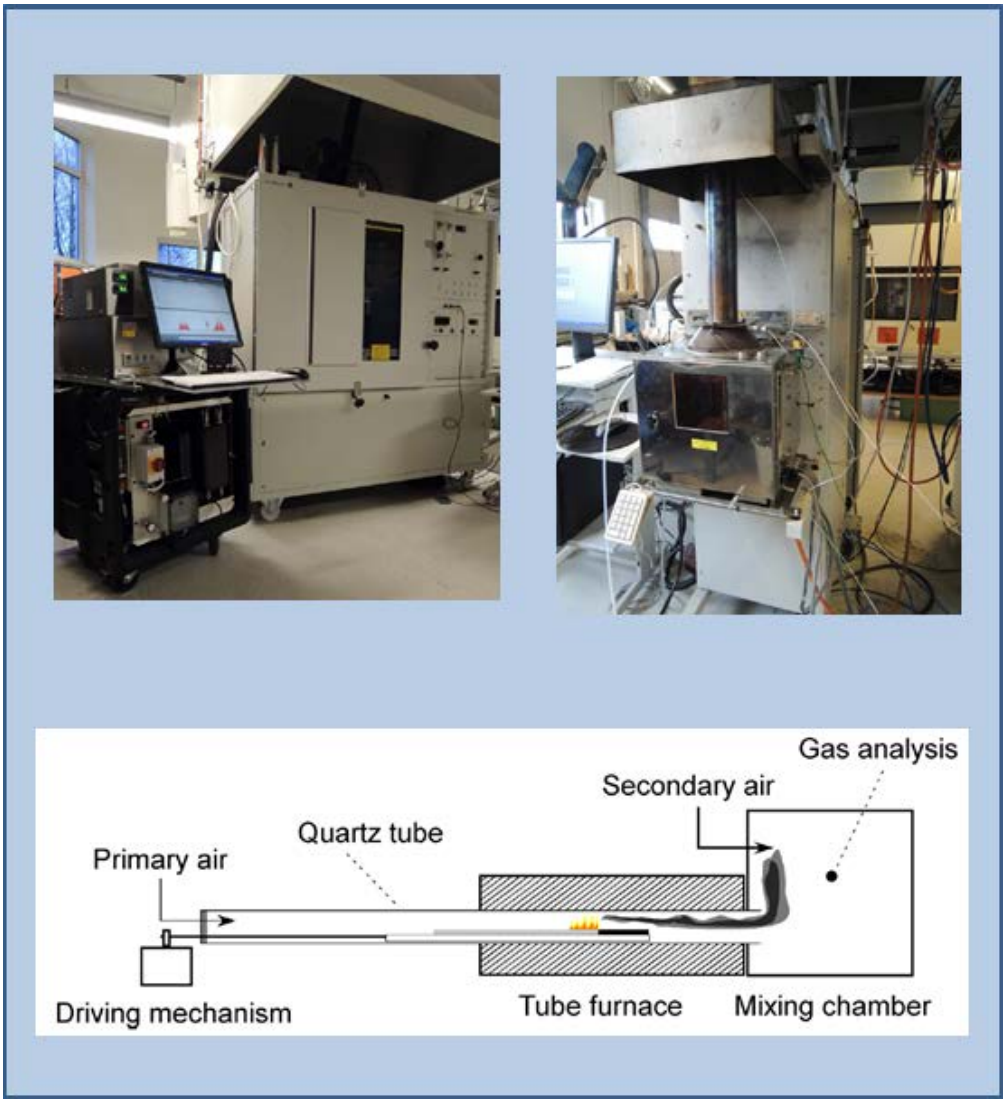
SAFETY AND TRANSPORT
FIRE RESEARCH



Experimental evaluation of fire toxicity test methods

Per Blomqvist and Anna Sandinge

RISE Report 2018:40

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Abstract

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An experimental evaluation of the most common bench-scale tests methods for fire toxicity was conducted by RISE Fire Research. The background of the work was the on-going discussion in the fire community on the applicability and relevance of these test methods.

The test methods included in the programme were the ISO/TS 19700 steady-state tube furnace (SSTF), the controlled atmosphere cone calorimeter (CACC), and the EN 45545-2 smoke chamber test (SC). In these tests the production of selected toxic gases was quantitatively analysed using FTIR. Tests for the measurement of toxic gas production were made with eleven different materials used as test specimens, both combustible and non-combustible materials. The materials were commercially available insulation products provided by EURIMA, the sponsor of the project. These materials should not be regarded as typical or fully representative of a product category.

The evaluation of the results from the different test methods was divided into combustible test specimens and non-combustible test specimens. That was because the test conditions in the first case are greatly influenced by the combustion behaviour of the test specimen, while in the second case the test conditions are more constant.

A general observation was that there in many cases was correlation between both species composition and level of toxic gas species yields between test methods when the combustion conditions were similar. In cases where yields differed significantly it could in most cases be explained by clear differences in test conditions.

For combustible materials it was concluded that the SSTF offers the best means for conducting tests at pre-decided and controlled flaming combustion conditions. The CACC does not give steady-state flaming combustion and the influence of vitiation was limited in the tests made. The SC generally accumulates a mixture of gases from both flaming and non-flaming combustion periods in a test, and the yields measured do not in those cases represent any specific combustion stage.

For non-combustible materials a general observation was that any of the test methods investigated in principle could be used since the influence on the test conditions from the material itself is limited compared to combustible materials. However, there were specific properties and limitations of the different test methods observed that are important to consider.

Key words: fire toxicity; test methods; combustion conditions; insulation materials

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Content

Preface

EURIMA (European Insulation Manufacturers Association) commissioned the testing work and the evaluation of the test results included in this report. We gratefully acknowledge the sponsor for allowing the open publication of this report.

Summary

An experimental evaluation on the most common bench-scale tests methods for fire toxicity was conducted by RISE Fire Research. The background of the work was the on-going discussion in the fire community on the applicability and relevance of these test methods.

The test methods included in the programme were the ISO/TS 19700 steady-state tube furnace (SSTF), the controlled atmosphere cone calorimeter (CACC), and the EN 45545-2 smoke chamber test (SC). In these tests the production of selected toxic gases was quantitatively analysed using FTIR. Comparative tests with a reference material were further conducted with the Fire propagation apparatus (FPA). Tests for the measurement of toxic gas production were made with eleven different materials used as test specimens, both combustible and non-combustible materials. The materials were commercially available insulation products provided by the sponsor. These materials should not be regarded as typical or fully representative of a product category.

The tests with the SSTF included tests modes for well-ventilated flaming, under-ventilated flaming and non-flaming conditions. The tests with the CACC at 50 kW/m^2 included tests modes for flaming combustion at 21% O_2, flaming combustion at vitiated conditions (normally 15% O_2), and non-flaming tests at vitiated conditions (normally 10% O_2). Tests with the SC were made at 25 kW/m^2, with a pilot-flame, and at 50 kW/m^2, without a pilot-flame. For the non-combustible materials, equivalent test method settings as above were used but the tests were in these cases non-flaming pyrolysis tests.

The evaluation of the test results includes an assessment of the actual combustion conditions in the tests conducted with the different test methods, as a basis of a comparison of the test results on toxic gas production. The comparison of the test results of the applied methods gives a basis for a general assessment of the applicability of the test methods.

In the SSTF, steady-state combustion is created by feeding a constant fuel-air flow into the combustion zone. The fuel-air ratio and the furnace temperature are the main parameters that determine the combustion condition. If those parameters can be maintained a prolonged steady-state is achieved. In the CACC tests the stationary sample is constantly irradiated by the heating cone during its dynamic combustion event within a constant flow of pure or vitiated air. The actual ventilation condition is thus influenced by the burning behaviour of the sample specimen. In the SC the stationary sample is constantly irradiated by the heating cone during its dynamic combustion event and the fire effluents are accumulating in the closed test chamber and will thus vitiate the combustion air.

Production yields of gas species from the SSTF tests were available as these are the output from the standardized test method. Yields for the CACC tests and the SC tests were specifically calculated. For the CACC, yields were calculated for the flaming period of the test and for the complete test time. For the SC, yields were calculated from the maximum concentration measured, representing the complete test.

The comparison of the results from the different test methods has been divided into combustible materials and non-combustible materials. That is because the test conditions in the first case are greatly influenced by the combustion behaviour of the test specimen, while in the second case the test conditions are more constant.

1 Introduction

1.1 Background

The work reported on here included a test programme with different bench-scale fire tests methods applicable for the determination of toxic gas production. The test methods applied were:

- ISO/TS 19700, Steady-state tube furnace (SSTF);
- ISO 5660-1, Cone calorimeter equipped with a controlled-atmosphere box, *i.e.* the Controlled Atmosphere Cone Calorimeter (CACC)[i];
- ASTM E-2058, Fire propagation apparatus (FPA); and
- EN ISO 5659-2, the smoke chamber (SC) with FTIR analysis according to the EN 45545-2 test procedure.

The programme included tests with a range of different materials, both combustible and non-combustible. The programme included tests with black PMMA, a polymer material which often is used as a reference material in fire tests comparisons (tests with the FPA were only conducted with PMMA). The sponsor selected the materials and provided these for the tests.

The evaluation of the test results included an assessment of the actual combustion conditions in the tests conducted, which was used as a basis for a comparison of the test results on toxic gas production. The comparison of the test results of the applied methods was made to give a basis for a general assessment of the applicability of the investigated test methods.

1.2 Fire conditions

The composition of the fire effluents from a burning material varies with the physical conditions of the fire, *e.g.* well-ventilated fires give more complete combustion with a high yield of carbon dioxide compared to under-ventilated or vitiated fires which give higher yields of toxic carbon monoxide and other products of incomplete combustion. When selecting a bench-scale test for analysis of fire toxicity it is thus central that the combustion condition in the fire scenario addressed is replicated as far as possible by the bench-scale test method.

Fire stages are classified in ISO 19706 [1] and here are important fire conditions such as: the heat flux to the fuel surface; temperatures on fuel surface and upper layer gas temperature; oxygen concentration in entrained- and exhausted effluents; and the fuel/air equivalence ratio (see definition below), listed for some defined fire stages.

[i] There is no standardised test procedure published for the controlled-atmosphere box with the cone calorimeter.

The Fire stages defined are:

1. Non-flaming
    a. self-sustaining (smouldering)
    b. oxidative pyrolysis from externally applied radiation
    c. anaerobic pyrolysis from externally applied radiation
2. Well-ventilated flaming
3. Under-ventilated flaming
    a. small, localized fire (generally in a poorly ventilated compartment)
    b. post-flashover fire

The combustion condition in any bench-scale test method used for analysis of fire toxicity should be possible to classify in terms of these fire stages.

It is clear from ISO 19706 that the *ventilation condition* in a fire is an critical factor, *e.g.*, a well-ventilated flaming fire, Fire stage 2, gives a considerably lower CO/CO_2 ratio (<0.05) compared to an under-ventilated flaming post-flashover fire, Fire stage 3b, with a CO/CO_2 ratio of 0.1-0.4. The ventilation conditions are in fact, in most cases, decisive for determining the type and quantity of toxic gases present in the fire effluents. For example, in the combustion of nitrogen-containing materials, nitrogen oxides (NO_X) are produced at well-ventilated conditions, while for under-ventilated conditions instead hydrogen cyanide (HCN) and ammonia (NH_3) are produced.

A parameter used to describe the ventilation conditions during combustion is the equivalence ratio, ϕ, defined in the equation below, where $\dot{m}_{fuel}$ is the mass loss rate of the fuel, $\dot{m}_{oxygen}$ is the mass flow rate of oxygen, and the subscript "*stoich.*" refers to the quotient under stoichiometric conditions.

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

$\phi = 1$ stoichiometric combustion

$\phi < 1$ well ventilated combustion

$\phi > 1$ under-ventilated combustion

The equivalence ratio describes the relationship between the actual fuel/oxygen ratio and the stoichiometric fuel/oxygen ratio. In cases where the overall combustion process is studied ϕ can be defined in a more general sense using the equivalence ratio for the total combustion process. This is usually referred to as the global equivalence ratio, GER.

The *thermal environment* sensed by the test specimen during combustion is the next important factor to consider and includes both the temperature of the material and the gas temperature. Flaming or non-flaming decomposition is crucial for the combustion and the production of toxic gases. Flaming combustion oxidizes the decomposition products and further produces heat that increases the decomposition rate. Non-flaming decomposition releases pyrolysis products.

Secondary factors that have an influence on the composition of the fire effluents are the extent of dilution with fresh air which cools and quenches gas phase reactions, and the age of the effluents which determines the time available for post-fire processes including soot coagulation and deposition of condensable compounds. It is clear that the composition of the effluents varies strongly between fires, during the course of a fire, and also between different locations in space within a plume of effluents. This fact complicates the use of bench-scale test data to represent real scale fire scenarios.

The form and composition of the *test specimen* is also important. In bench-scale tests with non-homogenous products, the test specimen should contain representative portions of different materials compared to the finished product. However, for layered products the production of toxic gases can depend on the surface exposed in a specific test. In a real fire or in a large-scale test with a non-homogeneous product, different part, or layers, are combusted and produce toxic gases during different phases of the fire. This process can be difficult or even unmanageable to capture with one single small-scale test.

1.3 Bench-scale test methods

The considerations discussed above give the basic requirements for using a bench-scale test as a relevant source of data on toxic gas production, but additional considerations may be necessary. A useful document is ISO 16312-1, “Guidance for assessing the validity of physical fire models for obtaining fire effluent toxicity data for fire hazard and risk assessment – Part 1: Criteria” [2]. This standard provides technical criteria and guidance for evaluating physical fire models used in effluent toxicity studies for obtaining data on the effluent from products and materials under fire conditions relevant to life safety. These criteria are applied for assessment of standardised bench scale tests in ISO/TR 16312-2, “Guidance for assessing the validity of physical fire models for obtaining fire effluent toxicity data for fire hazard and risk assessment – Part 2: Evaluation of individual physical fire models” [3].

Another useful document is ISO 29903, “Guidance for comparison of toxic gas data between different physical fire models and scales” [4]. This standard provides principles for characterizing the measured production of toxic gases from a laboratory fire test and provides bases for comparing the results between different types and scales of such tests.

The bench-scale test methods included in the test programme presented in this report were selected after their current use in commercial testing and the interest and work put on their development in research and standardisation.

2 Test programme

2.1 Methods and test procedures

2.1.1 Introduction

The different test methods applied, and the detailed test procedures are described in the next sections. All tests were conducted with sample specimen from core material extracted from the received products (see section 2.2). Duplicate tests were conducted with a product as normal practice for all test methods. In cases where the results from the duplicate tests deviated significantly, a third test was conducted. All tests with the reference material (PMMA) were run in triplicate.

2.1.2 Steady-state tube furnace (SSTF)

The SSTF tests were conducted according to ISO/TS 19700 [5]. The test set-up is shown schematically in Figure 1. The combustion conditions are established by feeding the sample material into the furnace together with primary air for combustion. The combination of the material feeding rate, the primary air flow rate, and the furnace temperature decides the combustion conditions.

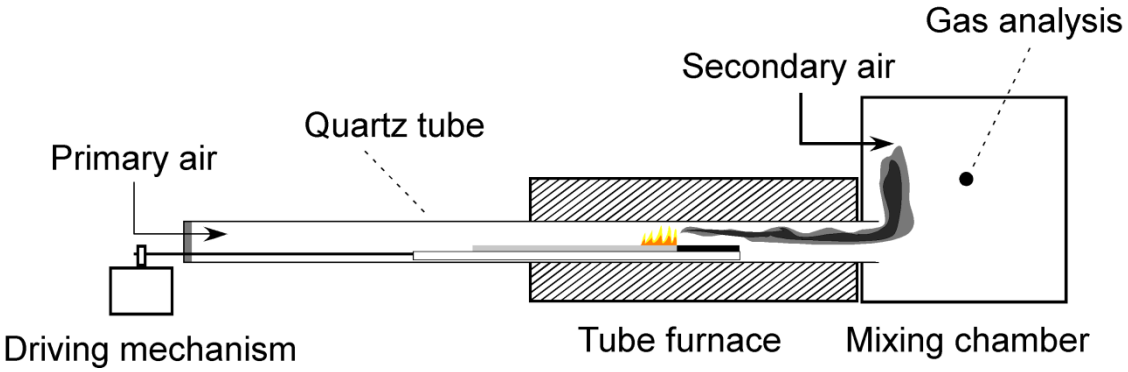


Figure 1 Schematic drawing of the ISO/TS 19700 steady-state tube furnace.

The fire stages aimed for in the in this test programme included (nominal furnace temperature in parenthesis):

Fire stage 1b – oxidative pyrolysis (350 °C);

Fire stage 2 – well-ventilated flaming fire (650 °C);

Fire stage 3b – post-flashover flaming fire, under-ventilated (825 °C).

ISO/TS 19700 specifies a nominal loading of 25 mg combustible material/mm with a feeding rate of 40 mm/min. The primary air flow is nominally 10 l/min for well-ventilated flaming combustion. This results in a material/air ratio of 100 mg combustible material/ l air. The feeding rate and the primary airflow rate can, however, be adjusted for allowing tests with, *e.g.*, low-density materials such as polymeric foams.

The combustible loading for the different sample species was calculated by determining the combustible content of the individual materials by combustion in a furnace at 550 °C. Information is available in Appendix 5.

Flaming combustion is required for attaining fire stages 2 and 3b. If the nominal temperature does not give flaming combustion the furnace temperature shall be raised in steps of 25 °C until flaming combustion occurs. Stable combustion was not attained at 650 °C in fire stage 2 tests with some of the combustible materials tested. In these cases, tests were made at a higher furnace temperature according to the standard. However, for essentially non-combustible insulation materials such as mineral fibre products, flaming combustion would not occur at any temperature as the combustible content is too low. In these cases, the temperature has not been increased from the nominal temperature.

The size of the sample boat and the diameter of the quarts tube of the furnace set restrictions on the maximum sample dimensions. It was decided to use the same sample width for all types of samples/materials and that dimension was set to 22 mm (this was not possible for PMMA). The total length of the sample species was in all cases 795 mm. The height of the sample specimen (maximum 22 mm) was then adjusted to give an optimal combustible loading for a well-ventilated test (fire stage 2).

The sample specimen data and calculated nominal combustible material-air ratio for well-ventilated tests are given in Table 1. The data presented in the table is that which was found most suitable for representing well-ventilated conditions and was the starting point for the testing. In several cases were other settings investigated and information on this can be found in the appendices with test results.

Table 1 Sample specimen data and calculated nominal combustible material-air ratio for Fs 2 (well-ventilated) tests. The materials are anonymized, see section 2.2.

Material	Height× width (in mm)	Combustible loading (mg/mm)	Advance rate (mm/min)	Primary air flow rate (l/min)	Material-air ratio (mg combustible/l air)
PF1	22×22	16	60	10	96
PF2	22×22	5.1	60	4	76
PF3	22×22	14	60	10	84
PF4	22×22	13	60	10	78
PF5	22×22	14	60	10	84
OF1	22×16	16	60	10	96
OF2	22×22	14	60	10	84
MF1[i]	22×22	0.55	40	10	2.2
MF2[i]	22×22	1.1	40	10	4.4
MF3[i]	22×22	0.9	40	10	3.6
MF4[i]	22×22	2.1	40	10	8.4
PMMA	5×4.5	26	40	10	104

[i] These materials are mineral fibre insulation products that do not show flaming combustion as the combustible content is very low.

As can be seen from Table 1, the primary air flow rate for well-ventilated tests was set to 10 l/min per default as this is the "start conditions" given in the standard. However, for PF2 this would have given a very low material-to-air ratio and 4.0 l/min was used instead.

Note that the mineral fibre products (MF1-MF4) all have a very low combustible material-air ratio and will not show flaming combustion. All tests with these materials are thus characterised as pyrolysis test.

A SSTF test series with a combustible material is always started with a Fire stage 2 test (well-ventilated) according to the standard. In the standard there are certain criteria on the results from the Fire stage 2 (Fs 2) test, and the results from this test is further used for calculating the primary air flow rate for the Fire stage 3b (under-ventilated) test.

The criterion for an acceptable Fs 2 test is that reduction of the oxygen concentration in the mixing box (D_{O2}) is < 3.14 % and > 1.8 %. This criterion results in a well-ventilated test with an equivalence ratio <0.75. There are more detailed instructions in the standard on how to proceed if this criterion is not met. The value of D_{O2} is then used in a simple formula for calculating the proper primary air flow in an under ventilated test. It has been shown[ii] that this calculation can result in a too low primary air flow rate, *e.g.*, for flame retarded materials and that it is proper to use 3.2 l/min as a minimum primary air flow value. This recommendation has been used in the tests conducted in this project.

In the case of the mineral fibre products, these were tested based on the default settings for the combustible materials as a starting point. Pyrolysis tests were made at 350 °C with a primary flow rate of 2.0 l/min; at 650 °C with a primary flow rate of 10 l/min; and at 825 °C with a primary flow rate also here of 10 l/min. The flow rate was kept the same in the 650 °C and 825 °C tests to clearly see the influence of the temperature. Additionally, for MF1 and MF4 the influence of the primary air-flow was investigated at 825 °C by conducting tests also with 3.2 l/min primary air flow rate (21 vol-% O_2) and 3.2 l/min flow rate with reduced oxygen content (5 vol-% O_2). In all cases above the material feeding rate was 40 mm/min. A single trial was also made at 650 °C and 10 l/min with a feeding rate of 60 mm/min with all non-combustible products to investigate the effect of the feeding rate.

The results of a SSTF test are the yields of selected combustion products. These yields are calculated from the concentrations measured during a steady-state (SS) combustion period in the test. The criteria on the SS period are that it as a minimum shall be 5 minutes long with requirements on drift and fluctuation on O_2- and CO_2-concentrations in the mixing chamber.

2.1.3 Controlled atmosphere cone calorimeter (CACC)

The ISO 5660-1 Cone calorimeter is used for measurement of ignition time, heat release, and smoke production. In the Cone calorimeter the horizontally mounted sample is exposed to thermal radiation (50 kW/m^2 was used in this test programme) from a cone heater in the presence of a spark ignition source. The sample size is 100×100 mm^2 with a maximum thickness of 50 mm (50 mm was used generally in this

[ii] Revision of ISO/TS 19700 that was published 2016-10-14.

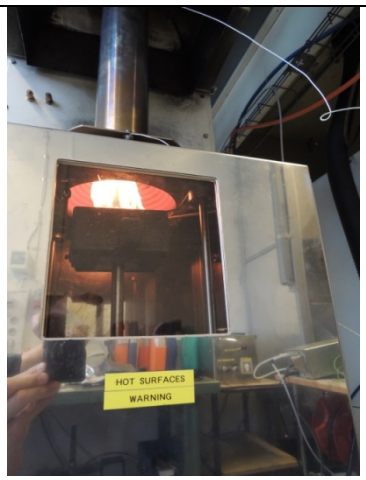
test programme). The sample is placed on a weighting device and a metal frame is used to protect the edges and sides of the sample specimen.

The equipment at RISE used for the tests are shown in Figure 2 - Figure 3 and test specifications for the CACC tests are given in Table 2. The test procedure applied for a CACC test is described in the end of this section.

Figure 2 The cone calorimeter with the controlled atmosphere box attached.

As an accessory to the Cone calorimeter there is a box available for conducting controlled atmosphere tests. The equipment consists of a box that encloses the sample holder/weighting device of the normal Cone calorimeter. The cone heater is mounted on-top of the box. The box has a door with a window for allowing putting the sample in test position and for visual inspection during the test. For controlling the atmosphere in the box nitrogen and air is introduced in the box in proportion giving the desired oxygen concentration and gas flow rate.

(a)



(b)

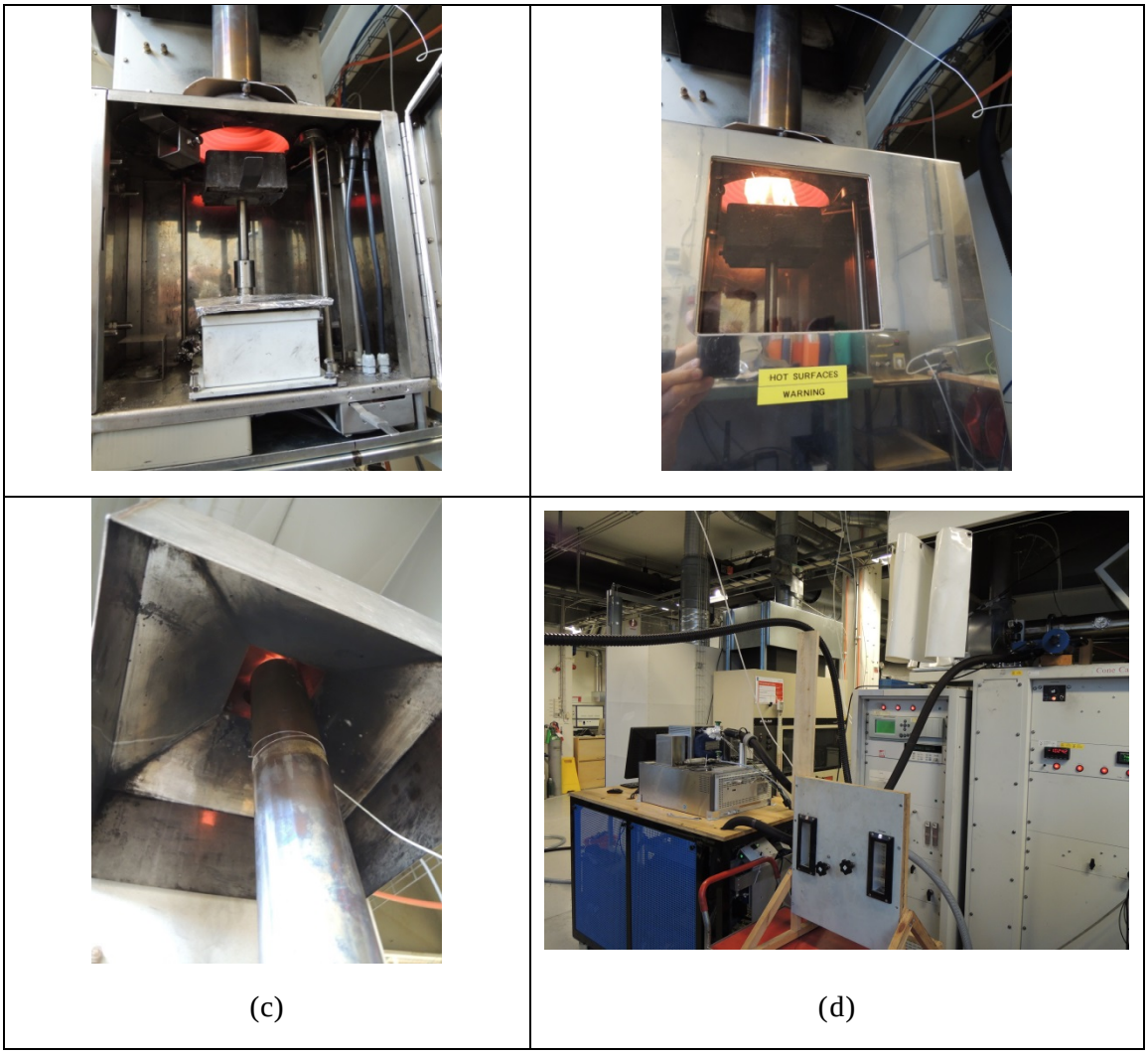


Figure 3 (a) The inside of the box with the sample holder put on the scale and the shutter for the heating cone open; (b) a sample (of PMMA) burning with high flames; (c) after-burning on top of the chimney (in a tests with PMMA); (d) the FTIR can be seen to the left in the picture and the blue sampling probe in the top right, in front are the gas flow regulators for the gas flow to the CA-box.

The Cone calorimeter test method is standardized in ISO 5660-1. However, tests with the controlled atmosphere box added to the Cone calorimeter are not standardised at present, but there is work on-going in ISO TC92/SC1/WG5.

The test set-up and test procedure to use were decided on after consulting literature and participating at the "Controlled-atmosphere Cone Calorimeter Workshop" at NIST on the 18th of October 2015. It was clear from these sources of information that the main issues included: the box flow-rate, the use of a chimney, and the calculation of Heat Release Rate (HRR) allowing corrections for added nitrogen. These issues were addressed, and specifications are given below.

Table 2 General test specifications for the CACC tests.

Instrumentation/parameter	Specification
Cone calorimeter and CA-box manufacturer	FTT (UK)
Cone calorimeter irradiance	50 kW/m^2
Cone calorimeter extraction flow-rate	24 l/s at 298 K
CA-box dimensions	380 mm (w) × 320 mm (d) × 340 mm (h); volume = 41 litres
CA-box chimney	600 mm height; 80 mm diameter; made in 1.5 mm thick stainless steel
CA-box flow-rate	160 ± 5 l/min
CA-box atmospheres	21 % O_2, 18 % O_2, 15 % O_2 and 10 % O_2
Sources of CA-box atmosphere	Nitrogen from a rack of gas cylinders and compressed air from a central delivery system at SP
Analysis of O_2 in the box	Yes
Time for sample specimen in CA-box before start of test (stabilization time)	90 s at 21 % O_2, 18 % O_2 and 15 % O_2 120 s at 10 % O_2
Calculation of HRR	Including corrections for heat-induced changes in the dilution ratio of ambient air and CA-box flow according to Werrel [6].

The test procedure used for the CACC tests was based on that from Werrel [6]. The basic steps in a test included:

- Calibration of the cone heater and the gas analysis system of the FTT cone calorimeter (daily).
- Start of FTIR measurement (duct) and O_2-analyser (CA-box).
- Measurement of a baseline value for the O_2-analyser of the Cone calorimeter with a duct flow of only ambient air (60 s).
- Start of air flow with reduced oxygen content through CA-box.
- Measurement of a reference value for the O_2-analyser with the duct flow including the flow from the CA-box with reduced oxygen content (60 s).
- Opening the CA-box and inserting the test sample (ambient air dilutes the CA-box atmosphere at this point).
- Stabilisation time to let the oxygen concentration again reach the set reduced level, 90 s or 120 s, see Table 2. (During this time the sample is slowly heated from insufficient insulation of the shutter, which can influence the ignition time.)
- The shutter is removed, and the test is started (this is the zero time of the test).
- The time of ignition (t_{ign}) is noted.
- The spark ignitor is removed in case of sustained burning.
- The time of extinction is noted.
- The test is continued for two minutes after extinction or a minimum of ten minutes in total.

The CACC test programme was designed to include duplicate tests at normal ambient oxygen level conditions (flaming), reduced oxygen conditions (flaming) and reduced oxygen conditions (non-flaming). To achieve this, the following procedure was applied:

1) All materials tested at 21 % O_2.
2) All materials tested at 15 % O_2.
3) Additional test mode:

- materials that burned with flames at 21 % O_2 and burned with flames at 15 % O_2 were tested at 10 % O_2;
- materials that burned with flames at 21 % O_2 and not at 15 % O_2 were tested with 18 % O_2;
- materials that did not burn with flames at 21 % O_2 and also not at 15 % O_2 were tested with 10 % O_2.

It was initially planned to use 5 % O_2 instead of 10 %, but the equipment for gas delivery to the CA-box had not the capacity to work on such a high mixing rate of nitrogen. We could not see any major deficiencies with using 10 % O_2 for the “reduced oxygen conditions (non-flaming)” mode, as none of the materials burned with flame at the 10 % O_2 atmosphere.

2.1.4 Fire propagation apparatus tests (FPA)

This test determines and quantifies material flammability characteristics. Parameters that are quantified include time to ignition, heat release rates, mass loss rate and effective heat of combustion. The test is also designed to obtain measurements of generation rates of fire products (CO_2, CO, and, if desired, gaseous hydrocarbons) for use in fire safety engineering.

The standard for the fire propagation apparatus (FPA) contains four separate test methods; for ignition, combustion, pyrolysis and fire propagation. The first three methods involve the use of horizontal specimen subjected to a controlled, external radiant heat flux, which are set from 0 kW/m^2 to 65 kW/m^2. The combustion, pyrolysis and fire propagation test methods can be performed using an inlet air supply that is normal air or other gaseous mixtures, *e.g.* air with added nitrogen, 100 % nitrogen or air enriched with up to 40 % oxygen.

Experiments were performed in the Fire Propagation Apparatus according to ASTM E2058-03 [7]. Three different conditions were analysed, defined by the oxygen concentration of the inlet air to the combustion chamber; 21 %, 15 % and 5 % O_2. Square PMMA samples with a length of 90 mm and thickness of 10 mm were exposed to a constant incident heat flux of 50 kW/m^2. Samples were tested in the horizontal orientation. The samples were wrapped in aluminium foil and the back face was insulated with mineral wool insulation (thickness >10 mm), as required by ISO 5660-1:2002. The experiments were conducted at an external testing laboratory.

Note that FPA-tests were only conducted with the reference material (PMMA).

2.1.5 Smoke chamber (SC)

The tests were conducted principally according to EN 45545-2:2013 [8], Annex C, C.2-C10. This specific test procedure was selected as it is very commonly used in test laboratories in Europe.

The test specimen is irradiated by a heating cone inside the EN ISO 5659-2 [9] test chamber. The sample is horizontally mounted, 75 mm square and up to 25 mm thick (25 mm was used generally in this test programme). The optical obscuration through the test chamber and the concentration of specified toxic combustion gases are measured in the test. The EN ISO 5659-2 smoke chamber at RISE and the FTIR attached are shown in Figure 4.

There are two test modes referred to in EN 45545-2:2013; 25 kW/m² with pilot flame, and 50 kW/m², without pilot flame. Both test modes were included in the tests programme.

The gases analysed by FTIR technique specified in EN 45545-2:2013 are carbon dioxide (CO_2), carbon monoxide (CO), hydrogen cyanide (HCN), nitrogen oxides (NO and NO_2 summarized as NO_X), sulphur dioxide (SO_2), hydrogen chloride (HCl), hydrogen fluoride (HF) and hydrogen bromide (HBr).

The standardized test procedure for the FTIR measurement is to sample from the test chamber for short discrete periods at 4 minutes and 8 minutes into the tests using a high sampling flow rate (3.5 l/min). A deviation from the standardized test procedure was that the sampling to the FTIR was made continuously during the full tests time. The sampling flow used was 1.5 l/min[iii] and the advantage is that the gas concentrations in the test chamber are monitored during the full tests time.

Figure 4 The EN ISO 5659-2 smoke chamber at RISE with the FTIR attached.

[iii] The method to sample continuously to the FTIR using a sampling flow of 1.5 l/min was verified in the European TRANSFEU project to not change the measured concentrations significantly.

FTIR measurements were conducted according to the specifications given in EN 45545-2:2013 with the deviations given above. The gas concentrations measured at 4 minutes and 8 minutes are used in EN 45545-2:2013 for calculating a Conventional Toxicity Index (CIT). The calculation of CIT is comprised of two terms:

CIT = [Precursor term] × [Summation term]

The precursor term is a scaling factor used to scale the results from the smoke chamber test to an analogous fire in a hypothetical train carriage. The summation term is calculated from the ratios of the measured concentrations in the smoke chamber test to reference values for each gas component. The CIT value is used in EN 45545-2:2013 as one (of several) performance criteria and the specific value for a product to pass the criteria is dependent on the product type (listed products) and the type of train for the intended application (Hazard level). Requirements on the CIT value vary between 0.75 and 1.8 dependent on product type and hazard level.

The results from the tests are reported according to the procedure in EN 45545-2:2013 based on the toxic gases found in concentrations above the 15 ppm, the limit of reporting used in EN 45545-2:2013. Additionally, as the concentrations of toxic gases were monitored continuously, CIT have been calculated for the time of maximum optical obscuration (D_S max).

2.1.6 FTIR analysis

Toxic gases were analysed in the SSTF-, the CACC- and the SC-test using Fourier Transfer Infra-Red (FTIR) technique. The following gases were included in the analysis: carbon dioxide (CO_2), carbon monoxide (CO), hydrogen cyanide (HCN), nitrogen oxides (NO and NO_2 summarized as NO_X), sulphur dioxide (SO_2), hydrogen chloride (HCl), hydrogen fluoride (HF) and hydrogen bromide (HBr). Specifications of the FTIR measurement system used are given in Table 3.

Table 3 Specification of the FTIR measurement system.

Instrumentation	Specification
Spectrometer	Thermo Scientific Antaris IGS analyzer (Nicolet)
Spectrometer parameters	Resolution: 0.5 cm^{-1} Spectral range: 4800 cm^{-1} – 650 cm^{-1} Scans/spectrum: 10; Time/spectrum: 12 seconds Detector: MCT
Gas cell	Volume: 0.2 litres; Path length: 2.0 m; Temperature: 180 °C; Cell pressure: 650 Torr
Limits of detection (LOD)	CO_2 = 150 ppm; CO = 2 ppm; HF = 2 ppm; HCl = 2 ppm; HBr = 7 ppm; HCN ppm = 3 ppm; NO_X = 5 ppm (NO = 4 ppm, NO_2 = 1 ppm); SO_2 = 2 ppm
Sampling probe	SSTF: stainless steel probe with single opening. CACC: stainless steel probe with single opening. SC: stainless steel probe with 5 mm inner diameter according to EN 45545-2:2013.
Sampling position	SSTF: mixing chamber of the SSTF test set-up. CACC: centre of duct 150 mm before the ring sampler of

Instrumentation	Specification
	the cone calorimeter. SC: 300 mm under the ceiling of the chamber (EN 45545-2:2013).
Primary filter	M&C ceramic filter heated to 180 °C
Secondary filter	M&C sintered steel filter heated to 180 °C
Sampling tubing	2.5 m of 4/6 mm diameter PTFE tubing heated to 180 °C
Pump	Position: after the gas cell Sampling flow: SSTF 3.5 l/min; CACC 3.5 l/min; SC 1.5 l/min (in all cases continuous sampling)

2.2 Materials for test specimens

The materials tested have been divided into groups of products with similar composition and are given anonymized below. The reason for anonymizing the individual materials is to avoid any direct comparison between products.

Polymeric foam (PF) insulation materials:

- PF1
- PF2
- PF3
- PF4
- PF5

Organic fibre (OF) insulation materials:

- OF1
- OF2

Mineral fibre (MF) insulation materials:

- MF1
- MF2
- MF3
- MF4

Homogenous thermoplastic material (reference material):

- Poly(methyl methacrylate), black (PMMA)

The materials tested were commercial insulation products provided by the sponsor for testing at RISE. The products received for testing were examples of commercial products found on the market and should not be regarded as typical products of each type. The PMMA material was provided by RISE.

The products were received at RISE as a batch of complete product, *i.e.*, as a roll of insulation material or a package of insulation boards. Sample specimens for the tests were produced at RISE and only core material was used in the case of roll- and board products.

The products received were measured and weighted, the combustible content was determined, and chemical elemental analysis was made (see Appendix 5). The data on the products (*i.e.* density and combustible content) referred to in this report is from measurement on the core material of the received products. Similarly, the chemical composition referred to is from measurement on the core material. Carbon (C), hydrogen (H) and nitrogen (N) were analysed quantitatively, further was XRF used for semi-quantitatively screening of elemental composition.

3 Methodology for comparison of test results

3.1 General principles

The first step in comparing the results on toxic gas production between different tests is to make an assessment of the current combustion conditions. That involves the identification of:

- flaming or non-flaming combustion,
- ventilation conditions (including air-flow restriction, or dilution of air, *i.e.* vitiation), and
- temperature influence.

The study of the combustion product distribution is an additional tool in characterizing the combustion conditions. A general example is the distribution between CO_2 and CO which quotient decreases with a decrease in ventilation for flaming combustion with non-flame retarded materials. Another example is the production of NO_X and HCN from flaming combustion of nitrogen containing products. Here is NO_X preferably produced for well-ventilated conditions and HCN preferably for under-ventilated conditions, as a rule of thumb.

The second step is to select a comparison parameter and here is production yields the preferred parameter for a quantitative comparison. Yields are calculated as the quotient of the produced amount of toxic gas specie and a normalizing entity. The most common types of yields used are mass-loss yields and mass-charge yields. These are calculated from the mass of toxic gas specie produced during a certain time period in a test divided with the mass lost or mass exposed (charged) during the same time period. Another type of yield that could be relevant for certain tests is surface charge yields. This is calculated from the mass of toxic gas specie produced during the complete test divided with the exposed surface of the sample specimen.

Production yields were calculated to be available for all tests included in the test programme and have been used for the comparison between test methods. Mass-loss yields (MLY) and mass-charge yields (MCY) were made available for all test methods. Surface charge yields (SCY) were additionally calculated for SC, CACC and FPA. This type of yield would not be of relevance for the SSTF. Surface yields are not discussed or evaluated in this report but available in the appendices.

3.2 Calculations and test data handling

3.2.1 Steady-state tube furnace (SSTF)

Production yields were calculated for the steady-state period in each test according to the instructions in ISO/TS 19700. Yields were calculated both as mass-loss yields (MLY) and mass-charge yields (MCY). The two flaming combustion modes with the SSTF described in ISO/TS 19700, stage 2 (well-ventilated) and stage 3b (under-

ventilated) are associated with defined ventilation rates, expressed as the equivalence ratio (Ø):

Fire stage 2: Ø < 0.75;

Fire stage 3b: Ø = 2.0.

These equivalence ratios are attained if instructions can be followed regarding material feed rate, air flow rate and combustion behaviour.

It is further possible to calculate the equivalence rate in a test from the elemental content of the material and alternatively from the oxygen depletion from complete combustion in a well-ventilated test (see ISO/TS 19700).

From the tests conducted in this test programme equivalence ratios have been calculated from elemental content and the measured combustible content which gives a theoretical optimal equivalence ratio. The equivalence ratio has further been calculated from the oxygen depletion in well-ventilated tests, in most cases from tests at 650 °C. This would not necessary represent complete combustion (900 °C is proposed in the standard) and this latter calculated equivalence ratio could thus be somewhat underestimated (*i.e.* a lower number for Ø).

3.2.2 Controlled atmosphere cone calorimeter (CACC)

The mass-loss yields for the CACC tests were calculated using the amount of gas species produced for certain periods in the test and the mass-loss data for the same period. Periods used for the calculation of yields were: 1) the flaming period of a test (from ignition to extinction) and 2) the total test time. For the non-flaming test mode there is thus mass-loss yields calculated only for the total test time.

The different types of yields and the calculation method used:

- Mass-loss yields (MLY): 1) produced mass of gas specie for the flaming period divided with the corresponding mass-loss, and 2) produced mass of gas specie for the total test divided with the total mass-loss.
- Mass-charge yields (MCY): produced mass of gas specie for the total test divided with the initial mass of the test specimen.
- Surface-charge yields (SCY): produced mass of gas specie for the total test divided with exposed test specimen surface area.

3.2.3 Fire propagation apparatus tests (FPA)

Mass-loss yields (MLY) were provided in the report from the external test laboratory. These were based on data between 10 and 90 % mass-loss of the sample. Additional types of yields could not be calculated with the information available.

3.2.4 Smoke chamber (SC)

The yields for the SC tests were calculated using the maximum concentration measured of each gas species as a basis. This was in the majority of cases the same time as that of

maximum optical obscuration (D_S max). The total amount was calculated from the concentration and the volume of the smoke chamber using the ideal gas law.

The different types of yields and the calculation method used:

- Mass-loss yields (MLY): total produced mass of gas specie divided with total mass-loss.
- Mass-charge yields (MCY): total produced mass of gas specie divided with initial mass of the test specimen.
- Surface-charge yields (SCY): total produced mass of gas specie divided with exposed test specimen surface area.

The oxygen concentration in the test chamber is not measured in this tests method. The oxygen concentration in the end of each test was here instead estimated based on the oxygen consumption for forming CO_2 and CO.

In the 25 kW/m^2 test mode there is a propane pilot flame burning centrally above the sample surface throughout the test. This flame contributes to the mix of combustion gases from the sample accumulated in the chamber. Tests were made to quantify the types and amounts of gases produced by the pilot flame. Duplicate tests were run and the results of the tests are given in Table 4. As can be seen from the table there is a rather large variability in the amounts of species produced.

Table 4 Measured species production from the propane pilot-flame in the 25 kW/m^2 test mode with the smoke chamber.

Gas specie	Test 1		Test 2		Average (mv) and deviation (md) for total production, in mg	
	mg/m^3	mg	mg/m^3	mg	mv	md
CO_2	11429	5824	6933	3533	4678	1146
CO	12.2	6.2	96.6	49.4	27.8	21.6
NO_X	12.1	6.2	8.5	4.3	5.3	0.9

Note: The deviation is calculated as the mean deviation (md) from the mean value (mv) of the repetitive tests.

4 Assessment and comparison of results between test methods

4.1 Introduction

The results of the evaluation and comparison of the test results on toxic gases from the different test methods used are given below. The results and discussion have been divided into separate sections on combustible tests specimens and non-combustible test specimens.

The yield measured for the different test methods are presented in bar graphs in the following sub sections (detailed test data is available in the appendices). The bar graphs are explained in the legend of the graphs as follows.

SSTF-tests: the bars for the different test conditions are marked with the furnace temperature and information on if the test was a flaming or non-flaming test.

CACC-test: the bars for the different test conditions are marked with the external heat flow (all 50 kW/m^2), the oxygen concentration in the air flow to the box, and if the test data was from pure flaming or non-flaming conditions, or from the complete test (with a mix of flaming/non-flaming).

SC-tests: the bars for the different test conditions are marked with the external heat flow used (25 or 50 kW/m^2), the estimated chamber oxygen concentration in the end of the test, if flaming combustion was taking place during the test (and the length of time for flaming in parenthesis) or if the test was non-flaming.

4.2 Combustible test specimens

4.2.1 Poly(methyl methacrylate), (PMMA)

4.2.1.1 Summary of information on the material

PMMA is a thermoplastic material that often is used as a reference material in fire testing. It decomposes predictably into monomers and burns steadily. The product used in these tests was a 10 mm thick black colour PMMA sheet with density of 1178 kg/m^3 and 100 % combustible content. The chemical analysis showed 60.1 weight-% carbon and 8.1 weight-% hydrogen (oxygen would be the remaining content). The general chemical formula for PMMA is $(C_5O_2H_8)_n$. The burning behaviour in the well-ventilated Controlled Atmosphere Cone Calorimeter (CACC) was that the material burned well but with comparable high total smoke production and did not leave a residue (CACC 50-21% tests: q_{max} = 958 kW/m^2, THR = 306 MJ/m^2 and TSP = 2560 m^2/m^2).

4.2.1.2 Combustion conditions - CO_2 and CO production

Mass-loss yield data for carbon dioxide (CO_2) for the tests with PMMA is presented in Figure 5 and data for carbon monoxide (CO) is presented in Figure 6. The data is the

average from triplicate tests for all test methods, except for the smoke chamber where duplicate tests were made (see appendix 4). Bars filled with solid colour represent tests with flaming combustion and bars filled with hatched lines represent strict non-flaming tests.

Flaming tests without restriction of oxygen for the combustion include SSTF 650, CACC 50-21% and FPA 50-21%.

These tests all give high yields of CO_2 and very low yields of CO. As PMMA is predictable efficiently combusted at well-ventilated conditions it is feasible to compare the measured yields with the maximum theoretical yield, which is 2202 mg/g. The yields of CO_2 are for these tests in the range of 84 % to 97 % of the maximum theoretical yield. The highest yield is from SSTF 650 and represents essentially complete combustion of PMMA.

Flaming tests with an intended restriction in oxygen for the combustion include SSTF 825, CACC 50-15% and FPA 50-15%. However, of these tests only SSTF 825 gave expected results, *i.e.*, a significant reduction in CO_2 and an increase in CO.

Both CACC 50-15% and FPA 50-15% showed high yields of CO_2 and low yields of CO. The oxygen vitiated atmosphere seems not to have influenced the combustion much for these tests. However, in the case of CACC 50-15% the explanation is that afterburning took place from early on in the test. The fire effluent burned with flames on top of the chimney, which changes the quality completely of the effluent measured in the smoke gas duct. After-burning is most probably also the case for FPA 50-15%, but there was no information on afterburning provided by the external testing lab. The very high yield of CO_2 (110 % of maximum theoretical) for the FPA 50-15% test is, however, difficult to explain.

Tests with mixed combustion conditions include the two tests modes of the smoke chamber, SC 25 and SC 50.

In initial tests with PMMA with the SC using full size sample specimens the material ignited early and burned very intensive in both test modes. The oxygen in the chamber was consumed and the chamber was filled with combustible pyrolysis gases. This was a risk and in worst case, this could have led to an explosion. Hence, only single tests were conducted. In following tests with PMMA, a smaller sample with a reduced exposed specimen area (19×19 mm^2) was used to reduce the risk for the operator.

Here are the results of duplicate tests using a reduced sample area evaluated. In the SC 25 test, there was flaming combustion during the majority of the test time (18 out of 20 minutes) and the oxygen concentration was reduced to 16.7 % in the end of the test. In this test mode there is a pilot flame burning throughout the test which contributes with the production of CO_2 from the combustion of the propane fuel. This means that the yield of 2238 mg/g from the SC 25 test should be corrected by the contribution from the pilot flame, and this result in a yield of 1926 mg/g (88 % of maximum theoretical yield). The SC 50 tests showed flaming combustion during 8 of the 20 minute test time and a reduction in oxygen concentration down to 17.7 %. In this test mode there is no pilot flame and the yield of CO_2 was 1735 mg/g (79 % of maximum theoretical yield).

One shall note that essentially the complete mass of sample was consumed in all cases in these test, and that the combustion rate was higher in the 50 kW/m² test compared to the 25 kW/m² test.

Both tests with the smoke chamber gave thus a relatively high yield of CO_2 with limited production of CO which shows that the combustion to a large part was well-ventilated.

Non-flaming tests include SSTF 350, CACC 50-10% and FPA 50-5%.

For the FPA 50-5% test there is no data on combustion products yields reported from the external lab, it is just reported that ignition did not occur.

In the SSTF 350 test none of CO_2 and CO could be detected. In the CACC 50-10% test, however, significant yields of both CO_2 and CO were measured. The reason is, again, after-burning. After-burning was occurring from about 2 min into the (10 min) test in all of the triplicate tests run.

A conclusion from the pyrolysis tests is that PMMA was not a proper reference material for non-flaming combustion, as *e.g.* neither CO_2 nor CO was produced in the SSTF 350 tests and that after-burning occurred in the CACC 50-10% tests.

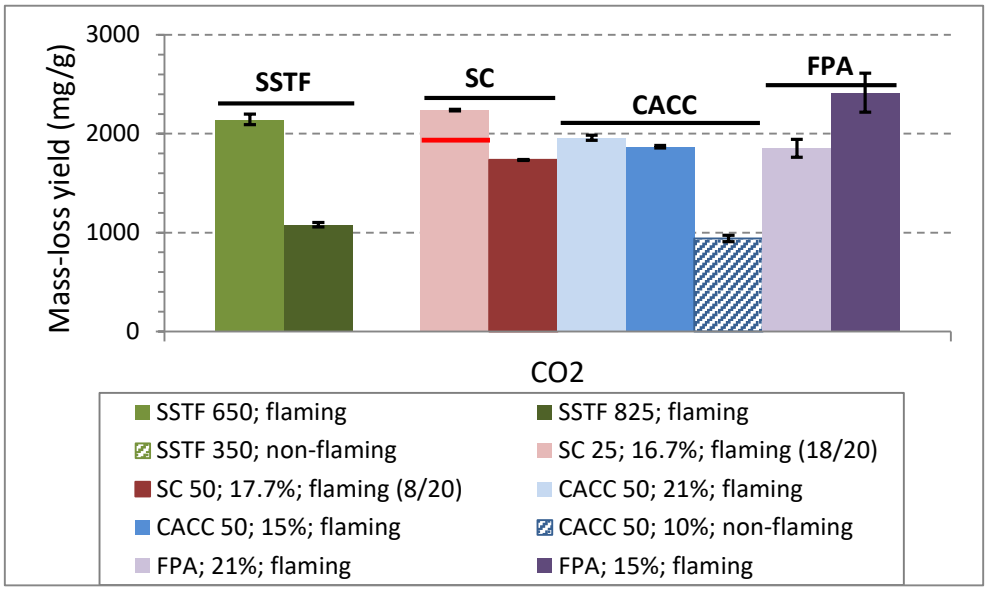


Figure 5 Mass-loss yields (average with error bars*) of CO_2 for tests with PMMA. The horizontal red line on the SC 25 bar indicates the approximate yield when the contribution from the pilot-flame has been corrected for.
** The error bars for the FPA tests are based on the reported standard deviation as this was the only information available.*

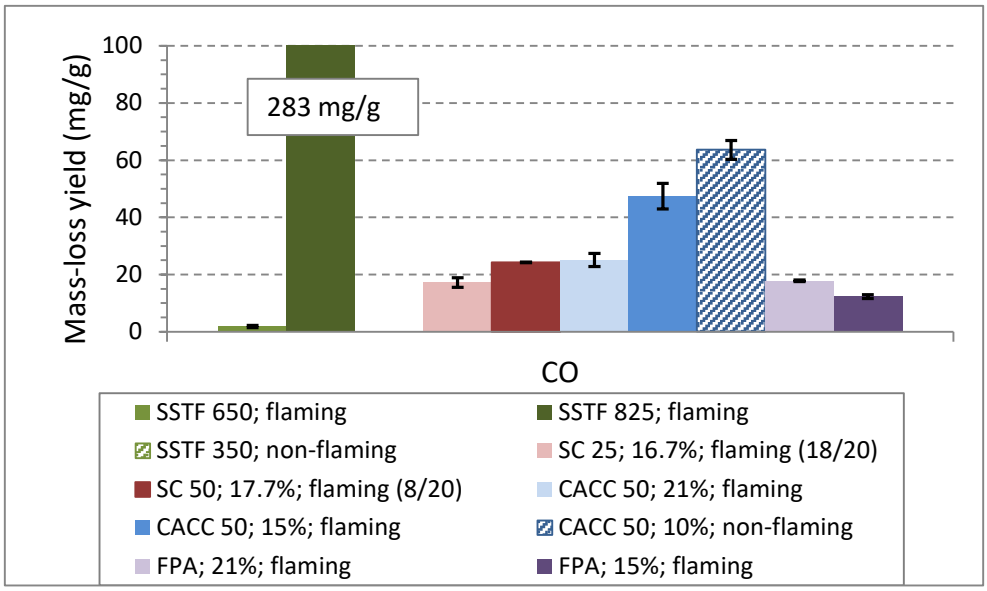


Figure 6 Mass-loss yields (average with error bars*) of CO for tests with PMMA.
** The error bars for the FPA tests are based on the reported standard deviation as this was the only information available.*

4.2.1.3 Production of HCN and NO_X

Hydrogen cyanide in quantifiable amounts was measured in all tests with CACC 50-21% and CACC 50-15% (see Figure 7). Traces of HCN were also detected in the SC tests but the concentrations were below the limit of quantification. Nitrogen oxide (NO) was additionally measured during these CACC tests, and also in all tests with the Smoke Chamber (SC) (see Figure 8).

As PMMA is not expected to contain nitrogen, and as the chemical analysis confirmed this, the measured HCN and NO do not origin directly from combustion of the PMMA. The origin of these specimens must thus be nitrogen from the ambient air, which contains 79 % nitrogen. However, NO_X production (where HCN is an intermediate product) from air-nitrogen only occur at very high combustion temperatures, but we must assume that this is the explanation.

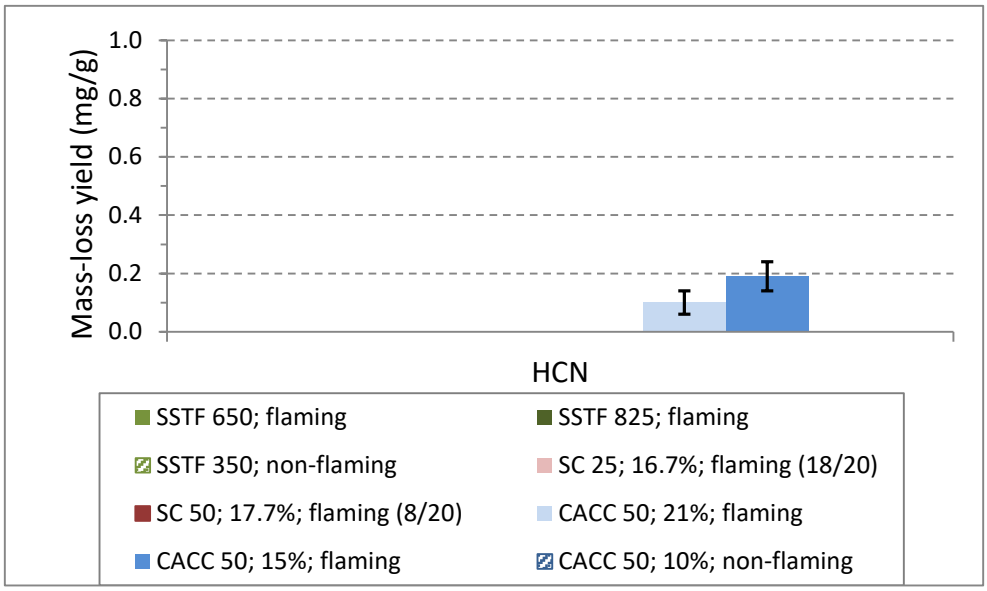


Figure 7 Mass-loss yields (average with error bars) of HCN for PMMA.

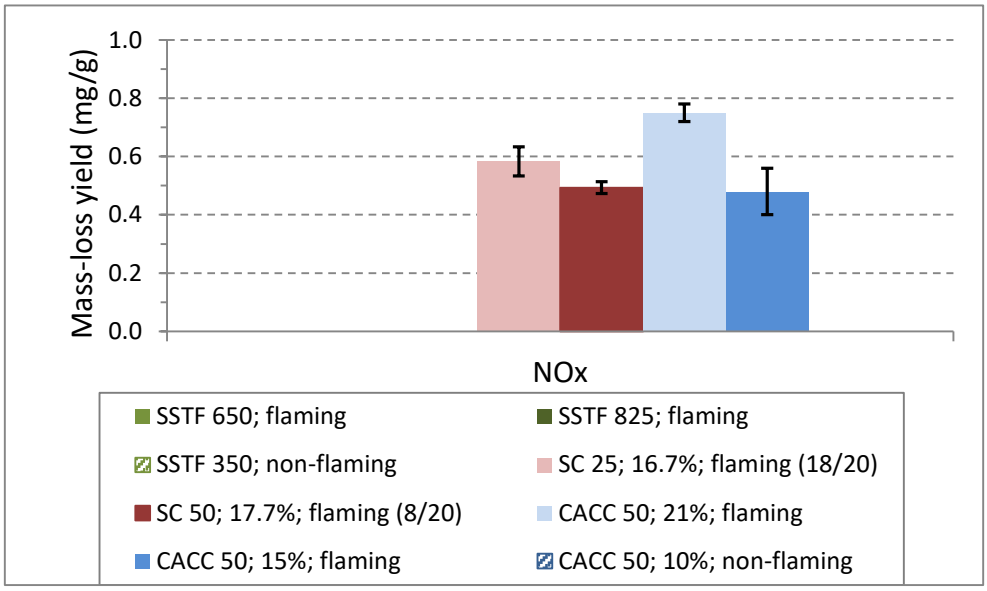


Figure 8 Mass-loss yields (average with error bars) of NO_x for PMMA.

4.2.1.4 Test method applicability

The **flaming** combustion tests with SSTF produced expected species yields which correspond to the attained combustion conditions.

The flaming combustion tests with the CACC gave after-burning outside of the combustion chamber and especially the reduced oxygen test gave thus not valid results.

The flaming combustion tests with the FPA gave high yields of CO_2 (although on the low side for the 21% O2 test) and low yields of CO, but the reduced oxygen test most probably gave after-burning outside of the combustion chamber and gave thus not valid results.

Both SC tests had long flaming periods and gave relatively high yields of CO_2 with limited production of CO, which shows that the combustion to a large part was well-ventilated although the oxygen concentration was clearly reduced in the end of these tests.

Of the **pure pyrolysis tests** none gave useful results. The CACC 50-10% test gave after-burning and thus not valid results. The SSTF 350 gave no measurable combustion products and no information on combustion products was given for the FPA 50-5% test.

An observation was that HCN and NO_X were detected in some of the tests (CACC and SC). This was unexpected except for the SC 25 tests, which was shown to produce NO_X from the pilot flame.

General observations on the applicability of the different methods and test modes regarding the representation of combustion conditions are summarized in Table 5. Here are also included comments on special observations on species production.

Table 5 Summary of general observations on combustion conditions and production yields for poly(methyl methacrylate), (**PMMA**).

Test method	Well-ventilated, flaming test mode	Reduced oxygen, flaming test mode	Non-flaming test mode
SSTF	Well-ventilated flaming combustion (Ø=0.7). Mass-loss of >95 %. Burns stable, no visible soot.	Under ventilated flaming combustion (Ø=2.2-2.1). Mass-loss of >95 %. Burns stable and sooty.	Mass-loss of ~14 %. Soot not noted. No measurable combustion products.
CACC	Afterburning outside the combustion chamber. Mass-loss of >95 %. Considerable total smoke production. Well-ventilated combustion but HCN and NO are detected.	Afterburning outside the combustion chamber. Mass-loss of ~95 %. Considerable total smoke production. Do not represent flaming combustion at reduced oxygen conditions. HCN and NO are detected.	Afterburning outside the combustion chamber. Mass-loss of ~83 %. Low soot. Do not represent non-flaming combustion.
FPA	Well-ventilated combustion.	Well-ventilated combustion. Probably afterburning outside the combustion chamber. Unreasonable high CO_2 yield.	No ignition at 5 % oxygen, but no information on combustion products.
SC 25	Total mass-loss of ~99 %. Well-ventilated combustion, the reduced oxygen concentration later in the test does not have a significant impact on the combustion products. NO is detected. Min oxygen concentration of 16.7 %.		
SC 50	Total mass-loss of ~100 %. Same observations as above. Min oxygen concentration of 17.7 %.		

4.2.2 PF1

4.2.2.1 Summary of information on the material

The material is an expanded polymer foam with a density of 32 kg/m^3 and a combustible content of 99.5 %. Chemical analysis showed 2.1 weight-% of nitrogen in addition to 63 weight-% carbon and 5.8 weight-% hydrogen, semi-quantitatively also

sulphur and chlorine were detected. The burning behaviour in the well-ventilated CACC test was that the material burned rather poorly and left a char residue (CACC 50-21% tests: q_{max} = 82 kW/m², THR = 26 MJ/m² and TSP = 48 m²/m²).

4.2.2.2 Combustion conditions - CO_2 and CO production

Mass-loss yield data for CO_2 for the tests with PF1 is presented in Figure 9 and data for CO is presented in Figure 10. The data is the average from at least duplicate tests for all test methods (see appendix 1). Bars filled with solid colour represent tests with flaming combustion and bars filled with hatched lines represent strict non-flaming tests.

Flaming tests without restriction of oxygen include SSTF 650 and CACC 50-21%.

The SSTF 650 test shows a high yield of CO_2 and a very low production of CO. The mass-loss was about 85 % for this test. This is a proper well-ventilated test. (The yield of CO_2 represents 99 % of theoretical maximum yield assuming representative combustion of combustibles in the sample.)

In the CACC 50-21% test only about 50 % of the mass is consumed and a lower yield of CO_2 is seen. The yield of CO was significantly higher compared to the SSTF 650 test. Actually, the CO_2 yield for the complete test period (not shown in the graph, including also the non-flaming parts of the test) was significantly higher (2100 mg/g) and close to that of the SSTF.

Flaming tests with an intended restriction in oxygen include SSTF 825 and CACC 50-18%. These tests actually show very similar results in CO_2 yields and SSTF 825 reflects the reduced oxygen availability and is a proper under-ventilated test. Regarding CO yield there is a difference. The CO yield is significantly lower for CACC 50-18%. However, also here the yield calculated from the complete test period for CACC 50-18% (221 mg/g of CO) correlated well with the results of SSTF 825.

Tests with mixed combustion conditions include only SC 25, where flaming combustion occurred for about 2 min of the 20 min test time. The total mass-loss was ~60 %. The measured CO_2-yield must here be corrected for the contribution from the pilot-flame and that results in a corrected yield of 2057 mg/g. The CO yield is comparatively high, close to that from the CACC 50-15% non-flaming test (see below), which indicates that pyrolysis played a major role in the production of combustion gases.

Non-flaming tests includes SSTF 350, SC 50 and CACC 50-15%.

In the SSTF 350 test the mass-loss was very low, only about 15 %. The yield of CO_2 was low and also the yield of CO was low compared to the other tests with non-flaming combustion.

SC 50 gave a high mass-loss (~95 %) and CACC 50-15% gave a mass-loss of only ~45 %. The yield of CO_2 was higher in the SC 50 tests compared to CACC 50-15% reflecting perhaps the higher oxygen availability in the first case; however, the yields of CO were rather similar.

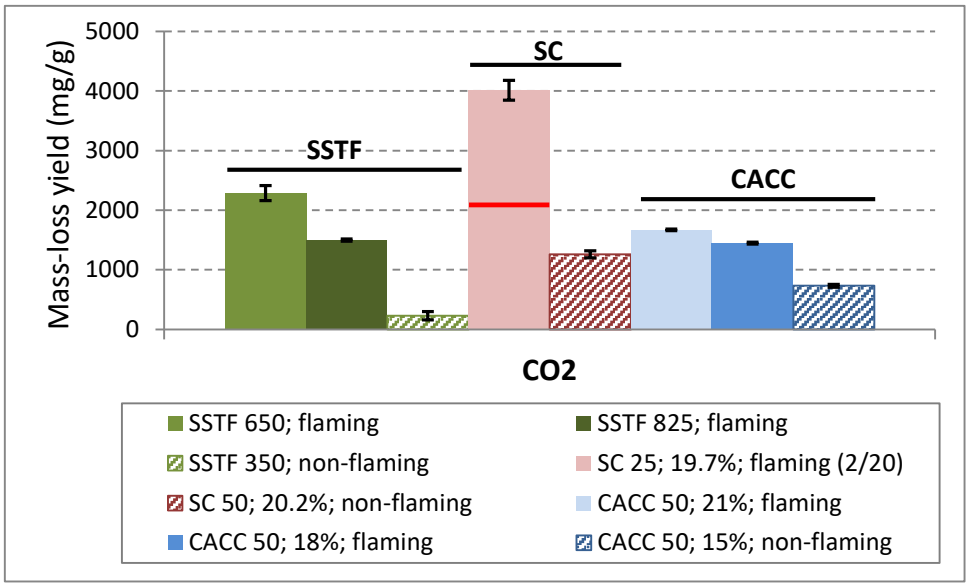


Figure 9 Mass-loss yields (average with error bars) of CO_2 for tests with PF1. The horizontal red line on the SC 25 bar indicates the approximate yield when the contribution from the pilot-flame has been corrected for.

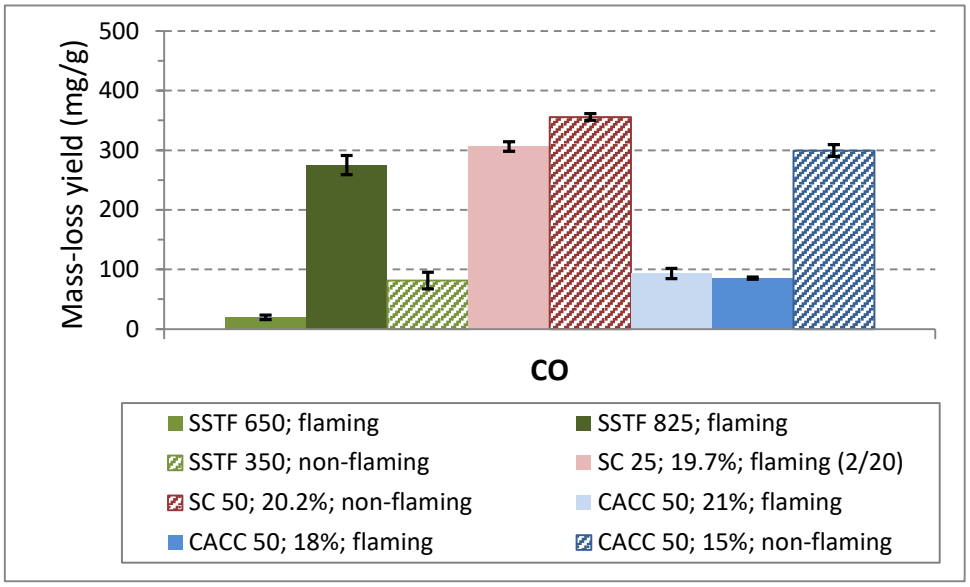


Figure 10 Mass-loss yields (average with error bars) of CO for tests with PF1.

4.2.2.3 Production of HCN and NO_X

The different species containing nitrogen that are produced in a fire are decided by the combustion conditions. Hydrogen cyanide (HCN) is produced from under-ventilated conditions and from pyrolysis, *i.e.*, incomplete combustion. Nitrogen oxides (NO_X) are produced during well-ventilated combustion.

The highest production of HCN is seen for the tests including non-flaming combustion, that are SSTF 350, both SC 25 and SC 50, and CACC 50-15% (see Figure 11). In the case of CACC 50-15% the actual concentration measured in the test is low, but valid. The yields are actually rather similar, around 5 mg/g. A significant but lower production is seen in the under-ventilated flaming tests with the SSTF (SSTF 825).

The measured yields of NO_X correlate well in most cases with the findings of HCN (see Figure 12). The highest yields of NO_X are found from the two flaming tests with the CACC, where HCN was not found. The non-flaming tests with the CACC did not give any NO_X. For SSTF the measured NO_X yields show the reversed trend compared to the HCN yields, which is logical.

The only tests showing deviating result is SC 25. Here it was measured a high level yield of NO_X together with a high level yield of HCN. The reason for the high NO_X yield is most probably an influence from the pilot-flame together with production from the shorter flaming phase of the test.

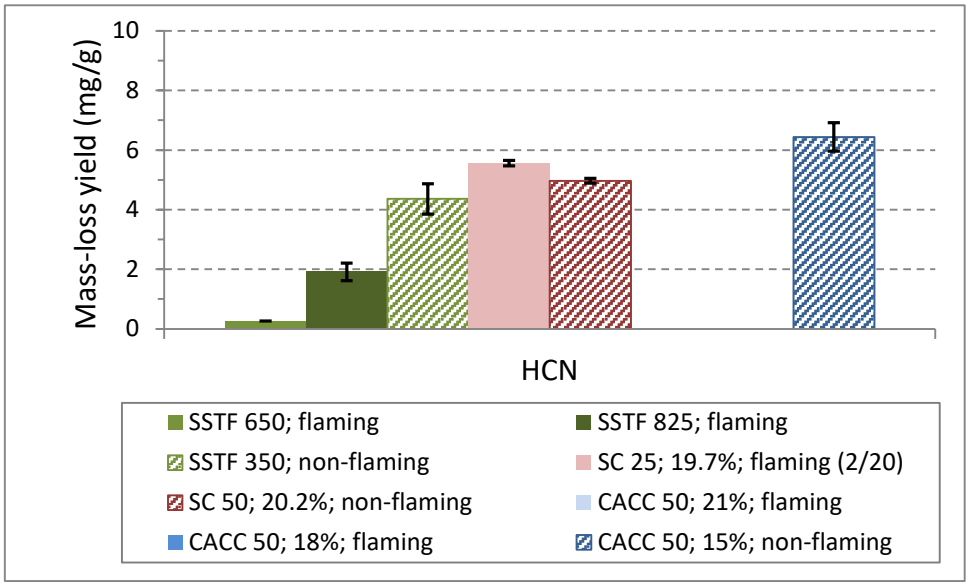


Figure 11 Mass-loss yields (average with error bars) of HCN for PF1.
Note: The concentration of HCN was close to the minimum detection limit (MDL) for SSTF 650 and CACC 50-15%.

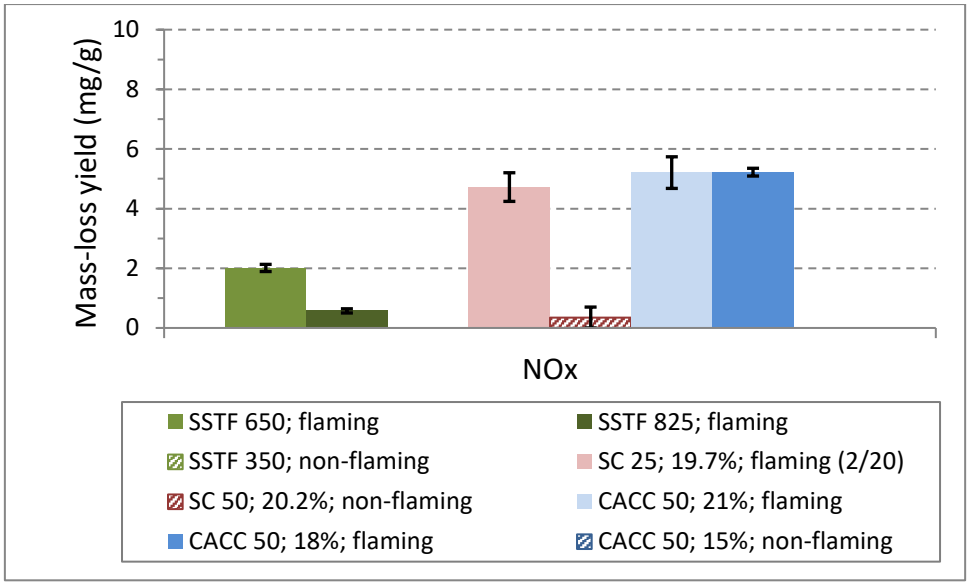


Figure 12 Mass-loss yields (average with error bars) of NO_X for PF1.
Note: The concentration of NO_X was close to MDL for SSTF 825, CACC 50-21%, CACC 50-15% and SC 50.

4.2.2.4 Production of HCl

The material contained chlorine as seen from the chemical analysis and HCl was found in most of the tests. HCl is produced both from pyrolysis and from complete combustion and it can be seen from Figure 13 that HCl is found in both flaming and non-flaming tests.

For the SSTF tests the yields are of similar magnitude in the two flaming tests. However, in the pyrolysis test (SSTF 350) the yield is higher. The explanation might be related to that HCl in many cases is quite easily released from the polymer matrix. And as the temperature in this test was relatively low, HCl release could have been promoted before the release of other major pyrolysis products. There is further no clear steady-state of HCl production seen in the SSTF 350 tests, which makes the determination of HCl yield uncertain.

The SC tests only gave a very low yield of HCl in the SC 25 test and none in the SC 50 test. This might very well be a result of losses in the (unheated) internal probe and the internal walls of the chamber.

In the case of the CACC tests, the highest yields were found from the two flaming tests and about half of that level was found in the non-flaming tests. A possible explanation is that a non-proportional amount of HCl is released in the flaming part of the CACC 50-21% and CACC 50-18% tests and thus resulting in a higher yield for this part of the tests. This is to some extent the case as can be seen if comparing yields from the complete tests (see appendix 1).

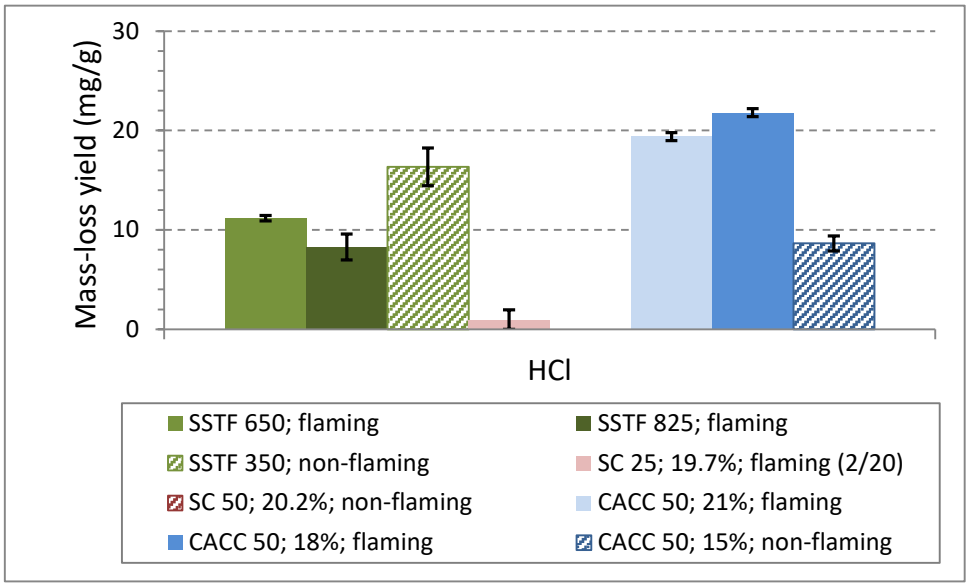


Figure 13 Mass-loss yields (average with error bars) of HCl for PF1.
Note: The concentration of HCl was above MDL only in one of the duplicate tests with SC 25.

4.2.2.5 Production of SO_2

Sulphur in the fuel is released as sulphur dioxide (SO_2) during well-ventilated flaming combustion and as *e.g.* carbonyl sulphide (COS) and possibly other sulphur containing species during under-ventilated flaming combustion. SO_2 is also the major sulphur containing product from pyrolysis of a sulphur containing fuel.

The yields of SO_2 from the different tests made are in the majority of cases in the same order of magnitude irrespectively of if the combustion was flaming or non-flaming (see Figure 14). A significant deviating result is, however, seen from the SSTF 350 tests. As discussed above for HCl, this could be a result of that SO_2 production (in this case) at this comparable low pyrolysis temperature could have been promoted before the release of other major degradation products. It is worth noting that the SO_2 production showed a prolonged steady-state in these tests.

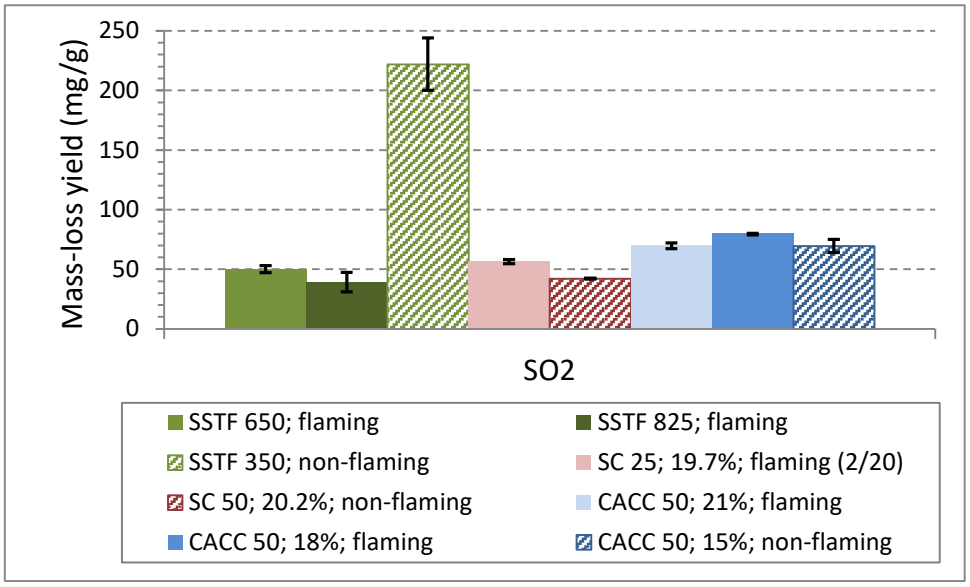


Figure 14 Mass-loss yields (average with error bars) of SO_2 for PF1.

4.2.2.6 Test method applicability

The **flaming** combustion tests with SSTF produced expected species yields which correspond to the attained combustion conditions.

The flaming combustion tests with the CACC produced CO_2-yields similar to the SSTF test but did not show any difference between tests in CO-yields. Both tests gave high NO_X-yields and no HCN. Both tests were thus largely well-ventilated.

The SC 25 tests had a short period of flaming combustion which gave a mixture of combustion products from different combustion conditions. Very low HCl indicates losses.

The **pure pyrolysis tests** (including SC 50) gave qualitative correlation in that CO and HCN were major products. HCl correlated acceptably between SSTF 350 and CACC 50-15% but was not detected in SC 50.

An observation was that SO_2 gave correlation between all tests except for SSTF 350 which gave a significantly higher yield.

General observations on the applicability of the different methods and test modes regarding the representation of combustion conditions are summarized in Table 6. Here are also included comments on special observations on species production.

Table 6 Summary of general observations on combustion conditions and production yields for **PF1**.

Test method	Well-ventilated, flaming test mode	Reduced oxygen, flaming test mode	Non-flaming test mode
SSTF	Well-ventilated flaming combustion (Ø=0.7-0.8). Mass-loss of ~85 %. Burns even with a small flame. No observations on soot. Expected distribution of product yields.	Under ventilated flaming combustion (Ø=2.1-2.5). Mass-loss of ~65 % Burns even with a small flame. No observations on soot. Expected distribution of product yields.	Mass-loss of only ~15 % (due to the low temp in this test mode). Limited soot production. High yield of HCN, HCl and unexpectedly high yield of SO_2.
CACC	Well-ventilated but partly incomplete combustion as evaluated for the flaming period. Mass-loss of ~49 % and low total soot. Both flaming test modes very similar.	Well-ventilated but partly incomplete combustion as evaluated for the flaming period. Mass-loss of ~30 % and low total soot. Both flaming test modes very similar.	Total mass-loss of ~45 % and low total soot. Expected distribution of product yields for a pyrolysis test.
SC 25	Total mass-loss of ~60 %. Min oxygen concentration of 19.7 %. A ~2 min flaming combustion period in the beginning of the 20 min test. Mixture of combustion conditions during this test mode gives non-representative results, except for SO_2 for which the combustion conditions seem to be less important. Only traces of HCl detected. Probably losses of HCl in the test. $D_{s,\,max}$ = 12.		
SC 50	Total mass-loss of ~96 %. Min oxygen concentration of 20.2 %. No ignition. Pyrolysis only during this test mode. Results comparable to pyrolysis tests with the other test methods except for HCl which is not detected. Probably losses of HCl. $D_{s,\,max}$ = 95.		

4.2.3 PF2

4.2.3.1 Summary of information on the material

The material is an expanded polymer foam with a density of 12 kg/m^3 and a combustible content of 100 %. Chemical analysis showed 0.31 weight-% of nitrogen in addition to 90.6 weight-% carbon and 7.9 weight-% hydrogen; semi-quantitatively also bromine was detected. The burning behaviour in the well-ventilated CACC test was that the material ignited late but then burned rather well, but with some soot production, and did not leave any substantial residue (CACC 50-21% tests: q_{max} = 213 kW/m^2, THR = 15 MJ/m^2 and TSP = 575 m^2/m^2).

4.2.3.2 Combustion conditions - CO_2 and CO production

Mass-loss yield data for CO_2 for the tests with PF2 is presented in Figure 15 and data for CO is presented in Figure 16. The data is the average from at least duplicate tests for all test methods (see appendix 1). Bars filled with solid colour represent tests with flaming combustion and bars filled with hatched lines represent strict non-flaming tests.

Flaming tests without restriction of oxygen include SSTF 650 and CACC 50-21%.

The SSTF 650 test shows a high yield of CO_2 and a moderately low production of CO. The mass-loss was about 90 % for this test. A high soot production was noted in this

test mode. (The yield of CO_2 represents 89 % of theoretical maximum yield assuming representative combustion of combustibles in the sample.)

In the CACC 50-21% test most of the mass is consumed (>95 %) but a somewhat lower yield of CO_2 is seen (compared to SSTF 650). The yield of CO was also lower compared to the SSTF 650 test. And this test showed the highest total soot production (TSP) of the CACC test modes.

Flaming tests with an intended restriction in oxygen include SSTF 825 and CACC 50-15%.

In the SSTF 825 test there is a clear influence on the production yields of CO_2 and CO that reflects the under-ventilated conditions. In this tests mode there was also an even higher soot production as noted visually.

The CACC 50-15% were similar to the CACC 50-21% in CO_2 yield (somewhat higher) but manifested the lower oxygen availability with an increase in CO yield. The total soot production was actually somewhat lower compared to CACC 50-21%.

Non-flaming tests includes SSTF 350, SC 25, SC 50 and CACC 50-10%.

In the SSTF 350 tests the mass-loss was very low, ~7 %. CO_2 was not detected. CO was detected but there was no steady-state production in any of the duplicate tests and yield calculation could thus not be made. This test was not acceptable according to the criteria in ISO/TS 19700.

The CACC 50-10% gave a mass-loss of ~64 % but neither CO_2 nor CO was detected in this test mode. As the smoke production was limited in this test mode the mass-loss must have been due to decomposition into styrene monomers or other molecular fragments.

In the SC 25 test mode the mass-loss was low (~20 %). The material probably melted away from the heat source. A very high yield of CO_2 was measured and a moderate CO-yield. The CO_2-yield measured if corrected for the contribution from the pilot flame is 13952 mg/g and this is about four times the maximum theoretical yield from this product. Quite possible this is an error originates from the low mass-loss and the correction of the pilot burner contribution. It is thus not possible to estimate any useful yield value in this case.

In the SC 50 test mode the mass-loss was high (~99 %). Here a very low yield of CO_2 was measured and a CO-yield in the magnitude of that from SC 25.

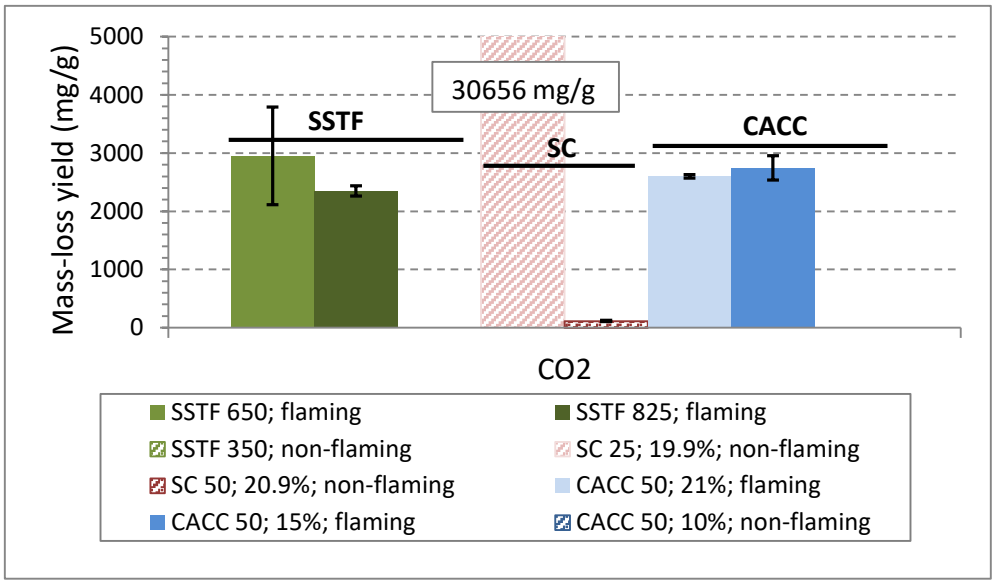


Figure 15 Mass-loss yields (average with error bars) of CO_2 for tests with PF2.
Note 1: The SSTF 350 tests were not acceptable.
Note 2: It was not possible to estimate the yield corrected for the contribution from the pilot flame in SC 25.
Note 3: The concentration of CO_2 in SC 50 was close to MDL.

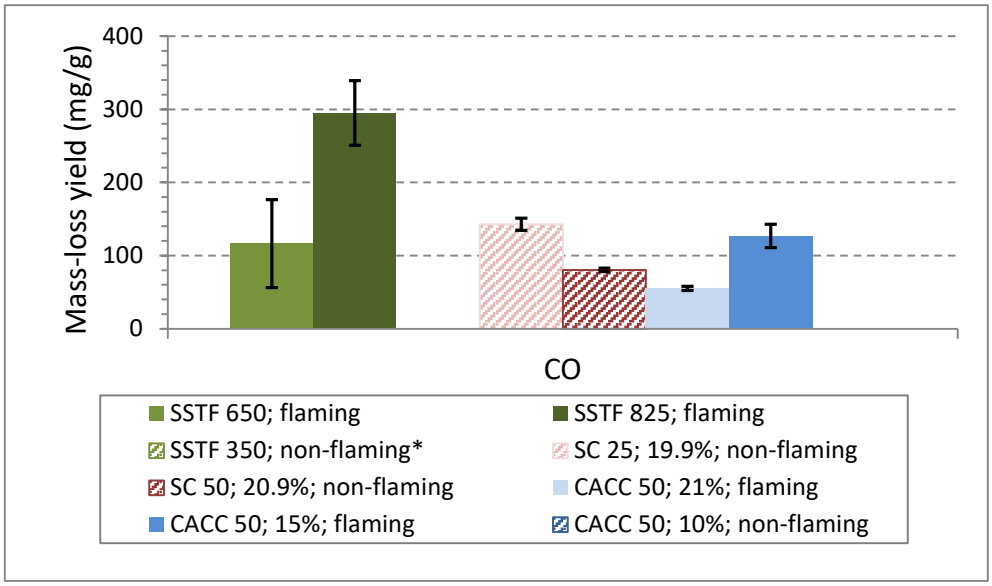


Figure 16 Mass-loss yields (average with error bars) of CO for tests with PF2.
Note 1: The SSTF 350 tests were not acceptable.
*CO was detected in the SSTF 350 tests but there was a large variability between duplicate tests and no steady-state production; a yield value is thus not included in the graph.

4.2.3.3 Production of NO_X

NO_X was detected in the SC 25 test mode only (see Figure 17). There was a low content of nitrogen in the product and NO_X production from fuel nitrogen is thus possible. But it could also be the presence of the pilot flame in the SC 25 test that promoted the production of NO_X.

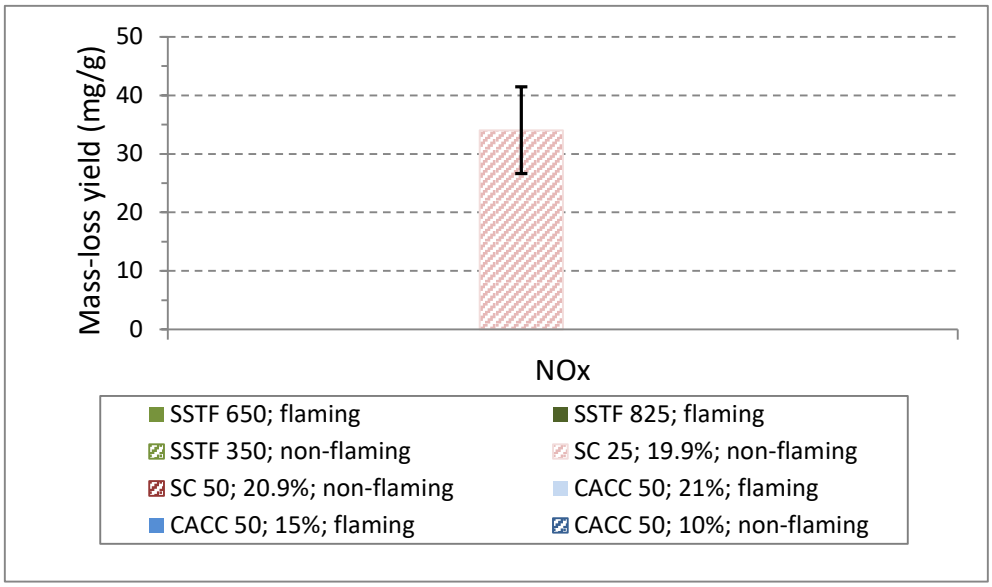


Figure 17 Mass-loss yields (average with error bars) of NO_X for PF2.

4.2.3.4 Test method applicability

The **flaming** combustion tests with SSTF produced expected species yields which correspond to the attained combustion conditions.

The flaming combustion tests with the CACC produced CO_2-yields similar to the SSTF test and also showed an expected difference between tests in CO-yields. The higher CO-yield in the CACC 50-15% test indicates an influence of the decreased oxygen concentration.

The **pure pyrolysis tests** gave variable results but generally very low yields of CO_2 and of CO. CACC 50-10% stands out as this test did not produced any measurable products.

An observation is that HBr was not detected in any of the tests although the semi-quantitative chemical analysis of the product showed a significant content of bromine.

General observations on the applicability of the different methods and test modes regarding the representation of combustion conditions are summarized in Table 7. Here are also included comments on special observations on species production.

Table 7 Summary of general observations on combustion conditions and production yields for **PF2**.

Test method	Well-ventilated, flaming test mode	Reduced oxygen, flaming test mode	Non-flaming test mode
SSTF	Well-ventilated flaming combustion (Ø=0.8-0.9) although considerable soot production. Mass-loss of ~90 %. Normal yield of CO_2 and somewhat high CO.	Under ventilated flaming combustion (Ø<1.6-1.8) and higher soot production. Mass-loss of ~80 %. Expected distribution of product yields.	Mass-loss of only ~7 %. CO produced but no steady state production.
CACC	Mass-loss of >95 %. Large variability in ignition time. Normal yield of CO_2, low CO and low soot. Well-ventilated.	Mass-loss of >95 %. Large variability in ignition time. Similar yield of CO_2 and higher CO. Lower soot.	Total mass-loss of ~64 %. No measurable species production.
SC 25	Total mass-loss of ~20 %. Min oxygen concentration of 19.9 %. No ignition. Unrealistically high yield of CO_2 measured. Probable too large error in the correction of the pilot-flame contribution. Normal yield of CO. $D_{s,\,max}$ = 51.		
SC 50	Total mass-loss of ~99 %. No ignition. Min oxygen concentration of 20.9 %. Very low CO_2 and reasonable CO-yield. $D_{s,\,max}$ = 253.		

4.2.4 PF3

4.2.4.1 Summary of information on the material

The material is an expanded polymer foam with a density of 35 kg/m^3 and a combustible content of 99.2 %. Chemical analysis showed 0.1 weight-% of nitrogen in addition to 89.4 weight-% carbon and 7.6 weight-% hydrogen; semi-quantitatively also bromine was detected. The burning behaviour in the well-ventilated CACC test was that the material burned rather well, but with some soot production, and did not leave any substantial residue (CACC 50-21% tests: q_{max} = 388 kW/m^2, THR = 57 MJ/m^2 and TSP = 2170 m^2/m^2).

4.2.4.2 Combustion conditions - CO_2 and CO production

Mass-loss yield data for CO_2 for the tests with PF3 is presented in Figure 18 and data for CO is presented in Figure 19. The data is the average from at least duplicate tests for all test methods (see appendix 1). Bars filled with solid colour represent tests with flaming combustion and bars filled with hatched lines represent strict non-flaming tests.

Flaming tests without restriction of oxygen include SSTF 650 and CACC 50-21%.

The SSTF 650 test shows a high yield of CO_2 and a medium production of CO. The mass-loss was about 80 %. A high soot production was noted in this test mode. (The yield of CO_2 represents 88 % of theoretical maximum yield assuming representative combustion of combustibles in the sample.)

In the CACC 50-21% test most of the mass is consumed (>95 %) but a significantly lower yield of CO_2 is seen (compared to SSTF 650). The yield of CO was also lower

compared to the SSTF 650 test. This test showed the highest total soot production (TSP) of the CACC test modes.

Flaming tests with an intended restriction in oxygen include SSTF 825 and CACC 50-15%.

In the SSTF 825 test there is a clear influence on the production yields of CO_2 and CO that reflects the under-ventilated conditions. In this tests mode there was also an even higher soot production as noted visually.

The CACC 50-15% were similar to the CACC 50-21% in CO_2 yield (somewhat lower) but manifested the lower oxygen availability with an increase in CO yield. The total soot production was actually somewhat lower compared to CACC 50-21%.

Tests with mixed combustion conditions include only SC 25, where flaming combustion occurred for about 4 min of the 20 min test time. Ignition did not occur until around the middle of the test. The total mass-loss was about 95 %. The measured CO_2 yield must here be corrected for the contribution from the pilot flame and that results in a corrected yield of 2957 mg/g, close to that from the SSTF 650. The CO yield is comparatively low, close to that from the CACC 50-21% test. The overall combustion seems thus to have been well-ventilated.

Non-flaming tests includes SSTF 350, SC 50 and CACC 50-10%.

In the SSTF 350 tests the mass-loss was very low, below 5 %. CO_2 was not detected, and the yield of CO was comparably low.

The CACC 50-10% gave a high mass-loss (~81 %) but only a very low yield of CO was detected. As the smoke production was limited in this test mode the mass-loss must have been due to decomposition into styrene monomers or other molecular fragments.

In the SC 50 test mode the mass-loss was high (~93 %). A very low yield of CO_2 was measured and a CO yield in the magnitude of that from SC 25.

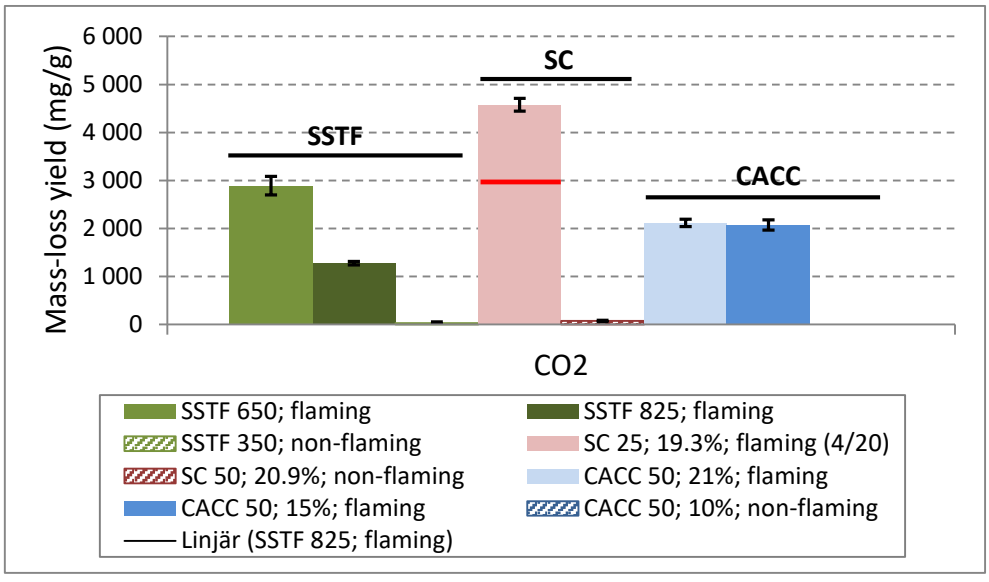


Figure 18 Mass-loss yields (average with error bars) of CO_2 for tests with PF3. The horizontal red line on the SC 25 bar indicates the approximate yield when the contribution from the pilot-flame has been corrected for.

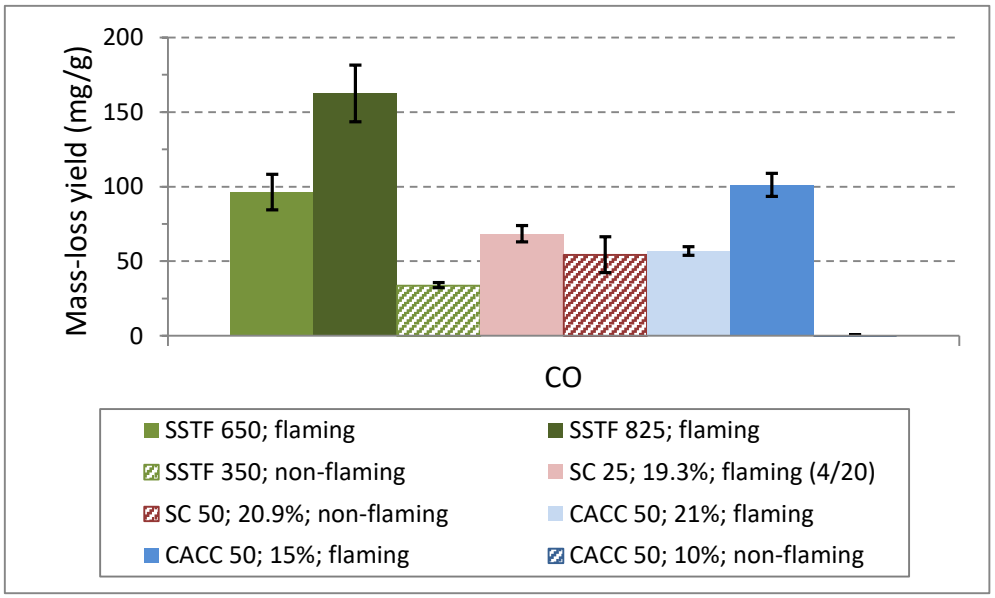


Figure 19 Mass-loss yields (average with error bars) of CO for tests with PF3.

4.2.4.3 Production of NO_X

NO_X was detected in the SC 25 test mode only (see Figure 20), which was also the case in the tests with PF2. There was a low content of nitrogen in the product, thus NO_X production from fuel nitrogen is possible. It could also be the presence of the pilot flame in the SC 25 test that promoted the production of NO_X.

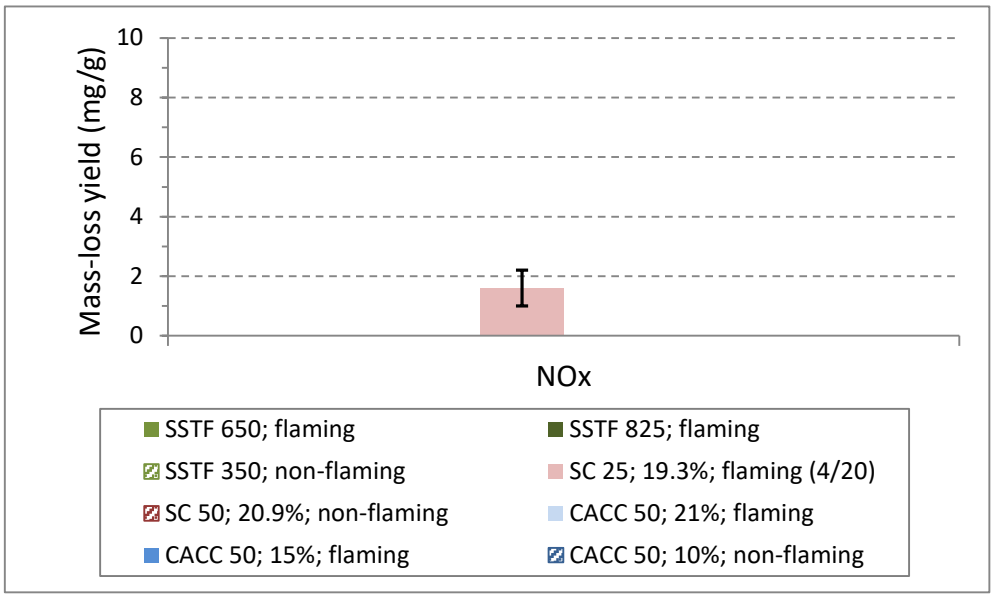


Figure 20 Mass-loss yields (average with error bars) of NO_X for PF3.
Note: The concentration of NO_X in SC 25 was close to MDL.

4.2.4.4 Production of HBr and HCl

The material contained bromine (Br) as showed by the semi-quantitative XRF analysis. Chlorine (Cl) was not found by the XRF analysis; however, the detection limit is lower for this element.

Hydrogen bromide (HBr) was actually found only in very low concentrations in the well-ventilated SSTF test mode (SSTF 650). Here traces of HBr were found in both tests made but the concentrations were below the limit of quantification. HBr was not found in any of the other tests.

Hydrogen chloride (HCl) was found in all of the tube furnace tests (SSTF) and in the CACC 50-15% tests. The yields were very low in all cases except in the SSTF 350 pyrolysis tests. It is clear that a low amount of chlorine was present in the product and losses of different magnitudes are the reason for not finding HCl in all tests modes. The deviating high yield in the SSTF 350 tests must be explained by the very low mass-loss in this test mode and that HCl is an early (regarding temperature) degradation product.

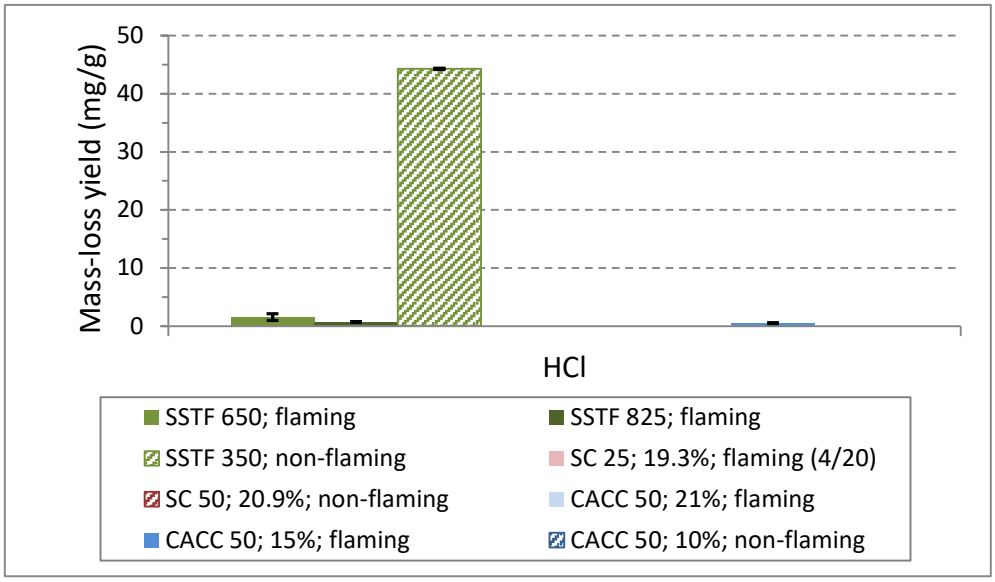


Figure 21 Mass-loss yields (average with error bars) of HCl for PF3.

4.2.4.5 Test method applicability

The **flaming** combustion tests with SSTF produced expected species yields which correspond to the attained combustion conditions.

The flaming combustion tests with the CACC produced similar CO_2-yields, clearly lower compared to the well-ventilated SSTF test. The soot production is high in both tests. The test seems largely well-ventilated but the higher CO-yield in the CACC 50-15% test indicates an influence of the decreased oxygen concentration.

The SC 25 tests showed overall signs of well-ventilated combustion. The (corrected) yield of CO_2 was realistic and the CO-yield was similar to those from the CACC test.

The **pure pyrolysis tests** (including SC 50) gave results with generally very low CO_2 and similar yields of CO. An exception was CACC 50-10% which did not produce any CO_2 and a very low yield of CO.

An observation is that HBr was only detected in the SSTF 650 test and not in any of the other tests although the semi-quantitative chemical analysis of the product showed a significant content of bromine.

General observations on the applicability of the different methods and test modes regarding the representation of combustion conditions are summarized in Table 8. Here are also included comments on special observations on species production.

Table 8 Summary of general observations on combustion conditions and production yields for **PF3**.

Test method	Well-ventilated, flaming test mode	Reduced oxygen, flaming test mode	Non-flaming test mode
SSTF	Well-ventilated flaming combustion (Ø=0.9) although considerable soot production. Mass-loss of ~80 %. Expected distribution of product yields, except that HCl was detected. HBr detected but not quantifiable.	Under ventilated flaming combustion (Ø=2.8-2.6) and higher soot production. Mass-loss of ~84 %. Expected distribution of product yields, except that HCl is detected.	Mass-loss of only ~4 %. Limited smoke. Low yield of CO produced. High yield of HCl, but possible misleading due to the low mass-loss.
CACC	Mass-loss of >95 %. Low yield of CO_2 (compared to SSTF) some CO and considerable soot production.	Mass-loss of >95 %. Marginally lower yield of CO_2, increased CO and considerable soot production.	Total mass-loss of ~82 %. Only low yield of CO detected. Lower smoke.
SC 25	Total mass-loss of ~95 %. Min oxygen concentration of 19.3 %. A short (~4 min) flaming combustion period in the middle of the 20 min test resulted in combustion product indicating well-ventilated combustion (comparable with SSTF 650). $D_{s,\,max}$ = 517.		
SC 50	Total mass-loss of ~93 %. Min oxygen concentration of 20.9 %. Pyrolysis only during this test mode. Only moderate CO production (equivalent to SC 25), that does not correlate with the mass lost. $D_{s,\,max}$ = 472.		

4.2.5 PF4

4.2.5.1 Summary of information on the material

The material is an expanded polymer foam with a density of 35 kg/m^3 and a combustible content of 98.6 %. Chemical analysis showed 7.4 weight-% of nitrogen in addition to 64.6 weight-% carbon and 6.2 weight-% hydrogen; semi-quantitatively also chlorine was detected. The burning behaviour in the well-ventilated CACC test was that the material burned rather well, with some soot production, and did leave some residue (CACC 50-21% tests: q_{max} = 319 kW/m^2, THR = 31 MJ/m^2 and TSP = 874 m^2/m^2).

4.2.5.2 Combustion conditions - CO_2 and CO production

Mass-loss yield data for CO_2 for the tests with PF4 is presented in Figure 22 and data for CO is presented in Figure 23. The data is the average from at least duplicate tests for all test methods (see appendix 1). Bars filled with solid colour represent tests with flaming combustion and bars filled with hatched lines represent strict non-flaming tests.

Note: SSTF 650 tests (650 °C, well-ventilated) and SSTF 825 tests (825 °C, under-ventilated) are not included in the comparisons below. The reason is that these tests were not acceptable from the criteria given in ISO/TS 19700. The position for flaming combustion spread quickly against the primary air flow direction and burning took place outside of the furnace. Information on the species detected in these tests is given in Table 9.

Flaming tests without restriction of oxygen include only CACC 50-21%.

In the CACC 50-21% tests a high proportion of the mass was consumed (~83 %) but a rather low yield of CO_2 resulted. The yield of CO was comparable low. The total soot production (TSP) was moderate. (The yield of CO_2 represents 54 % of theoretical maximum yield assuming representative combustion of combustibles in the sample.)

Flaming tests with an intended restriction in oxygen include only CACC 50-15%.

The CACC 50-15% test was somewhat lower in CO_2 yield compared to the CACC 50-21% and manifested the lower oxygen availability in an increase in CO yield. The total soot production was the lowest of the tests modes with the CACC.

Tests with mixed combustion conditions include SC 25 and SC 50.

In the SC 25 test flaming combustion occurred for about 2 min of the 20 min test time. Ignition occurred in the start of the test. The total mass-loss was ~58 %. The measured CO_2-yield must here be corrected for the contribution from the pilot flame and that results in a corrected yield of 3305 mg/g, which is comparably high. The CO yield is low, close to that from the CACC 50-21% test. It seems thus as pyrolysis was less important.

In the SC 50 test the flaming period was somewhat shorter compared to SC 25 and the total mass-loss was higher (~86 %). This resulted in lower CO_2 yield and a significantly higher CO yield.

Non-flaming tests include SSTF 350 and CACC 50-10%.

In the SSTF 350 tests the mass-loss was ~40 % and substantial smoke production was noted. A low yield of CO_2 was measured and also the yield of CO was comparably low.

The CACC 50-10% had a mass-loss of ~65 %. The yield of CO_2 was in the magnitude of that from SSTF 350 but the yield of CO was significantly higher. This test showed the highest smoke production of the CACC test modes.

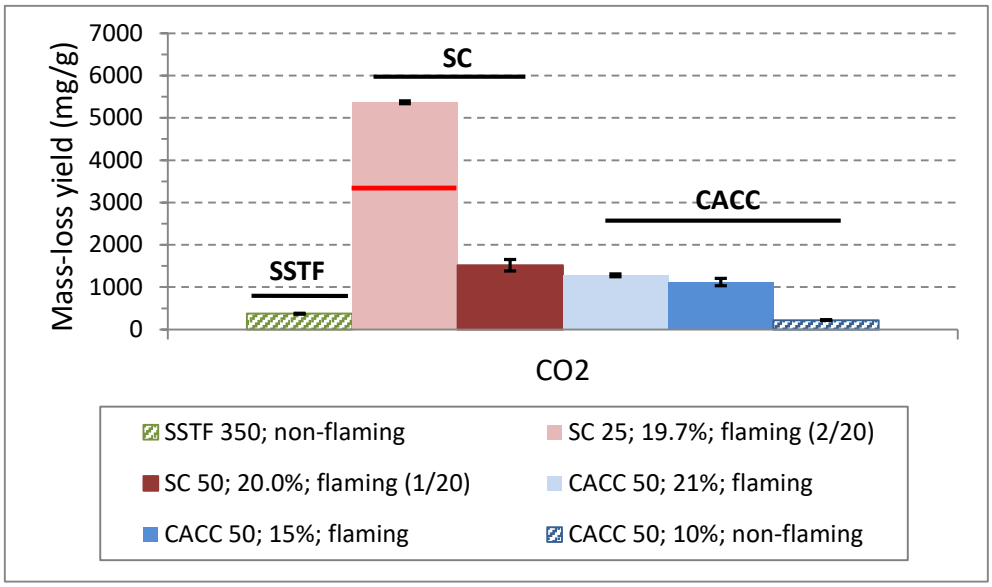


Figure 22 Mass-loss yields (average with error bars) of CO_2 for tests with PF4. The horizontal red line on the SC 25 bar indicates the approximate yield when the contribution from the pilot-flame has been corrected for.
Note: results from SSTF 650 and SSTF 825 are not included as these tests were not acceptable according to ISO/TS 19700.

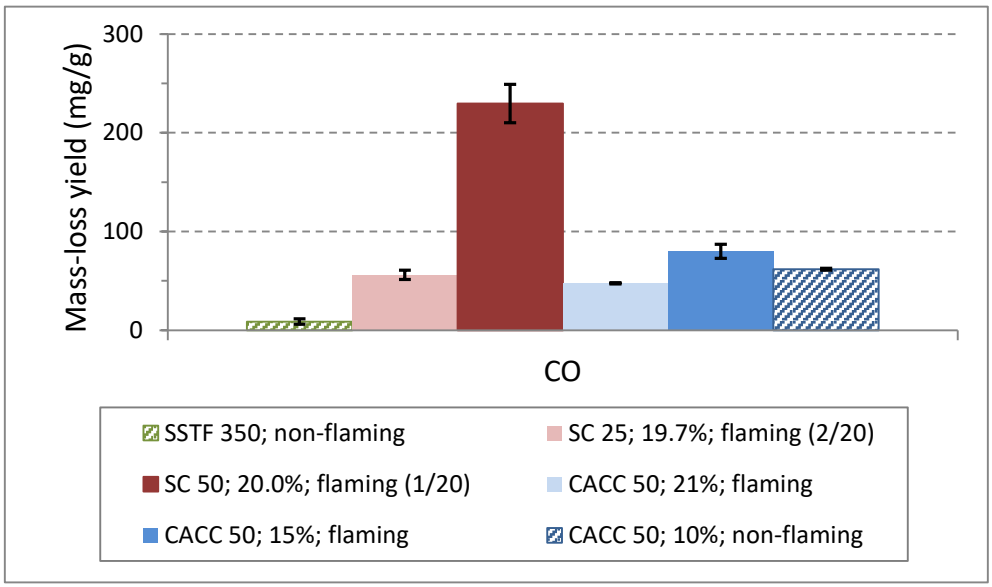


Figure 23 Mass-loss yields (average with error bars) of CO for tests with PF4.
Note: results from SSTF 650 and SSTF 825 are not included as these tests were not acceptable according to ISO/TS 19700.

4.2.5.3 Production of HCN and NO_X

HCN was detected in all tests with the smoke chamber (SC) and the controlled atmosphere cone calorimeter (CACC), see Figure 24. HCN was not detected in the pyrolysis test with the tube furnace (SSTF 350). This indicates that the temperature in the SSTF 350 was too low to promote conditions for HCN production.

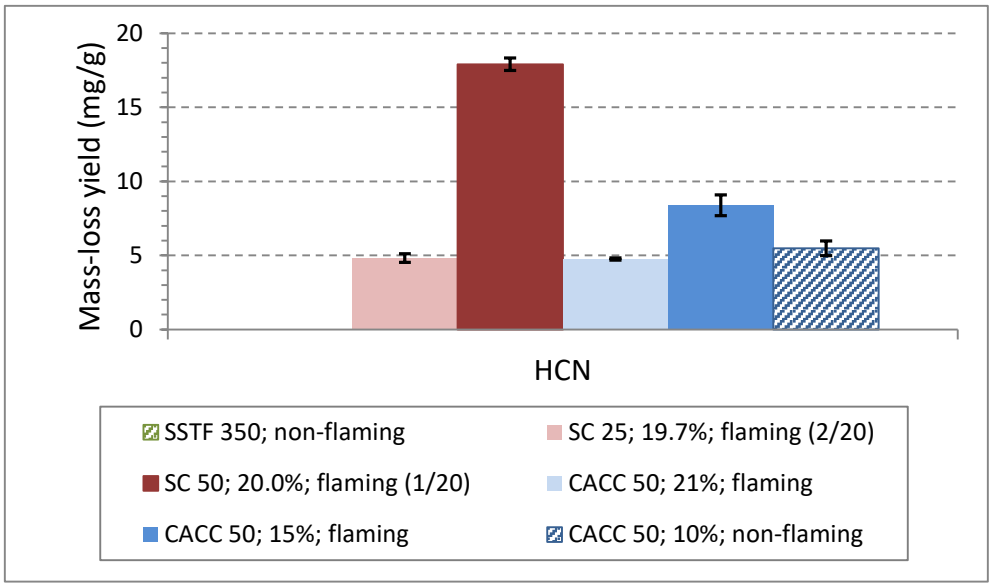


Figure 24 Mass-loss yields (average with error bars) of HCN for PF4.
Note: results from SSTF 650 and SSTF 825 are not included as these tests were not acceptable according to ISO/TS 19700.

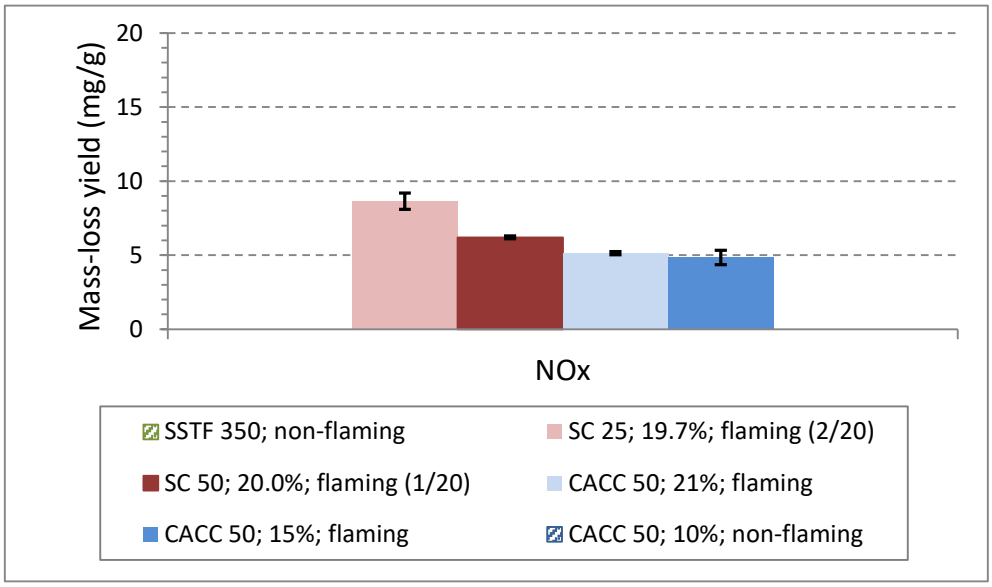


Figure 25 Mass-loss yields (average with error bars) of NO_X for PF4.
Note: results from SSTF 650 and SSTF 825 are not included as these tests were not acceptable according to ISO/TS 19700.

The HCN-yields were rather similar for SC25, CACC 50-21% and CACC 50-10%, somewhat higher for CACC 50-15% and significantly higher for SC 50. The higher yield of HCN in the SC 50 test correlates with the high CO yield in this test and indicates that pyrolysis was important.

NO_X was found in all of the tests were also HCN was found, except in the non-flaming CACC 50-10% (see Figure 25). This shows that the combustion in SC25 and SC50 included a mixture of combustion conditions (well-ventilated for the NO_X production and pyrolysis for the HCN production). CACC 50-21%, and CACC 50-15% were evaluated for the flaming part of the tests, but these must have included elements of

both pyrolysis and more complete combustion. Flaming combustion occurs only in smaller areas of the sample surface in the end of a flaming period normally.

4.2.5.4 Production of HCl

The product contained chlorine as seen from the chemical analysis and HCl was found in most of the tests (see Figure 26). The highest and similar yields were found from the CACC 50-21% and CACC 50-15% tests; the reason for not detecting HCl in the CACC 50-10% is unknown.

Low yields were found in both SC-tests. Losses in the test apparatus might be one component in the explanation for the comparative low yield. Also in the SSTF 350 tests a low yield was found (compared to CACC).

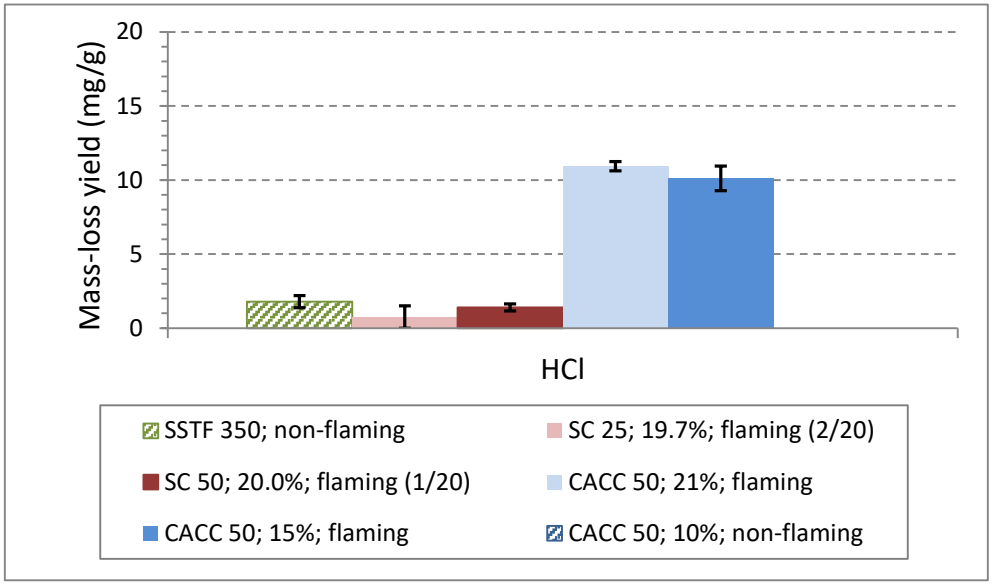


Figure 26 Mass-loss yields (average with error bars) of HCl for PF4.
Note 1: results from SSTF 650 and SSTF 825 are not included as these tests were not acceptable according to ISO/TS 19700.
Note 2: the concentration of HCl in SC 25 was on the level of MDL in one of the duplicate tests.

4.2.5.5 Test method applicability

The **flaming** combustion tests with SSTF were not possible to conduct in a representative manner with this product and there are no useful results available.

The flaming combustion tests with the CACC both gave a mixture of combustion products presumably originating from varied combustion conditions in the test.

Both SC tests included a shorter flaming period. The yields found indicate a mixture of combustion conditions in both cases, however, more well-ventilated conditions in the SC 25 tests and more of pyrolysis conditions in the SC 50 test. Yields from the SC 25 test of CO, HCN and NOx correlate with those from the CACC tests. Low HCl indicates losses.

The **pure pyrolysis tests** gave variable results but generally very low CO_2 and low CO. HCN was found in CCAC 50-10% but not in SSTF 350.

General observations on the applicability of the different methods and test modes regarding the representation of combustion conditions are summarized in Table 9. Here are also included comments on special observations on species production.

Table 9 Summary of general observations on combustion conditions and production yields for **PF4**.

Test method	Well-ventilated, flaming test mode	Reduced oxygen, flaming test mode	Non-flaming test mode
SSTF	*The tests made were unacceptable as the flame spread fast outside of the designated combustion zone.* CO_2, CO, HCN, NO and HCl were detected.	*The tests made were unacceptable as the flame spread fast outside of the designated combustion zone.* CO_2, CO, HCN and HCl were detected.	Mass-loss of ~40 %. Low yield of CO in comparison with non-flaming CACC. Considerable soot production. HCN was not detected.
CACC	Mass-loss of ~80 % but low yield of CO_2. Some CO and moderate soot production. Both HCN and NO_X produced. High HCl yield.	Mass-loss of ~70 % and similar CO_2, increased CO and the lowest soot production. Higher HCN and equal NO_X. High HCl yield.	Total mass-loss of ~65 %. Low yield of CO_2, equal CO and the highest soot production. HCN equal to CACC 21%. NO_X and HCl not detected.
SC 25	Total mass-loss of ~58 %. Min oxygen concentration of 19.7 %. A short (~2 min) flaming combustion period in the beginning of the 20 min test. Comparable high CO_2 yield and low CO. Production of both HCN and NO_X indicates a mixture of combustion conditions. $D_{s,max}$ = 233.		
SC 50	Total mass-loss of ~86 %. Min oxygen concentration of 20.0 %. A short (~1 min) flaming combustion period in the beginning of the 20 min test. Lower CO_2 yield and significantly higher CO. Higher yield of HCN but also NO_X shows that pyrolysis is more important here, but still a mixture of combustion conditions. $D_{s,max}$ = 336.		

4.2.6 PF5

4.2.6.1 Summary of information on the material

The material is an expanded polymer foam with a density of 44 kg/m^3 and a combustible content of 99.2 %. Chemical analysis showed 7.0 weight-% of nitrogen in addition to 65.5 weight-% carbon and 5.4 weight-% hydrogen. Semi-quantitatively analysis detected chlorine and traces of sulphur. The burning behaviour in the well-ventilated CACC test was that the material burned poorly, with some soot production, and did leave a residue (CACC 50-21% tests: q_{max} = 114 kW/m^2, THR = 26 MJ/m^2 and TSP = 263 m^2/m^2).

4.2.6.2 Combustion conditions - CO_2 and CO production

Mass-loss yield data for CO_2 for the tests with PF5 is presented in Figure 27 and data for CO is presented in Figure 28. The data is the average from at least duplicate tests for all test methods (see appendix 1). Bars filled with solid colour represent tests with flaming combustion and bars filled with hatched lines represent strict non-flaming tests.

Note: CACC 50-10% is not included in the graphs showing mass-loss yields as there is no reliable data on mass-loss available for this test. The mass-loss was low and there was a disturbance of the load-cell signal. Graphs with mass-charge yields are available in appendix 1.

Flaming tests without restriction of oxygen include SSTF 700 and CACC 50-21%.

The SSTF 700 test shows a high yield of CO_2 and a low production of CO. The mass-loss was ~88 % for this test. The temperature was increased from 650 °C to 700 °C as the burning was not continuous at the lower temperature. At 700 °C the sample burned still somewhat unsteady but continuously. A high soot production was noted in this test mode. (The yield of CO_2 represents 114 % of theoretical maximum yield assuming representative combustion of combustibles in the sample.)

In the CACC 50-21% tests a much lower part of the mass is consumed (~51 %) and a lower yield of CO_2 is seen. The yield of CO was comparable high. The total soot production (TSP) was low.

Flaming tests with an intended restriction in oxygen include SSTF 825 and CACC 50-15%.

In the SSTF 825 test there is a clear influence on the production yields of CO_2 and CO that reflects the under-ventilated conditions. In this tests mode the combustion was more stable and there was a lower soot production as noted visually (compared to SSTF 650).

The CACC 50-15% test was run in triplicate as the ignition time varied considerably. The result on especially CO_2 is not as expected as the yield is higher compared to CACC 50-21% (see Figure 27). If comparing the yields for the complete test period the influence of the lower oxygen concentration in CACC 50-15% is clear (see Figure 29). However, in these yields are both flaming and non-flaming combustion included.

Tests with mixed combustion conditions include only SC 25.

In the SC 25 test flaming combustion occurred for about 4 min of the 20 min test time. Ignition occurred in the start of the test. The total mass-loss was only ~34 %. The measured CO_2 yield must here be corrected for the contribution from the flame and that results in a corrected yield of 4033 mg/g which is very high. The CO yield is comparatively low, close to that from the CACC 50-21% test. It seems thus as pyrolysis did not contribute significantly.

Non-flaming tests include SSTF 350, CACC 50-10% (not shown in the graphs below) and SC 50.

In the SSTF 350 tests the mass-loss was only ~22 %. A low yield of CO_2 was measured and also the yield of CO was very low. There is no information on smoke available.

For the CACC 50-10% test there is no quantitative information available on mass-loss. The mass-loss was low and there was a disturbance of the load-cell signal which made the data unreliable. The gas species measured from this test included CO, HCl and HCN. Mass-charge data (see appendix 1) shows production comparable (but overall higher) to that from the flaming part of CACC 50-15% test.

The SC 50 test gave a total mass-loss of ~85 %. There was a low production of CO_2 and a high production of CO. The mass-charge yields of CO and HCN were significantly higher compared to the CACC 50-10% test (see appendix 1). The effect of pyrolysis is clear in this test.

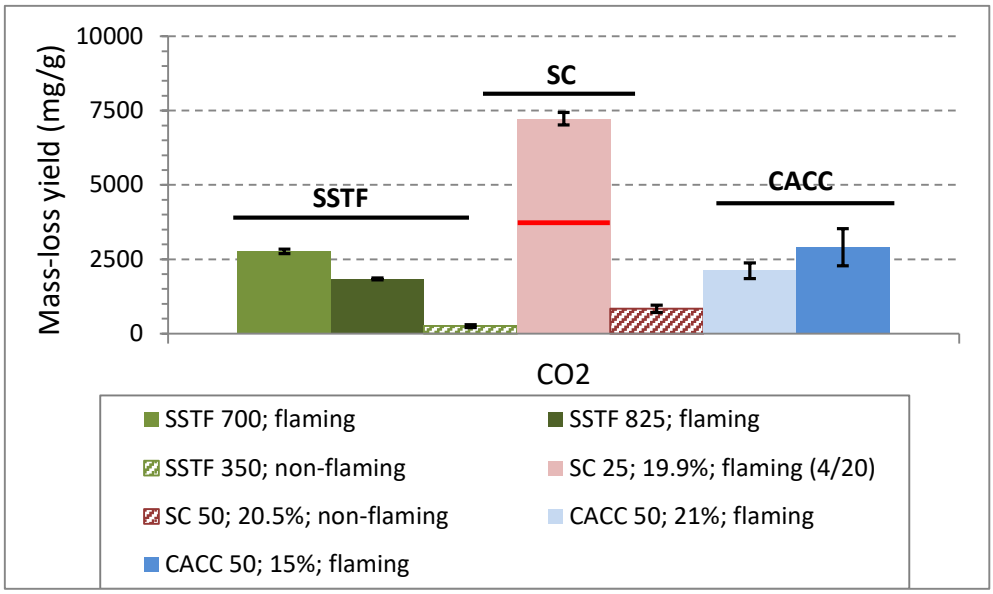


Figure 27 Mass-loss yields (average with error bars) of CO_2 for tests with PF5. The horizontal red line on the SC 25 bar indicates the approximate yield when the contribution from the pilot-flame has been corrected for.
Note: there was no reliable mass-loss data for the calculation of yields for the CACC-10% test (CO_2 was not detected).

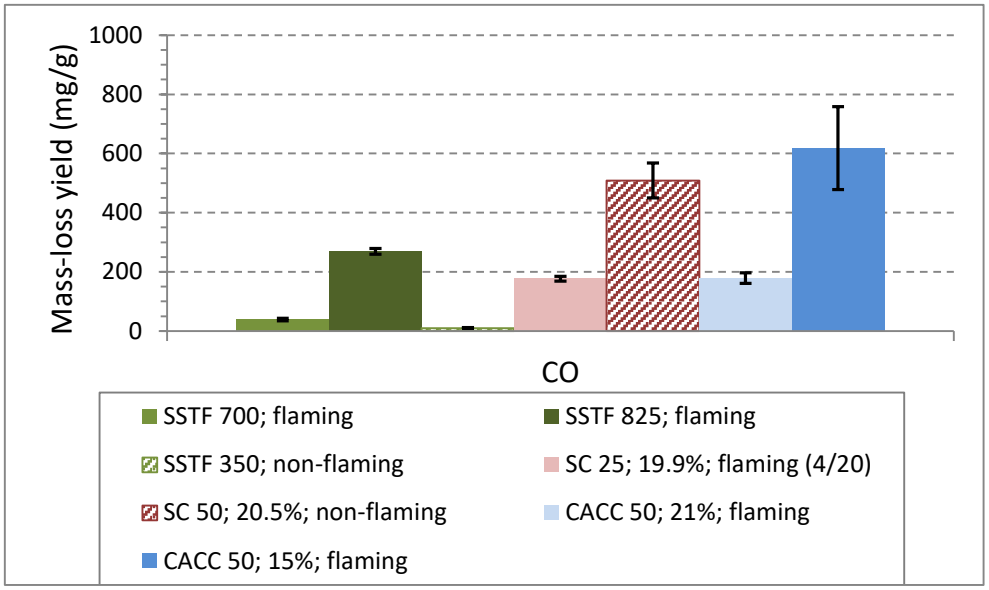


Figure 28 Mass-loss yields (average with error bars) of CO for tests with PF5.
Note: CO was produced in the CACC-10% test but there was no reliable mass-loss data for the calculation of yields.

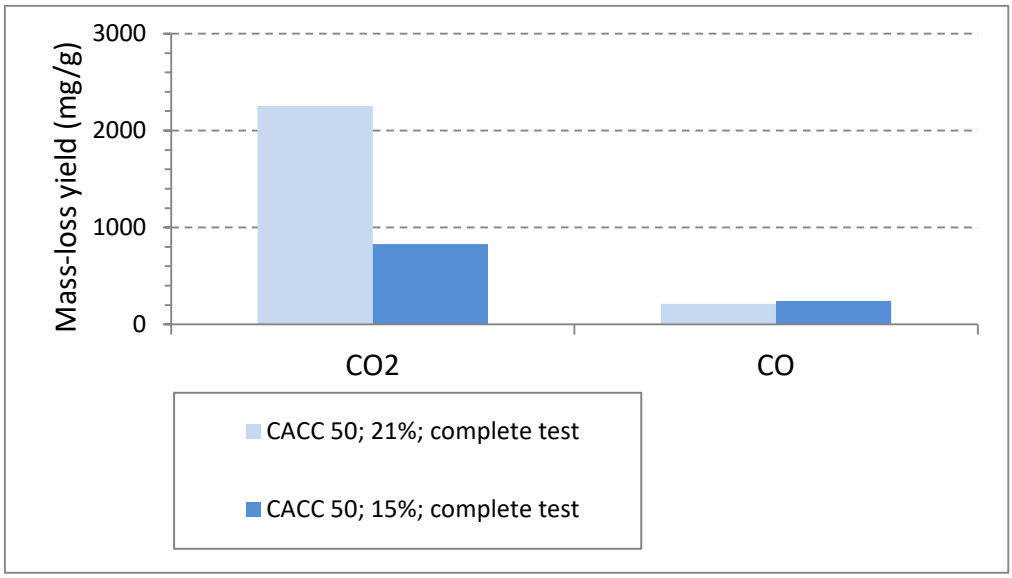


Figure 29 Mass-loss yields (average) of CO_2 and CO for the CACC tests with PF5. The yields are here calculated for the complete test time (including both flaming and non-flaming combustion). For deviation between the repeated tests see Appendix 1.

4.2.6.3 Production of HCN and NO_X

HCN was detected in the two flaming tests with the SSTF and in all tests with the smoke chamber (SC) and the cone calorimeter (CACC), see Figure 30 and Appendix 1. HCN was not detected in the pyrolysis test with the tube furnace (SSTF 350). This shows that the temperature in the SSTF 350 was too low to promote conditions for HCN production.

Low yields of HCN were found from SC 25 and CACC 50-21%, where also NO_X were found (see Figure 31). This indicates that the combustion conditions were largely well-ventilated. The lowest yield of HCN was from SSTF 650 in where also NO_X was produced.

The HCN-yields were comparably high for both SSTF 825 and CACC 50-15%, which both are flaming tests with restricted oxygen availability. Further, NO_X was low or not detected in these tests which indicate that the combustion conditions were determined by the restriction in oxygen availability.

The SC 50 test gave a high yield of HCN and no production of NOx which makes sense as this was a pure pyrolysis test and a large part of the sample was consumed.

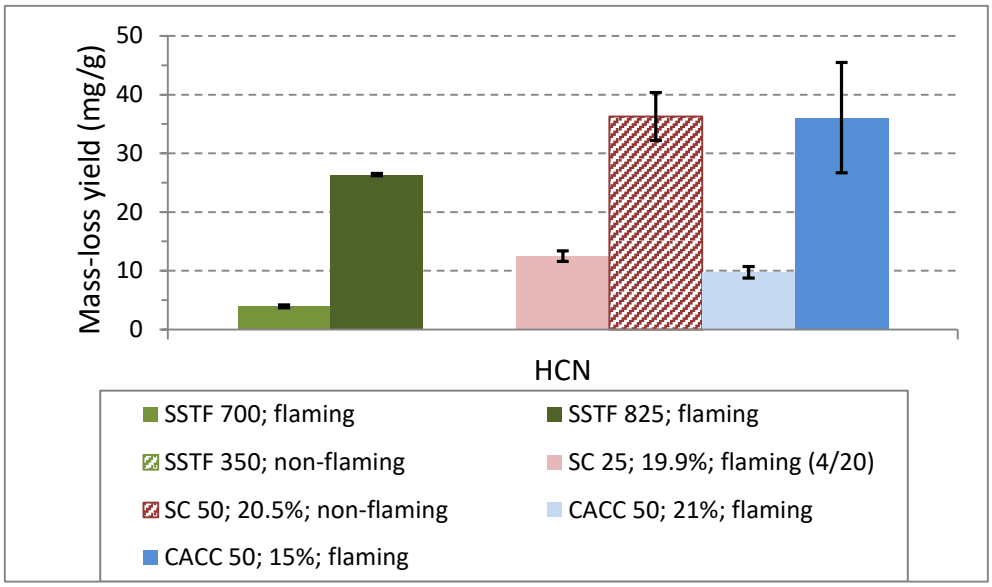


Figure 30 Mass-loss yields (average with error bars) of HCN for PF5.
Note 1: HCN was produced in the CACC-10% test but there was no reliable mass-loss data for the calculation of yields.

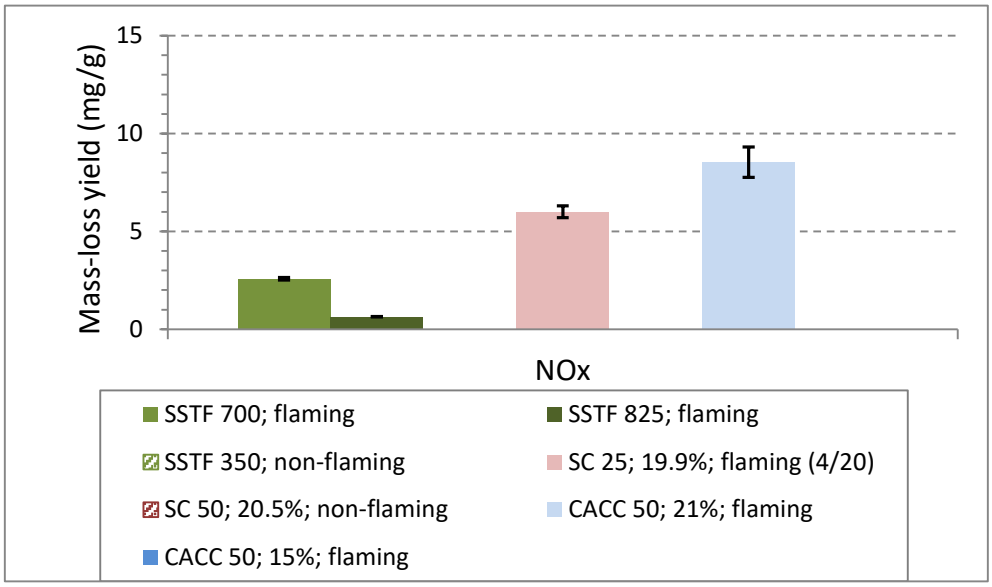


Figure 31 Mass-loss yields (average with error bars) of NO_X for PF5.
Note 1: The concentration of NO_X was on the level of MDL in SSTF 825 and CACC 50-21%.

4.2.6.4 Production of HCl

The product contained chlorine as seen from the chemical analysis, and HCl was found in all tests with the SSTF and all tests with the CACC (see Figure 32 and Appendix 1).

The highest and similar yields were found from the CACC 50-21% and CACC 50-15% tests. HCl was also found in the CACC 50-10% test (not shown below) and mass-charge yields were of the same magnitude for all CACC tests.

The SSTF tests gave the highest yields for the well-ventilated test (SSTF 650), lower compared to the CACC tests, but of the same magnitude.

HCl was not detected in the SC tests. Losses in the test apparatus must be the explanation.

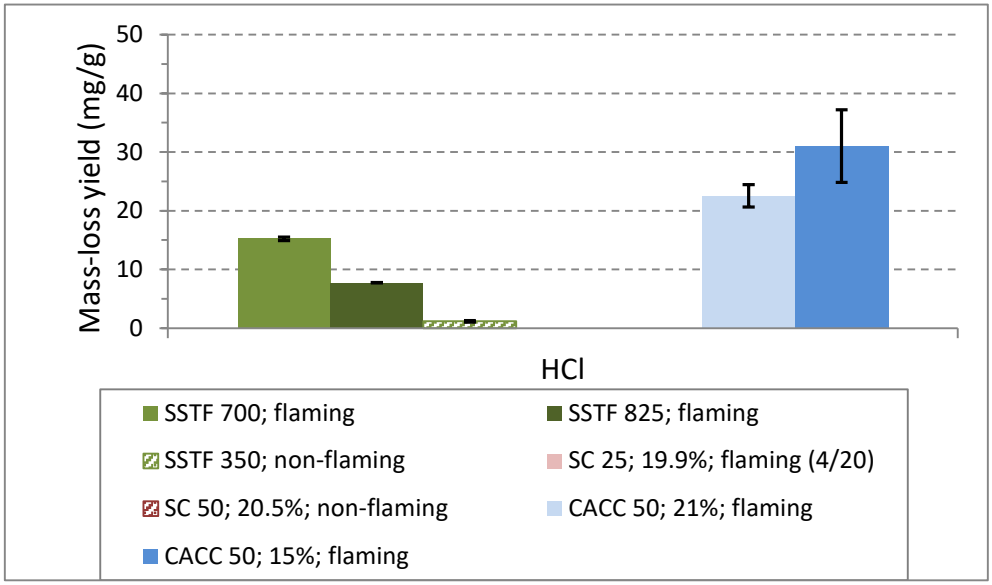


Figure 32 Mass-loss yields (average with error bars) of HCl for PF5.
Note 1: HCl was produced in the CACC-10% test but there was no reliable mass-loss data for the calculation of yields.
Note 2: The concentration of HCl was close to MDL in SSTF 350.

4.2.6.5 Test method applicability

The **flaming** combustion tests with SSTF produced expected species yields which correspond to the attained combustion conditions.

The flaming combustion tests with the CACC produced similar CO_2-yields, of the same magnitude compared to SSTF tests. The CACC 50-21% gave both HCN and NO_X indicating a mix of combustion conditions. There was a clear influence of the decreased oxygen concentration in the CACC 50-15%, with increased yields of CO and HCN.

The SC 25 test gave yield of CO, HCN and NO_X very similar to CACC 50-21%.

The **pure pyrolysis tests** (including SC 50) gave very variable results. Both CO and HCN were produced in SC 50 and CACC 50-10%, but HCN was not in SSTF 350. The SSTF generally gave very low productions yields.

An observation is that HCl was found in all tests except the SC tests.

General observations on the applicability of the different methods and test modes regarding the representation of combustion conditions are summarized in Table 10. Here are also included comments on special observations on species production.

Table 10 Summary of general observations on combustion conditions and production yields for **PF5**.

Test method	Well-ventilated, flaming test mode	Reduced oxygen, flaming test mode	Non-flaming test mode
SSTF	Well-ventilated flaming combustion (Ø=0.6). Mass-loss of 88 %. Test run at 700 °C to get continuous combustion. High yield of CO_2 and a low production of CO. Considerable soot production. Low HCN and some NO_X and HCl.	Under-ventilated flaming combustion (Ø=1.8-1.9). Mass-loss of 63 %. Burns stable. Lower yield of CO_2 and higher of CO. Less soot. High HCN, low NO_X and some HCl.	Mass-loss of 22 %. Low yields of both CO_2 and CO. No info on soot. HCN was not detected but low yield of HCl.
CACC	Mass-loss of ~51 %. High yield of CO_2, some CO and low soot. Both HCN and NO_X produced. High HCl yield.	Mass-loss of ~39 %. Large spread in ignition time. Higher yield of CO_2 compared to CACC 50-21% for flaming period. Yields for the complete test more logical. High CO and increased soot. High HCN and HCl yield.	Mass-loss data not available. Products measured were CO, HCl and HCN. Mass-charge data comparable, but overall higher, with flaming part of CACC 50-15% test.
SC 25	Total mass-loss of ~34 %. Min oxygen concentration of 19.9 %. A ~4 min flaming combustion period in the beginning of the 20 min test. Comparable high CO_2 yield and moderate CO. Production of both HCN and NO_X indicates a mixture of combustion conditions. $D_{s,\,max}$ = 22.		
SC 50	Total mass-loss of ~85 %. Min oxygen concentration of 20.5 %. No ignition in this test. Lower CO_2 yield and significantly higher CO compared to SC 25. Higher yield of HCN but no NO_X which is typical for pyrolysis. $D_{s,\,max}$ = 138.		

4.2.7 OF1

4.2.7.1 Summary of information on the material

The material is an organic fibre material with a density of 93 kg/m^3 and a combustible content of 99.4 %. Chemical analysis showed 45.6 weight-% carbon, 6.6 weight-% hydrogen and 1.1 weight-% nitrogen. Semi-quantitatively analysis showed the presence of sulphur. The burning behaviour in the well-ventilated CACC test was that the material burned poorly, with low soot production, and left a limited amount of residue (CACC 50-21% tests: q_{max} = 193 kW/m^2, THR = 34 MJ/m^2 and TSP = 26 m^2/m^2).

4.2.7.2 Combustion conditions - CO_2 and CO production

Mass-loss yield data for CO_2 for the tests with OF1 is presented in Figure 33 and data for CO is presented in Figure 34. The data is the average from at least duplicate tests for all test methods (see appendix 2). Bars filled with solid colour represent tests with flaming combustion and bars filled with hatched lines represent strict non-flaming tests.

Flaming tests without restriction of oxygen include SSTF 650 and CACC 50-21%.

The SSTF 650 test shows a high yield of CO_2 and a low production of CO. The mass-loss was ~92 % for this test. The sample burned unsteady but continuously and showed tendencies of spreading against the primary flow direction. Soot production was not noted. (The yield of CO_2 represents 132 % of theoretical maximum yield assuming representative combustion of combustibles in the sample.)

In the CACC 50-21% tests the mass-loss was ~76 % and a comparable low yield of CO_2 is seen. The yield of CO was low. The total soot production (TSP) was very low.

Flaming tests with an intended restriction in oxygen include SSTF 825 and CACC 50-15%.

In the SSTF 825 test there is a clear influence on the production yields of CO_2 and CO that reflects the under-ventilated conditions. In this tests mode the combustion was more stable but it was burning with a small weak flame. The mass-loss was ~83 %. Soot production was not noted.

The CACC 50-15% gave a mass-loss of ~57 %. An influence of the reduced oxygen atmosphere is indicated by the results. The yield of CO_2 was slightly lower and the yield of CO was higher (but with high variability) compared to CACC 50-21%. There is a higher soot production (TSP) in this test.

Tests with mixed combustion conditions include SC 25 and SC 50.

In the SC 25 test flaming combustion occurred for 2-7 min of the 20 min test time. Ignition occurred in the start of the test. The total mass-loss was ~91 %. The measured CO_2 yield must here be corrected for the contribution from the pilot flame and that results in a corrected yield of 1533 mg/g. The CO yield is comparatively high, above that from the two pure pyrolysis tests (see below).

In the SC 50 test flaming combustion occurred for about 4-5 min of the 20 min test time. Ignition occurred in the start of the test. The total mass-loss was ~98 %. The CO_2 yield is close to the corrected yield from the SC 25 test. The CO yield is also here high.

The two SC tests showed thus indication of very similar combustion conditions.

Non-flaming tests include SSTF 350 and CACC 50-10%.

In the SSTF 350 tests the mass-loss was ~50 %. A low yield of CO_2 was measured and a higher yield of CO. Smoke production was noted.

In the CACC 50-10% test the mass-loss was ~71 %. Also here, a low yield of CO_2 was measured and a higher yield of CO. There highest total soot production (TSP) of the CACC tests was seen in this test.

The two non-flaming tests showed thus indication of very similar combustion conditions.

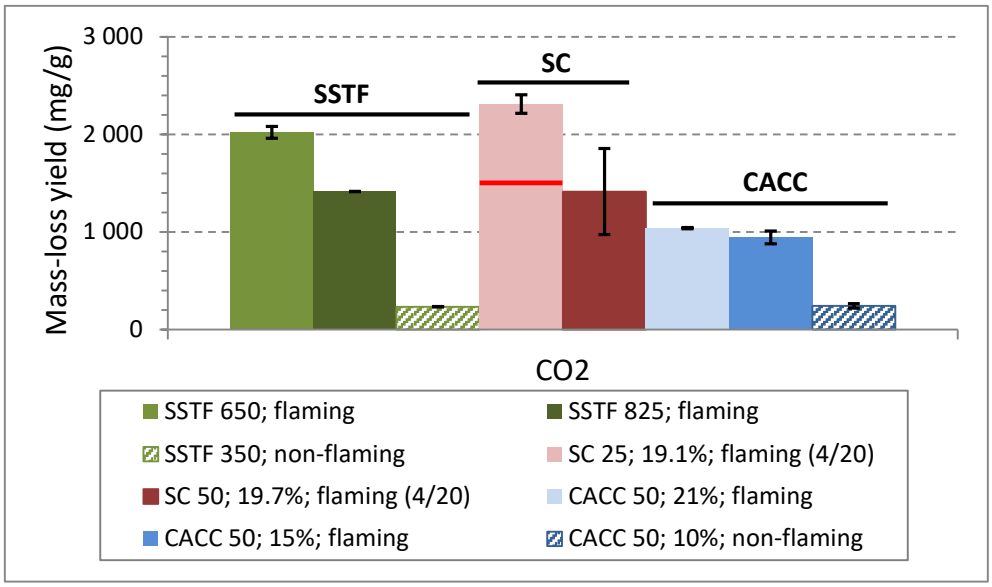


Figure 33 Mass-loss yields (average with error bars) of CO_2 for tests with OF1. The horizontal red line on the SC 25 bar indicates the approximate yield when the contribution from the pilot-flame has been corrected for.
Note: the concentration of CO_2 was close to MDL in CACC 50-10%.

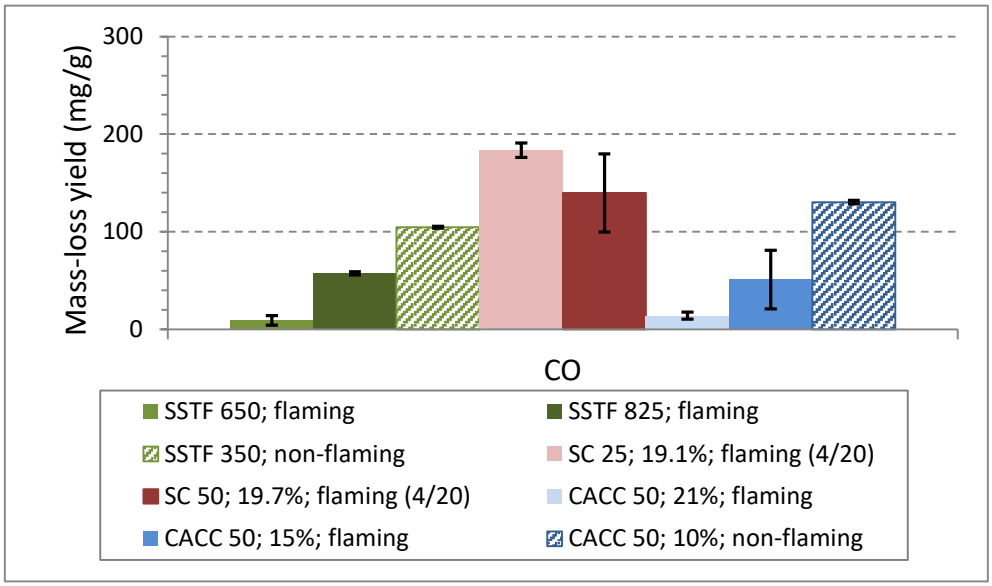


Figure 34 Mass-loss yields (average with error bars) of CO for tests with OF1.

4.2.7.3 Production of HCN and NO_X

HCN was detected in all tests with the SSTF and with the SC (see Figure 35). HCN was not detected in any of the tests with the CACC. NO_X was detected in the two flaming tests with the SSTF (see Figure 36), both tests with the SC and in the flaming tests with the CACC.

The results of the SSTF tests make sense considering the different combustion conditions that they do represent.

The results of the SC tests show that there was a mixture of well-ventilated and non-flaming combustion.

The two flaming CACC tests only gave NO_X and therefor the combustion must have been largely well-ventilated. HCN was not detected in the non-flaming CACC test which above showed correlation with the non-flaming SSTF test, were HCN was found. If HCN not was produced in the CACC test or if it was produced and the concentration was below the limit of detection is not known.

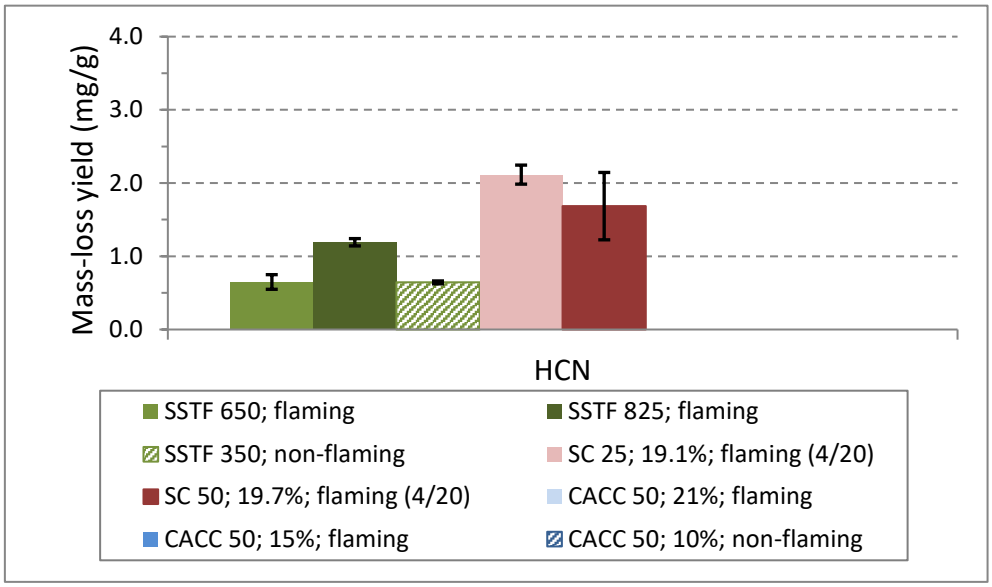


Figure 35 Mass-loss yields (average with error bars) of HCN for OF1.

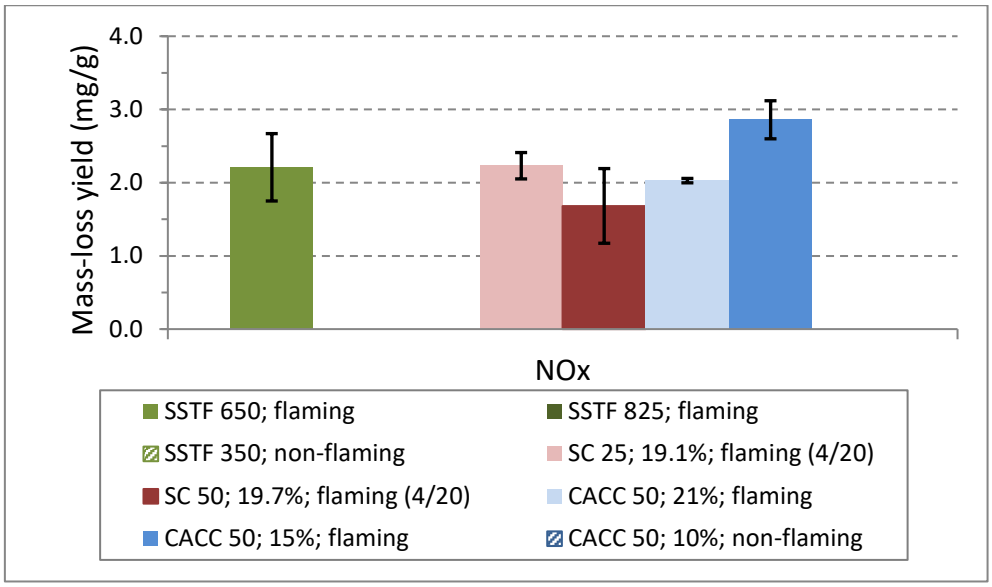


Figure 36 Mass-loss yields (average with error bars) of NO_X for OF1.
Note: the concentration of NO_X was close to MDL in CACC 50-21% and CACC 50-15%. NO_X was detected in SSTF 825 but was just below MDL.

4.2.7.4 Production of SO_2

The product contained sulphur as seen from the chemical analysis and SO_2 was found in all of the tests (see Figure 37). The yields found differed somewhat between tests but not very significantly.

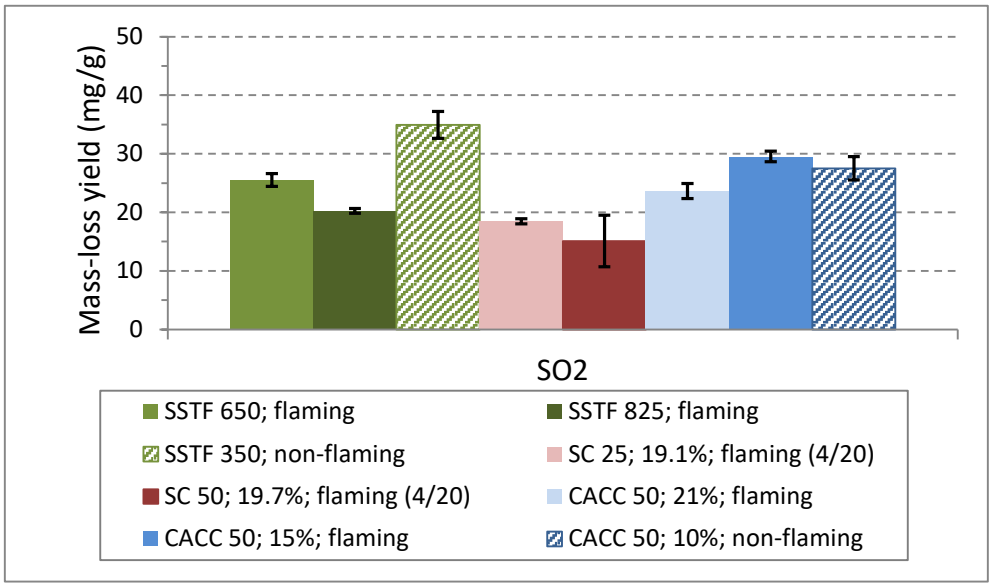


Figure 37 Mass-loss yields (average with error bars) of SO_2 for OF1.

4.2.7.5 Test method applicability

The **flaming** combustion tests with SSTF produced expected species yields which correspond to the attained combustion conditions. However, the yield of CO_2 for the well-ventilated test was overly high.

The flaming combustion tests with the CACC produced a similar yield distribution and seem both to represent mainly well-ventilated combustion. However, the CO_2-yield of CACC 50-21% was on the low side.

Both SC tests included a flaming period. The yields found indicate a mixture of combustion conditions in both cases and the yields of the two tests are rather similar

The two **pure pyrolysis tests** gave similar results except that HCN was found in SSTF 350 and not in the CACC 50-10% test.

An observation was that SO_2 was found in all tests and that the yields found differed somewhat but not significantly.

General observations on the applicability of the different methods and test modes regarding the representation of combustion conditions are summarized in Table 11. Here are also included comments on special observations on species production.

Table 11 Summary of general observations on combustion conditions and production yields for **OF1**.

Test method	Well-ventilated, flaming test mode	Reduced oxygen, flaming test mode	Non-flaming test mode
SSTF	Well-ventilated flaming combustion (Ø=0.5). Mass-loss of 92 %. Burned unsteady. High yield of CO_2 (too high) and a low production of CO. Soot not noted. Low HCN and high NO_X.	Under-ventilated flaming combustion (Ø=1.5-1.6). Mass-loss of 83 %. Burned stable but weakly. Lower yield of CO_2 and higher of CO. Soot not noted. Higher HCN and low NO_X.	Mass-loss of 50 %. Low yield of CO_2 and high CO. Soot production noted. Low HCN and no NO_X.
CACC	Mass-loss of ~76 %. Moderate yield of CO_2, low CO and low soot. NO_X produced.	Mass-loss of ~57 %. Lower yield of CO_2 and higher CO. Increased soot. NO_X produced.	Total mass-loss of ~71 %. Low yield of CO_2 and high CO. Highest soot of CACC. Similar CO_2 and CO yields as SSTF 350.
SC 25	Total mass-loss of ~91 %. Min oxygen concentration of 19.1 %. A 2-7 min flaming combustion period in the beginning of the 20 min test. Reasonable CO_2 yield but high CO. Production of both HCN and NO_X indicates a mixture of combustion conditions. $D_{s,\,max}$ = 37.		
SC 50	Total mass-loss of ~98 %. Min oxygen concentration of 19.7 %. A 4-5 min flaming combustion period in the beginning of the 20 min test. Similar CO_2 yield and somewhat lower CO compared to SC 25. Production of both HCN and NO_X indicates a mixture of combustion conditions. $D_{s,\,max}$ = 31.		

4.2.8 OF2

4.2.8.1 Summary of information on the material

The material is an organic fibre product with a density of 36 kg/m^3 and a combustible content of 80 %. Chemical analysis showed 36.5 weight-% carbon, 5.4 weight-% hydrogen and 0.1 weight-% nitrogen. Semi-quantitatively analysis showed traces of sulphur. The results of the analysis of content suggest that some major component has not been identified. This is likely to be boric acid which is commonly used as a flame retardant for cellulosic products. The burning behaviour in the well-ventilated CACC test was that the material burned very poorly, with moderate soot production, and left some residue (CACC 50-21% tests: q_{max} = 155 kW/m^2, THR = 19 MJ/m^2 and TSP = 236 m^2/m^2).

4.2.8.2 Combustion conditions - CO_2 and CO production

Mass-loss yield data for CO_2 for the tests with OF2 is presented in Figure 38 and data for CO is presented in Figure 39. The data is the average from at least duplicate tests for most test methods (see appendix 2). However, for the well-ventilated SSTF tests single tests at different temperatures were made (see more on this below). Bars filled with solid colour represent tests with flaming combustion and bars filled with hatched lines represent strict non-flaming tests.

Flaming tests without restriction of oxygen include SSTF 650, SSTF 700, SSTF 825 and CACC 50-21%.

SSTF tests for well-ventilated burning (10 l/min combustion air flow rate) were made at successively increased temperatures; 650°C, 700°C and 825°C. This was due to that continuous burning would not occur, not even at the highest temperature (this was likely due to a high content of flame retardant). This means that these tests are not acceptable to represent well-ventilated flaming combustion and are not valid according to the criteria in ISO/TS 19700. However, as OF2 burned very poorly in all tests methods, are these SSTF tests presented below.

The three well-ventilated single SSTF tests showed an increased yield of CO_2 with increased temperature and the CO yield decreased accordingly. The mass-loss was ~80 % in all of these tests. The CO_2-yield at 825°C was high and the CO-yield was very low (not distinguishable in Figure 39). (The yield of CO_2 at this temperature represents 118 % of theoretical maximum yield assuming representative combustion of combustibles in the sample.) Soot production was not noted in any of the tests.

In the CACC 50-21% test the flaming period lasted for less than 1 min, and the mass-loss for this period was ~23 %. The yield of CO_2 was very low, and the same for the CO-yield (not distinguishable in Figure 39). The total soot production (TSP) was low.

One should note that the uncertainty is higher when only a short time period can be used for the evaluation of the flaming period. Yields for the total test period for the CACC tests are discussed below.

Flaming tests with an intended restriction in oxygen include SSTF 825 and CACC 50-15%.

The SSTF 825 (less ventilated, 3.2 l/min combustion air flow rate) test shows a decreased CO_2-yield and an increased CO-yield compared to the well-ventilated test run at that temperature. The mass-loss was ~73 % for this test. Also here the sample burned unsteady and not continuously and was not valid according to criteria. Soot production was not noted.

In the CACC 50-15% the flaming period lasted for ~2 min, and the mass-loss was ~31 % for the flaming period. An influence of the reduced oxygen atmosphere is seen. The yield of CO_2 was marginally lower, and the yield of CO significantly increased compared to CACC 50-21%. But there is a lower total soot production (TSP) in this test.

Tests with mixed combustion conditions include SC 25 and SC 50. CACC 50-21% and CACC 50-15% evaluated for the complete test period are also included for comparison. See Figure 40.

In the SC 25 test flaming combustion occurred for only ~1.5 min of the 20 min test time. Ignition occurred in the start of the test. The total mass-loss was ~67 %. The measured CO_2 yield must here be corrected for the contribution from the pilot flame and that results in a corrected yield of 2937 mg/g. The CO yield is of the same magnitude as for the pure pyrolysis tests.

In the SC 50 test flaming combustion occurred for about 2-3 min of the 20 min test time. Ignition occurred in the start of the test. The total mass-loss was ~79 %. The CO_2

yield is much lower compared to the (corrected) yield of the SC 25 test. The CO yield is also here high.

Yields calculated for the complete test periods in CACC 50-21% and CACC 50-15% are included in Figure 40. These CACC tests had a very short period of flaming combustion, similar to the SC tests. The yield data for both CO_2 and CO for the two test methods shows here comparable yield distribution, although that SC 25 deviates with the high CO_2-yield.

Non-flaming tests include SSTF 350 and CACC 50-10%.

In the SSTF 350 tests the mass-loss was ~49 %. A low yield of CO_2 was measured and a high yield of CO (compared to the other SSTF tests). Smoke production was noted.

In the CACC 50-10% test the mass-loss was ~48 %. Also here, a low yield of CO_2 was measured and a higher yield of CO (a distribution very similar to SSTF 350). The total soot production (TSP) was low.

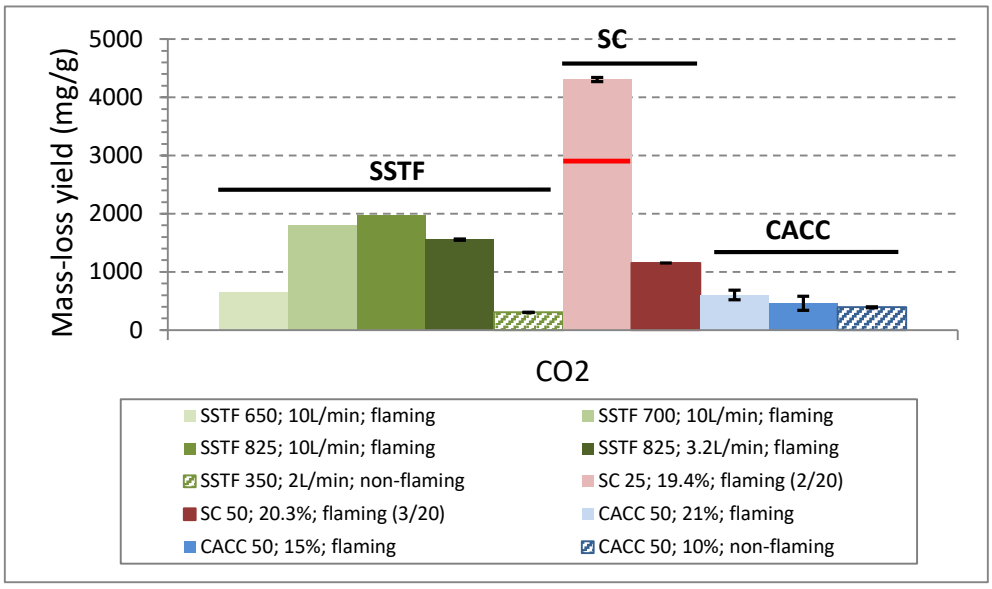


Figure 38 Mass-loss yields (average, with error bars for the repeated tests) of CO_2 for tests with OF2. The horizontal red line on the SC 25 bar indicates the approximate yield when the contribution from the pilot-flame has been corrected for.
Note: the concentration of CO_2 was close to MDL in CACC 50-10%.

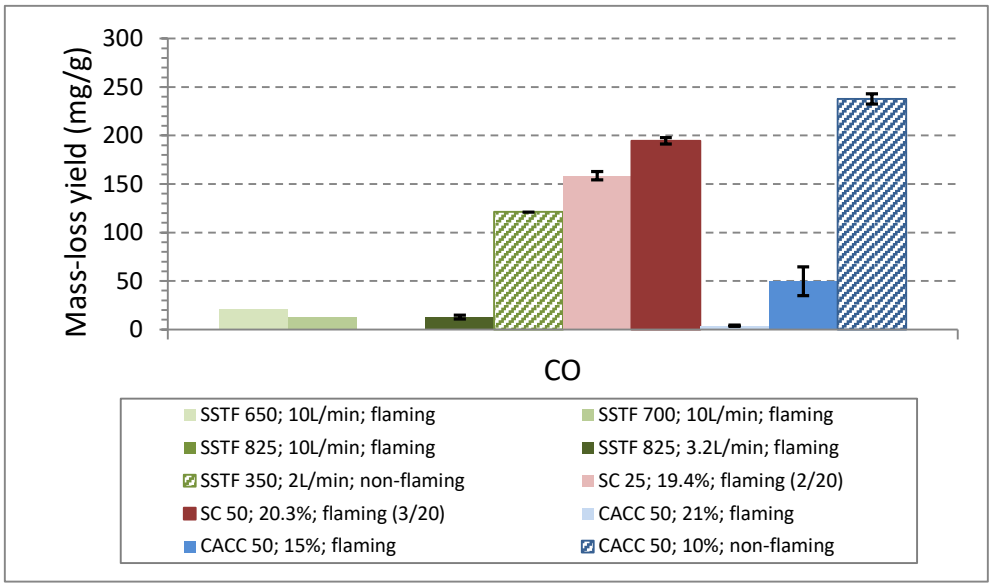


Figure 39 Mass-loss yields (average, with error bars for the repeated tests) of CO for tests with OF2.

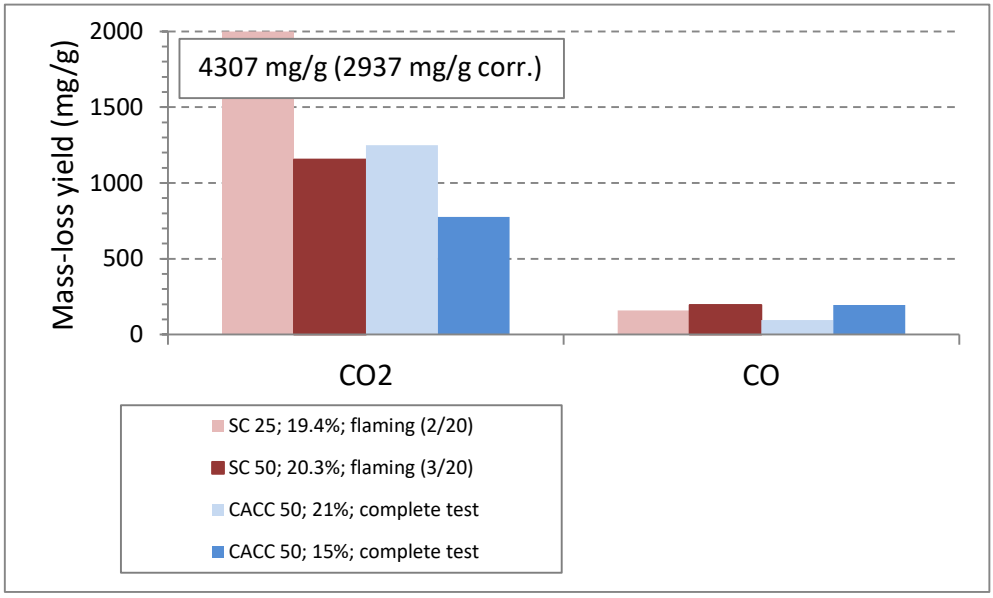


Figure 40 Mass-loss yields (average) of CO_2 and CO for OF2 from tests with mixed combustion conditions. The CACC tests are evaluated for the complete test period (both flaming and non-flaming conditions). For deviation between the repeated tests see appendix 2.

4.2.8.3 Production of HCN and NO_X

HCN was not detected in any of the test. NO_X was produced in all flaming tests with the SSTF with the lowest production in SSTF 825 (less ventilated, 3.2 l/min combustion air flow rate). This indicates that this test was not properly under-ventilated. Also SC 25 showed production of NO_X, whereas NO_X was not found in SC 50.

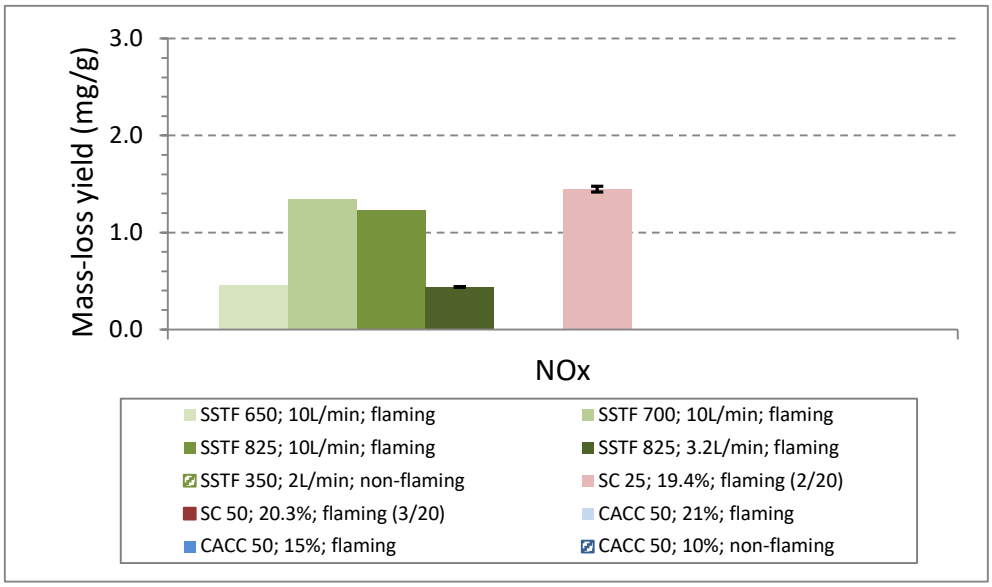


Figure 41 Mass-loss yields (average with error bars) of NO_X for OF2.
Note: the concentration of NO_X was close to MDL in SSTF 650-10L/min and SSTF 825-3.2L/min.

4.2.8.4 Test method applicability

The **flaming** combustion tests with SSTF did not give continuous flaming combustion despite that well-ventilated tests were made with increased temperatures up to 825°C. All tests showed yield distribution indicating well ventilation.

The flaming combustion tests with the CACC produced low CO_2-yields but the results might be influenced from short flaming periods.

The two SC tests both included short flaming periods and thus longer periods of non-flaming combustion. Comparably high yields of CO were seen in these tests, similar to the yields from the pure pyrolysis tests. The two SC tests and the flaming CACC tests all showed short flaming periods and the yields compared for the SC tests and the complete CACC tests showed clear similarities.

The two **pure pyrolysis tests** gave similar results with only CO_2 and CO production.

General observations on the applicability of the different methods and test modes regarding the representation of combustion conditions are summarized in Table 12. Here are also included comments on special observations on species production.

Table 12 Summary of general observations on combustion conditions and production yields for **OF2**.

Test method	Well-ventilated, flaming test mode	Reduced oxygen, flaming test mode	Non-flaming test mode
SSTF	Single tests were made at successively increased temperatures; 650°C, 700°C and 825°C; due to that continuous burning would not occur. Mass-loss of ~80 %. These tests were not acceptable by ISO 19700. The 825°C gave a valid CO_2-yield for complete combustion and very low CO. NO_X was found in all tests. (Ø=0.3 but no cont. burning.)	Unsteady flaming and no continuous burning. Not acceptable test. Mass-loss of ~73 %. Lower yield of CO_2 and higher CO. No HCN and production of NO_X. This test was not properly under-ventilated. (Ø=0.9 but no cont. burning.)	Mass-loss of 49 %. Low yield of CO_2 and high CO. Soot production noted. No production of HCN or NO_X.
CACC	Mass-loss of ~23 % during a very short flaming period. Low yield of CO_2, very low CO and low soot. Yields for the complete test showed similarities to the SC tests.	Mass-loss of ~31 % during a short flaming period. Lower yield of CO_2 and higher CO. Lower soot. Yields for the complete test showed similarities to the SC tests.	Total mass-loss of ~48 %. Low yield of CO_2 and high CO. Low soot. Only SO_2 additionally produced. No production of HCN. Results similar to SSTF 350.
SC 25	Total mass-loss of ~67 %. Min oxygen concentration of 19.4 %. A ~1.5 min flaming combustion period in the beginning of the 20 min test. Very high CO_2 yield and high CO. Production of NO_X. $D_{s,\,max}$ = 18.		
SC 50	Total mass-loss of ~79 %. Min oxygen concentration of 20.3 %. A ~2.5 min flaming combustion period in the beginning of the 20 min test. Much lower CO_2 yield and somewhat higher CO compared to SC 25. NO_X not detected. $D_{s,\,max}$ = 22.		

4.3 Non-combustible test specimens

4.3.1 Introduction

These materials all have a low combustible content which excludes the possibility for flaming combustion. All tests are thus different types of non-flaming heating/pyrolysis tests.

The low combustible content must be considered when comparing species yields between different groups of materials. Materials that can undergo flaming combustion have a high combustible content, and also a lower mass-loss yield of a certain species could result in a significant total emission in a specified fire scenario.

Materials that will not undergo flaming combustion have a very low combustible content, and although the mass-loss yield of a certain species would be high may the total emission in the specific fire scenario be low.

The low combustible content for mineral fibre insulating materials and thus the low mass-loss in a test makes the calculations of mass-loss yields more uncertain. Especially for the CACC tests, the mass-loss data was unreliable in some cases (especially for MF3). This was because that the signal of the load-cell was disturbed by the elevated temperature of the controlled atmosphere chamber in combination with a very low mass-loss.

A comparison using mass-charge data would in this case be more robust regarding the measured input values. However, one must keep in mind that the sample specimen size may have an influence on the production yield. A thick sample that not is uniformly heated would have a lower mass-charge yield compared to a thin sample.

Mass-charge yield are compared and discussed below for the mineral fibre materials included in the test programme. Mass-loss yield comparison graphs are additionally available in appendix 3.

4.3.2 MF1

4.3.2.1 Summary of information on the material

The material is a mineral fibre board material with a density of 21 kg/m^3 and a combustible content of 5.0 %. Chemical analysis of the product showed 2.9 weight-% carbon, 0.4 weight-% hydrogen and 0.57 weight-% nitrogen. Semi-quantitatively analysis showed the presence of sulphur.

4.3.2.2 Species production

Mass-charge yield data for CO_2 for the tests with MF1 is presented in Figure 42 and data for CO is presented in Figure 43. Further are yields for HCN and NO_X given in Figure 44 and yields for SO_2 in Figure 46. The data is the average from at least duplicate tests for all test methods (see appendix 3). All tests showed in the graphs are non-flaming tests.

Tests without intended restriction in oxygen include SSTF 650 (10 l/min), SSTF 825 (10 l/min), CACC 50-21%, SC 25 and SC50.

In the two high-ventilated SSTF tests the CO_2-yield increases with temperature but the CO-yield is constant. HCN is further produced in similar yields from both tests. NO_X was only produced in the 825°C test. SO_2 was produced in similar yields from both tests. Actually, SO_2 was only found in the SSTF tests.

The CACC 50-21% test did not produce any measurable CO_2, but CO was produced in a yield of the same order of magnitude as that from the SSTF tests. HCN and NO_X were not detected in the test.

The CO_2 measured from SC 25 includes also the CO_2 production from the pilot flame, as discussed above for the combustible insulation materials. However, as the amount of combustible material is very low for mineral wool products it is not possible to correct for the contribution from the pilot flame. The amount of CO_2 produced from the flame is several times higher compared to the production from the sample and the error in correction would be too large. CO was produced from SC 25 giving a low yield. Further was NO_X measured in a relatively high yield but HCN was not detected.

The SC50 test gave a CO_2-yield and a CO-yield close to that from the SSTF test. Here HCN was produced (in similar yield as from the SSTF tests) and NO_X was not detected; the opposite compared to the SC 25 test.

Tests with reduced oxygen availability include SSTF 350 (2.0 l/min), SSTF 825 (3.2 l/min), SSTF 825 (3.2 l/min, 5% O_2), CACC 50-15% and CACC 50-10%.

The two SSTF tests at 825 °C both gave similar yields of CO_2, and CO was not detected in any of these tests. SO_2 was the only additional specie found, and in similar yields as in the two high-ventilated SSTF tests.

The SSTF test at 350 °C produced only a low yield CO.

Also the two vitiated CACC tests only produced CO. The CACC 50-15% a higher yield compared to SSTF 350, and CACC 50-10% a lower yield.

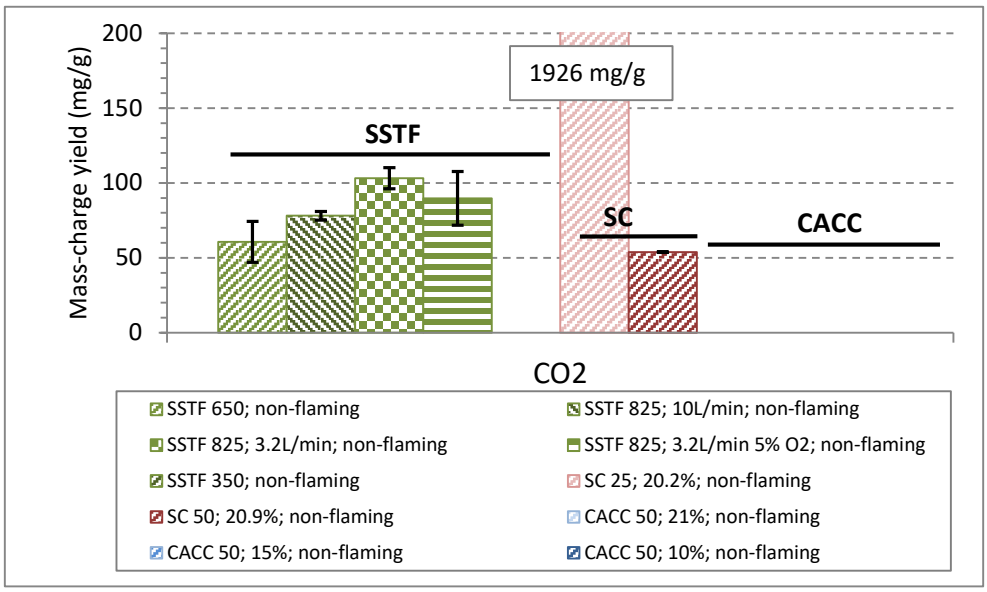


Figure 42 Mass-charge yields (average with error bars) of CO_2 for tests with MF1.

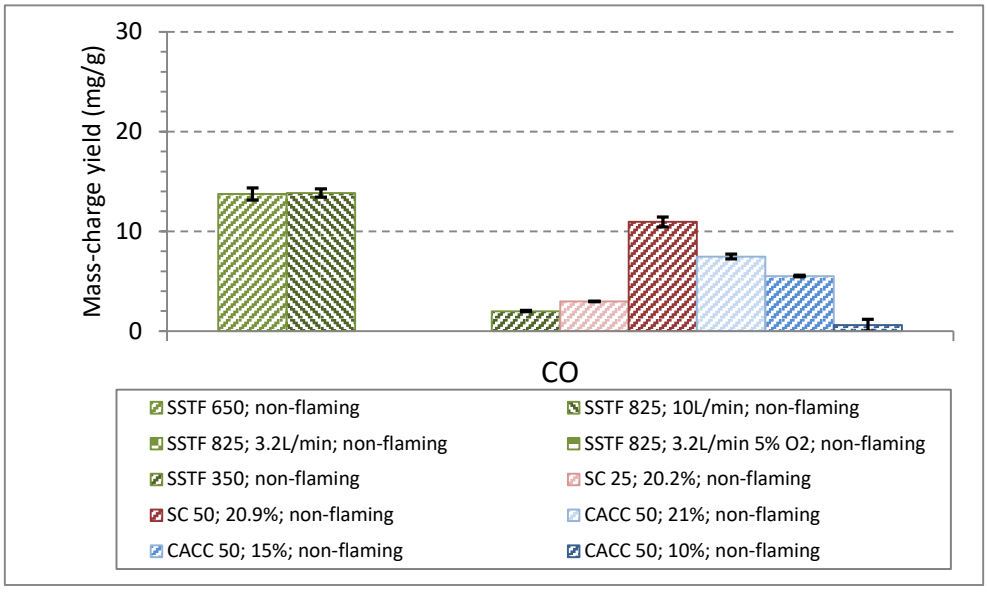


Figure 43 Mass-charge yields (average with error bars) of CO for tests with MF1.

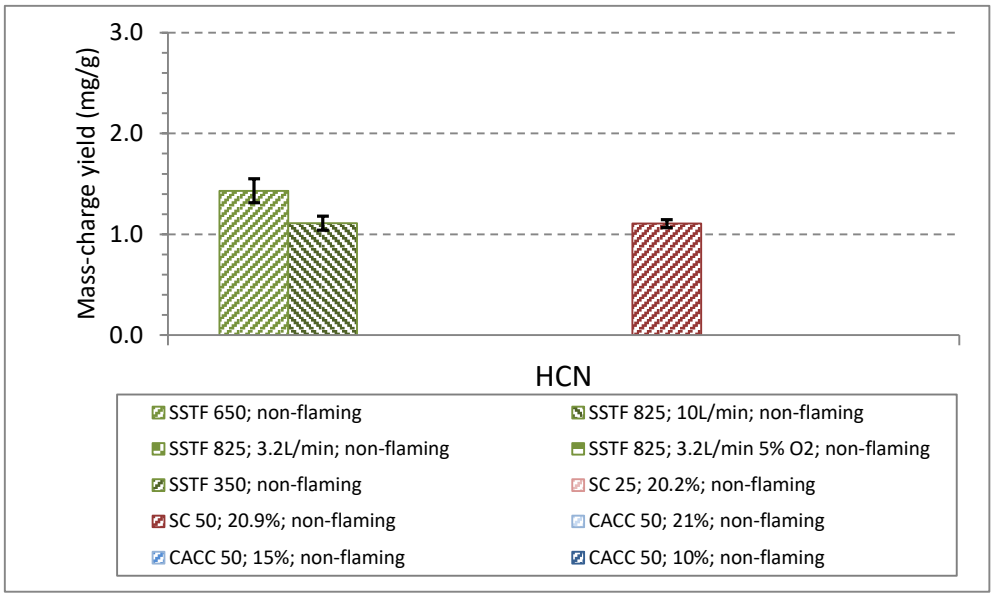


Figure 44 Mass-charge yields (average with error bars) of HCN for MF1.

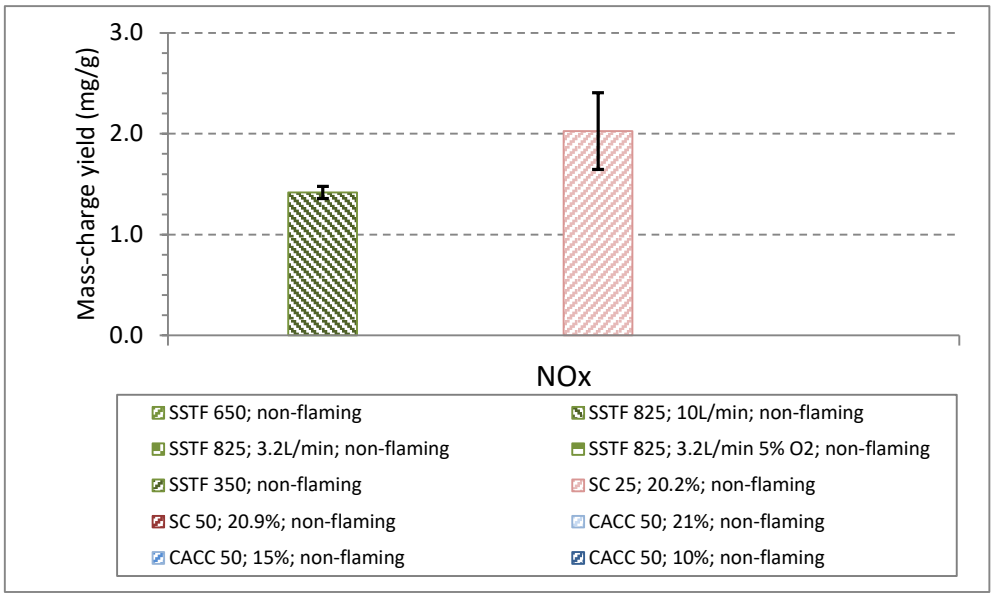


Figure 45 Mass-charge yields (average with error bars) of NO_X for MF1.

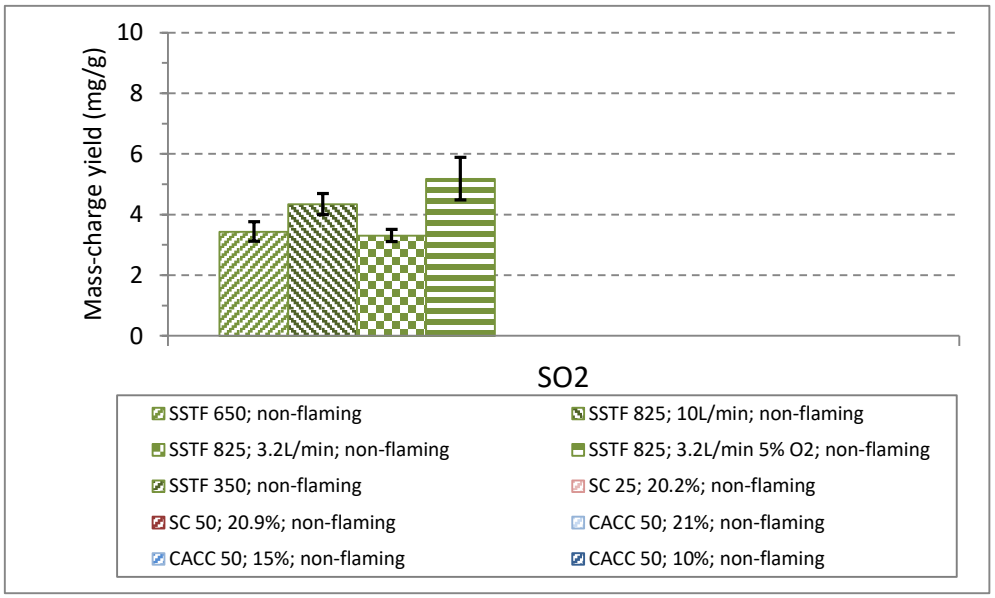


Figure 46 Mass-charge yields (average with error bars) of SO_2 for MF1.

4.3.2.3 Test method applicability

The high temperature **SSTF** test showed increase CO_2 production with increased temperature. A reduced air flow-rate (and oxygen flow) seemed not to influence the CO_2 production significantly. The CO, HCN and SO_2 production was similar for the two tests with high air flow-rate, but CO and HCN was not detected in the low flow-rate tests. The low temperature SSTF test only produced a very low yield of CO.

The **CACC** tests only produced CO in detectable amounts. The yield of CO decreased with decreasing oxygen concentration.

Especially the **SC** 50 tests gave very similar yields to the high temperature high ventilated SSTF tests. The SC 25 test gave correlation in CO yield with the low temperature SSTF test. SO_2 was not detected in any of the SC tests.

The mass-charge yields measured with the different tests are summarized in Table 13. The tests are sorted in modes without intended restriction in oxygen availability (high O_2) and modes with an intended oxygen restriction (restricted O_2).

Table 13 Summary of measured mass-charge yields from the different tests for **MF1**.

Test method	Test mode	Mass-charge yields (mg/g)				
		CO_2	CO	HCN	NO_X	SO_2
SSTF **high O_2**	SSTF 650 (10 l/min) SSTF 825 (10 l/min)	61 78	14 14	1.4 1.1	ND 1.4	3.4 4.3
CACC high O_2	CACC 50-21%	ND	7	ND	ND	ND
SC (high O_2)	SC 25 (pilot flame) SC 50	1926* 54	3.0 11	ND 1.1	2.0 ND	ND ND
SSTF **restricted O_2**	SSTF 350 (2 l/min) SSTF 825 (3.2 l/min) SSTF 825 (3.2 l/min, 5% O_2)	ND 103 89	2.0 ND ND	ND ND ND	ND ND ND	ND 3.3 5.2
CACC	CACC 50-15%	ND	5.5	ND	ND	ND

Test	Test mode	Mass-charge yields (mg/g)				
restricted O_2	CACC 50-10%	ND	0.6	ND	ND	ND

* Contains the contribution from the pilot flame.

ND = Not detected.

4.3.3 MF2

4.3.3.1 Summary of information on the material

The material is a mineral fibre board material with a density of 28 kg/m^3 and a combustible content of 7.2 %. Chemical analysis of the product showed 3.2 weight-% carbon, 0.51 weight-% hydrogen and <0.05 weight-% nitrogen. Semi-quantitatively analysis showed traces of sulphur and chlorine.

4.3.3.2 Species production

Mass-charge yield data for CO_2 for the tests with MF2 is presented in Figure 47 and data for CO is presented in Figure 48. HCN and SO_2 were not detected in any of the tests with MF2. NO_X was detected only in the SC 25 test (see Figure 49). The data is the average from at least duplicate tests for all test methods (see appendix 3). All tests showed in the graphs are non-flaming tests.

Tests without intended restriction in oxygen include SSTF 650 (10 l/min), SSTF 825 (10 l/min), CACC 50-21%, SC 25 and SC50.

In the two high-ventilated SSTF tests the CO_2-yield increases with temperature and the CO-yield decreased.

The CACC 50-21% test produced CO_2 of the same level and CO in about half the yield compared to the SSTF 650.

The SC 25 test gave a high yield of CO_2 as this includes the contribution from the burner which cannot be corrected for without giving an unacceptable large error. CO was produced giving a comparable low yield in the test. Also NO_X was detected from this test which probably is an effect of the pilot-burner. The SC50 test gave both CO_2- and CO-yields close to that from the CACC 50-21% test.

Tests with reduced oxygen availability include SSTF 350 (2.0 l/min), CACC 50-15% and CACC 50-10%.

The SSTF test at 350 °C produced comparably low yields of both CO_2 and CO. The two vitiated CACC tests only produced CO and that of similar yields.

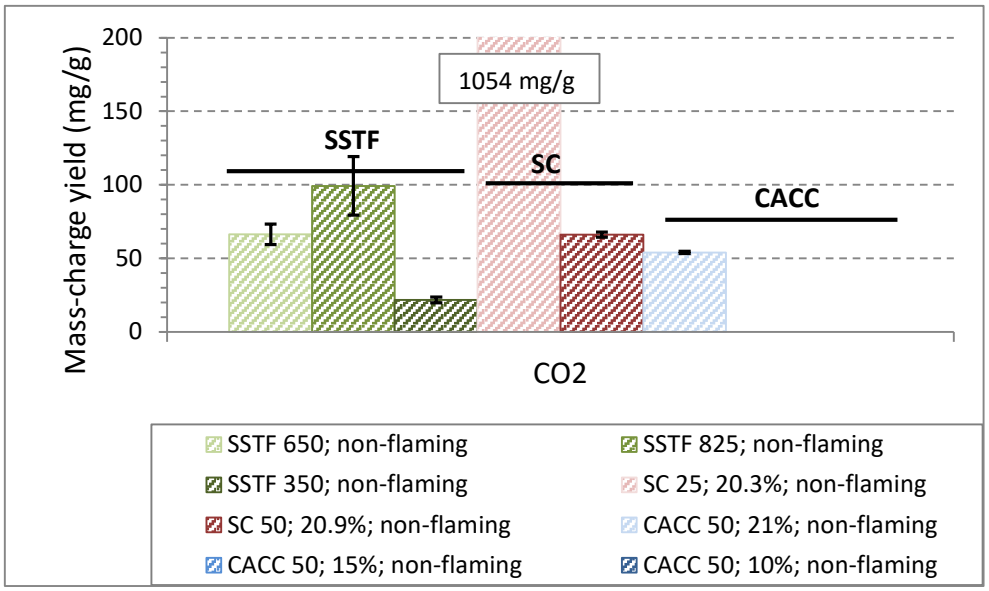


Figure 47 Mass-charge yields (average with error bars) of CO_2 for tests with MF2.
Note: the concentration of CO_2 was close to MDL in CACC 50-21%.

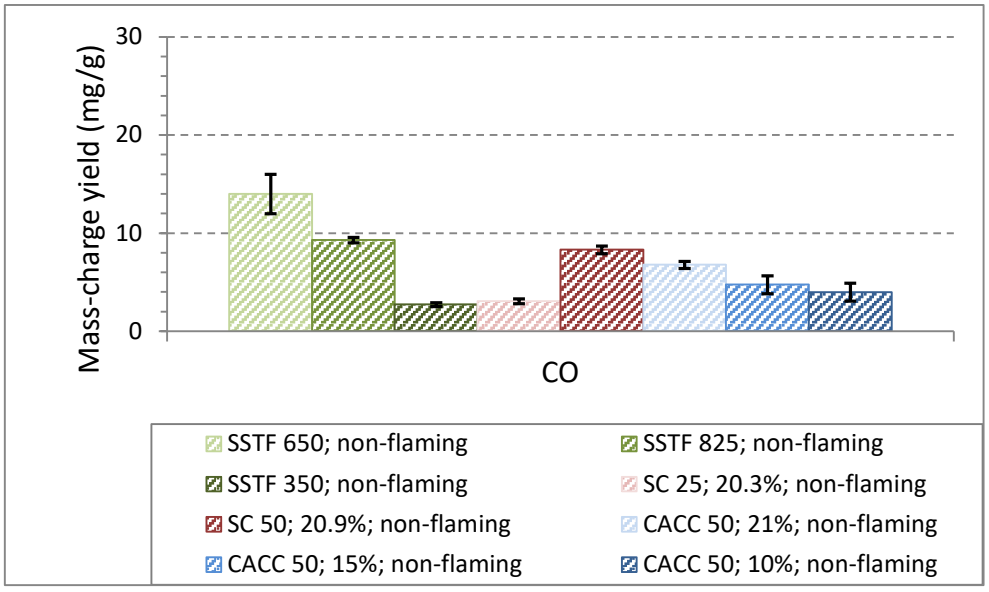


Figure 48 Mass-charge yields (average with error bars) of CO for tests with MF2.

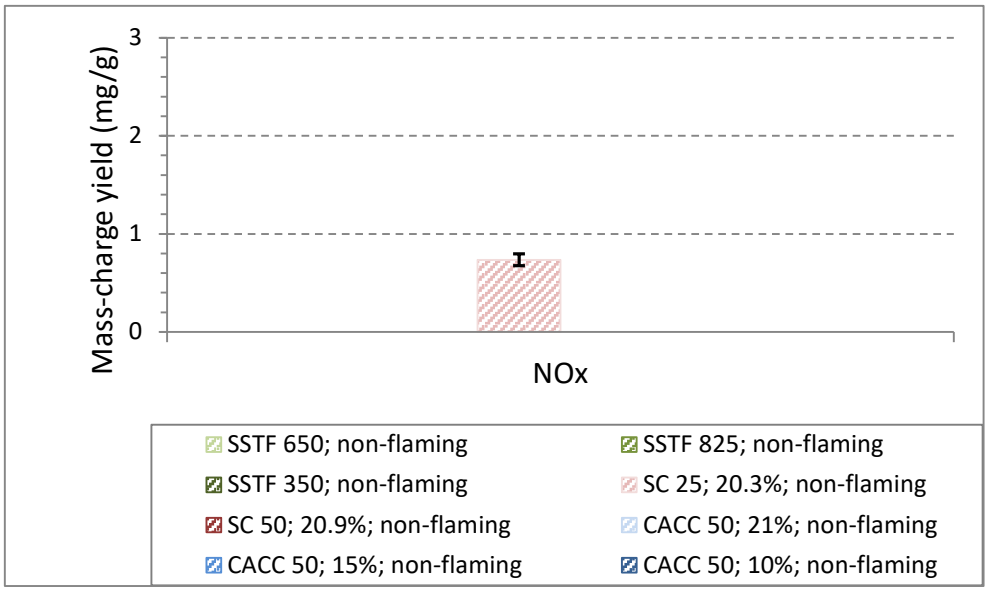


Figure 49 Mass-charge yields (average with error bars) of NO_X for MF2.
Note: the concentration of NO_X was close to MDL in SC 25.

4.3.3.3 Test method applicability

The two high-temperature **SSTF** test showed increase CO_2 production with increased temperature and the CO production was decreased. The low temperature SSTF test produced low yields of both CO_2 and CO.

Only the **CACC** 50-21% test produced CO_2 in detectable amounts. All CACC test modes produced CO and the yield decreased with decreasing oxygen concentration.

Especially the **SC** 50 tests gave very similar yields to the high temperature SSTF tests. The SC 25 test gave correlation in CO-yield with the low temperature SSTF test.

The mass-charge yields measured with the different tests are summarized in Table 14. The tests are sorted in modes without intended restriction in oxygen availability (high O_2) and modes with an intended oxygen restriction (restricted O_2).

Table 14 Summary of measured mass-charge yields from the different tests for **MF2**.

Test method	Test mode	Mass-charge yields (mg/g)				
		CO_2	CO	HCN	NO_X	SO_2
SSTF **high O_2**	SSTF 650 (10 l/min) SSTF 825 (10 l/min)	66 99	14 9.3	ND ND	ND ND	ND ND
CACC high O_2	CACC 50-21%	54	7.0	ND	ND	ND
SC (high O_2)	SC 25 (pilot flame) SC 50	1054* 66	3.1 8.3	ND ND	0.73 ND	ND ND
SSTF **restricted O_2**	SSTF 350 (2 l/min)	22	2.7	ND ND	ND ND	ND ND
CACC restricted O_2	CACC 50-15% CACC 50-10%	ND ND	4.7 4.0	ND ND	ND ND	ND ND

* Contains the contribution from the pilot flame.

ND = Not detected.

4.3.4 MF3

4.3.4.1 Summary of information on the material

The material is a mineral fibre board material with a density of 126 kg/m^3 and a combustible content of 1.7 %. Chemical analysis of the product showed 1.5 weight-% carbon, 0.2 weight-% hydrogen and 0.28 weight-% nitrogen. Semi-quantitatively analysis showed traces of sulphur.

4.3.4.2 Species production

Mass-charge yield data for CO_2 for the tests with MF3 is presented in Figure 50 and data for CO is presented in Figure 51. Further are yields for HCN given in Figure 52 and yields for NO_X in Figure 53. The data is the average from at least duplicate tests for all test methods (see appendix 3). All tests showed in the graphs are non-flaming tests.

Tests without intended restriction in oxygen include SSTF 650 (10 l/min), SSTF 825 (10 l/min), CACC 50-21%, SC 25 and SC50.

In the two high-ventilated SSTF tests the CO_2-yield increases with temperature and the CO-yield decreased. Both HCN and NO_X are produced in these tests of similar yields between tests.

The CACC 50-21% test did not produce measurable CO_2 and only gave a low yield of CO.

The SC 25 test gave a high yield of CO_2 as this includes the contribution from the burner. CO was produced giving a comparable low yield. Both HCN and NO_X are produced in the test. The SC 50 test gave CO_2-, CO-, and NO_X-yields close to that from the SSTF 650 test.

Tests with reduced oxygen availability include SSTF 350 (2.0 l/min), CACC 50-15% and CACC 50-10%.

The SSTF test at 350 °C did not produce measurable CO_2 and gave yields of CO and HCN close to that from SC 25.

The two vitiated CACC tests only produced CO. The yields were very similar.

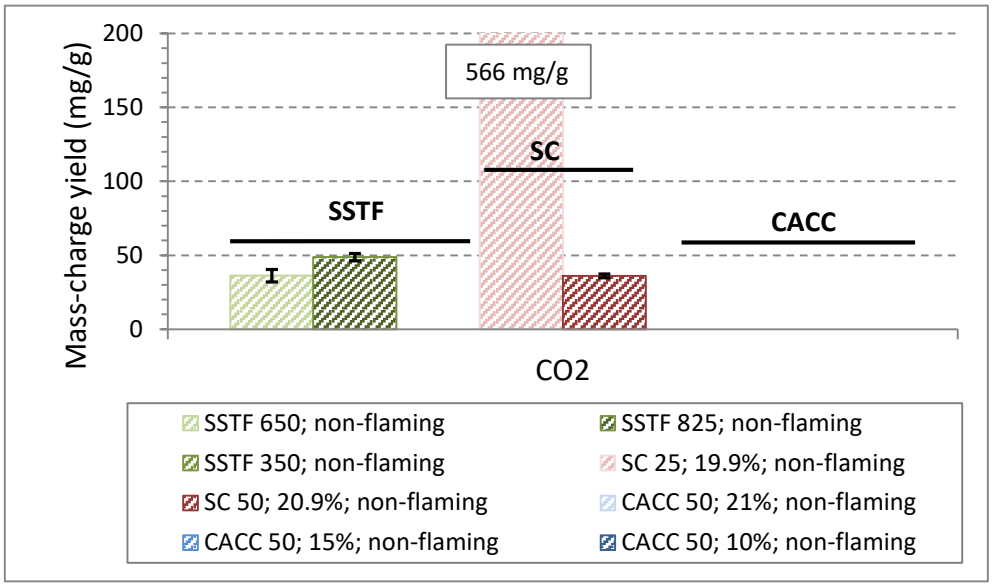


Figure 50 Mass-charge yields (average with error bars) of CO_2 for tests with MF3.

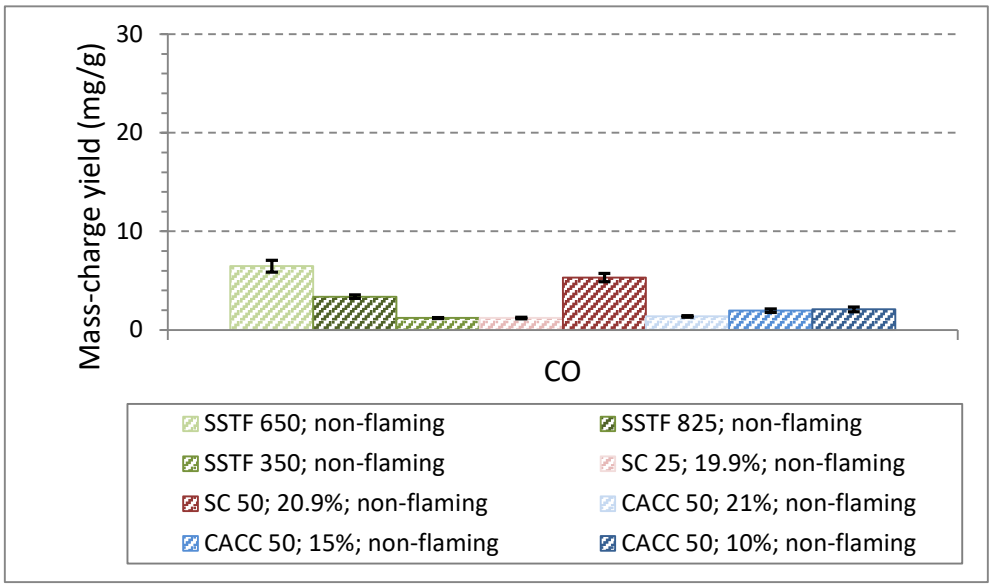


Figure 51 Mass-charge yields (average with error bars) of CO for tests with MF3.

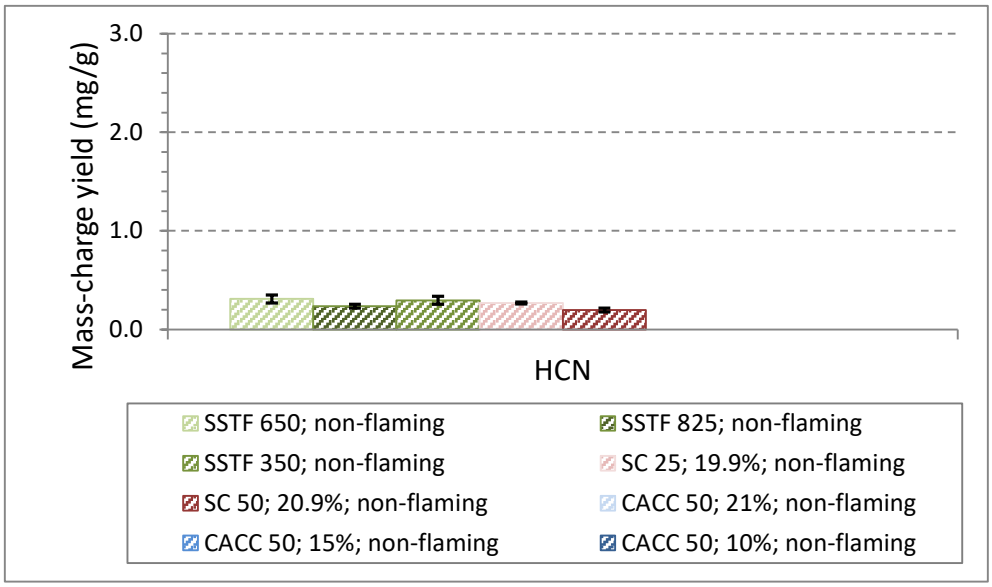


Figure 52 Mass-charge yields (average with error bars) of HCN for tests with MF3.

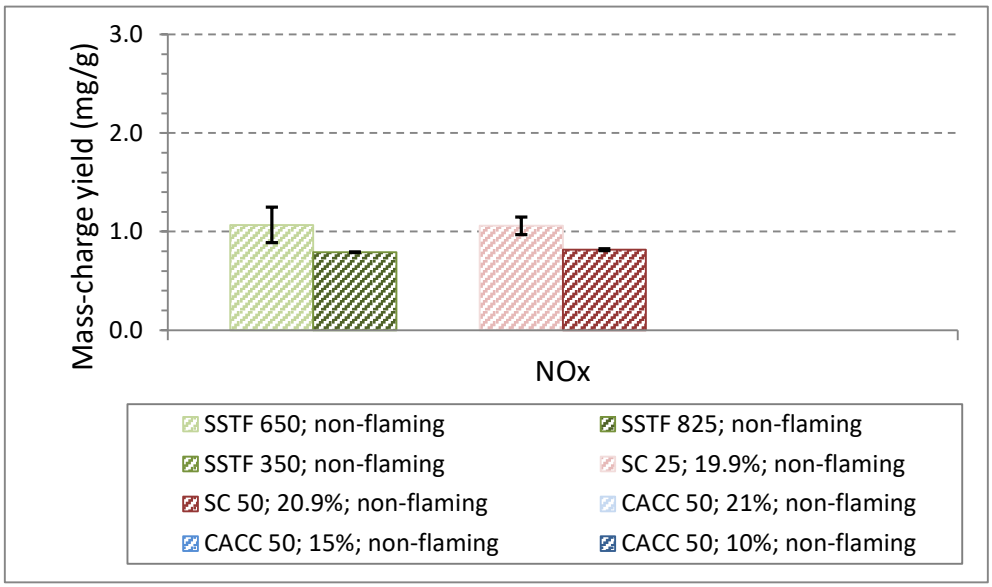


Figure 53 Mass-charge yields (average with error bars) of NO_X for tests with MF3.

4.3.4.3 Test method applicability

The two high temperature **SSTF** test showed increase CO_2 production with increased temperature and a decrease in the CO production. The low temperature SSTF test produced only a low yield of CO. All SSTF tests produced a similar yield of HCN and the two high temperature tests additionally produced NO_X.

The **CACC** tests only produced CO in low yields.

The **SC** 50 tests gave similar yields compared to the high temperature SSTF tests. The SC 25 test gave correlation in CO-yield with the low temperature SSTF test and the CACC tests, but also similar yields of HCN and NO_X as the high temperature SSTF tests.

The mass-charge yields measured with the different tests are summarized in Table 15. The tests are sorted in modes without intended restriction in oxygen availability (high O_2) and modes with an intended oxygen restriction (restricted O_2).

Table 15 Summary of measured mass-charge yields from the different tests for **MF3**.

Test method	Test mode	Mass-charge yields (mg/g)				
		CO_2	CO	HCN	NO_X	SO_2
SSTF **high O_2**	SSTF 650 (10 l/min) SSTF 825 (10 l/min)	36 49	6.5 3.4	0.31 0.24	1.1 0.79	ND ND
CACC high O_2	CACC 50-21%	ND	1.4	ND	ND	ND ND
SC (high O_2)	SC 25 (pilot flame) SC 50	566* 36	1.2 5.3	0.27 ND	1.1 0.82	ND ND
SSTF **restricted O_2**	SSTF 350 (2 l/min)	ND	1.2	0.30	ND	ND ND
CACC restricted O_2	CACC 50-15% CACC 50-10%	ND ND	2.0 2.1	ND ND	ND ND	ND ND

* Contains the contribution from the pilot flame.

ND = Not detected.

4.3.5 MF4

4.3.5.1 Summary of information on the material

The material is a mineral fibre board material with a density of 147 kg/m^3 and a combustible content of 4.3 %. Chemical analysis of the product showed 2.6 weight-% carbon, 0.2 weight-% hydrogen and 0.44 weight-% nitrogen. Semi-quantitatively analysis showed the presence of sulphur.

4.3.5.2 Species production

Mass-charge yield data for CO_2 for the tests with MF4 is presented in Figure 54 and data for CO is presented in Figure 55. Further are yields for HCN given in Figure 56 and yields for NO_X in Figure 57. The data is the average from at least duplicate tests for all test methods (see appendix 3). All tests showed in the graphs are non-flaming tests.

Tests without intended restriction in oxygen include SSTF 650 (10 l/min), SSTF 825 (10 l/min), CACC 50-21%, SC 25 and SC50.

In the two high-ventilated SSTF tests the CO_2-yield increases with temperature and the CO-yield decreases significantly. HCN was produced in both tests and the yield decreased with increased temperature. NO_X was produced from both tests and the yield showed the same dependence on the temperature as for CO and HCN.

The CACC 50-21% test did not produce any measurable CO_2, but CO was produced in a comparable average yield between tests methods. HCN was detected but below the limit of quantification. NO_X were not detected in the test.

The CO_2 measured from SC 25 gave a high yield as this includes the contribution from the burner. CO was found in a low yield, and further were both HCN and NO_X produced. The SC50 test gave a low CO_2-yield, and a higher CO-yield compared to SC 25. Also here were both HCN and NO_X found in similar yields as in SC 25.

Tests with reduced oxygen availability include **oxygen** include SSTF 350 (2.0 l/min), SSTF 825 (3.2 l/min), SSTF 825 (3.2 l/min, 5% O_2), CACC 50-15% and CACC 50-10%.

The two SSTF tests at 825°C both gave similar yields of CO_2, but CO was not detected in any of these tests (as was the case for MF1). NO_X was additionally found in both tests but in lower yields compared to the two high-ventilated SSTF test.

The SSTF test at 350°C produced a low yield of CO_2 and yields of CO and HCN similar to those from SC 25.

The two vitiated CACC tests produced CO with a slightly decreasing yield with increased vitiation. Also HCN was produced, but in low amounts. HCN was detected (but below the limit of quantification) in the CACC 50-15% and in quantifiable amounts in CACC 50-10%.

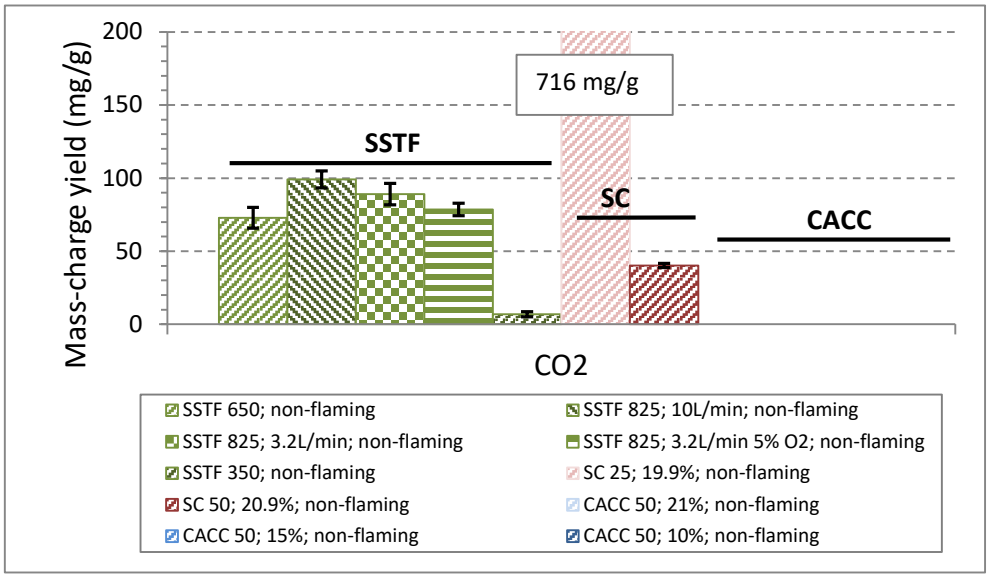


Figure 54 Mass-charge yields (average with error bars) of CO_2 for tests with MF4.

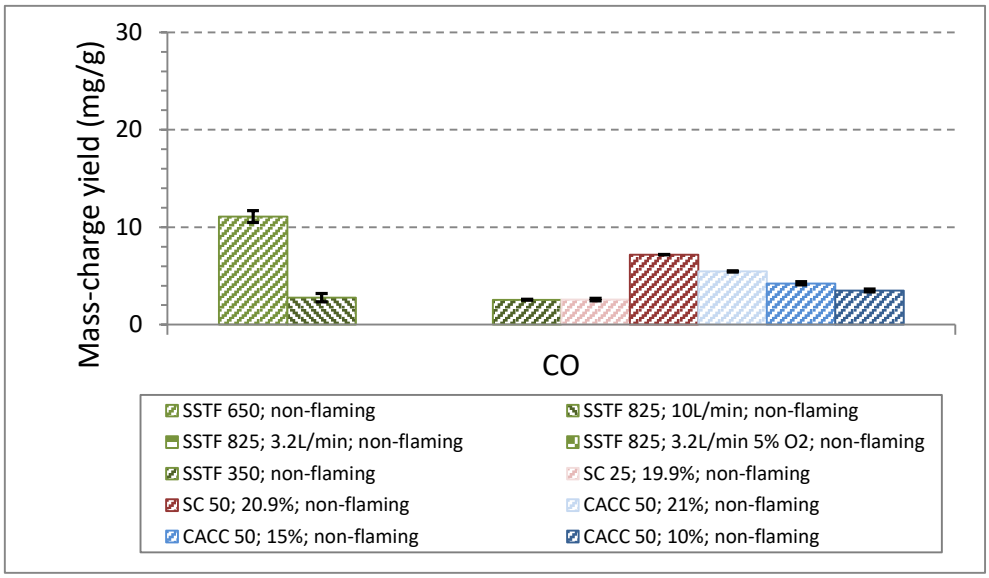


Figure 55 Mass-charge yields (average with error bars) of CO for tests with MF4.

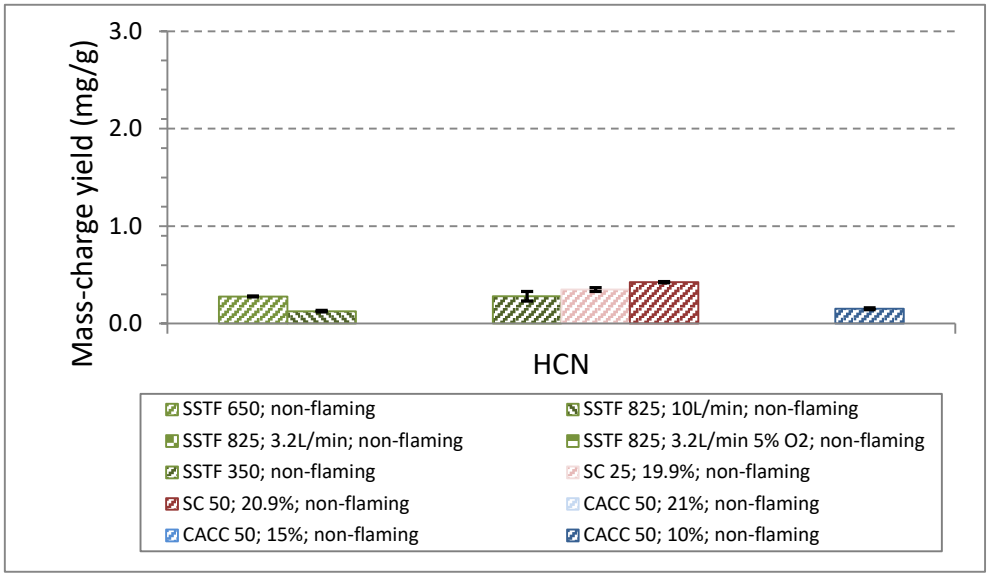


Figure 56 Mass-charge yields (average with error bars) of HCN for MF4.
Note 1: HCN was detected in CACC 50-21% and CACC 50-15% but was below MDL in those tests.
Note 2: HCN was close to the minimum detection limit (MDL) in SSTF 825-10 L/min.

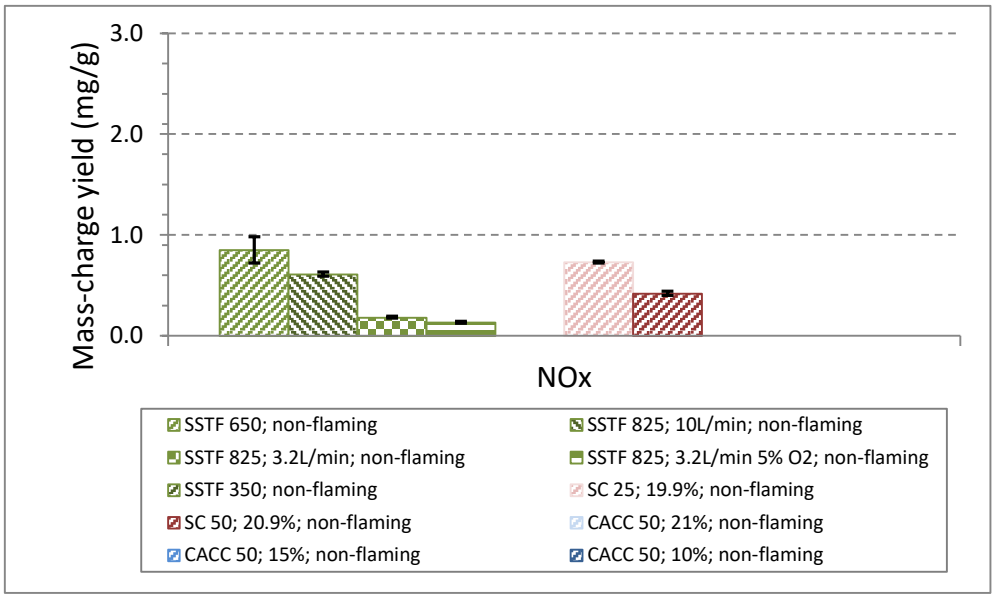


Figure 57 Mass-charge yields (average with error bars) of NO_X for MF4.
Note: NO_X was close to MDL in SSTF 825-3.2L/min, 5% O_2.

4.3.5.3 Test method applicability

The high temperature **SSTF** test showed an increase in CO_2 production with increased temperature. The reduced air flow-rate (and oxygen flow) marginally decreased the CO_2 production. The CO, HCN and NO_X production were decreased with temperature for the two tests with high air flow-rate, but CO and HCN was not detected in the low flow rate tests. NO_X-yields were clearly decreased in the two reduced air flow-rate (and oxygen flow) tests compared to the high flow-rate tests.

The low temperature SSTF test produced both CO and HCN in significant yields.

The **CACC** tests produced CO and HCN in detectable amounts. The yield of CO decreased with decreasing oxygen concentration. HCN was only produced in quantifiable amounts in the test with the lowest oxygen concentration.

Especially the **SC** 50 tests gave similar yields to the STTF 650 tests. The **SC 25** test gave partly yields similar to the SSTF 350 test.

The mass-charge yields measured with the different tests are summarized in Table 16. The tests are sorted in modes without intended restriction in oxygen availability (high O_2) and modes with an intended oxygen restriction (restricted O_2).

Table 16 Summary of measured mass-charge yields from the different tests for **MF4**.

Test method	Test mode	Mass-charge yields (mg/g)				
		CO_2	CO	HCN	NO_X	SO_2
SSTF **high O_2**	SSTF 650 (10 l/min) SSTF 825 (10 l/min)	73 99	11 2.8	0.28 0.13	0.85 0.61	ND ND
CACC high O_2	CACC 50-21%	ND	5.0	ND	ND	ND
SC (high O_2)	SC 25 (pilot flame) SC 50	716* 40	2.6 7.2	0.35 0.40	0.73 0.40	ND ND
SSTF **restricted O_2**	SSTF 350 (2 l/min) SSTF 825 (3.2 l/min) SSTF 825 (3.2 l/min, 5% O_2)	6.9 89 79	2.6 ND ND	0.28 ND ND	ND 0.19 0.14	ND ND ND
CACC restricted O_2	CACC 50-15% CACC 50-10%	ND ND	4.0 ND	ND 0.15	ND ND	ND ND

* Contains the contribution from the pilot flame.

ND = Not detected.

5 Assessment of test method applicability

5.1 Introduction

The assessment of the applicability of the different test methods has been divided into separate sections for combustible sample specimens and non-combustible sample specimens. That is because the test conditions in the first case are greatly influenced by the combustion behaviour of the test specimen, while in the second case the test conditions are more constant.

5.2 General observations

There are some observations that concerns all test methods and types of sample specimen regarding the results of the tests and the applicability of the tests, which are given below.

- There is in many cases a clear correlation between both species composition and level of toxic gas species yields between test methods when the combustion conditions are similar.
- In cases where yields differ significantly it can in most cases be explained by clear differences in test conditions.
- It is important to consider detection limits when making assessments of trends in species production. All concentration data was investigated regarding validity, and yield data close to detection limit was noted.
- HBr was in the majority of cases not detected in a test although it was confirmed that it was present in the product tested. This is most probably due to losses of HBr in the test apparatus and/or the sampling equipment. The sampling filter for the FTIR is known to be a potential source of losses. The sampling filter for the FTIR was not analysed for Br in the test programme.
- It was shown that the variability in yield results for the duplicate tests conducted with a material generally was low (as showed by the error bars for the averages in the report).
- But it has to be stressed that repeatability and reproducibility regarding sampling of the different products included in the test program was not in focus.

5.3 Combustible test specimens

The combustible sample specimen materials tested included quite different groups of materials; PMMA, a solid thermoplastic material, a variety of polymeric foams (PF1, PF2, PF3, PF4, and PF5) and two organic fibre products (OF1 and OF2).

Significant practical observations made in these tests and assessments of the method applicability are made below for the test methods evaluated.

5.3.1 Steady-state tube furnace (SSTF)

5.3.1.1 Practical observations

PMMA is used for method validation tests in the revised ISO/TS 19700 standard [5]. Tests (Fs 2, well-ventilated flaming) that passed the validation requirements in the revised standard were conducted in this programme. It was seen from initial tests that the specifications on the dimensions of the sample specimen are very important. A slightly too heavy or un-even sample bar failed the validation requirements. The pyrolysis tests conducted with PMMA (Fs 1b) did not show any measurable emissions at all.

Polymeric foams have a low density and a higher mass feeding rate (60 mm/min instead of the standard 40 mm/min) had to be used for all materials in this category. This resulted in a shorter test time and in some cases that the steady state period was too short (< 5 min). PF1 showed flame spread against the primary air flow direction and burned eventually outside of the furnace (at the rear side). Dividing the sample specimen in 50 mm pieces did not help. PF2 showed a very unsteady burning behaviour at well-ventilated conditions (Fs 2). Increasing the furnace temperature from 650 °C up to 700 °C was an improvement but did not give stable burning.

Both **organic fibre products** tested, OF1 and OF2 showed a very unsteady flaming burning behaviour, also at the higher temperature levels investigated. For OF2 it was not possible to attain continuous flaming combustion even if the furnace temperature was increased, most probably due to fire retardant treatment of the product.

5.3.1.2 Test method applicability

The SSTF was seen to offers the best means for conducting tests at pre-decided and controlled **flaming combustion** conditions.

Flaming combustion tests with PMMA gave a yield of CO_2 close to theoretical complete combustion. Species yields for flaming combustion (well-ventilated and under-ventilated) of expected composition and in plausible yield levels were found for five combustible materials out of seven tested.

Problems with the method for flaming combustion tests that were found included flame-spread against the feeding direction (one single case) and unsteady burning (a few cases). It is possible that these issues could have been handled by investigating additional settings of the method, but this was outside of the scope of the project.

In several of the **non-flaming** tests low mass-loss and low production yields were observed. The prescribed temperature for oxidative pyrolysis in ISO/TS 19700 (350°C) should probably be more adapted to the specific material tested.

5.3.2 Controlled atmosphere cone calorimeter (CACC)

5.3.2.1 Practical observations

The **load-cell** used for weighting the sample specimen during the test is located inside the CA-box. The load cell is to some extent influenced by the temperature in the box

and from the air-flow through the box. The magnitude of these influences has not been investigated here, but it was observed that the load-cell signal drifted slowly upwards (to a higher weight) during a test. This was especially significant for sample specimen with a low total mass and for sample specimen with a low mass-loss. In some tests this had the consequence that there was no useful information on mass-loss during the tests. In some cases, an assessment of the final mass could be made, in other cases there was no reliable information available.

The **influence of the CA-box** on ignition time and heat release rate was investigated by running PMMA tests with the normal cone calorimeter set-up (ISO 5660) and the set-up with the CA-box and a 21 % oxygen atmosphere. The difference in results was rather small, with a slightly longer time of ignition, t_{ign}, (~30 %) and a somewhat lower q_{max} (~10 %) for the CA-box tests. However, the standard stabilisation time in the CA-box tests was not applied in these tests which most probably would have influenced t_{ign}.

In the tests with **PMMA** the material burned very intensive in all test conditions and gave the highest HRR of the materials tested. The reason for high heat release rates (HRR) also at the oxygen deficient conditions was “afterburning”. At the 10 % O2-level the material did not ignite in the CA-box at all, instead burning took place only on top of the chimney.

The issue of the burning of combustible gases after that the effluents have left the CA-box has also earlier been mentioned as a negative characteristic of the CACC. Such afterburning leads to that the combustion conditions changes to more well-ventilated compared to that intended when conducting a test with a reduced oxygen atmosphere in the CA-box. In the tests conducted in this project it was only PMMA that showed afterburning. This means that the tests with the combustible insulating materials that were conducted at a reduced oxygen concentration at flaming conditions, burned at the intended oxygen atmosphere.

The **polymeric foams** ignited and burned at the 21 % and the 15 % O_2-levels. The exception was PF1 which did not ignite at 15 % and was then tested at 18 % instead. The materials PF2 and PF3 melted away during the stabilisation time for the oxygen to reach the set reduced level, before the shutter was removed and the test started. This must have influence the time for ignition.

The **organic fibre products** both ignited and burned at the 21 % and the 15 % O_2-levels. OF2, however, extinguished only after a short time at both levels.

5.3.2.2 Test method applicability

Species yields for **flaming combustion** were in some cases of expected composition and magnitude, but vitiation only gave limited impact in several cases.

Flaming well-ventilated combustion tests with PMMA gave a somewhat lower yield of CO_2 (compared to SSTF) and a higher yield of CO, indicating a less complete combustion.

Species yields for the flaming period of a test indicate a mix of combustion conditions in some cases. This could be an effect of that the evaluated burning period may have contained pyrolysis products also from non-flaming parts of the specimen surface.

Test with PMMA at vitiated conditions resulted in after-burning in the non-vitiated air outside of the test apparatus. After-burning was, however, not observed in any of the tests with the insulation materials. This shows that the gas-flows used for the test apparatus contained enough O_2 to avoid after-burning in these tests, but also indicates that higher equivalence ratios never were reached.

It seems that to achieve under-ventilated flaming combustion with the CACC one has to reduce the total oxygen flow through the apparatus, adjusted for each specific product tested. And as the test specimen almost in all cases shows a dynamic burning behaviour it would be difficult to achieve such conditions while avoiding after-burning.

More often than observed for the other test methods were the concentrations of gas species low, close to the detection limit or species were not detected, especially in the **non-flaming tests**. This must be an effect of the high dilution of the combustion products in this test.

5.3.3 Smoke chamber (SC)

5.3.3.1 Practical observations

In the SC 25 tests the **pilot-flame** produces CO_2 that influences the quality of the air in the test chamber and makes evaluation of the CO_2-yield from the product unreliable. Tests with only the pilot-flame showed that low amounts of CO and NO_X were additionally produced from the propane flame. These tests also showed a rather high variability in the yields produced from the flame.

In initial tests with **PMMA** using full size sample specimens the material ignited early and burned very intensive in both test modes. The oxygen in the chamber was consumed and the chamber was filled with combustible pyrolysis gases. This was a risk and in worst case, this could have led to an explosion. Hence, only single tests were conducted. In the following tests with PMMA, a smaller sample with a reduced exposed specimen area was used to reduce the risk for the operator.

In the tests with **polymeric foams**, PF2 melted away from the heat source, and this influenced the test results significantly as there was no ignition of PF2 in any of the tests modes.

There was ignition and burning of the **organic fibre products** (OF1 and OF2) in both test modes.

5.3.3.2 Test method applicability

The atmosphere in the smoke chamber in the end of a test includes most often gas species produced from different combustion conditions and does thus not represent any specific fire stage. The species composition depends on the relative length and production rate of the flaming, respective the non-flaming period.

Tests with PMMA using a reduced sized sample specimen gave a long period of flaming combustion and the resulting species yield indicated overall a rather effective well-ventilated combustion, although the oxygen concentration in the end of the test was significantly reduced.

In cases especially when a single combustion condition (well-ventilated flaming or pyrolysis) dominated the tests there were similarities in yield composition and levels compared to other test methods.

Losses of HCl were typical for the smoke chamber test. HCl was not detected or only detected in low amounts when HCl was found in higher amounts in the other tests.

5.4 Non-combustible test specimens

The non-combustible sample specimen materials tested included a range of different mineral fibre insulations (MF1-MF4).

Significant practical observations made in these tests and assessments of the method applicability are made below for the test methods evaluated.

5.4.1 Steady-state tube furnace (SSTF)

5.4.1.1 Practical observations

It was seen that the furnace temperature had a significant impact on the composition and yields of pyrolysis products. An increased temperature from 650°C to 825°C generally resulted in a higher yield of CO_2 and a lower yield of CO. The standard temperature for oxidative pyrolysis (for combustible materials), 350°C, generally produced very low yields of these gas species.

NO_X production was always higher or only occurring in high temperature tests. HCN production on the other hand, could be on an equal level or higher in low temperature tests compared to high temperature tests.

The primary air-flow rate was seen to have a significant impact (MF1 and MF4 investigated) on the test results for specific gas species. In high temperature tests (825 °C) with a low flow rate there was no production of CO and HCN at all, and also a lowered or no production of NO_X. This was the case although there was significant production of these species in the corresponding high flow rate tests. However, for CO_2 this effect was not seen for any of the two products investigated. Similarly, for SO_2, there was no significant effect on the yield from the low flow rate (only MF1 produced SO_2).

If it is the lower O_2-flow through the furnace or the longer residence time for the pyrolysis products in the hot zone in the high-temperature low flow-rate tests which gives this effect is not clear from the tests made. However, the fact that CO_2 and SO_2 are not significantly affected by the lowered flow rate indicates that it might be the residence time that is the major factor.

As noted above for combustible materials, the boat speed (material feeding rate) can be important in pyrolysis tests. A low boat speed, which gives more time for heating of the complete sample specimen, generally gave better steady-state production for the non-combustible materials.

5.4.1.2 Test method applicability

The SSTF is a useful test method for pyrolysis tests with non-combustible materials in that the temperature of the combustion zone can be adjusted to different levels and also that the air-flow rate and oxygen concentration in the combustion air can be adjusted.

However, as discussed above, the flow rate through the tube furnace seems to be an essential parameter in these tests for, *e.g.*, species such as CO, HCN and NO_X. It is thus of important that a test is adjusted to replicate the specific pyrolysis scenario that is under investigation.

5.4.2 Controlled atmosphere cone calorimeter (CACC)

5.4.2.1 Practical observations

Disturbance of the **load-cell** signal (see also 5.2.2.1) in combination with low combustible content resulted in that mass loss data was not available in parts of these test or for the complete test in some cases.

The CACC tests with non-combustible products only gave measurable production of CO in most cases, although additional products were found with the other test methods. However, significant from the time resolved gas analysis is that the peak concentration of CO always occurs early or even at the very start of the test. This shows that major gas emission can occur already in the stabilization phase of the test (stabilization to reach the set O_2-level after inserting the sample specimen, see Table 2). This has most probably resulted in an underestimation of gas yields in these tests with non-combustible materials. (One shall note that this behaviour was not seen in the tests with combustible materials.)

An additional reason for the low production measured with the CACC is most probably the high dilution in the apparatus. The flow-rate through the collection duct of the cone calorimeter is 1440 l/min and compared to the 50 l/min for the SSTF this is a ~30 times higher dilution.

5.4.2.2 Test method applicability

The CACC appears to be less suitable for testing pyrolysis gas yields from non-combustible materials such as mineral fibre products. Gas production during the stabilization time after inserting the sample specimen in the box and a high dilution of the gases seems to be limiting factors.

5.4.3 Smoke chamber (SC)

5.4.3.1 Practical observations

The concentration levels measured in the test chamber were often high compared to the two other test methods (especially the CACC), due to that the pyrolysis products are accumulated in the chamber.

In the SC 25 tests the pilot-flame produces CO_2 and low amounts of CO and NO_X that influences the quality of the air in the test chamber (see earlier discussion in 5.2.3.1).

The smoke chamber (SC) test gave in all cases the lowest concentrations of HCl of the test methods when chlorine was present in the material, and in many cases HCl was not detected at all. This is most probably due to losses of HCl in the sampling probe system of the chamber and in the sampling filter.

5.4.3.2 Test method applicability

The SC seems to be suitable for testing pyrolysis gas yields from non-combustible materials such as mineral fibre products.

The SC 50 test gave in many cases yield compositions and levels similar to the high temperature (825 °C, high flow) SSTF tests. The SC 25 test gave in many cases yield compositions and levels similar to the low temperature (650 °C) SSTF tests.

However, the pilot flame should not be used if the emission from the flame interferes with products that are under study.

6 Conclusions

The main findings on method applicability of the investigated test methods for toxic gas production are summarized in this section.

6.1 Steady-state tube furnace (SSTF)

The general conclusions on test applicability is that the SSTF offers the best means for conducting tests at pre-decided and controlled **flaming combustion conditions**.

Flaming combustion tests with PMMA gave a yield of CO_2 close to theoretical complete combustion. Species yields for flaming combustion were of expected composition and in plausible yield levels for five combustible materials out of seven tested. Problems with the method in flaming combustion tests that were found, included flame-spread against the feeding direction (one single case) and unsteady burning (a few cases). It is possible that these issues could have been handled by investigating additional settings of the method, but this was outside of the scope of the project.

In several of the non-flaming tests low mass-loss and low production yields were observed. The prescribed temperature for oxidative pyrolysis in ISO/TS 19700 (350°C) should probably be more adapted to the specific material tested.

The SSTF is a useful test method for **pyrolysis tests with non-combustible materials** in that the temperature of the combustion zone can be adjusted to different levels and also that the air-flow rate and oxygen concentration in the combustion air can be adjusted.

However, the air-flow rate through the tube furnace seems to be an essential parameter in these tests for the production of species such as CO, HCN and NO_X. It is thus of importance that a test is adjusted to replicate the specific pyrolysis scenario that is under investigation.

For using the SSTF as a standard test method for non-combustible materials further studies of the importance of the primary air-flow rate is recommended.

6.2 Controlled atmosphere cone calorimeter (CACC)

Species yields for **flaming combustion** were in some cases of expected composition and magnitude, but vitiation only gave limited impact in several cases. It seems that to achieve under-ventilated flaming combustion with the CACC one has to reduce the total oxygen flow through the apparatus, adjusted for each specific product tested. In the test conducted the flow rate through the box was the same in all cases, but the oxygen concentration was varied (21 %, 15 % respective 10 %).

Test with PMMA at vitiated conditions resulted in after-burning in the non-vitiated air outside of the test apparatus. As the test specimen almost in all cases shows a very dynamic burning behaviour (PMMA is an exception) in the cone calorimeter it would

be difficult to achieve such conditions for any longer time period while avoiding after-burning.

More often than observed for the other test methods were the concentrations of gas species low, close to the detection limit or species were not detected, especially in the **non-flaming tests**. This must be an effect of the high dilution of the combustion products in this test.

The CACC appears to be less suitable for testing pyrolysis gas yields from **non-combustible materials** such as mineral wool products. Gas production during the stabilization time after inserting the sample specimen in the box and a high dilution of the gases are limiting factors.

6.3 Smoke chamber (SC)

The atmosphere in the smoke chamber in the end of a test with a **combustible material** includes most often gas species produced from different combustion conditions and does thus not represent any specific fire stage. The species composition depends on the relative length and production rate of the flaming, respective the non-flaming period.

Tests with PMMA using a reduced sized sample specimen gave a long period of flaming combustion and the resulting species yield indicated overall a rather effective well-ventilated combustion, although the oxygen concentration in the end of the test was significantly reduced. It seems thus that under-ventilated flaming combustion is not achievable with the smoke chamber.

In cases especially when a single combustion condition (well-ventilated flaming or non-flaming) dominated the tests there were similarities in yield composition and levels compared to other test methods.

It was noted that losses of HCl were typical for the smoke chamber test. HCl was not detected or only detected in low amounts when HCl was found in higher amounts in the other tests.

The SC seems to be suitable for testing pyrolysis gas yields from **non-combustible materials** such as mineral fibre products.

The SC 50 test (high heat flow to the sample) gave in many cases yield compositions and levels similar to the high temperature (825 °C, high flow) SSTF tests. The SC 25 test (lower heat flow to the sample) gave in many cases yield compositions and levels similar to the low temperature (650 °C) SSTF tests.

7 References

[1] ISO 19706:2012, Guidelines for assessing the fire threat to people

[2] ISO 16312-1:2010, Guidance for assessing the validity of physical fire models for obtaining fire effluent toxicity data for fire hazard and risk assessment – Part 1: Criteria

[3] ISO/TR 16312-2:2007, Guidance for assessing the validity of physical fire models for obtaining fire effluent toxicity data for fire hazard and risk assessment – Part 2: Evaluation of individual physical fire models

[4] ISO 29903, Guidance for comparison of toxic gas data between different physical fire models and scales

[5] ISO/TS 19700:2016, Controlled equivalence ratio method for the determination of hazardous components of fire effluents -- Steady-state tube furnace

[6] Werrel et al., “The calculation of the heat release rate by oxygen consumption in a controlled-atmosphere cone calorimeter”, Fire Material 2014; 38:204–226

[7] ASTM E 2058-3 (2013), Standard Test Methods for Measurement of Material Flammability Using a Fire Propagation Apparatus (FPA)

[8] EN 45545-2:2013, Railway applications – Fire protection on railway vehicles – Part 2: Requirements for fire behavior of materials and components

[9] EN ISO 5659-2:2017, Plastics -- Smoke generation -- Part 2: Determination of optical density by a single-chamber test

Appendix 1. Test results for polymeric foam materials

Contents of appendix 1

Table 1.1 Summary of averaged results from the steady-state tube furnace (SSTF) for polymeric foam materials.

Product	Furnace temp (°C)	Primary air flow rate (l/min)	Sample feeding rate (mm/min)	Type of combustion	Comments	CO_2 mass-charge yield (mg/g)	CO mass-charge yield (mg/g)	HCN mass-charge yield (mg/g)	HCl mass-charge yield (mg/g)	HBr mass-charge yield (mg/g)	NO_X mass-charge yield (mg/g)	SO_2 mass-charge yield (mg/g)
PF1	350	2.0	60	Pyrolysis	SS not OK	39 ± 12	13.9 ± 2.4	0.7 ± 0.1	2.8 ± 0.3	ND	ND	38 ± 4
	650	10	-"-	Flaming	-	1974 ± 129	17 ± 3	0.23± 0.00	9.6 ± 0.4	ND	1.7 ± 0.1	43 ± 3
	825	3.2	-"-	-"-	-	976 ± 1	179 ± 12	1.3 ± 0.2	5.4 ± 0.8	ND	0.37 ± 0.05	26 ± 6
PF2	350	2.0	60	Pyrolysis	SS not OK	NQ	1.9 ± 1.1	ND	ND	ND	ND	ND
	650	10	-"-	Flaming	Single test[iii]	2020	54	ND	ND	ND	ND	ND
	650	4	-"-		Single test	2948	137	ND	ND	ND	ND	ND
	825	2	-"-	-"-	-	1862 ± 70	234 ± 35	ND	ND	ND	ND	ND
PF3	350	2.0	60	Pyrolysis	SS not OK	NQ	1.3 ± 0.1	ND	1.7 ± 0.1	ND	ND	ND
	650	10	-"-	Flaming	-	2341 ± 189	78 ± 11	ND	1.3 ± 0.5	NQ	ND	ND
	825	3.2	-"-	-"-	-	1081 ± 9	138 ± 18	ND	0.61 ± 0.02	ND	ND	ND
PF4	350	2.0	60	Pyrolysis	-	145 ± 5	3.4 ± 1.1	ND	0.7 ± 0.2	ND	ND	ND
	650	10	-"-	Flaming	Not acceptable test[i]	1991 ± 355	183 ± 37	14.7 ± 2.9	9.2 ± 0.1	ND	3.2 ± 0.4	ND
	825	3.2	-"-	-"-	-"-	953 ± 36	321 ± 20	31 ± 2	1.6 ± 0.3	ND	NQ	ND
PF5	350	2.0	60	Pyrolysis	SS not OK	53 ± 8	2.1 ± 0.4	ND	0.2 ± 0.0	ND	ND	ND
	700	10	-"-	Flaming	[ii]	2412 ± 47	34 ± 3	3.4 ± 0.2	13.3 ± 0.4	ND	2.2 ± 0.0	ND
	825	3.2	-"-	-"-	-	1168 ± 5	171 ± 10	16.7 ± 0.2	4.9 ± 0.1	ND	ND	ND

ND = Not detected; NQ = Not quantified (concentration close to limit of detection).

[i] Fire spread towards mass- and air-feed direction.
[ii] Unsteady burning.
[iii] Much too low material/air ratio.

Table 1.2 Summary of averaged results from the controlled atmosphere cone calorimeter (CACC) for polymeric foam materials.

Product	Oxygen conc. (%)	t_{ign} (s)	t_{ext} (s)	q_{max} (kW/m^2)	SPR_{max} (m^2/m^{2}s)	Toxic gases, max (ppm)				At time (s)		
PF1	21	4 ± 2	427 ± 13	82 ± 6	3.75 ± 0.01	CO2	717	±	6	209	±	6
						CO	153	±	7	428	±	25
						HCl	11	±	0.4	209	±	6
						SO2	21	±	1	209	±	6
	18	24 ± 3	236 ± 21	62 ± 1	3.09 ± 0.15	CO2	920	±	28	21	±	0.3
						CO	155	±	6	258	±	50
						HCl	16	±	0.3	45	±	12
						NOx	6	±	1	52	±	31
						SO2	45	±	5	8	±	0
	15	NI	-	28 ± 1	3.61 ± 0.27	CO2	333	±	24	553	±	38
						CO	170	±	0	90	±	13
						HCl	11	±	0.9	9	±	7
						HCN	6	±	0.1	9	±	6
						SO2	44	±	1	3	±	0.3
PF2	21[i]	168 ± 49	317 ± 43	213 ± 30	8.2 ± 1.6	CO2	3823	±	543	191	±	57
						CO	145	±	34	187	±	54
	15[i]	124 ± 54	333 ± 49	180 ± 68	4.6 ± 0.8	CO2	2684	±	443	148	±	46
						CO	209	±	41	139	±	57
	10	NI	-	16 ± 3	1.2 ± 0.3	ND						
PF3	21	41 ± 2	263 ± 3	388 ± 10	17.3 ± 0.89	CO2	5180	±	1822	203	±	0.0
						CO	253	±	142	122	±	81
	15	85 ± 9	446 ± 39	309 ± 13	13.4 ± 0.03	CO2	5072	±	16	78	±	0.0
						CO	398	±	25	84	±	6
						HCl	12			28		
	10	NI	-	40 ± 20	5.8 ± 0.97	CO	6	±	1	46	±	17

PF4	21	1	± 0	135	± 5	319	± 0	15.2	± 0.38	CO2	5475	± 158	3	± 0.0
										CO	341	± 10	16	± 13
										HCl	54	± 1.2	16	± 0
										HCN	39	± 1	16	± 13
										NOx	33	± 1	3	± 0
	15[i]	9	± 8	172	± 18	253	± 34	9.3	± 1.7	CO2	3926	± 310	7	± 6
										CO	431	± 22	7	± 6
										HCl	35	± 4	37	± 11
										HCN	54	± 3	24	± 14
										NOx	24	± 2	12	± 11
	10	NI		-		26	± 1	10.5	± 0.3	CO2	527	± 8	7	± 6.3
										CO	58	± 4	614	± 0
										HCN	7	± 1	563	± 0
PF5	21[i]	1	± 0	695	± 63	114	± 14	8.1	± 0.2	CO2	1285	± 397	96	± 105
										CO	178	± 96	846	± 38
										HCl	16	± 4	100	± 94
										HCN	10	± 4	579	± 375
										NOx	8	± 2	108	± 122
	15[i]	219	± 120	534	± 18	7	± 9	8.4	± 0.2	CO2	485	± 214	273	± 146
										CO	127	± 13	523	± 143
										HCl	7	± 2.0	242	± 139
										HCN	9	± 1	302	± 218
										NOx	6		66	
	10	NI		-		29	± 5	5.7	± 0.1	CO	75	± 1	605	± 4
										HCN	7	± 0	98	± 35

[i] Triplicate tests. ND = no gases detected.

Table 1.3 Summary of averaged results from the smoke chamber (SC) for polymeric foam materials.

Product	Irradiance level (kW/m^2)	Ds max	$t_{DS\ max}$ (s)	Ignition (s)	CIT_G 240s	Toxic gases	CIT_G 480s	Toxic gases	CITG Ds max	Toxic gases
PF1	25, pilot flame	11 ± 2	614 ± 9	4 ± 1	0.057 ± 0.003	CO2 CO SO2	0.095 ± 0.005	CO2 CO SO2	0.127 ± 0.023	CO2 CO HCN
	50	95 ± 7	254 ± 4	NI	0.164 ± 0.002	CO2 CO HCN SO2	0.260 ± 0.004	CO2 CO HCN SO2	0.171 ± 0.001	CO2 CO HCN SO2
PF2	25, pilot flame	51 ± 7	1200 ± 0	NI	0.004 ± 0.000	CO2	0.008 ± 0.000	CO2	0.023 ± 0.001	CO2 CO
	50	253 ± 0	758 ± 92	NI	0.000 ± 0.000	-	0.003 ± 0.001	CO	0.006 ± 0.000	CO
PF3	25, pilot flame[i]	517 ± 232	845 ± 196	627 ± 162	0.003 ± 0.001	CO2 CO	0.013 ± 0.005	CO2 CO	0.063 ± 0.027	CO2 CO
	50	471 ± 83	741 ± 84	NI	0.001 ± 0.000	CO	0.005 ± 0.001	CO	0.011 ± 0.001	CO2 CO
PF4	25, pilot flame	232 ± 7	86 ± 3	1 ± 0	0.084 ± 0.004	CO2 CO NOx	0.092 ± 0.004	CO2 CO NOx	0.112 ± 0.011	CO2 CO HCN NOx
	50[ii]	336 ± 9	78 ± 7	3 ± 1.3	0.235 ± 0.124	CO2 CO HCN NOx	0.320 ± 0.163	CO2 CO HCN NOx	0.253 ± 0.134	CO2 CO HCN NOx
PF5	25, pilot flame	22 ± 2	86 ± 6	1 ± 0	0.010 ± 0.001	CO2 CO	0.019 ± 0.000	CO2 CO	0.006 ± 0.000	CO2 CO
	50	138 ± 2	290 ± 33	NI	0.114 ± 0.009	CO2 CO HCN	0.210 ± 0.008	CO2 CO HCN	0.131 ± 0.021	CO2 CO HCN

[i] Three tests were performed due to no ignition of specimen during the first test. [ii] A third test was conducted due to not repeatable CIT-values.

Table 1.4 Mass-loss yield (MLY) reported as mean value (mv) and mean deviation (md) of repeated tests.

Product	Gas	Steady-state tube furnace (SSTF)						Smoke chamber (SC)				Controlled atmosphere cone calorimeter (CACC)									
		650°C		825°C		350°C		25 kW/m², pilot flame		50 kW/m²		21% flaming		21% complete test		18% flaming		18% complete test		15% non-flaming	
		MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)
PF1	CO_2	2287	124	1498	19.0	229	70	4010	167	1261	59.7	1668	12.8	2100	91	1448	17.0	1459	12.4	732	25
	CO	19.6	3.8	275	16	81	10	306	8.1	356	5.4	93	0.5	208	8.7	85	9.1	221	2.0	300	10
	HCl	11.2	0.28	8.29	1.3	16.3	1.9	0.97	0.97	ND	-	19.4	0.40	15.6	0.62	22	0.4	13.9	0.71	8.64	0.75
	HCN	0.27	0.001	1.91	0.29	4.36	0.51	5.6	0.09	4.97	0.08	ND	-	ND	-	ND	-	ND	-	6.44	0.48
	NO_X	2.01	0.12	0.57	0.07	ND	-	4.7	0.48	0.35	0.35	5.21	0.53	4.40	0.63	5.22	0.13	2.92	0.004	ND	-
	SO_2	50	2.9	39	8.1	222	22	56	1.8	42	0.4	70	2.4	68	2.1	80	1.2	72	0.6	70	5.4

Table 1.4, cont. Mass-loss yield (MLY) reported as mean value (mv) and mean deviation (md) of repeated tests.

Product	Gas	Steady-state tube furnace (SSTF)						Smoke chamber (SC)				Controlled atmosphere cone calorimeter (CACC)									
		650°C		825°C		350°C		25 kW/m², pilot flame		50 kW/m²		21% flaming		21% complete test		15% flaming		15% complete test		10% non-flaming	
		MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)
PF2	CO_2	2952	837	2351	87.0	ND	-	30656	5521	118	11	2600[b]	27.7	2144[b]	86.6	2746	208	1914	311	ND	-
	CO	116	60	295	44	38	20	143	8.3	80	2.4	55[b]	2.8	49[b]	5.5	127	16	88	16	ND	-
	HCl	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	HCN	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	NO_X	ND	-	ND	-	ND	-	34	7.4	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	SO_2	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
PF3	CO_2	2890	192	1277	34.9	27	27	4578[a]	136	72	15	2117	76.4	2306	34	2072	106	2104	31	ND	-
	CO	96	12	163	19	34	1.7	68[a]	5.5	54	12	57	2.9	69	1.0	101	7.7	104	2.5	0.55	0.11
	HCl	1.57	0.58	0.72	0.03	44	0.11	ND	-	ND	-	ND	-	ND	-	0.46	0.10	1.22	0.31	ND	-
	HCN	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	NO_X	ND	-	ND	-	ND	-	1.60[a]	0.60	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	SO_2	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-

PF4[c]	CO_2	-	-	-	-	375	12	5370	32.2	1517[a]	134	1279	30.9	1345	57.8	1122[b]	86.2	1216[b]	2.75b	220	4.6
	CO	-	-	-	-	8.78	2.8	56	4.6	230[a]	19	48	0.76	241	0.15	80[b]	7.1	162[b]	8.3b	62	0.9
	HCl	-	-	-	-	1.79	0.41	0.75	0.75	1.39[a]	0.24	10.9	0.31	11.4	0.15	10.1[b]	0.83	11.1[b]	0.64b	ND	-
	HCN	-	-	-	-	ND	-	4.82	0.30	17.9[a]	0.42	4.76	0.07	17.2	0.80	8.38[b]	0.70	15.5[b]	0.88b	5.48	0.49
	NO_X	-	-	-	-	ND	-	8.65	0.55	6.20[a]	0.10	5.14	0.11	5.13	0.05	4.84[b]	0.48	3.96[b]	2.17b	ND	-
	SO_2	-	-	-	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
PF5[d]	CO_2	2764	76.0	1840	30.2	251	52	7226	212	831	120	2114[b]	262	2256[b]	148	2906[b]	625	829[b]	210	-	-
	CO	39	4.2	269	10.2	9.86	1.5	176	7.9	509	59	179[b]	18	212[b]	18	618[b]	140	242[b]	28	-	-
	HCl	15.2	0.30	7.74	0.04	1.16	0.12	ND	-	ND	-	23[b]	1.9	23[b]	0.47	31[b]	6.2	10.9[b]	1.7	-	-
	HCN	3.95	0.25	26	0.19	ND	-	12.5	0.90	36	4.1	9.74[b]	1.0	11.3[b]	1.1	36[b]	9.4	15.4[b]	3.0	-	-
	NO_X	2.58	0.07	0.64	0.01	ND	-	6.00	0.30	ND	-	8.54[b]	0.78	5.80[b]	3.9	ND	-	ND	-	-	-
	SO_2	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	-	-

[a] Triplicate tests were conducted. One of the tests was discarded as it was clearly deviating.

[b] Triplicate tests were conducted.

[c] The results from SSTF 650 and SSTF 825 were not acceptable according to ISO/TS 19700.

[d] A furnace temperature of 700 °C (instead of 650 °C) was used in the well-ventilated SSTF tests with PF5.

Table 1.5 Mass-charge yield (MCY) reported as mean value (mv) and mean deviation (md) of repeated tests.

Product	Gas	Steady-state tube furnace (SSTF)						Smoke chamber (SC)				Controlled atmosphere cone calorimeter (CACC)									
		650°C		825°C		350°C		25 kW/m², pilot flame		50 kW/m²		21% flaming		21% complete test		18% flaming		18% complete test		15% non-flaming	
		MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)
PF1	CO_2	1974	129	976	1.3	39	10	2391	99.3	1211	58.4	765	3.3	1291	6.1	346	2.3	700	0.6	328	1.9
	CO	17	3.4	179	12	13.9	2.4	184	20.1	342	4.9	43	0.3	128	0.42	20	2.5	106	2.2	134	0.63
	HCl	9.64	0.35	5.39	0.78	2.80	0.34	0.53	0.53	ND	-	8.90	0.08	9.60	0.01	5.20	0.01	6.65	0.28	3.87	0.23
	HCN	0.23	0.004	1.25	0.21	0.75	0.09	3.33	0.33	4.77	0.07	ND	-	ND	-	ND	-	ND	-	2.89	0.13
	NO_X	1.74	0.12	0.37	0.05	ND	-	2.80	0.05	0.35	0.35	2.39	0.27	2.72	0.49	1.25	0.01	1.40	0.02	ND	-
	SO_2	43	3.0	26	5.6	38	3.7	33.6	1.7	40	0.4	32	0.7	42	0.3	19.0	0.05	345	0.01	31	1.6

Table 1.5, cont. Mass-charge yield (MCY) reported as mean value (mv) and mean deviation (md) of repeated tests.

Product	Gas	Steady-state tube furnace (SSTF)						Smoke chamber (SC)				Controlled atmosphere cone calorimeter (CACC)									
		650°C		825°C		350°C		25 kW/m², pilot flame		50 kW/m²		21% flaming		21% complete test		15% flaming		15% complete test		10% non-flaming	
		MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)
PF2	CO_2	2484	464	1862	70	ND	-	6064	34.7	117	11	1930[b]	56.6	2104[b]	89.9	1779	275	1856	323	ND	-
	CO	96	42	234	35	1.89	1.11	28.9	3.7	80	1.8	41[b]	2.8	48[b]	5.5	82	20	85	20	ND	-
	HCl	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	HCN	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	NO_X	ND	-	ND	-	ND	-	6.69	0.22	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	SO_2	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
PF3	CO_2	2341	189	1081	8.55	1.93	0.000	4359[a]	50	65	8.5	2164	0.11	1942	74.9	1748	91.7	2001	21.6	ND	-
	CO	78	10	138	18	1.28	0.15	65[a]	4.1	50	7.1	64	0.04	52	2.8	85	6.7	99	0.17	0.45	0.10
	HCl	1.28	0.49	0.61	0.02	1.67	0.11	ND	-	ND	-	ND	-	ND	-	0.39	0.09	1.16	0.27	ND	-
	HCN	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	NO_X	ND	-	ND	-	ND	-	1.53[a]	0.55	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	SO_2	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-

PF4[c]	CO_2	-	-	-	-	145	5.0	3107	62.7	846[a]	25	969	19	1117	10.3	718[b]	82	862[b]	12	142	3.3
	CO	-	-	-	-	3.40	1.1	32.4	2.2	129[a]	18	36	1.0	200	6.6	51[b]	7.2	115[b]	5.3	40	0.5
	HCl	-	-	-	-	0.69	0.16	0.44	0.44	0.78[a]	0.18	8.29	0.13	9.49	0.19	6.50[b]	0.86	7.89[b]	0.54	ND	-
	HCN	-	-	-	-	ND	-	2.79	0.21	10.0[a]	0.35	3.61	0.11	14.3	0.18	5.39[b]	0.72	11.0[b]	0.57	3.54	0.31
	NO_X	-	-	-	-	ND	-	5.01	0.37	3.45[a]	0.15	3.90	0.09	4.27	0.10	3.08[b]	0.24	2.81[b]	1.5	ND	-
	SO_2	-	-	-	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
PF5[d]	CO_2	2412	47.2	1168	4.76	53	7.6	2454	94.5	698	31.6	1027[b]	83.6	1113[b]	73.9	249[b]	120	333[b]	85	ND	-
	CO	34	3.4	171	10	2.12	0.45	60	2.1	428	8.5	87[b]	5.3	105[b]	7.6	47[b]	20	98[b]	10	63	0.19
	HCl	13.3	0.37	4.92	0.13	0.25	0.04	ND	-	ND	-	11.0[b]	0.83	11.4[b]	0.73	2.74[b]	1.3	4.38[b]	0.57	3.16	0.25
	HCN	3.44	0.19	16.7	0.22	ND	-	4.24	0.27	31	0.5	4.72[b]	0.23	5.57[b]	0.35	3.44[b]	0.19	2.72[b]	0.84	6.20	1.3
	NO_X	2.25	0.04	0.405	0.015	ND	-	2.03	0.13	ND	-	4.16[b]	0.41	2.87[b]	1.9	2.25[b]	0.04	ND	-	ND	-
	SO_2	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-

[a] Triplicate tests were conducted. One of the tests was discarded as it was clearly deviating.

[b] Triplicate tests were conducted.

[c] The results from SSTF 650 and SSTF 825 were not acceptable according to ISO/TS 19700.

[d] A furnace temperature of 700 °C (instead of 650 °C) was used in the well-ventilated SSTF tests with PF5.

Table 1.6 Surface-charge yield (SCY) reported as mean value (mv) and mean deviation (md) of repeated tests.

Product	Gas	Smoke chamber (SC)				Controlled atmosphere cone calorimeter (CACC)									
		25 kW/m², pilot flame		50 kW/m²		21% flaming		21% complete test		18% flaming		18% complete test		15% non-flaming	
		SCY (mv)	SCY (md)	SCY (mv)	SCY (md)	SCY (mv)	SCY (md)	SCY (mv)	SCY (md)	SCY (mv)	SCY (md)	SCY (mv)	SCY (md)	SCY (mv)	SCY (md)
PF1	CO_2	2242950	67708	1120443	42587	1277894	5407	2155168	28513	582718	587	1180036	7734	547686	1148
	CO	172111	16872	316299	7766	71294	155	213897	2515	34428	4090	178778	4346	224089	703
	HCl	505	500	ND	-	14856	255	16036	156	8771	40	11199	409	6453	332
	HCN	3121	275	4419	109	ND	-	ND	-	ND	-	ND	-	4812	183
	NO_X	2626	73.2	332	330	3992	421	4539	785	2102	26	2359	38	ND	-
	SO_2	31543	1232	37390	8.2	53403	1672	70104	49	32001	93	58391	356	51961	2200

Table 1.6, cont. Surface-charge yield (SCY) reported as mean value (mv) and mean deviation (md) of repeated tests.

Product	Gas	Smoke chamber (SC)				Controlled atmosphere cone calorimeter (CACC)									
		25 kW/m², pilot flame		50 kW/m²		21% flaming		21% complete test		15% flaming		15% complete test		10% non-flaming	
		SCY (mv)	SCY (md)	SCY (mv)	SCY (md)	SCY (mv)	SCY (md)	SCY (mv)	SCY (md)	SCY (mv)	SCY (md)	SCY (mv)	SCY (md)	SCY (mv)	SCY (md)
PF2	CO_2	1966289	3094	37491	3501	1141275[b]	33924	1243780[b]	49325	1038581	150686	1083784	179009	ND	-
	CO	9368	1140	25590	682	24235[b]	1595	28651[b]	3182	48112	8382	49634	9175	ND	-
	HCl	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	HCN	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	NO_X	2170	86	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	SO_2	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
PF3	CO_2	4896410[a]	112610	71670	11990	3773294	152113	4205076	7591	3386924	170679	3878887	49845	ND	-
	CO	73168[a]	5425	54492	9750	101221	5550	125295	300	165466	12540	191845	732	885	190
	HCl	ND	-	ND	-	ND	-	ND	-	757	170	2239	513	ND	-
	HCN	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	NO_X	1721[a]	634	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	SO_2	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-

PF4[c]	CO_2	2879254	61746	1182146[a]	95676	1603494	33034	1848685	15805	1187472[b]	132106	1426551[b]	15690	235142	5439
	CO	30052	1996	179158[a]	16483	59622	1709	331537	11209	84729[b]	11630	189871[b]	9298	66042	789
	HCl	408	410	1085[a]	196	13711	225	15700	328	10745[b]	1386	13051[b]	888	ND	-
	HCN	2587	199	13964[a]	219	5966	178	23620	289	8910[b]	1160	18160[b]	992	5857	515
	NO_X	4647	349	4836[a]	14	6445	152	7059	168	5098[b]	383	4650[b]	2540	ND	-
	SO_2	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
PF5[d]	CO_2	2505965	81963	712057	24014	1728850[b]	146514	1874074[b]	133680	420452[b]	209380	560684[b]	146750	ND	-
	CO	61186	2528	436846	3597	145788[b]	9485	175990[b]	13416	79961[b]	26640	164199[b]	18269	106153	41
	HCl	ND	-	ND	-	18487[b]	1480	19173[b]	1317	4616[b]	2160	7359[b]	992	5307	407
	HCN	4328	297	31176	150	7941[b]	412	9376[b]	614	4573[b]	1430	10408[b]	2043	7851	159
	NO_X	2078	122	ND	-	7012[b]	729	4827[b]	3220	ND	-	ND	-	ND	-
	SO_2	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-

[a] Triplicate tests were conducted. One of the tests was discarded as it was clearly deviating.

[b] Triplicate tests were conducted.

[c] The results from SSTF 650 and SSTF 825 were not acceptable according to ISO/TS 19700.

[d] A furnace temperature of 700 °C (instead of 650 °C) was used in the well-ventilated SSTF tests with PF5.

Appendix 2. Test results for organic fibre materials

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Table 2.1 Summary of averaged results from the steady-state tube furnace (SSTF) for organic fibre materials.

Product	Furnace temp (°C)	Primary air flow rate (l/min)	Sample feeding rate (mm/min)	Type of combustion	Comments	CO_2 mass-charge yield (mg/g)	CO mass-charge yield (mg/g)	HCN mass-charge yield (mg/g)	HCl mass-charge yield (mg/g)	HBr mass-charge yield (mg/g)	NO_X mass-charge yield (mg/g)	SO_2 mass-charge yield (mg/g)
OF1	350	2.0	60	Pyrolysis	SS not OK	116 ± 11	52 ± 4	0.32 ± 0.02	ND	ND	ND	17.3 ± 0.3
	650	10	-"-	Flaming	Triplicate tests[i]	1851 ± 51	8.4 ± 4.6	0.60 ± 0.10	ND	ND	2.0 ± 0.4	23 ± 1
	825	3.2	-"-	-"-	-	1173 ± 27	47 ± 2	0.99 ± 0.06	ND	ND	0.21 ± 0.02	16.8 ± 0.0
OF2	350	2.0	60	Pyrolysis	SS not OK	146 ± 3	59 ± 1	ND	ND	ND	0.35	ND
	650	10	-"-	Flaming	Not acceptable test[i]	502	16.5	ND	ND	ND	0.35	ND
	700	-"-	-"-	-"-	-"-	1441	10.5	ND	ND	ND	1.07	ND
	825	-"-	-"-	-"-	-"-	1549	0.44	ND	ND	ND	0.97	ND
	825	3.2	-"-	-"-	-"-	1139 ± 0	9.4 ± 1.6	ND	ND	ND	0.32 ± 0.00	ND

ND = Not detected.

[i] Unsteady burning.

Table 2.2 Summary of averaged results from the controlled atmosphere cone calorimeter (CACC) for organic fibre materials.

Product	Oxygen conc. (%)	t_{ign} (s)	t_{ext} (s)	q_{max} (kW/m^2)	SPR_{max} (m^2/m^{2}s)	Toxic gases, max (ppm)		At time (s)	
OF1	21	1 ± 0	438 ± 38	201 ± 9	2.2 ± 0.2	CO2	2579 ± 51	3	± 0
						CO	155 ± 10	741	± 75
						NOx	8 ± 1	3	± 0
						SO2	44 ± 1	3	± 0
	15	27 ± 15	301 ± 89	96 ± 13	18.3 ± 2.4	CO2	1550 ± 220	48	± 20
						CO	306 ± 99	167	± 161
						NOx	7 ± 1	42	± 14
						SO2	40 ± 3	10	± 5
	10	NI	-	32 ± 1	15.4 ± 0.4	CO2	217 ± 18	426	± 24
						CO	356 ± 12	1	± 0
						SO2	45 ± 4	1	± 0
OF2	21	1 ± 0	51 ± 6	155 ± 4	1.4 ± 0.2	CO2	1790 ± 38	3	± 0
						CO	116 ± 7	403	± 13
	15[i]	6 ± 4	126 ± 29	132 ± 36	3.6 ± 2.1	CO2	1784 ± 275	7	± 5
						CO	207 ± 17	132	± 22
	10	NI	-	35 ± 1	13.8 ± 0.3	CO2	241 ± 21	1	± 0
						CO	363 ± 7	1	± 0

[i] Triplicate tests.

Table 2.3 Summary of averaged results from the smoke chamber (SC) for organic fibre materials.

Product	Irradiance level (kW/m^2)	Ds max	$t_{DS\ max}$ (s)	Ignition (s)	CIT_G 240s	Toxic gases	CIT_G 480s	Toxic gases	CITG Ds max	Toxic gases
OF1	25, pilot flame	37 ± 11	580 ± 53	1 ± 0	0.108 ± 0.022	CO2 CO SO2	0.179 ± 0.007	CO2 CO SO2	0.192 ± 0.007	CO2 CO NOx SO2
	50	30 ± 1	892 ± 293	7 ± 1.5	0.141 ± 0.014	CO2 CO NOx SO2	0.179 ± 0.012	CO2 CO NOx SO2	0.234 ± 0.034	CO2 CO HCN SO2
OF2	25, pilot flame	18 ± 1	263 ± 1	1 ± 0	0.047 ± 0.000	CO2 CO	0.076 ± 0.003	CO2 CO	0.051 ± 0.001	CO2 CO
	50	21 ± 5	1200 ± 0	3 ± 0.5	0.047 ± 0.002	CO2 CO	0.089 ± 0.003	CO2 CO	0.096 ± 0.004	CO2 CO

Table 2.4a Mass-loss yield (MLY) reported as mean value (mv) and mean deviation (md) of repeated tests.

Product	Gas	Steady-state tube furnace (SSTF)						Smoke chamber (SC)				Controlled atmosphere cone calorimeter (CACC)									
		650°C		825°C		350°C		25 kW/m^2, pilot flame		50 kW/m^2		21% flaming		21% complete test		15% flaming		15% complete test		10% non-flaming	
		MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)
OF1	CO_2	2020	60.3	1415	1.47	233	1.6	1693[b]	96.0	1069	442	1039	6.4	1351	26.0	727	65	944	440	242	22
	CO	9.14	4.9	57	1.6	105	1.0	134[b]	7.5	107	40	13.9	3.6	66	2.9	88	30	51	10	130	1.8
	HCl	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	HCN	0.65	0.10	1.19	0.05	0.64	0.02	1.55[b]	0.13	1.29	0.46	ND	-	ND	-	ND	-	ND	-	ND	-
	NO_X	2.21	0.46	*0.25*[c]	*0.01*	ND	-	1.63[b]	0.18	1.27	0.51	2.03	0.03	1.98	0.01	2.00	0.26	2.86	1.3	ND	-
	SO_2	26	1.1	20	0.4	35	2.3	13.5[b]	0.44	11.5	4.4	24	1.3	24	1.9	25	0.9	30	10	27.5	2.0

[b] Triplicate tests were conducted.

[c] Species detected but below MDL.

Table 2.4b Mass-loss yield (MLY) reported as mean value (mv) and mean deviation (md) of repeated tests.

Product	Gas	Steady-state tube furnace (SSTF)							Smoke chamber (SC)				Controlled atmosphere cone calorimeter (CACC)									
		650°C [d]	700°C [d]	825°C [d] 10 l/min	825°C 3.2 l/min		350°C		25 kW/m², pilot flame		50 kW/m²		21% flaming		21% complete test		15% flaming		15% complete test		10% non-flaming	
		MLY (mv)	MLY (mv)	MLY (mv)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)
OF2	CO_2	646	1808	1967	1554	8.34	303	1.2	2184	35.3	696	2.0	605	83	1250	12.5	459[b]	120	776 [b]	76	393	7.6
	CO	21	13.1	0.55	12.8	2.1	121	0.57	81	4.3	117	3.3	3.92	0.70	95	5.7	50 [b]	20	195 [b]	15	238	5.3
	HCl	ND	ND	ND	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	HCN	ND	ND	ND	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	NO_X	0.46	1.34	1.23	0.44	0.001	ND	-	0.73	0.03	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	SO_2	ND	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-

[b] Triplicate tests were conducted.
[d] Only single tests were conducted.

Table 2.5a Mass-charge yield (MCY) reported as mean value (mv) and mean deviation (md) of repeated tests.

Product	Gas	Steady-state tube furnace (SSTF)						Smoke chamber (SC)				Controlled atmosphere cone calorimeter (CACC)									
		650°C		825°C		350°C		25 kW/m², pilot flame		50 kW/m²		21% flaming		21% complete test		15% flaming		15% complete test		10% non-flaming	
		MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)
OF1	CO_2	1851	51.5	1173	27.3	116	11	2104	99.6	1325	564	791	24	1073	8.88	417	100	534	57	171	16
	CO	8.43	4.6	47	2.4	52	3.9	167	9.1	132	49	10.7	3.0	53	3.8	24	0.6	64	20	92	0.8
	HCl	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	HCN	0.60	0.1	0.99	0.06	0.32	0.02	1.93	0.16	1.59	0.57	ND	-	ND	-	ND	-	ND	-	ND	-
	NO_X	2.03	0.41	*0.21*[c]	*0.02*	ND	-	2.03	0.25	1.59	0.65	1.55	0.06	1.57	0.05	1.26	0.31	1.47	0.22	ND	-
	SO_2	23	0.7	16.8	0.016	17.3	0.31	16.8	0.72	14.4	5.5	18.0	1.4	19.0	2.0	13.2	2.5	18.1	0.99	19.5	1.3

[c] Species detected but below MDL.

Table 2.5b Mass-charge yield (MCY) reported as mean value (mv) and mean deviation (md) of repeated tests.

Product	Gas	Steady-state tube furnace (SSTF)							Smoke chamber (SC)				Controlled atmosphere cone calorimeter (CACC)									
		650°C [d]	700°C [d]	825°C [d] 10 l/min	825°C 3.2 l/min		350°C		25 kW/m², pilot flame		50 kW/m²		21% flaming		21% complete test		15% flaming		15% complete test		10% non-flaming	
		MCY (mv)	MCY (mv)	MCY (mv)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)
OF2	CO_2	502	1441	1549	1139	0.09	146	2.9	2874	50.0	917	1.2	141	12	865	10	187	14	462	32	189	4.7
	CO	16.5	10.5	0.44	9.36	1.6	59	1.2	106	5.8	155	5.0	0.91	0.12	66	5.4	19.0	7.1	117	13	114	1.9
	HCl	ND	ND	ND	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	HCN	ND	ND	ND	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	NO_X	0.35	1.07	0.97	0.32	0.001	ND	-	0.96	0.04	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	SO_2	ND	ND	ND	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-

[d] Only single tests were conducted.

Table 2.6 Surface-charge yield (SCY) reported as mean value (mv) and mean deviation (md) of repeated tests.

Product	Gas	Smoke chamber (SC)				Controlled atmosphere cone calorimeter (CACC)									
		25 kW/m^2, pilot flame		50 kW/m^2		21% flaming		21% complete test		15% flaming		15% complete test		10% non-flaming	
		SCY (mv)	SCY (md)	SCY (mv)	SCY (md)	SCY (mv)	SCY (md)	SCY (mv)	SCY (md)	SCY (mv)	SCY (md)	SCY (mv)	SCY (md)	SCY (mv)	SCY (md)
OF1	CO_2	3287917	131621	2107748	897246	2159583	71867	2927721	34600	1102196	289302	1409909	173196	464783	43437
	CO	261664	20506	213580	77230	29108	8290	143832	10755	63270	442	168781	50137	250450	2416
	HCl	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	HCN	3019	321	2575	902	ND	-	ND	-	ND	-	ND	-	ND	-
	NO_X	3185	408	2526	909	4218	178	4286	157	3339	866	3876	630	ND	-
	SO_2	26286	1332	23071	8695	49222	3945	51888	5742	34937	7114	47822	3387	52860	3610
OF2	CO_2	3475486	53641	1109817	2500	291838	24346	1784985	20468	386439	25940	957210	68622	388372	9267
	CO	128179	6728	187167	6211	1887	237	136350	11080	39268	14470	242045	26762	234590	4129
	HCl	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	HCN	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	NO_X	1165	48	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	SO_2	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-

Appendix 3. Test results for mineral fibre materials

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Table 3.1 Summary of averaged results from the steady-state tube furnace (SSTF) for mineral fibre materials.

Product	Furnace temp (°C)	Primary air flow rate (l/min)	Sample feeding rate (mm/min)	Type of combustion	Comments	CO_2 mass-charge yield (mg/g)	CO mass-charge yield (mg/g)	HCN mass-charge yield (mg/g)	HCl mass-charge yield (mg/g)	HBr mass-charge yield (mg/g)	NO_X mass-charge yield (mg/g)	SO_2 mass-charge yield (mg/g)
MF1	350	2.0	40	Pyrolysis	-	NQ	2.0 ± 0.1	ND	ND	ND	ND	NQ
	650	10	60	-"-	Single test, SS not OK	2.9	4.6	0.41	ND	ND	ND	NQ
	-"-	-"-	40	-"-	-	61 ± 14	13.7 ± 0.6	1.4 ± 0.1	ND	ND	ND	3.4 ± 0.3
	825	10	-"-	-"-	-	78 ± 3	13.8 ± 0.4	1.1 ± 0.1	ND	ND	1.4 ± 0.1	4.3 ± 0.3
	-"-	3.2	-"-	-"-	-	103 ± 7	ND	ND	ND	ND	ND	3.3 ± 0.2
	-"-	3.2 (5% O_2)	-"-	-"-	5% O_2 in primary air	90 ± 18	ND	ND	ND	ND	ND	5.2 ± 0.7
MF2	350	2.0	40	Pyrolysis		22 ± 2	2.7 ± 0.2	ND	ND	ND	ND	ND
	650	10	60	-"-	Single test	19.1	5.1	ND	ND	ND	ND	ND
	650	10	40	-"-		66 ± 7	14.0 ± 2.0	ND	ND	ND	ND	ND
	825	10	-"-	-"-		99 ± 16	9.3 ± 0.3	ND	ND	ND	ND	ND
MF3	350	2.0	40	Pyrolysis	-	NQ	1.2 ± 0.1	0.30 ± 0.04	ND	ND	ND	ND
	650	10	60	-"-	Single test	36	6.9	0.44	ND	ND	0.91	ND
	650	10	40	-"-	-	36 ± 4	6.5 ± 0.6	0.31 ± 0.04	ND	ND	1.1 ± 0.2	ND
	825	10	-"-	-"-	-	49 ± 2	3.4 ± 0.2	0.24 ± 0.02	ND	ND	0.79 ± 0.00	ND
MF4	350	2.0	40	Pyrolysis	-	6.9 ± 1.8	2.6 ± 0.1	0.28 ± 0.05	ND	ND	ND	ND
	650	10	60	-"-	Single test	19.4	3.0	0.14	ND	ND	0.19	ND
	-"-	-"-	40	-"-	-	73 ± 7	11.1 ± 0.6	0.3 ± 0.00	ND	ND	0.9 ± 0.1	ND
	825	10	-"-	-"-	-	99 ± 6	2.8 ± 0.4	0.13 ± 0.01	ND	ND	0.61 ± 0.02	ND
	-"-	3.2	-"-	-"-	-	89 ± 7	ND	ND	ND	ND	0.19 ± 0.01	ND
	-"-	3.2 (5% O_2)	-"-	-"-	5% O_2 in primary air	79 ± 4	NQ	ND	ND	ND	0.14 ± 0.01	ND

ND = Not detected; NQ = Not quantified (concentration close to limit of detection).

Table 3.2 Summary of averaged results from the controlled atmosphere cone calorimeter (CACC) for mineral fibre materials.

Product	Oxygen conc. (%)	t_{ign} (s)	t_{ext} (s)	q_{max} (kW/m^2)	SPR_{max} (m^2/m^{2}s)	Toxic gases, max (ppm)		At time (s)
MF1	21	NI	-	7 ± 1	0.2 ± 0.0	CO	30 ± 4	3 ± 0
	15	NI	-	27 ± 3	0.2 ± 0.0	CO	19 ± 2	4 ± 1
	10	NI	-	23 ± 0	0.1 ± 0.0	CO	12 ± 2	1 ± 0
MF2	21	NI	-	8 ± 2	0.2 ± 0.0	CO2	187 ± 6	3 ± 0
						CO	42 ± 1	3 ± 0
	15	NI	-	16 ± 1	0.1 ± 0.1	CO	17 ± 1	3 ± 0
	10	NI	-	31 ± 3	0.2 ± 0.0	CO	22 ± 1	1 ± 0
MF3	21	NI	-	6 ± 0	0.1 ± 0.0	CO	11 ± 0.5	3 ± 0
	15	NI	-	27 ± 8	0.1 ± 0.0	CO	18 ± 1	367 ± 306
	10	NI	-	29 ± 3	0.1 ± 7.1	CO	24 ± 2	341 ± 340
MF4	21	NI	-	8 ± 0	0.1 ± 0.1	CO	48 ± 0.2	3 ± 0
						HCN	5	4
	15	NI	-	19 ± 2	0.2 ± 0.0	CO	38 ± 1	3 ± 0
						HCN	5	3
	10	NI	-	34 ± 0	0.2 ± 0.0	CO	32 ± 0.2	13 ± 0
						HCN	6 ± 0.2	1 ± 0

Table 3.3 Summary of averaged results from the smoke chamber (SC) for mineral fibre materials.

Product	Irradiance level (kW/m^2)	Ds max	$t_{DS\ max}$ (s)	Ignition (s)	CIT_G 240s	Toxic gases	CIT_G 480s	Toxic gases	CITG Ds max	Toxic gases
MF1	25, pilot flame	2 ± 0	28 ± 0	NI	0.002 ± 0.001	CO2	0.006 ± 0.000	CO2	0.007 ± 0.007	CO2
	50	9 ± 0	995 ± 148	NI	0.002 ± 0.000	CO	0.002 ± 0.000	CO	0.004 ± 0.000	CO
MF2	25, pilot flame	2 ± 0	1111 ± 8	NI	0.003 ± 0.000	CO2	0.006 ± 0.000	CO2 CO	0.012 ± 0.001	CO2 CO
	50	2 ± 0	30 ± 1	NI	0.003 ± 0.000	CO	0.004 ± 0.000	CO2 CO	0.001 ± 0.001	CO[i]
MF3	25, pilot flame	1 ± 0	851 ± 40	NI	0.004 ± 0.000	CO2	0.009 ± 0.000	CO2 CO	0.059 ± 0.004	CO2 CO NOx
	50	1 ± 0	459 ± 426	NI	0.021 ± 0.017	CO NOx	0.006 ± 0.000	CO2 CO	0.004 ± 0.003	CO2 CO
MF4	25, pilot flame	1 ± 0	27 ± 4	NI	0.005 ± 0.000	CO2 CO	0.010 ± 0.000	CO2 CO	0.000 ± 0.000	-
	50	2 ± 0	25 ± 3	NI	0.007 ± 0.000	CO2 CO	0.010 ± 0.000	CO2 CO	0.000 ± 0.000	-

[i] CO above the threshold concentration (15 ppm) in one of the two tests only.

Table 3.4 Mass-loss yield (MLY) reported as mean value (mv) and mean deviation (md) of repeated tests.

Product	Gas	Steady-state tube furnace (SSTF)										Smoke chamber (SC)				Controlled atmosphere cone calorimeter (CACC)					
		650°C		825°C 10 L/min		825°C 3.2 L/min		825°C 3.2 L/min 5% O_2		350°C		25 kW/m², pilot flame		50 kW/m²		21% complete test		15% complete test		10% non-flaming	
		MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)
MF1	CO_2	1131	255	1733	393	1866	32.4	1547	220	ND	-	81600	17110	1669	185	533	63	49	30	165	32
	CO	256	11	303	50	ND	-	ND	-	66	20	126	3.5	341	52	ND	-	ND	-	ND	-
	HCl	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	HCN	27	2.3	24	3.2	ND	-	ND	-	ND	-	ND	-	34	4.8	ND	-	ND	-	ND	-
	NO_X	ND	-	31	4.6	ND	-	ND	-	ND	-	86	20	ND	-	ND	-	ND	-	ND	-
	SO_2	64	5.9	97	30	60	1.6	90	6.8	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
MF2	CO_2	944	40	1423	115					579	81	22204	2571	1183	107	735	120	ND	-	ND	-
	CO	198	16	135	7.2					72	1.2	64	7.4	149	16	91	10	66	20	25	-[a]
	HCl	ND	-	ND	-					ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	HCN	ND	-	ND	-					ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	NO_X	ND	-	ND	-					ND	-	15.5	1.9	ND	-	ND	-	ND	-	ND	-
	SO_2	ND	-	ND	-					ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
MF3	CO_2	1718	28.1	2259	125.1					ND	-	55274	9316	2247	38.6	ND	-	ND	-	ND	-
	CO	308	12	156	8.00					130	3.7	117	12	331	20	172	78	164	75	92	3.8
	HCl	ND	-	ND	-					ND	-	ND	-	ND	-	ND	-	ND	-	ND	-

	HCN	14.7	0.14	10.9	0.75					32	3.8	26	0.30	12.3	0.87	ND	-	ND	-	ND	-
	NO_X	50	1.7	37	0.1					ND	-	103	14	51	1.7	ND	-	ND	-	ND	-
	SO_2	ND	-	ND	-					ND	-	124	22	32	1.3	ND	-	ND	-	ND	-
MF4	CO_2	1793	102	2546	58.9	2569	242	2257	52.6	344	77	38732	10520	1390	52.1	ND	-	ND	-	ND	-
	CO	273	3.2	71	8.3	ND	-	ND	-	129	2.3	142	46	249	0.38	203	73	209	7.8	179	31
	HCl	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	HCN	6.89	0.39	3.26	0.08	ND	-	ND	-	14.0	2.1	21	4.6	14.7	0.23	ND	-	ND	-	7.65	0.40
	NO_X	21	4.0	15.8	0.08	5.30	0.10	3.90	0.000	ND	-	43	8.1	14.6	0.52	ND	-	ND	-	ND	-
	SO_2	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-

[a] Mass-loss data available only from one of the two tests conducted.

Table 3.5 Mass-charge yield (MCY) reported as mean value (mv) and mean deviation (md) of repeated tests.

Product	Gas	Steady-state tube furnace (SSTF)										Smoke chamber (SC)				Controlled atmosphere cone calorimeter (CACC)					
		650°C		825°C 10 L/min		825°C 3.2 L/min		825°C 3.2 L/min 5% O_2		350°C		25 kW/m², pilot flame		50 kW/m²		21% complete test		15% complete test		10% non-flaming	
		MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)
MF1	CO_2	61	10	78	2.9	103	7.1	90	20	ND	-	1929	429	54	0.25	ND	-	ND	-	ND	-
	CO	13.7	0.60	13.8	0.40	ND	-	ND	-	2.00	0.07	2.97	0.04	11.0	0.50	7.47	0.23	5.51	0.08	4.42	0.59
	HCl	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	HCN	1.43	0.12	1.11	0.07	ND	-	ND	-	ND	-	ND	-	1.11	0.04	ND	-	ND	-	ND	-
	NO_X	ND	-	1.42	0.06	ND	-	ND	-	ND	-	2.03	0.38	ND	-	ND	-	ND	-	ND	-
	SO_2	3.44	0.32	4.35	0.35	3.31	0.20	5.19	0.70	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
MF2	CO_2	66	6.9	99	20					22	1.9	1054	82.0	66	1.8	54	0.70	ND	-	ND	-
	CO	14.0	2.0	9.29	0.29					2.70	0.19	3.06	0.24	8.30	0.39	6.75	0.37	4.73	0.90	4.89	0.91
	HCl	ND	-	ND	-					ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	HCN	ND	-	ND	-					ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	NO_X	ND	-	ND	-					ND	-	0.73	0.06	ND	-	ND	-	ND	-	ND	-
	SO_2	ND	-	ND	-					ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
MF3	CO_2	36	4.2	49	2.4					ND	-	566	71	36	1.3	ND	-	ND	-	ND	-
	CO	6.47	0.61	3.38	0.19					1.20	0.06	1.21	0.07	5.31	0.42	1.37	0.07	1.96	0.17	2.08	0.23
	HCl	ND	-	ND	-					ND	-	ND	-	ND	-	ND	-	ND	-	ND	-

	HCN	0.31	0.04	0.24	0.02					0.30	0.04	0.27	0.01	0.20	0.02	ND	-	ND	-	ND	-
	NO_X	1.07	0.18	0.79	0.003					ND	-	1.06	0.09	0.82	0.01	ND	-	ND	-	ND	-
	SO_2	ND	-	ND	-					ND	-	1.27	0.17	0.51	0.01	ND	-	ND	-	ND	-
MF4	CO_2	73	7.2	99	5.8	89	7.3	79	4.3	6.9	1.8	716	2	40	1.5	ND	-	ND	-	ND	-
	CO	11.1	0.60	2.77	0.42	ND	-	ND	-	2.6	0.06	2.58	0.13	7.20	0.02	5.47	0.06	4.24	0.16	3.50	0.14
	HCl	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	HCN	0.28	0.004	0.13	0.008	ND	-	ND	-	0.28	0.05	0.35	0.02	0.42	0.007	ND	-	ND	-	0.15	0.01
	NO_X	0.85	0.13	0.61	0.02	0.19	0.01	0.14	0.01	ND	-	0.73	0.01	0.42	0.02	ND	-	ND	-	ND	-
	SO_2	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-

Table 3.6 Surface-charge yield (SCY) reported as mean value (mv) and mean deviation (md) of repeated tests.

Product	Gas	Smoke chamber (SC)				Controlled atmosphere cone calorimeter (CACC)					
		25 kW/m², pilot flame		50 kW/m²		21% complete test		15% complete test		10% non-flaming	
		SCY (mv)	SCY (md)	SCY (mv)	SCY (md)	SCY (mv)	SCY (md)	SCY (mv)	SCY (md)	SCY (mv)	SCY (md)
MF1	CO_2	1621413	247740	46959	1300	ND	-	ND	-	ND	-
	CO	2544	219	9556	656	9012	112	6441	171	5336	709
	HCl	ND	-	ND	-	ND	-	ND	-	ND	
	HCN	ND	-	966	55	ND	-	ND	-	ND	-
	NO_X	1708	197	ND	-	ND	-	ND	-	ND	-
	SO_2	ND	-	ND	-	ND	-	ND	-	ND	-
MF2	CO_2	1202660	87386	76898	5565	94915	3041	ND	-	ND	-
	CO	3491	251	9669	887	11845	109	8260	413	7401	1751
	HCl	ND	-	ND	-	ND	-	ND	-	ND	-
	HCN	ND	-	ND	-	ND	-	ND	-	ND	-
	NO_X	839	69	ND	-	ND	-	ND	-	ND	-
	SO_2	ND	-	ND	-	ND	-	ND	-	ND	-
MF3	CO_2	1994722	145538	122344	2103	ND	-	ND	-	ND	-
	CO	4268	6.3	18013	1082	9172	186	13987	1827	13012	968
	HCl	ND	-	ND	-	ND	-	ND	-	ND	-

	HCN	951	103	669	47	ND	-	ND	-	ND	-
	NO_X	3738	131	2778	92	ND	-	ND	-	ND	-
	SO_2	4484	351	1745	73	ND	-	ND	-	ND	-
MF4	CO_2	2192218	255861	128333	4813	ND	-	ND	-	ND	-
	CO	7955	1350	22939	35	36998	1713	29625	1997	24368	1697
	HCl	ND	-	ND	-	ND	-	ND	-	ND	-
	HCN	1187	72	1353	21	ND	-	ND	-	1055	58
	NO_X	2488	69	1344	48	ND	-	ND	-	ND	-
	SO_2	ND	-	ND	-	ND	-	ND	-	ND	-

Appendix 4. Test results for PMMA

Contents of appendix 4

Table 4.1 Summary of averaged results from the steady-state tube furnace (SSTF) for PMMA.

Product	Furnace temp (°C)	Primary air flow rate (l/min)	Sample feeding rate (mm/min)	Type of combustion	Comments	CO_2 mass-charge yield (mg/g)	CO mass-charge yield (mg/g)	HCN mass-charge yield (mg/g)	HCl mass-charge yield (mg/g)	HBr mass-charge yield (mg/g)	NO_X mass-charge yield (mg/g)	SO_2 mass-charge yield (mg/g)
PMMA	350	2.0	60	Pyrolysis	No emissions detected	ND	ND	ND	ND	ND	ND	ND
	650	10	-«-	Flaming	-	2055 ± 67	1.8 ± 0.4	ND	ND	ND	ND	ND
	825	3.2	-«-	-«-	-	1037 ± 21	266 ± 0.2	ND	ND	ND	ND	ND

ND = Not detected.

Table 4.2 Summary of averaged results from the controlled atmosphere cone calorimeter (CACC) for PMMA.

Product	Oxygen conc. (%)	t_{ign} (s)	t_{ext} (s)	q_{max} (kW/m^2)	SPR_{max} (m^2/m^{2}s)	Toxic gases, max (ppm)		At time (s)	
PMMA	21[i] (no CA-box)	29 ± 2	761 ± 72	1071 ± 42	6.64 ± 0.45	-	-	-	-
	21[i]	42 ± 1	650 ± 8	958 ± 42	10.8 ± 0.4	CO2 CO HCN NOx	24257 ± 829 1222 ± 172 5.6 ± 0.1 13.4 ± 0.4	405 ± 11 396 ± 6 386 ± 10 400 ± 11
	15[i]	33 ± 6	1036 ± 260	651 ± 77	7.3 ± 1.0	CO2 CO HCN[ii] NOx[ii]	16059 ± 2526 1374 ± 280 7.8 ± 0.4 7.2 ± 0.1	459 ± 16 455 ± 11 459 ± 8 338 ± 163
	10[i]	NI	-	780 ± 4	0.67 ± 0.05	CO2 CO	15338 ± 631 1867 ± 286	484 ± 14 480 ± 11

[i] Triplicate tests.

[ii] Found in 2 tests of 3 only. NO_X close to limit of detection.

Table 4.3 Summary of averaged results from the fire propagation apparatus (FPA) for PMMA.

Product	Oxygen conc. (%)	t_{ign} (s)	t_{ext} (s)	q_{max} (kW/m^2)	Time to q_{max} (s)	Toxic gases, max (ppm)		At time (s)
PMMA	21[i]	92.7 ± 2.1	401.3 ± 4.6	1783 ± 111	339 ± 20	CO2 CO	2946 ± 74 48.5 ± 2.5	352 ± 4 341 ± 5
	15[i]	100.3 ± 1.7	454 ± 0.8	1913 ± 70	382 ± 14	CO2 CO	3291 ± 166 39.1 ± 4.4	382 ± 14 403 ± 5
	5[i]	NI	-	-	-	CO2 CO	NR NR	

[i] Triplicate tests.
NR = results of gas measurements are not reported.

Table 4.4 Summary of averaged results from the smoke chamber (SC) for PMMA.

Product	Irradiance level (kW/m^2)	Ds max	$t_{DS\ max}$ (s)	Ignition (s)	CIT_G 240s	Toxic gases	CIT_G 480s	Toxic gases	CITG Ds max	Toxic gases
PMMA	25, pilot flame[i]	331	155	79	0.047	CO2 CO	0.152	CO2 CO	0.147	CO2 CO
	25, pilot flame[ii]	294 ± 9	7 ± 1	91 ± 1	0.011 ± 0.000	CO2 CO	0.029 ± 0.001	CO2 CO	0.117 ± 0.013	CO2 CO
	50[i]	486	220	87	0.084	CO2 CO	0.191	CO2 CO	0.257	CO2 CO
	50[ii]	477 ± 2	162 ± 4	72 ± 13	0.026 ± 0.001	CO2 CO	0.088 ± 0.001	CO2 CO	0.087 ± 0.000	CO2 CO

[i] Three tests conducted. First test made with regular size of specimen. Following two tests made with reduced specimen size.

Table 4.5 Mass-loss yield (MLY) reported as mean value (mv) and mean deviation (md) of repeated tests.

Product	Gas	Steady-state tube furnace (SSTF)						Smoke chamber (SC)				Controlled atmosphere cone calorimeter (CACC)									
		650°C		825°C		350°C		25 kW/m^2, pilot flame		50 kW/m^2		21% flaming		21% complete test		15% flaming		15% complete test		10% non-flaming	
		MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)	MLY (mv)	MLY (md)
PMMA	CO_2	2145	53.0	1079	23.2	ND	-	2238	8.13	1735	5.44	1960	26.1	1959	21.6	1869	13.7	1861	15.4	941	32
	CO	1.83	0.41	283	10	ND	-	17.2	1.7	24	0.15	25	2.3	25	2.2	47	4.5	47	4.4	64	3.3
	HCl	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	HCN	ND	-	ND	-	ND	-	ND	-	ND	-	0.10	0.04	0.11	0.04	0.19	0.04	0.20	0.05	ND	-
	NO_X	ND	-	ND	-	ND	-	0.58	0.05	0.49	0.02	0.75	0.03	0.58	0.27	0.48	0.08	0.36	0.12	ND	-
	SO_2	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	0.04	0.04	ND	-	ND	-

Table 4.5, cont. Mass-loss yield (MLY) reported as mean value (mv) and standard deviation (sd) of repeated tests.

Product	Gas	Fire Propagation Apparatus (FPA)									
		21% flaming		21% complete test		15% flaming		15% complete test		5% non-flaming	
		MLY (mv)	MLY (sd)	MLY (mv)	MLY (sd)	MLY (mv)	MLY (sd)	MLY (mv)	MLY (sd)	MLY (mv)	MLY (sd)
PMMA	CO_2	1852	90	NA	-	2415	197	NA	-	-	-
	CO	17.8	0.3	NA	-	12.3	0.7	NA	-	-	-
	HCl	-	-	-	-	-	-	-	-	-	-
	HCN	-	-	-	-	-	-	-	-	-	-
	NO_X	-	-	-	-	-	-	-	-	-	-
	SO_2	-	-	-	-	-	-	-	-	-	-

NA = Not available.

Table 4.6 Mass-charge yield (MCY) reported as mean value (mv) and mean deviation (md) of repeated tests.

Product	Gas	Steady-state tube furnace (SSTF)						Smoke chamber (SC)				Controlled atmosphere cone calorimeter (CACC)									
		650°C		825°C		350°C		25 kW/m², pilot flame		50 kW/m²		21% flaming		21% complete test		15% flaming		15% complete test		10% non-flaming	
		MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)	MCY (mv)	MCY (md)
PMMA	CO_2	2055	67.0	1032	17.4	ND	-	2219	16.7	1737	4.23	1915	27.8	1924	23.2	1758	38.9	1766	47.7	780	25
	CO	1.76	0.42	271	7.0	ND	-	17.0	1.6	24	0.13	24	2.2	25	2.2	45	3.5	45	3.4	53	2.5
	HCl	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-
	HCN	ND	-	ND	-	ND	-	ND	-	ND	-	0.10	0.04	0.11	0.04	0.18	0.04	0.19	0.05	ND	-
	NO_X	ND	-	ND	-	ND	-	0.58	0.05	0.49	0.02	0.73	0.03	0.57	0.27	0.45	0.08	0.34	0.12	ND	-
	SO_2	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	ND	-	0.03	0.04	ND	-	ND	-

Table 4.7 Surface-charge yield (SCY) reported as mean value (mv) and mean deviation (md) of repeated tests.

Product	Gas	Smoke chamber (SC)				Controlled atmosphere cone calorimeter (CACC)					
		25 kW/m², pilot flame		50 kW/m²		21% complete test		15% complete test		10% non-flaming	
		SCY (mv)	SCY (md)	SCY (mv)	SCY (md)	SCY (mv)	SCY (md)	SCY (mv)	SCY (md)	SCY (mv)	SCY (md)
PMMA	CO_2	7946550	42609	5747839	103153	24258501	857081	24377368	867739	22902880	419504
	CO	61105	6629	80270	1191	309734	24180	314246	23950	580140	49531
	HCl	ND	-	ND	-	ND	-	ND	-	ND	-
	HCN	ND	-	ND	-	1229	402	1344	395	2328	532
	NO_X	2069	168	1635	113	9303	552	7161	3340	5906	1030
	SO_2	ND	-	ND	-	ND	-	ND	-	436	470

Appendix 5. Measured test specimen data and elemental analysis

5.1 Measured data

Measurement of data was made on duplicate samples of the received products. Averaged values are given in Table 5.1.

Table 5.1 Measured data of the received product.

Product	Thickness (mm)	Area weight (kg/m^2)	Density (kg/m^3)
PF1	97	3.6	37
PF2	100	1.2	12
PF3	50	1.3	35
PF4	78	2.8	35
PF5	99	4.4	44
OF1	50	4.6	93
OF2	100	1.8	36
MF1	100	2.1	21
MF2	100	2.8	28
MF3	50	6.1	126
MF4	105	15	147
PMMA	9.8	11	1178

Measurement of data was made on duplicate samples of core material samples intended as test specimens for the Cone calorimeter tests. Analysis of combustible content was made by placing duplicate samples of core material in a furnace at 550 °C. Average values are given in Table 5.2.

Table 5.2 Measured data of the core material.

Product	Thickness (mm)	Area weight (kg/m^2)	Density (kg/m^3)	Combustible amount (%)[i]
PF1	48	1.5	32	99.5
PF2	50	0.5	11	100
PF3	50	1.7	34	99.2
PF4	50	1.5	30	98.6
PF5	48	1.5	31 - 32	99.2
OF1	49	2.4	48	99.4
OF2	50	1.8	36	80.0
MF1	50	1.1	22	5.0
MF2	50	1.8	36	7.2
MF3	50	5.9	119	1.7
MF4	50	6.4	131	4.3
PMMA	9.8	11	1178	100

[i] Measured on separate samples of core material.

5.2 Chemical elemental analysis

Carbon (C), hydrogen (H) and nitrogen (N) were quantitatively determined with an elemental analyzer for C, H and N (*Leco CHN 628*).

Survey of the elemental composition was performed by X-ray fluorescence (XRF) according to method SP 4343. The method is a semi-quantitative analysis of surface layer and is applicable for 70 of the 80 most common elements in the periodic system (Sodium, Na, and heavier elements). Important elements not measured are boron, carbon, nitrogen, oxygen and fluorine. The detected elements are presented below in order of occurrence from the XRF analysis. Note that the detection limit differs between the different elements and that lighter elements have higher limits of detection.

Table 5.3 Results from chemical elemental analysis.

Material	Analysis results
PF1	Carbon, C = 63.0 weight-% Hydrogen, H = 5.8 weight-% Nitrogen, N = 2.1 weight-% Semi-quantitative XRF: Sulphur, S Chlorine, Cl Calcium, Ca Potassium, K
PF2	Carbon, C = 90.6 weight-% Hydrogen, H = 7.9 weight-% Nitrogen, N = 0.31 weight-% Semi-quantitative XRF: Bromine, Br
PF3	Carbon, C = 89.4 weight-% Hydrogen, H = 7.6 weight-% Nitrogen, N = 0.1 weight-% Semi-quantitative XRF: Bromine, Br Silicon, Si Magnesium, Mg
PF4	Carbon, C = 64.6 weight-% Hydrogen, H = 6.2 weight-% Nitrogen, N = 7.4 weight-% Semi-quantitative XRF: Chlorine, Cl Phosphorous, P Silicon, Si
PF5	Carbon, C = 65.5 weight-% Hydrogen, H = 5.4 weight-% Nitrogen, N = 7.0 weight-% Semi-quantitative XRF:

	Chlorine, Cl Phosphorous, P Potassium, K Silicon, Si Sulphur, S
OF1	Carbon, C = 45.6 weight-% Hydrogen, H = 6.6 weight-% Nitrogen, N = 1.1 weight-% Semi-quantitative XRF: Sulphur, S Calcium, Ca Sodium, Na Silicon, Si Magnesium, Mg Potassium, K
OF2	Carbon, C = 36.5 weight-% Hydrogen, H = 5.4 weight-% Nitrogen, N = 0.10 weight-% Semi-quantitative XRF: Calcium, Ca Silicon, Si Aluminium, Al Sodium, Na Iron, Fe Magnesium, Mg Sulphur, S Potassium, K Titanium, Ti
MF1	Carbon, C = 2.9 weight-% Hydrogen, H = 0.4 weight-% Nitrogen, N = 0.57 weight-% Semi-quantitative XRF: Silicon, Si Sodium, Na Calcium, Ca Aluminium, Al Magnesium, Mg Potassium, K Sulphur, S Iron, Fe Barium, Ba Manganese, Mn Zinc, Zn Chromium, Cr Titanium, Ti Chlorine, Cl
MF2	Carbon, C = 3.2 weight-% Hydrogen, H = 0.51 weight-% Nitrogen, N = <0.05 weight-%

	Semi-quantitative XRF: Silicon, Si Sodium, Na Calcium, Ca Aluminium, Al Magnesium, Mg Potassium, K Manganese, Mn Sulphur, S Phosphorus, P Iron, Fe Rubidium, Rb Chlorine, Cl Barium, Ba
MF3	Carbon, C = 1.5 weight-% Hydrogen, H = 0.2 weight-% Nitrogen, N = 0.28 weight-% Semi-quantitative XRF: Silicon, Si Calcium, Ca Aluminium, Al Iron, Fe Magnesium, Mg Sodium, Na Titanium, Ti Potassium, K Manganese, Mn Phosphorus, P Sulphur, S Strontium, Sr
MF4	Carbon, C = 2.6 weight-% Hydrogen, H = 0.2 weight-% Nitrogen, N = 0.44 weight-% Semi-quantitative XRF: Silicon, Si Calcium, Ca Aluminium, Al Iron, Fe Magnesium, Mg Sodium, Na Titanium, Ti Manganese, Mn Potassium, K Sulphur, S Phosphorus, P Chromium, Cr Barium, Ba Strontium, Sr
Poly(methyl methacrylate), black (PMMA)	Carbon, C = 60.1 weight-% Hydrogen, H = 8.1 weight-% Nitrogen, N = <0.05 weight-%

	Semi-quantitative XRF: (No elements detected)

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RISE Research Institutes of Sweden AB
Box 857, SE-501 15 BORÅS, Sweden
Telephone: +46 10 516 50 00
E-mail: info@ri.se, Internet: www.ri.se

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