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Fire Technology

SP Report 2010:01

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Abstract

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The present project has examined the question of distribution patterns of important chemical compounds between gas phase and particle phase. It has also, in some cases, addressed the question of the distribution of individual particle-associated species between the different size-ranges of particles produced in a fire. The chemical compounds studied were hydrogen chloride (HCl), polycyclic aromatic hydrocarbons (PAHs), and isocyanates.

The steady-state tube furnace, ISO/TS 19700, was chosen as the physical fire model in order to study the production of particles from different types of fire exposure. Three different fire types were investigated: oxidative pyrolysis, well-ventilated flaming fires and vitiated post flashover. Two materials were chosen for investigation, PVC-carpet and wood board, based on their prevalence fire exposure scenarios and their chemical composition. The particle production from the two materials investigated varied both concerning the amounts produced and the particle size distributions. The production of particles on a mass basis was generally significantly lower from the wood board compared with the PVC-carpet. The tests with the PVC-carpet showed that relatively large particles are produced from all combustion conditions examined. The tests made with the wood board show preferably predisposition towards the production of small-sized particles during flaming combustion.

The analysis of PAHs in the tests with the PVC-carpet showed that volatile PAHs were dominate during all types of combustion. However, when the toxicity of the individual species was taken into account, the relative importance between volatile and particle associated PAHs changed. From the tests with the wood board material (OSB) it was noted that the highest yields of total PAHs were found from under ventilated conditions, and the volatile part of the total PAH dominated for this material as well. The yields found from the well-ventilated tests were very low. Toxicity weighted data showed that the particle associated part dominated the toxicity both for under ventilated and well-ventilated conditions.

A study made of the presence of chlorine on particles showed that it is clear that the major part of the HCl produced during combustion of the PVC-carpet is present in the gas phase. Chlorine was found associated with particulates but these results were, however, inconclusive due to the difficulty in determining the source of the chlorine found in the soot fractions studied.

The low polyurethane (PUR) content and the substantial degradation of the PUR in the tests resulted in no or very small amounts of quantifiable isocyanate dimers (i.e. high molecular species). Monoisocyanates such as ICA and MIC dominated in the emitted degradation products. These kinds of monoisocyanates are volatile compounds and almost exclusively present in the gas phase.

Key words: particles, aerosol, size distribution, PAH, HCl, isocyanates

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Sammanfattning (In Swedish)

Detta projekt har undersökt frågan om fördelningen mellan gasfas och partikelfas för några viktiga kemiska föreningar. Projektet har också, i några fall, undersökt fördelningen av enskilda partikelbundna ämnen mellan de olika storleksfördelningar som förekommer i en brand. De kemiska föreningar som studerades var väteklorid (HCl), polycykliska aromatiska kolväten (PAH), och isocyanater.

En småskalig rörugnsmetod, ISO/TS 19700, valdes som den fysiska brandmodellen för att studera produktion av partiklar från olika typer av brandexponering. Tre olika typer brandförhållanden undersöktes: oxidativ pyrolys, välventilerad flammande brand och underventilerad brand efter övertändning. Två material valdes för undersökningen, en PVC-matta och en träfiberskiva (OSB), baserat på deras förekomst som vanliga byggnadsmaterial vilka involveras i bränder och deras kemiska sammansättning.

Partikelproduktionen från de båda materialen undersöktes både med avseende på den producerade mängder partiklar och partikelstorleksfördelningen. Produktionen av partiklar på massbasis var generellt betydligt lägre från träskiva jämfört med PVC-mattan. Försöken med PVC-mattan visade att relativt stora partiklar bildades vid alla förbränningsförhållanden som undersöktes. De försök som gjorts med träskiva visade på en produktion av i huvudsak små partiklar under flammande förbränning.

Analyserna av PAH-ämnen i försöken med PVC-mattan visade att flyktiga PAH-ämnen dominerade på massbasis under alla typer av förbränning. Men när toxiciteten av enskilda PAH-ämnen beaktades, förändrades den relativa betydelsen mellan flyktiga och partikelbundna PAH. Från försöken med träfiberskivan noterades att den högsta produktionen av total-PAH skedde vid underventilerade förhållanden, och den flyktiga delen av den totala PAH sammansättningen dominerade för också detta material. Produktionen från välventilerat tester var mycket låg. Toxicitetsvägda data visade att partikelbundna PAH-ämnen dominerade giftighet för både underventilerade och välventilerade förhållanden.

Undersökningen av förekomsten av klor på partiklar visade tydligt att större delen av den HCl som bildas vid förbränning av en PVC-matta finns i gasfas i brandröken. Klor uppmättes också i vid analys av partiklar, men dessa resultat var svårtolkade på grund av svårigheten att avgöra källan till klor i sotfraktioner som studerades.

Den låga polyuretan (PUR) mängden och den betydande termiska nedbrytningen av PUR vid försöken, gav inga eller mycket små mängder kvantifierbara isocyanatdimerer (dvs. isocyanater med hög molvikt). Monoisocyanater som ICA och MIC dominerade i nedbrytningsprodukterna. Dessa typer av monoisocyanater är flyktiga ämnen och förekommer nästan uteslutande i gasfas.

1 Introduction

Combustion generated particles have an impact on our environment and health and has been studied intensively in recent years. The starting point of this research has been in reports from the early 90s that showed that the health of a population correlates with the amount of particles in the air [1]. Despite this and despite the obvious health risks resulting from the very large amounts of particulate generated during fires, little has been done to investigate the composition of fire-generated particles closer.

In a previous project [2], a first attempt was made to investigate particle generation in fires. That project examined the mass and number distribution of particles from fires in various typical building materials and other materials found in buildings. It showed that although the amount of particles produced varied widely depending on the material that burned, the particle-size distributions were quite similar. It also showed that the amount of particles in the smoke that was submicron was very high. Most particles were ultrafine, i.e. they had a diameter less than 100 nanometres. It is known that submicron particles are easily transported into the deeper parts of the lungs by inhalation and various studies show that the ultra-fine are the potentially most dangerous [3-4]. There are also studies showing that a blend of ultrafine particles and gas together, can give rise to increased toxicities [5].

Whether a chemical substance is found in the vapour phase or in the condensed phase associated with particles, may be important in different ways. First, a toxic molecule behaves chemically differently depending on whether the molecule is bound to a particle or not, but above all gives the particle-association other forms of transport than a gas phase. Species in the gas phase have a high diffusion rate and reactive molecules are rapidly absorbed in the respiratory tract mucosa, which thereby protects the deeper parts of the respiratory tract. However, a particle-bound molecular substance can be transported much longer before contact with the respiratory tract occurs.

Small particles have a higher proportion of surface area per mass than larger particles, and because smoke generally contains a high proportion of ultrafine particles, is the ultrafine fraction a major part of the total area that is available for absorption. It is therefore plausible that substances may be enriched by absorption on the smaller particles. Should this be the case, it is important information since these particles are easily transported far into the lungs.

An earlier project involved the reconstruction of the fire at St. Sigfrid's Hospital in Växjö in 2003, where two patients died and several were injured [6-7]. An important conclusion from that project was that most of the heavy smoke that was produced in the fire was caused by a PVC carpet. This was also confirmed by soot samples taken at the scene of the fire that contained high amounts of chlorine (~ 10 weight-%). The amount of hydrogen chloride in the gas phase respective particle phase in the actual fire is not known, but a hydrogen chloride concentration of ~ 10 000 ppm was measure during flashover in a reconstruction test. The actual distribution of HCl is obviously dependent on various factors including ageing of the smoke gas, involving condensation of water which can dissolve the HCl.

Another group of toxic substances that is largely associated with the particulate phase in fire effluents is polycyclic aromatic hydrocarbons, PAHs. The toxicity of PAH substances is due to that a that number of PAHs are highly carcinogenic. It has previously been shown that the often incomplete combustion in a fire produces significantly more PAHs compared to other combustion sources [8]. The PAH-production from fires has typically been measured as the sum of PAH substances in the vapour phase and the particle phase. However, there is a need for knowledge about the proportion of PAHs that are associated to the particulate phase and if there is an enrichment of specific PAHs for smaller particle sizes.

There are two main reasons for this knowledge to be important. PAHs associated with respirable particles can be transported into the lungs where there are opportunities for effective absorption into the body. It is important to examine this association patterns to gain insight on which PAH substances that the lungs are exposed to in a fire and in which part of the respiratory system. The second reason is that the exposure is also possible by absorption through the skin (dermal) and mouth (oral). The issue of exposure to PAH-substances is perhaps most important for people who frequently come into contact with fire, such as e.g. fire fighters.

The present project aimed at examining the questions regarding the distribution patterns of important chemical compounds between gas phase and particle phase. It further, in some cases, addressed the question about the distribution of individual particle-associated species between the different size-ranges of particles produced in a fire.

The chemical compounds studied were hydrogen chloride (HCl), a gas that readily dissolves in water and is known to adhere to surfaces [9-10], polycyclic aromatic hydrocarbons (PAHs), and isocyanates. Isocyanates are a group of toxic species (irritants) that have a high acute toxicity in very low concentrations.

2 Experimental Methodology

The experimental work was conducted in bench-scale. The ISO/TS 19700 steady-state tube furnace was selected as a suitable fire model. This fire model was selected as it can vary the combustion conditions in a controlled manner and creates steady-state conditions for a prolonged time period allowing sampling for chemical analysis.

The experimental work was conducted in two test series. The first series of tests was conducted at SP Technical Research Institute in Borås, Sweden, and the second series of tests was conducted at the University of Central Lancashire (UCLAN) in Preston, UK.

2.1 Materials investigated

Two different types of materials were selected for tests, a PVC-carpet and a wood based building board. These are both commercial products that are commonly found in domestic buildings. The reason for selecting the PVC-carpet was that earlier investigations had shown that this type of product can produce heavy smoke in fires together with a high yield of HCl [6-7]. The wood board was of OSB-type (OSB = Oriented Strand Board), which is a particle board with relatively large wood particles.

Both products contained polyurethane components, the carpet as a lacquer while the wood board contained polyurethane in the binder. Polyurethane can produce isocyanates during fires [11]. One of the aims of the tests was to investigate the production of isocyanates during fires and their distribution between gaseous and condensed (particulate) phase.

2.1.1 Data on materials

The PVC-carpet had a thickness of 2.0 mm and data on the composition of the product as given by the producer is shown in Table 1. The wood board was purchased from a building supplier as one single board with the dimensions of 2440 mm × 1197 mm × 11mm. No detailed data was available from the supplier concerning the composition of the wood board.

Both products were further characterized and analysed regarding chemical composition prior to the tests, see Table 2 in section 2.1.2.

Table 1 Composition of the PVC-carpet as given by the manufacturer.

Component	Weight-%	Surface weight (g/m^2)
Polyvinyl chloride (PVC)	53	1490
Diisononylftalat (DINP)	18	510
Mineral fillers	24	670
Titanium dioxide	2	60
Other components	3	80

2.1.2 Analysis of materials

The tested materials were characterized regarding elemental content and combustible content. Elemental analysis is often referred to as CHNX analysis and determines the percentage weights of carbon, hydrogen, nitrogen, and heteroatoms (X) like chlorine, bromine or fluoride, in the sample. This information is important to help determine the combustion characteristics of an unknown material which is tested under different fire conditions. It also helps to predict possible products formed under different temperatures and their interactions. CHN analysis was made using a *Carlo Erba EA1108* elemental analyser. Halide analysis (chlorine, bromine, iodine) for the PVC carpet was conducted using a *Metrohm* potentiometric autotitrator [12].

Information on the combustible content of the materials was needed for determination of the material loading for the tube furnace experiments (see section 2.2.1). Determination of total combustible content was made gravimetrically with multiple samples by the combustion of gram-sized samples in a combustion furnace.

Table 2 Characteristics of the products.

Element/characteristics	**PVC-carpet**	**Wood board**
Carbon, C	38.6 weight-%	47.7 weight-%
Hydrogen, H	4.96 weight-%	6.51 weight-%
Nitrogen, N	Not detected	2.96 weight-%
Chlorine, Cl	29.1 weight-%	Not detected
Combustible part	76.2 weight-%	99.7 weight-%
Density	1360 kg/m^3	580 kg/m^3

2.2 Fire experiments

2.2.1 Steady-state tube furnace

The steady-state tube furnace is a bench-scale test apparatus designed for controlled steady-state combustion of a sample and analysis of the combustion products. The method is described in ISO/TS 19700 [13]. The principle of the test method is that a known amount of fuel is continuously fed into the furnace together with a specified flow of air. These parameters, together with the furnace temperature, allow the replication of specified fire conditions. The combustion products from the furnace are diluted in a mixing chamber where sampling for analysis is made. A schematic picture of the apparatus is shown in Figure 1.

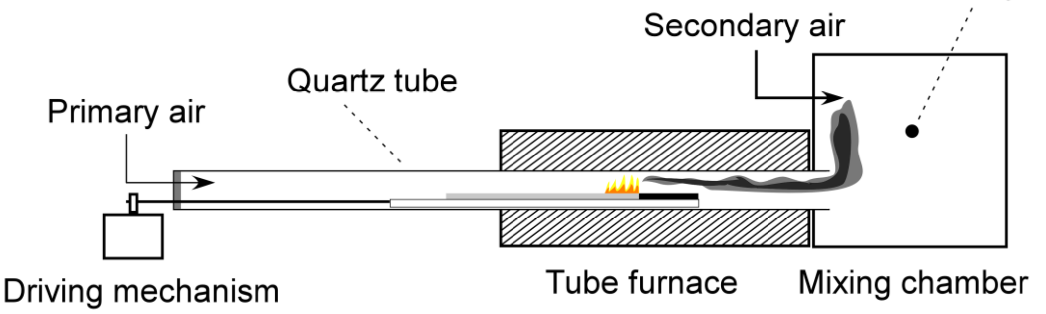


Figure 1 Schematic picture of the steady-state tube furnace, ISO/TS 19700.

2.2.1.1 Data on the SP tube furnace

The tube furnace is 800 mm long with a diameter of 50 mm. The quartz tube is 1700 mm long with an outer diameter of 47.5 ± 1 mm and a wall thickness of 2 ± 0.5 mm. A quartz sample boat with a length of 800 mm was used. The mixing chamber is made of steel and PMMA, with the parts that are in contact with the quartz tube constructed in steel. The dimensions of the chamber are 315 mm (depth) × 315 mm (width) × 345 mm (height), with a total volume of 34 litres. A driving mechanism with an advance rate of nominally 40 mm/min, but capable of more than 60 mm/min, was used for introducing the sample into the furnace. Primary air was introduced with flow rates between 2 l min^{-1} and 10 l min^{-1}. The flow of secondary air for dilution and cooling of the smoke gases introduced into the mixing chamber was in the range of 32-39 l min^{-1}. The total flow through the mixing chamber resulted in a residence time of about 50 seconds.

2.2.1.2 Data on UCLAN tube furnace

The tube furnace is 740 mm long with a diameter of 55 mm. The quartz tube is 2000 mm long with an outer diameter of 45.0 ± 1 mm and a wall thickness of 2 ± 0.5 mm. A quartz sample boat with a length of 800 mm was used. The mixing chamber is made of steel. A driving mechanism with an advance rate of nominally 36 or 42 mm/min, but capable of more than 90 mm/min, was used for introducing the sample into the furnace. Primary air was introduced with flow rates between 2 l min^{-1} and 10 l min^{-1}. The flow of secondary air for dilution and cooling of the smoke gases introduced into the mixing chamber was in the range of 32-39 l min^{-1}.

2.2.1.3 Combustion conditions

The combustion in a fire is controlled by the amount of available fuel, oxygen, and the combustion temperature. If an excess of oxygen is available, the combustion is efficient. This type of combustion is named well-ventilated. If there is a lack of oxygen, the combustion is less efficient, and the conditions are under-ventilated or vitiated. If there is just enough oxygen present for complete combustion of the fuel, the combustion conditions are defined as stoichiometric.

The equivalence ratio, ϕ, is used to describe the ventilation conditions during combustion and is defined as:

$$\phi = \frac{\dot{m}_{fuel} / \dot{m}_{oxygen}}{\left(\dot{m}_{fuel} / \dot{m}_{oxygen}\right)_{stoich.}}$$

$\phi = 1$ stoichiometric combustion
$\phi < 1$ well-ventilated combustion
$\phi > 1$ under-ventilated combustion

where $\dot{m}_{fuel}$ is the mass flow of fuel, $\dot{m}_{oxygen}$ is the mass flow rate of oxygen, and the subscript "*stoich.*" refers to the quotient under stoichiometric conditions. The equivalence ratio is thus the quotient of the actual fuel-to-oxygen ratio and the stoichiometric fuel-to-oxygen ratio.

The method for managing the ventilation conditions in a tube-furnace test is to determine the stoichiometric fuel-to-oxygen ratio for the tested material and to select an actual fuel-to-oxygen ratio for achieving the desired equivalence ratio. Guidance on how to select the primary air flow rate and the fuel flow rate was taken from ISO/TS 19700 [13].

The fire stages [14] investigated in this work included:

- **Fire type 1b** – oxidative pyrolysis
- **Fire type 2** – well-ventilated flaming fires ($\phi < 0.75$)
- **Fire type 3b** – vitiated post flashover fires in large or open compartments ($\phi = 2$)

Analysis of oxygen (O_2) is required to allow determination of the actual combustion conditions in a test. Additionally, the analysis of carbon dioxide (CO_2) is required for the determination of the occurrence of a steady-state period. These analyses are detailed in section 2.3.1.

The procedure in ISO/TS 19700 for replicating **Fire type 1b** is to set the furnace at 350°C, use a loading of 25 mg/mm combustible material in the sample boat and a primary air flow rate of 2 l min^{-1}. **Fire type 2** is replicated by setting the furnace at 650°C, use a loading of 25 mg/mm and a primary air flow rate of 10 l min^{-1}. By using a sample feed rate of 40 mm/min this results in a fuel-to-air ratio of 100 mg material/l air which for most material will give a well-ventilated combustion with $\phi < 0.75$. **Fire type 3b** requires a furnace temperature 825°C and the correct primary air flow rate for achieving a ϕ of 2.0 is calculated from the oxygen depletion in the mixing chamber in the well-ventilated test.

The time for the combustion products to react in the hot furnace zone is dependent on the primary air flow-rate through the quartz tube. In the SP tube furnace, e.g., assuming that the flame front is established in the centre of the furnace gives a residence time in the tube of 23 seconds in under-ventilated tests and 5 seconds in well-ventilated tests.

2.2.2 Test Series 1

The first series of tests was conducted at SP. The individual tests are listed in Table 3 including information on combustion conditions and type of analyses of the smoke gases in each test (see explanatory text below the table).

Tests 1-7 were preparatory tests to determine the right settings for the tube furnace and for preliminary analysis of isocyanate content in the smoke gases. Tests 17-21 were reference tests conducted as validation of the method. Of the 21 tests conducted in the main tests series with the PVC-carpet and the Wood board (OSB), two tests failed, which resulted in 19 acceptable tube furnace tests. The analysis of smoke gases always included O_2, CO and CO_2. In the majority of tests the FTIR was also included. Sampling with an impactor, sampling for PAH, isocyanates and total soot, was conducted in the number of tests required to achieve at least duplicate results for each fire stage. Note that particle distribution analysis with a multi stage impactor was the focus in the second test series.

Table 3 List of tests conducted in Test series 1.

Test id	Material	Fire stage	Analyses
Test 1*	PVC	2	O_2, FTIR, Isocya_1
Test 2*	OSB	2	O_2, FTIR, Isocya_1
Test 3*	OSB	3b	O_2, FTIR, Isocya_1
Test 4*	PVC	3b	O_2, FTIR, Isocya_1
Test 5*	OSB	3b	O_2, FTIR, Isocya_1
Test 6*	PVC	2	O_2, NDIR
Test 7*	OSB	3b	O_2, NDIR
Test 8	PVC	3b	O_2, NDIR, FTIR
Test 9	OSB	2	O_2, NDIR, FTIR, Isocya_1, PAH, Tot-soot
Test 10	OSB	3b	O_2, NDIR, FTIR, Isocya_2, PAH, Tot-soot
Test 11	OSB	2	O_2, NDIR, FTIR, Impactor, Tot-soot
Test 12**	PVC	2	O_2, NDIR, FTIR, PAH, Impactor
Test 13	OSB	2	O_2, NDIR, FTIR, PAH, Impactor, Tot-soot
Test 14	OSB	2	O_2, NDIR, FTIR, PAH, Impactor, Tot-soot

Test 15	OSB	3b	O_2, NDIR, FTIR, PAH, Impactor, Tot-soot
Test 16	OSB	3b	O_2, NDIR, FTIR, PAH, Impactor, Tot-soot
Test 17-21***	PMMA	2, 3b	O_2, NDIR, FTIR
Test 22	OSB	1	O_2, NDIR, FTIR, Isocya_3, PAH, Tot-soot
Test 23	PVC	2	O_2, NDIR, FTIR, Isocya_1, PAH, Tot-soot
Test 24	PVC	3b	O_2, NDIR, FTIR, Isocya_1, PAH, Tot-soot
Test 25	OSB	2	O_2, NDIR, FTIR, Isocya_1, PAH, Impactor
Test 26**	PVC	1	O_2, NDIR, FTIR, Isocya_2, PAH, Tot-soot
Test 27	PVC	3b	O_2, NDIR, FTIR, Isocya_2, PAH, Tot-soot
Test 28	OSB	1	O_2, NDIR, FTIR, Isocya_2, PAH, Impactor
Test 29	PVC	1	O_2, NDIR, FTIR, Isocya_1, PAH, Tot-soot
Test 30	OSB	3b	O_2, NDIR, FTIR, Isocya_3, PAH, Impactor
Test 31	PVC	1	O_2, NDIR, FTIR, Isocya_2, PAH, Tot-soot
Test 32	PVC	2	O_2, NDIR, FTIR, Isocya_1, PAH, Tot-soot
Test 33	PVC	3b	O_2, NDIR, PAH

* Pre-tests. ** Test incomplete or failed. *** Reference tests for validation of test method.

Materials

PVC = PVC-carpet

OSB = wood board of OSB-type

Fire stages

Stage 1b: oxidative pyrolysis from externally applied radiation (350ºC furnace temp).

Stage 2: well-ventilated flaming (650ºC furnace temp).

Stage 3b: post-flashover fires, underventilated (825ºC furnace temp).

Analyses

O_2:	On-line analysis of oxygen.
NDIR:	On-line analysis of carbon monoxide (CO) and carbon dioxide (CO_2) using NDIR analyser.
FTIR:	On-line analysis of selected gases (e.g. CO_2, CO, HCl, HCN, NO, NO_2).
Tot-soot:	Soot/particles sampled on filter. Soot samples from PVC tests analysed for chlorine.
Isocya_1:	Gas phase and particle associated isocyanates analysed using denuder method.
Isocya_2:	Gas phase and particle associated isocyanates analysed using impinger method.
Isocya_3:	Particle associated isocyanates (size distribution) analysed using specially designed impactor method.
PAH:	Gas phase and particle associated PAHs analysed using filter/adsorbent method.
Impactor	Cascade impactor for analysis of size distribution of soot. Soot samples from cascade impactor analysed for PAHs.

Details concerning the sampling and analysis are given in section 2.4 – section 2.3.

2.2.3 Test Series 2

The second series of tube furnace tests were conducted at UCLAN. These tests focused on characterisation of the particle distribution using a multi stage impactor with a broader range of stages compared to the impactor used in Test Series 1. Further, the particles sampled on each stage were analysed to determine their elemental composition. The distribution of chlorine between the different size distribution ranges was in focus. The tests conducted in Test Series 2 are summarized in Table 2.

Table 4 List of tests conducted in Test Series 2.

Test id	Material	Fire stage	Analyses
PVC Carpet 1	PVC	1b	Cascade Impactor, XRF, total-soot
PVC Carpet 2	PVC	1b	Cascade Impactor
PVC Carpet 3	PVC	1b	Cascade Impactor
PVC Carpet 4	PVC	2	Cascade Impactor, XRF, total-soot
PVC Carpet 5	PVC	2	Cascade Impactor, XRF, total-soot
PVC Carpet 6	PVC	2	Cascade Impactor
PVC Carpet 7	PVC	3b	Cascade Impactor, XRF, total-soot
PVC Carpet 8	PVC	3b	Cascade Impactor, XRF, total-soot
PVC Carpet 9	PVC	3b	Cascade Impactor
OSB 1	OSB	2	Cascade Impactor
OSB 2	OSB	2	Cascade Impactor
OSB 3	OSB	2	Cascade Impactor
OSB 4	OSB	3b	Cascade Impactor
OSB 5	OSB	3b	Cascade Impactor
OSB 6	OSB	3b	Cascade Impactor
OSB 7	OSB	1b	Cascade Impactor
OSB 8	OSB	1b	Cascade Impactor
OSB 9	OSB	1b	Cascade Impactor

2.3 Gas analysis

The gas analysis normally included analysis of O_2, CO and CO_2. A more extensive analysis of additional inorganic gases using FTIR was made in Test series 1.

2.3.1 Analysers

The analysis of smoke gases in Test Series 1 always included O_2, CO and $CO_{2.}$ In Test Series 2, O_2, CO/CO_2 were analysed in the initial test for each combustion condition but not in the following tests where identical tube furnace apparatus settings were used. The detailed description below refers to the instrumentation used in Test Series 1.

2.3.1.1 Sampling

Smoke gases were sampled from the mixing chamber using unheated sampling lines where the gases were filtered (*M&C SP2K*, ceramic filter, 2µm) and dried (*Drierite®, W.A. Hammond*) before reaching the analysis instruments. The total sampling flow for the analysers was 1.0 L min^{-1}.

2.3.1.2 Instruments and calibration

The oxygen (O_2) concentration in the mixing chamber was continuously measured by an *M&C PMA10* O_2-analyser. The instrument was calibrated against the oxygen concentration in ambient air (20.95 %). Carbon dioxide (CO_2) and carbon monoxide (CO) were measured with a *BINOS 100 NDIR* combination instrument. This instrument was calibrated with a certified gas mixture of 6.0 % CO_2 and 1.0 % CO in nitrogen (*Air Liquide*). Zero-levels were calibrated against nitrogen gas (*Air Liquide*) for both instruments.

2.3.2 FTIR

2.3.2.1 Sampling

Smoke gases were continuously drawn from the mixing chamber to the gas-cell of the FTIR with a sampling rate of 4 L min^{-1} using a probe with a cylindrical ceramic filter (*M&C SP2K,* ceramic filter, 2µm). Both the filter and the gas sampling line (4 mm i.d. PTFE) were heated to 180°C.

2.3.2.2 FTIR instrument and calibration

Time resolved measurements of the concentration of selected inorganic gases were obtained using a *BOMEM MB 100* FTIR spectrometer. The spectrometer was equipped with a heated gas cell (volume = 0.92 L, path-length = 4.8 m, temperature = 150°C) and a DTGS detector. A spectral resolution of 4 cm^{-1} was used, with 4 averaged spectra (based on 3 full scans) recorded per minute. The proper function of the FTIR equipment was verified by measurement on a control gas.

The FTIR data (spectra) was quantitatively evaluated for a selected number of gas species. These gases included: carbon dioxide (CO_2), carbon monoxide (CO), hydrogen chloride (HCl), hydrogen cyanide (HCN), nitrogen monoxide (NO), nitrogen dioxide (NO_2) and ammonia (NH_3).

2.4 Characterisation of particles

2.4.1 Impactor sampling

The equipment most often used to study particle size distribution is a multistage cascade impactor. In a cascade impactor, particles are separated according to their “aerodynamic size”. The term aerodynamic size is used in order to provide a method for categorizing the sizes of particles having different shapes and densities with a single dimension. The aerodynamic diameter of an arbitrary particle is equal to the diameter of a spherical particle having a density of 1 gm/cm^3 that has the same inertial properties in the gas as the particle of interest.

In a cascade impactor the sampled aerosol stream is directed against a flat plate through an input nozzle. An advanced cascade impactor consists of several such impaction plates with nozzles of gradually decreasing diameters. At each stage, the output stream is forced to make a 90-degree bend, which is the basic mechanism for separation of particles in size-classes according to their aerodynamic diameter. In the output stream, particles with inertia higher than a certain limiting value cannot follow the 90-degree bend of the gas stream, and therefore impact on the next collection plate. The gradually decreased diameter of the nozzle at each subsequent stage increase the velocity of the incoming aerosol and smaller sized particles impact and are captured. A schematic representation of the principle for a multi stage cascade impactor is shown in Figure 2.

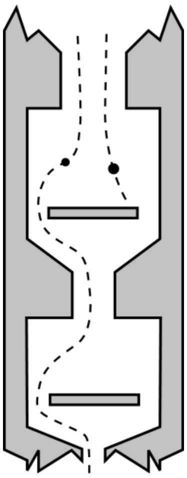


Figure 2 Schematic figure of the principle of a cascade impactor [15].

The stages of an impactor are characterized by their cut-off sizes. The *cut-off size* ($D_{50\%}$) is related to the Stokes number (particle inertia) that gives 50 % collection efficiency, *i.e.*, an impactor plate does not have perfect collection characteristics, and thus some under-sized particles are collected and some over-sized particles are admitted to the next plate.

Three different impactors were used in the experimental work. In Test Series 1, a 4-stage *Sioutas Cascade Impactor* was used primarily for collecting samples of different size distribution for subsequent PAH-analysis. Further, in Test Series 1, a special impactor for collecting particle associated isocyanates was used. That impactor and analysis method is described in section 2.7.2.3. In Test Series 2, a *Marple Series 290 Personal Cascade Impactor* with 8 stages was used for a more detailed characterization of the particle distribution. Further, elemental analysis was made on the samples collected in this case.

Samples were collected from the mixing chamber of the tube furnace during the steady state period of a test in all cases. The sampling time varied for the various impactors used and is given below.

The *Sioutas Impactor* is a simple cascade impactor, consisting of four impactor stages (25-mm PTFE plates) and a post-filter (37-mm PTFE filter), which collects particles in five size ranges. A pump maintained a sample flow of 9 l min^{-1} during the collection period which normally was 1 minute. It was found that longer sampling times generally led to over-load of the impactor and thus misleading results. It was found that the *Sioutas Impactor* was unsuitable for sampling in tests with the PVC-carpet as it was blocked after a short time. Information concerning the impact stages for the *Sioutas Cascade Impactor* is given in Table 5 [16].

Table 5 Collection stages for the cascade impactor used in Test Series 1.

Impactor stage	50% Cut-point, aerodynamic diameter (µm)	Approximate maximum aerodynamic diameter (µm)
1	2.5	2.60
2	1.0	0.95
3	0.50	0.52
4	0.25	0.23
5 (filter)	<0.25	Backup filter

The cascade impactor used in Test Series 2 had eight impactor stages (34 mm-diameter, stainless steel) and remaining fine particles are collected by the built –in filter (34 mm diameter; 5 micron pore size and glass fibre). Information concerning the impact stages for the *Marple Series 290 Personal Cascade Impactor* is given in Table 6 [17]. Fire effluents were sampled at a flow rate of 2.0 l min^{-1} for a period of five minutes for the OSB material and 4 minutes for PVC-carpet sample. The cascade impactor analysis was always carried out in triplicate.

Table 6 Collection stages for the cascade impactor used in Test Series 2.

Impactor stage	50% Cut-point, aerodynamic diameter (µm)	Approximate maximum aerodynamic diameter (µm)
1	21.3	21.5
2	14.8	15
3	9.8	10
4	6.0	6.5
5	3.5	4
6	1.55	2
7	0.93	1
8	0.52	0.5
9 (filter)	<0.52	Backup filter

2.4.2 Filter sampling of total soot

Total soot content was determined by sampling smoke gases from the mixing chamber on a filter. The unheated filter housing was connected directly to one of the sampling outlets of the mixing chamber to avoid any losses. The filter used was of the type “SKC – MCE, low BGD” with a pore size of 0.8 µm and a diameter of 37 mm. The sampling flow was 1 l min^{-1} and the sampling period normally lasted for 3 minutes. Conditioned filters were pre-weighed before use and sampled filters were stored in an excicator before weighing the amount of soot sampled.

2.5 Elemental analysis of soot

Selected total soot filters from tests with the PVC-carpet in Test Series 1 were analysed for total chlorine content. The filters were leached in water in an ultrasonic bath for 10 minutes. The solution was analysed for chlorine using High Pressure Ion Chromatography (HPIC).

Elemental analysis of the soot from cascade impactor filters and the total-soot filters was carried out using XRF for selected tests in Test Series 2. The elemental analysis was carried out using a Portable X-ray Fluorescence Spectrometer (PXRF). The spectrometer used in this work was a Bruker Tracer III-SD handheld XRF equipped with an Rh target X-ray tube and a 10 mm^2 X-flash detector. For both analysis of the residues and chlorine calibration, a tube voltage of 40 KeV and a current of 3.3 µA, together with a data collection time of 200 seconds were used. In addition, no filters were used throughout the data collection. Calibration for chlorine was carried out using sodium chloride (99.99 %

Aldrich). Specific amounts of sodium chloride were weighed and ground in corn flour, which acted as an inert matrix. In each case the total mass of sodium chloride and corn flour was kept constant at 0.5 g. A plot of the weight % Cl versus integrated counts for the Cl Kα line resulted in a straight line, the slope of which could then be used to calculate the % weight of Cl in the residues.

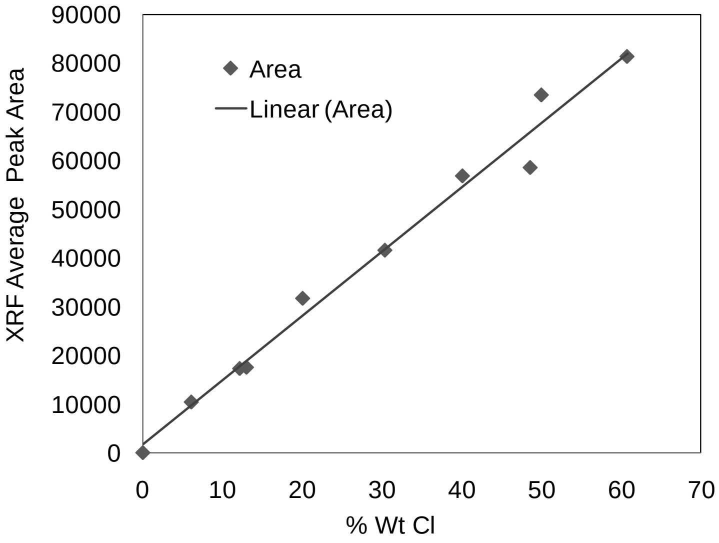


Figure 3 XRF Calibration.

A typical XRF spectrum obtained from the residues is shown in Figure 4. The peak of interest is the Chlorine Kα line which occurs at approximately 2.622 KeV. Other elements which have been identified in the spectrum include Rhodium (Kα 2.697 KeV). Calcium (Kα 3.691 KeV), Titanium (Kα 4.509 KeV), Iron (Kα 6.399 KeV), Copper (Kα 8.041 KeV) and Zinc (Kα 8.631 KeV). The presence of Rhodium is a consequence of the X-ray source, while the presence of the other elements from Calcium and higher is due to the fittings of the spectrometer. The majority of Calcium is from the sample; however, quantification of the amount is outside the scope of this work.

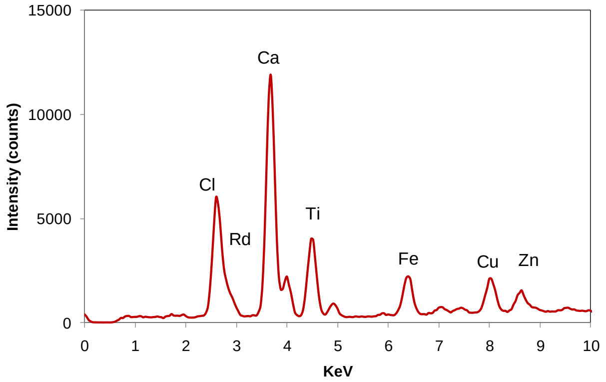


Figure 4 XRF spectrum of vinyl flooring residue after burning under oxidative pyrolysis conditions at 350°C.

2.6 Analysis of PAH

Samples for PAH-analysis were collected in tests with both the Wood board (OSB) and the PVC-carpet in Test Series 1. Two methods for sampling were employed. In several tests with both materials, smoke gases were sampled for PAH using a commercial PAH-sampler (*SKC OVS-sampler*) on which particle associated and gaseous phase PAHs are separated (see section 2.6.1). In some of the tests with the wood board, the particles captured on the *Sioutas Cascade Impactor* collector plates were subsequently analysed for PAH (see section 2.6.2).

The distribution of PAH species could be determined by this combination of sampling methods; between gaseous phase and condensed phase for both materials, and additionally between size classes of particles for the wood board.

2.6.1 Sampling with OVS-sampler

Sampling of PAH species was made using a *SKC no.226-30-16 OVS-sampler* consisting of a particle filter (glass fibre) and a XAD-2 adsorbent. A small piece of glass fibre wool was placed prior to the filter to increase the particle load capacity. The smoke gases were sampled with a flow rate of 1.0 L min^{-1} during a sampling period of 3 minutes. The samples were subsequently extracted with toluene at the analysis lab where the filter/glass wool and the XAD-2 adsorbent were treated separately. The extracts were analysed focusing on the 16 EPA priority pollutant PAH-compounds using GC-MS (see section 2.6.3).

2.6.2 Sampling with impactor

The collection plates of the *Sioutas Cascade Impactor* were analysed for PAH species in selected tests. The collection plates were extracted with toluene before GC-MS analysis (see section 2.6.3).

2.6.3 GC-MS analysis

2.6.3.1 Calibration standard

Internal Standard Solutions were obtained from Sigma-Aldrich and contained naphthalene-*d*8, chrysene-*d*12 (product no. 442523), and benzopyrene-*d*12 (product no. 442847). These internal standards were mixed together in a 100 ml flask filled with toluene. The concentrations of the internal standards in the stock solution were approximately 0.1-0.3 g/litre.

PAH Standards for GC-MS analysis were obtained from Sigma Aldrich as a calibration mixture (product number 47940-U). The PAH standards contained all the EPA PAH’s (10 µg/ml of each PAH). The standard solutions made, which included the EPA PAH-standards and internal standards, are given in Table 7.

Table 7 Standard solutions used for calibrating the GC-MS.

	Volume flask (ml)	PAH Mix (µl)	Conc. EPA PAH (pg/µl)	Internal standard Stock solution	Naphtalene-d8	Chysene-d12	Benzopyrene-d12
S1	5	250 µl	500	5 µl	150	62.4	86
S2	5	100 µl	200	5 µl	150	62.4	86
S3	10	50 µl	50	10 µl	150	62.4	86
S4	10	20 µl	20	10 µl	150	62.4	86
S5	10	10 µl	10	10 µl	150	62.4	86
S6	10	5 µl	5	10 µl	150	62.4	86

2.6.3.2 Extraction

The extraction solvent was made by adding 500 µl of the internal standard stock solution to a 500 ml flask and then diluting with toluene. The concentrations of internal standards in the extraction solvent are given in Table 8.

Table 8 Internal standards in extraction solution.

Extraction Solvent	Naphthalene-d8 (pg/µl)	Chrysene-d12 (pg/µl)	Benzopyrene-d12 (pg/µl)
500 µl of internal standard stock solution in 500 ml toluene	150	62.4	86

The work up of the OSV-samples included individual extraction of glass wool (from the inlet of the sampler to capture large soot particles), filter, and XAD-2 resin. The sample items were placed in individual vials and 5 ml of the extraction solvent was added. The samples were placed in an ultra sonic bath for 45 minutes. The samples were left to stand for 2-3 minutes before filtering of the samples, which was required in some cases. An equivalent extraction procedure was used for the impactor plates.

2.6.3.3 Analysis

The analysis system was designed as described below. Retention times for individual PAH compounds are given in

Table 9. A chromatogram from an analysis of a standard solution is shown in Figure 5.

GC column:	BPX5 non polar capillary column from SGE, 25 m, 0.22 mm ID, 0.25 µm film thickness.
Injection volume:	2µl
Inlet temperature:	300°C
MS transfer line:	280°C
Temperature programme:	100°C for 2 min, 8°C/min to 210°C, and then 2°C/min to 280°C, 280°C for 3 minutes.

Quantification was made using SIM mode (Selected Ion Monitoring).

Table 9 **Retention times for individual PAH compounds.**

PAH compound	**Quantification Ion**	**Retention Time (min)**
Naphthalene	128	4.990
Acenaphthylene	152	9.064
Acenaphthene	153	9.552
Fluorene	166	11.065
Phenenanthrene	178	13.890
Anthracene	178	14.049
Fluoranthene	202	17.647
Pyrene	202	18.532
Benzo(a)anthracene	228	25.358
Chrysene	228	25.593
Benzo(b)fluoranthene	252	33.547
Benzo(k)fluoranthene	252	33.782
Benzo(a)pyrene	252	36.079
Indeno(1.2.3-cd)pyrene	276	44.929
Dibenzo(ah)anthracene	278	45.428
Benzo(ghi)perylene	276	46.804

Internal Standard Compounds	**Quantification Ion**	**Retention Time (min)**
naphthalene-*d*8	136	4.942
chrysene-*d*12	240	25.448
benzopyrene-*d*12	264	35.899

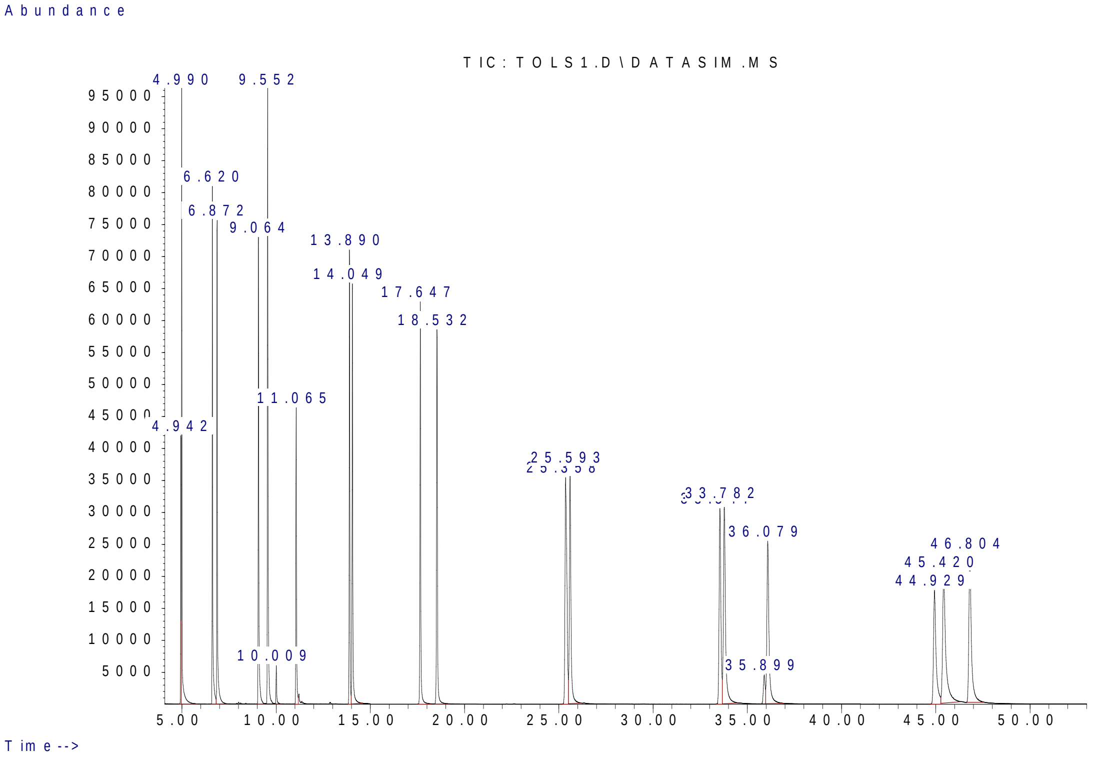


Figure 5 **GC chromatogram from analysis of standard solution of EPA PAH's and internal standards.**

2.7 Isocyanates

2.7.1 Pre study

Prior to the tube furnace studies the materials (PVC carpet and OSB) were tested with regards to isocyanate emission during thermal degradation. The sample material was placed in a glass tube connected to duplicate impinger-filters using only glass connections. A small piece, about 120 mg, was heated and thermally degraded with a heat gun. Duplicate impinger-filter samples were collected for each material, with a flow rate of 1.0 l/min and with a sampling time of 5 min, was used.

2.7.2 Air sampling

2.7.2.1 Impinger-filter

Air sampling was performed during 1 min using 30 ml midget impinger flasks containing 10 ml 0.01 mol 1^{-1} DBA in toluene and a glass fibre filter in series (Swinnex 13 mm; Millipore, Bedford, MA, USA). A flow rate of 1.0 l min^{-1} was maintained using a multiport connected to a *Laboport* twin diaphragm vacuum pump (KNF Neuberger GmbH, Freiburg, Germany). The air flow was measured with a *TSI 4140 flow meter* (TSI Inc., USA). Air samples were collected from the mixing chamber using glass connections. The two impinger-filter samplers were connected in parallel to one inlet (all glass connection). The sampling inlet (glass tube) was positioned about 15 cm above the floor of the chamber.

2.7.2.2 Dry sampler

The sampler consisted of a polypropylene tube (L = 7 cm, ID = 0.8 cm; BD, Temse, Belgium) coupled in series with a 13 mm polypropylene filter holder (Swinnex 13 mm; Millipore, Bedford, MA, USA). The inner wall of the tube was coated with an impregnated glass fibre filter (tube-filter, 25 x 60 mm), and a V-shaped impregnated glass fibre filter (V-filter, 13.5 x 60 mm). In-house manufactured from MG160 (Munktell, Grycksbo, Sweden). In the filter holder an impregnated 13 mm round glass fibre filter was placed (end-filter). The glass fibre filters were of type MG 160 with a pore size of 0.3 mm (Munktell, Grycksbo, Sweden). The filters were impregnated with reagent solutions containing equimolar amounts of DBA and acetic acid in methanol. The impregnation was performed by adding 1.5 ml of a 1.5 mol l^{-1} DBA reagent solution to the tube-filter, V-filter and 0.1 ml of 0.7 mol l^{-1} DBA reagent solutions to the end-filter. Impregnation, evaporation of solvent and assembling of the samplers were performed in a nitrogen atmosphere. The flow rate through the sampler was 0.2 l min^{-1}. The samplers were stored in zip bags prior air sampling [18].

Air sampling was performed during 1 min using assembled and impregnated dry samplers. A flow rate of 0.2 l min^{-1} was maintained using a multiport connected to a Laboport twin diaphragm vacuum pump (KNF Neuberger GmbH, Freiburg, Germany). The air flow (0.2 l min^{-1}) was measured with TSI 4140 flow meter (TSI Inc., USA). Air samples were collected from the mixing chamber (0.03 m^3) using glass connections. Three dry samplers were connected in parallel to one inlet (all glass connection). The sampling inlet (glass tube) was positions about 15 cm above the floor of the chamber.

A background was sampled for 5 min between every test using three dry sampler connected in parallel to one inlet (all glass connections).

2.7.2.3 Denuder – impactor sampler

The denuder-impactor (DI) sampler consisted of three central parts, a denuder, a three stage cascade impactor and an end filter. The denuder is collecting gas phase isocyanates and the particle borne isocyanates are collected in size separated fraction in the cascade impactor (2.5 µm, 1.0 µm and 0.5 µm with a cut of diameter of d_{50}). Small particles (< 0.5 µm) are collected in the end filter. The filters were impregnated with reagent solutions containing equimolar amounts of DBA and acetic acid in methanol. All impregnation work was performed in a nitrogen atmosphere. Each denuder plate (40 x 73 mm, MGF, Munktell, Grycksbo, Sweden) was impregnated with 1.5 ml of a 1.4 M DBA acetic acid and methanol solution. The 15 mm impactor glass fibre plates (in-house manufacture from MGC, Munktell, Grycksbo, Sweden) were impregnated with 65 µl of a saturated DBA methanol solution containing 2 ml DBA, 673 µl acetic acid and 50 µl distilled H_2O. The end filter (30 mm MG160, in-house manufactured from MG 160 Munktell, Grycksbo, Sweden) was impregnated with 0.7 M DBA and acetic acid in methanol. All filters were dried in nitrogen atmosphere before assembling the denuder-impactor. The flow rate through the DI sampler was 5 l min^{-1}. The samplers were stored in zip bags prior air sampling [19].

Air sampling was performed during 3 min using assembled and impregnated denuder-impactor. A flow rate of 5 l min^{-1} was maintained using a multiport connected to a Laboport twin diaphragm vacuum pump (KNF Neuberger GmbH, Freiburg, Germany). The air flow rate (5 l min^{-1}) was measured with TSI 4140 flow meter (TSI Inc., USA). Air samples (denuder-impactor sampler) were collected from the mixing chamber (0.03 m^3) using a stainless steel connection. The sampling inlet (stainless steel tube) was positioned about 15 cm above the floor of the chamber.

2.7.3 Work-up

2.7.3.1 Impinger-filter sampler

After completed sampling, the impinger solutions and filters were transferred to separate test tubes, and internal standard (deuterium-labelled isocyanate –DBA derivatives) was added. The samples were evaporated to dryness and dissolved in 0.5 ml acetonitrile. The isocyanates corresponding urea-derivatives were analyzed using LC-MS/MS. Calibration standards (n=7) for air samples were prepared in 10 ml 0.01 M toluene-DBA, by spiking with 2-70 ng of ICA, MIC, EIC, PIC, PhI, 1,6-HDI, 2,4- /2,6-TDI, IPDI, 4,4´-MDI as DBA derivatives and 10 ng IS. The calibration standards were evaporated and dissolved in 0.5 ml acetonitrile and analyzed in the same proceedings as the samples [20].

2.7.3.2 Dry sampler

After sampling, the sampler was extracted with 3 ml of 1 mmol l^{-1} H_2SO_4 (aq), 3 ml of methanol, 6 ml of toluene and 50 µl IS in a four step extraction procedure, as described previously [21]. The four step extraction procedure was repeated twice and after each extraction procedure was 5.5 ml toluene phase extracted to the same test tube. The extracted toluene phase (11 ml) and the excess DBA-reagent were removed by evaporation of the samples and the calibration standards in a vacuum centrifuge, and the dry residues were dissolved in 0.5 ml acetonitrile. The test tubes were placed in an ultrasonic bath for 10 min and manually shaken, and the sample solution was transferred to vials for injection into the LC-MS/MS. Calibration standards (n = 9) were prepared in spiked solutions (1-70 ng of ICA, MIC, EIC, PIC, PhI, 1,6-HDI, 2,4- /2,6-TDI, IPDI, 4,4´-MDI as DBA derivatives) and 10 ng IS. The calibration standards were evaporated and dissolved in 0.5 ml acetonitrile and analyzed in the same procedure as the urea-derivatives [20].

2.7.3.2.1 Denuder-impactor sampler

Denuder: After completed air sampling, the glass-fiber filter-plates were cut out and folded using tweezers. Every filter-plate was transferred to test tubes. The filter-plates were extracted with 3 ml of 1 mmol l^{-1} H_2SO_4 (aq), 3 ml of methanol, 6 ml of toluene and 50 µl IS in a four step extraction procedure, as described previously. The four step extraction procedure was repeated twice and 5.5 ml toluene phase was transferred from each extraction procedure. A total of 11 ml toluene phase and the excess DBA-reagent were removed by evaporation of the samples and the calibration standards in a vacuum centrifuge. The dry residues were dissolved in 0.5 ml acetonitrile [19].

Impactor substrate and end filter: After completed air sampling the impactor-substrate and end filter were transferred to test tubes containing 5 ml toluene. 50 µl IS and 2 ml mmol l-1 H2SO4 (aq) was added. The samples were extracted by sonication for 10 min, shaking for 10 min and centrifugation for 10 min at 3000 rpm. The toluene were separated and transferred to new test tubes. The extracted toluene phase and the excess DBA-reagent were removed by evaporation of the samples and the calibration standards in a vacuum centrifuge, and the dry residues were dissolved in 0.5 ml acetonitrile [19].

The test tubes with 0.5 ml acetonitrile were placed in an ultrasonic bath for 10 min and manual shaken, and the sample solution was transferred to vials for injection into the LC-MS/MS. Calibration standards (n = 7) were prepared in spiked solutions (2-70 ng of ICA, MIC, EIC, PIC, PhI, 1,6-HDI, 2,4- /2,6-TDI, IPDI, 4,4´-MDI as DBA derivatives) and 10 ng IS. The calibration standards were evaporated and dissolved in 0.5 ml acetonitrile and analyzed in the same procedure as the urea-derivatives [20].

2.7.4 Analysis

The isocyanates were analyzed as their corresponding urea-derivatives using LC-MS/MS. The LC-MS/MS system consisted of a micro-LC pump (Shimadzu LC10ADVP, Shimadzu Inc., Kyoto Japan) with a *CTC-pal autosampler* (CTC Analytics AG, Zwingen, Switzerland) connected to a *Quattro Micro* (Waters, Altrincham, Cheshire, UK) mass spectrometer. The mass spectrometer was operated in the positive mode performing multiple reaction monitoring (MRM) of $[M+H]^+$ => $[DBA+H]^+$. 2.5 µl sample was injected into a 20 µl sample loop containing 17.5 µl of a focus liquid of 5/95 (% v/v) acetonitrile/water solution. The flow rate was 70 µl min^{-1} using an Xterra® C18, 50 mm x 1.0 mm with 2.5 µm particles (Waters, Massachusetts, USA). A gradient was used with the mobile composition of (A) 5/95/0.05 and (B) 95/5/0.05 acetonitrile/water/formic acid (v/v/v). Elution was performed using a linear gradient from 40% B to 100% A in 12 min. The gradient was followed by isocratic elution with 100% B during 3 min. The mass spectrometry was operating with capillary voltage of 4 kV, ion source was 130°C, and the desolvation gas temperature was 200°C. The desolvation gas flow was set to 500 l h^{-1}. Argon was used as collision gas with a collision cell pressure of 3 x 10^{-3} mbar. Collision energies and entrance cone voltage were individually optimized for the different urea derivatives. Further description of the analysis for the urea derivatives are presented in [20].

2.7.5 Chemicals

Di-n-butylamine (DBA), Ethyl isocyanates (EIC), Technical toluene diisocyanate (80% 2,4-TDI, 20% 2,6-TDI), n-propyl isocyanate, phenyl isocyanate, isophorone diisocyanate (IPDI), 4,4´- methylene diphenyl diisocyanate (MDI) were obtained from Acros organics (New Jersey, USA). 1,6-hexamethylene diisocyanate (HDI), acetic acid, acetonitrile, formic acid, isooctane, sulphuric acid (H_2SO_4), toluene were obtained from Merck (Darmstadt, Germany). All solvent used were HPLC-graded or higher. Deuterium-labelled DBA [$NH(C_4H_9)(C_4D_9)$] from *Synthelec* (Lund, Sweden) was used for synthesis of internal standard [20].

3 Results and discussion

3.1 Tube furnace experiments

3.1.1 Test Series 1

The tube furnace tests in Test Series 1 are summarized in Table 10. Duplicate tests or more were conducted for each fire stage (combustion condition).

For the *oxidative pyrolysis tests* (Fire stage 1b) no flaming combustion was observed in any of the tests. This is the desired behaviour according to ISO/TS 19700. For the *well-ventilated tests* (Fire stage 2) and the *under-ventilated tests* (Fire stage 3b), steady flaming combustion was observed in all tests which is the desired behaviour according to ISO/TS 19700.

The completeness of the combustion was close to maximum in the well-ventilated tests with the wood board material (OSB). A small amount of residue remained in the under-ventilated tests, and a somewhat larger amount in the pyrolysis tests. The PVC-carpet contained about 24 wt-% inorganic residue, and it can be seen from Table 10 that the combustion in the well-ventilated tests with PVC was complete. In the under-ventilated tests about 10 % of combustible material remained, and about 30 % in the pyrolysis tests.

Table 10 Summary of tube furnace data for Test series 1.

Test id	Mat-erial	Fire stage	Furnace temp (ºC)	Flaming comb-ustion	Sample weight (g); mass loss (%)	Primary flow; Secondary flow (L/min)	Mixing box temp (ºC)	O_2 – depletion (%)	Equiv-alence ratio (ø)
29	PVC	1b	350	No	21.7; 46.2	2.0; 39	26	0.30	-
31	PVC	1b	350	No	21.5; 45.5	2.0; 39	26	0.36	-
23	PVC	2	650	Yes	21.2; 76.2	9.6; 32	43	2.46	0.52
32	PVC	2	650	Yes	21.7; 77.6	9.6; 32	48	3.06	0.66
8	PVC	3b	825	Yes	21.2; 65.4	2.1; 39	31	2.37	2.37
24	PVC	3b	825	Yes	22.2; 66.8	2.1; 39	33	2.49	2.49
27	PVC	3b	825	Yes	22.0; 66.8	2.1; 39	34	2.51	2.51
33	PVC	3b	825	Yes	20.4; 69.1	2.1; 39	33	No data available	-
22	OSB	1b	350	No	17.6; 69.2	2.0; 39	25	0.35	-
28	OSB	1b	350	No	17.3; 69.0	2.0; 39	25	0.39	-
9	OSB	2	650	Yes	17.8; 99.3	9.6; 32	43	2.57	0.53
11	OSB	2	650	Yes	16.6; 99.8	9.6; 32	43	2.39	0.50
13	OSB	2	650	Yes	17.2; 99.3	9.6; 32	41	2.47	0.50
14	OSB	2	650	Yes	17.2; 99.3	9.6; 32	42	2.21	0.46
25	OSB	2	650	Yes	16.8; 99.6	9.6; 32	45	2.54	0.53
10	OSB	3b	825	Yes	16.7; 94.2	2.2; 39	31	1.75	2.11
15	OSB	3b	825	Yes	17.5; 93.1	2.2; 39	32	1.37	2.24
16	OSB	3b	825	Yes	17.1; 89.8	2.2; 39	34	1.36	2.10
30	OSB	3b	825	Yes	16.7; 90.1	2.2; 39	33	1.43	2.02

The equivalence ratio for the well-ventilated tests fulfilled the requirement of $\phi < 0.75$ which is defined in ISO/TS 19700. The under-ventilated tests shall nominally have a ϕ of 2.0. This is nearly the case for the tests with the wood board material, but the under-ventilated tests with the PVC-carpet have a slightly higher equivalence ratio.

3.1.2 Test Series 2

During the second test series initial studies were carried out in order to set primary and secondary flows as well as temperatures to replicate the combustion conditions studied in Test Series 1. During these tests the filters for the gas analyzers (O_2, CO_2/CO) were often blocked. Therefore these analysers were not used in subsequent tests where the correct apparatus settings were already identified. The main focus in Test Series 2 was on measurements using the cascade impactor and analysis of HCl in the soot. Other fire effluents were not measured in this series, as these analyses had already been carried out in the first test series. The individual tests conducted in Test Series 2 are listed in Table 4.

3.2 Combustion gases

All major combustion gases were analysed in Test Series 1 using FTIR. These results are summarized in Table 11 and Table 12. Graphs of measured concentrations in the mixing chamber are available in Annex 1.

3.2.1 PVC-carpet

The major inorganic combustion gases found in the tests with the PVC-carpet were carbon dioxide (CO_2), carbon monoxide (CO) and hydrogen chloride (HCl). These are the major gases expected to be found from this type of product [22].

Table 11 Mass-loss yields of combustion gases in tube-furnace tests with PVC.

Test id	Material	Fire stage	CO_2, yield (g/g)	CO, yield (g/g)	HCl, yield (g/g)
29	PVC	1b	0.11	0.040	0.43
31	PVC	1b	0.10	0.040	0.42
23	PVC	2	1.23	0.058	0.27
32	PVC	2	1.23	0.078	0.30
8	PVC	3b	0.72	0.094	0.31
24	PVC	3b	0.56	0.13	0.32
27	PVC	3b	0.61	0.092	0.31

The CO_2/CO ratio in the well-ventilated tests (Fire stage 2) and the under-ventilated tests (Fire stage 3b) are logical, i.e. they show a lower ratio and thus less complete combustion in the under-ventilated tests. The yield of HCl is high for both the well-ventilated and the under-ventilated tests. The maximum HCl mass-loss yield (calculated on the combustible part of the product) is 38 %. This means that the recovery of chlorine as HCl was around 80 relative-% in these tests. The pyrolysis tests (Fire stage 1b), where the material degraded without any flames, show low yields of CO_2, moderate yields of CO and high yields of HCl. The high yield (i.e. greater than theoretically possible) of HCl in the pyrolysis experiments can be explained by the fact that chlorine is degraded and emitted as HCl at a lower temperature compared to the thermal degradation of the hydrocarbon backbone of the PVC material [23]. In others words a greater amount of the HCl present is emitted than the amount of PVC burned.

3.2.2 Wood board (OSB)

The inorganic combustion gases found in all tests with the wood board were carbon dioxide (CO_2), carbon monoxide (CO) and hydrogen cyanide (HCN). Additionally, nitrogen oxides (NO and NO_2) were found in both the well-ventilated and the under-ventilated tests. Ammonia (NH_3) was found in the under-ventilated tests only.

The CO_2/CO ratio in the well-ventilated tests and the under-ventilated tests are logical, i.e. a lower ratio corresponding to less complete combustion was found in the under-ventilated tests. Hydrogen cyanide, which is highly toxic, is important when assessing the toxic effects of fire effluents. The results show the highest production of HCN for under-ventilated combustion but also significant production from pyrolysis.

Table 12 Mass-loss yields of combustion gases in tube-furnace tests with OSB.

Test id	Material	Fire stage	CO_2, yield (g/g)	CO, yield (g/g)	HCN, yield (g/g)	NH_3, yield (g/g)	NO, yield (g/g)	NO_2, yield (g/g)
22	OSB	1b	0.26	0.076	0.0012	-	-	-
28	OSB	1b	0.27	0.083	0.0014	-	-	-
9	OSB	2	1.53	0.0039	0.0002	-	0.0044	-
11	OSB	2	1.53	0.0059	0.0002	-	0.0045	0.0007
13	OSB	2	1.63	0.0024	0.0002	-	0.0045	0.0005
14	OSB	2	1.60	0.0045	0.0002	-	0.0048	0.0005
25	OSB	2	1.51	0.0055	0.0002	-	0.0043	0.0005
10	OSB	3b	0.86	0.12	0.0023	0.0013	0.0033	0.0004
15	OSB	3b	0.78	0.10	0.0022	0.0014	0.0028	0.0004
16	OSB	3b	0.83	0.15	0.0034	0.0028	0.0045	0.0006
30	OSB	3b	0.91	0.13	0.0025	0.0024	0.0030	0.0004

3.3 Particles

Particles were sampled in ranges of size fractions using cascade impactor techniques. In Test Series 1, the impactor used separated particles into 5 size categories. Such measurements were only made in tests with the wood board material (OSB). An important use of these samples was for the analysis of PAH species in order to investigate the distribution of condensed phase PAH species with particle size fraction.

In Test Series 2, a more advanced impactor was used. This impactor separated the sampled particles into nine size categories. Measurements were made both in tests with the wood board material and in tests with the PVC-carpet. This was the main method for characterisation of the particle size distribution in this project. Additionally, the impactor samples taken in Test Series 2 was analysed for elemental content when chlorine from the PVC-carpet was in focus.

The formation of soot particles is closely linked to the formation of PAHs (see section 3.4). The first step in soot formation is the particle interception of heavy molecules (PAHs) to form particle-like structures. These structures can subsequently grow through condensation and surface growth by addition of mainly acetylene. Larger structures can be formed by coagulation and agglomeration. These larger agglomerates may then be degraded by oxidation reactions. After the particle interception zone the size of the particles is a few nano meters (nm), whereas they have grown to 20-50 nm after the coagulation zone [26]. As the smoke leaves the flames of a fire and cools, vapour phase PAH condense on the surface of the soot particles. The amount of condensed organics varies from under 20% to up to 50% for well-ventilated and under-ventilated fires, respectively [26].

3.3.1 PVC-carpet

Particle size-distribution analysis in tests with the PVC-carpet was made in Test Series 2. Figure 6 shows the particle size distribution for tests with the PVC-carpet under well-ventilated condition expressed as relative mass for each size fraction. Results are expressed in terms of the aerodynamic diameter (particle size, $D_{50\%}$) using a log scale on the X-axis. The distribution shows a peak at the 3.50 µm stage and lower peaks at the 0.52 µm and 14.80 µm stages. The particles captured on the 3.50 µm plate, represented about 20 mass-% of the particles sampled. An increase of relative particles mass can be seen for the region smaller than 0.52 µm.

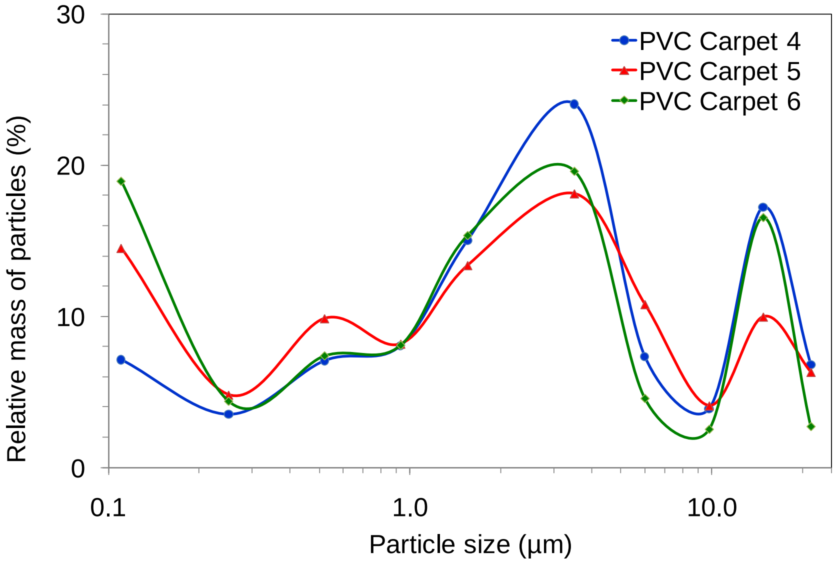


Figure 6 **PVC-carpet relative mass captured on the different impactor plates at well-ventilated conditions.**

Figure 7 presents results for the PVC-carpet for under-ventilated fire conditions. The main peak in the size distribution curve is in this case centred at the 0.93 µm stage. The mass peak in the size distribution curve is thus moved to a smaller particle size in the under-ventilated experiments. This is not what was expected from previous experience of other materials and is discussed more below.

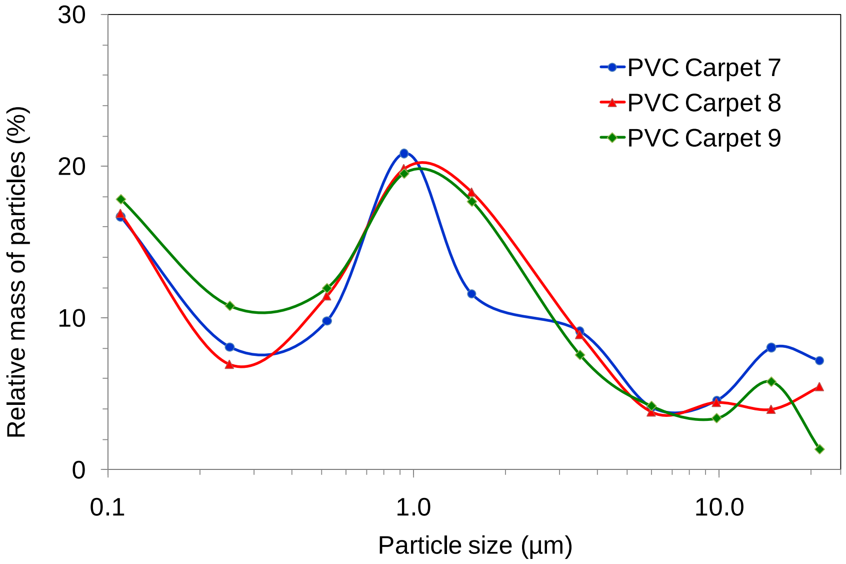


Figure 7 **PVC-carpet relative mass captured on the different impactor plates at under-ventilated conditions.**

Figure 8 shows results for the PCV-carpet from tests under oxidative pyrolysis conditions. The greatest amount of soot is produced within the size range 0.52 – 0.93 µm. For these conditions the particle distribution is concentrated to this peak in the distribution curve and there is no trend of increasing amounts of particles for the smallest particle sizes as was seen for tests at well-ventilated and under-ventilated conditions.

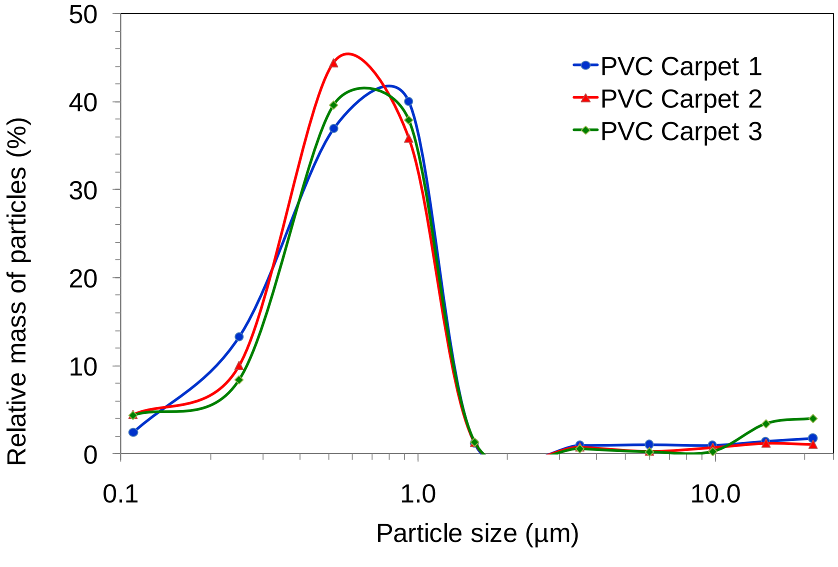


Figure 8 **PVC carpet relative mass captured on the different impactor plates at oxidative pyrolysis conditions.**

Both the well-ventilated and under-ventilated tube furnace experiments gave a major mass-peak at a relatively large particle size diameter, in the order of 1-4 µm. This is a large particle size when comparing to particles from fires with other common materials which normally have a median aerodynamic diameter around 0.3 µm [24]. Butler and Mulholland [26] have shown in a review that mass median aerodynamic diameters in the range of 0.4-3 µm, have been found from fires with PVC. In a test with a PVC-carpet in previous work [2], a mass-peak was seen at a particle size around 0.35 µm. Note that this test was conducted with the Cone Calorimeter, where the conditions are very well-ventilated.

The particle-size maximum was found at a somewhat smaller particle size in the under-ventilated tests compared to the well-ventilated tests which was unexpected. Normally the less complete combustion found for under-ventilated conditions should result in particles of larger size. However, for PVC the difference in combustion efficiency is not that significant between the two combustion conditions compared to halogen free materials, as the chlorine in PVC disrupts the combustion reactions in the gas phase and significantly reduces the combustion efficiency even for well-ventilated conditions. An additional factor is the higher furnace temperature in the under-ventilated tests, which could possibly result in more efficient oxidation of the soot before the reactions are quenched in the mixing chamber.

The total amounts of particles produced for the different combustion conditions examined varied. The mass-charge yield from oxidative pyrolysis was about half of that produced from well-ventilated conditions. The yield produced during under-ventilated conditions was even higher (see Annex 2.2).

3.3.2 Wood board (OSB)

The particle size distribution for the wood board material was investigated in both test series. In tests for well-ventilated conditions, the maxima in particle mass captured found was at the smallest sizes studied. This was seen both in Test Series 1 (Figure 9) and Test Series 2 (Figure 10).

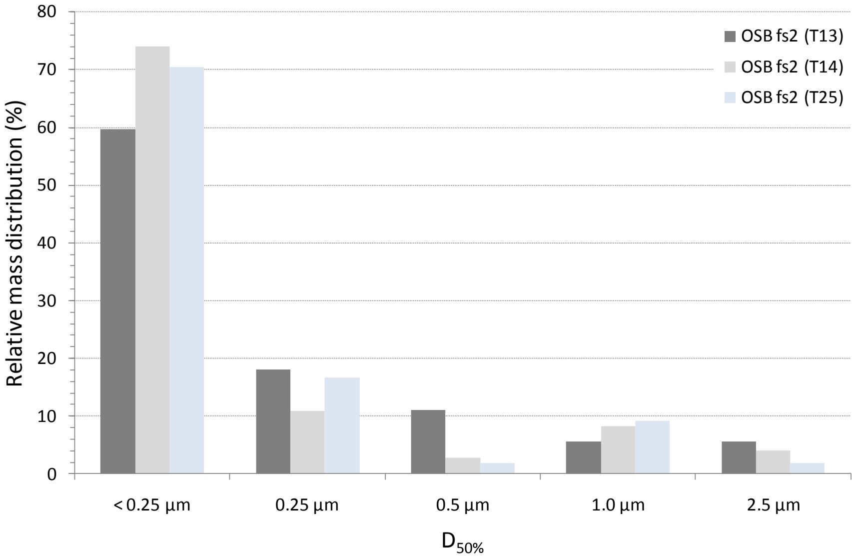


Figure 9 Relative particle mass captured on the different impactor plates in tests with the wood board (OSB) at well-ventilated conditions (Test Series 1).

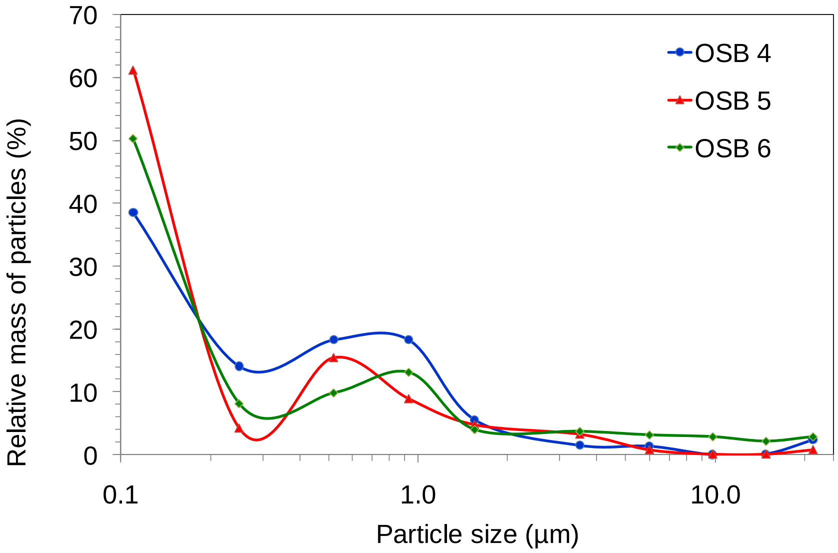


Figure 10 **Relative particle mass captured on the different impactor plates in tests with the wood board (OSB) at well-ventilated conditions (Test Series 2).**

Results from tests with the wood board for under-ventilated conditions are shown in Figure 11 (Test Series 1) and Figure 12 (Test Series 2). The results concerning the particle size distribution from the two test series are comparable also for this combustion condition. The size distribution for under-ventilated combustion is similar to the distribution pattern seen for well-ventilated conditions, with the maxima in mass of particles found at the smallest sizes.

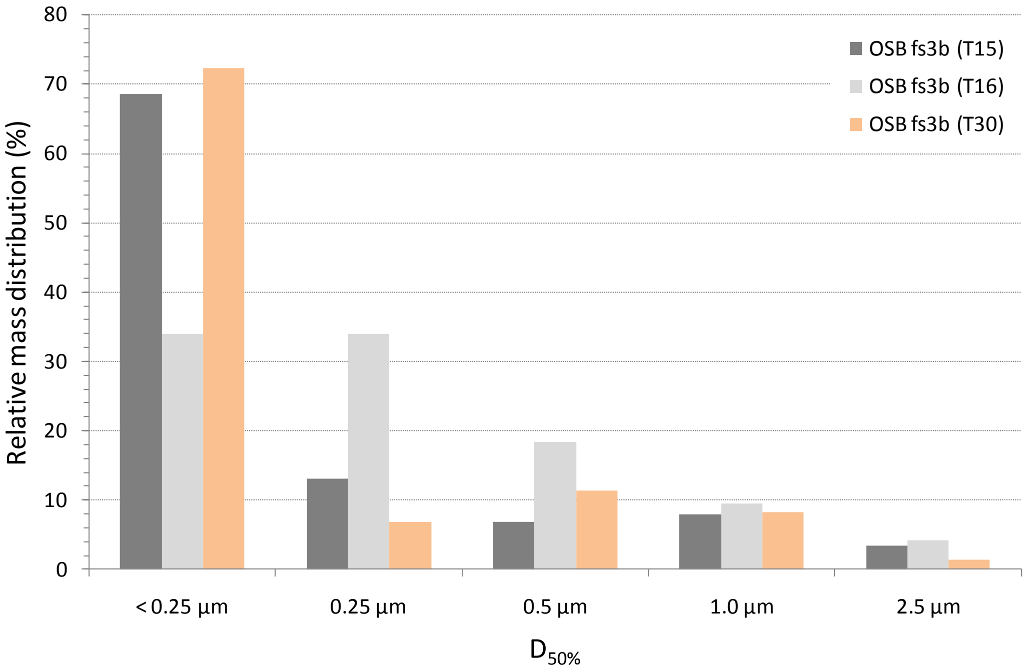


Figure 11 **Relative particle mass captured on the different impactor plates in tests with the wood board (OSB) at under-ventilated conditions (Test Series 1).**

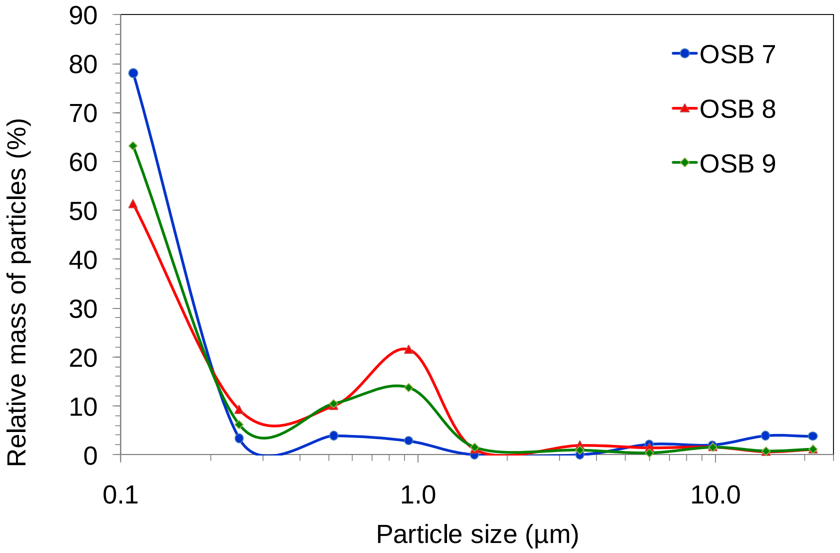


Figure 12 **Relative particle mass captured on the different impactor plates in tests with the wood board (OSB) at under-ventilated conditions (Test Series 2).**

Results from tests with the wood board during conditions of oxidative pyrolysis are shown in Figure 13 (Test Series 1) and Figure 14 (Test Series 2). Figure 14 shows a solitary peak with a center at the 0.93 µm plate and there is no tendency for any rise in the size distribution curve at the smallest sizes. The result from the single test with impactor data from oxidative pyrolysis conditions in Test Series 1 (Figure 13) show similar result, but with some differences. The peak in the mass distribution is in this case for the highest fraction of sizes measured (D_{50} 2.5 µm) which could be interpreted to indicate that the maximum in this test was skewed somewhat towards a larger particle size compared to the results from Test Series 2. This is, however, quite difficult to interpret as the impactor used in Test Series 2 has a higher resolution than that used in Test Series 1. As only a single test was run in Test Series 1 there is insufficient data to draw any conclusions concerning whether the differences seen are significant or not. It is, however, obvious from the results from both test series that oxidative pyrolysis conditions result in the production of larger particles than does flaming combustion.

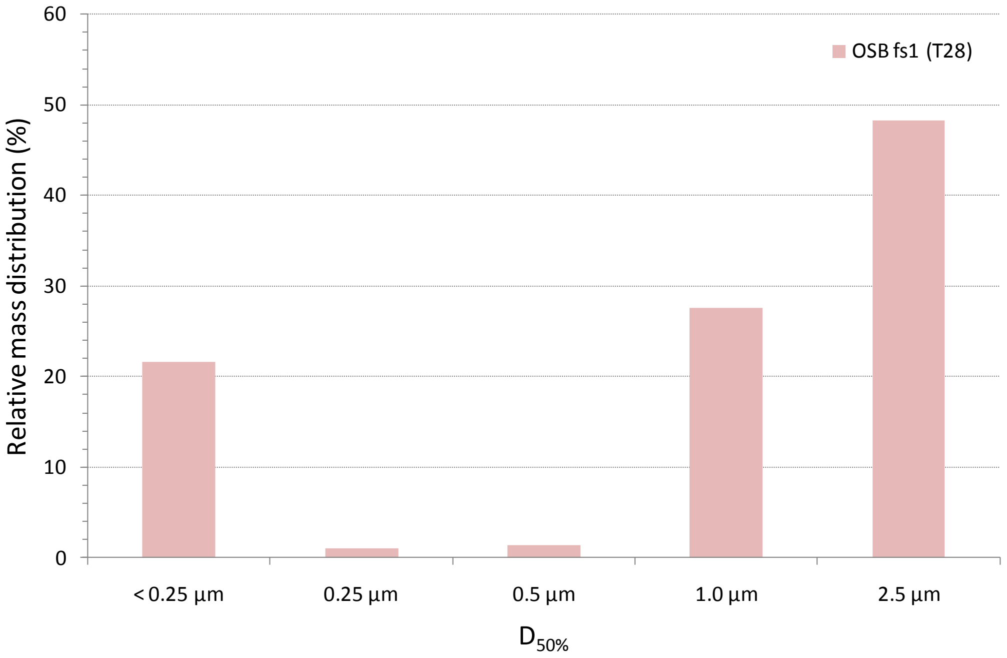


Figure 13 **Relative particle mass captured on the different impactor plates in tests with the wood board (OSB) at oxidative pyrolysis conditions (Test Series 1).**

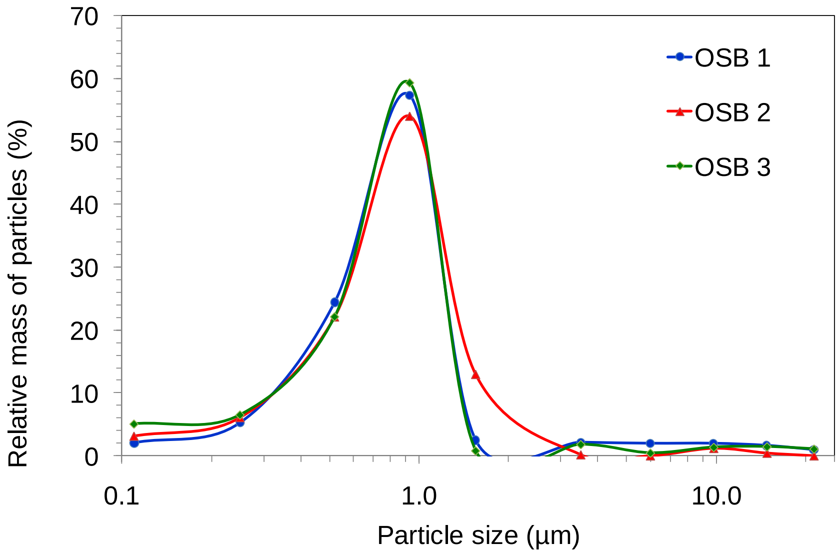


Figure 14 **Relative particle mass captured on the different impactor plates in tests with the wood board (OSB) at oxidative pyrolysis conditions (Test Series 2).**

The tests conducted using wood board show that small-sized particles are preferably produced during flaming combustion. The difference in particle sizes was not significant between well-ventilated and under-ventilated combustion with the tube furnace. A significantly different particle size distribution was seen in the tests with oxidative pyrolysis conditions where the maximum in particle mass was found skewed towards a larger particle size.

Production of small-sized particles in flaming combustion of wood has been shown previously by Blomqvist et al. [25] in well-ventilated tests with the Cone Calorimeter, where median aerodynamic diameters were found between 0.1 and 0.2 µm. Butler et al.

[26] reported median aerodynamic diameters from wood fires mainly in the range of 0.1 µm but also values in the vicinity of 1 µm from a large under-ventilated wood crib fire.

The total amounts of particles produced for the different combustion conditions examined varied strongly for the wood board. The mass-charge yield from oxidative pyrolysis was significantly higher compared to the production from the other combustion conditions. The yields produced during well-ventilated conditions were low compared to the production from under-ventilated (see Annex 2.2).

3.3.3 Comparison of particle yields

The absolute total production of particles, on a mass basis, was generally significant lower from the wood board compared with the PVC-carpet, with the exception of the high production seen from oxidative pyrolysis of the wood board material (see Annex 2.2). During well-ventilated combustion conditions the particle production was about 10 times higher for the PVC-carpet.

One can note that the particle measurements from both tube furnace tests-series gave relatively equivalent results, which indicates that the combustion conditions were equivalent and that the particle analysis was reliable.

3.4 PAH

Polycyclic aromatic hydrocarbons (PAHs) are defined as being comprised of two or more joined aromatic rings. The toxicity of individual PAHs varies widely, and a range of non-cancer and cancer effects have been demonstrated [27]. The PAH that has been investigated the most is benzo(a)pyrene (BaP). BaP is metabolised to oxygenated forms that act as a carcinogen in the body [28]. PAHs can be formed directly from saturated hydrocarbons in vitiated combustion atmospheres. Low molecular mass hydrocarbons act as precursors in the *pyrosynthesis* of PAH compounds that take place at temperatures above 500°C. The tendency for fuels to form PAH via pyrosynthesis varies depending on the structure of the basic organic fuel. While all organic fuels can form PAH, the greatest yields are obtained from aromatic fuels followed by cyclic aliphatics, olefins and paraffins, in decreasing order of magnitude. Thermal break-down of heavier hydrocarbons through *pyrolysis* is another path to form small unstable precursor compound for PAH synthesis [28].

PAHs are present in air in the gaseous phase or adsorbed onto particles. The phase distribution of individual PAHs in air is important when assessing their fate because of the difference in rates of chemical reactions and transport between the two phases. The phase distribution of any specific PAH depends on the vapour pressure of the PAH, the ambient temperature, the PAH concentration, the affinity of the PAH for suspended particles (K_{OC}), and the nature and concentrations of the particles [29].

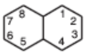
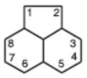
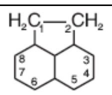
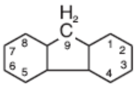
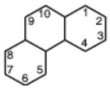
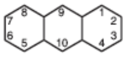
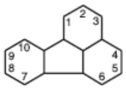
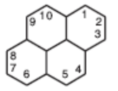
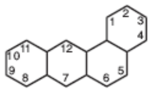
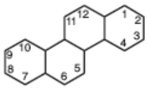
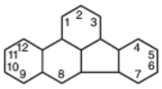
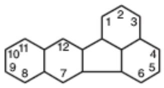
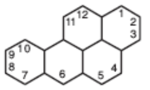
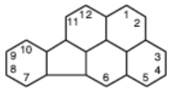
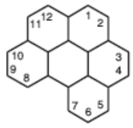
The K_{OC} of a chemical is an indication of its potential to bind to organic carbon in soil and sediment. The low molecular weight PAHs have K_{OC} values in the range of 10^3-10^4, which indicates a moderate potential to be adsorbed. The medium molecular weight compounds have K_{OC} values in the $l0^4$ range. High molecular weight PAHs have K_{OC} values in the range of 10^5-10^6, which indicates stronger tendencies to adsorb to organic carbon [30].

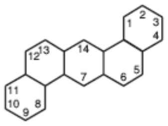
PAHs having two to three aromatic rings are present in air predominantly in the vapour phase. PAHs with four aromatic rings are both present in the vapour and particulate phase, and PAHs having five or more aromatic rings are found predominantly in the particle phase [29].

The PAHs analysed in this work are listed in Table 13. The PAH species are numbered after increasing molecular weight. These numbers are later used in this section for identification of the individual species. Table 13 further contains information related to phase distribution, cancer classifications from EPA and IARC, and Toxic Equivalence Factors (TEFs) used for normalising the cancer potential for individual PAH species. TEF factors are normalized against benzo(a)pyrene which has a factor of unity. The unit is expressed in BaP-TEQ (Toxicity Equivalence).

The results from the PAH-analysis are discussed in sections 3.4.2-3.4.3. Detailed analysis results are given in Appendix 3.

Table 13 Information on the PAH species analysed.

PAH no.	PAH	amu	Structure formula[a]	Vapour pressure (mm Hg 20-25ºC); Log Koc (-) [30]	Classificat-ion[b]	TEF[c]
1	Naphthalene	128		0.082: N/A	USEPA: D IARC: 3	0.001
2	Acenaphthalene	152		0.029; 1.40	USEPA: D IARC: N/A	0.001
3	Acenaphthene	154		4.5×10^{-3}; 3.66	USEPA: N/A IARC: N/A	0.001
4	Fluorene	166		3.2×10^{-4}; 3.86	USEPA: N/A IARC: 3	0.001
5	Phenanthrene	178		6.8×10^{-4}; 4.15	USEPA: D IARC: 3	0.001
6	Anthracene	178		1.7×10^{-5}; 4.15	USEPA: D IARC: 3	0.01
7	Fluoranthene	202		5.0×10^{-6}; 4.58	USEPA: D IARC: 3	0.001
8	Pyrene	202		2.52×10^{-6}; 4.58	USEPA: D IARC: 3	0.001
9	Benzo(a) anthracene	228		2.2×10^{-8}; 5.30	USEPA: B2 IARC: 2A	0.1
10	Chrysene	228		6.3×10^{-7}; 5.30	USEPA: B2 IARC: 3	0.01
11	Benzo(b) fluoranthene	252		5.0×10^{-7}; 5.74	USEPA: B2 IARC: 2B	0.1
12	Benzo(k) fluoranthene	252		9.6×10^{-11}; 5.74	USEPA: B2 IARC: 2B	0.1
13	Benzo(a)pyrene	252		5.6×10^{-9}; 6.74	USEPA: B2 IARC: 2A	1.0
14	Indeno(1,2,3-c,d) pyrene	276		$\sim10^{-11}$ - 10^{-6}; 6.20	USEPA: B2 IARC: 2B	0.1
15	Benzo(g,h,i) perylene	276		1.0×10^{-10}; 6.20	USEPA: D IARC: 3	0.01

16	Dibenz (a,h) anthracene	278		1.0×10^{-10}; 6.52	USEPA: B2 IARC: 2A	1.0 or 5.0[d]

[a] Chemical structures of PAHs are reproduced from NIST Special Publication 922 on-line internet site.

[b] USEPA, U.S. Environmental Protection Agency [31]: B2-Probable human carcinogen; D-Not classifiable. IARC, International Agency for Research on Cancer [32]: 2A-Probable human carcinogen; 2B-Possible Human Carcinogen; 3-Not classifiable.

[c] Toxic Equivalence Factors (TEFs) from Nisbet and LaGoy [33].

[d] A TEF of 1 is appropriate for high doses whereas a TEF of 5 is recommended for environmental exposures [33].

N/A: No information available.

3.4.1 Summary of total PAH results

PAH-analysis was made in selected tests using the *OVS-sampler* which consists of a filter that collects particles before the sampled air is led through an *XAD-2* adsorbent. The sum of the PAHs collected on both the filter (particle associated) and by the adsorbent (gas phase) is given in Table 14. It is clear from the results that PAHs are predominantly produced during under-ventilated conditions. This is true both for the Wood board and the PVC-carpet. However, the yield is significantly higher from the PVC-carpet. The yields produced from well-ventilated combustion, and from oxidative pyrolysis, are much lower. Further, for these combustion conditions it is clear that the PVC-carpet produces significantly higher total yields.

A presentation of the results on the distribution of PAHs between gas phase and particle phase is made in the following sections. Detailed analysis results are given in Annex 3.

Table 14 Summary of total PAH results.

Test condition	Wood board (OSB)		PVC-carpet	
	Test id	Total PAH, mass-loss yield (g/kg)	Test id	Total PAH, mass-loss yield (g/kg)
Well-ventilated (fs 2)	T13	0.004	T23	0.050
	T14	0.004	T32	0.19
Under-ventilated (fs 3b)	T16	4.2	T27	9.0
	T30	2.7	T33	9.8
Oxidative pyrolysis (fs 1b)	T22	0.007	T29	0.19
	-	-	T31	0.15

3.4.2 PVC-carpet

The results from the *OVS-sampler*, which are separated in gas phase and particle associated PAHs, are given in Figure 15. The highest yield of total PAHs is produced for under-ventilated conditions. It is clear that the volatile part (adsorbent) of the total mass of PAHs is larger than the particle associated part (filter). This is true for all three combustion conditions investigated.

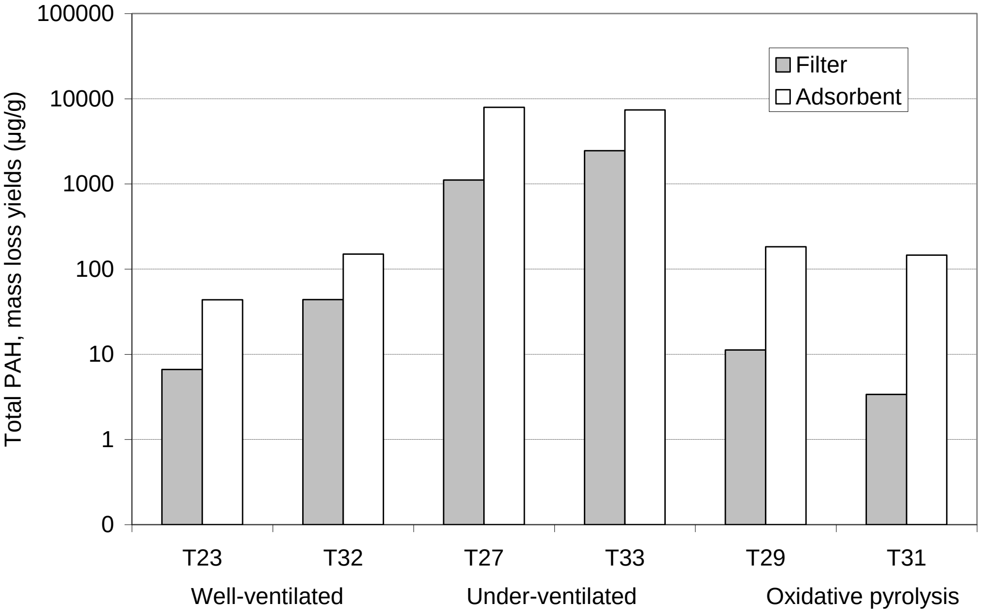


Figure 15 Data from *OVS-sampler*. Yields of total PAH from tests with PVC-carpet separated in particle associated (Filter) and gas-phase (Adsorbent). Note logarithmic scale on Y-axis.

The yields for individual PAHs have been normalized against the TEFs given in Table 13 and are expressed in BaP-TEQ. The normalized yields are shown in Figure 16. This changes the distribution pattern between volatile and particle phase. For both well-ventilated and under-ventilated conditions, the toxicity weighted yields for the particle associated PAHs increases in importance and often dominates over the volatile PAHs. The toxicity weighted yields for the under-ventilated tests are magnitudes higher than those from the well-ventilated tests.

Yield data is shown for individual PAHs in Figure 17. This data is based on sums of filter and adsorbent parts for each PAH. A general trend with decreasing yield for increasing molecular mass is seen for all combustion conditions studied. The data is rather consistent, with reasonable repeatability in distribution pattern between the duplicate samples. It is interesting to note that both well-ventilated (fs2) and under-ventilated (fs3b) combustion of the PVC-carpet produces the complete range of PAHs. In the pyrolysis tests (fs1b), however, only volatile and semi-volatile PAHs are produced.

Data on the distribution of individual PAHs between the condensed phase (filter) and gaseous phase (adsorbent) is presented in Annex 3.1. The data is presented both as mass-loss yields and toxicity weighted (BaP-TEQ) mass-loss yields. Generally, for the *well-ventilated tests* naphthalene, phenanthrene and acenaphthylene (PAH no. 1, 2 and 5) dominated the gaseous phase while chrysene (PAH no. 10) and other heavier species dominated the condensed phase. The toxicity weighted data was totally dominated by species in the condensed phase including benzo(a)pyrene, benzo(a)anthracene and benzo(b)fluoranthene (PAH no. 13, 9 and 11).

The *under-ventilated tests* were dominated by naphthalene and phenanthrene (PAH no. 1 and 2) in the gaseous phase, while a range of heavier species (PAH no. 5-13) were present in higher amounts in the condensed phase. The toxicity weighted data was dominated by benzo(a)pyrene, benzo(a)anthracene, benzo(b)fluoranthene and dibenzo(ah)anthracene (PAH no. 13, 9, 11 and 16). These species were present in significant amounts both in filter and adsorbent samples.

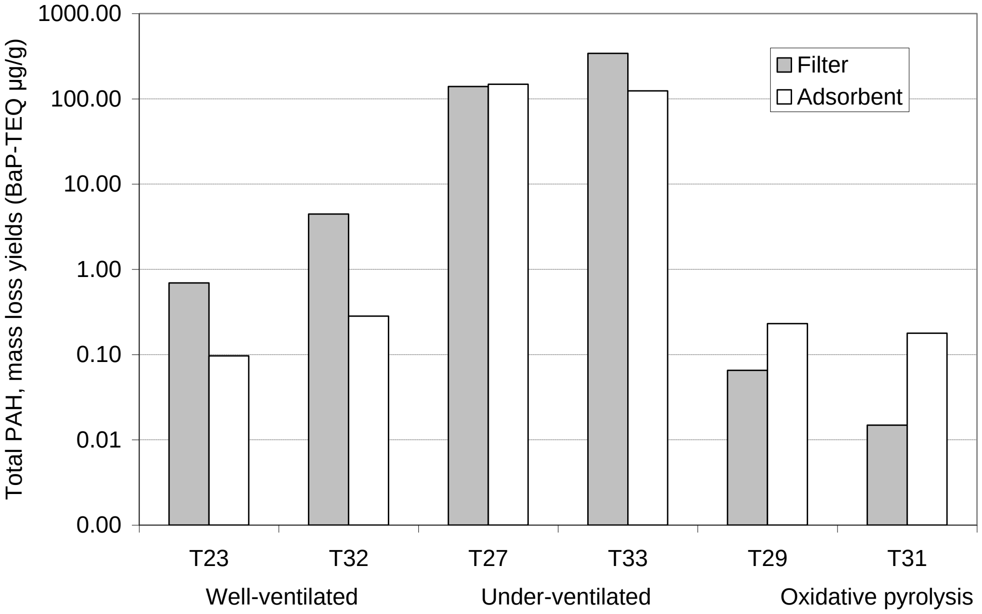


Figure 16 **Toxicity weighted yields of total PAH from tests with PVC-carpet.**

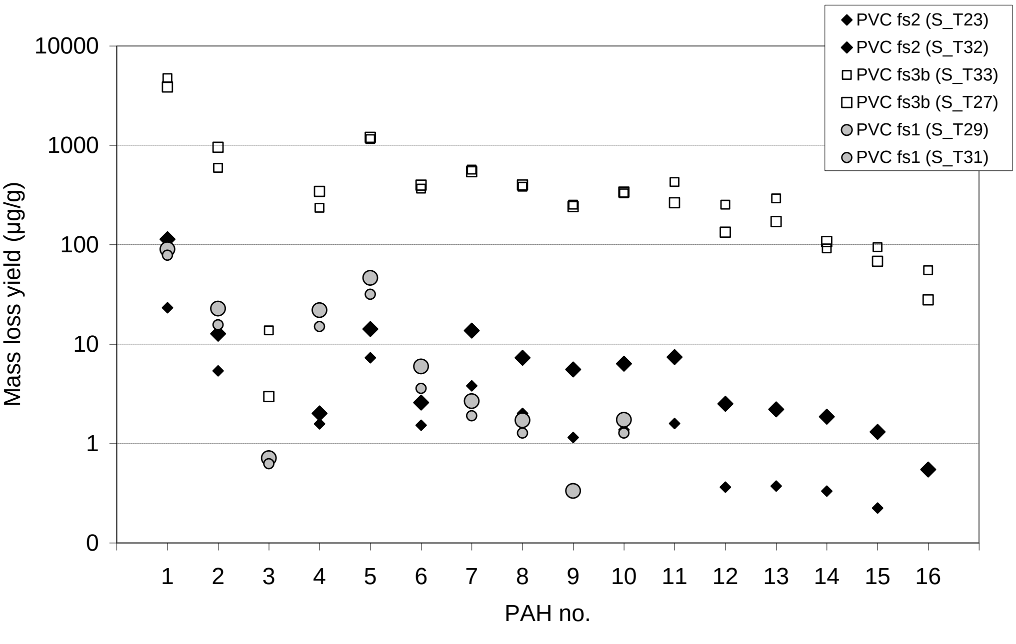


Figure 17 **Yields of individual PAHs (particle associated + gas phase) in the tests with PVC-carpet.**

3.4.3 Wood board (OSB)

In the tests with wood board material, PAH-analysis was made using the *OSV-sampler* and additionally through analysis of the particle phases separated by the *Sioutas* impactor.

The results from the *OVS-sampler*, which are separated in gas phase and particle associated PAHs, are given in Figure 18. The highest yield of total PAHs is clearly seen for under-ventilated conditions. The volatile part of the total PAH is dominating. The yields found from the well-ventilated tests are very low. The measured concentrations in these tests were of the same order of magnitude, but significantly exceeded, the concentration of a blank-sample taken between the tests (see Figure 29). A single pyrolysis test was analysed for PAH. Only volatile PAHs were found for this combustion condition.

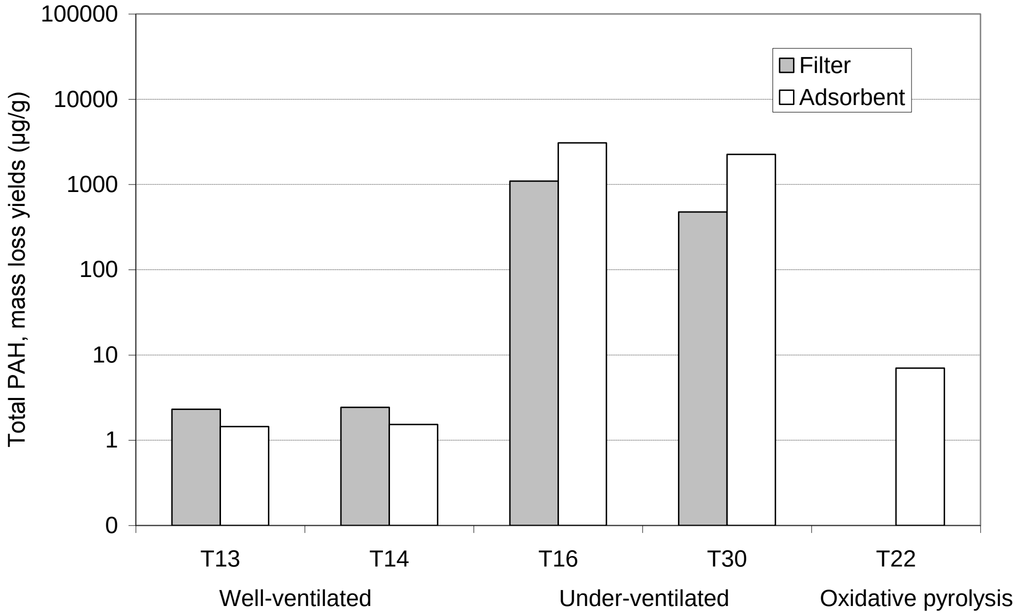


Figure 18 Data from *OVS-sampler*. Yields of total PAH from tests with the wood board (OSB) divided in particle associated (Filter) and gas-phase (Adsorbent).

Toxicity weighted yields have been calculated and are shown in Figure 19. This data shows that the particle associated part of total PAHs dominates the toxicity both for under-ventilated and well-ventilated conditions. The toxicity weighted yields for the under-ventilated tests are several orders of magnitude higher compared to the yields from the well-ventilated tests.

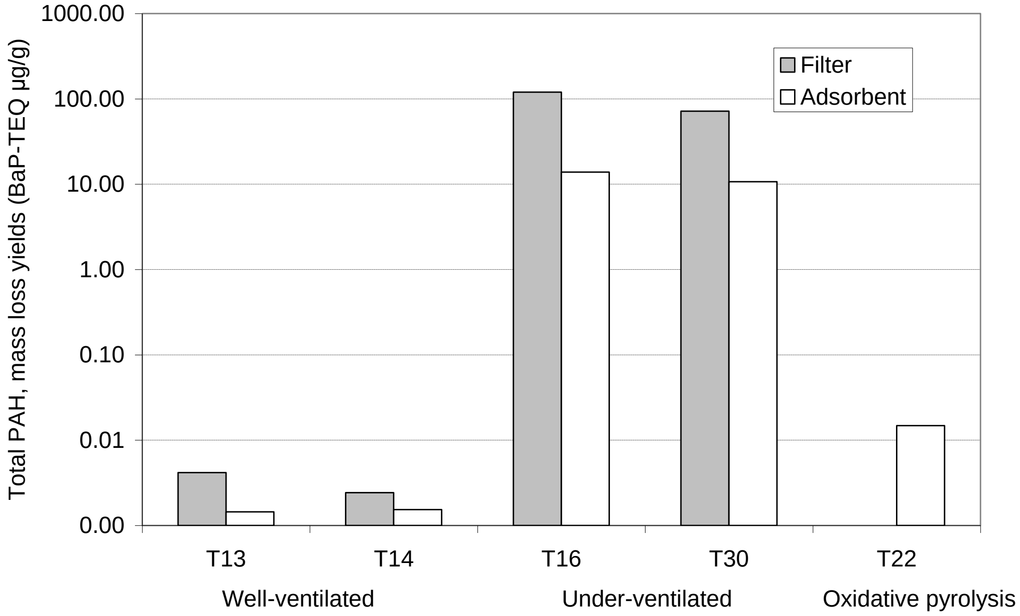


Figure 19 Toxicity weighted yields of total PAH from tests with the wood board (OSB).

Yield data from the *OVS-sampler* is shown for individual PAHs in Figure 20. The complete range of PAHs is found in the under-ventilated tests, whereas only volatile and semi-volatile PAHs were found in the well-ventilated tests and the pyrolysis test. The repeatability between duplicate tests is acceptable.

Data on the distribution of individual PAHs between the condensed phase (filter) and gaseous phase (adsorbent) is presented in Annex 3.2. The data is presented both as mass-loss yields and toxicity weighted (BaP-TEQ) mass-loss yields. Generally, for the *well-ventilated tests* naphthalene (PAH no. 1) dominated in the gaseous phase while phenanthrene (PAH no. 5) dominated in the condensed phase. The toxicity weighted data was dominated by phenanthrene.

The under-ventilated tests were dominated by naphthalene and acenaphthylene (PAH no. 1 and 2) in the gaseous phase, while fluoranthene and pyrene (PAH no. 7 and 8) were present in highest amounts in the condensed phase. The toxicity weighted data was dominated by benzo(a)pyrene (PAH no. 13) present predominately in the condensed phase.

The oxidative pyrolysis test only produced PAHs that were found in the gaseous phase of which phenanthrene (PAH no. 5) dominated.

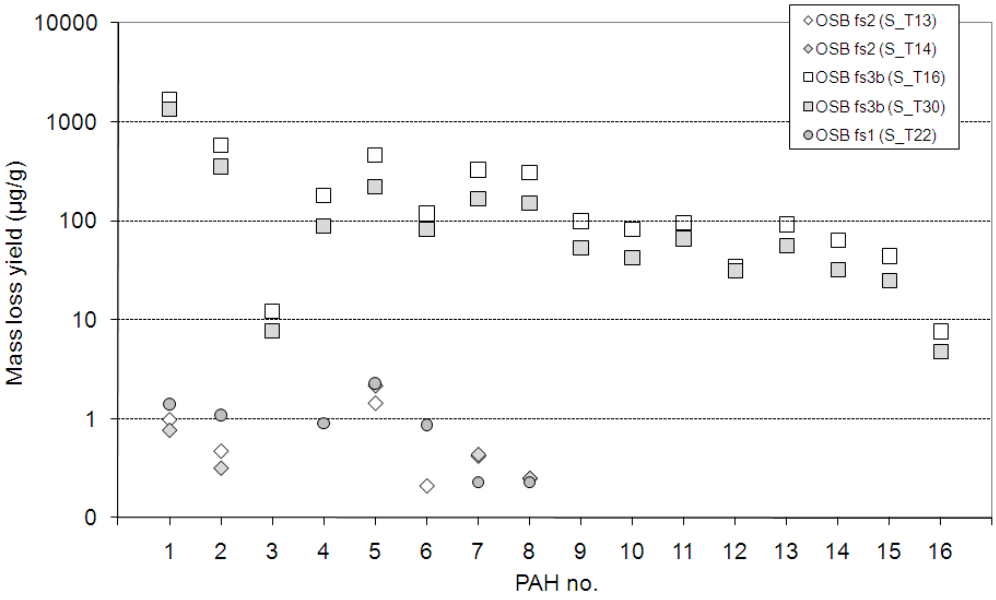


Figure 20 Data from *OVS-sampler*. Yields of individual PAHs in the tests with wood board (OSB).

The yield-data from the *OVS-analyser* is plotted together with the data from analysis of the impactor samples in Figure 21. The impactor data is presented here as sums of all particle size stages for individual PAHs.

Volatile and semi-volatile PAHs are captured poorly by the impactor sampling as only particulates are sampled. One would therefore expect very low concentrations of those compounds. This is clearly seen in Figure 21, where the data for the under-ventilated tests correlates for particle associated PAHs between the *OVS-sampler*, which samples both particle associated and vapour phase PAHs, and the data from the *Sioutas* impactor which only samples particulates. The yield values calculated for the impactor samples are generally somewhat lower compared to the yields from the *OVS-sampler*. This is expected as the PAHs that vaporise from the particle surfaces are effectively captured by the *XAD-2* in the *OVS-sampler*.

The quality of the measurements is to a degree validated by the correlation between the *OVS-sampler* and the data from the *Sioutas* impactor for particle associated PAHs.

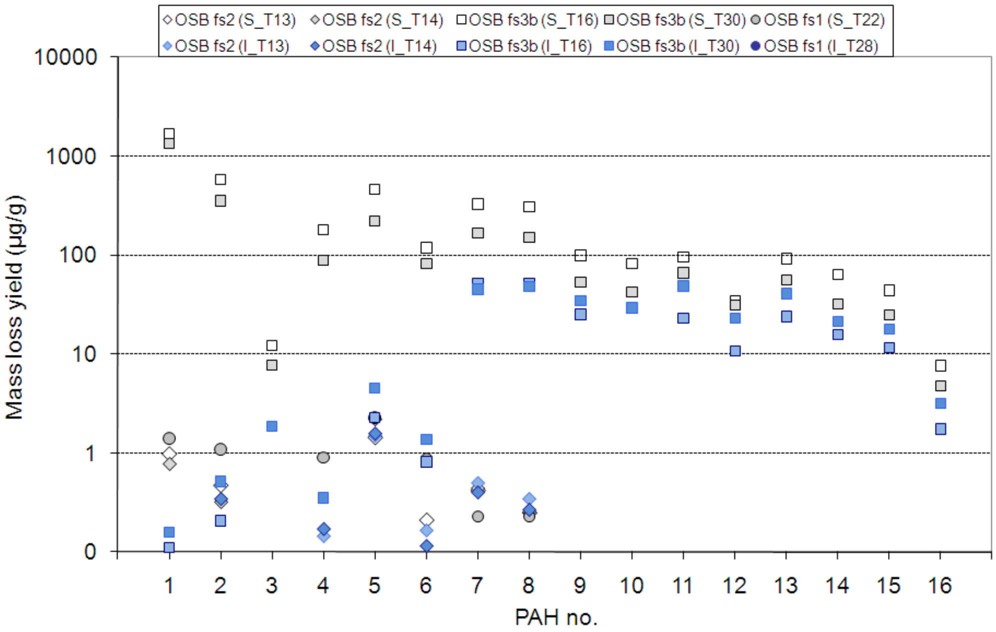


Figure 21 **Yields of individual PAHs in the tests with the wood board (OSB). Data from *OVS-sampler* (white or grey symbols) compared with data from analysis of the particles on the impaction plates of the *Sioutas impactor* (blue symbols).**

The distribution of individual PAHs between the different particle size stages (impactor plates) from the *Sioutas impactor* is shown in the figures below.

Figure 22 – Figure 23 show data from well-ventilated tests. PAHs were, in principal, only found in the < 0.25 µm-stage, i.e. PAHs were only associated to very fine particulates. Only volatile to semi-volatile PAHs were found, in low amounts.

Figure 24 – Figure 27 show data from the under-ventilated tests. Much higher yields of PAHs were found there and only semi-volatile to non-volatile PAHs are present in significant amounts. Yields are calculated relative to the amount of particulates captured on each stage in Figure 24 and Figure 26. There is no obvious trend seen in the relative distribution of individual PAHs between particulate size-distribution stages, i.e., relatively, there is generally no accumulation of any individual PAH for finer or coarser particulates. However, in absolute terms, the highest amounts of particle associated PAHs are found with particulates of the smallest sizes as the < 0.25 µm-stage often containing the absolutely highest mass of particulates, which is clear from Figure 25and Figure 27 where the yields of individual PAHs are calculated relative to the total amount of particulates captured by the impactor.

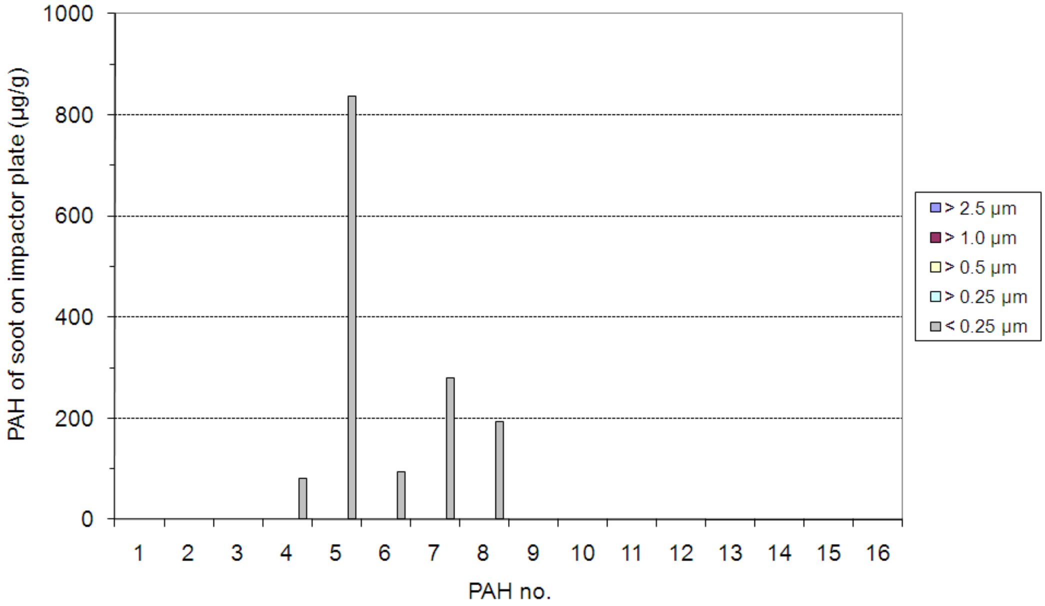


Figure 22 Well-ventilated test with the wood board material (T13) - Yields of individual PAHs relative the amount of soot captured on the different impactor plates.

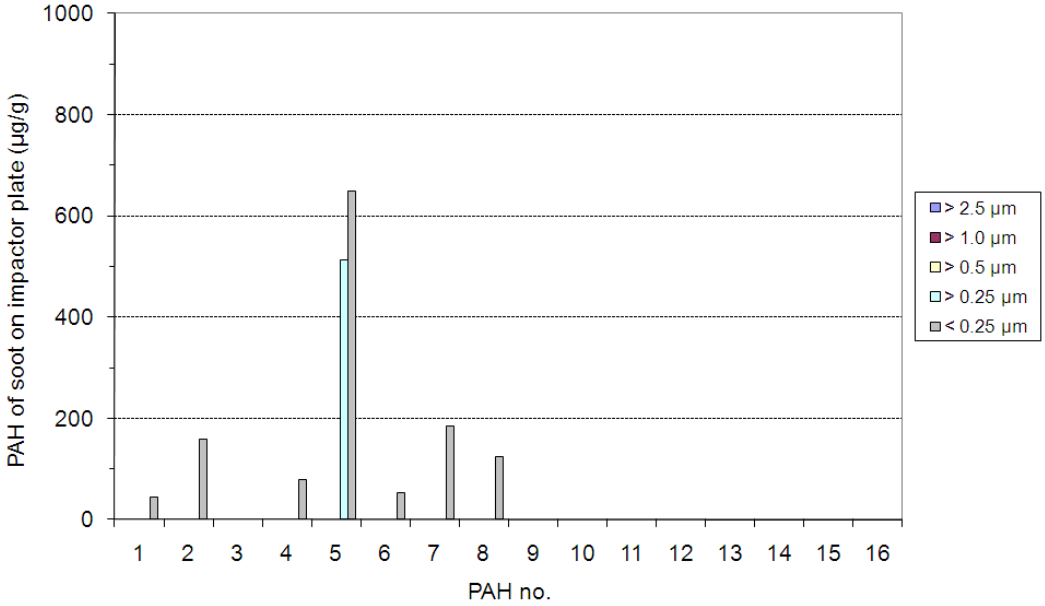


Figure 23 Well-ventilated test with the wood board material (T14) - Yields of individual PAHs relative the amount of soot captured on the different impactor plates.

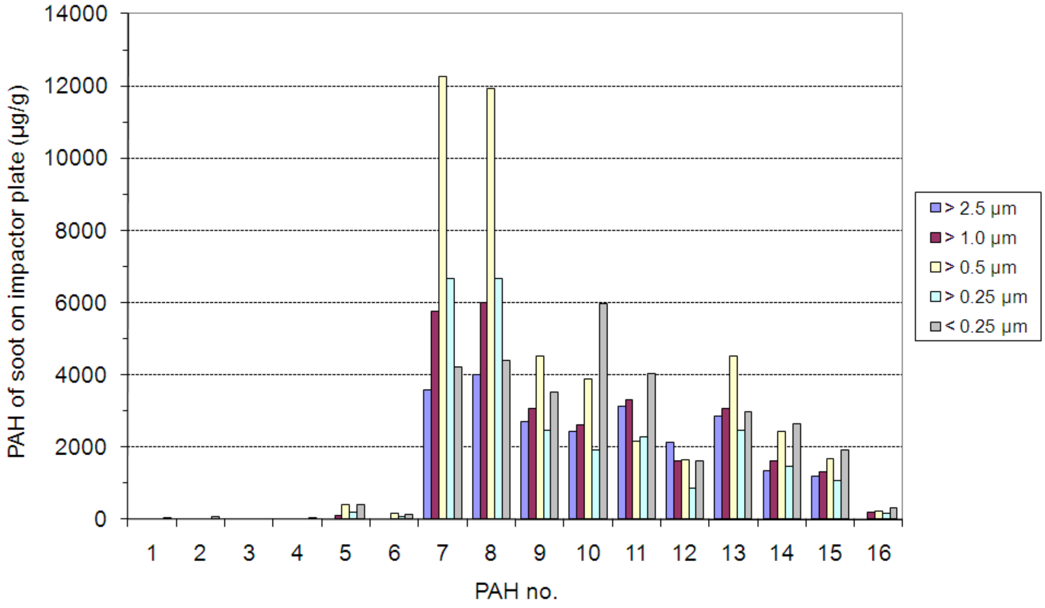


Figure 24 **Under-ventilated test with the wood board (T16) - Yields of individual PAHs relative the amount of soot captured on the different impactor plates.**

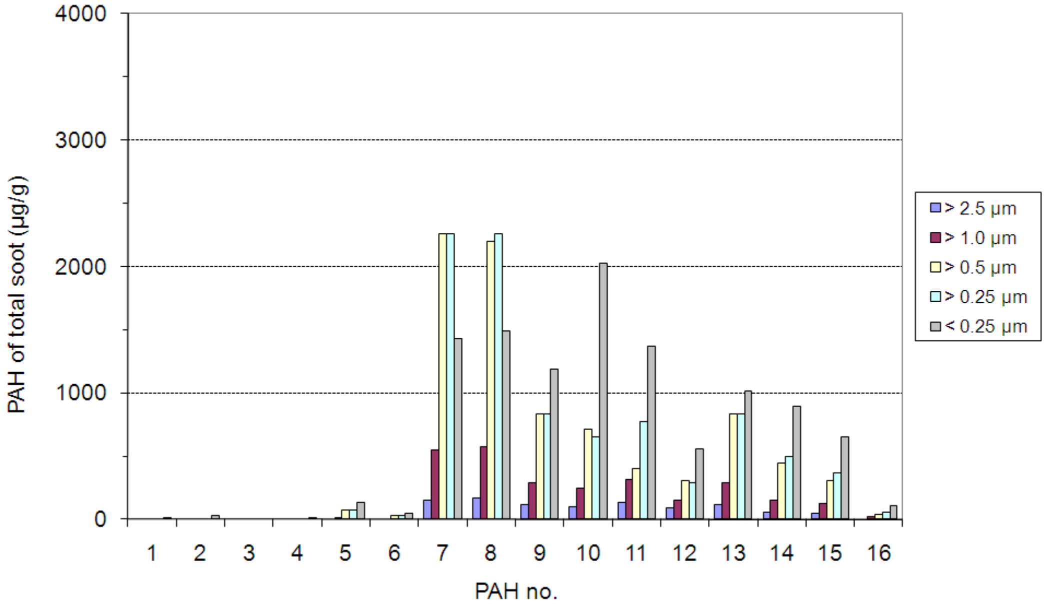


Figure 25 **Under-ventilated test with the wood board (T16) - Yields of individual PAHs relative the total amount of soot captured by the impactor.**

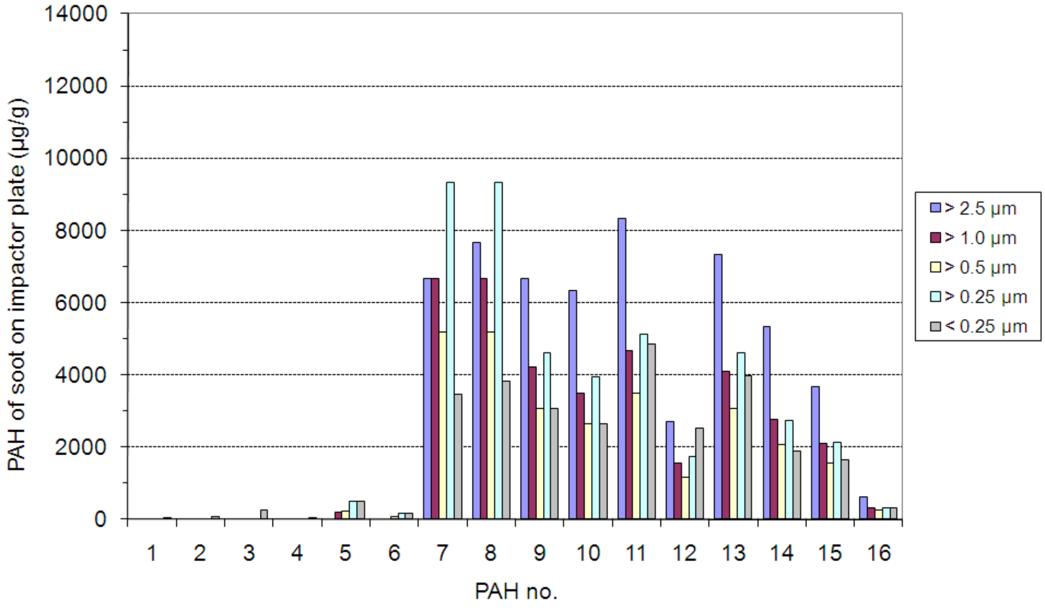


Figure 26 **Under-ventilated test with the wood board (T30) - Yields of individual PAHs relative the amount of soot captured on the different impactor plates.**

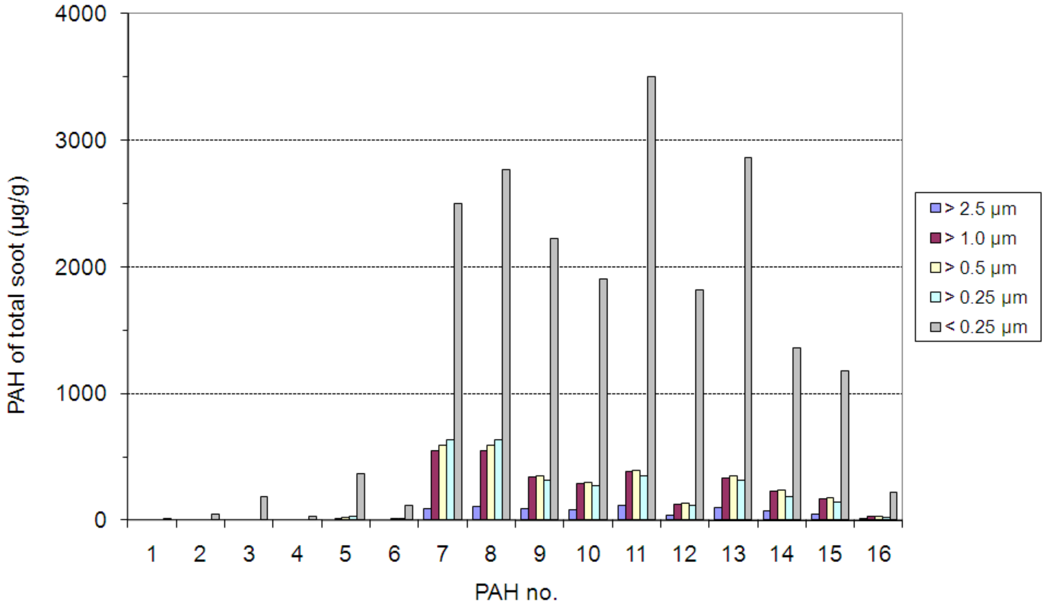


Figure 27 **Under-ventilated test with the wood board (T30) - Yields of individual PAHs relative the total amount of soot captured by the impactor.**

Figure 28 shows data for individual PAHs for the different particle size stages from the *Sioutas impactor*, in the single pyrolysis test. PAHs were only found from the two stages that capture the largest particulates. These were also the stages which captured the highest masses of particulates (see Figure 13). Only semi-volatile PAHs were found.

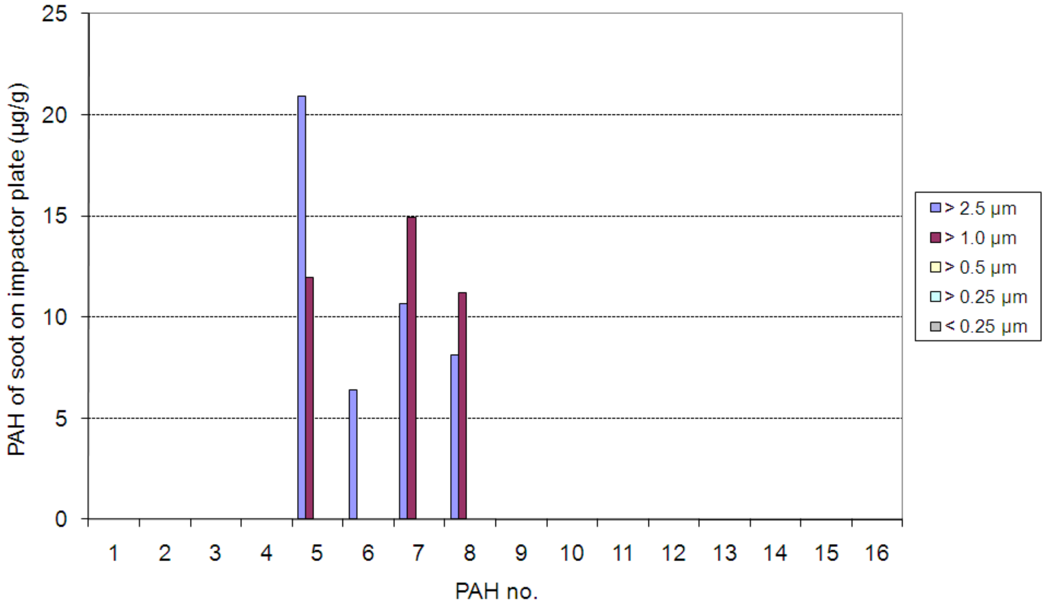


Figure 28 **Pyrolysis test with the wood board material (T28) - Yields of individual PAHs relative the amount of soot captured on the different impactor plates.**

3.4.4 Blank tests for PAH-analysis

Information concerning any contamination of the test and sampling equipment is important when analysing low concentrations of organic compounds. That is why blank samples were taken for PAH regularly between tests. Total PAH concentrations measured with the *OSV-sampler* for individual tests and blank samples are shown in Figure 29. The numbering of the tests is chronological. Contamination of PAHs was found in all blank samples, but the concentrations found in the blank tests were generally very low in comparison with the concentrations in the actual tests. Volatile to semi-volatile PAHs were found in the blank test only (see Annex 3.4).

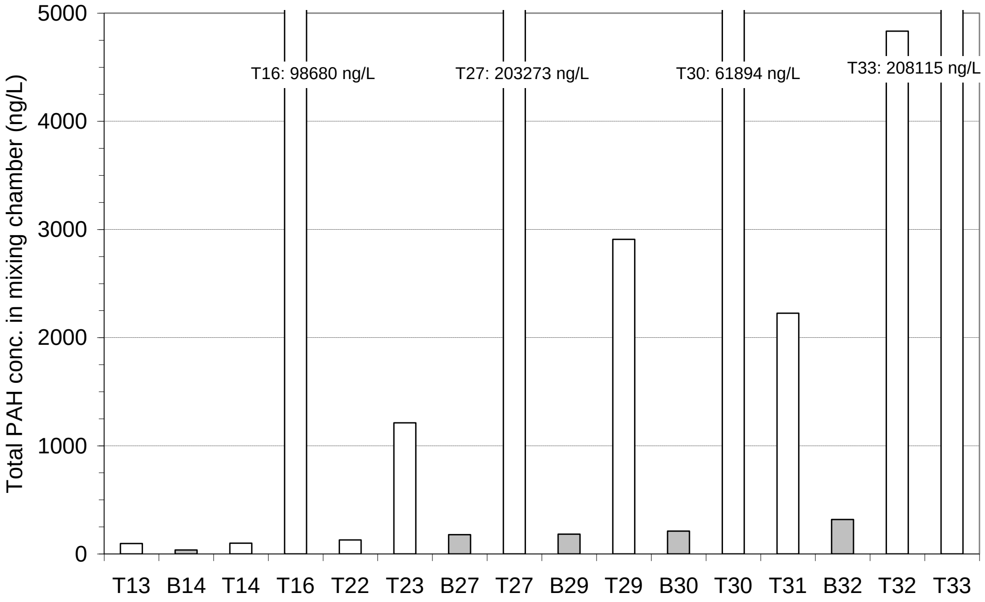


Figure 29 **Concentration of total PAH in all tests measured with *OVS-sampler*. Background concentrations measured in mixing chamber in grey colour.**

3.5 Distribution of chlorine

Analyses of the chlorine content and -distribution in the particle phase were attempted in Test Series 2 in selected tests with the PVC-carpet. Analyses were made of all impactor plates from the cascade impactor in these tests. The results expressed as weight-% chlorine in the soot for each impactor plate are presented in Figure 30 - Figure 32.

The chlorine content found in the soot is in the range between 0.5 and 2.5 weight-%. There is no significant difference between the well-ventilated and the under-ventilated tests. The chlorine content found in the pyrolysis test is, however, generally somewhat lower. For all three combustion conditions studied, the maximum chlorine content is found in the soot from the impactor plate that captured the highest amounts of particles (see section 3.3.1).

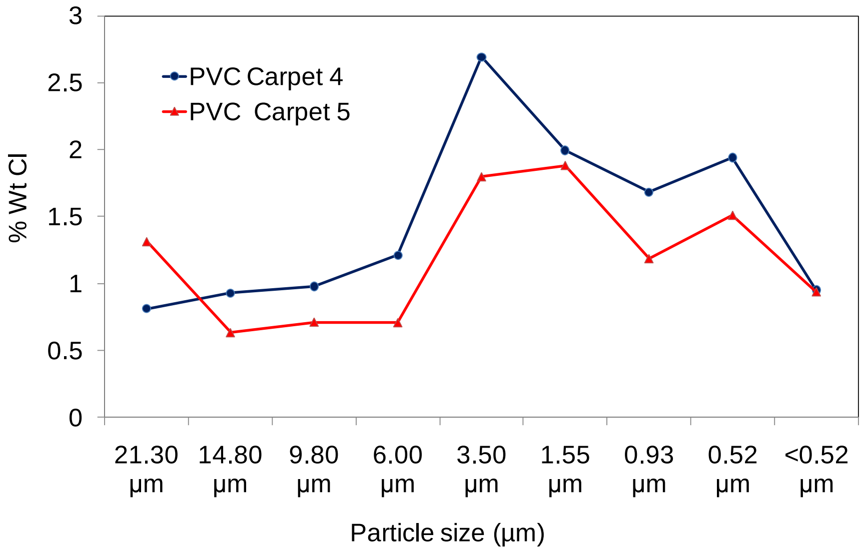


Figure 30 Chlorine content in PVC samples for well-ventilated fire conditions.

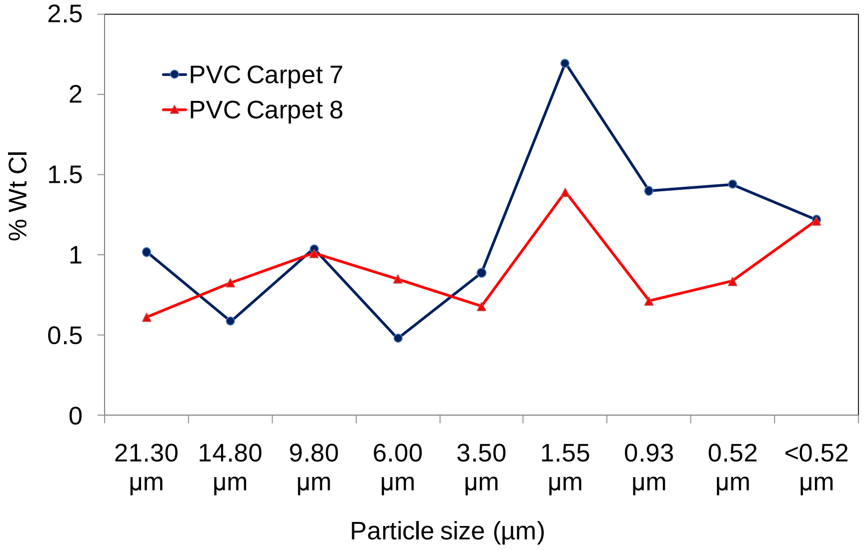


Figure 31 Chlorine content in PVC samples for under-ventilated fire conditions.

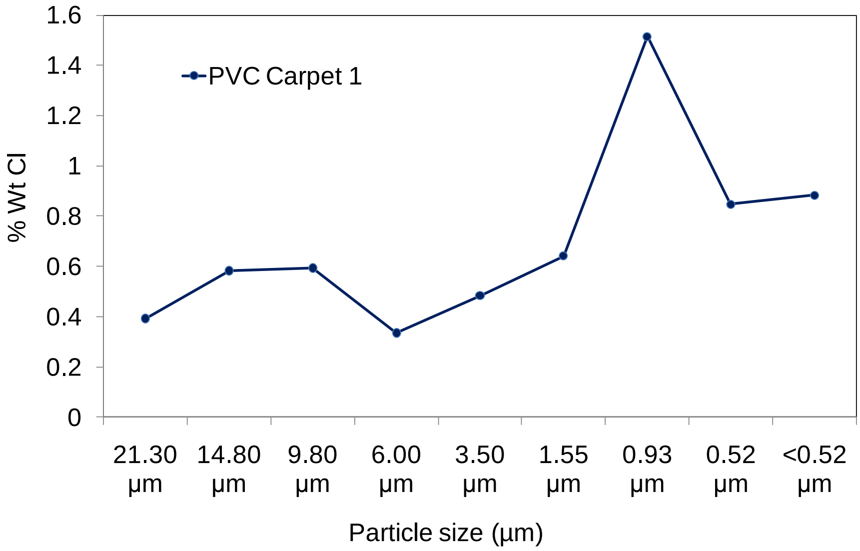


Figure 32 Chlorine content in PVC samples under oxidative pyrolysis conditions.

Soot was also sampled on “total-soot filters” and analysed for chlorine content in the tests with PVC-carpet in both Test Series 2 and Test Series 1. This data is tabulated in Appendix 2.3. Different analysis techniques were used for analysis of chlorine in the soot in the two test series. X-ray diffraction, XRF which is a surface analysis method was used in Test Series 2, and the High-Performance Ion Chromatography, HPIC where the chlorine in the sample first is dissolved in a solution were used in Test Series 1. Details of the analysis methods are given in section 2.5.

The analysis results do not give an unambiguous answer regarding the distribution of chlorine between the gaseous and condensed phases. The results from the analysis of the impactor palates in Test Series 2 indicate chloride concentrations in the approximate range 0.5 – 2.5 weight-% of the soot. The analysis of the total soot sampled in Test Series 1 shows chloride concentrations of the same range, while the analysis of total soot in Test Series 2 indicates concentrations about ten times higher (see Annex 2.3). These scattered results could be explained by limitations in the analysis methods utilized or that the chlorine concentration in the soot captured is related to the sampling procedure.

In the HPIC method, the total sample is dissolved and analysed, while the XRF method which is a point surface analysis method. There is the possibility that the XRF results are influenced by the thickness of the soot layer or by a variation of the chlorine concentration across the filter surface and the choice of specific measurement point. However, the XRF was carefully calibrated and triplicate analysis was made at different locations of the filter for each filter analysed. Another possible explanation would be that the chloride concentration was higher on the surface of the sampled soot, which would result in a higher measured chloride concentration from the XRF compared to the HPIC. A higher concentration on the surface of the sampled soot could be due to accumulation of HCl from the gas phase during the sampling which was not desired but could not be ruled out due to the sampling method.

The concentration of HCl in the smoke gases from the tests with the PVC-carpet was high. During well-ventilated tests, e.g., the concentration was about 4000 ppm in the gas phase as measured by FTIR. This concentration equals 5.7 mg/l HCl in gas phase which can be compared to the approximate 1.5 mg/l soot that was found. The amount of HCl in gas phase was therefore considerably larger compared to any HCl associated with the soot.

The HCl concentration found in the well-ventilated tests equals a mass-loss yield of HCl of about 0.3 g/g (see section 3.2.1). The theoretical maximum mass-loss yield of HCl is 0.38 g/g. If comparing with the yield of total soot found in these tests, which was about 0.05 g/g, the amount of HCl "remaining" for possible association to the soot is of the same magnitude as the amount of soot present. In other words, theoretically, the relative amount of chlorine from HCl could be very high in the soot, even though the major part of the HCl produced was shown to be present in the gas phase.

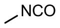
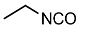
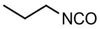
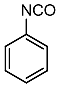
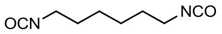
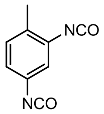
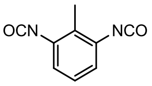
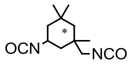
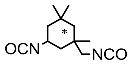
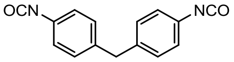
Hydrogen chloride is notoriously difficult to quantify with extractive methods in fire gases. There are numerous sources of error that have been studied in detail elsewhere [34]. The main reason for loss of HCl when using extractive methods is due to adsorption between the point of extraction and the point of analysis. This is in gas analysis minimised by keeping the temperature of the extraction devices (sampling probe, etc) above 150 °C. Despite this measure there is still a documented risk that HCl will be lost when going through a filter prior to entry into the FTIR. This is important when interpreting the amount of chlorine found on the soot. It is clear that the amount (in weight-%) is theoretically possible as not all HCl is recovered in the gas fraction as explained above. It is, however, impossible to state whether this chlorine is adsorbed onto the soot during combustion or whether it is in fact present due to HCl caught during extraction.

One method to investigate whether the chlorine found in the soot fraction is actually adsorbed onto soot particles during combustion or a result of the extraction method would be to study the effect of residence time of the fire gases in the post-tube chamber. This was not, however, within the scope of the project and has therefore not been done. It remains a question for future work.

3.6 Isocyanates

During thermal degradation of polyurethane, isocyanate monomers are formed together with corresponding amines and amino isocyanates [35]. Low molecular weight isocyanates such as isocyanic acid (ICA) and methyl isocyanate (MIC) are also formed during the thermal degradation of PUR or during thermal degradation of other nitrogen containing polymers, such as different phenol-formaldehyde-urea resins [36-37]. Data on isocyanates are given in Table 15.

Table 15 Data on isocyanates.

Isocyanate	Abbreviations	Amu	Structure formula	Henry's law constant ($atm.m^3/mol$)
Isocyanic acid	ICA	43.02	HNCO	N/A
Methyl isocyanate	MIC	57.05		405 (20 °C)[1]
Ethyl isocyanate	EIC	71.08		224 (20 °C)[2]
Propyl isocyanate	PIC	85.10		N/A
Phenyl isocyanate	PhI	119.12		1.5 (20 °C)[1]
Hexamethylene diisocyanate	HDI	168.20		0.05 (25 °C)[1]
2.4-Toluene diisocyanate	2.4-TDI	174.16		0.015 (20 °C)[1]
2.6-Toluene diisocyanate	2.6-TDI	174.16		0.015 (20 °C)[1]
Isophorone diisocyanate 1	IPDI 1	222.29		$3E^{-4}$ (20 °C)[1]
Isophorone diisocyanate 2	IPDI 2	222.29		$3E^{-4}$ (20 °C)[1]
4,4´-Methylenediphenyl diisocyanate	MDI	250.25		5 E^{-6} (25 °C)[3]

[1] www.inchem.org
[2] www.sigmaaldrich.com
[3] www.epa.gov
N/A = No information available

3.6.1 Preparatory tests

The wood board (OSB) and the PVC-carpet both emitted isocyanates during thermal degradation prompted using a hot air gun. Isocyanate monomers used in the PUR polymer, MDI for the wood board and HDI for the PVC-carpet, could be determined together with different kinds of monoisocyanates, see Table 16.

Table 16 Pre-test, indication of isocyanates for the two tested materials.

	ICA	MIC	EIC	PIC	PhI	HDI	TDI	IPDI 1	IPDI 2	MDI
PVC carpet	X	X		X		X		X		
Wood board, OSB	X	X	X		X					X

3.6.2 PVC-carpet

High concentrations of ICA were determined during the tests with the PVC-carpet. No HDI could be determined in the mixing chamber. The carpet only contained a relatively small layer of PUR coating and during the conditions tested almost all emitted HDI was further degraded.

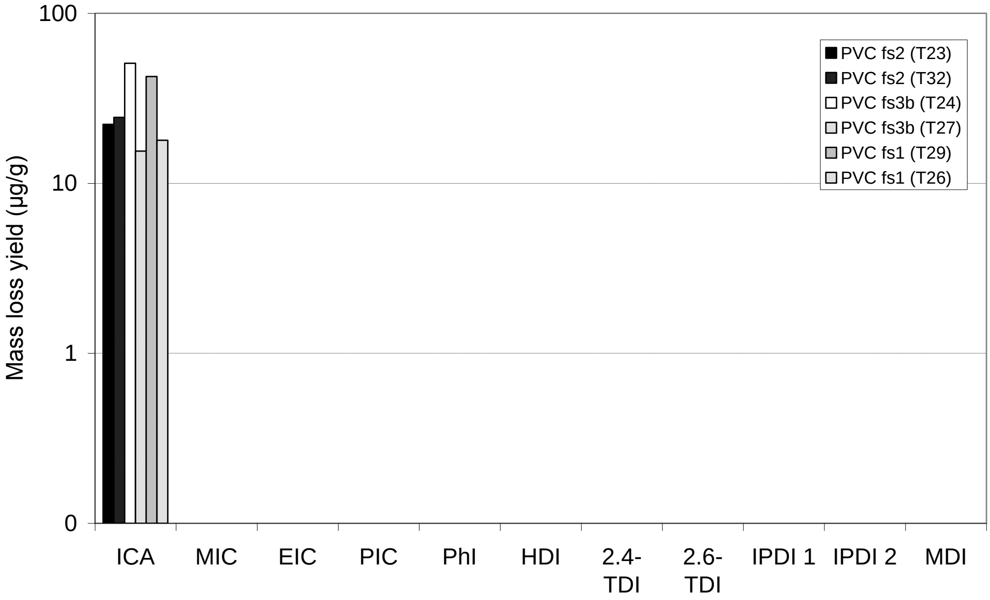


Figure 33 Yields of isocyanates in tests with PVC-carpet.

3.6.3 Wood board (OSB)

The tests showed high concentration of ICA and MIC and lower concentration of EIC, PhI and MDI. The results from the tests are consistent with the result from the pre-test. EIC, PIC and PhI is a result of thermal decomposition of MDI-based PUR and the ICA and MIC concentration are produced from thermal decomposition of the urea resin and PUR.

The well-ventilated tests (fs2) resulted in thermal degradation of the material to solely ICA. The pyrolysis tests (fs1) indicated less degradation compared to the well-ventilated tests which is consistent with the lower temperature found in the pyrolysis test (see Figure 34). The under-ventilated tests (fs3b) also exhibited less degradation and thus a higher number of degradation products compared to the tests with well-ventilated conditions. The reason for the less efficient degradation in spite of the higher temperature in the under-ventilated tests must be the high equivalence ratio with a lack of oxygen for oxidation of the material.

Monoisocyanates, such as ICA, MIC and PhI dominated the isocyanate content in the mixing chamber. ICA, MIC and PhI were predominately present in the gas phase and mainly collected in the denuder part in the denuder-impactor sampler. For ICA >85% were found in the denuder, for MIC >98% and for PhI >93 %. In addition to the gas phase monoisocyanates, particle bound MDI was determined in impactor stage 1 (d_{50}=2.5 µm) during the pyrolysis test. For both sampling occasions using the denuder-impactor sampler (described in Figure 35 and Figure 36), the end filter, present after the last impactor stage was not analysed.

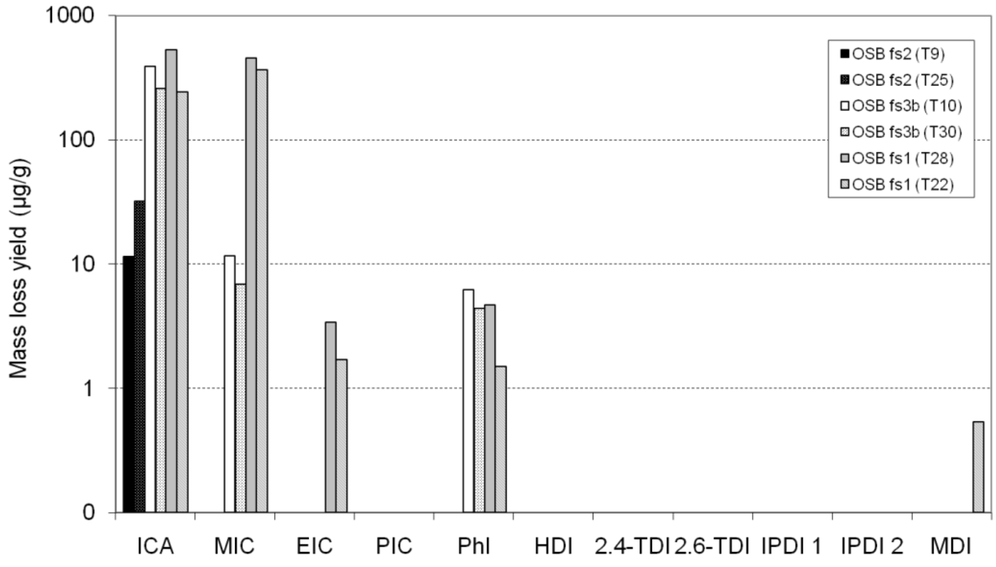


Figure 34 Yields of isocyanates in tests with the wood board (OSB).

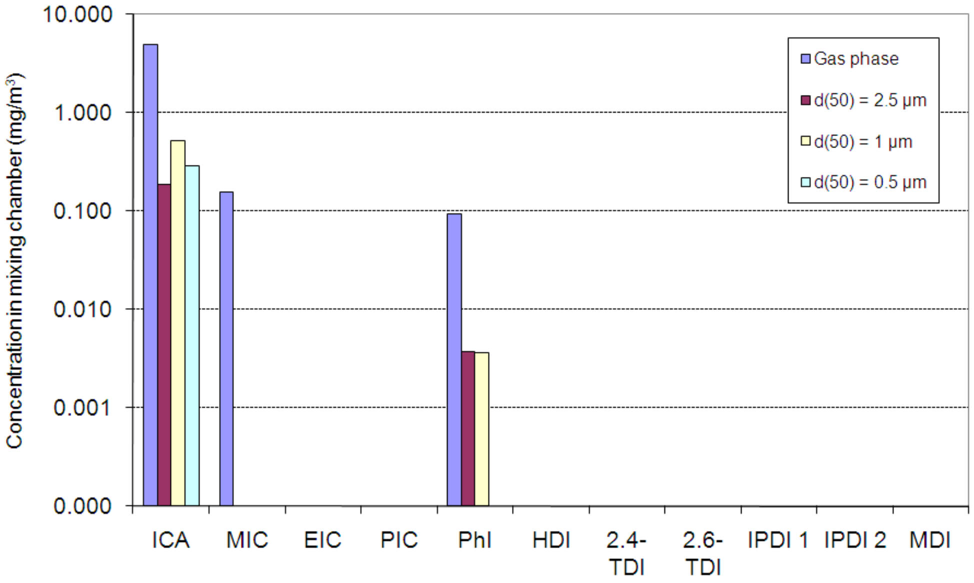


Figure 35 Distribution of isocyanates between impactor stages in an under-ventilated test (fs 3b) with the wood board (OSB).

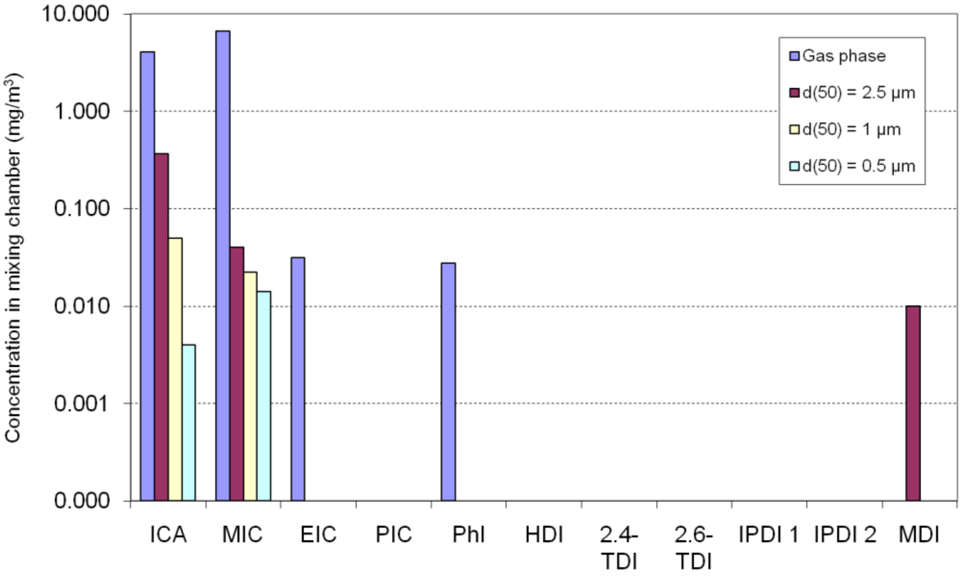


Figure 36 **Distribution of isocyanates between impactor stages in a pyrolysis tests (fs1b) with the wood board (OSB).**

3.6.1 Discussion and comparison of results

The test scenario used, ISO/TS 19700 - the steady-state tube furnace, represents a controlled and constant combustion model. Ideally, once the steady-state period is established no major disturbances of the combustion taking place in the furnace tube are seen, and the combustion products are effectively diluted and cooled in the mixing chamber where the sampling for analysis takes place. This is intended to enable the analysis of combustion products from isolated and well-defined combustion conditions. However, the variability of a real fire is not captured by this model and it would be interesting, e.g., to compare the results on isocyanates from the tube furnace with data from other fire models of different scales.

No prior data are available from measurements on fires where isocyanates are separated into gas phase and particle size distribution stages. There are, however, data available on isocyanates from previous work where fire tests were conducted with the cone calorimeter (ISO 5660) [11]. The cone calorimeter is a small-scale test where the sample material has unlimited access to air for the combustion, i.e. the test is inherently well-ventilated. A PVC-carpet and a Particle board were included in the cone calorimeter study. Note that these products might differ considerably in composition from the products studied in this current project. The results on isocyanates from the cone calorimeter tests are, however, similar to the results from the tube furnace tests. In the cone calorimeter, the PVC-carpet produced only ICA. The Particle board product produced ICA, MIC and MDI, although ICA and MIC dominated and only traces of MDI were found.

In an investigation of a hospital fire [6], a fully furnished room fire test was conducted where the room contained a PUR-mattress and a PVC-carpet as part of the fire load. The sampling of smoke gases for isocyanate analysis was divided in three periods, where the last period coincided with flashover and ignition of the PVC-carpet. The individual isocyanates found from this sample included ICA, MIC, PHI and traces of TDI, where ICA was the dominating species (>95%).

The distribution of isocyanates in the denuder-impactor sampler has been described previously from exposure chamber studies [38] [39]. Similar to this study it was observed that during collection of thermal degradation products of polyurethane, volatile monoisocyanates were collected on the denuder part, whereas diisocyanates were distributed over all the different sampler stages, e.g. 4,4-MDI, which is a non-volatile compound, was never present in the vapour phase. Condensation of MDI is fast and it was instantaneously associated to particles. Immediately after generation, 50% of the MDI was found on the end filter (d_{50}=0.5µm), i.e., on the smallest particles.

4 Conclusions

Whether a chemical substance is found in the vapour phase or in the condensed phase associated with particles, may be important in different ways. Species in the gas phase have a high diffusion rate and reactive molecules are rapidly absorbed in the respiratory tract mucosa, which thereby protects the deeper parts of the respiratory tract. However, a particle-bound molecular substance can be transported much longer before contact with the respiratory tract occurs.

Small particles have a higher proportion of surface area per mass than larger particles, and because smoke contains a high proportion of ultrafine particles, the ultrafine fraction is a major part of the total area that is available for absorption. It is therefore plausible that substances may be enriched by absorption on the smaller particles. Should this be the case, it is important information since these particles are easily transported far into the lungs.

The present project has examined the question of distribution patterns of important chemical compounds between gas phase and particle phase. It has also, in some cases, addressed the question of the distribution of individual particle-associated species between the different size-ranges of particles produced in a fire. The chemical compounds studied were hydrogen chloride (HCl), a gas that readily dissolves in water and is known to adhere to surfaces, polycyclic aromatic hydrocarbons (PAHs), and isocyanates.

In order to study the production of particles from different types of fire exposure, three different fire types were investigated: Fire type 1b – oxidative pyrolysis, Fire type 2 – well-ventilated flaming fires ($\phi < 0.75$), and Fire type 3b – vitiated post flashover fires in large or open compartments ($\phi = 2$). Further two materials were chosen for investigation (PVC-carpet and wood board) based on their prevalence fire exposure scenarios and their chemical composition.

The particle production from the two materials investigated varied both concerning the amounts produced and the particle size distributions. The production of particles on a mass basis was generally significantly lower from the wood board compared with the PVC-carpet (approx. 10 times lower), with the exception of the high production seen from oxidative pyrolysis of the wood board material.

The tests with the PVC-carpet showed that relatively large particles are produced from all combustion conditions examined. The well-ventilated and under-ventilated tests showed production of both large and small particles whereas the particles from oxidative pyrolysis were found in a narrow distribution of large particle sizes.

The tests made with the wood board show preferably predisposition towards the production of small-sized particles during flaming combustion. The difference in particle sizes was not significant between well-ventilated and under ventilated combustion. A significantly different particle size distribution was, however, seen in the tests with oxidative pyrolysis conditions where the maximum in particle mass was found at a larger particle size and the production of small sized particles was limited.

It was noted that the particle measurements in both tube furnace test-series gave relatively equivalent results which indicates that the combustion conditions were equivalent and that the particle analysis was reliable.

The analysis of PAHs in the tests with the PVC-carpet showed that volatile PAHs are quantitatively dominating during all types of combustion. However, when the toxicity of the individual species was taken into account, the relative importance between volatile and particle associated PAHs changed. For both well-ventilated and under ventilated conditions, the toxicity weighted yields for the particle associated PAHs increased in importance and generally dominated over the volatile species. The toxicity weighted data was dominated by species in the condensed phase including benzo(a)pyrene, benzo(a)anthracene and benzo(b)fluoranthene. The toxicity weighted yields for the under ventilated tests were magnitudes higher compared to the yields from the well-ventilated tests. For oxidative pyrolysis conditions, however, the volatile part dominated the toxicity.

Regarding the occurrence of individual PAHs, a general trend towards decreasing yields with increasing molecular mass was seen for all combustion conditions studied. It is interesting to note that both well-ventilated and under ventilated combustion of the PVC-carpet produced the complete range of PAHs. In the pyrolysis tests, however, only volatile and semi-volatile PAHs were produced.

From the tests with the wood board material (OSB) it was noted that the highest yields of total PAHs were found from under-ventilated conditions, and the volatile part of the total PAH dominated for this material as well. The yields found from the well-ventilated tests were very low. Toxicity weighted data showed that the particle associated part dominated the toxicity both for under ventilated and well-ventilated conditions. The toxicity weighted yields for the under ventilated tests were several magnitudes higher than those for the well-ventilated tests and benzo(a)pyrene was provided the greatest contribution to the toxicity. The complete range of individual PAHs was found in the under-ventilated tests, whereas only volatile and semi-volatile PAHs were found in the well-ventilated tests and the pyrolysis test.

The different stages of the impactor were analysed for PAHs in tests with the wood board material. PAHs were in principally only found associated with very fine particles in well-ventilated tests, and only volatile to semi-volatile PAHs were found in very low concentrations. Much higher yields of PAHs were found in the under-ventilated tests. Only semi-volatile to non-volatile PAHs were present, but in significant amounts. No clear trend was seen in the relative amounts of individual PAHs on the different stages of the impactor, i.e., there was no accumulation of any individual PAH for finer or coarser particulates. In absolute terms, however, particle-associated PAHs were found associated with particulates of the smallest sizes as these particles were seen to dominate in general.

Analysis of combustion gases in the tests with the PVC-carpet showed that the yield of gas phase HCl is high for all types of combustion with the PVC-carpet. The HCl yields found from well-ventilated and under-ventilated combustion were close to the theoretical maximum mass-loss yield. The yield from the pyrolysis test was actually above the theoretical maximum due to the fact that HCl is abstracted from otherwise non-combusted PVC-carpet in these tests resulting in the production of HCl despite the fact that the polymer backbone was otherwise largely intact.

Some study was made of the presence of chlorine on particles. It is clear that the major part of the HCl produced during combustion is present in the gas phase. Chlorine was found associated with particulates but these results were, however, inconclusive due to the difficulty in determining the source of the chlorine found in the soot fractions studied. The effect of ageing of the smoke gases must, however, be importance in determining the distribution of chlorine between the gas phase and particles and requires further study.

Both the PVC carpet and the OSB board had low polyurethane (PUR) content. This, in combination with the substantial degradation of the PUR in the tests, resulted in no or very small amounts of quantifiable isocyanate dimers (i.e. high molecular species). Monoisocyanates such as ICA and MIC dominated completely in the emitted degradation products, even during the pyrolysis test. These kinds of monoisocyanates are volatile compounds and almost exclusively present in the gas phase, which was illustrated by the denuder-impactor samples. From the preparatory tests where the conditions were completely different compared to the tube furnace tests, the formation of di-isocyanates compared to mono-isocyanates was much higher. In an actual fire situation the combustion conditions will vary temporally and spatially depending on the stage of the fire, the ventilation conditions and the material present in the combustion zone. The formation of both mono and di-isocyanates at high concentrations will probably be possible during different periods of a fire. However, results from a room fire experiment showed almost exclusively gaseous mono-isocyanates in the fire effluents after flashover, which is the period of a room fire with the highest effluent production rate. More study needs to be performed to determine isocyanate emissions in detail and its contents in different particle size fractions during controlled and actual fire conditions.

5 References

[1] Pope C.A. et al., “Daily mortality and PM10 pollution in Utah Valley”, Ach Environ Health, 47, 211-217, 1992.

[2] Hertzberg T., Blomqvist P., Dalene M., Skarping G., “Particles and isocyanates from fires”, SP Fire Technology, SP Report 2003:05.

[3] D’Alessio A., D’Anna A., Gambi G., Minutolo P., Sgro L.A och Violo A., Combustion-generated Nanoparticles, Chim. Ind., 81, 1001-1006, 1999.

[4] Wichmann H-E. et al., “Daily Mortality and Fine and Ultrafine Particles in Erfurt, Germany”. Part I: Role of Particle Number and Particle Mass, Report, Health Effects Institute, Nov. 2000.

[5] Johnston CJ, Finkelstein JN, Mercer P, Corson N, Gelein R, Oberdorster G., “Pulmonary effects induced by ultrafine PTFE particles”, Toxicol Appl Pharmacol. ,Nov 1;168(3):208-15, 2000.

[6] Hertzberg T., Blomqvist P., “Tuovinen H., Measurement and simulation of fire smoke”, SP Fire Technology, SP Report 2005:29, 2005.

[7] Tommy Hertzberg, Per Blomqvist and Heimo Tuovinen, ”Reconstruction of an arson hospital fire”, Fire and Materials, 31, 225-240, 2007.

[8] Blomqvist P., “Emissions from Fires - Consequences for Human Safety and the Environment”, Doctoral Dissertation, Department of Fire Safety Engineering, Lund University, Lund 2005.

[9] Galloway, F. M., and Hirschler, M. M., "A Model for the Spontaneous Removal of Airborne Hydrogen Chloride by Common Surfaces", Fire Safety Journal, 14, 251-268, 1989.

[10] Edgerley, P. G., and Oldland, S. R. D., "The loss of HCl from the smoke from burning PVC", Imperial Chemical Industries Limited, 1979.

[11] Blomqvist, P., Hertzberg, T., Dalene, M. and Skarping, G., ” Isocyanates, aminoisocyanates and amines from fires - a screening of common materials found in buildings”, Fire and Materials, 27, 275-294, 2003.

[12] http://www.chemistry.manchester.ac.uk/research/facilities/manal/

[13] ISO/TS 19700, “Controlled equivalence ratio method for the determination of hazardous components of fire effluents”, 2007.

[14] ISO 19706, “Guidelines for assessing the fire threat to people”, 2007.

[15] Johansson, L. S., "Characterization of Particle Emissions from Small-Scale Biomass Combustion", Licentiate Thesis, Department of Energy Technology, Chalmers University of Technology, Göteborg, 2002.

[16] http://www.sph.uth.tmc.edu/mleland/attachments/MLeland_Sioutas2.pdf

[17] http://www.newstarenvironmental.com/pdfs/74126marpleSeries290_brochure.pdf*

[18] Marand, Å., Karlsson, D., Dalene, M., & Skarping, G., ”Solvent-free sampling with di-n-butylamine for monitoring of isocyanates in air”, Journal of Environmental Monitoring 7, 335-343, 2005.

[19] Dahlin, J., Spanne, M., Karlsson, D., Dalene, M., & Skarping, G., “Size-Separated Sampling and Analysis of Isocyanates in Workplace Aerosols. Part I. Denuder-Cascade Impactor Sampler”, Annals of Occupational Hygiene, Vol 52, No 5 , 361-374, 2008.

[20] Karlsson, D., Dahlin, J., Marand, Å., Skarping, G., & Dalene, M., ”Determination of airborne isocyanates as di-n-butylamine derivatives using liquid chromatography and tandem mass spectrometry”, Analytica Chimica Acta, 534 , 263-269, 2005.

[21] Marand, Å., Karlsson, D., Dalene, M., & Skarping, G., “Solvent-free sampling with di-n-butylamine for monitoring of isocyanates in air”, Journal of Environmental Monitoring, 7, 335-343, 2005.

[22] Blomqvist P., Hertzberg T., Tuovinen H., Arrhenius K. and Rosell L., ”Detailed determination of smoke gas contents using a small-scale controlled equivalence ratio tube furnace method”, Fire and Materials, 31, 495-521, 2007.

[23] Purser D., Stec A.A. and Hull T.R., ”Effect of material and fire conditions on toxic product yields”, chapter 14 in *Fire Toxicity*, edited by Hull and Stec, Woodhead publishing limited, 2010.

[24] Blomqvist P., ”Emissions from fires – Consequences for Human Safety and the Environment”, *PhD-thesis*, Lund University, Sweden, 2005.

[25] Hertzberg T. and Blomqvist P., ”Particles from fires – a screening over common materials found in buildings”, Fire and Materials, 27, 295-314, 2003.

[26] Butler K.M. and Mulholland G.W., ”Generation and transport of smoke components”, Fire Technology, 40-2, 149-176, 2004.

[27] Delistraty, D., "Toxic equivalency factor approach for risk assessment of polycyclic aromatic hydrocarbons", Toxicological and Environmental Chemistry, 64, 81-108, 1997.

[28] Manahan, S. E., Environmental Chemistry, 6:th ed., Lewis Publishers, 1994.

[29] S.O. Baek, M.E. Goldstone, P.W.W. Kirk, J.N. Lester, R. Perry, ”Phase distribution and particle size dependency of polycyclic aromatic hydrocarbons in the urban atmosphere”, Chemosphere, Volume 22, Issues 5-6, pages 503-520, 1991.

[30] U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES, Public Health Service, Agency for Toxic Substances and Disease Registry, ” TOXICOLOGICAL PROFILE FOR POLYCYCLIC AROMATIC HYDROCARBONS”, 1995.

[31] EPA, Integrated Risk Information System (IRIS). Chemical Specific Reference Doses and Cancer Potency Factors”, Environmental Protection Agency, Cincinnati, USA.

[32] IARC, ”IARC Monographs on the Evaluation of Carcinogenic Risks to Humans”, IARC International Agency for Research on Cancer.

[33] Nisbet, I. C. T. and LaGoy, P. K., ”Toxic Equivalence Factors (TEFs) for Polycyclic Aromatic Hydrocarbons (PAHs)”, Regulatory Toxicology and Pharmacology, 16, 290-300, 1992.

[34] Hakkarainen (Ed.), ”Smoke gas analysis by Fourier transform infrared spectroscopy”, Final report of the SAFIR project, EU contract no. SMT4-CT96-2136, 1999.

[35] Karlsson D., Dalene M., Skarping G., Marand Å., (2001) Determination of Isocyanic Acid in Air, J. Environ. Monit., 3, 432-436.

[36] Karlsson D, Dalene M and Skarping G (1998). Determination of complex mixtures of airborne isocyanates and amines. Part 5. Determination of low molecular weight aliphatic isocyanates as dibutylamine derivatives. Analyst, 123, 1507-1512.

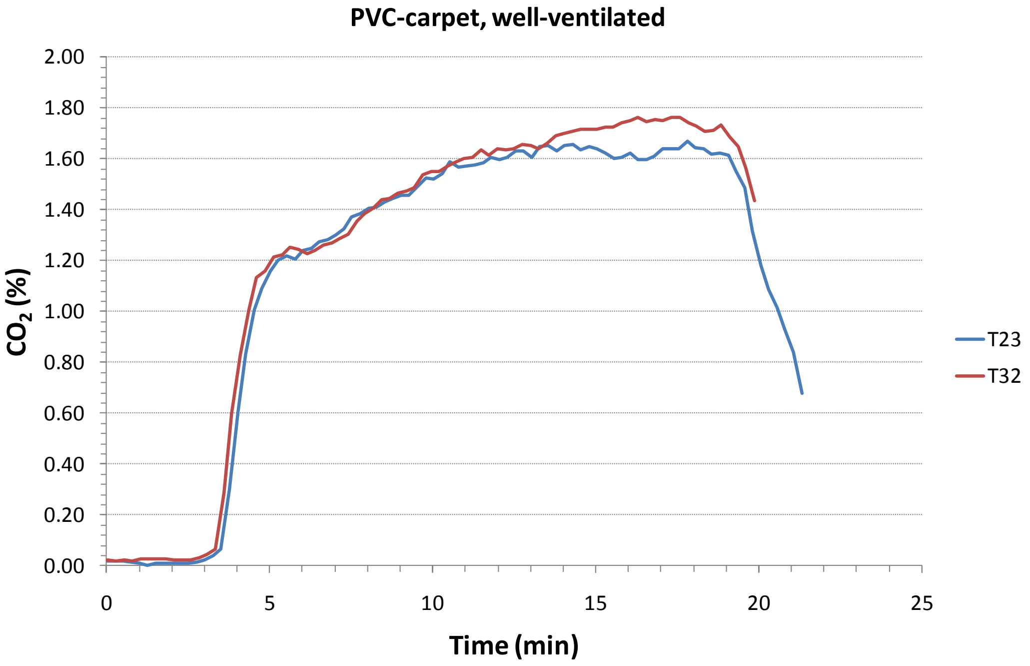
[37] Karlsson D., Spanne M., Dalene M., Skarping G., (2000) Airborne Thermal Degradation Products of Polyurethane Coatings in Car Repair Shops, J. Environ. Monit., 2, 462-469.

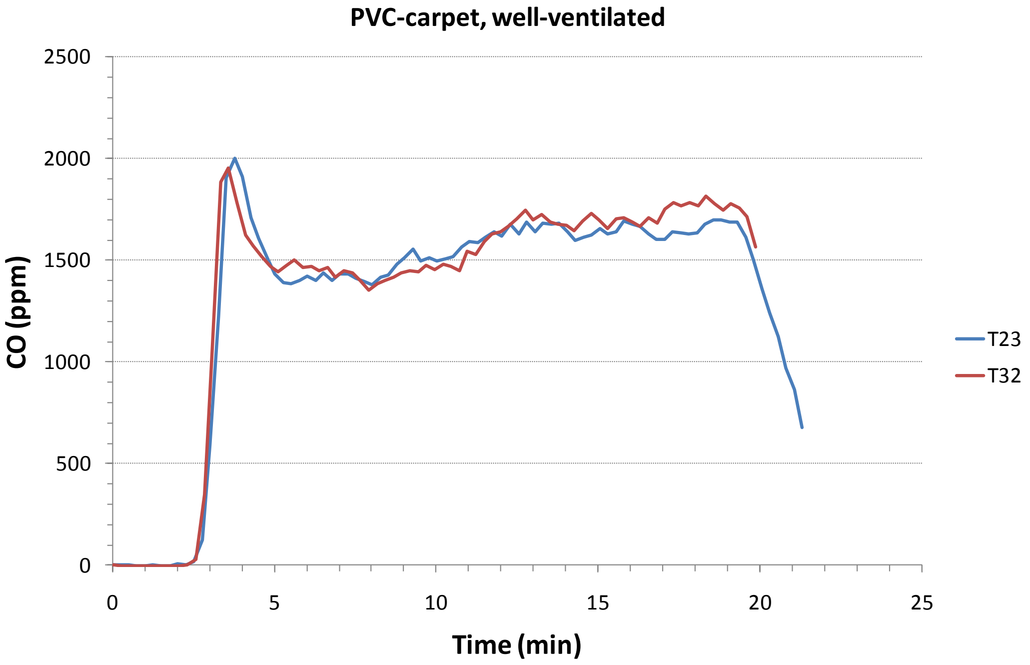
[38] Dahlin J., Spanne M., Karlsson D., Dalene M and Skarping G., Size-separated sampling and analysis of isocyanates in workplace aerosols. Part I. Denuder-cascade impactor sampler, ANNALS OF OCCUPATIONAL HYGIENE, 52(5), 361-374, 2008.

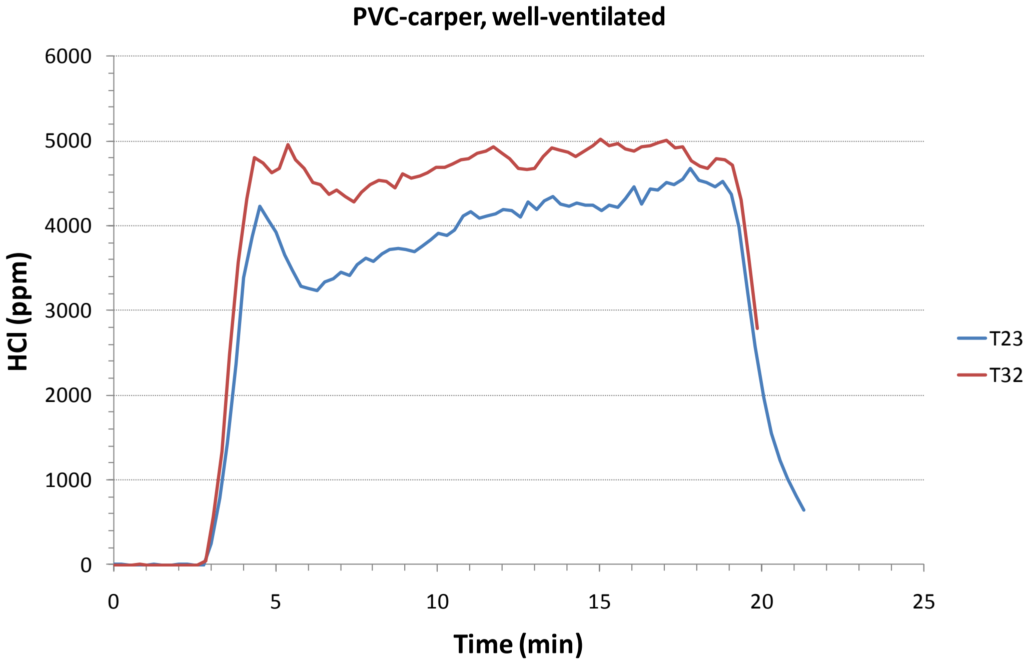
[39] Dahlin J., Spanne M., Dalene M., Karlsson D and Skarping G., Size-separated sampling and analysis of isocyanates in workplace aerosols - Part II: Aging of aerosols from thermal degradation of polyurethane, ANNALS OF OCCUPATIONAL HYGIENE, 52(5), 375-383, 2008.

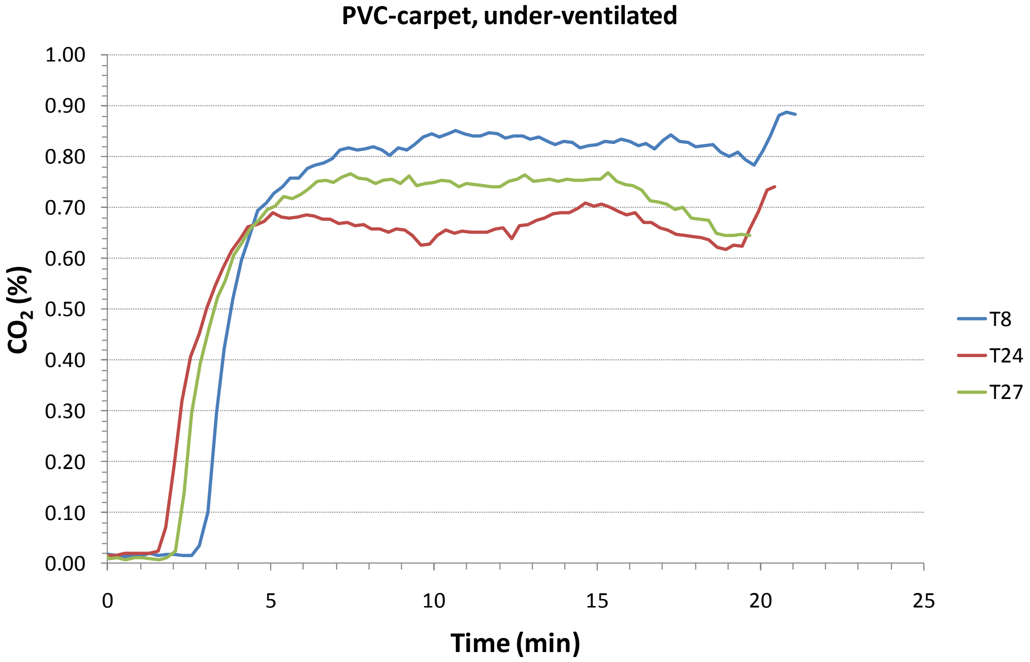
Annex 1 Gas analysis data

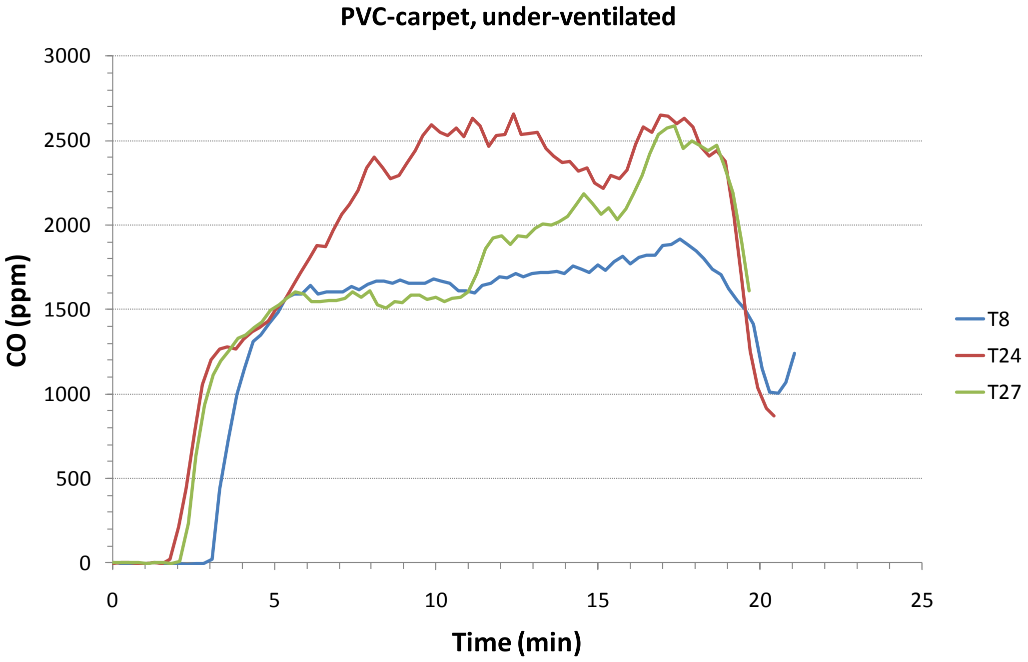
A 1.1 PVC-carpet

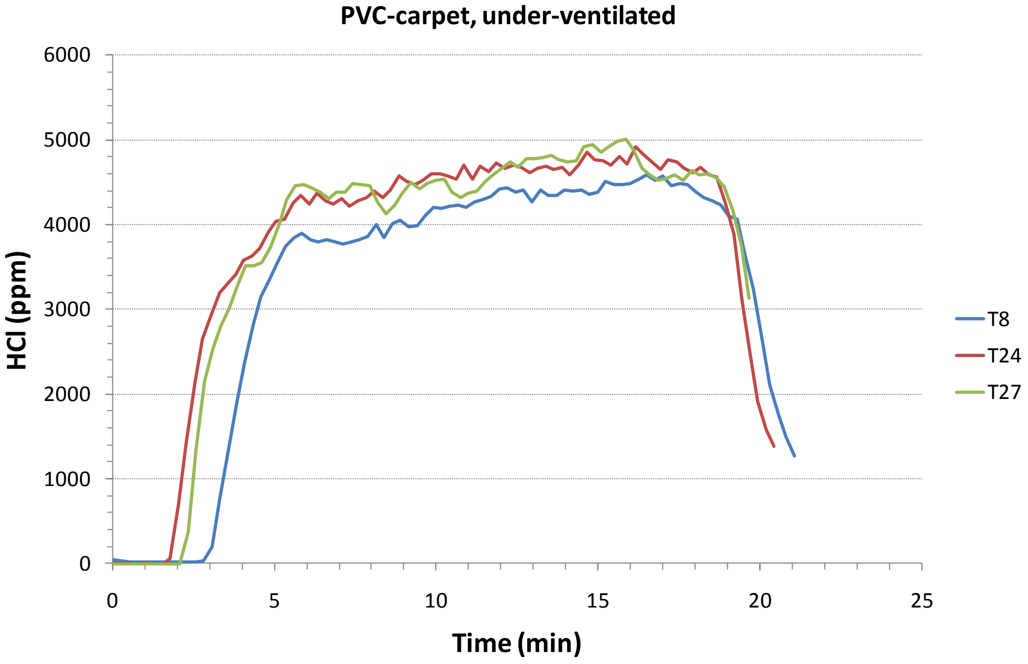


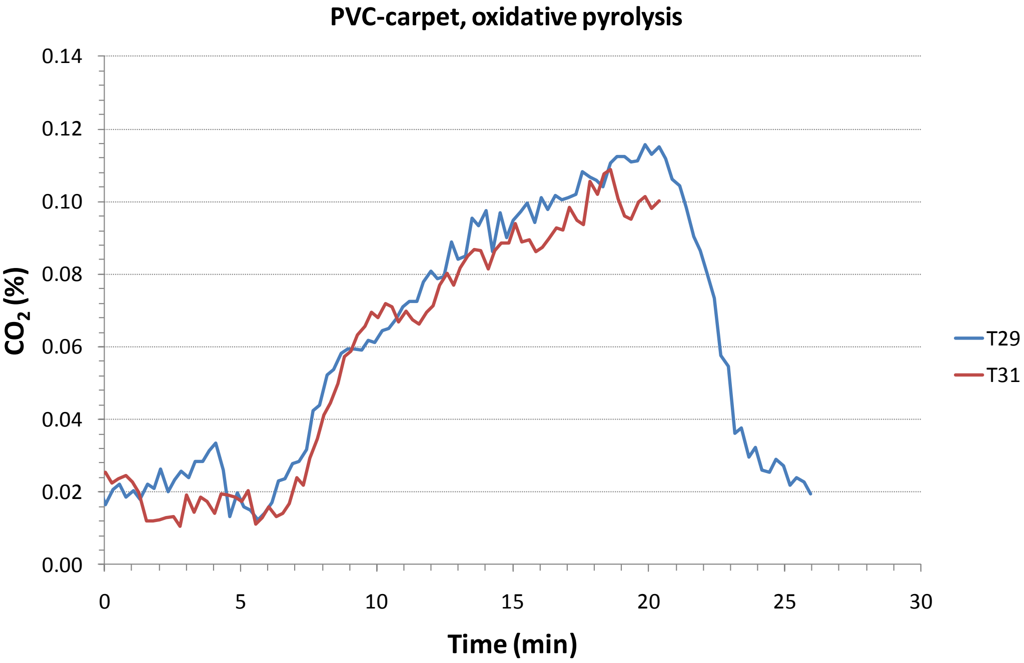


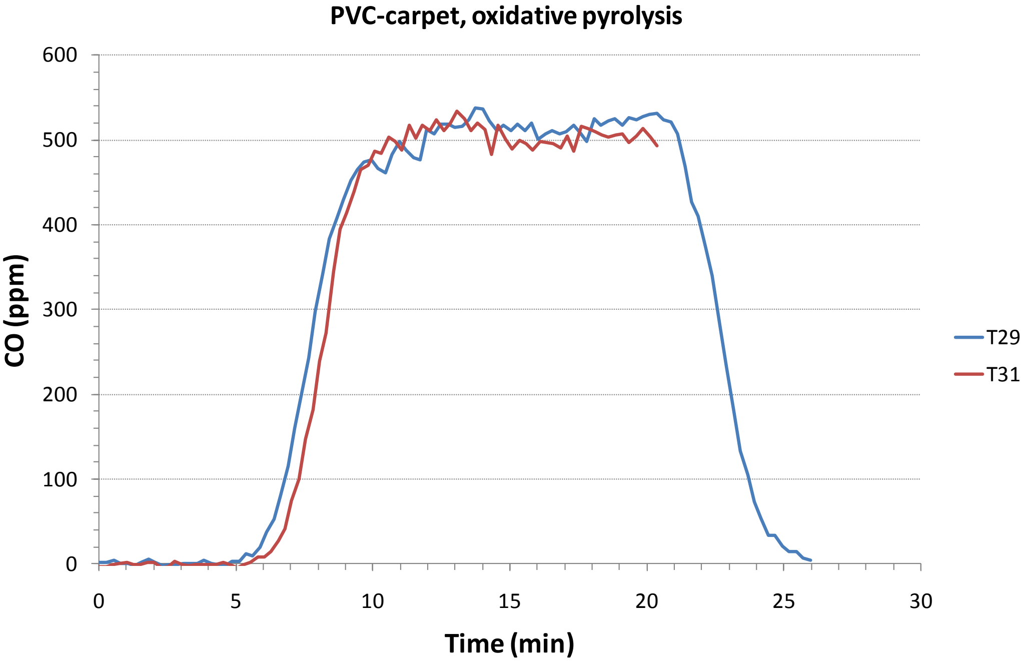

PVC-carper, well-ventilated
HCl (ppm)
6000
5000
4000
3000
2000
1000
0
0
5
10
15
20
25
Time (min)
T23
T32

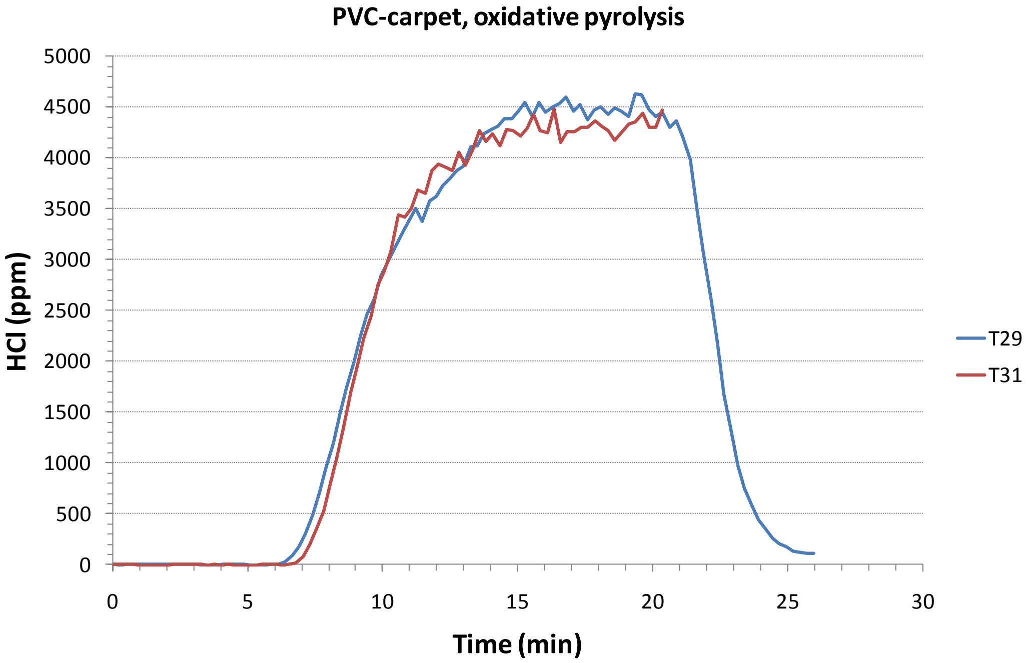

PVC-carpet, under-ventilated
CO_2 (%)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
5
10
15
20
25
Time (min)
T8
T24
T27


PVC-carpet, under-ventilated
CO (ppm)
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
Time (min)
T8
T24
T27

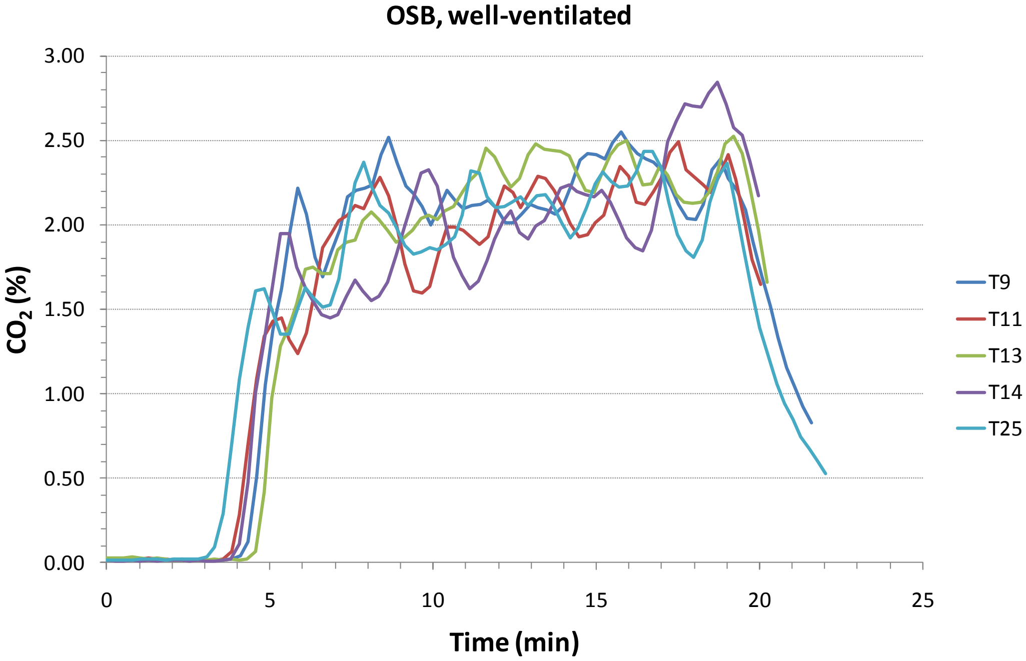

PVC-carpet, under-ventilated
HCl (ppm)
6000
5000
4000
3000
2000
1000
0
0
5
10
15
20
25
Time (min)
T8
T24
T27

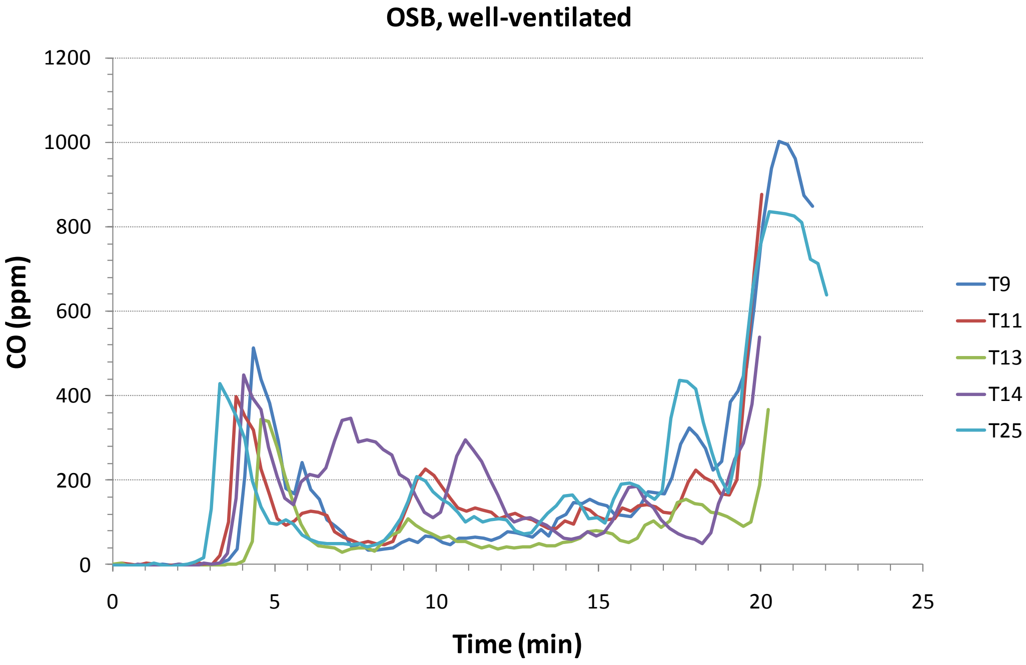

PVC-carpet, oxidative pyrolysis
CO_2 (%)
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
5
10
15
20
25
30
Time (min)
T29
T31

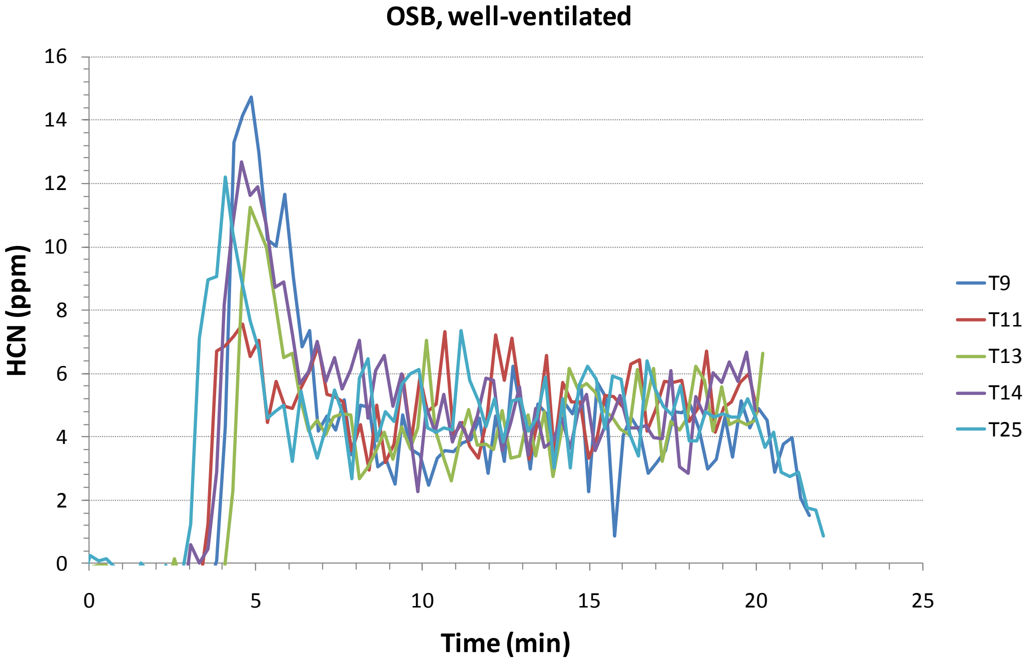

PVC-carpet, oxidative pyrolysis
CO (ppm)
600
500
400
300
200
100
0
0
5
10
15
20
25
30
Time (min)
T29
T31

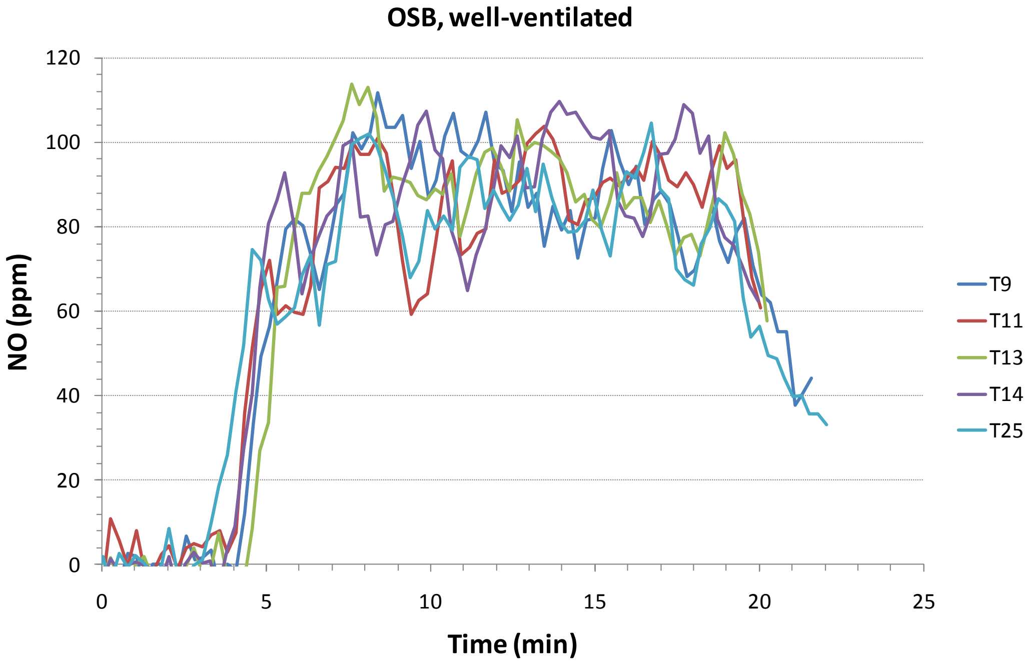

PVC-carpet, oxidative pyrolysis
HCl (ppm)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
Time (min)
T29
T31

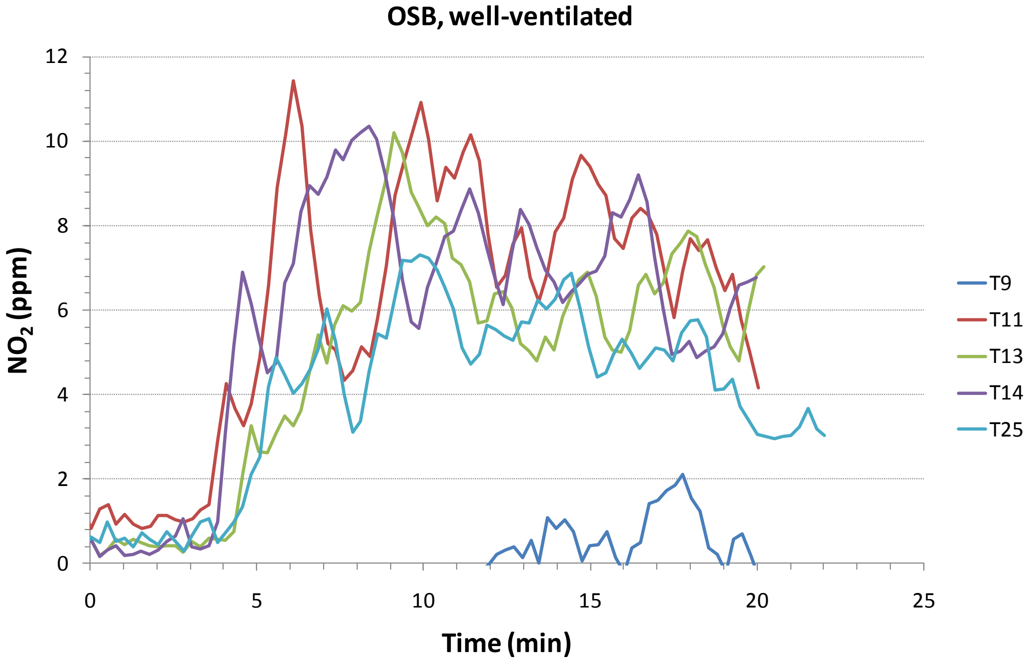
A 1.2 OSB

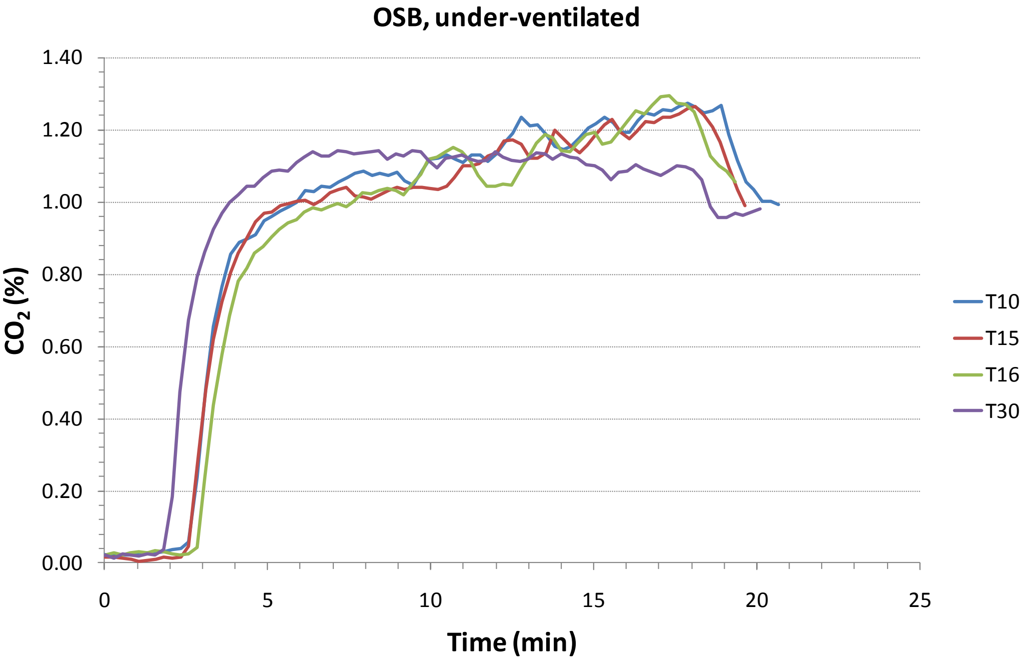

OSB, well-ventilated
CO_2 (%)
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
5
10
15
20
25
Time (min)
T9
T11
T13
T14
T25

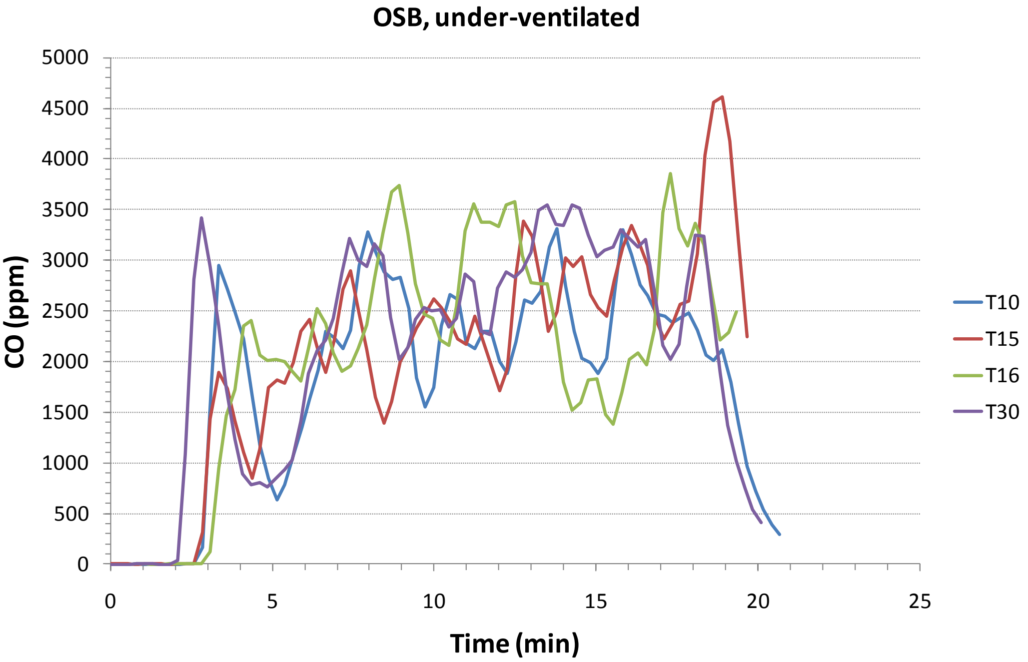

OSB, well-ventilated
CO (ppm)
1200
1000
800
600
400
200
0
0
5
10
15
20
25
Time (min)
T9
T11
T13
T14
T25

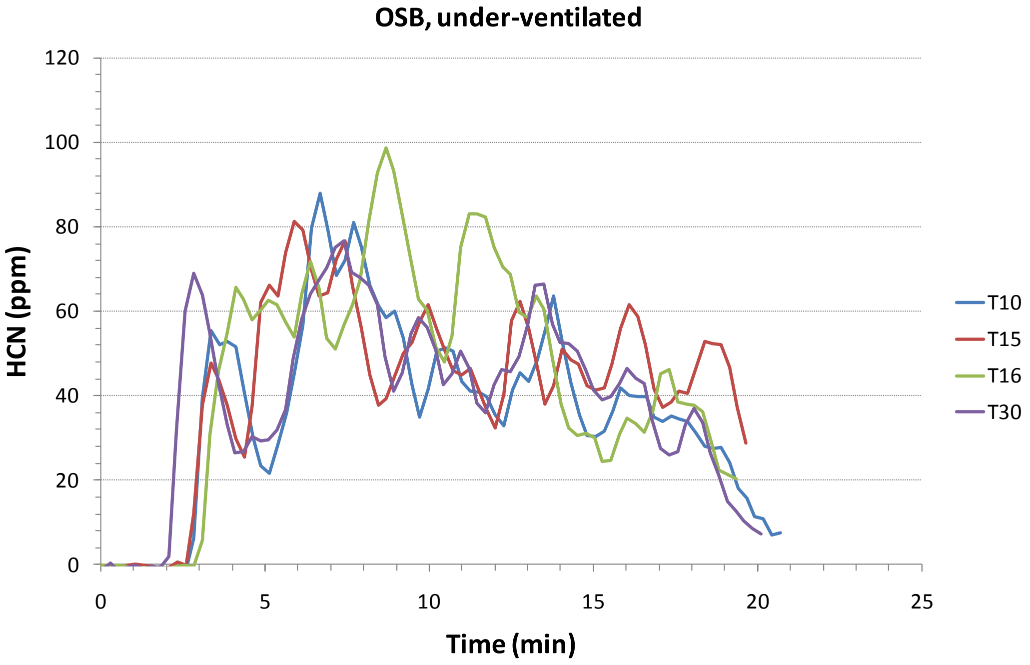

OSB, well-ventilated
HCN (ppm)
16
14
12
10
8
6
4
2
0
0
5
10
15
20
25
Time (min)
T9
T11
T13
T14
T25

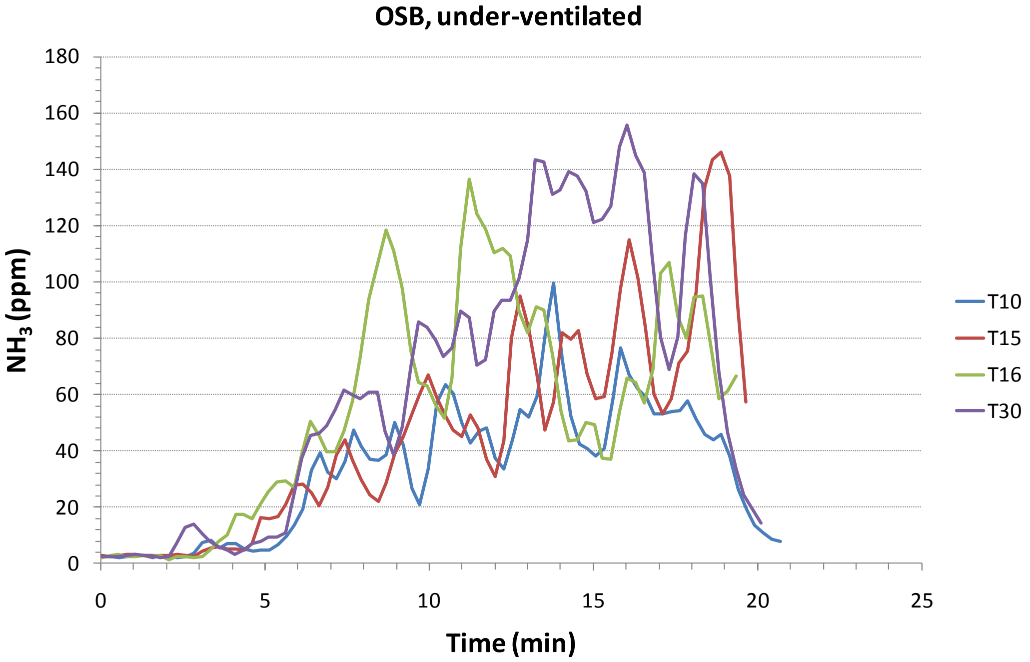

OSB, well-ventilated
NO (ppm)
Time (min)
0
20
40
60
80
100
120
0
5
10
15
20
25
T9
T11
T13
T14
T25

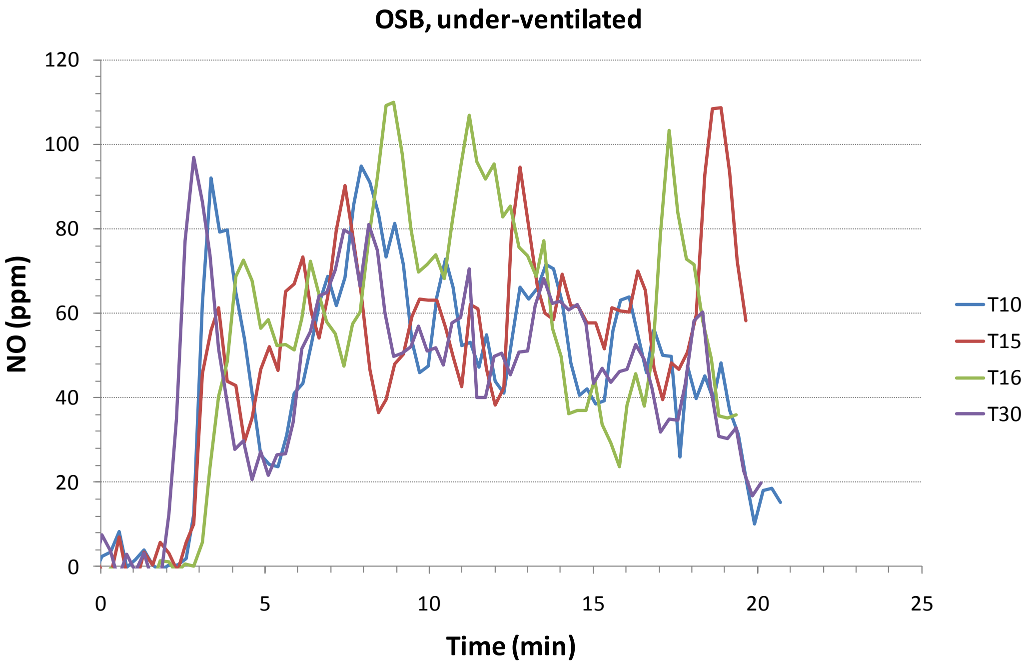

OSB, well-ventilated
NO_2 (ppm)
Time (min)
0
2
4
6
8
10
12
0
5
10
15
20
25
T9
T11
T13
T14
T25

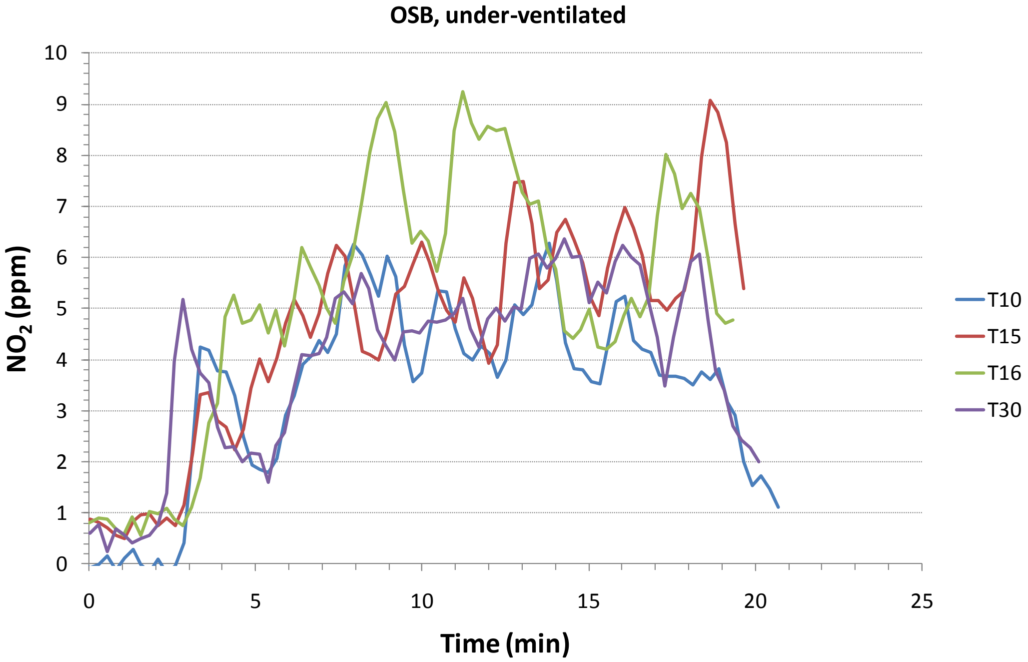

OSB, under-ventilated
CO$_2$ (%)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
5
10
15
20
25
Time (min)
T10
T15
T16
T30

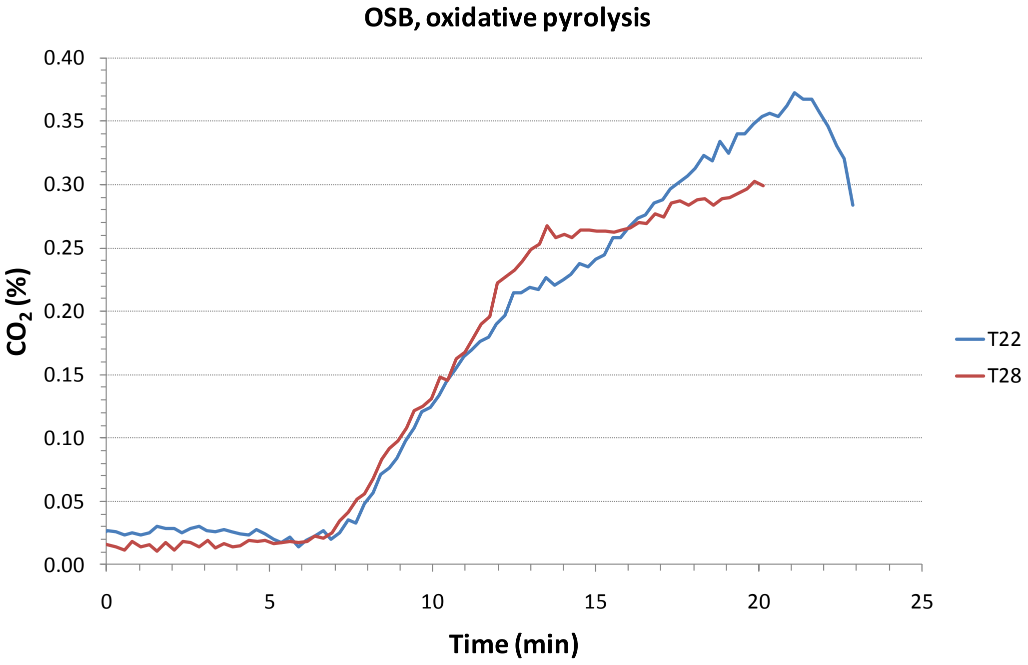

OSB, under-ventilated
CO (ppm)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
Time (min)
T10
T15
T16
T30

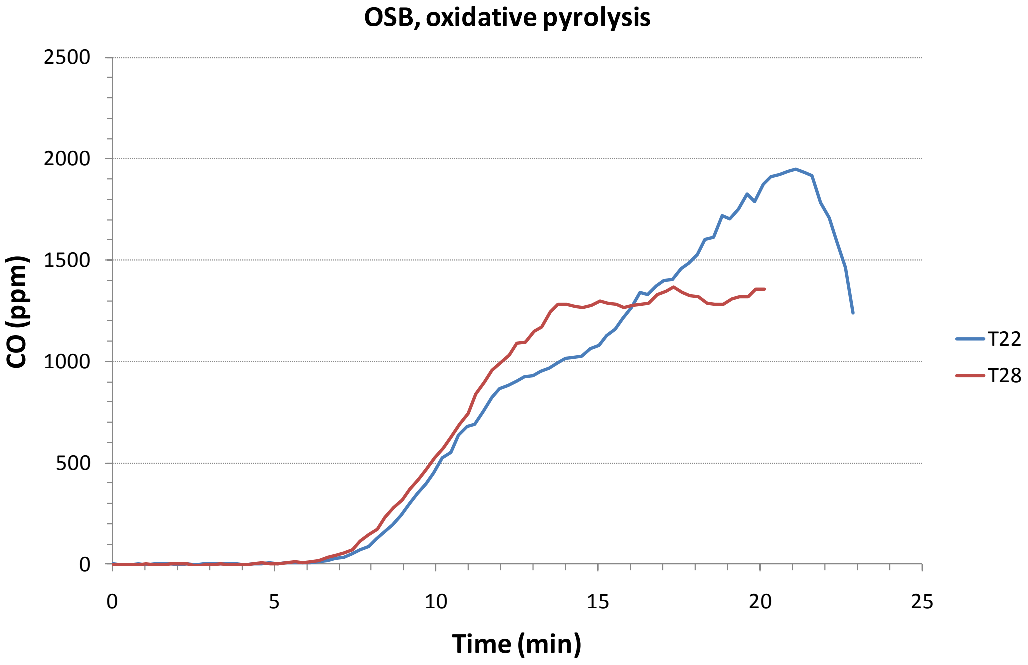

OSB, under-ventilated
HCN (ppm)
0
20
40
60
80
100
120
0
5
10
15
20
25
Time (min)
T10
T15
T16
T30

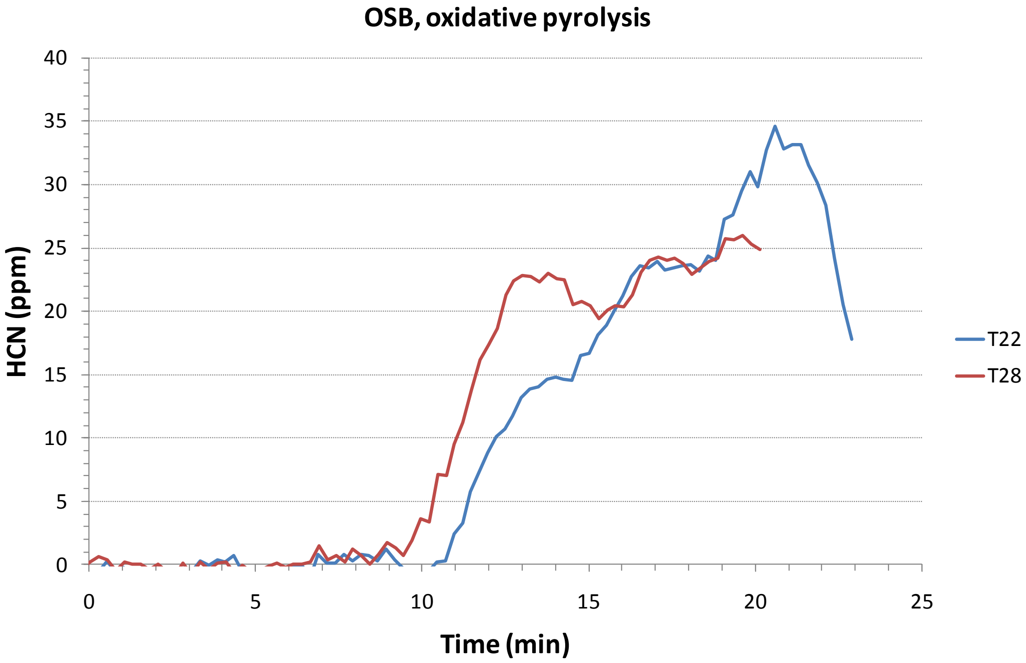

OSB, under-ventilated
NH_3 (ppm)
0
20
40
60
80
100
120
140
160
180
0
5
10
15
20
25
Time (min)
T10
T15
T16
T30


OSB, under-ventilated
NO (ppm)
120
100
80
60
40
20
0
0
5
10
15
20
25
Time (min)
T10
T15
T16
T30


OSB, under-ventilated
NO_2 (ppm)
10
9
8
7
6
5
4
3
2
1
0
0
5
10
15
20
25
Time (min)
T10
T15
T16
T30


OSB, oxidative pyrolysis
CO_2 (%)
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
5
10
15
20
25
Time (min)
T22
T28


OSB, oxidative pyrolysis
CO (ppm)
2500
2000
1500
1000
500
0
0
5
10
15
20
25
Time (min)
T22
T28


OSB, oxidative pyrolysis
HCN (ppm)
40
35
30
25
20
15
10
5
0
0
5
10
15
20
25
Time (min)
T22
T28

Annex 2 Particle and soot data

A 2.1 Particle distribution data

Data from tests with wood board (OSB) in Test Series 1:

Test/stage	> 2.5 µm (mg)	> 1.0 µm (mg)	> 0.5 µm (mg)	> 0.25 µm (mg)	< 0.25 µm (mg)	Total sampled (mg)	Volume sampled (litres)	Particle conc. (mg/l)
OSB fs1b (T28)	2.34	1.34	0.07	0.05	1.05	4.85	5.0	0.97
OSB fs2 (T13)	0.04	0.04	0.08	0.13	0.43	0.72	5.0	0.14
OSB fs2 (T14)	0.03	0.06	0.02	0.08	0.54	0.73	5.0	0.15
OSB fs2 (T25)	0.01	0.05	0.01	0.09	0.38	0.54	5.0	0.11
OSB fs3b (T15)	0.06	0.14	0.12	0.23	1.2	1.75	5.0	0.35
OSB fs3b (T16)	0.07	0.16	0.31	0.57	0.57	1.68	5.0	0.34
OSB fs3b (T30)	0.03	0.18	0.25	0.15	1.59	2.2	5.0	0.44

Data from tests with wood board (OSB) in Test Series 2:

Test/ stage (µm)	Stage 0.25*	Stage < 0.52	Stage 0.52	Stage 0.93	Stage 1.55	Stage 3.5	Stage 6.0	Stage 9.8	Stage 14.8	Stage 21.3	Total (mg)	Volume sampled (litres)	Particle conc. (mg/l)
OSB 1, fs1b	0.048	0.124	0.578	1.358	0.058	0.05	0.046	0.046	0.038	0.022	2.37	5.01	0.47
OSB 2, fs1b	0.074	0.144	0.522	1.276	0.306	0.004	0	0.028	0.01	0	2.36	5.00	0.47
OSB 3, fs1b	0.112	0.144	0.489	1.311	0.018	0.04	0.01	0.03	0.032	0.024	2.21	5.02	0.44
OSB 4, fs2	0.624	0.228	0.296	0.296	0.09	0.024	0.022	0	0.002	0.038	1.62	5.00	0.32
OSB 5, fs2	0.89	0.062	0.225	0.13	0.07	0.048	0.012	0.002	0.002	0.012	1.45	5.02	0.29
OSB 6, fs2	0.706	0.114	0.138	0.184	0.056	0.052	0.044	0.04	0.03	0.04	1.40	5.01	0.28
OSB 7, fs3b	1.162	0.05	0.058	0.042	0	0	0.032	0.03	0.058	0.056	1.49	5.01	0.30
OSB 8, fs3b	0.652	0.064	0.108	0.142	0.016	0.01	0.004	0.016	0.008	0.012	1.03	5.00	0.21
OSB 9, fs3b	0.634	0.114	0.124	0.266	0.014	0.024	0.018	0.02	0.008	0.014	1.24	5.01	0.25

Data from tests with PVC-carpet in Test Series 2:

Test/ stage (µm)	Stage 0.25*	Stage < 0.52	Stage 0.52	Stage 0.93	Stage 1.55	Stage 3.5	Stage 6.0	Stage 9.8	Stage 14.8	Stage 21.3	Total (mg)	Volume sampled (litres)	Particle conc. (mg/l)
PVC 1, fs1b	0.13	0.70	1.95	2.11	0.06	0.05	0.05	0.05	0.07	0.09	5.27	5.00	1.05
PVC 2, fs1b	0.20	0.46	2.04	1.65	0.06	0.03	0.01	0.03	0.05	0.05	4.59	5.01	0.92
PVC 3, fs1b	0.22	0.42	1.98	1.90	0.07	0.03	0.01	0.01	0.17	0.20	5.00	5.01	1.00
PVC 4, fs2	0.702	0.346	0.696	0.794	1.482	2.37	0.722	0.382	1.696	0.672	9.86	5.02	1.96
PVC 5, fs2	1.864	0.616	1.266	1.05	1.718	2.328	1.386	0.524	1.28	0.81	12.8	5.00	2.56
PVC 6, fs2	2.039	0.47	0.794	0.87	1.652	2.11	0.49	0.27	1.78	0.29	10.8	5.00	2.16
PVC 7, fs3b	2.342	1.136	1.376	2.926	1.624	1.28	0.576	0.64	1.128	1.008	14.0	5.01	2.79
PVC 8, fs3b	2.462	1.012	1.67	2.892	2.666	1.298	0.554	0.646	0.58	0.798	14.6	5.01	2.91
PVC 9, fs3b	2.221	1.344	1.489	2.432	2.202	0.94	0.52	0.42	0.72	0.164	12.4	5.01	2.48

A 2.2 Total soot

Data from Test Series 1:

Test no	Type	Total weight soot sampled (g)	Total volume sampled in box (l)	Soot conc. in box (mg/l)	Mass-loss conc. box (mg/l)	Soot yield 1 (mg/g)	Mass-charge conc. box (mg/l)	Soot yield 2 (mg/g)
29	PVC, fs1b	0.0035	5.21	0.67	15.0	44.7	32.5	20.6
31	PVC, fs1b	0.0045	5.32	0.84	14.9	56.4	32.8	25.6
23	PVC, fs2	0.0069	5.07	1.36	24.1	56.4	31.7	42.9
32	PVC, fs2	0.0083	5.0	1.66	24.9	66.7	32.1	51.7
24	PVC, fs3b	0.0222	5.18	4.29	22.3	192	33.4	128
27	PVC, fs3b	0.0094	5.12	1.84	22.5	81.7	33.6	54.7
22	OSB, fs1b	0.0132	5.02	2.63	18.4	143	26.6	98.9
9	OSB, fs2	0.0007	4.78	0.15	25.7	5.7	25.9	5.8
13	OSB, fs2	0.0003	4.63	0.058	25.6	2.3	25.8	2.2
14	OSB, fs2	0.0005	3.19	0.17	25.0	6.9	25.2	6.7
10	OSB, fs3b	0.0007	4.70	0.15	23.8	6.2	25.2	6.0
15	OSB, fs3b	0.0017	3.15	0.55	25.2	21.7	27.1	20.3
16	OSB, fs3b	0.0011	3.12	0.35	23.6	14.9	26.3	13.3

Data from Test Series 2:

Test no	Type	Total weight soot sampled (g)	Total volume sampled in box (l)	Soot conc. in box (mg/l)	Mass-loss conc. box (mg/l)	Soot yield 1 (mg/g)	Mass-charge conc. box (mg/l)	Soot yield 2 (mg/g)
1	PVC, fs1b	0.00923	7.0	1.32	20.7	63.6	39.1	33.7
2	PVC, fs2	0.00716	6.00	1.19	26.6	44.8	38.3	31.1
3	PVC, fs2	0.00803	6.00	1.34	25.6	52.1	36.6	36.5
4	PVC, fs3b	0.01105	6.00	1.84	26.0	70.8	38.1	48.3
5	PVC, fs3b	0.01089	6.00	1.81	28.2	64.2	38.4	47.2
1	OSB, fs1b	0.00148	10.00	0.15	7.96	18.8	20.2	7.4
2	OSB, fs1b	0.00147	9.80	0.15	1.11	134	20.2	7.4
3	OSB, fs2	0.00129	10.00	0.13	21.7	5.9	21.9	5.9
4	OSB, fs2	0.00105	10.00	0.11	21.4	5.1	21.7	5.1
5	OSB, fs3b	0.00107	6.00	0.178	18.6	9.5	21.1	8.4
6	OSB, fs3b	0.00125	6.00	0.208	19.8	10.4	22.3	9.3

A 2.3 Chlorine analysis of soot

Test Series 1 - Chlorine concentration in total soot samples (weight-%):

Test ID	Test Series	Fire stage	Analysis method	Chlorine content in soot (weight-%)
23	1	2	HPIC	1.45
32	1	2	HPIC	1.32
24	1	3b	HPIC	0.99
27	1	3b	HPIC	1.17
29	1	1b	HPIC	0.57
31	1	1a	HPIC	0.67

Test Series 2 - Chlorine concentration in total soot samples (weight-%):

Test ID	Test Series	Fire stage	Analysis method	Chlorine content in soot (weight-%)
PVC carpet 4	2	2	XRF	10.2
PVC carpet 5	2	2	XRF	12.9
PVC carpet 7	2	3b	XRF	12.6
PVC carpet 8	2	3b	XRF	15.9
PVC carpet 1	2	1b	XRF	4.1

Annex 3 PAH data

A 3.1 PAH sampler data in tests with PVC-carpet

Test no	T23					
Material	PVC					
Fire stage	Fire stage 2 (well-ventilated)					
Sampler	OVS-sampler					
	Total sampled amount (pg)			Concentration in box (ng/l)		
	Glass wool	Filter	XAD-2	Condensed	Gaseous	Total
Naphthalene	-	-	2800000	-	560	560
Acenaphthylene	-	-	650000	-	130	130
Acenaphthene	-	-	-	-	-	-
Fluorene	-	-	190000	-	38	38
Phenanthrene	-	19000	860000	3.8	172	176
Anthracene	-	14000	170000	2.8	34	36.8
Fluoranthene	37000	81000	340000	23.6	68	91.6
Pyrene	23000	49000	170000	14.4	34	48.4
Benzo(a)anthracene	30000	86000	23000	23.2	4.6	27.8
Chrysene	34000	100000	32000	26.8	6.4	33.2
Benzo(b)fluoranthene	39000	130000	23000	33.8	4.6	38.4
Benzo(k)fluoranthene	-	44000	-	8.8	-	8.8
Benzo(a)pyrene	-	45000	-	9.0	-	9.0
Indeno(1.2.3-cd)pyrene	-	40000	-	8.0	-	8.0
Benzo(ghi)perylene	-	27000	-	5.4	-	5.4
Dibenzo(ah)anthracene	-	-	-	-	-	-

Test no	T23 cont.					
	Mass loss yields (µg/g)			Mass loss yields in BaP-TEQ (µg/g)		
	Condensed	Gaseous	Total	Condensed	Gaseous	Total
Naphthalene	-	23.22	23.22	-	0.0232	0.0232
Acenaphthylene	-	5.39	5.39	-	0.0054	0.0054
Acenaphthene	-	-	-	-	-	-
Fluorene	-	1.58	1.58	-	0.0016	0.0016
Phenanthrene	0.16	7.13	7.29	0.00016	0.0071	0.0073
Anthracene	0.12	1.41	1.53	0.0012	0.0141	0.0153
Fluoranthene	0.98	2.82	3.80	0.0010	0.0028	0.0038
Pyrene	0.60	1.41	2.01	0.00060	0.0014	0.0020
Benzo(a)anthracene	0.96	0.19	1.15	0.096	0.019	0.115
Chrysene	1.11	0.27	1.38	0.011	0.0027	0.0138
Benzo(b)fluoranthene	1.40	0.19	1.59	0.14	0.019	0.159
Benzo(k)fluoranthene	0.36	-	0.36	0.036	-	0.036
Benzo(a)pyrene	0.37	-	0.37	0.37	-	0.37
Indeno(1.2.3-cd)pyrene	0.33	-	0.33	0.033	-	0.033

Benzo(ghi)perylene	0.22	-	0.22	0.00022	-	0.00022
Dibenzo(ah)anthracene	-	-	-	-	-	-
Sum of total yields			50.22			0.785

Test no	T32					
Material	PVC					
Fire stage	Fire stage 2 (well-ventilated)					
Sampler	OVS-sampler					
	Total sampled amount (pg)			Concentration in box (ng/l)		
	Glass wool	Filter	XAD-2	Condensed	Gaseous	Total
Naphthalene	-	-	8500000	-	2833	2833
Acenaphthylene	-	-	953000	-	318	318
Acenaphthene	-	-	-	-	-	-
Fluorene	-	-	150000	-	50	50
Phenanthrene	140000	29000	890000	56	297	353
Anthracene	53000	-	140000	18	47	64
Fluoranthene	620000	93300	310000	238	103	341
Pyrene	340000	54000	150000	131	50	181
Benzo(a)anthracene	290000	87000	39000	126	13	139
Chrysene	330000	100000	46000	143	15	159
Benzo(b)fluoranthene	380000	130000	44000	170	15	185
Benzo(k)fluoranthene	150000	38000	-	63	-	63
Benzo(a)pyrene	120000	45000	-	55	-	55
Indeno(1.2.3-cd)pyrene	100000	39000	-	46	-	46
Benzo(ghi)perylene	72000	26000	-	33	-	33
Dibenzo(ah)anthracene	41000	-	-	14	-	14

Test no	T32 cont.					
	Mass loss yields (µg/g)			Mass loss yields in BaP-TEQ (µg/g)		
	Condensed	Gaseous	Total	Condensed	Gaseous	Total
Naphthalene	-	114	114	0.000	0.114	0.114
Acenaphthylene	-	13	13	-	0.013	0.013
Acenaphthene	-	-	-	-	-	-
Fluorene	-	2.0	2.0	0.000	0.0020	0.0020
Phenanthrene	2.3	12	14	0.0023	0.012	0.014
Anthracene	0.71	1.9	2.6	0.0071	0.019	0.026
Fluoranthene	10	4.1	14	0.010	0.0041	0.014
Pyrene	5.3	2.0	7.3	0.0053	0.0020	0.0073
Benzo(a)anthracene	5.0	0.5	5.6	0.50	0.052	0.56
Chrysene	5.7	0.62	6.4	0.057	0.0062	0.064
Benzo(b)fluoranthene	6.8	0.59	7.4	0.68	0.059	0.74
Benzo(k)fluoranthene	2.5	-	2.5	0.25	-	0.25
Benzo(a)pyrene	2.2	-	2.2	2.21	-	2.21
Indeno(1.2.3-cd)pyrene	1.9	-	1.9	0.19	-	0.19
Benzo(ghi)perylene	1.3	-	1.3	0.0013	-	0.0013
Dibenzo(ah)anthracene	0.55	-	0.55	0.55	-	0.55
Sum of total yields			194.75			4.76

Test no	T27					
Material	PVC					
Fire stage	Fire stage 3b (under-ventilated)					
Sampler	OVS-sampler					
	Total sampled amount (pg)			Concentration in box (ng/l)		
	Glass wool	Filter	XAD-2	Condensed	Gaseous	Total
Naphthalene	-	140000	260000000	47	86667	86713
Acenaphthylene	-	270000	64000000	90	21333	21423
Acenaphthene	-	-	200000	-	67	67
Fluorene	-	150000	23000000	50	7667	7717
Phenanthrene	110000	2700000	78000000	937	26000	26937
Anthracene	55000	1700000	25000000	585	8333	8918
Fluoranthene	360000	11200000	25000000	3853	8333	12187
Pyrene	280000	8600000	18000000	2960	6000	8960
Benzo(a)anthracene	290000	7000000	9000000	2430	3000	5430
Chrysene	270000	14000000	8500000	4757	2833	7590
Benzo(b)fluoranthene	290000	9000000	8500000	3097	2833	5930
Benzo(k)fluoranthene	110000	6900000	2000000	2337	667	3003
Benzo(a)pyrene	190000	5500000	5800000	1897	1933	3830
Indeno(1.2.3-cd)pyrene	140000	2700000	4400000	947	1467	2413
Benzo(ghi)perylene	86000	2100000	2400000	729	800	1529
Dibenzo(ah)anthracene	37000	840000	1000000	292	333	626

Test no	T27 cont.					
	Mass loss yields (µg/g)			Mass loss yields in BaP-TEQ (µg/g)		
	Condensed	Gaseous	Total	Condensed	Gaseous	Total
Naphthalene	2.1	3855	3857	0.0021	3.9	3.9
Acenaphthylene	4.0	949	953	0.0040	0.9	1.0
Acenaphthene	-	3.0	3.0	-	0.0030	0.0030
Fluorene	2.2	341	343	0.0022	0.34	0.34
Phenanthrene	42	1157	1198	0.042	1.2	1.2
Anthracene	26	371	397	0.26	3.7	4.0
Fluoranthene	171	371	542	0.17	0.37	0.54
Pyrene	132	267	399	0.13	0.27	0.40
Benzo(a)anthracene	108	133	242	11	13	24
Chrysene	212	126	338	2.1	1.3	3.4
Benzo(b)fluoranthene	138	126	264	14	13	26
Benzo(k)fluoranthene	104	30	134	10	3.0	13
Benzo(a)pyrene	84	86	170	84	86	170
Indeno(1.2.3-cd)pyrene	42	65	107	4.2	6.5	11
Benzo(ghi)perylene	32	36	68	0.032	0.036	0.068
Dibenzo(ah)anthracene	13	15	28	13	15	28
Sum of total yields			9043			286.8

Test no	T33					
Material	PVC					
Fire stage	Fire stage 3b (under-ventilated)					
Sampler	OVS-sampler					
	Total sampled amount (pg)			Concentration in box (ng/l)		
	Glass wool	Filter	XAD-2	Condensed	Gaseous	Total
Naphthalene	41000	130000	210000000	81	100000	100081
Acenaphthylene	160000	180000	26000000	162	12381	12543
Acenaphthene	-	-	610000	-	290	290
Fluorene	190000	340000	9900000	252	4714	4967
Phenanthrene	2200000	14000000	35000000	7714	16667	24381
Anthracene	870000	4400000	11000000	2510	5238	7748
Fluoranthene	2500000	15000000	7800000	8333	3714	12048
Pyrene	1700000	10000000	5300000	5571	2524	8095
Benzo(a)anthracene	1200000	6600000	3400000	3714	1619	5333
Chrysene	1200000	7000000	6400000	3905	3048	6952
Benzo(b)fluoranthene	1500000	11000000	6500000	5952	3095	9048
Benzo(k)fluoranthene	3400000	6200000	1600000	4571	762	5333
Benzo(a)pyrene	2600000	6700000	3700000	4429	1762	6190
Indeno(1.2.3-cd)pyrene	610000	2900000	560000	1671	267	1938
Benzo(ghi)perylene	1200000	2700000	290000	1857	138	1995
Dibenzo(ah)anthracene	1400000	920000	140000	1105	67	1171

Test no	T33 cont.					
	Mass loss yields (µg/g)			Mass loss yields in BaP-TEQ (µg/g)		
	Condensed	Gaseous	Total	Condensed	Gaseous	Total
Naphthalene	3.85	4726	4730	-	4.7	4.7
Acenaphthylene	7.65	585	593	-	0.59	0.59
Acenaphthene	-	14	14	-	-	-
Fluorene	12	223	235	-	-	-
Phenanthrene	365	788	1152	-	0.79	1.2
Anthracene	119	248	366	1.2	2.5	3.7
Fluoranthene	394	176	569	-	-	0.6
Pyrene	263	119	383	-	-	-
Benzo(a)anthracene	176	77	252	18	7.7	25
Chrysene	185	144	329	1.8	1.4	3.3
Benzo(b)fluoranthene	281	146	428	28	15	43
Benzo(k)fluoranthene	216	36	252	22	3.6	25
Benzo(a)pyrene	209	83	293	209	83	293
Indeno(1.2.3-cd)pyrene	79	13	92	7.9	1.3	9.2
Benzo(ghi)perylene	88	6.5	94	-	-	-
Dibenzo(ah)anthracene	52	3.2	55	52	3	55
Sum of total yields			9837			464.3

Test no	T29					
Material	PVC					
Fire stage	Fire stage 1b (oxidative pyrolysis)					
Sampler	OVS-sampler					
	Total sampled amount (pg)			Concentration in box (ng/l)		
	Glass wool	Filter	XAD-2	Condensed	Gaseous	Total
Naphthalene	120000	20000	3900000	47	1300	1347
Acenaphthylene	26000	-	1000000	8.7	333	342
Acenaphthene	-	-	32000	-	11	11
Fluorene	-	17000	970000	5.7	323	329
Phenanthrene	-	84000	2000000	28	667	695
Anthracene	-	28000	240000	9.3	80	89
Fluoranthene	-	68000	52000	23	17	40
Pyrene	-	49000	28000	16	9.3	26
Benzo(a)anthracene	-	15000	-	5.0	-	5.0
Chrysene	-	78000	-	26	-	26
Benzo(b)fluoranthene	-	-	-	-	-	-
Benzo(k)fluoranthene	-	-	-	-	-	-
Benzo(a)pyrene	-	-	-	-	-	-
Indeno(1.2.3-cd)pyrene	-	-	-	-	-	-
Benzo(ghi)perylene	-	-	-	-	-	-
Dibenzo(ah)anthracene	-	-	-	-	-	-

Test no	T29 cont.					
	Mass loss yields (µg/g)			Mass loss yields in BaP-TEQ (µg/g)		
	Condensed	Gaseous	Total	Condensed	Gaseous	Total
Naphthalene	3.1	87	90	0.0031	0.087	0.090
Acenaphthylene	0.58	22	23	0.00058	0.022	0.023
Acenaphthene	-	0.71	0.71	-	0.00071	0.00071
Fluorene	0.38	22	22	0.00038	0.022	0.022
Phenanthrene	1.9	44	46	0.0019	0.044	0.046
Anthracene	0.62	5.3	5.9	0.0062	0.053	0.059
Fluoranthene	1.5	1.2	2.7	0.0015	0.0012	0.0027
Pyrene	1.1	0.62	1.7	0.0011	0.00062	0.0017
Benzo(a)anthracene	0.33	-	0.33	0.033	-	0.033
Chrysene	1.7	-	1.7	0.017	-	0.017
Benzo(b)fluoranthene	-	-	-	-	-	-
Benzo(k)fluoranthene	-	-	-	-	-	-
Benzo(a)pyrene	-	-	-	-	-	-
Indeno(1.2.3-cd)pyrene	-	-	-	-	-	-
Benzo(ghi)perylene	-	-	-	-	-	-
Dibenzo(ah)anthracene	-	-	-	-	-	-
Sum of total yields			194.0			0.2951

Test no	T31					
Material	PVC					
Fire stage	Fire stage 1b (oxidative pyrolysis)					
Sampler	OVS-sampler					
	Total sampled amount (pg)			Concentration in box (ng/l)		
	Glass wool	Filter	XAD-2	Condensed	Gaseous	Total
Naphthalene	-	-	3500000	-	1167	1167
Acenaphthylene	-	-	700000	-	233	233
Acenaphthene	-	-	28000	-	9.3	9.3
Fluorene	-	-	670000	-	223	223
Phenanthrene	-	18000	1400000	6.0	467	473
Anthracene	-	-	160000	-	53	53
Fluoranthene	-	43000	42000	14	14	28
Pyrene	-	33000	24000	11	8.0	19
Benzo(a)anthracene	-	-	-	-	-	-
Chrysene	-	57000	-	19	0	19
Benzo(b)fluoranthene	-	-	-	-	-	-
Benzo(k)fluoranthene	-	-	-	-	-	-
Benzo(a)pyrene	-	-	-	-	-	-
Indeno(1.2.3-cd)pyrene	-	-	-	-	-	-
Benzo(ghi)perylene	-	-	-	-	-	-
Dibenzo(ah)anthracene	-	-	-	-	-	-

Test no	T31 cont.					
	Mass loss yields (µg/g)			Mass loss yields in BaP-TEQ (µg/g)		
	Condensed	Gaseous	Total	Condensed	Gaseous	Total
Naphthalene	-	78	78	-	0.078	0.078
Acenaphthylene	-	16	16	-	0.016	0.016
Acenaphthene	-	0.63	0.63	-	0.00063	0.00063
Fluorene	-	15	15	-	0.015	0.015
Phenanthrene	-	31	32	-	0.031	0.032
Anthracene	-	3.6	3.6	-	0.036	0.036
Fluoranthene	0.96	0.94	1.9	0.0010	0.00094	0.0019
Pyrene	0.74	0.54	1.3	0.00074	0.00054	0.0013
Benzo(a)anthracene	-	-	-	-	-	-
Chrysene	1.3	-	1.3	0.013	-	0.013
Benzo(b)fluoranthene	-	-	-	-	-	-
Benzo(k)fluoranthene	-	-	-	-	-	-
Benzo(a)pyrene	-	-	-	-	-	-
Indeno(1.2.3-cd)pyrene	-	-	-	-	-	-
Benzo(ghi)perylene	-	-	-	-	-	-
Dibenzo(ah)anthracene	-	-	-	-	-	-
Sum of total yields			149.7			0.1938

A 3.2 PAH sampler data in tests with OSB-board

Test no	T13					
Material	OSB					
Fire stage	Fire stage 2 (well-ventilated)					
Sampler	OVS-sampler					
	Total sampled amount (pg)			Concentration in box (ng/l)		
	Glass wool	Filter	XAD-2	Condensed	Gaseous	Total
Naphthalene	-	-	75000	-	25	25
Acenaphthylene	-	-	36000	-	12	12
Acenaphthene	-	-	-	-	-	-
Fluorene	-	-	-	-	-	-
Phenanthrene	-	110000	-	36.67	0.00	36.67
Anthracene	-	16000	-	5.33	0.00	5.33
Fluoranthene	-	32000	-	10.67	0.00	10.67
Pyrene	-	19000	-	6.33	0.00	6.33
Benzo(a)anthracene	-	-	-	-	-	-
Chrysene	-	-	-	-	-	-
Benzo(b)fluoranthene	-	-	-	-	-	-
Benzo(k)fluoranthene	-	-	-	-	-	-
Benzo(a)pyrene	-	-	-	-	-	-
Indeno(1.2.3-cd)pyrene	-	-	-	-	-	-
Benzo(ghi)perylene	-	-	-	-	-	-
Dibenzo(ah)anthracene	-	-	-	-	-	-

Test no	T13 cont.					
	Mass loss yields (µg/g)			Mass loss yields in BaP-TEQ (µg/g)		
	Condensed	Gaseous	Total	Condensed	Gaseous	Total
Naphthalene	-	0.98	0.98	-	0.00098	0.00098
Acenaphthylene	-	0.47	0.47	-	0.00047	0.00047
Acenaphthene	-	-	-	-	-	-
Fluorene	-	-	-	-	-	-
Phenanthrene	1.43	-	1.43	0.00143	-	0.00143
Anthracene	0.21	-	0.21	0.00208	-	0.00208
Fluoranthene	0.42	-	0.42	0.00042	-	0.00042
Pyrene	0.25	-	0.25	0.00025	-	0.00025
Benzo(a)anthracene	-	-	-	-	-	-
Chrysene	-	-	-	-	-	-
Benzo(b)fluoranthene	-	-	-	-	-	-
Benzo(k)fluoranthene	-	-	-	-	-	-
Benzo(a)pyrene	-	-	-	-	-	-
Indeno(1.2.3-cd)pyrene	-	-	-	-	-	-
Benzo(ghi)perylene	-	-	-	-	-	-
Dibenzo(ah)anthracene	-	-	-	-	-	-
Sum of total yields			3.76			0.00563

Test no	T14					
Material	OSB					
Fire stage	Fire stage 2 (well-ventilated)					
Sampler	OVS-sampler					
	Total sampled amount (pg)			Concentration in box (ng/l)		
	Glass wool	Filter	XAD-2	Condensed	Gaseous	Total
Naphthalene	-	-	58000	-	19.3	19.3
Acenaphthylene	-	-	24000	-	8.0	8.0
Acenaphthene	-	-	-	-	-	-
Fluorene	-	-	-	-	-	-
Phenanthrene	-	130000	33000	43.3	11.0	54.3
Anthracene	-	-	-	0.0	-	-
Fluoranthene	-	33000	-	11.0	-	11.0
Pyrene	-	19000	-	6.3	-	6.3
Benzo(a)anthracene	-	-	-	-	-	-
Chrysene	-	-	-	-	-	-
Benzo(b)fluoranthene	-	-	-	-	-	-
Benzo(k)fluoranthene	-	-	-	-	-	-
Benzo(a)pyrene	-	-	-	-	-	-
Indeno(1.2.3-cd)pyrene	-	-	-	-	-	-
Benzo(ghi)perylene	-	-	-	-	-	-
Dibenzo(ah)anthracene	-	-	-	-	-	-

Test no	T14 cont.					
	Mass loss yields (μg/g)			Mass loss yields in BaP-TEQ (μg/g)		
	Condensed	Gaseous	Total	Condensed	Gaseous	Total
Naphthalene	-	0.77	0.77	-	0.00077	0.00077
Acenaphthylene	-	0.32	0.32	-	0.00032	0.00032
Acenaphthene	-	-		-	-	-
Fluorene	-	-		-	-	-
Phenanthrene	1.73	0.44	2.17	0.00173	0.00044	0.00217
Anthracene	-	-		0.00000	-	-
Fluoranthene	0.44	-	0.44	0.00044	-	0.00044
Pyrene	0.25	-	0.25	0.00025	-	0.00025
Benzo(a)anthracene	-	-	-	-	-	-
Chrysene	-	-	-	-	-	-
Benzo(b)fluoranthene	-	-	-	-	-	-
Benzo(k)fluoranthene	-	-	-	-	-	-
Benzo(a)pyrene	-	-	-	-	-	-
Indeno(1.2.3-cd)pyrene	-	-	-	-	-	-
Benzo(ghi)perylene	-	-	-	-	-	-
Dibenzo(ah)anthracene	-	-	-	-	-	-
Sum of total yields			3.95			0.00395

Test no	T16					
Material	OSB					
Fire stage	Fire stage 3b (under-ventilated)					
Sampler	OVS-sampler					
	Total sampled amount (pg)			Concentration in box (ng/l)		
	Glass wool	Filter	XAD-2	Condensed	Gaseous	Total
Naphthalene	-	176000	117776000	59	39259	39317
Acenaphthylene	-	448000	40663000	149	13554	13704
Acenaphthene	-	15000	848000	5	283	288
Fluorene	-	246000	12579000	82	4193	4275
Phenanthrene	27000	3767000	29184000	1265	9728	10993
Anthracene	27000	1309000	7065000	445	2355	2800
Fluoranthene	952000	18385000	3984000	6446	1328	7774
Pyrene	979000	17770000	3222000	6250	1074	7324
Benzo(a)anthracene	377000	6024000	629000	2134	210	2343
Chrysene	339000	4956000	521000	1765	174	1939
Benzo(b)fluoranthene	461000	5746000	512000	2069	171	2240
Benzo(k)fluoranthene	155000	2074000	187000	743	62	805
Benzo(a)pyrene	393000	5615000	485000	2003	162	2164
Indeno(1.2.3-cd)pyrene	218000	3910000	349000	1376	116	1492
Benzo(ghi)perylene	188000	2709000	229000	966	76	1042
Dibenzo(ah)anthracene	27000	469000	46000	165	15	181

Test no	T16 cont.					
	Mass loss yields (µg/g)			Mass loss yields in BaP-TEQ (µg/g)		
	Condensed	Gaseous	Total	Condensed	Gaseous	Total
Naphthalene	2.5	1661	1664	0.0025	1.7	1.7
Acenaphthylene	6.3	573.6	580	0.0063	0.57	0.58
Acenaphthene	0.21	12.0	12.2	0.00021	0.012	0.012
Fluorene	3.5	177	181	0.0035	0.18	0.18
Phenanthrene	53.5	412	465	0.054	0.41	0.47
Anthracene	18.8	99.7	119	0.19	1.00	1.19
Fluoranthene	273	56.2	329	0.27	0.056	0.33
Pyrene	264	45.5	310	0.26	0.045	0.31
Benzo(a)anthracene	90.3	8.9	99.2	9.0	0.89	9.9
Chrysene	74.7	7.3	82.0	0.75	0.073	0.82
Benzo(b)fluoranthene	87.6	7.2	94.8	8.8	0.72	9.5
Benzo(k)fluoranthene	31.4	2.6	34.1	3.1	0.3	3.4
Benzo(a)pyrene	84.8	6.8	91.6	85	6.8	92
Indeno(1.2.3-cd)pyrene	58.2	4.9	63.2	5.8	0.49	6.3
Benzo(ghi)perylene	40.9	3.2	44.1	0.041	0.0032	0.044
Dibenzo(ah)anthracene	7.0	0.65	7.6	7.0	0.6	7.6
Sum of total yields			4176.8			134.3

Test no	T30					
Material	OSB					
Fire stage	Fire stage 3b (under-ventilated)					
Sampler	OVS-sampler					
	Total sampled amount (pg)			Concentration in box (ng/l)		
	Glass wool	Filter	XAD-2	Condensed	Gaseous	Total
Naphthalene	-	-	92000000	-	30667	30667
Acenaphthylene	-	-	24000000	-	8000	8000
Acenaphthene	-	-	530000	-	177	177
Fluorene	-	-	6000000	-	2000	2000
Phenanthrene	39000	120000	14800000	53	4933	4986
Anthracene	14000	36000	5500000	17	1833	1850
Fluoranthene	2700000	4000000	4600000	2233	1533	3767
Pyrene	2600000	4100000	3500000	2233	1167	3400
Benzo(a)anthracene	1000000	2100000	500000	1033	167	1200
Chrysene	890000	1600000	400000	830	133	963
Benzo(b)fluoranthene	1000000	3100000	400000	1367	133	1500
Benzo(k)fluoranthene	380000	1600000	140000	660	47	707
Benzo(a)pyrene	950000	2500000	360000	1150	120	1270
Indeno(1.2.3-cd)pyrene	730000	1200000	270000	643	90	733
Benzo(ghi)perylene	520000	1000000	180000	507	60	567
Dibenzo(ah)anthracene	90000	200000	34000	97	11	108

Test no	T30 cont.					
	Mass loss yields (µg/g)			Mass loss yields in BaP-TEQ (µg/g)		
	Condensed	Gaseous	Total	Condensed	Gaseous	Total
Naphthalene	-	1350	1350	-	1.35	1.35
Acenaphthylene	-	352	352	-	0.35	0.35
Acenaphthene	-	7.8	7.8	-	0.0078	0.0078
Fluorene	-	88	88	-	0.088	0.088
Phenanthrene	2.3	217	220	0.0023	0.22	0.22
Anthracene	0.73	81	81	0.0073	0.81	0.81
Fluoranthene	98	68	166	0.10	0.07	0.17
Pyrene	98	51	150	0.10	0.05	0.15
Benzo(a)anthracene	45	7.3	53	4.5	0.73	5.28
Chrysene	37	5.9	42	0.37	0.059	0.42
Benzo(b)fluoranthene	60	5.9	66	6.0	0.59	6.6
Benzo(k)fluoranthene	29	2.1	31	2.9	0.21	3.1
Benzo(a)pyrene	51	5.3	56	51	5.28	56
Indeno(1.2.3-cd)pyrene	28	4.0	32	2.8	0.40	3.2
Benzo(ghi)perylene	22	2.6	25	0.022	0.0026	0.025
Dibenzo(ah)anthracene	4.3	0.50	4.8	4.3	0.50	4.8
Sum of total yields			2724.6			82.6

Test no	T22					
Material	OSB					
Fire stage	Fire stage 1b (oxidative pyrolysis)					
Sampler	OVS-sampler					
	Total sampled amount (pg)			Concentration in box (ng/l)		
	Glass wool	Filter	XAD-2	Condensed	Gaseous	Total
Naphthalene	-	-	130000	-	26	26
Acenaphthylene	-	-	100000	-	20	20
Acenaphthene	-	-	-	-	-	-
Fluorene	-	-	83000	-	16.6	16.6
Phenanthrene	-	-	210000	-	42	42
Anthracene	-	-	80000	-	16	16
Fluoranthene	-	-	21000	-	4.2	4.2
Pyrene	-	-	21000	-	4.2	4.2
Benzo(a)anthracene	-	-	-	-	-	-
Chrysene	-	-	-	-	-	-
Benzo(b)fluoranthene	-	-	-	-	-	-
Benzo(k)fluoranthene	-	-	-	-	-	-
Benzo(a)pyrene	-	-	-	-	-	-
Indeno(1.2.3-cd)pyrene	-	-	-	-	-	-
Benzo(ghi)perylene	-	-	-	-	-	-
Dibenzo(ah)anthracene	-	-	-	-	-	-

Test no	T22 cont.					
	Mass loss yields (µg/g)			Mass loss yields in BaP-TEQ (µg/g)		
	Condensed	Gaseous	Total	Condensed	Gaseous	Total
Naphthalene	-	1.41	1.41	-	0.0014	0.0014
Acenaphthylene	-	1.09	1.09	-	0.0011	0.0011
Acenaphthene	-	0.00		-	0.0000	0.0000
Fluorene	-	0.90	0.90	-	0.00090	0.00090
Phenanthrene	-	2.28	2.28	-	0.0023	0.0023
Anthracene	-	0.87	0.87	-	0.0087	0.0087
Fluoranthene	-	0.23	0.23	-	0.00023	0.00023
Pyrene	-	0.23	0.23	-	0.00023	0.00023
Benzo(a)anthracene	-	-	-	-	-	-
Chrysene	-	-	-	-	-	-
Benzo(b)fluoranthene	-	-	-	-	-	-
Benzo(k)fluoranthene	-	-	-	-	-	-
Benzo(a)pyrene	-	-	-	-	-	-
Indeno(1.2.3-cd)pyrene	-	-	-	-	-	-
Benzo(ghi)perylene	-	-	-	-	-	-
Dibenzo(ah)anthracene	-	-	-	-	-	-
Sum of total yields			7.01			0.0146

A 3.3 PAH impactor data in tests with OSB-board

Test no	T13					
Material	OSB					
Fire stage	Fire stage 2 (well-ventilated)					
Sampler	Impactor					
	Total sampled amount (pg):					
Impactor stage	> 2.5 µm	> 1.0 µm	> 0.5 µm	> 0.25 µm	< 0.25 µm	Σ
Naphthalene	-	-	-	-	-	-
Acenaphthylene	-	-	-	-	-	-
Acenaphthene	-	-	-	-	-	-
Fluorene	-	-	-	-	35000	35000
Phenanthrene	-	-	-	-	360000	360000
Anthracene	-	-	-	-	40000	40000
Fluoranthene	-	-	-	-	120000	120000
Pyrene	-	-	-	-	83000	83000
Benzo(a)anthracene	-	-	-	-	-	-
Chrysene	-	-	-	-	-	-
Benzo(b)fluoranthene	-	-	-	-	-	-
Benzo(k)fluoranthene	-	-	-	-	-	-
Benzo(a)pyrene	-	-	-	-	-	-
Indeno(1.2.3-cd)pyrene	-	-	-	-	-	-
Benzo(ghi)perylene	-	-	-	-	-	-
Dibenzo(ah)anthracene	-	-	-	-	-	-

Test no	T13 cont.		
	Total sampled amount (ng)	Concentration in box (ng/l)	Mass loss yields (µg/g)
Naphthalene	-	-	-
Acenaphthylene	-	-	-
Acenaphthene	-	-	-
Fluorene	35	3.7	0.14
Phenanthrene	360	38.2	1.49
Anthracene	40	4.2	0.17
Fluoranthene	120	12.7	0.50
Pyrene	83	8.8	0.34
Benzo(a)anthracene	-	-	-
Chrysene	-	-	-
Benzo(b)fluoranthene	-	-	-
Benzo(k)fluoranthene	-	-	-
Benzo(a)pyrene	-	-	-
Indeno(1.2.3-cd)pyrene	-	-	-
Benzo(ghi)perylene	-	-	-
Dibenzo(ah)anthracene	-	-	-

Test no	T13 cont.				
Impactor stage	> 2.5 µm	> 1.0 µm	> 0.5 µm	> 0.25 µm	< 0.25 µm
Sampled weight of particles (µg)	40	40	80	130	430
	PAH content of soot (µg /g):				
Naphthalene	-	-	-	-	-
Acenaphthylene	-	-	-	-	-
Acenaphthene	-	-	-	-	-
Fluorene	-	-	-	-	81.4
Phenanthrene	-	-	-	-	837.2
Anthracene	-	-	-	-	93.0
Fluoranthene	-	-	-	-	279.1
Pyrene	-	-	-	-	193.0
Benzo(a)anthracene	-	-	-	-	-
Chrysene	-	-	-	-	-
Benzo(b)fluoranthene	-	-	-	-	-
Benzo(k)fluoranthene	-	-	-	-	-
Benzo(a)pyrene	-	-	-	-	-
Indeno(1.2.3-cd)pyrene	-	-	-	-	-
Benzo(ghi)perylene	-	-	-	-	-
Dibenzo(ah)anthracene	-	-	-	-	-

Test no	T14					
Material	OSB					
Fire stage	Fire stage 2 (well-ventilated)					
Sampler	Impactor					
	Total sampled amount (pg):					
Impactor stage	> 2.5 µm	> 1.0 µm	> 0.5 µm	> 0.25 µm	< 0.25 µm	Σ
Naphthalene	-	-	-	-	24000	24000
Acenaphthylene	-	-	-	-	86000	86000
Acenaphthene	-	-	-	-	-	-
Fluorene	-	-	-	-	43000	43000
Phenanthrene	-	-	-	41000	350000	391000
Anthracene	-	-	-	-	29000	29000
Fluoranthene	-	-	-	-	100000	100000
Pyrene	-	-	-	-	67000	67000
Benzo(a)anthracene	-	-	-	-	-	-
Chrysene	-	-	-	-	-	-
Benzo(b)fluoranthene	-	-	-	-	-	-
Benzo(k)fluoranthene	-	-	-	-	-	-
Benzo(a)pyrene	-	-	-	-	-	-
Indeno(1.2.3-cd)pyrene	-	-	-	-	-	-
Benzo(ghi)perylene	-	-	-	-	-	-
Dibenzo(ah)anthracene	-	-	-	-	-	-

Test no	T14 cont.		
	Total sampled amount (ng)	Concentration in box (ng/l)	Mass loss yields (µg/g)
Naphthalene	24	2.4	0.10
Acenaphthylene	86	8.6	0.34
Acenaphthene	-	-	-
Fluorene	43	4.3	0.17
Phenanthrene	391	39.0	1.56
Anthracene	29	2.9	0.12
Fluoranthene	100	10.0	0.40
Pyrene	67	6.7	0.27
Benzo(a)anthracene	-	-	-
Chrysene	-	-	-
Benzo(b)fluoranthene	-	-	-
Benzo(k)fluoranthene	-	-	-
Benzo(a)pyrene	-	-	-
Indeno(1.2.3-cd)pyrene	-	-	-
Benzo(ghi)perylene	-	-	-
Dibenzo(ah)anthracene	-	-	-

Test no	T14 cont.				
Impactor stage	> 2.5 µm	> 1.0 µm	> 0.5 µm	> 0.25 µm	< 0.25 µm
Sampled weight of particles (µg)	30	60	20	80	540
	PAH content of soot (µg /g):				
Naphthalene	-	-	-	-	44.4
Acenaphthylene	-	-	-	-	159
Acenaphthene	-	-	-	-	-
Fluorene	-	-	-	-	80
Phenanthrene	-	-	-	512	648
Anthracene	-	-	-	-	54
Fluoranthene	-	-	-	-	185
Pyrene	-	-	-	-	124
Benzo(a)anthracene	-	-	-	-	-
Chrysene	-	-	-	-	-
Benzo(b)fluoranthene	-	-	-	-	-
Benzo(k)fluoranthene	-	-	-	-	-
Benzo(a)pyrene	-	-	-	-	-
Indeno(1.2.3-cd)pyrene	-	-	-	-	-
Benzo(ghi)perylene	-	-	-	-	-
Dibenzo(ah)anthracene	-	-	-	-	-

Test no	T16					
Material	OSB					
Fire stage	Fire stage 3b (under-ventilated)					
Sampler	Impactor					
	Total sampled amount (pg):					
Impactor stage	> 2.5 µm	> 1.0 µm	> 0.5 µm	> 0.25 µm	< 0.25 µm	Σ
Naphthalene	-	-	-	-	24000	24000
Acenaphthylene	-	-	-	-	45000	45000
Acenaphthene	-	-	-	-	-	-
Fluorene	-	-	-	-	19000	19000
Phenanthrene	-	15000	130000	120000	230000	495000
Anthracene	-	-	47000	44000	86000	177000
Fluoranthene	250000	920000	3800000	3800000	2400000	11170000
Pyrene	280000	960000	3700000	3800000	2500000	11240000
Benzo(a)anthracene	190000	490000	1400000	1400000	2000000	5480000
Chrysene	170000	420000	1200000	1100000	3400000	6290000
Benzo(b)fluoranthene	220000	530000	670000	1300000	2300000	5020000
Benzo(k)fluoranthene	150000	260000	510000	490000	930000	2340000
Benzo(a)pyrene	200000	490000	1400000	1400000	1700000	5190000
Indeno(1.2.3-cd)pyrene	95000	260000	750000	840000	1500000	3445000
Benzo(ghi)perylene	84000	210000	520000	610000	1100000	2524000
Dibenzo(ah)anthracene	-	31000	70000	97000	180000	378000

Test no	T16 cont.		
	Total sampled amount (ng)	Concentration in box (ng/l)	Mass loss yields (µg/g)
Naphthalene	24	2.6	0.11
Acenaphthylene	45	4.9	0.21
Acenaphthene	-	-	-
Fluorene	19	2.1	0.09
Phenanthrene	495	54	2.3
Anthracene	177	19.2	0.81
Fluoranthene	11170	1214	51
Pyrene	11240	1222	52
Benzo(a)anthracene	5480	596	25
Chrysene	6290	684	29
Benzo(b)fluoranthene	5020	546	23
Benzo(k)fluoranthene	2340	254	10.8
Benzo(a)pyrene	5190	564	24
Indeno(1.2.3-cd)pyrene	3445	374	15.8
Benzo(ghi)perylene	2524	274	11.6
Dibenzo(ah)anthracene	378	41.1	1.74

Test no	T16 cont.				
Impactor stage	> 2.5 µm	> 1.0 µm	> 0.5 µm	> 0.25 µm	< 0.25 µm
Sampled weight of particles (µg)	70	160	310	570	570
	PAH content of soot (µg /g):				
Naphthalene	-	-	-	-	42.1
Acenaphthylene	-	-	-	-	79
Acenaphthene	-	-	-	-	-
Fluorene	-	-	-	-	33
Phenanthrene	-	94	419	211	404
Anthracene	-	-	152	77	151
Fluoranthene	3571	5750	12258	6667	4211
Pyrene	4000	6000	11935	6667	4386
Benzo(a)anthracene	2714	3062	4516	2456	3509
Chrysene	2429	2625	3871	1930	5965
Benzo(b)fluoranthene	3143	3312	2161	2281	4035
Benzo(k)fluoranthene	2143	1625	1645	860	1632
Benzo(a)pyrene	2857	3062	4516	2456	2982
Indeno(1.2.3-cd)pyrene	1357	1625	2419	1474	2632
Benzo(ghi)perylene	1200	1312	1677	1070	1930
Dibenzo(ah)anthracene		194	226	170	316

Test no	T30					
Material	OSB					
Fire stage	Fire stage 3b (under-ventilated)					
Sampler	Impactor					
	Total sampled amount (pg):					
Impactor stage	> 2.5 µm	> 1.0 µm	> 0.5 µm	> 0.25 µm	< 0.25 µm	Σ
Naphthalene	0	0	0	0	34000	34000
Acenaphthylene	0	0	0	0	110000	110000
Acenaphthene	0	0	0	0	400000	400000
Fluorene	0	0	0	0	75000	75000
Phenanthrene	0	36000	54000	76000	800000	966000
Anthracene	0	0	18000	23000	250000	291000
Fluoranthene	200000	1200000	1300000	1400000	5500000	9600000
Pyrene	230000	1200000	1300000	1400000	6100000	10230000
Benzo(a)anthracene	200000	760000	770000	690000	4900000	7320000
Chrysene	190000	630000	660000	590000	4200000	6270000
Benzo(b)fluoranthene	250000	840000	870000	770000	7700000	10430000
Benzo(k)fluoranthene	81000	280000	290000	260000	4000000	4911000
Benzo(a)pyrene	220000	740000	770000	690000	6300000	8720000
Indeno(1.2.3-cd)pyrene	160000	500000	520000	410000	3000000	4590000
Benzo(ghi)perylene	110000	380000	390000	320000	2600000	3800000
Dibenzo(ah)anthracene	19000	58000	61000	48000	490000	676000

Test no	T30 cont.		
	Total sampled amount (ng)	Concentration in box (ng/l)	Mass loss yields (µg/g)
Naphthalene	34	3.6	0.16
Acenaphthylene	110	11.7	0.52
Acenaphthene	400	43	1.9
Fluorene	75	8.0	0.35
Phenanthrene	966	103	4.5
Anthracene	291	31	1.4
Fluoranthene	9600	1021	45
Pyrene	10230	1088	48
Benzo(a)anthracene	7320	779	34
Chrysene	6270	667	29
Benzo(b)fluoranthene	10430	1110	49
Benzo(k)fluoranthene	4911	522	23
Benzo(a)pyrene	8720	928	41
Indeno(1.2.3-cd)pyrene	4590	488	21
Benzo(ghi)perylene	3800	404	17.8
Dibenzo(ah)anthracene	676	72	3.2

Test no	T30 cont.				
Impactor stage	> 2.5 µm	> 1.0 µm	> 0.5 µm	> 0.25 µm	< 0.25 µm
Sampled weight of particles (µg)	30	180	250	150	1590
	PAH content of soot (µg /g):				
Naphthalene	0.0	0	0	0	21
Acenaphthylene	0.0	0	0	0	69
Acenaphthene	0.0	0	0	0	252
Fluorene	0.0	0	0	0	47
Phenanthrene	0.0	200	216	507	503
Anthracene	0.0	0	72	153	157
Fluoranthene	6667	6667	5200	9333	3459
Pyrene	7667	6667	5200	9333	3836
Benzo(a)anthracene	6667	4222	3080	4600	3082
Chrysene	6333	3500	2640	3933	2642
Benzo(b)fluoranthene	8333	4667	3480	5133	4843
Benzo(k)fluoranthene	2700	1556	1160	1733	2516
Benzo(a)pyrene	7333	4111	3080	4600	3962
Indeno(1.2.3-cd)pyrene	5333	2778	2080	2733	1887
Benzo(ghi)perylene	3667	2111	1560	2133	1635
Dibenzo(ah)anthracene	633	322	244	320	308

Test no	T28					
Material	OSB					
Fire stage	Fire stage 1b (oxidative pyrolysis)					
Sampler	Impactor					
	Total sampled amount (pg):					
Impactor stage	> 2.5 µm	> 1.0 µm	> 0.5 µm	> 0.25 µm	< 0.25 µm	Σ
Naphthalene	-	-	-	-	-	-
Acenaphthylene	-	-	-	-	-	-
Acenaphthene	-	-	-	-	-	-
Fluorene	-	-	-	-	-	-
Phenanthrene	49000	16000	-	-	-	65000
Anthracene	15000	-	-	-	-	15000
Fluoranthene	25000	20000	-	-	-	45000
Pyrene	19000	15000	-	-	-	34000
Benzo(a)anthracene	-	-	-	-	-	-
Chrysene	-	-	-	-	-	-
Benzo(b)fluoranthene	-	-	-	-	-	-
Benzo(k)fluoranthene	-	-	-	-	-	-
Benzo(a)pyrene	-	-	-	-	-	-
Indeno(1.2.3-cd)pyrene	-	-	-	-	-	-
Benzo(ghi)perylene	-	-	-	-	-	-
Dibenzo(ah)anthracene	-	-	-	-	-	-

Test no	T28 cont.		
	Total sampled amount (ng)	Concentration in box (ng/l)	Mass loss yields (µg/g)
Naphthalene	-	-	-
Acenaphthylene	-	-	-
Acenaphthene	-	-	-
Fluorene	-	-	-
Phenanthrene	65	6.9	0.38
Anthracene	15.0	1.6	0.088
Fluoranthene	45	4.8	0.27
Pyrene	34	3.6	0.20
Benzo(a)anthracene	-	-	-
Chrysene	-	-	-
Benzo(b)fluoranthene	-	-	-
Benzo(k)fluoranthene	-	-	-
Benzo(a)pyrene	-	-	-
Indeno(1.2.3-cd)pyrene	-	-	-
Benzo(ghi)perylene	-	-	-
Dibenzo(ah)anthracene	-	-	-

Test no	T28 cont.				
Impactor stage	> 2.5 µm	> 1.0 µm	> 0.5 µm	> 0.25 µm	< 0.25 µm
Sampled weight of particles (µg)	2340	1340	70	50	1050
	PAH content of soot (µg /g):				
Naphthalene	-	-	-	-	-
Acenaphthylene	-	-	-	-	-
Acenaphthene	-	-	-	-	-
Fluorene	-	-	-	-	-
Phenanthrene	20.9	11.9	-	-	-
Anthracene	6.4	-	-	-	-
Fluoranthene	10.7	14.9	-	-	-
Pyrene	8.1	11.2	-	-	-
Benzo(a)anthracene	-	-	-	-	-
Chrysene	-	-	-	-	-
Benzo(b)fluoranthene	-	-	-	-	-
Benzo(k)fluoranthene	-	-	-	-	-
Benzo(a)pyrene	-	-	-	-	-
Indeno(1.2.3-cd)pyrene	-	-	-	-	-
Benzo(ghi)perylene	-	-	-	-	-
Dibenzo(ah)anthracene	-	-	-	-	-

A 3.4 PAH sampler data in background measurements

Measurement no	B14		B27		B29	
	Total sampled amount (ng)	Conc. in box (ng/l)	Total sampled amount (ng)	Conc. in box (ng/l)	Total sampled amount (ng)	Conc. in box (ng/l)
Naphthalene	63	21	240	48	300	60
Acenaphthylene	27	9.0	90	18	260	52
Acenaphthene	0	0	0	0	0	0
Fluorene	0	0	120	24	150	30
Phenanthrene	18	6.0	340	68	170	34
Anthracene	0	0	61	12.2	31	6.2
Fluoranthene	0	0	24	4.8	0	0
Pyrene	0	0	18	3.6	0	0
Benzo(a)anthracene	0	0	0	0	0	0
Chrysene	0	0	0	0	0	0
Benzo(b)fluoranthene	0	0	0	0	0	0
Benzo(k)fluoranthene	0	0	0	0	0	0
Benzo(a)pyrene	0	0	0	0	0	0
Indeno(1.2.3-cd)pyrene	0	0	0	0	0	0
Benzo(ghi)perylene	0	0	0	0	0	0
Dibenzo(ah)anthracene	0	0	0	0	0	0

Measurement no	B30		B32	
	Total sampled amount (ng)	Conc. in box (ng/l)	Total sampled amount (ng)	Conc. in box (ng/l)
Naphthalene	360	72	510	102
Acenaphthylene	220	44	350	70
Acenaphthene	0	0	0	0
Fluorene	190	38	240	48
Phenanthrene	230	46	370	74
Anthracene	42	8.4	71	14.2
Fluoranthene	15	3.0	28	5.6
Pyrene	0	0	20	4
Benzo(a)anthracene	0	0	0	0
Chrysene	0	0	0	0
Benzo(b)fluoranthene	0	0	0	0
Benzo(k)fluoranthene	0	0	0	0
Benzo(a)pyrene	0	0	0	0
Indeno(1.2.3-cd)pyrene	0	0	0	0
Benzo(ghi)perylene	0	0	0	0
Dibenzo(ah)anthracene	0	0	0	0

Annex 4 Isocyanate data

A 4.1 Isocyanate sampler data in tests with OSB-board

Test no	T9			
Material	OSB			
Fire stage	Fire stage 2 (Well-ventilated)			
Sampler	ES1	ES2	ES3	$\bar{x}$
ICA (mg/m^3)	0.28	0.33	0.28	0.30
MIC	-	-	-	-
EIC	-	-	-	-
PIC	-	-	-	-
PhI	-	-	-	-
HDI	-	-	-	-
2.4-TDI	-	-	-	-
2.6-TDI	-	-	-	-
IPDI 1	-	-	-	-
IPDI 2	-	-	-	-
MDI	-	-	-	-

Test no	T25			
Material	OSB			
Fire stage	Fire stage 2 (Well-ventilated)			
Sampler	ES22	ES23	ES24	$\bar{x}$
ICA (mg/m^3)	0.77	0.77	0.89	0.81
MIC	-	-	-	-
EIC	-	-	-	-
PIC	-	-	-	-
PhI	-	-	-	-
HDI	-	-	-	-
2.4-TDI	-	-	-	-
2.6-TDI	-	-	-	-
IPDI 1	-	-	-	-
IPDI 2	-	-	-	-
MDI	-	-	-	-

Test no	T10			
Material	OSB			
Fire stage	Fire stage 3b (Under-ventilated)			
Sampler	Impinger 1	Impinger 2		$\bar{x}$
ICA (mg/m^3)	8.7	9.8		9.2
MIC	0.29	0.27		0.28
EIC	-	-		-
PIC	-	-		-
PhI	0.15	0.15		0.15
HDI	-	-		-
2.4-TDI	-	-		-

2.6-TDI	-	-		-
IPDI 1	-	-		-
IPDI 2	-	-		-
MDI	-	-		-

Test no	T28			
Material	OSB			
Fire stage	Fire stage 1b (oxidative pyrolysis)			
Sampler	Impinger 7	Impinger 8		$\bar{x}$
ICA (mg/m^3)	12	7.4		9.6
MIC	9.5	6.9		8.2
EIC	0.061	0.061		0.061
PIC	-	-		-
PhI	0.084	0.086		0.085
HDI	-	-		-
2.4-TDI	-	-		-
2.6-TDI	-	-		-
IPDI 1	-	-		-
IPDI 2	-	-		-
MDI	-	-		-

A 4.2 Isocyanate impactor data in tests with OSB-board

Test no	T30				
Material	OSB				
Fire stage	Fire stage 3b (Under-ventilated)				
Sampler	Denuder	2.5 µm impactor stage	1.0 µm impactor stage	0.5 µm impactor stage	Σ
ICA (mg/m^3)	4.9	0.19	0.52	0.29	5.9
MIC	0.16				0.16
EIC	-	-	-	-	-
PIC	-	-	-	-	-
PhI	0.093	0.0037	0.0036	-	0.10
HDI	-	-	-	-	-
2.4-TDI	-	-	-	-	-
2.6-TDI	-	-	-	-	-
IPDI 1	-	-	-	-	-
IPDI 2	-	-	-	-	-
MDI	-	-	-	-	-

Test no	T22				
Material	OSB				
Fire stage	Fire stage 1b (oxidative pyrolysis)				
Sampler	Denuder	2.5 µm impactor stage	1.0 µm impactor stage	0.5 µm impactor stage	Σ
ICA (mg/m^3)	4.1	0.36	0.05	0.004	4.5
MIC	6.7	0.040	0.022	0.014	6.8
EIC	0.032	-	-	-	0.032
PIC	-	0.0095	-	-	0.095
PhI	0.028	-	-	-	0.028
HDI	-	-	-	-	-
2.4-TDI	-	-	-	-	-
2.6-TDI	-	-	-	-	-
IPDI 1	-	-	-	-	-
IPDI 2	-	-	-	-	-
MDI	-	0.010	-	-	0.010

A 4.3 Isocyanate sampler data in tests with PVC-carpet

Test no	T23			
Material	PVC			
Fire stage	Fire stage 2 (Well-ventilated)			
Sampler	ES 10	ES 11	ES 12	$\bar{x}$
ICA (mg/m^3)	0.49	0.49	0.63	0.54
MIC	-	-	-	-
EIC	-	-	-	-
PIC	-	-	-	-
PhI	-	-	-	-
HDI	-	-	-	-
2.4-TDI	-	-	-	-
2.6-TDI	-	-	-	-
IPDI 1	-	-	-	-
IPDI 2	-	-	-	-
MDI	-	-	-	-

Test no	T32			
Material	PVC			
Fire stage	Fire stage 2 (Well-ventilated)			
Sampler	ES 45	ES 46	ES 47	$\bar{x}$
ICA (mg/m^3)	0.60	0.68	0.55	0.61
MIC	-	-	-	-
EIC	-	-	-	-
PIC	-	-	-	-
PhI	-	-	-	-
HDI	-	-	-	-
2.4-TDI	-	-	-	-
2.6-TDI	-	-	-	-
IPDI 1	-	-	-	-
IPDI 2	-	-	-	-
MDI	-	-	-	-

Test no	T24			
Material	PVC			
Fire stage	Fire stage 3b (Under-ventilated)			
Sampler	ES 16	ES 17	ES 18	$\bar{x}$
ICA (mg/m^3)	1.0	1.2	1.2	1.1
MIC	-	-	-	-
EIC	-	-	-	-
PIC	-	-	-	-
PhI	-	-	-	-
HDI	-	-	-	-
2.4-TDI	-	-	-	-
2.6-TDI	-	-	-	-
IPDI 1	-	-	-	-
IPDI 2	-	-	-	-
MDI	-	-	-	-

Test no	T27			
Material	PVC			
Fire stage	Fire stage 3b (Under-ventilated)			
Sampler	Impinger 5	Impinger 6		$\bar{x}$
ICA (mg/m^3)	0.34	0.36		0.35
MIC	-	-		-
EIC	-	-		-
PIC	-	-		-
PhI	-	-		-
HDI	-	-		-
2.4-TDI	-	-		-
2.6-TDI	-	-		-
IPDI 1	-	-		-
IPDI 2	-	-		-
MDI	-	-		-

Test no	T31			
Material	PVC			
Fire stage	Fire stage 1b (oxidative pyrolysis)			
Sampler	Impinger 9	Impinger 10		$\bar{x}$
ICA (mg/m^3)	0.64	0.64		0.64
MIC	-	-		-
EIC	-	-		-
PIC	-	-		-
PhI	-	-		-
HDI	-	-		-
2.4-TDI	-	-		-
2.6-TDI	-	-		-
IPDI 1	-	-		-
IPDI 2	-	-		-
MDI	-	-		-

Test no	T29			
Material	PVC			
Fire stage	Fire stage 1b (oxidative pyrolysis)			
Sampler	ES 34	ES 35		$\bar{x}$
ICA (mg/m^3)	0.29	0.28		0.29
MIC	-	-		-
EIC	-	-		-
PIC	-	-		-
PhI	-	-		-
HDI	-	-		-
2.4-TDI	-	-		-
2.6-TDI	-	-		-
IPDI 1	-	-		-
IPDI 2	-	-		-
MDI	-	-		-

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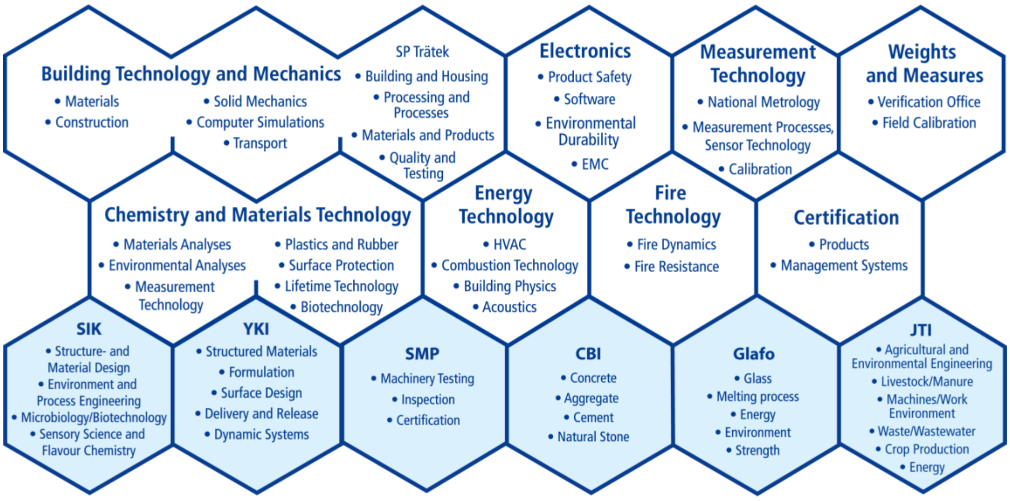

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