist, SP. The authors would like to thank the reference group for their valuable input in the project.

Acknowledgment is also given to the staff of SP Fire Technology involved in this project. Special thanks to Germain Lannegrand for his work with respect to the CFD modelling which he performed during his training period at SP. The training period was performed during his last year of engineering studies at the University of Valenciennes, France.

Sammanfattning

I kraftverk och i underjordiska anläggningar med svåråtkomliga utrymmen monteras kablar ofta i separata utrymmen. Dessa kan t ex vara vertikala schakt, horisontella kabelgallerior och korridorer. Ibland är stora mängder kablar gömda i s k plenumutrymmen ovanför undertak eller under undergolv. Konsekvenserna av en kabelbrand i dessa utrymmen kan bli katastrofala om man tänker på förlust av elektricitet och kommunikation, svåra räddningsinsatser och förlust eller skada på egendom. Ofta utnyttjas normal ventilation i dessa installationer men det förekommer även system med kraftigt forcerad ventilation i händelse av brand. Hur ventilationen påverkar brandutvecklingen i sådana fall har hittills inte noggrant studerats och det saknas fortfarande en hel del kunskap på området. Därför initierade Brandforsk ett forskningsprojekt på området. Totalt kördes 5 horisontella och 10 vertikala provningar med olika ventilation och brandbelastning. I båda uppställningarna användes olika typer av kablar ur brandsynpunkt, både högpresterande kablar och kablar som beter sig mindre bra vid brand. Under försöken mättes värmeutveckling, rökproduktion samt rökgasernas sammansättning (t ex HCl, HF). Samtidigt valdes ett specifikt scenario för att simulera flamspridningen med hjälp av en modell i CFD-programmet SOFIE. Från försöksresultaten och beräkningarna kan följande slutsatser dras:

1. Positiv eller negativ effekt på flamspridningen beror främst på riktningen och storleken av ventilationen, storleken på den initierande branden och geometrin hos utrymmet. För varje situation existerar en ”optimal” ventilationshastighet där flamspridningen är mycket snabb jämfört med ett oventilerat fall.

2. CFD-beräkningar är ett utmärkt verktyg för att bestämma farliga situationer eller som ett komplement till ett eller två experiment.

3. Användandet av förbättrade kablar reducerar risken för flamspridning men valet av kabeltyp skall ändå övervägas. Det visades att den mest högpresterande kabeln producerade stora mängder av halogener per gram förbränt material när den är inblandad i en utvecklad brand.

I lokaler med hög risk bör användning av aktiva system övervägas som en kompromiss till användandet av de mest högpresterande kablarna.

1 Background

In power plants and underground constructions with difficultly accessible areas, cables are often mounted in separated rooms. These can be vertical shaft and horizontal galleries or corridors. Sometimes even large amounts of cables are hidden in so-called plenum spaces above suspended ceiling or under increased floors, see Figure 1. The consequences of a cable fire in these areas can be catastrophic taking into account the loss of power and communications, difficult rescue operations and loss of property.

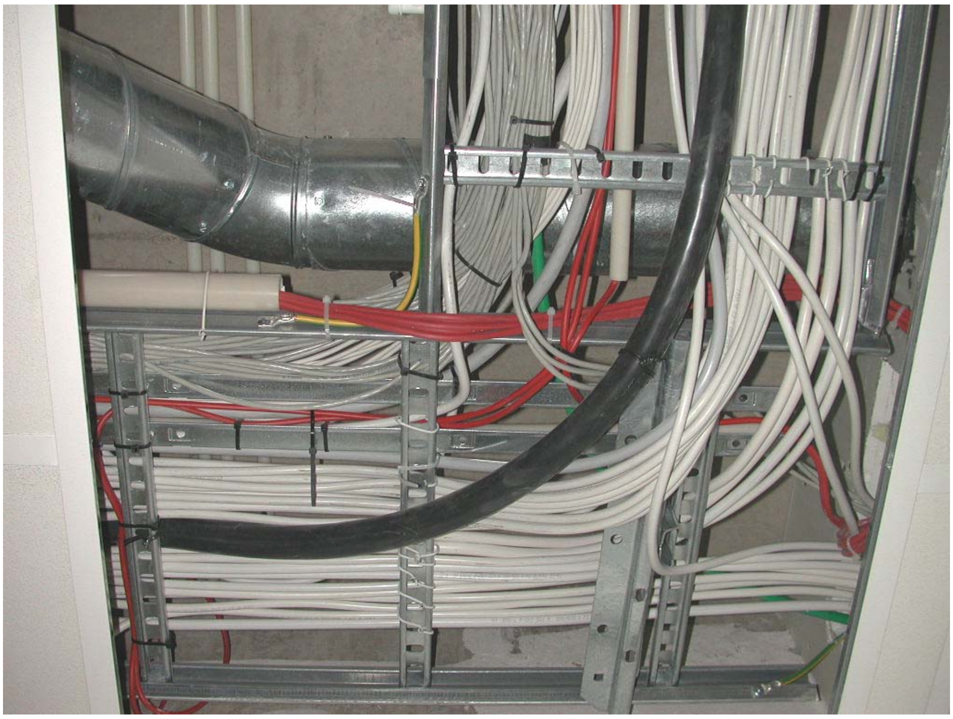


Figure 1. Photograph of cables in a plenum void in a modern Swedish building constructed during 2000. There is a mix of power cables, data cables and optical cables.

Recent tests in the UK [1, 12] tried to show the evidence for the use of improved cables, so-called plenum cables in difficultly accessible areas. However these types of cables are very expensive because of the use of improved materials. The type of materials used for these cables are in most cases fluoropolymers or advanced PVC. Most of the tests were performed within ventilated areas but a general sensitivity study with different ventilation conditions showing the evidence of the scenario was not well performed. A more general approach was hence necessary. In the FIPEC project [2] it was namely shown that ventilation could have both a positive and a negative effect on the flame spread and that general rules could not be made. However in the FIPEC project it was not a major focus to investigate ventilation effects and much more work was done on general flame spread. This is especially important for underground constructions such as tunnels or areas where large cable concentrations are present such as power plants. Here the ventilation could have a decisive role in the fire spread i.e. whether fire would only be limited or whether the fire would spread to uncontrollable proportions. Another factor apart from the normal ventilation conditions is the possible influence of smoke gas extraction ventilation after the start of a fire. Recently there was an example of a cable fire in a tunnel under Stockholm, which caused power loss for more than 50 000 people and several industries during several days. The ventilation in the tunnel was considered to have worsened the consequences of the fire [10].

It is also very difficult to defend that only the fire properties of the cables should be improved to obtain a safe situation. All factors of such a decision should be taken into account. One factor is the high content of halogen in the highly improved cables, so-called plenum cables. This can result in production of corrosive and toxic gases when the cables do burn. The production of these gases can lead to a difficult rescue intervention, exhaust of gases in the atmosphere leading to evacuation of public areas and damage on electronics. In many cases one is obliged to use the actual cables and exchanging cables is not immediate a possible solution.

For these reasons a project was initiated where both horizontal and vertical scenarios with different ventilation conditions would be studied. This could lead to a better understanding of the effect of ventilation on the flame spread.

2 Scope

The project had the following objectives:

- Increase the knowledge about cable fires in difficultly accessible areas with respect to the interaction of flame spread and ventilation. Both the normal ventilation in cable installations and the smoke extraction ventilation should be considered.
- Investigate the possible use of CFD calculations for these types of scenarios, including simulation of the flame spread.
- If possible draw up a number of guidelines for these types of fires.

3 Research programme

The project was divided in a number of work packages, which are described below.

3.1 Flame spread experiments in a horizontal and vertical scenario

A number of tests were conducted with different ventilation conditions. Both normal ventilation and smoke gas extraction were used. The tests were conducted both in a horizontal and a vertical test set-up. Measurements were made for heat release rate, flame spread rates, smoke production and temperatures. In the majority of the tests a detailed analysis of the gases with respect to hazardous and corrosive species was conducted by using FTIR measurements. Cables were selected to represent different types of cables and levels of fire performance. Originally a maximum of 5 horizontal and 5 vertical tests were planned but the final number was 6 horizontal and 10 vertical tests.

3.2 CFD Calculation of flame spread and smoke transport

CFD calculation of flame spread in cables was performed. A sensitivity study of the model was also made. The results were used to check the possibility to model the influence of ventilation on flame spread rates. If necessary additional small scale tests would be performed. An evaluation of these types of tools was made at the end of the project.

3.3 Guidelines

If possible a number of guidelines would be given with respect to ventilation and fire spread. These guidelines would be informative for those who design the type of cable installation studied.

3.4 Conclusions and reporting

In this work package reporting of the tests and modelling work was done. Conclusions were drawn concerning the full-scale test and the modelling.

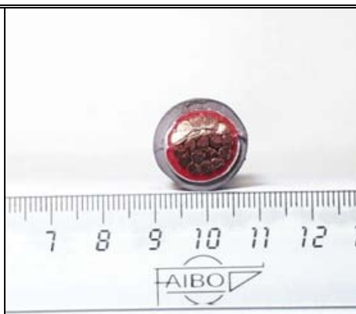
4 Flame spread experiments in a horizontal and vertical scenario

4.1 Cables used in the testing

Four types of cables were chosen for the testing. The aim was to choose cables that exist on the market and with properties that suited the objectives of this project. The main objective was to study the ventilation effect on flame spread and a set of cables with too low or too high fire performance could make it difficult to see the effect of ventilation. Another objective was to investigate any toxic emissions from cables with very high fire performance. The cables should also be able to represent reasonably realistic installation, which is often a mix of different types of cables. Experience from FIPEC [2] allowed us to choose four cables which should be able to give many answers.

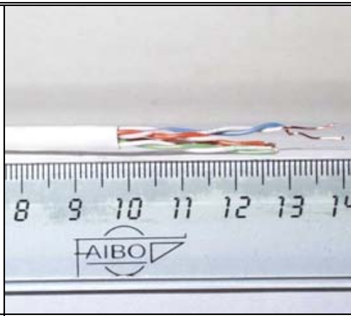
Table 1 and Table 2 give the main characteristics of the four cables. Cable A is a low-voltage power cable with PVC sheath and XLPE (Polyethylene) insulation. Cable B is a telephone cable with PVC sheath and insulation. Cable C is a data cable with PVC sheath and PEF insulation. Cable D is a data cable with Polyolefin sheath and Polypropylene insulation.

Table 1. Description of cables A and B.

		
Cable ID	A	B
Cable Type	Low Voltage 0.6/1 kV	Telephone Cable
Conductor size	1×95 mm^2	10×2×0.6 mm^2
Screen	None	None
Armour	None	None
Conductor	Copper	Copper
Insulation	XLPE	PVC
Filler Mass	None	None
Sheath	RPPVC	PVC
Combustible Vol.	0.1402 l/m	0.048 l/m
Fire rating*	IEC 60332-3 cat C	IEC 60332-3 cat C (possibly better performing)

* Estimated from labelling and/or test data within FIPEC

Table 2. Description of cables C and D.

		
Cable ID	C	D
Cable Type	Data Cable	Data Cable
Conductor size	4×2×0.2 mm^2	1x3x1.5 mm^2
Screen	None	None
Armour	None	None
Conductor	Copper	Copper
Insulation	PEF	PP
Filler Mass	None	30 g/m
Sheath	RPPVC	Polyolefin
Combustible Vol.	0.007 l/m	0.051 l/m
Fire rating*	Plenum rated, UL 910	IEC 60332-1

* Estimated from labelling and/or test data within FIPEC

4.2 Horizontal scenario

4.2.1 Choice of set-up

The horizontal test set-up was chosen to represent real installations in confined spaces. A comprehensive review [2] of European installations has shown that a tunnel-like enclosure is a good representation. This type of scenario also allows for examining the influence of forced ventilation on the flame spread. The enclosure had to be built so that all smoke gases could be collected in a hood and led to a measurement section.

The ignition source used for the horizontal tests was a square propane diffusion burner placed close to one end of the enclosure, see Figure 3. The burner used is according to the alternative ignition source in ISO 9705 [9]. The heat release rate from the burner was set to a constant 100 kW, corresponding approximately to a burning waste paper bin. This relatively high level was chosen to ensure ignition of the cables and making it possible to study the subsequent flame spread.

4.2.2 Description of test set-up

Figure 2 shows a photograph of the test enclosure. The “tunnel” was 1.2 x 0.5 x 5.0 m with the walls and ceiling constructed of incombustible silicate boards. Along one side a large fireproof window was mounted to make it possible to study the flame spread visually and by video recording or photographing. Approximately 20 cm below the ceiling five thermocouples were mounted to record the hot gas layer temperatures and, if bad visibility would occur, to assist in estimating the flame spread rate on the top ladder. Two cable ladders were mounted in each test, including different types of cables, see Figure 3.

Forced ventilation was achieved by placing axial fans of different sizes in front of the tunnel opening, sufficiently far from the tunnel to produce a uniform flow over the opening cross-section and in the tunnel.

All smoke gases escaping the enclosure were collected in a large hood and led to a ISO 9705 [9] measuring section where several dynamic measurements were made: temperature, flow rate, Heat Release Rate (HRR), Smoke Production Rate (SPR) and gas analysis (FTIR, see Annex A). The HRR was measured by standard oxygen consumption calorimetry and the SPR was measured by a white light smoke extinction measurement system [9].

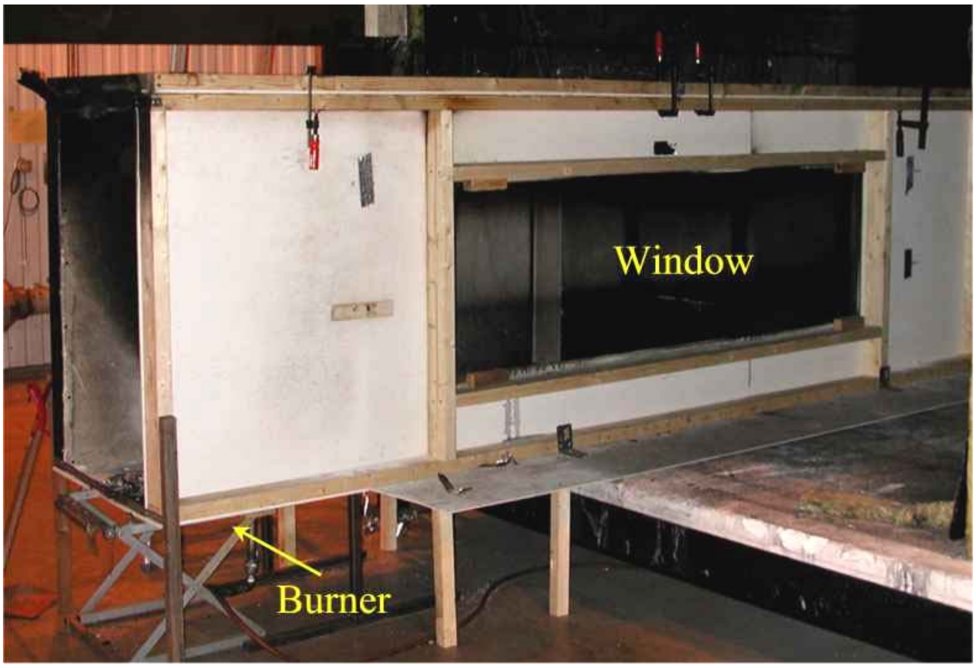


Figure 2. The horizontal test enclosure. See also Figure 3 for front view.

4.2.3 Overview of performed tests

The background study had showed that there are often different cable types installed in the same space and therefore this test series was run with a mix of cables. In all tests the cables were mounted with spacing of approximately one cable diameter, since this was shown to be most severe in the FIPEC study [2]. Cable C was bundled and the bundles were mounted with spacing. The cable set-up was the same in all tests except H1, where no cable D was included. Figure 3 shows how the cables were mounted in the tests.

Table 3 describes the six tests, H1-H6, run in the horizontal scenario. The second column in the table shows the number and type of cables mounted on the top and bottom ladder respectively. The third column shows the horizontal ventilation rate where “natural” means no forced ventilation.

The burner was ignited at t = 2 min in all tests and the gas was turned off at different times depending on the fire development in the cables.

Table 3. Overview of horizontal tests.

Test ID	No and type of Cables Top/Bottom ladder	Ventilation	Burner programme
H1	8 B, 5x4 C (bundled) 7 A	Natural	03:00 - 20:10 100 kW
H2	8 B, 6x3 C (bundled) 6 D, 4 A, 6 D	Natural	02:00 - 22:00 100 kW
H3	8 B, 5x3 C (bundled) 6 D, 4 A, 6 D	00:00 - 04:00 natural 04:00 - 23:00 0.6 - 0.7 m/s	02:00 - 22:00 100 kW
H4	8 B, 5x3 C (bundled) 6 D, 4 A, 6 D	00:00 - 04:00 natural 04:00 - 07:30 1.5 - 1.8 m/s 07:30 - 20:00 natural	02:00 - 18:00 100 kW
H5	8 B, 5x3 C (bundled) 6 D, 4 A, 6 D	00:00 - 02:20 natural 02:20 - 12:30 1.5 - 1.8 m/s	02:00 - 12:30 100 kW
H6	8 B, 5x3 C (bundled) 6 D, 4 A, 6 D	00:00 - 04:00 natural 04:00 - 16:00 3.0 - 3.2 m/s	02:00 - 16:00 100 kW

The forced ventilation was accomplished by placing fans of different sizes approximately 5 m in front of the tunnel opening. Flow velocity and homogeneity were checked with anemometers at several positions in the tunnel. The sizes of the fans and corresponding velocity is presented below

small fan, ∅ 300 mm, horizontal velocity in tunnel 0.6 - 0.7 m/s
medium fan ∅ 400 mm, horizontal velocity in tunnel 1.5 - 1.8 m/s
large fan, ∅ 610 mm, horizontal velocity in tunnel 3.0 - 3.2 m/s

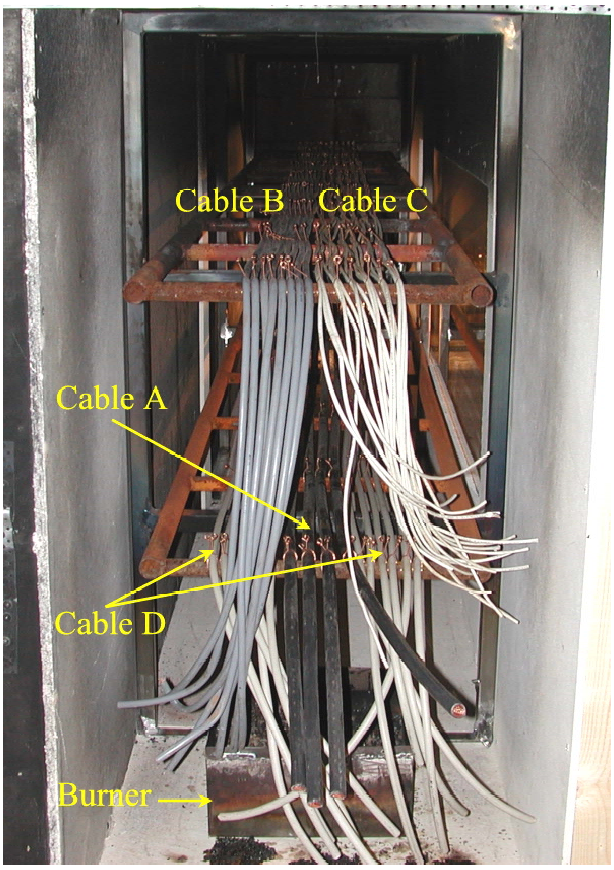


Figure 3. Mounting configuration in the horizontal tests H2-H6.

4.2.4 Results of test series

4.2.4.1 Flame spread results

Flame spread was recorded visually and by video through the glass window in one wall of the tunnel. The bottom ladder and the top ladder were observed separately for flame spread and the result is shown in Figure 4 for the bottom ladder and in Figure 5 for the top ladder. No distinction was made between different types of cables on the same ladder. Each test H2-H6 is represented by a line that shows the pyrolysis front versus time, i.e. a steeper line means faster flame spread. Test H1 showed very limited flame spread and heat release, see Figure 8, and it was decided to run the remaining tests with a different cable configuration, including cable D on the bottom ladder.

In Figure 4 there is a clear difference between tests H2-H3 and tests H4-H6. Tests H2-H3 spreads only slowly and the pyrolysis front does not reach the end of the ladder while tests H4-H6 all spreads quickly to the end. The difference in flame spread is directly connected to the ventilation rate, test H2 has no forced ventilation and H3 has only 0.6-0.7 m/s while tests H4-H5 has a forced ventilation rate of 1.5-1.8 m/s and H6 3-3.2 m/s. This means that there is a limit somewhere between 0.7-1.5 m/s where the flame spread is accelerating instead of declining in this specific scenario. The governing phenomena are flame leaning and cooling, see further discussion in chapter 4.2.5.

For the top ladder the results are not quite as easy to interpret, see Figure 5. The top ladder cables are also better than the bottom ladder. Still the non- and low-ventilated tests H2-H3 are relatively slowly spreading and do not reach the end of the ladder during the test. Tests H4-H5 shows a very fast flame spread to the end of the ladder. In the case of H5 the ignition of the top ladder was delayed but the cables were heated and the complete ladder ignited at almost the same time. However, in the most ventilated test, H6, the cables on the top ladder does only spread very little. This fact is probably due to cooling and that the high air flow forces the flames from the bottom ladder to lean strongly, therefore not constantly reaching the top ladder. A comparison of the photographs in Figure 6 and Figure 7 shows this effect.

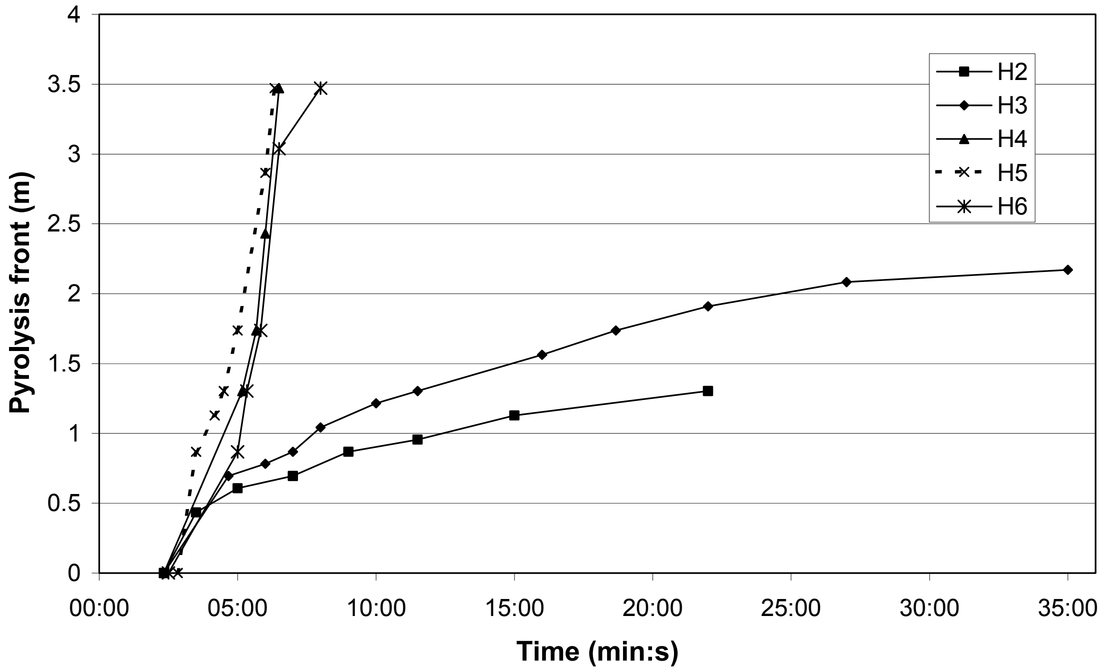


Figure 4. Comparison of flame spread in the horizontal tests, bottom ladder with cables A+D.

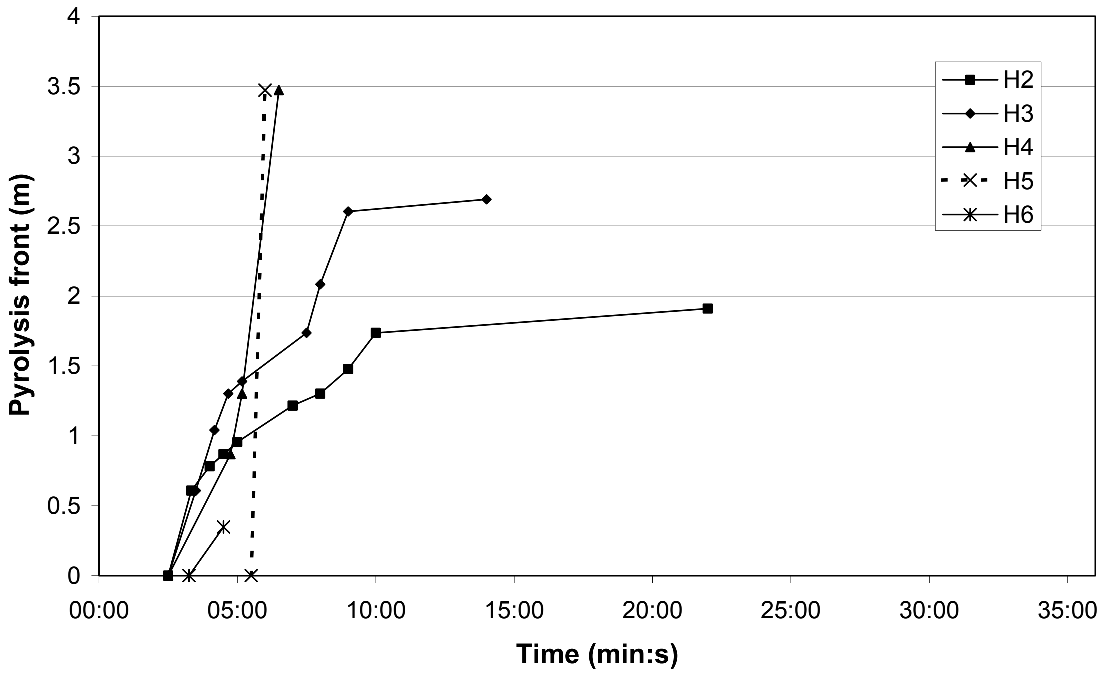


Figure 5. Comparison of flame spread in the horizontal tests, top ladder with cables B+C.

Figure 6. Side view of test H4, forced ventilation rate 1.5-1.8 m/s.

Figure 7. Side view of test H6, forced ventilation rate 3-3.2 m/s. The flames are not reaching the top ladder.

4.2.4.2 Comparison of HRR measurements

The Heat Release Rate (HRR) was measured in each test and a comparison between consecutive tests is shown in Figure 8 - Figure 12. In the graphs the HRR contribution from the burner is included (100 kW).

Test H1 had a different cable configuration from tests H2-H6, see Section 4.3.2, and the HRR in this test is, in analogue with the flame spread results, considerably lower than in the main test series H2-H6. This is due to the better cables in H1.

The difference in flame spread between the low- and high-ventilated tests shows very clearly in the HRR results. Figure 9 shows the low-ventilated tests H2 and H3 giving almost identical HRR curves with a peak HRR about 275 kW. The higher ventilated tests in Figure 11 produces a much higher HRR with peaks about 1100 kW.

It is interesting to note the early behaviour of test H4, where the ventilation was switched on only after 4 minutes, i.e. 2 minutes after the burner was switched on (see Table 3). For the first two minutes the HRR follows the H3 curve, see Figure 10, and when the ventilation is activated there is first a dip but soon the HRR rises very fast. This demonstrates the sensitivity of a HRR measurement, the dip effect is not possible to observe when studying the flame spread only.

Test H6 produces about half of the HRR compared to tests H4-H5. This is due to the very high ventilation rate, see discussion above on flame spread.

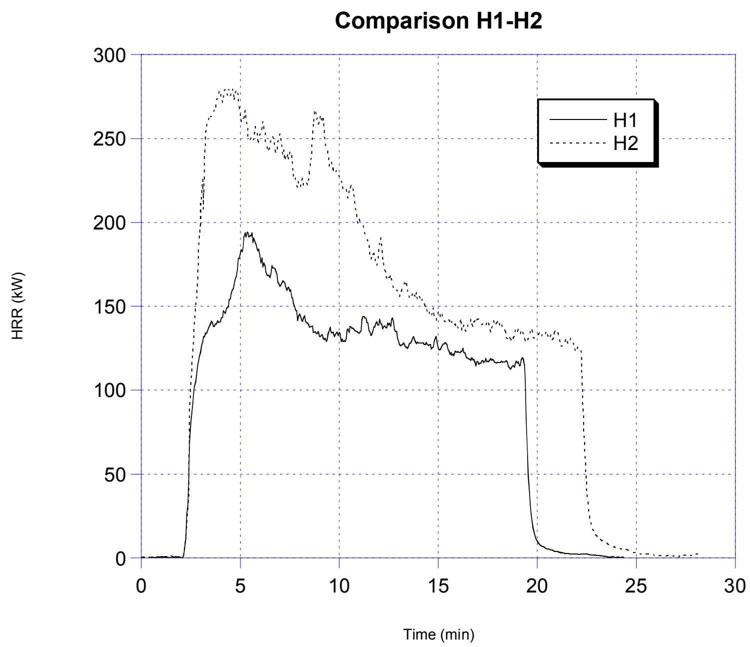


Figure 8. Comparison of HRR between tests H1 and H2.

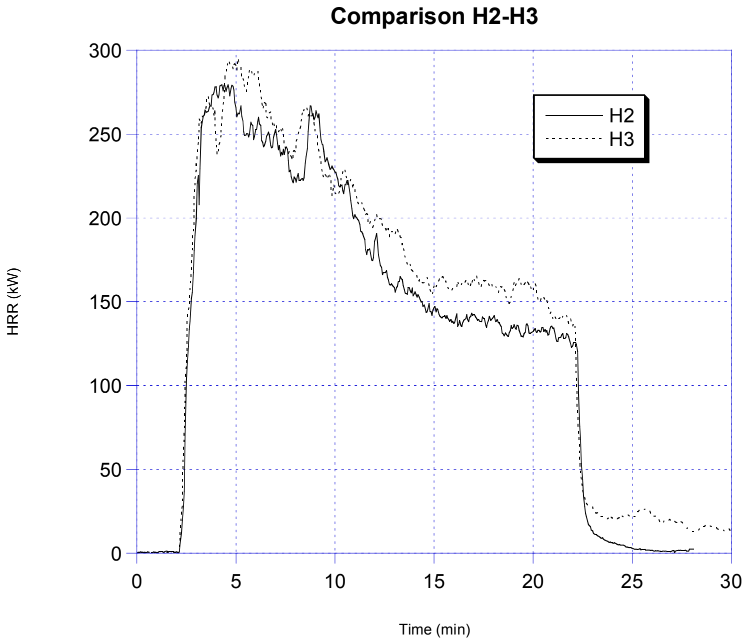


Figure 9. Comparison of HRR between tests H2 and H3.

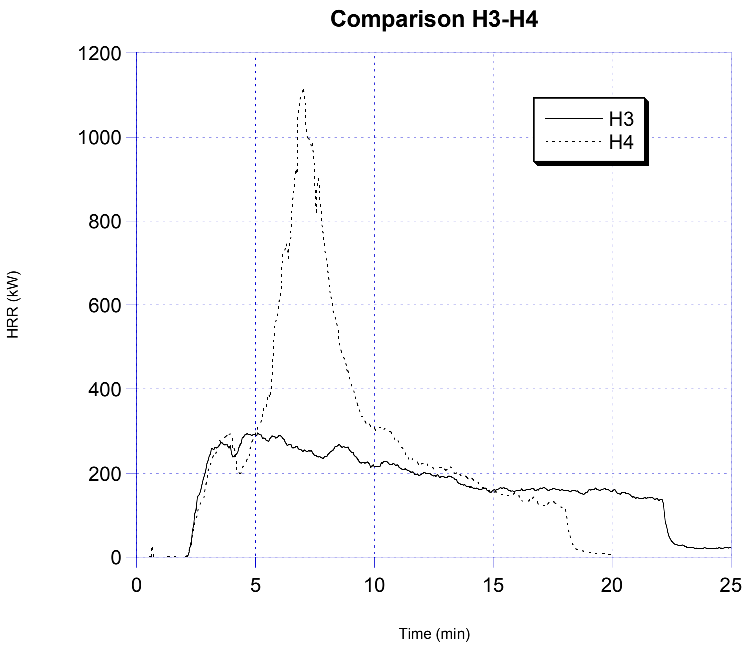


Figure 10. Comparison of HRR between tests H3 and H4.

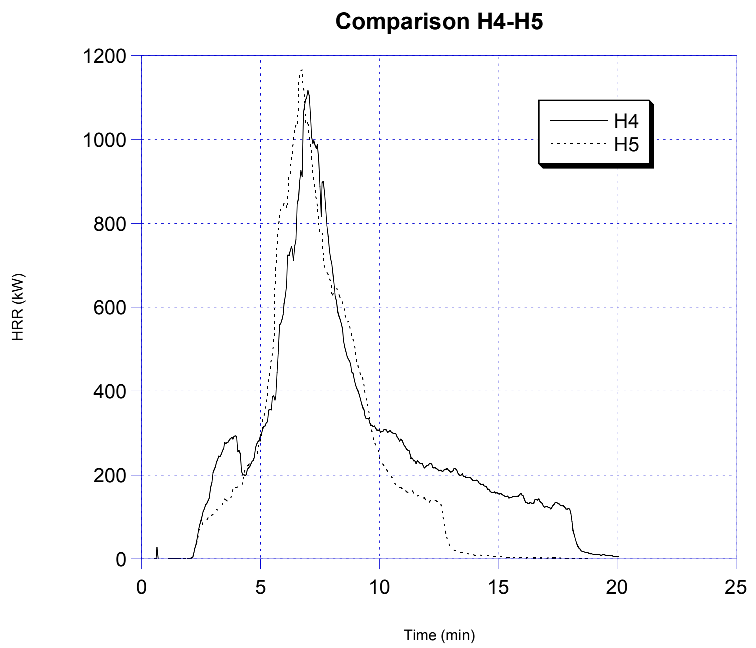


Figure 11. Comparison of HRR between tests H4 and H5.

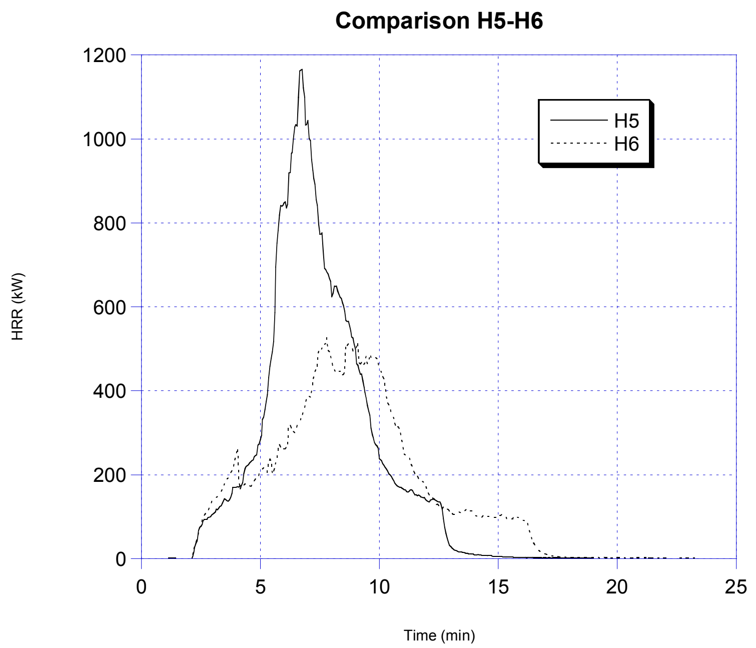


Figure 12. Comparison of HRR between tests H5 and H6.

4.2.4.3 Toxic gases results

The results from the gas measurements with FTIR for the horizontal tests can be found in Table 4. Of the gases calibrated for (see Annex A) carbon monoxide (CO), hydrogen chloride (HCl) and hydrogen fluoride (HF) were found in the smoke gases from all horizontal tests. The concentrations of these gases were all within the calibrated concentration span of the FTIR. Additionally, COF_2 was identified in all horizontal tests but could not be quantified, as no calibration was available for this species. A semi-quantitative interpretation of the occurrence of this gas is however shown in Figure 13.

It could be seen from the results presented in Table 4 that HCl was the toxic species produced in highest amounts from all tests. Further were considerable quantities of HF found.

Table 4. Results from measurements of toxic gas species in the horizontal tests.

Test	**H1**	**H2**	**H3**	**H4**	**H5**
CO					
Max concentration (ppm) *	440	430	460	1240	1230
Max production (g/s)	0.72	1.05	1.11	4.0	4.5
Total amount in test (g)	235	370	458	862	619
HCl					
Max concentration (ppm) *	390	330	380	1230	1140
Max production (g/s)	0.84	1.06	1.18	4.9	5.4
Total amount in test (g)	325	447	609	994	807
HF					
Max concentration (ppm) *	29	82	156	430	480
Max production (g/s)	0.04	0.15	0.28	0.95	1.23
Total amount in test (g)	9.1	34	56	116	97

* Concentration measured in smoke gas duct.

Yields of the gases found have been calculated and are presented in Table 5. Yields are presented in two forms; as amount gas produced per meter cable consumed in the fire, and also as amount produced per gram cable material combusted. An uncertainty in these calculations is however that the combusted amount of cable material in each test is based on a rather subjective assessment. It was assumed in the calculation that all cable material affected by the fire was totally consumed.

The yields for the various gases were calculated slightly differently depending on the gas in question due to the mix of different cables with varying composition used in the tests. All cables were included in the calculation of yields for CO. For HCl and HF, however, only the cables/amount of material containing chlorine respective fluorine were included.

It can be seen from Table 5 that the yield of CO was normally around 0.1 g/g with the exception of test H1 where twice this yield was found. This was the only test, however, that exclusively included halogenated cables, which could be a possible explanation for a poorer combustion. Also the estimate of burned amount was more uncertain due to the limited flame spread.

For HCl the normal yield found was around 0.15 g/g. This is approximately half the maximum theoretical yield from a normal PVC cable. Also for HCl was test H1 an exception with a significantly higher yield.

For HF the yields found varied between test conditions. In the tests with natural ventilations yields of approximately 0.1 g/g were found, whereas in the tests with forced ventilations yields between 0.2 and 0.3 g/g were found. This implicates that approximately 1/3 of the fluorine from the cables (a FEP cable contains approximately 75 weight % fluorine) was found in the smoke gases in these tests.

One has to keep in mind, however, that losses of HCl and HF before reaching the sampling point is possible due to the tendency of these species to get retained on surfaces and dissolve in any condensed water.

Table 5. Yields based on measured total amounts of respective gas species and an estimation of combusted cable length/amount combusted cable material.

Test	**H1**	**H2**	**H3**	**H4**	**H5**
CO					
Yield (g/m)	7.8	4.6	4.6	6.5	4.7
Yield (g/g)	0.18	0.088	0.078	0.11	0.076
HCl					
Yield (g/m)	11	6.4	7.2	9.2	7.5
Yield (g/g)	0.25	0.13	0.13	0.15	0.12
HF					
Yield (g/m)	0.5	0.8	1.2	1.9	1.6
Yield (g/g)	0.07	0.11	0.17	0.28	0.23

Only a semi-quantitative interpretation of the occurrence of COF_2 in the smoke gases is possible to give. In Figure 13 the absorbance at the wavenumber 1929 cm^{-1} as measured with FTIR is given for all horizontal tests. This is a specific wavenumber where COF_2 strongly absorbs infrared radiation (see Annex A). Note that concentration is normally not a linear function of absorbance in FTIR measurements with a spectral resolution of 4 cm^{-1}. Normally the increase in absorbance with concentration decreases at higher concentrations.

It can be seen from Figure 13 that significant absorption at 1929 cm^{-1} was found in all tests. A number of spectra in each test were further manually inspected to verify that the specific spectral feature of COF_2 was present. Highest absorbance, indicating the highest concentrations of COF_2, was seen in tests H4 and H5 where also the highest concentrations of HF were measured. If comparing with the production of HF (see Appendix A.2) it can be seen that peaks in absorbance indicating maximum COF_2 production occurs at approximately the same time as peaks in HF production.

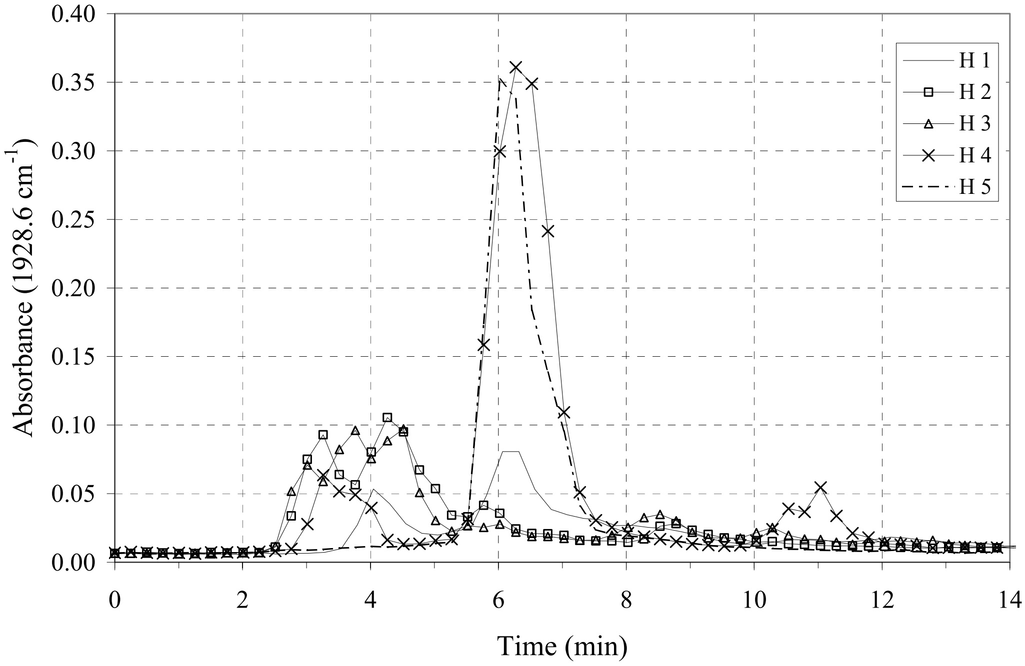


Figure 13. Plot of absorbance at 1929 cm^{-1} measured with FTIR. COF_2 exhibits its strongest absorbance at this wavenumber.

4.2.5 Discussion of horizontal results

The horizontal tests have shown the ventilation rate to be an important factor for longitudinal flame spread in horizontal cable installations. An increased ventilation rate will result in much faster flame spread rate and also higher heat release. The fire spread is enhanced mainly by flame leaning leading to faster heating by radiation. Above a certain high ventilation rate the effect will change and the fire development will be slowed by the ventilation, due to cooling and heavy disturbance of the flames. The actual critical wind speeds found in this study are of course unique for the specific geometry and cable set-up but the general trend is clear.

The analysis of toxic and corrosive gas species has given some interesting results. The total amount of gases produced and maximum concentrations follow the same trends as the flame spread and heat release. The ventilated tests produced significantly higher amounts of toxic species than the non- or low-ventilated tests. An estimate of the yields showed that the production of CO and HCl per gram of burned cable was approximately constant for the different ventilation rates while for HF the yield was significantly increased in the tests with a higher ventilation rate. The yield results should be considered as approximate since the combusted amount of each cable type was estimated rather than weighed.

It is interesting to note the presence of COF_2 in the smoke gases. This gas is normally not analysed in fire tests though it is rather toxic with a LC50 value about three times lower than HF [11]. In this test series it could only be detected but not quantified, however it would be interesting to do further study on the production of this species when testing fluorinated cables. The times of peak COF_2 production matched well the times of peak HF production.

4.3 Vertical scenario

4.3.1 Choice of set-up

The vertical set-up was chosen to represent a cable shaft with cables mounted on a vertical ladder. An existing test chamber was modified to create a shaft with a sufficiently small area to allow control of the ventilation. The set-up also had to allow extraction ventilation and measurements of the combustion gases.

The ignition source used for the tests was a premixed propane burner with a directed flame. This burner was chosen because it is well known and suited for cable testing. The burner is capable of producing an effect of 20-50 kW.

4.3.2 Description of test set-up

Figure 14 shows a sketch of the test set-up. A wall divides the chamber with an opening at the bottom. Two fireproof windows are mounted in the wall for observation and recording of flame spread in the cables. The cables were in all tests mounted on a single cable ladder in different combinations and with a backing board behind the cable ladder, see Figure 15 - Figure 16. The backing board has been shown to enhance flame spread [2] and was used to get results over a wider range.

Thermocouples were mounted at different heights in the shaft to monitor the gas temperature. In the first test series V1-V5 thermocouples were also mounted at several positions inside the sheath of cable B. This was done in order to investigate whether the assessment of flame spread could be helped by the temperature readings if bad visibility would occur.

Forced ventilation was created in two ways, by blowing and by suction. The blowing flow was created by a fan placed in front of the opening in the dividing wall. The suction ventilation was accomplished by fitting a tube from the opening in the exhaust hood to the outlet of the shaft and sealed in a suitable way. In the lab there is a possibility to control the smoke extraction exhaust flow accurately and therefore it was possible to control the suction flow in the shaft. Most tests were run with suction flow as this created the most uniform flow in the shaft.

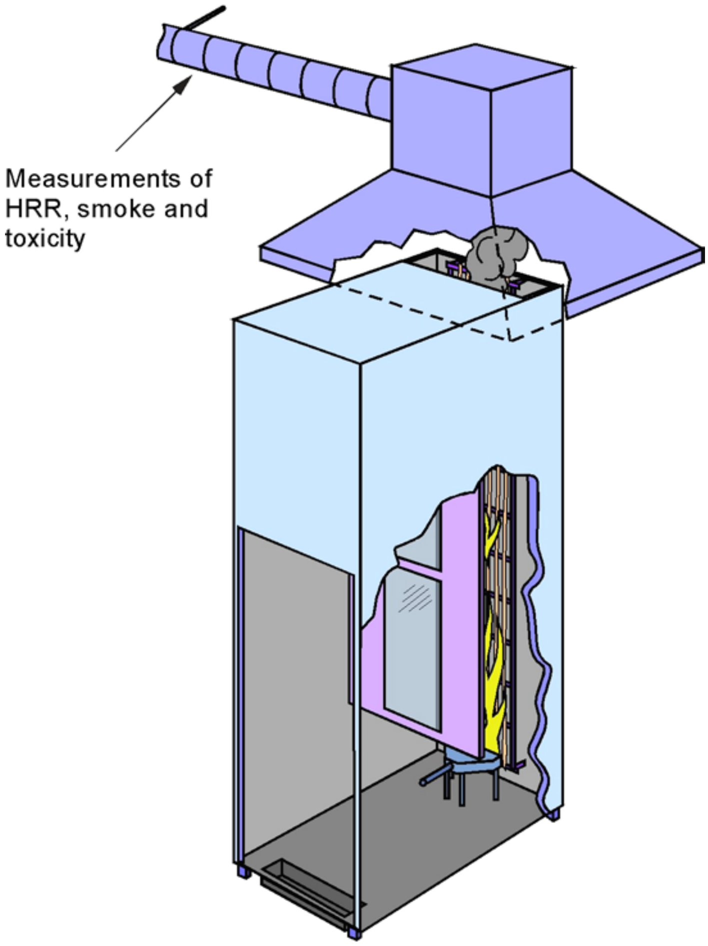


Figure 14. **Sketch of the vertical test set-up with a cut-out in the left wall. The dividing wall is visible with two windows. The suction pipe (not shown) was fitted between the test chamber and the extraction hood.**

4.3.3 Overview of performed tests

Two test series were run in the vertical scenario, making a total of 10 tests. The first test series includes tests V1-V5 and the second series includes tests V6-V10, see Table 6. The main difference between the series is the cables, in the first series a mix of cables was mounted A, B and C and in the second series only cable D was mounted. The motivation for the two series was to cover a greater range of fire behaviour as this increases the possibility to study the effect of ventilation on flame spread. All cables were mounted with a spacing of approximately half to one cable diameter, see Figure 15 - Figure 16.

The burner programme was not identical in the two series, see Table 6. The heat release from the burner was higher in the first series due to better performing cables.

All tests with suction ventilation, except V8, were started with a low flow of 750 m^3/h, corresponding to approximately 0.2-0.3 m/s. This low flow had to be maintained for practical and safety reasons. The higher flow was started some time after the burner was ignited and the cables had started burning. This was also considered to be realistic taking into account detection time for a smoke extraction system.

Table 6. Vertical tests (see below table for explanation).

Test ID	No and type of cables	Ventilation	Burner programme
V1	5 A, 8 B, 5x4 C (bundled)	Natural	02:00 - 17:00 30 kW 17:00 - 32:00 50 kW 32:00 - 46:00 0 kW
V2	5 A, 8 B, 5x4 C (bundled)	00:00 - 03:40 natural 03:40 - 15:00 fan2 15:00 - 23:00 natural 23:00 - 28:00 fan2	02:00 - 30:30 30 kW
V3	5 A, 8 B, 5x4 C (bundled)	00:00 - 03:40 750 m^3/h 03:40 - 22:00 3000 m^3/h *	02:00 - 22:00 30 kW
V4	5 A, 8 B, 5x4 C (bundled)	00:00 - 03.40 750 m^3/h * 03:40 - 07:20 1000 m^3/h * 07:20 - 25:00 750 m^3/h *	02:00 - 13:00 30 kW
V5	5 A, 8 B, 5x4 C (bundled)	00:00 - 03:40 750 m^3/h * 03:40 - 19:00 1000 m^3/h *	02:00 - 04:00 30 kW
V6	12 D	Natural	02:00 - 17:00 20 kW
V7	12 D	00:00 - 03:30 natural 03:30 - 17:00 fan2	02:00 - 17:00 20 kW
V8	12 D	00:00 - 02:00 2000 m^3/h * 02:00 - 17:00 6000 m^3/h *	02:00 - 04:10 20 kW
V9	12 D	00:00 - 03:30 750 m^3/h * 03:30 - 14:00 6000 m^3/h *	02:00 - 14:10 20 kW
V10	12 D	00:00 - 01:45 750 m^3/h * 01:45 - 17:00 6000 m^3/h *	02:00 - 17:00 20 kW

* Extraction flow (upwards flow in chamber)

750 m^3/h extract	= 0.2 - 0.3 m/s vertical velocity in chamber
3000 m^3/h extract	= 0.6 - 1.0 m/s vertical velocity in chamber
6000 m^3/h extract	= 2.0 - 2.5 m/s vertical velocity in chamber
fan 2, ∅ 400 mm	= unsteady forced flow

Figure 15. Mounting configuration in the vertical tests, first series. The white backing board is visible behind the cable ladder.

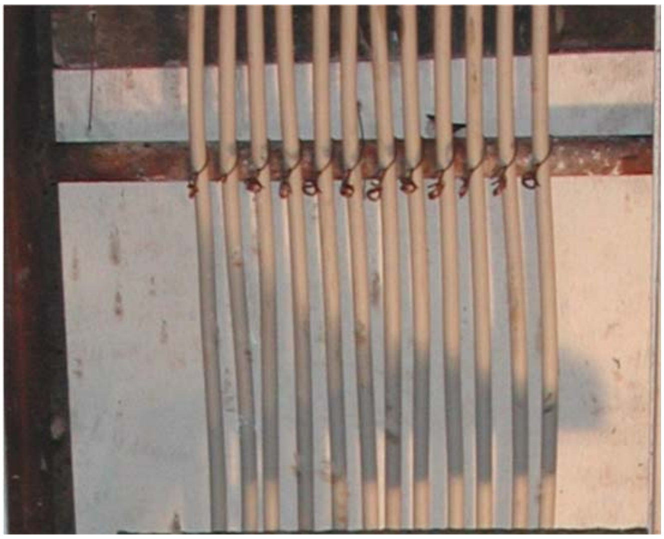


Figure 16. Mounting configuration in the vertical tests, second series, cable D only.

4.3.4 Results of first test series

4.3.4.1 Flame spread results

In the first series the flame spread was studied and plotted individually for cables A and B. Cable C did not propagate fire by itself in any test and the flame spread was not possible to record or distinguish from cable B. In most cases the bundles closest to cable B were burnt but the bundles closest to the edge were less damaged. Figure 17 - Figure 18 shows the flame spread in cable A and B.

The flame spread in Cable A, shown in Figure 17, was very limited in all tests. A maximum pyrolysed length of 1.75 m was reached in test V1 without forced ventilation. The cable A has a very large heat sink due to the amount of copper in the conductor (Table 1) and this is the dominating parameter. However, some conclusions can be drawn.

In the suction ventilation tests V3 and V4 the flame spread was almost identical for the two ventilation rates, the higher ventilated test V3 being slightly faster.

Test V2 was ventilated by a fan and in this case the flame spread was limited by the cooling effect of the flow and the disturbance of the burner flames.

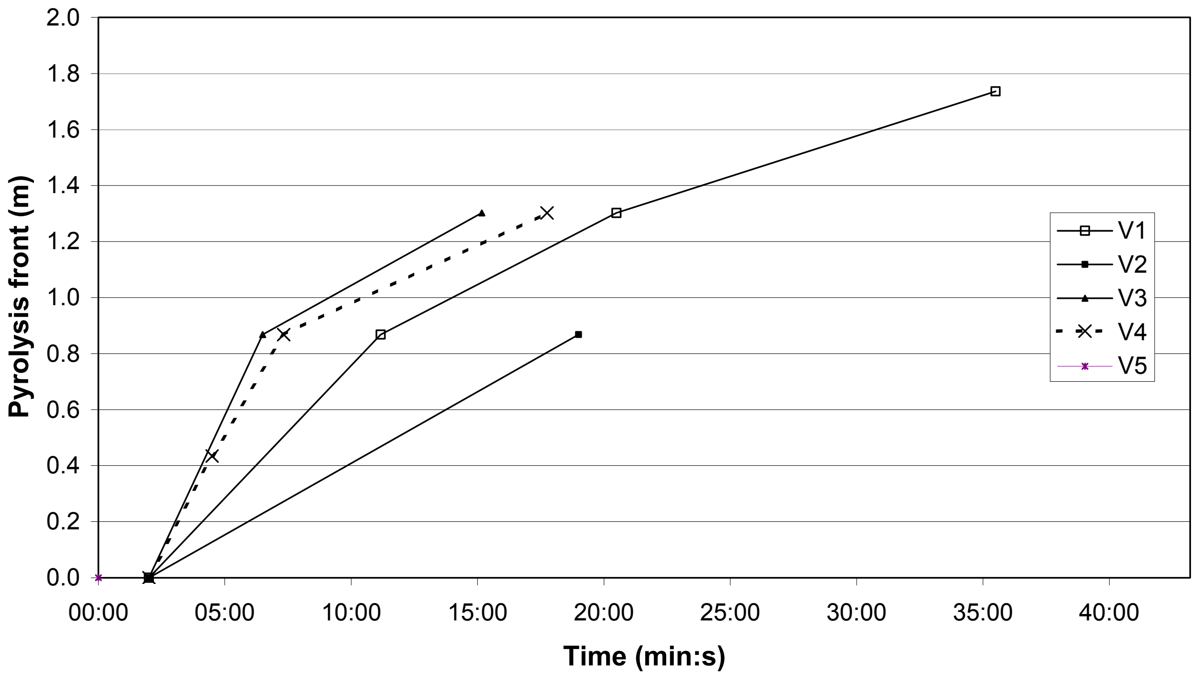


Figure 17. Flame spread in the vertical tests first series, cable A.

Figure 18 shows the flame spread in cable B and in this case we see a little more spread. The main observation is that tests V2-V4 behave quite similarly, while in tests V1 and V5 the flame spreads to the top of the ladder. The common parameter for these two tests is that the burner was switched off while cable B was still burning, at 32 and 4 minutes respectively. A conclusion from this observation is that the burner causes an oxygen deficit in the hot plume significant enough to affect the combustion and flame spread. This effect is probably enhanced due to the small cross-section of the shaft.

In the tests with higher ventilation the burner was not switched off until the fire had gone out. Figure 19 shows a photograph from a test in the first series.

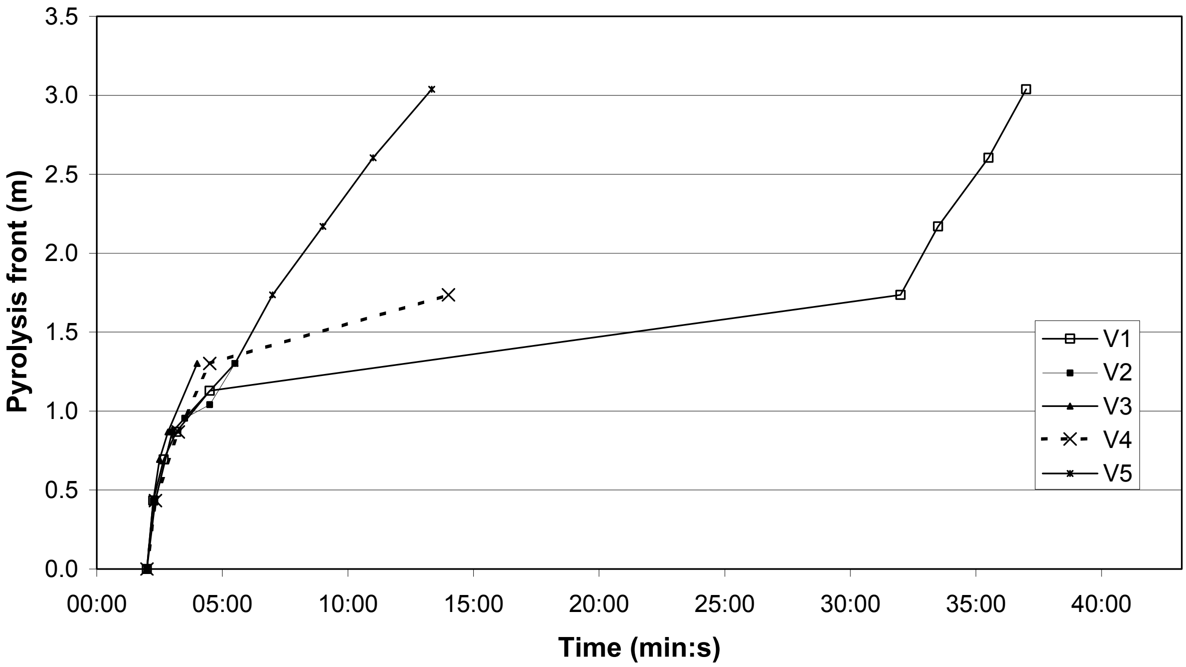


Figure 18. Flame spread in the vertical tests first series, cable B.

Figure 19. Photograph of a test in the vertical first series.

4.3.4.2 Comparison HRR measurements

The Heat Release Rate (HRR) was measured in each test and a comparison between tests is shown in Figure 20 and Figure 21. The heat release from the gas burner is included in the graphs (20-30 kW).

For the vertical tests first series the analysis of the HRR is not quite as straightforward as in the horizontal tests. The cables gave off very limited heat release and the effect of ventilation is best seen in the flames spread plots for the individual cables.

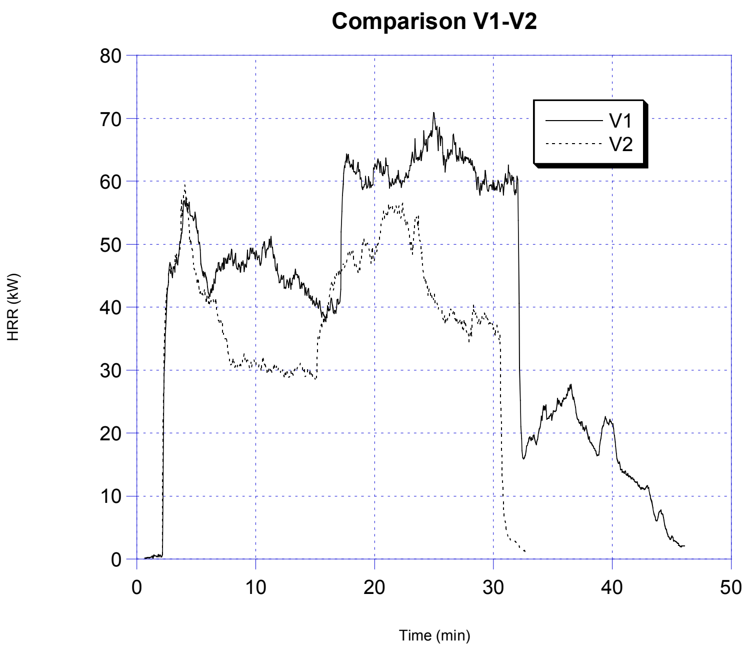


Figure 20. Comparison of HRR between tests V1-V2 (fan ventilation).

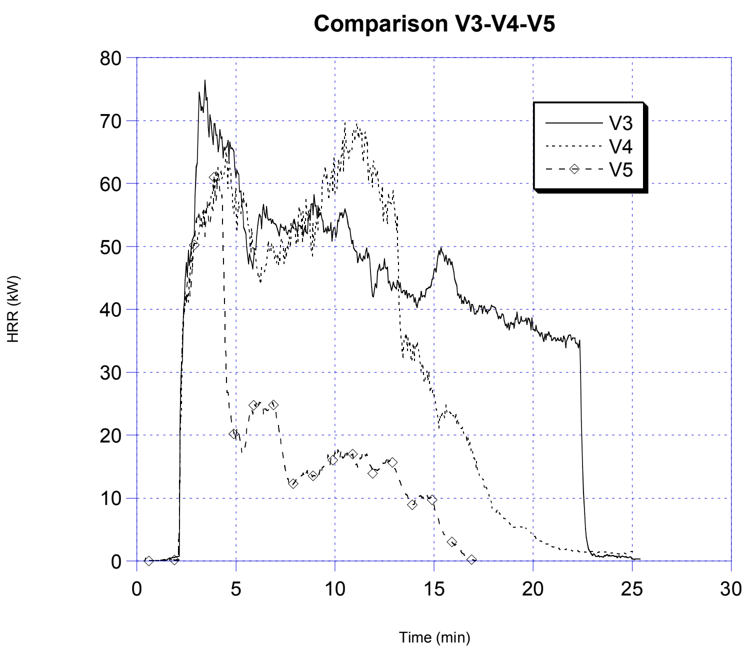


Figure 21. Comparison of HRR between tests V3-V5 (extraction ventilation).

4.3.4.3 Toxic gases results

The results from the gas measurements with FTIR for the vertical tests can be found in Table 7. The gases quantified were the same as those in the horizontal tests, i.e. CO, HCl and HF. Also in the vertical tests (first series) COF_2 was identified.

HCl was found in amounts up to two times the amounts of CO found. HF was found in lower but significant amounts.

Table 7. Results from measurements of toxic gas species in the vertical tests.

Test	**V1**	**V2**	**V3**	**V4**	**V5**
CO					
Max concentration (ppm) *	500	470	1640	1700	1750
Max production (g/s)	0.58	0.54	0.62	0.50	0.54
Total amount in test (g)	220	191	161	218	154
HCl					
Max concentration (ppm) *	430	450	1150	1680	1490
Max production (g/s)	0.65	0.67	0.97	0.70	0.61
Total amount in test (g)	362	293	296	331	292
HF					
Max concentration (ppm) *	37	42	140	146	153
Max production (g/s)	0.031	0.034	0.064	0.032	0.036
Total amount in test (g)	6.5	6.9	11.2	9.3	7.0

* Concentration measured in smoke gas duct.

Yield values can be found in Table 8. The yields were calculated according to the methodology used for the horizontal tests (see Section 4.2.4.3). The yields of CO and HCl found were in the same order of magnitude as those found from the horizontal tests. The yields of HF found in the vertical experiments were however significantly lower compared to what was found from the horizontal tests. One possible reason for the low yields found might be an overestimation of the amount of cable C that was consumed by the fire. In the vertical tests the spread behaviour of cable C varied for individual cable bundles. The bundle closest to cable B showed significant spread in some experiments whereas the bundles placed further away showed a very limited spread. This behaviour made it very difficult to quantify the total length/amount of cable C that was consumed in the experiments.

Table 8. Yields based on measured total amounts of respective gas species and an estimation of combusted cable length/amount combusted cable material.

Test	**V1**	**V2**	**V3**	**V4**	**V5**
CO					
Yield (g/m)	4.1	4.7	4.7	5.3	3.4
Yield (g/g)	0.054	0.094	0.068	0.081	0.062
HCl					
Yield (g/m)	6.7	7.2	8.6	8.1	6.4
Yield (g/g)	0.09	0.14	0.13	0.12	0.12
HF *					
Yield (g/m)	0.30	0.27	0.64	0.45	0.32
Yield (g/g)	0.04	0.04	0.09	0.06	0.05

* The yields calculated for HF must be regarded as indicative only as assessment of combusted length/mass was rather subjective for cable C in the vertical tests.

A plot of absorbance at the wavenumber 1929 cm^{-1} from the FTIR measurements are shown in Figure 22 for the vertical tests. The absorbance gives semi-quantitatively information of the occurrence of COF_2 in the smoke gases during the tests. For a discussion on this subject see Annex A and Section 4.2.4.3. It can be seen from Figure 22 that the absorbance at the wavenumber indicative of COF_2 was highest in experiments V3 –V5.

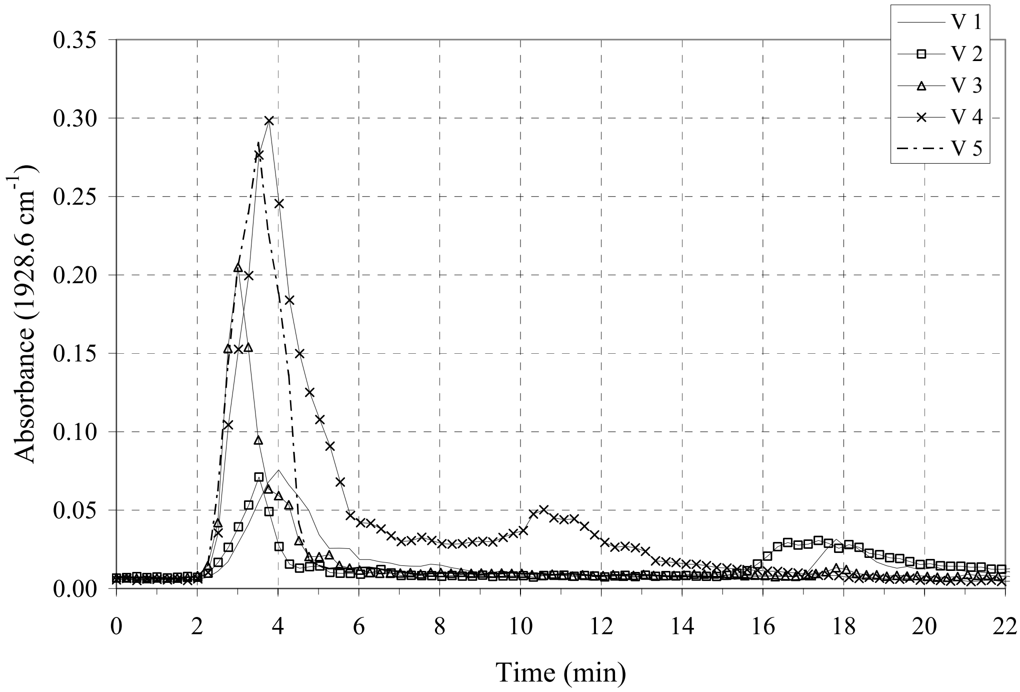


Figure 22. Plot of absorbance at 1929 cm^{-1} measured with FTIR. COF_2 exhibits its strongest absorbance at this wavenumber.

4.3.5 Results of second test series

In this test series no FTIR measurements of toxic gases were performed. This decision was made because the only cable in the test was cable D, which contains no halogens and will not produce any HCl or HF.

4.3.5.1 Flame spread results

The cable in the second test series had lower fire performance than those in the first series and the flame spread was much faster. A first look at Figure 23 shows that the four tests V6-V7 and V9-V10 spread all the way to the top while test V8 stops early.

There is no big difference in flame spread between the naturally ventilated test V6 and tests V7 and V9. In test V7 blowing ventilation was activated at 3.5 min but the influence is negligible considering the flame spread. In test V9 extraction was activated at 3.5 min but the cables were already burning sufficiently not to be affected much by the suction flow. Test V10 has a clearly slower flame spread and in this test the high suction flow was activated earlier, thus limiting the fire development to some extent. These tendencies are also clear in the heat release rate plot, Figure 25.

Test V8 was started with a relatively high extraction rate, 2000 m^3/h, which was increased at 2 minutes. This resulted in almost no flame spread. The explanation is cooling and the high flow forcing the flames from the burner to lean out from the cables, not fuelling the fire, which soon went out. The higher initial flow also delayed the ignition of the cables, compared to the tests with 750 m^3/h initial flow. Figure 24 shows a photograph from a test in the second series.

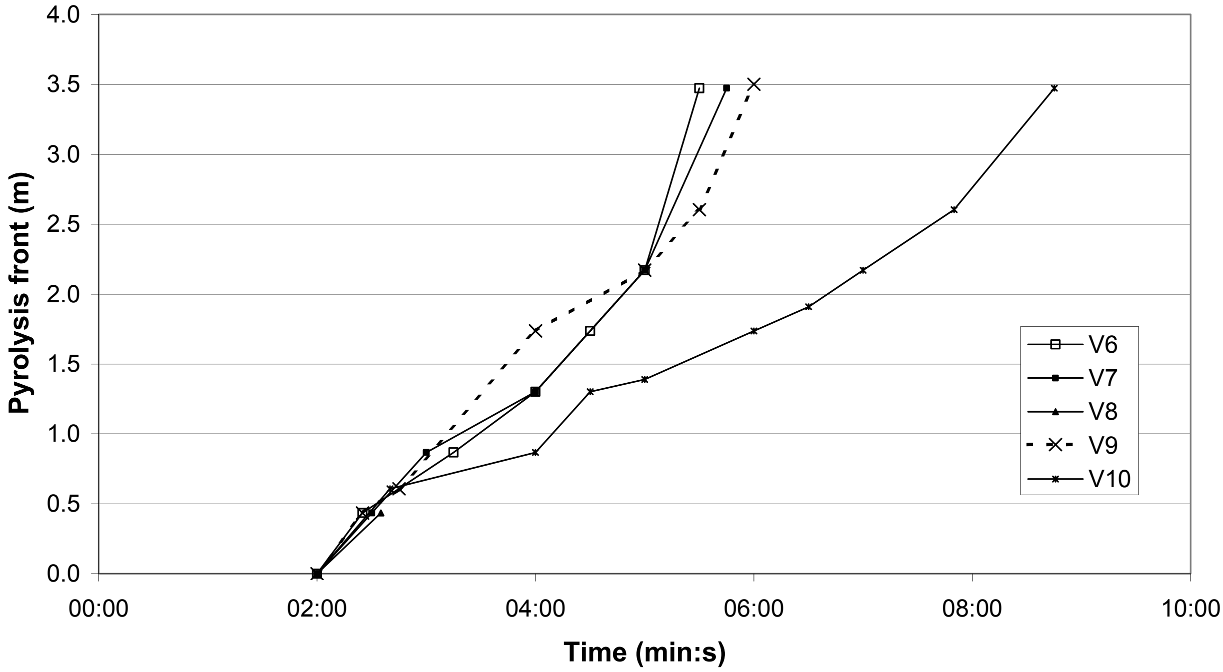


Figure 23. Flame spread in the vertical tests second series, cable D.

Figure 24. Photograph of a test in the vertical second series.

4.3.5.2 Comparison HRR measurements

Figure 25 shows the heat release rate from the second vertical test series. Test V8 gave almost no heat release and is not included in the plot. The cable (D) in the second vertical test series produced more HRR than the cables in the first series and it is possible to see the same behaviour as in the flame spread analysis. A low flame spread gives a lower HRR increase.

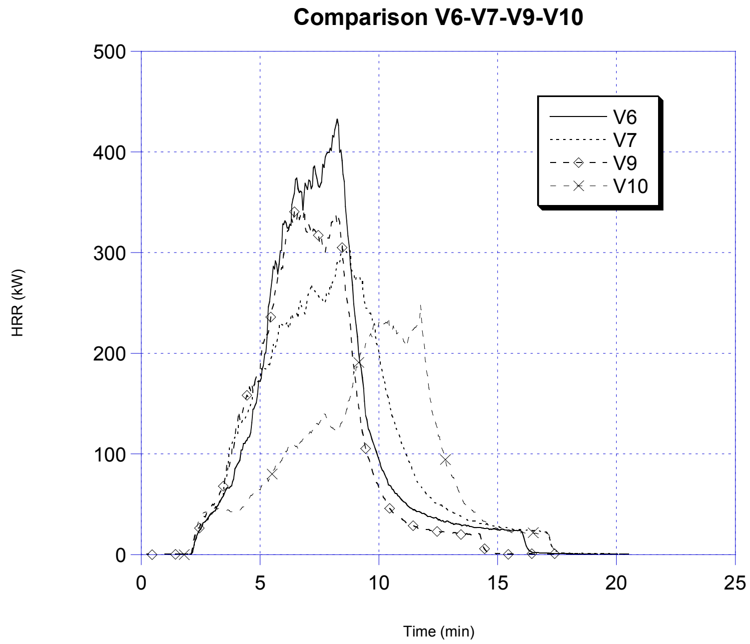


Figure 25. Comparison of HRR between tests V6-V7, V9-V10.

4.3.6 Discussion of vertical results

The results from the vertical test series have shown the ventilation not being as influencing parameter as in the horizontal tests. One important reason for this is that the buoyancy creates a natural airflow, which enhances the flame spread in vertical set-ups. Increased ventilation has in some cases decreased the flame spread and the heat release rate and this is probably due to disturbance of the hot plume and flames which decelerates the fire propagation.

5 Calculation of flame spread and smoke transport

In order to be able to work simultaneously on the modelling and the fire testing it was decided to use the horizontal real scale tests conducted in the FIPEC project [2] as a basis for the modelling. This could teach us whether CFD models could be used and how the success of these models could be judged.

5.1 Real scale test used for the simulation

In the FIPEC project various real-scale test configurations were investigated to find scenarios, both for horizontal- and vertical mounting, that produced fire performance results sufficiently sensitive to efficiently differentiate between the tested cables. The investigated test set-ups included open-, semi-closed, and closed configurations. The configurations found most efficient to separate between different cables, were a closed configuration for horizontally mounted cables, and a semi-closed configuration for the vertically mounted cables. A limited number of experiments with forced ventilation were conducted with a closed configuration in both cases.

The mathematical simulations carried out during this work were all considering the horizontal configuration. Details of this configuration and the test procedures are discussed below.

5.1.1 Test set-up

A schematic view of the horizontal real-scale test set-up can be seen in Figure 26. The cables were mounted on three cable trays (ladders), with six cables per tray and a distance of 2 cm between each cable. The length of each cable section was 4 meters. The installation was a corridor configuration; 5 m long, 0.8 m wide, and 1.6 m high. The three cable trays were centred in the corridor and positioned above the floor at a height of 0.7 m, 1.0 m, 1.3 m, respectively. Additionally, there was a small spacing between the cable trays and the sidewalls.

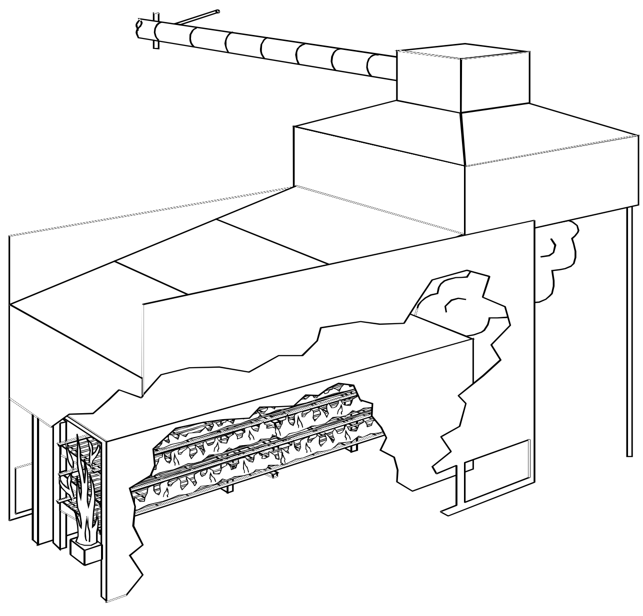


Figure 26. Schematic view of the horizontal real-scale test set-up (FIPEC).

In order to collect the smoke gases from the burning cables for measurement of the heat release rate (HRR), an enclosure was built around the corridor leading the smoke gases to the hood of the ISO 9705 room. The enclosure had openings at floor level to ascertain that enough air was allowed to reach the combustion zone, thus to not interfere with the burning behaviour of the cables.

The ignition source in these tests was propane diffusion burner, positioned 0.5 m from the ends of the cables. A heat source programme with a step-wise increased burner output was adapted. The heat source programme was as follows: 40 kW for 5 min, 100 kW for 10 min and 300 kW for 10 min. When flame spread or sufficient heat release from the cables was observed, the heat output from the burner was not increased to the next level. In cases where the complete cable tray configuration was burning, the tests were stopped by extinguishment.

5.1.2 Experimental results

Only one experiment was conducted using forced ventilation in the horizontal scenario described above. In this experiment a forced ventilation rate of 0.8 m/s was created in the corridor. This was obtained by placing an axial fan in front of the corridor opening closest to the burner. The exact position of the fan to give the desired external flow conditions in the corridor was decided after pre-tests with flow measurements in the corridor opening.

Figure 27 shows the results from the experiment with forced ventilation compared with the results from a corresponding experiment with natural ventilation. The same type of EPR/EVA 3×95 mm^2 cable was used in both tests.

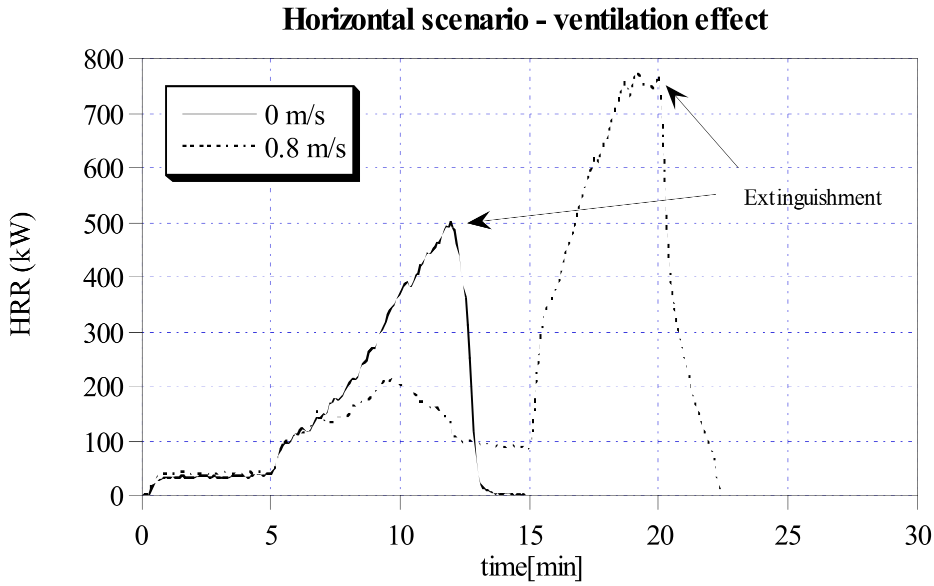


Figure 27. HRR measured in experiments with horizontally mounted cables, with and without forced ventilation (HRR from the burner included).

It can be seen from Figure 27 that the test with natural ventilation (forced ventilation = 0 m/s) actually showed a faster flame spread and thus a higher HRR compared to the experiment with forced ventilation (0.8 m/s). (Note that the HRR produced by the burner is not subtracted from the data presented in Figure 27.) The non-ventilated test showed a propagating flame spread at the 100 kW burner level and had to be extinguished after 13 minutes. At this burner level the ventilated test showed limited and receding flame spread only. When the ignition source was increased to 300 kW (at 15 min) in the ventilated test, the cables showed faster spread rates than the non-ventilated test had exhibited at the 100 kW level but one should realise that the thermal attack is three times higher in this case. Also the test with forced ventilation had to be stopped before the end of that heat source programme.

5.2 CFD Simulations

The numerical simulations were carried out using the CFD code SOFIE (Simulation of Fires in Enclosures), which is specifically designed for prediction of fires within enclosures [5]. The code has been developed at Cranfield University (UK) within the framework of a European consortium, including SP. The SOFIE code is based on a finite volume algorithm using a non-orthogonal coordinate system with co-located velocities and a SIMPLEC type pressure correction scheme.

For the simulations reported in this work the dependent variable interpolation was achieved using a first order hybrid scheme and a TDMA solver. The turbulent model used was the standard κ-ε model with additional buoyancy correction incorporated. Combustion was simulated using an eddy break-up model [6] with different fuels depending on the materials. Soot was introduced into the computational domain through conversion of a constant fuel mass fraction into soot at the fuel source. A conversion factor of 2 % was used in this work, as this has previously been reported to be a reasonable approximation [7].

Further, the thermal radiation was simulated using the discrete transfer radiation model with gaseous optical properties described by a weighted sum of grey gases model. Aksit et al. [8] have previously shown that the number of rays utilized in the iterative calculation of radiation is critical in simulation of flame spread. As a compromise between accuracy of the simulation and reduced computational time 32 rays were selected for the discrete transfer model in this work.

5.2.1 Geometry and computational domain

The virtual geometry used for the simulations is schematically shown in Figure 28. The dimensions of the corridor, and positions of cables and cable trays were the same as in the experiments discussed above. The representation of the cables and the trays was however simplified in the geometry for the simulations. The cable trays were represented as long bars positioned along both sides of the cables. The main reason for including a representation of the trays was to account for their function as heat sinks, i.e. heat conduction calculation was included in the trays. The six cables mounted on each tray in the experiments were represented as three pairs of cables in the simulations. Due to geometric restrictions in the CFD software the representations of the cables were rectangular instead of cylindrical. However, the total surface-area of cables was the same in the simulations as in the experiments. There was no calculation of heat conduction in the cables due to the nature of the flame spread sub model used. Heat conduction was, however, calculated for walls and ceiling of the corridor.

The computational domain was extended above and on both sides of the corridor in order to allow inspection of the smoke movement and velocity profiles, and also to achieve a faster convergence of the calculation. The total number of cells in the computational grid was 111720.

Different combinations of fluid boundary conditions (b.c.) for the computational domain were investigated, with the goal of achieving a good physical representation of the flow field and also to minimize the number of iterations to reach convergence. The fluid b.c. applied for the flame spread simulations were a combination of static pressure and extractive boundary conditions. On both sides in front of the corridor openings the b.c. were of static pressure type, *i.e.*, the boundary allows both flow in and out of the computational domain according to the local pressure gradient. The investigation showed that using only static pressure b.c. gave very slow convergence. However, in combination with extractive b.c. the time to reach convergence decreased considerably. Extractive b.c. were included in the top plane of the computational domain in front of both openings of the corridor. The sum of the flow extracted from these two positions (extraction at a velocity of 0.5 m/s at each b.c.) represented approximately the flow extracted with the smoke gas collecting system in the experiments.

Simulations were conducted in order to investigate if the inclusion of extractive b.c. influenced the results of the flame spread simulations. These simulations were conducted in the scenario with natural ventilation (no forced ventilation), and the input parameters for the flame spread sub model used were those reported in Table 1 as "settings C". As can be seen from Figure 29, there is no significant difference between the results (here presented as resulting HRR) from the simulation with an extraction velocity of 0.5 m/s and the simulation with a significantly lower extraction velocity. There was, however, a significant difference in terms of computational time between these two cases, the higher velocity case being several times faster. Hence, 0.5 m/s was used as extractive b.c. in the subsequent simulations as there were no indications that this would compromise the results of the simulations.

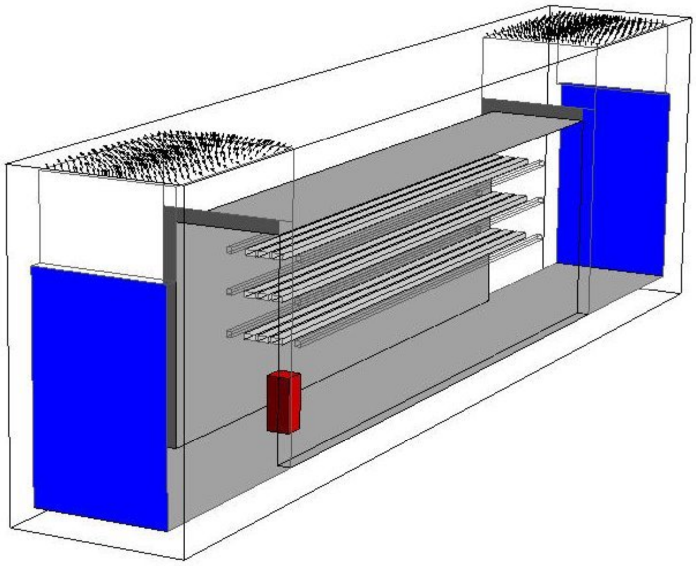


Figure 28. Schematic view of the geometry used in the CFD simulations.

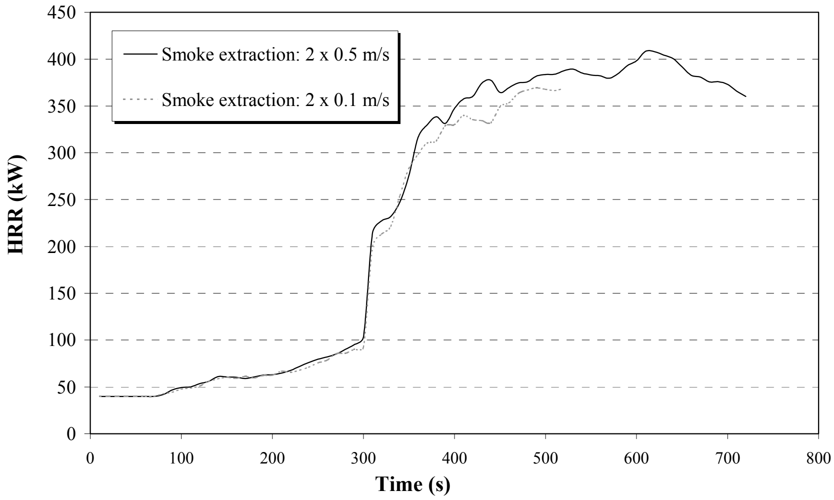


Figure 29. Comparison of HRR from simulations of the non-ventilated scenario using different velocities at extractive boundaries.

5.2.2 Flame spread model

The sub model used to include flame spread in the simulations was a simple semi-empirical model that did not calculate pyrolysis nor heat conduction within the cable material, i.e., no computational mesh was needed within the cable. It was assumed that a simple flame spread model would fulfil the need for the rather qualitative work presented in this study. Further, it was advantageous to use a less computationally demanding model considering the rather complex scenarios simulated.

The model used is based upon an empirically determined heat of gasification and an ignition delay correlated by the net incident heat flux. This model was developed at Cranfield University (UK) [8] and has showed promising preliminary results for simulations of flame spread on wall linings in compartments.

The physical flame spread process is simulated in two stages by the model. Before ignition a specified amount of energy ($E_{critical}$) must be accumulated from the incident heat flux (q_{net}) to the surface of the material. A defined amount of this heat flux (q_{min}) is at the same time subtracted, as a representation of the conductive heat losses in the material. The application of this simple theory is shown in equation (1) below.

$$E_{critical} = \int_0^{t_{ignition}} \dot{q}\,dt = \sum_0^{t_{ignition}} Max(\dot{q}_{net} - \dot{q}_{\min}, 0)\Delta t \qquad (1)$$

Once the ignition criterion is fulfilled for a cell surface, fuel is released at a rate governed by the incident heat flux and the specified value of the heat of gasification. Additionally, the formation of char and the corresponding reduction in heat release rate are simulated by reducing the fuel flow from the cell surface as a function of the accumulated mass loss. The reduction ends at a value of 40 % of what is initially calculated. The fuel release stops once q_{net} goes below q_{min} ,or the calculated char depth is equal to the thickness of the material. The char depth is in the model approximated from input values for char density, virgin material density and the calculated mass loss.

5.2.3 Parameter study in non-ventilated case

As a first step towards qualitatively sound simulations of ventilation controlled flame spread, the sensitivity of the flame spread model in the non-ventilated cable fire case had to be studied. There are no reports in the literature from comparable studies, thus no guidance could be found on appropriate input parameters for the flame spread model. However, available data from cone calorimeter tests on a wide selection of different cables from the FIPEC project was used as a starting point for the parameters where it was applicable.

The sensitivity of the model for changes in the various empirical parameters was studied for the non-ventilated scenario. The different parameters were varied within a rather wide range; however, all parameters were kept within physically sound limits. It was found, more or less as expected, that the critical accumulated heat flux had the strongest influence on the ignition time, and that the heat of gasification had the strongest influence on HRR. However, also the minimum heat flux had a rather strong influence on HRR.

A large number of simulations were conducted within the parameter study and the most reasonable combinations of the input parameters are shown in Table 9.

Table 9. Different settings of input parameters for simulations of non-ventilated scenario.

Parameter	Settings **A**	Settings **B**	Settings **C**	Settings **D**
Parameters for flame spread sub model:				
Heat of gasification (J/kg)	1500000	1800000	1500000	1500000
Ignition temperature (K)	450	450	450	450
Critical accumulated heat flux (J/m^2)	2700000	2700000	2700000	3500000
Minimum heat flux (W/m^2)	500	2000	1500	1500
Virgin material density (kg/m^3)	1200	2500	2000	2000
Char material density (kg/m^3)	120	150	150	150
Maximum char depth (m)	0.003	0.003	0.003	0.003

The results from the simulations in the non-ventilated case with the different settings discussed above are shown in Figure 30-Figure 31. In these simulations a burner output of 40 kW was maintained for 5 minutes, and then increased to 100 kW. In the experiments discussed above the burner output was also increased to 300 kW after another 10 minutes, this was however not included in the simulation time.

It could be seen that all simulations give reasonable results for the studied scenario. One of these settings had to be selected for the further study of effects from forced ventilation. It was decided that “settings D” was most suitable for the further study. In this simulation there is no flame spread in the cables on the third tray (cables closest to the ceiling of the corridor) at the lowest burner output (5 min at 40 kW); subsequently, at the higher burner output (100 kW) the flame spread increases rapidly to reach its maximal length, 75 % of the total length of the cables on the third tray. The HRR is in this case limited at the low burner output (from limited flame spread in the cables on the two lower trays), but increases rapidly at the higher burner output to reach a maximum, and finally decreases in the end of the simulation as the material is consumed.

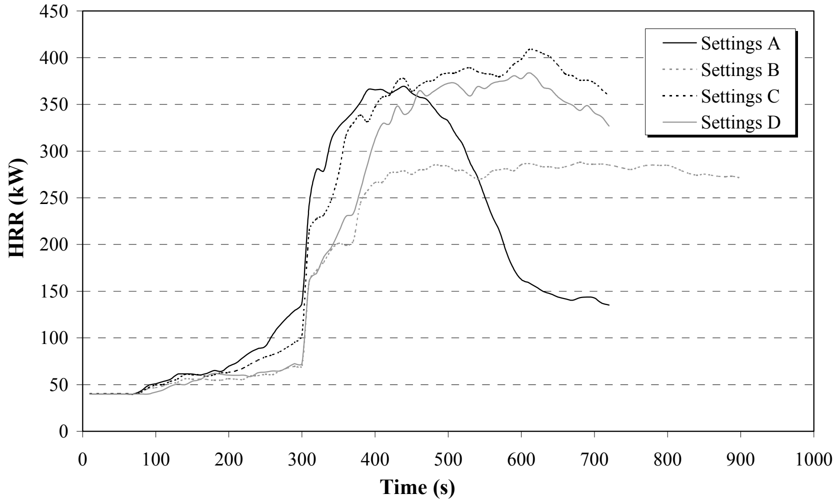


Figure 30. Resulting HRR from simulations of the non-ventilated scenario.

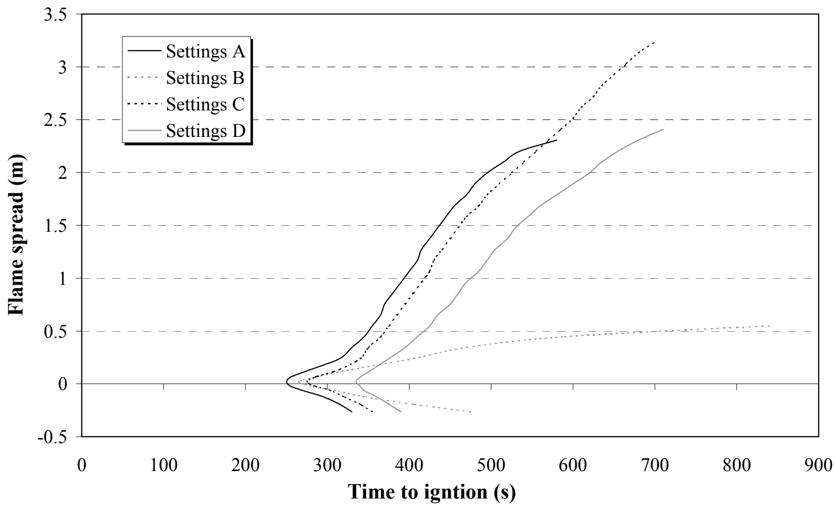


Figure 31. Resulting flame spread for cables on the third (upper) tray in simulations of the non-ventilated scenario. (The burner is placed at flame spread = 0 m.)

5.2.4 Effect of ventilation

In the study of the effect of forced ventilation on the flame spread behaviour, the same geometry and computational grid as in the natural ventilated scenario were adopted. The choice of the input parameters for the flame spread sub model, was set according to settings D in Table 2 above. The only difference was that the static pressure boundary condition in the end of the computational domain closest to the burner was replaced with an *inflow boundary condition* in this case. A schematic view of the geometry with the various fluid boundary conditions indicated is shown in Figure 32.

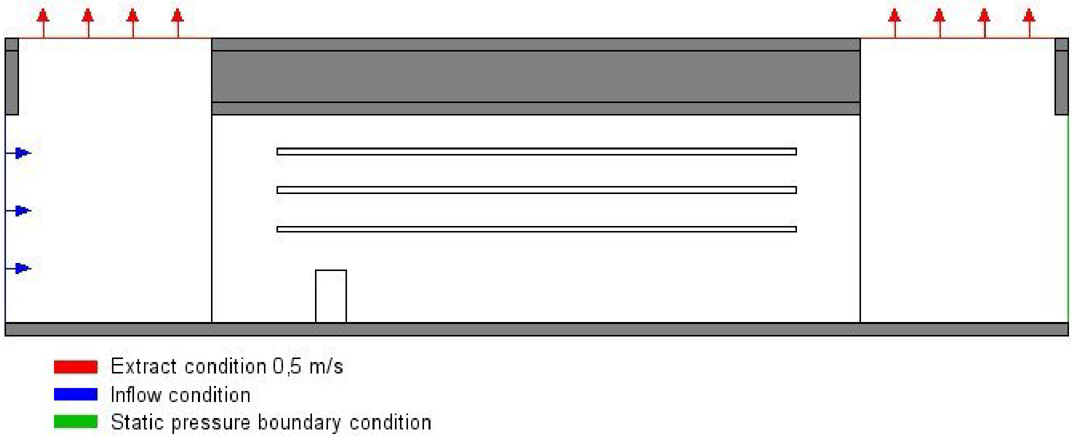


Figure 32. Schematic view of the geometry used in the simulations of ventilated scenarios; boundary conditions are indicated in the figure.

Two different cases with forced ventilation were studied: one case with forced ventilation set to 0.5 m/s, and one case with forced ventilation set to 0.8 m/s. The results from these simulations are presented in Figure 33-Figure 34. Included in these figures are also the results from the corresponding simulation with natural ventilation only.

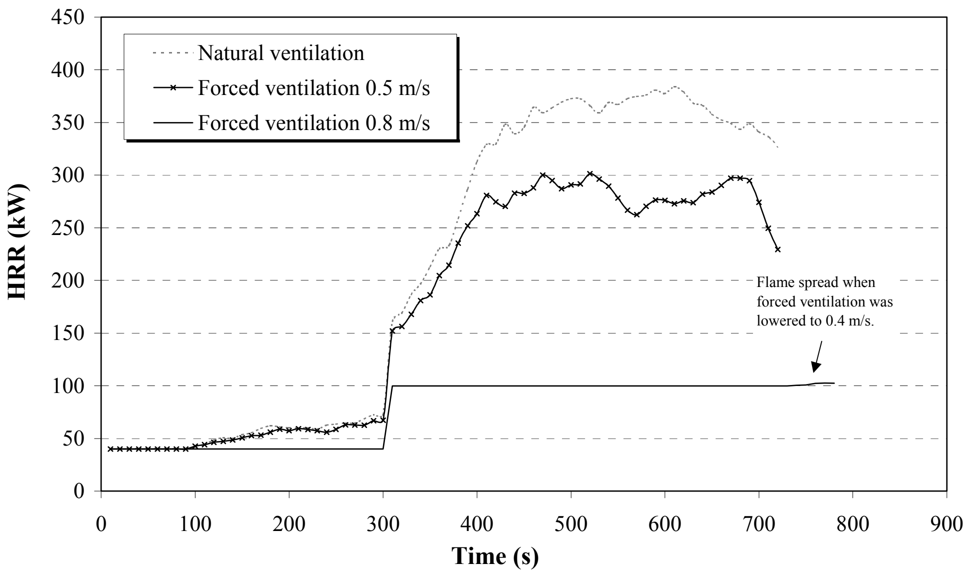


Figure 33. Resulting HRR from simulations of ventilated scenarios.

The strong influence of forced ventilation on the flame spread rate and accompanying HRR of the horizontally mounted cables is clearly seen in Figure 33-Figure 34. The introduction of a forced ventilation of 0.5 m/s considerably reduces the predicted HRR compared with the case with natural ventilation only. Further, in the case where the forced ventilation is increased to 0.8 m/s, no burning at all is predicted, not even at a burner output of 100 kW. Additionally, in this simulation the forced ventilation was lowered from 0.8 m/s to 0.4 m/s after 720 s. This decreased forced ventilation resulted in ignition of the cables on the first tray after an additional 25 seconds, and the corresponding increase in HRR can be seen in Figure 33.

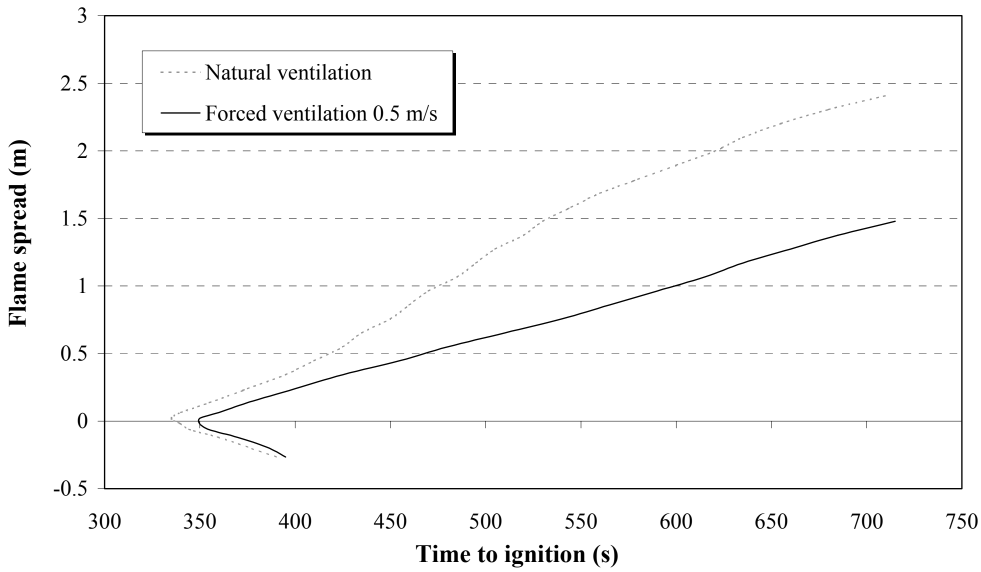


Figure 34. Resulting flame spread for cables on the third (upper) tray in simulations of ventilated scenarios. (The burner is placed at flame spread = 0 m.)

A more comprehensive picture of the results from the simulations is given in Figure 35. These figures show schematically the calculated pyrolysis front on the cables and the smoke layer in the computational domain. The simulations clearly predict the general flame spread behaviour observed in the experiments. The ignited length of the cables was seen to increase with the height from the floor. The explanation of this behaviour can be found in the results from the simulations. Closer to the ceiling of the corridor the smoke layer increases, and more convective heat interacts with the cables and thus promotes ignition and flame spread. In the case with forced ventilation the smoke gas layer is more diluted (this can not be seen clearly in Figure 35) and the convective heat transfer in the upper part of the corridor is thus reduced.

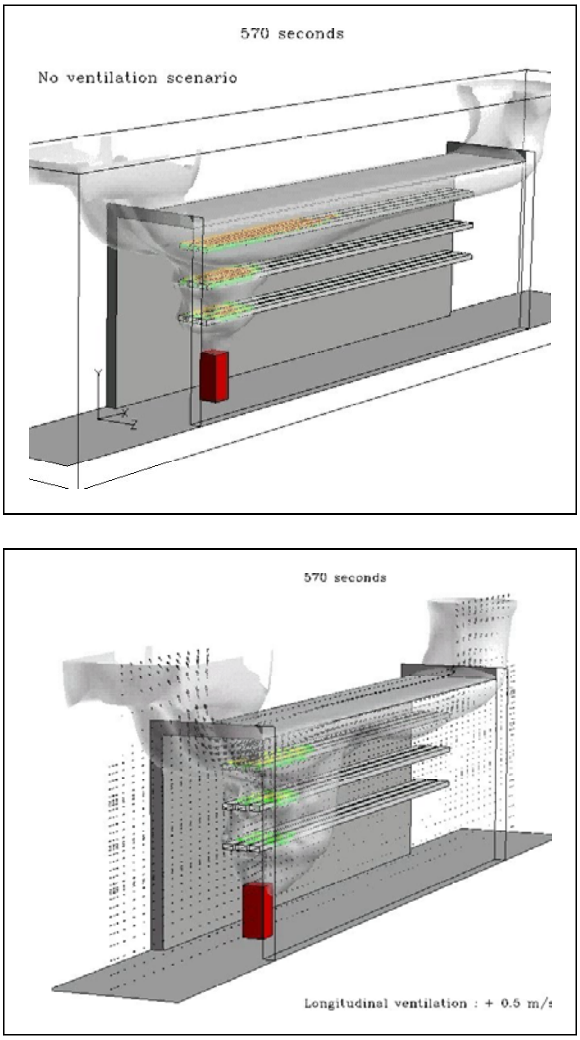


Figure 35. Schematic views of pyrolysis fronts and smoke movement in non-ventilated and ventilated cases.

The results from the simulations thus seem to qualitatively capture the general trends of the ventilation effect on cable flame spread as observed in the experiments. Limitations in the flame spread sub model used regarding heat losses/conduction within the cables sets however a restrain to the quantitative accuracy one might obtain from such a model.

5.2.5 Discussion of simulation result

In a limited series of experiments, within FIPEC, cables were horizontally mounted in a corridor configuration and it was observed that if introducing forced ventilation the flame spread and thus the burning of the cables decreased. It is important to note that the simulations modelled the specific cables and scenario tested in FIPEC. The fire behaviour of the cables tested in FIPEC was different from the fire behaviour of the cables tested in this Brandforsk project and the scenario was also different. The FIPEC cables simulated were of a larger dimension and contained a very large heat sink due to the copper conductor. This means a high thermal inertia and a slower heating and ignition phase which can be further delayed or inhibited by ventilation

The present study showed that the experimentally observed effect of forced ventilation on the flame spread behaviour could be qualitatively reproduced using CFD simulation including a simple semi-empirically flame spread model. This is an important progress, as it is a step against better prediction of the overall fire growth in real scale scenarios. It will also allow a better definition of the design fire based on the materials/products involved in the fire, and is hence an important step towards more advanced fire engineering.

Improvement of the flame spread models are however still necessary, but it has been shown that even with a rather simple model, the major trends of the results of real-scale fire were predicted. Improvements on the present model can be made e.g. on the heat conduction in the solid material and on the determination of material parameters.

6 Guidelines/conclusions

The effect of ventilation on the flame spread of cables have been studied in this project with respect to cables placed in difficultly accessible places such a plenums in buildings, vertical riser shafts in buildings and power plants, horizontal cable galleries or cable tunnels. The study did not cover under-ventilated conditions.

From the study a number of conclusions/guidelines can be drawn:

1. Positive of negative ventilation effect on flame spread depends mainly on direction, magnitude of the ventilation, size of the initial fire and geometry of the compartment.

It is well known that depending on the ventilation direction with respect to the flame spread the flame-spread velocity can be influenced considerably. General statements are often used. A so-called wind opposed flame spread will result in a reduction of the flame spread while a wind aided would lead to increase of the flame spread. The results of this project however show that such general rules should not be applied. For a horizontal situation it is clearly shown in this project that the flame spread velocity increases considerably above a certain forced ventilation threshold value but that once above another forced ventilation threshold the flame spread velocity decreases. It is obvious that there is a forced ventilation value, which is the “optimum” one i.e., which creates the most hazardous situation. However this value is dependent on the initial fire area, the number of cables and the boundaries, i.e. the volume and dimensions of the compartment. In a small compartment such as a cable riser shaft or a small tunnel all these factors are extremely important and although simple calculations could give a good first impression a detailed study of the situation is necessary. In a vertical situation it was also seen that the ventilation could in some cases result in cooling down the plume temperature and the cable surface while in other cases it increases the flame spread velocity. When installing cables within enclosures it is important to make a risk assessment considering the effect of forced ventilation in case of a fire. The results from this project has shown that in some cases the consequences of the fire can be much worse by using ventilation.

2. CFD calculation can provide an excellent tool for determining hazardous situations.

In this project a flame spread model incorporated in a CFD code was used. The results clearly showed that the use of CFD codes such as SOFIE is an excellent tool to investigate a number of scenarios and to define which are the hazardous ones. It also allows deciding if certain ventilation situations would be acceptable or not. It is desirable to use such a tool in these situations were the occurrence of a fire and the spread of the fire is critical.

3. Use of improved cables is recommended but the selection of the type of cables should be considered.

The project clearly showed that enhanced fire performing cables will reduce the hazard substantially. These cables have lower flame spread velocities and in many cases also lower heat release rates. However it was seen in the project that the highest class of cables, the so-called plenum cables, contain high amounts of halogens. At this moment this is almost the only technical solution to obtain this class. Despite the fact that this project has no intention to evaluate certain cables the results show that high production levels of corrosive gases were produced. Especially the amounts and yields of HF should be considered in an overall risk assessment both with respect to human health and functionality of systems.

4. Use of active systems should be considered in cases where it is difficult to estimate the ventilation effect in case of a fire and in those cases were a high protection level is necessary. Also when forced air or extraction will be used in case of fire one should consider these systems.

7 References

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Annex A FTIR measurement of toxic gases

Toxic combustion products from the fire tests with the cables were measured using FTIR technique. Measurements were conducted in all tests except in the tests with the halogen free D cable in the vertical scenario. The measurement technique and the test procedure are described below. Results from the tests are reported in the following sections.

In general, all compounds except for elemental diatomic gases such as N_2, H_2 and O_2 have IR spectra and most component present for instance in combustion gases can be analysed by their characteristic IR absorption. An example of a FTIR spectrum of HCl can be seen in Figure 36.

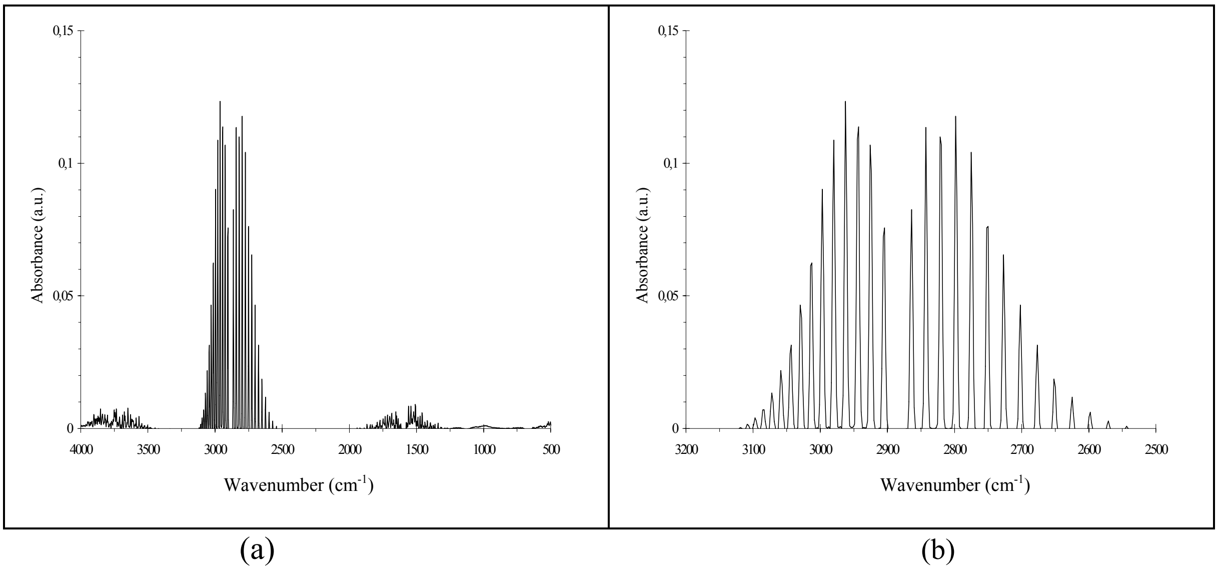


Figure 36. (a) Absorbance of HCl - full spectrum also showing some water. (b) Spectral range for quantification of HCl.

An advantage with FTIR spectrometry is the possibility of continuous monitoring of several gases simultaneously. Using FTIR, it is possible to set up a calibration and prediction method for each gas showing a characteristic spectral band in the infrared region of the spectrum.

The FTIR instrument consists of a spectrometer, a gas cell and a computer with software for storing and evaluating the measurement data. The spectrometer used was a BOMEM MB 100 equipped with a DTGS detector. The gas cell was of multi-path type, and was heated to avoid condensation in the cell. The temperature and the pressure in the cell were monitored during measurement. Specifications on the spectrometer and the cell can be found in Table 10.

Table 10. Specifications of FTIR equipment.

Parameter	Specification
Resolution	4 cm^{-1}
Wavenumber	4500 – 400 cm^{-1}
Data, time resolution	15 s
Cell, path length	4.8 m
Cell, volume	0.92 L
Cell, temperature	150 °C

The probe for the smoke gases was mounted in the duct collecting smoke gases from the cable test rig. The probe was mounted well away from the bend in the duct, approximately at the same distance as other measurement equipment. A ceramic filter was mounted (2 µm) directly after the probe. The smoke gases were drawn to the FTIR from the gas probe through a 7-m PTFE sampling line. Both the filter and the sampling line were heated to 180 °C. The suction pump used was placed after the gas cell and the gas flow through the cell was 4 litres/min.

Time synchronisation of the FTIR data and data collected by the main data logger system was important. As CO_2 and CO also were measured by other means than FTIR, and logged by the main system, a comparison was possible. The time synchronisation of the data was good; also the differences in absolute concentrations were small.

The different gases quantified in the tests were CO_2, CO, HCl and HF. These results, with the exception of CO_2, which is not regarded as toxic, will be presented in detail in the following sections. The FTIR was also calibrated for HBr, HCN, SO_2, NH_3, NO and NO_2. None of these gases were found in any test in concentrations exceeding the respective detection limit. Additionally, the species COF_2 was identified in the smoke gases in all tests involving the fluoropolymer-containing cable C. As there were no specific calibration for this gas available quantification was not possible and only qualitative results will be presented.

The identification of COF_2 was based on the work done by Su et al. [3] and molecular vibrational frequency data compiled by Shimanouchi [4]. A spectrum showing the most intense vibrational feature of COF_2 is shown in Figure 37 as an example. This spectrum is from the test H5 at a time of 6.3 min. The spectral feature of CO is also showed.

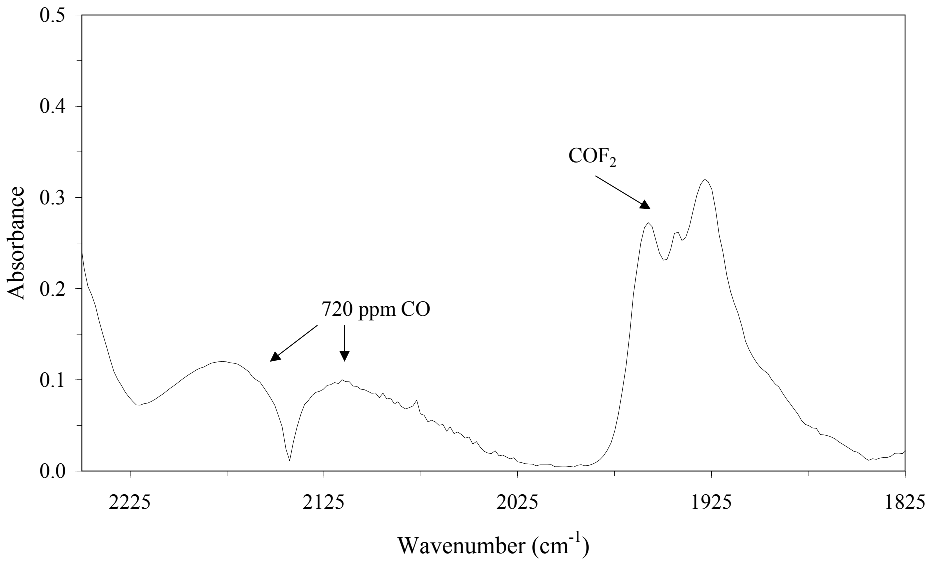
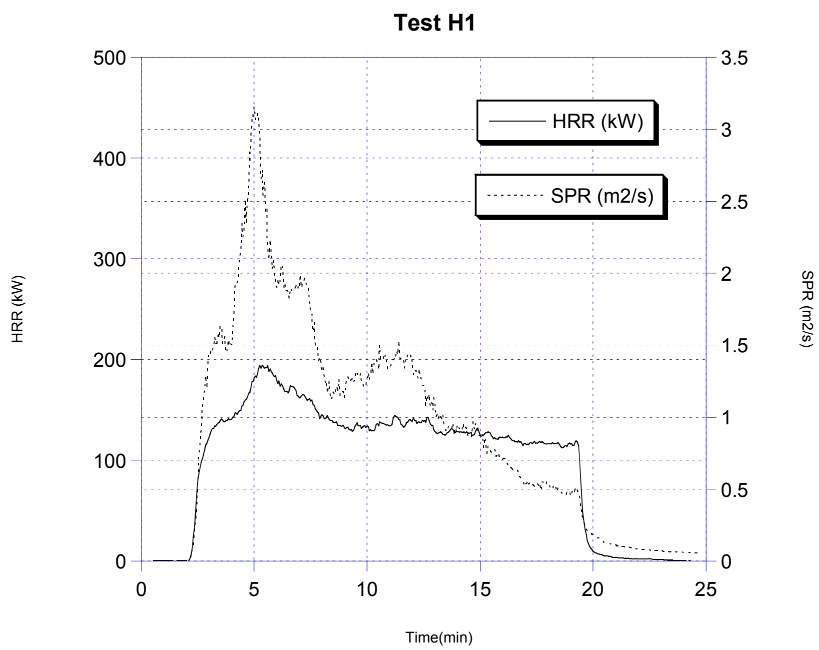


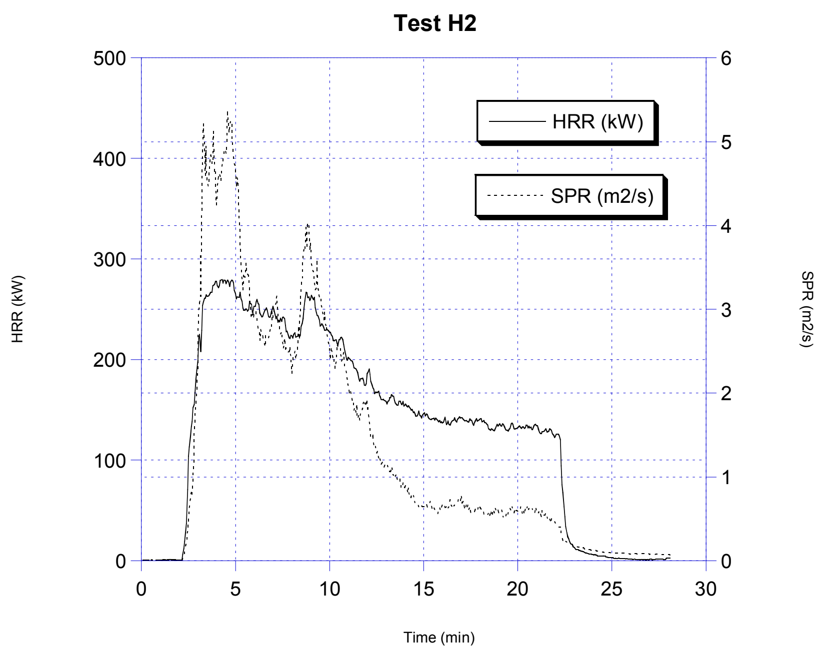
Figure 37. Infrared spectrum from test H5 at 6.3 min showing the spectral features of COF_2 and CO. COF_2 was not quantified, as the instrument was not calibrated for this species. (Water has been subtracted from this spectrum.)

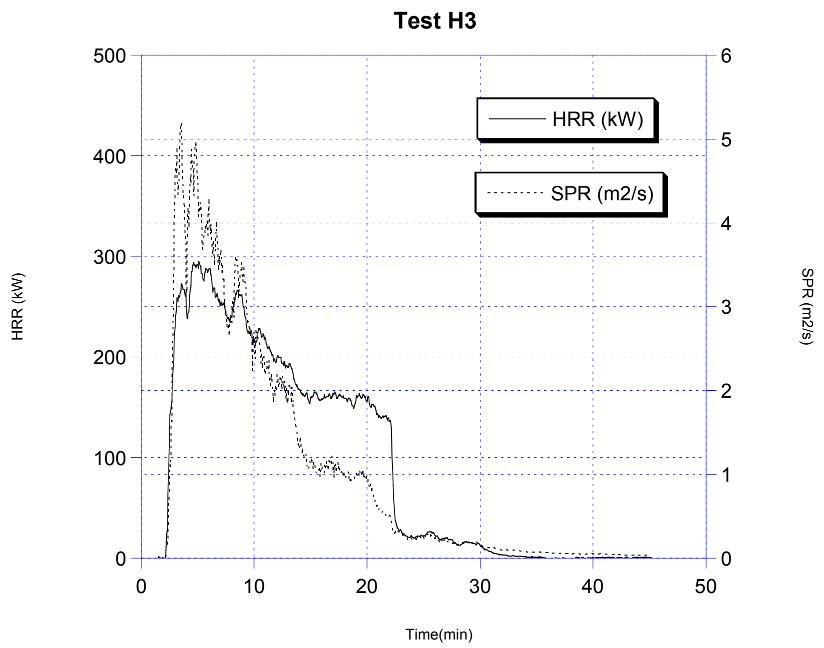
Annex B Detailed test results of horizontal tests

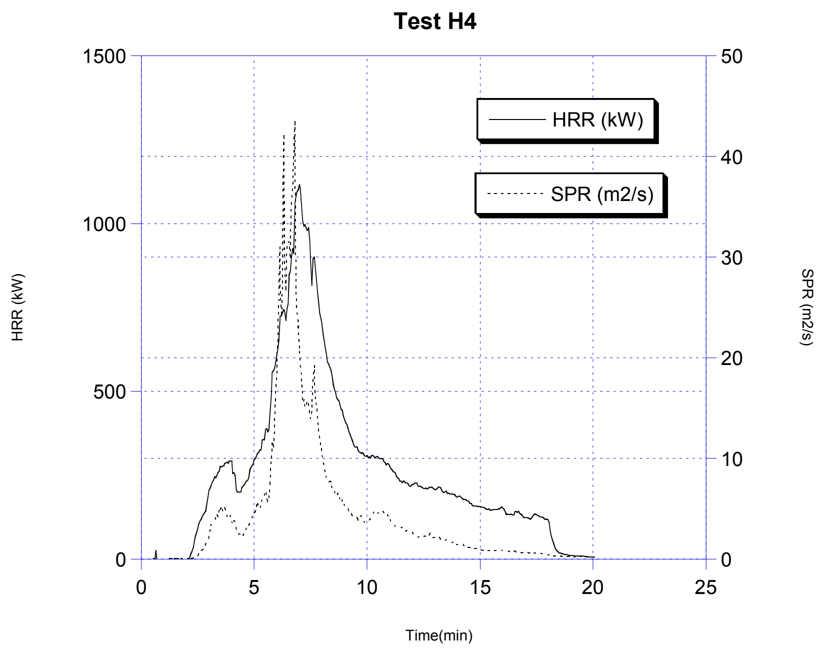
In this annex plots are presented of heat release rate (HRR), smoke production rate (SPR) and toxic gases for each individual horizontal test. The burner heat release rate is included in the graphs.

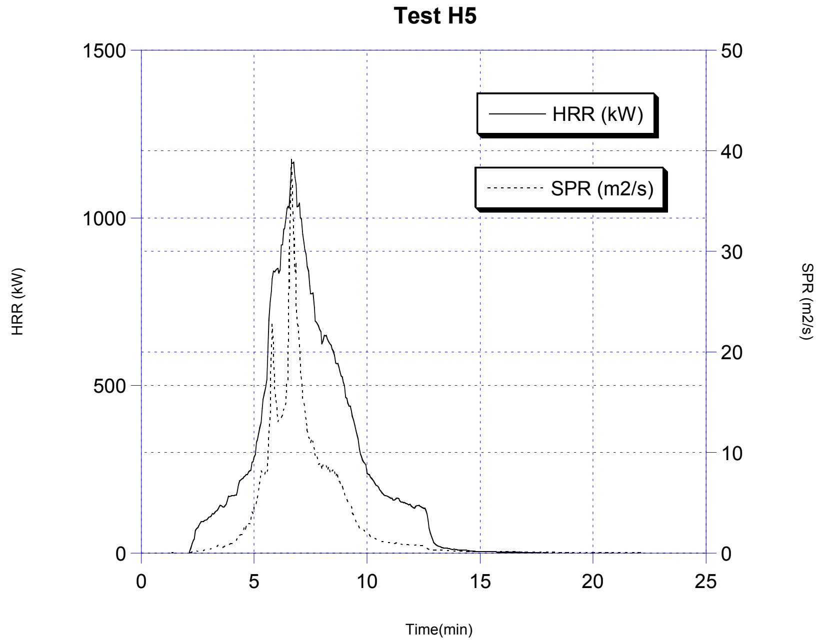
B.1 Heat release rate and smoke production rate

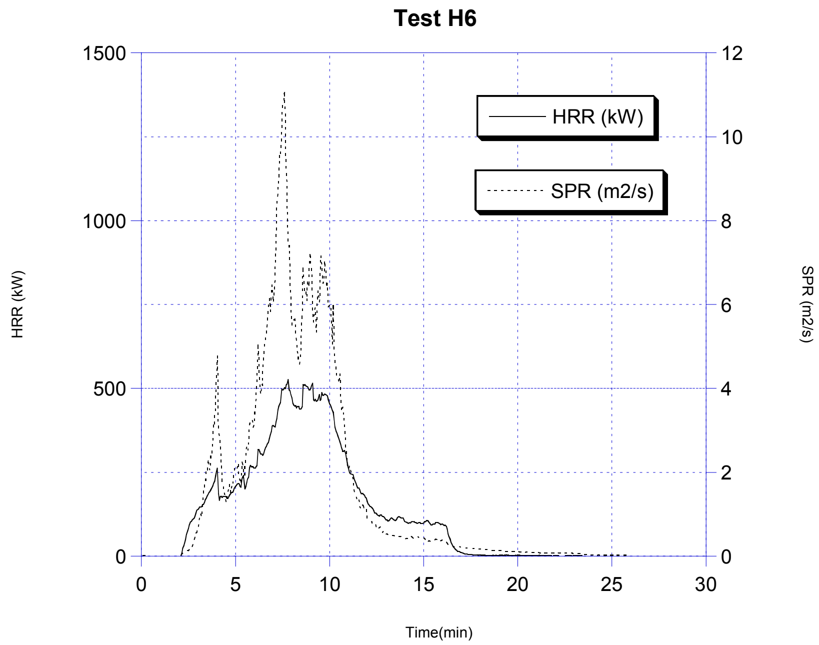




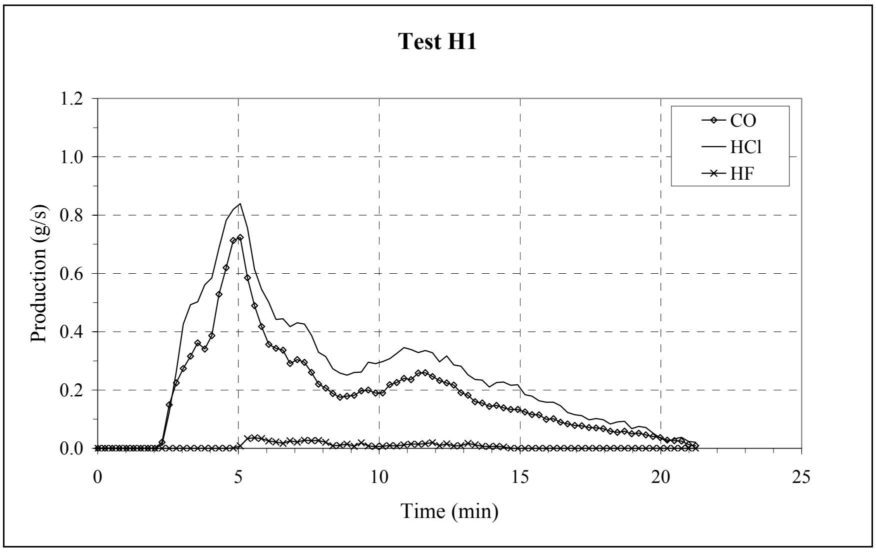

Test H3
HRR (kW)
SPR (m2/s)
Time(min)
500
400
300
200
100
0
0
10
20
30
40
50
6
5
4
3
2
1
0

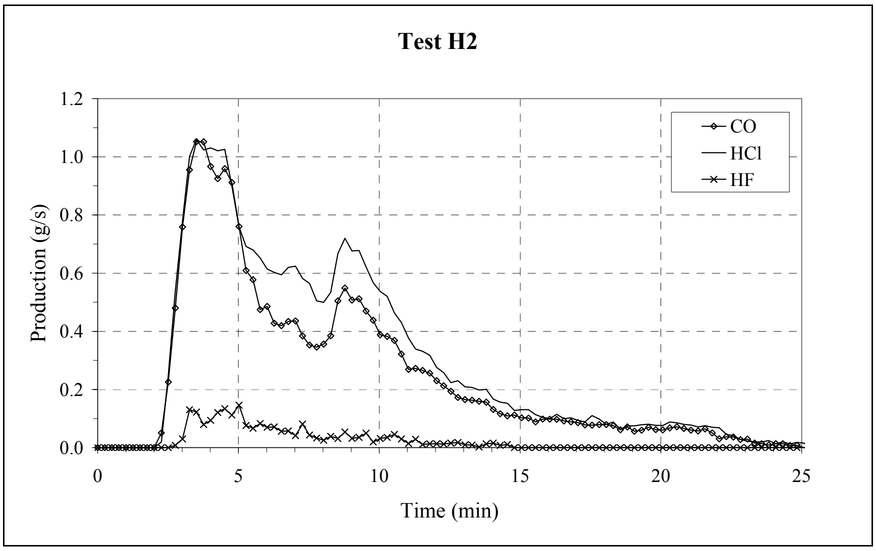

Test H4
HRR (kW)
SPR (m2/s)
Time(min)
1500
1000
500
0
0
5
10
15
20
25
50
40
30
20
10
0

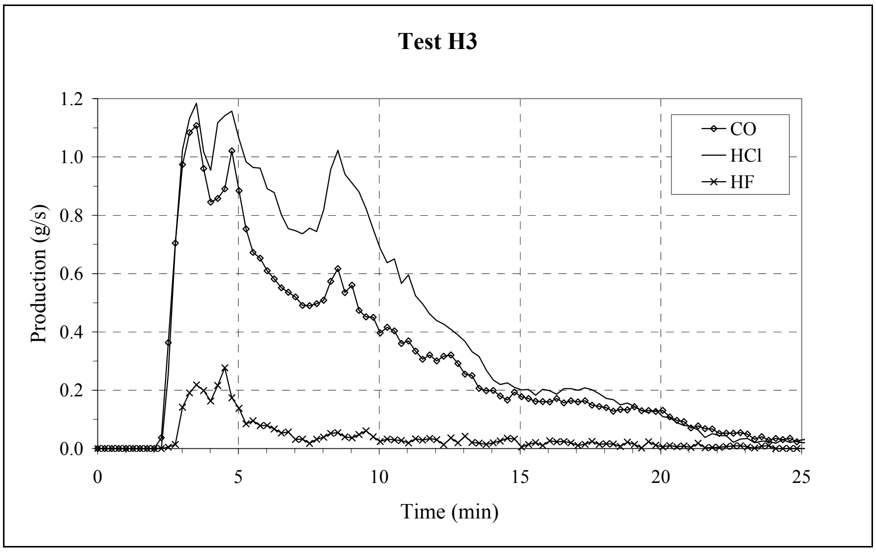

Test H5
HRR (kW)
SPR (m2/s)
HRR (kW)
SPR (m2/s)
1500
1000
500
0
50
40
30
20
10
0
0
5
10
15
20
25
Time(min)

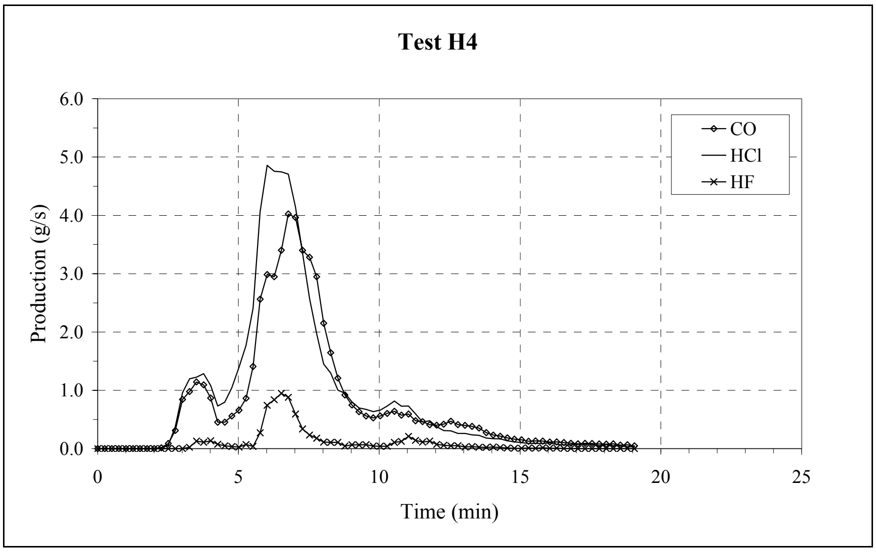

Test H6
HRR (kW)
SPR (m2/s)
HRR (kW)
SPR (m2/s)
1500
1000
500
0
12
10
8
6
4
2
0
0
5
10
15
20
25
30
Time(min)

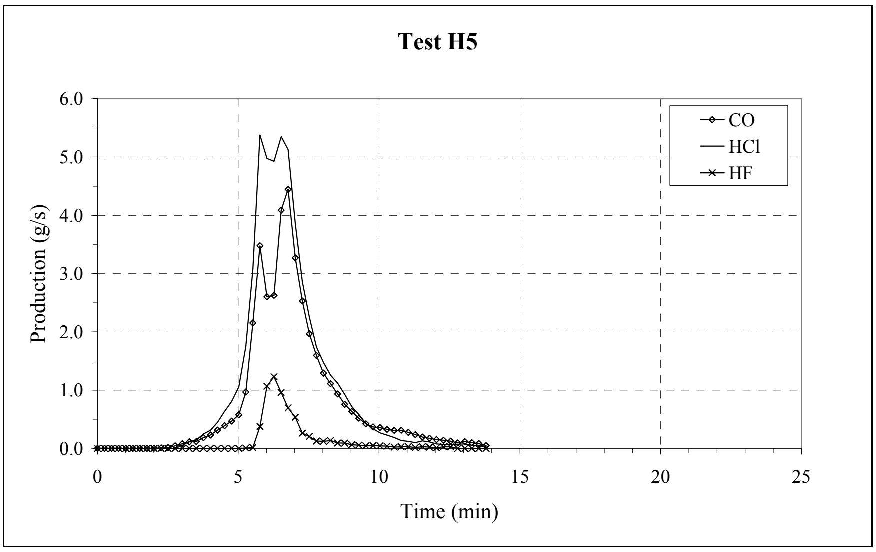
B.2 Toxicity measurements







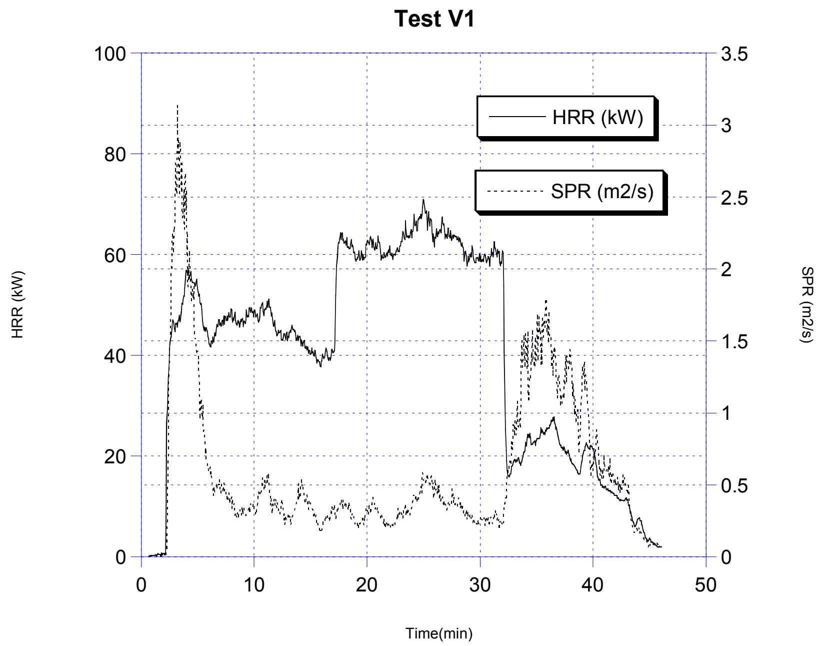

Test H4
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Production (g/s)
0
5
10
15
20
25
Time (min)
CO
HCl
HF

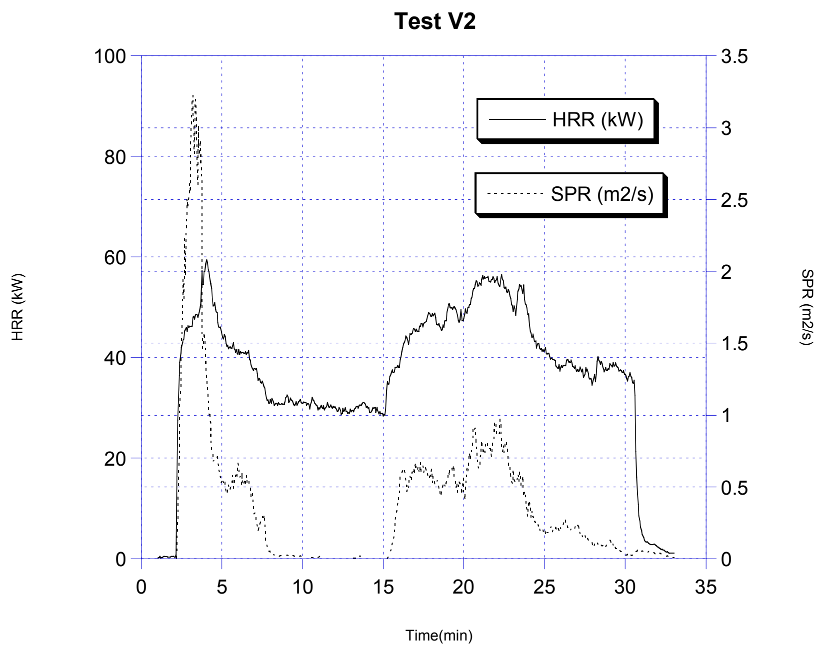

Test H5
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Production (g/s)
0
5
10
15
20
25
Time (min)
CO
HCl
HF

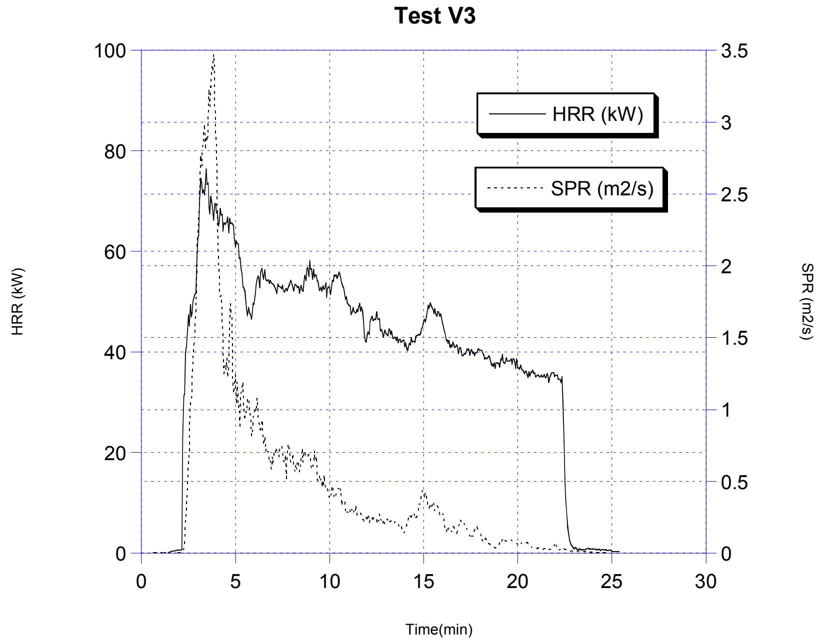
Annex C Detailed test results of vertical tests

In this annex plots are presented of heat release rate (HRR), smoke production rate (SPR) and toxic gases for each individual vertical test. The burner heat release rate is included in the graphs.

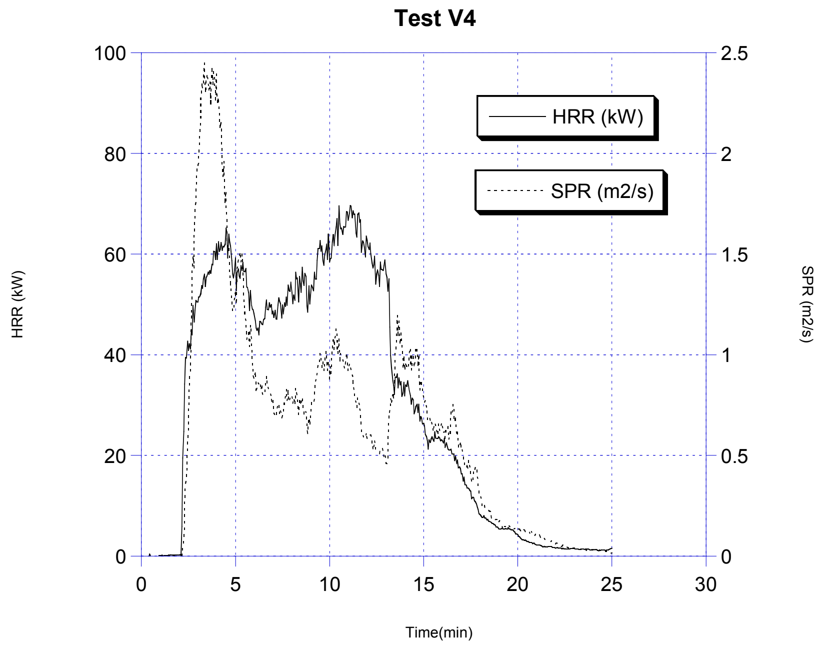
C.1 Heat release rate and smoke production rate



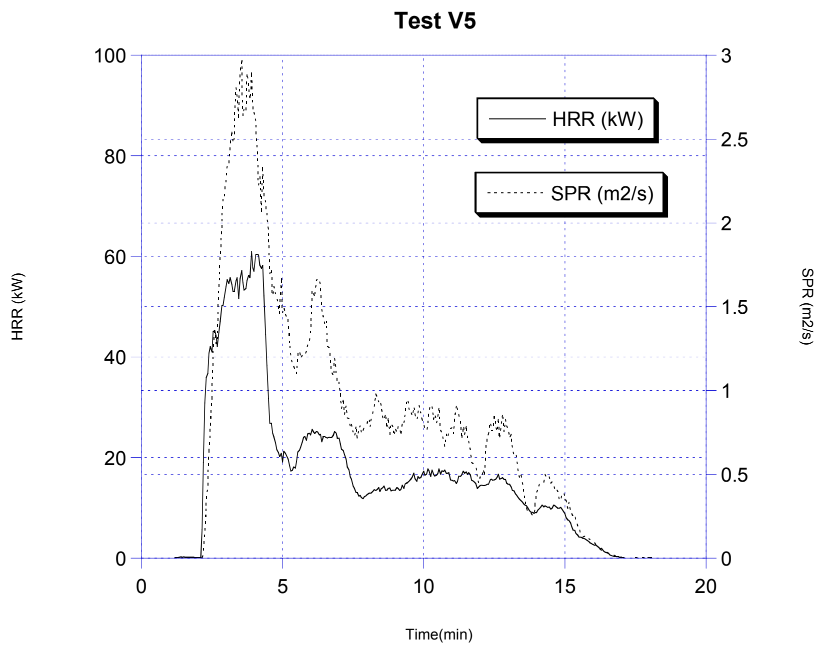


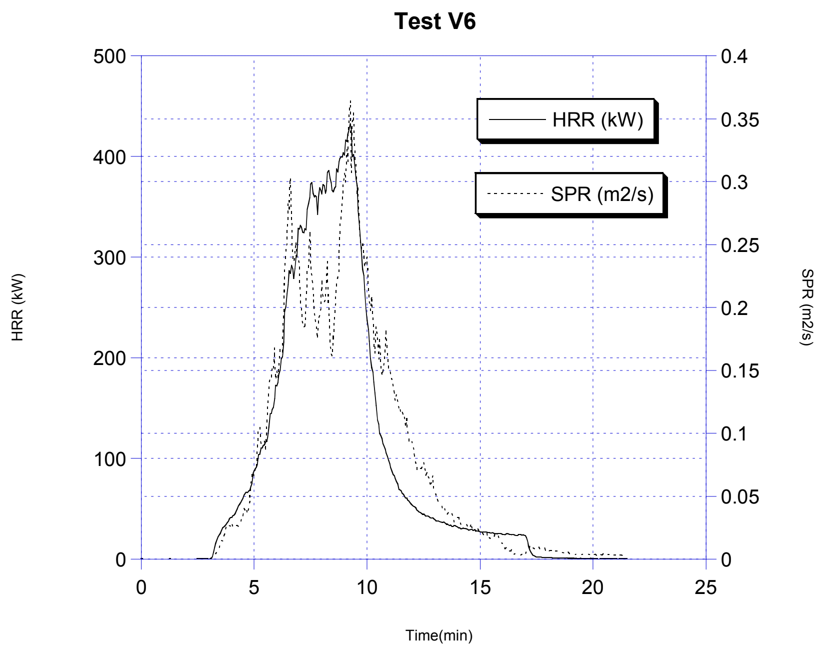


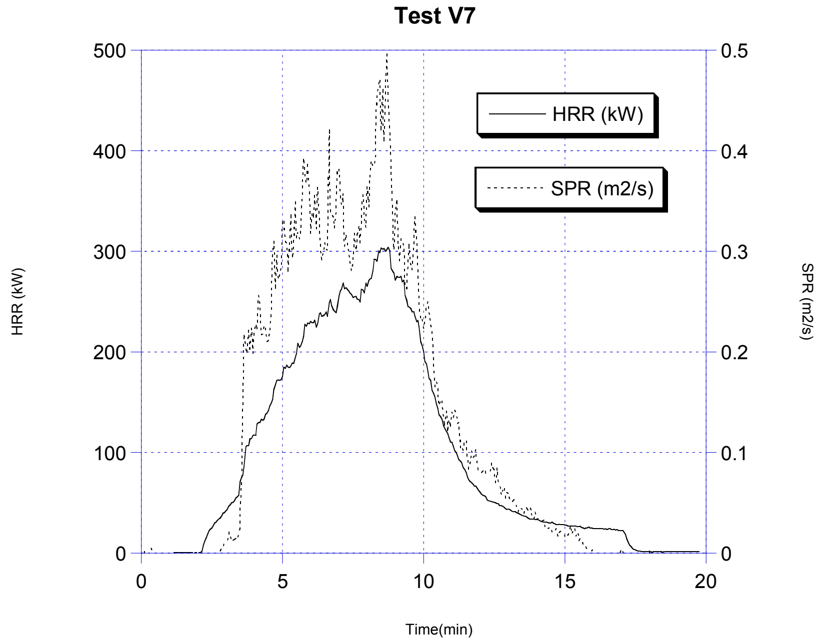
Test V3
HRR (kW)
SPR (m2/s)
Time(min)
100
80
60
40
20
0
3.5
3
2.5
2
1.5
1
0.5
0
5
10
15
20
25
30

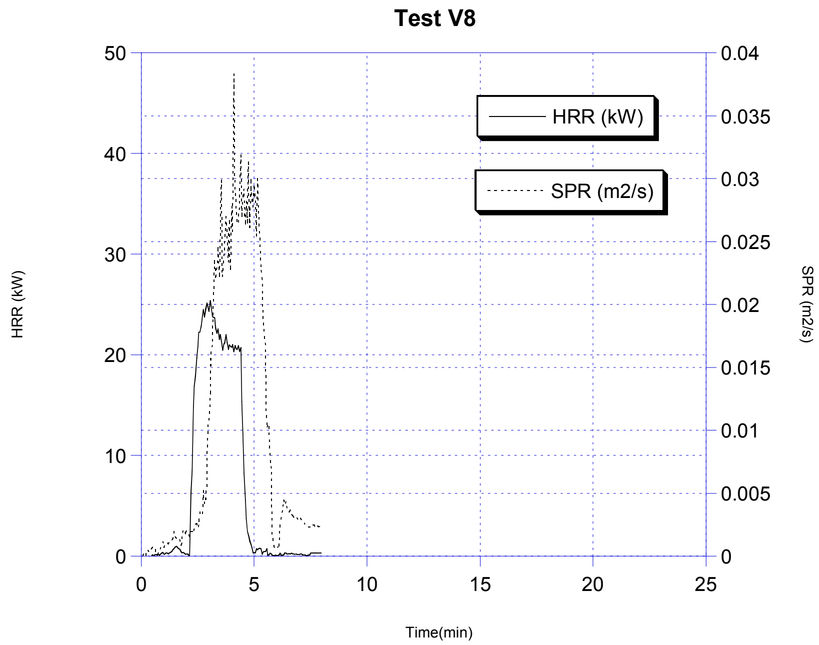


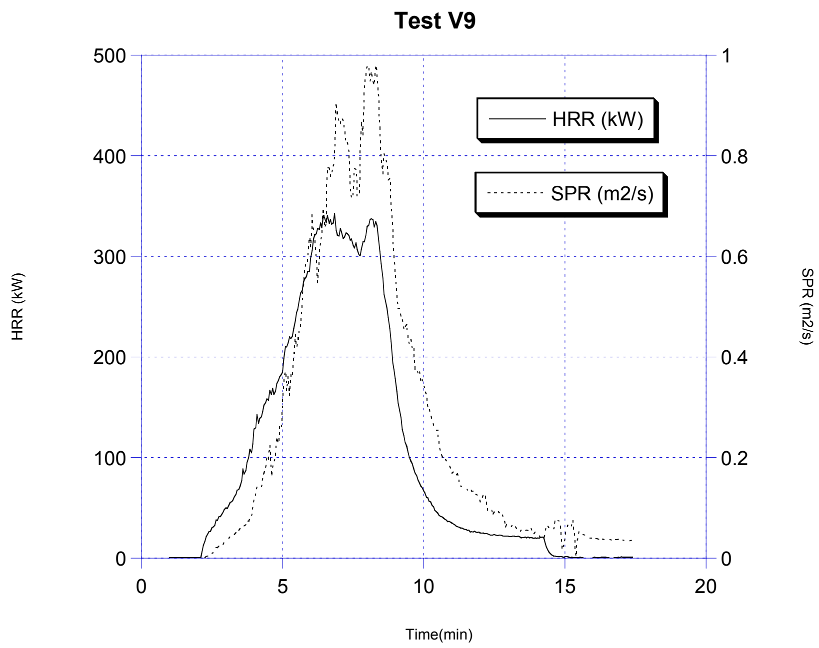
Test V4
HRR (kW)
SPR (m2/s)
Time(min)
100
80
60
40
20
0
2.5
2
1.5
1
0.5
0
5
10
15
20
25
30

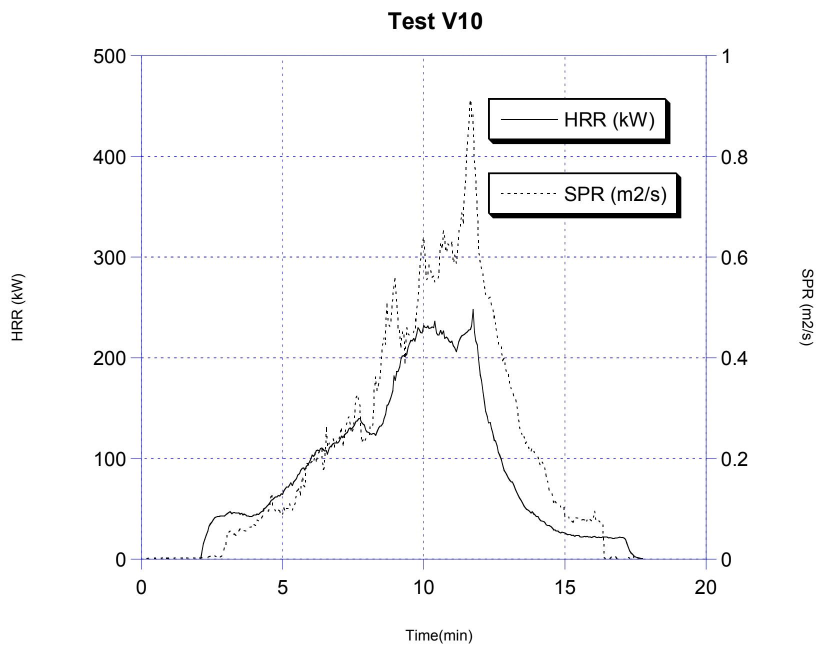

Test V5
HRR (kW)
SPR (m2/s)
HRR (kW)
SPR (m2/s)
Time(min)
100
80
60
40
20
0
3
2.5
2
1.5
1
0.5
0
0
5
10
15
20


Test V6
HRR (kW)
SPR (m2/s)
HRR (kW)
SPR (m2/s)
Time(min)
500
400
300
200
100
0
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20
25

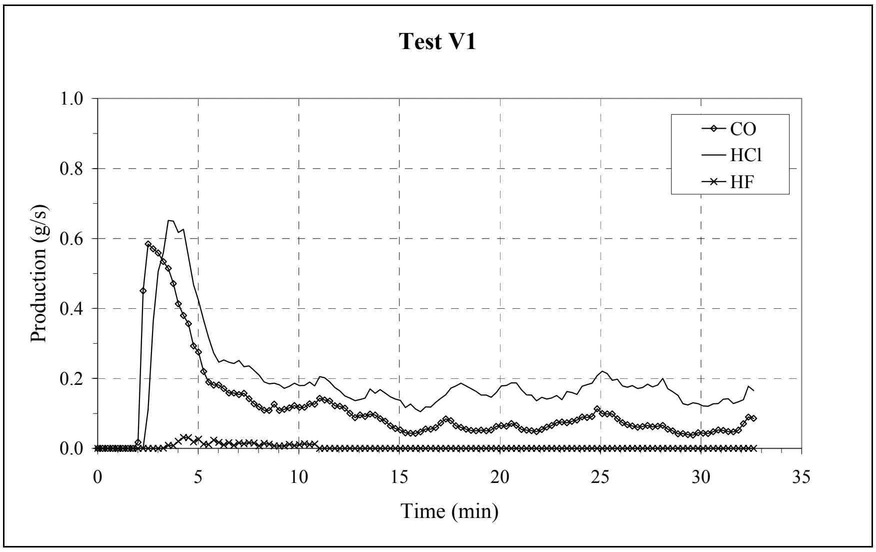

Test V7
HRR (kW)
SPR (m2/s)
500
400
300
200
100
0
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
Time(min)

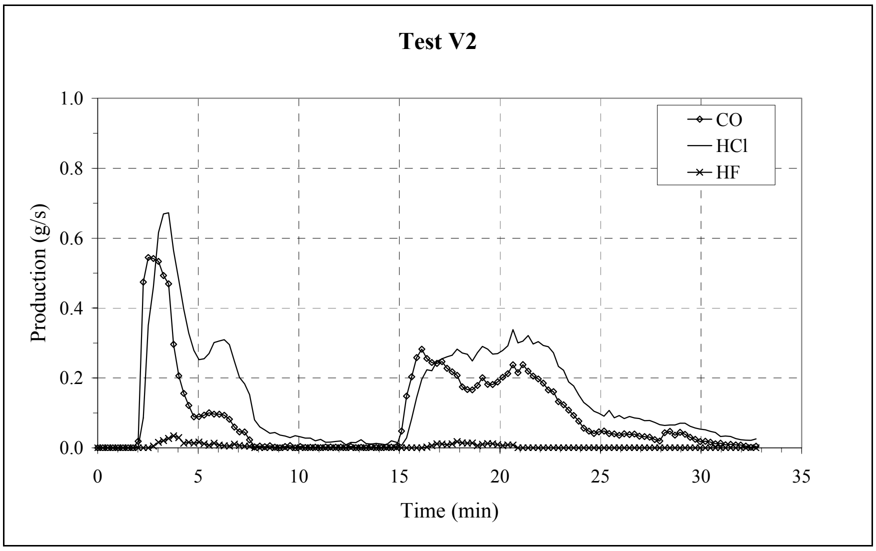

Test V8
HRR (kW)
SPR (m2/s)
50
40
30
20
10
0
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
5
10
15
20
25
Time(min)

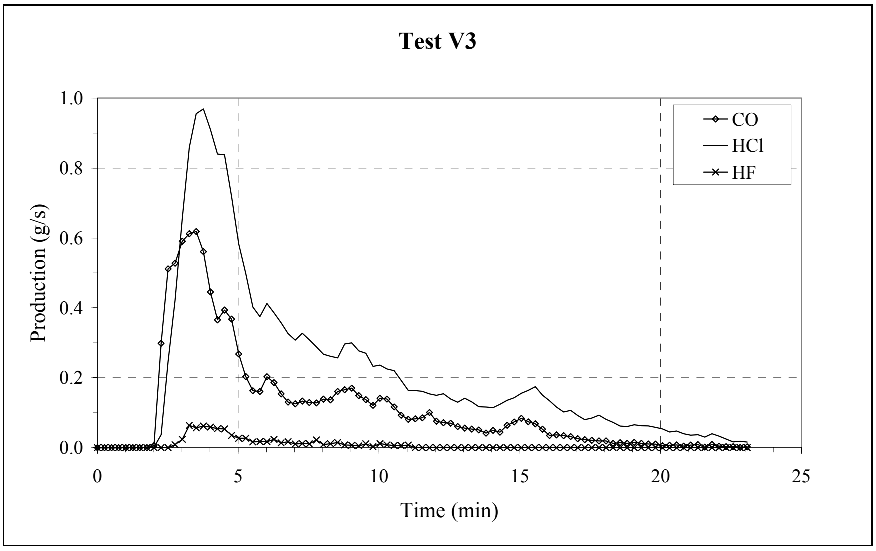

Test V9
500
400
300
200
100
0
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
HRR (kW)
SPR (m2/s)
HRR (kW)
SPR (m2/s)
Time(min)

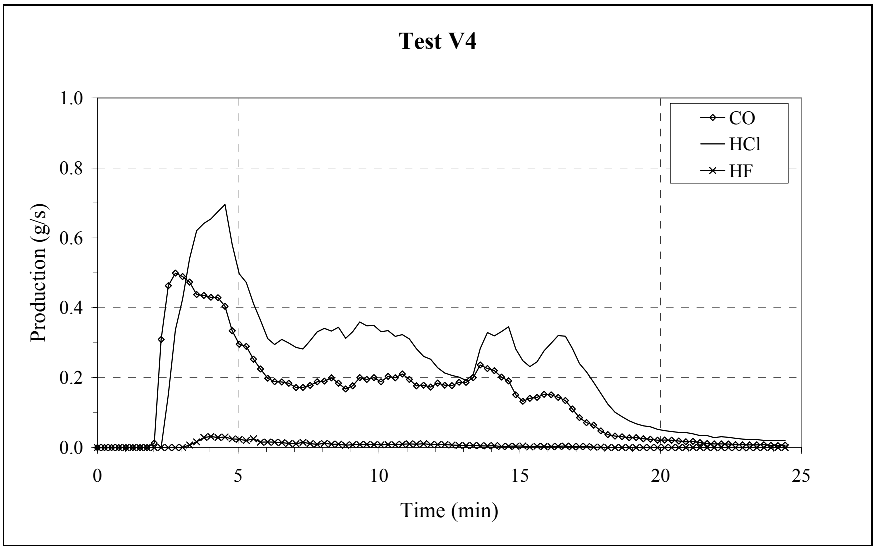

Test V10
500
400
300
200
100
0
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
HRR (kW)
SPR (m2/s)
HRR (kW)
SPR (m2/s)
Time(min)

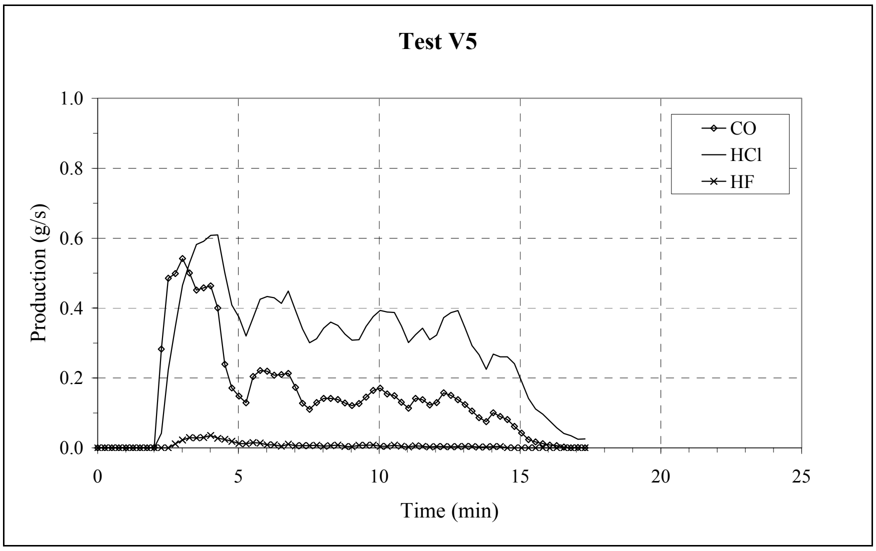
C.2 Toxicity measurements








Test V4
1.0
0.8
0.6
0.4
0.2
0.0
Production (g/s)
0
5
10
15
20
25
Time (min)
CO
HCl
HF


Test V5
1.0
0.8
0.6
0.4
0.2
0.0
Production (g/s)
0
5
10
15
20
25
Time (min)
CO
HCl
HF