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Reaction-to-fire testing of bus interior materials: Assessing burning behaviour and smoke gas toxicity

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Abstract

Although fire safety regulations for buses have been adapted in recent years regarding, for example, fire detection and engine fire suppression systems, the changes in regulations for bus interior materials are minimal. A comparison of fire safety regulations for interior materials in other transport sectors for trains, ships or aircraft reveals a much lower level of requirements for bus materials. Although repeated bus accidents as well as fire statistics show the danger a bus fire can pose to passengers. In particular, the combination of a fire incident and passengers with reduced mobility led to severe disasters in Germany and other European countries. To enhance the fire safety for passengers, the interior bus materials are crucial as the fire development in the bus cabin determines whether escape and rescue is possible. Against this background, bus interior materials were tested in different fire test scenarios. Measurement of a wide variety of parameters, for example, the mass loss, ignition time, smoke gas composition, heat release rate among others were carried out. Tested materials complied to the newest set of requirements. For this purpose, interior materials and their components had to be identified according to their chemical structure. Parts of the tests were funded by BAST (Federal Highway Research Institute) in the project 82.0723/2018. Experimental results show reaction-to-fire behaviour which lead to very limited times for escape and rescue in case of fire in a bus cabin. Based on the studies on fire behaviour and toxicity assessment, recommendations for improved fire safety regulations for interior materials could be made.

KEYWORDS

burning behaviour, bus interior materials, cone calorimeter, DIN tube furnace, FTIR spectroscopy, reference values, smoke toxicity

1 | INTRODUCTION INTO BUS FIRES

In recent years, there have been repeated bus accidents with numerous deaths and injuries. In particular, the combination of a fire incident with people with restricted mobility led to particularly severe events in Germany and other European countries. Traffic accidents or technical defects are often the cause of fires in buses. Especially, the rapid

spread of fire and smoke represents a high risk potential for passengers travelling with them.¹ Often, passengers only have a few minutes to save themselves before irritating and toxic smoke products spread inside the bus. In addition, time elapses from discovering a fire until the bus is able to stop. Especially, when people are not able to save themselves quickly enough due to mobility or age restrictions, there is an imminent danger. This is demonstrated by the most serious and

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(A) extinguishing work on the bus



(B) burned-out bus wreck

FIGURE 1 Bus fire on the A9 near Münchberg, pictures from Freiwillige Feuerwehr Münchberg. (A) Extinguishing work on the bus. (B) Burned-out bus wreck.

devastating bus fires in recent years: a bus fire on the A8 near Hannover in 2008, in which 20 passengers lost their lives and the tragic bus accident in 2017 on the A9 in which the bus burst into flames after a traffic accident and killed 18 people (see Figure 1). Both tour groups consisted primarily of elderly.

Research based on these events led to a large number of fire protection measures that were incorporated into international vehicle regulations. Fire protection requirements for bus interior materials have been increased and incorporated into international regulations. Requirements for the burning rate as well as for the melting and dripping behaviour of interior materials already exist. It remains unclear to what extent the release of fire smoke, combustion products and the toxicity of these should be limited. For this reason, a BAST-funded research and development project 82.0723 was initiated to develop a simplified procedure for testing the toxicity and smoke development in the event of fire of interior materials installed in buses. The scope of research included calculations for the evaluation of the toxicity of fire gases and the derivation of specifications for the formation of practicable limit values for fire smoke toxicity. The suitable measuring equipment that can be used to derive these limit values for smoke toxicity or the other physical quantities that can be used to derive these limit values has not yet been researched. A large number of scientific publications dealt with the fire safety of buses nationally and internationally in the last years.¹⁻⁵

Regulations for train interior materials according to European standards (EN 45545-2) are much more strict than the regulations for bus materials and offer high level fire safety for trains.^{6,7}

This publication is the first part of a series on research and development work on fire safety in buses. In this paper, we focus on experimental investigations in the DIN tube and on cone calorimeter tests with bus materials. The bus materials tested in this work fulfil the newest set of regulations for buses, considering the extended use of the vertical fire test for bus interior materials. Both test set-ups in the DIN tube furnace and the cone calorimeter have been modified for research purposes, for example, the initial

specimen mass in the DIN tube furnace was kept constant to 1 g in all tests and an FTIR was coupled with the cone calorimeter, details are described in Section 3.

This is followed by detailed considerations on assessing the burning behaviour of bus materials using the cone calorimeter, DIN tube furnace and numerical calculations on fire and smoke propagation in a bus geometry using the evaluated experimental data with commercial fluid flow solvers.

1.1 | Normative background and existing fire safety regulations

The United Nations Economic Commission for Europe (UNECE)⁸ has had recommendations drawn up on uniform regulations for the safety of buses in the event of fire since 2018. The regulations that apply to the fire safety of buses include the UN R 36 bus and coach uniform provisions on the approval of larger passenger vehicles with regard to their general construction, UN R 107⁹ for vehicle requirements of categories M21 and M32 and UN R 118,¹⁰ which deals with fire protection requirements for interior materials. The regulation EG 661/2009 of the European Parliament and Council regulates uniform criteria for the type approval of motor vehicles, sets functional requirements for non-flammable and fire-retardant materials in the interior of buses and defines the UN R 118 as binding. The current tests on the burning behaviour of bus interior materials are limited to the horizontal and vertical burning velocity as well as to the melting and dripping behaviour. It does not regulate how the smoke toxicity can be assessed and limited for burning bus interior materials. The basis for fire safety requirements for buses are the following categories of buses defined in the UN regulations⁹:

- Category M2: Vehicles for the transport of passengers who have more than eight seats in addition to the driver's seat and do not exceed a maximum weight of 5 tons,

- Category M3: Vehicles for the transport of passengers with more than eight seats in addition to the driver's seat, the maximum weight of which exceeds 5 tons,
- Class 1: Vehicles with standing places for regular boarding and alighting,
- Class 2: Vehicles for the transport of seated passengers, which have aisles or areas for the transport of standing passengers, which do not exceed the space of two double seats.

Two classes are defined for M2 and M3 vehicles whose capacity does not exceed 22 passengers plus driver:

- Class A: Vehicles designed to carry standing passengers, a vehicle in this class has seats and areas for standing passengers
- Class B: Vehicles designed to carry seated passengers; these vehicles do not have designated areas for standing passengers.

The fire tests for bus interior materials according to UN ECE Regulation No. 118 Appendix 6, 7 and 8 which are based on the Standard FMVSS 302 are described as follows:

The fundamental reaction-to-fire test for interior materials of buses is a horizontal test procedure to limit the horizontal burning rate of a small flame. The principle of the test is: A sample is held horizontally in a U-shaped holder and is exposed to the action of a defined low-energy flame for 15 s in a combustion chamber, the flame acting on the free end of the sample. The test determines if and when the flame extinguishes or the time in which the flame passes a measured distance. Five specimens have to be tested in their practice-oriented orientation. The specimens are fixed in U-shaped specimen holders and are marked in a distance of 38 and 292 mm from the leading edge. During the test procedure the horizontal burning rate is determined. The holder is horizontally inserted in a combustion box and is flamed on the leading edge for 15 s by a 38-mm flame of a Bunsen burner. The burning rate between the two marks is timed. If the flame does not reach the second mark the burning distance has to be measured. A specimen passes the burning test if the worst result does not exceed a horizontal burning rate of 100 mm/min.

Ceiling materials and bordered parts have to pass an additional drip test which is focused on the melting behaviour of the material. Principle of the test: A sample is placed in a horizontal position and is exposed to an electric radiator. A receptacle is positioned under the specimen to collect resultant drops. Some cotton wool is put in this receptacle in order to verify if any drop is flaming. In the drip test the specimen is located on a horizontal grate which is fixed 300 mm over the bottom and 30 mm below the Epiradiateur. A cotton ball is also placed on the bottom below the specimen. The Epiradiateur is an electrical heater which radiates a thermal intensity of 30 kW/m² to the specimen. During the test period the ignition and the drip behaviour of the specimen and the underlying cotton ball are monitored for 10 min. If the specimen ignites in the first 5 min of the test the Epiradiateur has to be immediately removed.

Drapes, jalousies and hangings as well as vertical mounted materials also have to pass an additional test which limits the vertical

burning rate. In this process three specimens have to be tested in their practice-oriented direction. During the test procedure a 40 mm burner flame is directed towards the bottom edge for 5 s. If the specimen does not ignite a next specimen has to be flamed for 15 s. The sample gets marks in a height of 220, 370 and 520 mm. The requirements of the test are passed if the fastest vertical burning rate between the both lower marks is less than 100 mm/min or if the flame extinguishes before reaching the last measuring point.

2 | ASSESSMENT OF SMOKE TOXICITY

The amount of fire smoke and its chemical composition largely depend on material properties, ventilation and ignition conditions. There are different approaches to appropriately define the term fire smoke. According to ISO 13943,¹¹ smoke is considered as the more visible part of volatile combustion products. Characterising fire smoke appropriately offers the categorisation of the main components: fire gases and aerosols and their respective components. Fire smoke not only affects the visibility in the event of a fire, but also contains a large number of toxicants and irritants. Depending on the duration of exposure and concentrations, inhalation of fire effluents can lead to death or long-term damage within a few minutes.

A large number of scientifically proven limit values are available to the engineer to evaluate the effects of a substance or mixture release or to calculate tenability effects on humans. Several values have been developed to assess the short-term exposure of the general population to harmful gases. ERPG values (Emergency Response Planning Guidelines)¹² or AEGL values (Acute Exposure Guideline Levels) are mostly used for impact assessments.¹³ With regard to the effects of exposure to pollutants, the approaches mentioned are based on four impact categories with assigned concentration ranges that can be distinguished from each other by three concentration thresholds:

- first sensory effects (perceptibility),
- adverse but reversible health effects (nuisance),
- first irreversible or serious health effects or impairment of the possibility of escape,
- life-threatening effects and fatal poisoning.

AEGLs are used for acute substance-related effects in periods of less than 8 h. These values are being established for a growing number of substances using standardized procedures. The AEGL values are given for exposure times of 10 min, 30 min, 1 h, 4 h and 8 h. With regard to personal safety in buses in the event of fire, AEGL-2 values in the two shortest intervals of 10 and 30 min could be regarded as limit values.

In the event of an accident the IDLH values (Immediately Dangerous to Life and Health)¹⁴ are used to evaluate leaking gases or smoke in the industry. These are limiting values for the case that a dangerous atmosphere occurs. Exposure of 30 min without personal protective

equipment should not lead to life-threatening or other serious damage to health.

In addition to that the assessment of toxicity can be achieved by the application of appropriate physiological methods or calculation models for time and dose incapacitation/other impacts: for example, fractional effective dose (FED) model¹⁵⁻¹⁷ or N-Gas-model.^{18,19} Other existing modelling approaches are fractional effective concentration model, $C^n t$ model or respiratory rate depression models for the assessment of time to and severity of sensory irritancy in human fire victims during fires.²⁰ The FED model in general is used in accordance with ISO 13571,²¹ which applies the dose concept for asphyxiants, and is extensively described in literature. The basic principle for estimating the asphyxiant component of toxic hazard analysis involves the exposure dose of each toxicant, that is, the integrated area under each concentration-time curve. Basically, the point in time is calculated at which the accumulated sums of the individual smoke gases reach a defined end value. After this time, the tolerable doses of the smoke gases are reached. Depending on the selected criterion, incapacitation or compromised tenability occurs. According to the model, incapacitation is achieved when the FED reaches a threshold criteria of 1. If the FED reaches unity its considered statistically safe for 50% of the average population. The FED is determined by the following general relation:

$$X_{\text{FED}} = \sum_{i=0}^n \sum_{t_1}^{t_2} \frac{C_i}{(Ct)_i} \Delta t, \quad (1)$$

where C_i in [$\mu\text{L}/\text{L}$] is an average concentration of an asphyxiant i over a chosen time interval, $(Ct)_i$ in [$\mu\text{L}/\text{L}$] exposure dose for a given effect, for example, incapacitation or compromised tenability and Δt in [min] is the chosen time interval.

In the end of these studies, the FED model is the model of choice with which the smoke toxicity of bus interior materials is to be assessed. The most challenging aspect is the scale-up of the measured gas concentrations in the bench-scale test to the real size of the passenger compartment of the bus and their evaluation.

However, it must be taken into account that a model is needed which transfers bench-scale test results to real-scale fire scenarios.

Therefore, after completion of all studies, the assignment of the measured gas concentrations from the bench-scale tests should be used to evaluate the smoke gas toxicity using (i) defined threshold values to limit toxic hazards from burning bus interior materials and (ii) application of the FED concept to assess smoke toxicity related to personal safety. Past work and similar studies on this approach can be found in literature.²²

3 | EXPERIMENTAL SET-UP AND INSTRUMENTATION

To proceed methodically to determine the fire smoke toxicity of materials installed in buses and coaches, appropriate fire tests had to be selected and typical materials for furnishing bus interiors were

identified. As the focus was on smoke gas analysis, measurement equipment was sought that would allow coupling with an FTIR spectrometer:

1. Smoke density chamber, an already standardized method for toxicity evaluation in the rail vehicle sector, but without control over the atmosphere in the chamber,
2. Cone calorimeter, which is also a standardized method in the rail vehicle sector, but it is not used for determining smoke gas toxicity,
3. Mass loss calorimeter (MLC), which allows testing under a controlled combustion atmosphere,
4. DIN tube furnace, which enables thermal oxidative decomposition at a continuous flow rate.

Fire tests of the same materials were carried out with all apparatuses. The present study reports on charring tests on polyurethane (PU) foams and various textiles that are used as upholstery fabrics. To investigate the burning behaviour of the given materials and to evaluate the smoke gas toxicity, the samples were examined under flaming and non-flaming combustion conditions. For further research purposes the cone calorimeter with FTIR coupling was selected as well as the DIN tube furnace.

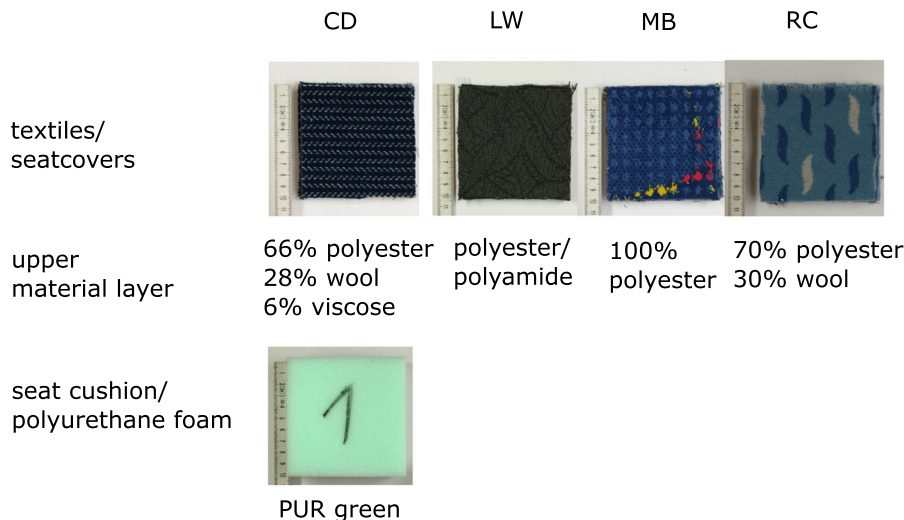
3.1 | Bus interior materials

The bus seats, parts of the interior trim and the floor were identified as typical bus interior fittings (see Figure 2). These include PU, polyester (PE), acrylonitrile butadiene styrene, polyvinyl chloride, chip boards, polyamide, polyethylene, polypropylene as well as cotton, fleece, viscose, leather and synthetic leather. Various materials were made available by manufacturers for the experimental investigations: seat cushions and foams as well as samples of the seat covers and textiles from public and intercity buses.



FIGURE 2 Bus interior of a typical German public bus in the city of Berlin.

FIGURE 3 Material samples, cut to size for the cone calorimeter tests.



3.2 | Experimental procedures

The cone calorimeter according to ISO²³ and the DIN tube furnace according to DIN^{24,25} were chosen to investigate the burning behaviour and smoke toxicity of the interior bus materials (see Figure 3) presented. The two test apparatuses differ with regard to the investigation of the respective fire stage. The bus interior materials should be examined under well-ventilated flaming and under thermally oxidative decomposition conditions. Not only the measurement of the heat release rate (HRR), the maximum rate of heat emission MARHE or the smoke production rate (SRP) during the cone calorimeter tests but the quantitative analysis of the smoke gas composition were in the foreground when selecting the two test methods. Combustion processes of typical bus interior materials (Figure 3) form the following products and were identified during the experiments: CO₂ (carbon dioxide), CO (carbon monoxide), HCN (hydrogen cyanide), HCl (hydrogen chloride), CH₂O (formaldehyde), NO_x (nitrogen oxides), C₆H₆ (benzene), NH₃ (ammonia) and acrolein. A very well-described classification of the effects of smoke gas components are given by Wakefield.²⁶

3.3 | Cone calorimeter with FTIR spectroscopy

The cone calorimeter allows the measurement of the HRR, mass loss, the smoke density and the smoke gas composition. Materials can be tested with different radiance levels, with or without a spark ignition. The cone calorimeter is a standardized method that is used in the assessment of rail vehicle materials, but not for toxicity assessment and was used according ISO 5660-1. In addition to the standard procedure, an external Ansyco DX4000 FTIR spectrometer²⁷ was connected to the exhaust air shaft as described in ISO/TS 21397:2021. This was used to determine the composition of the fire effluents. The FTIR was equipped with a spectral resolution of 4 cm⁻¹ and an optical path length of 5 m. The temperature in the optical cell is 180°C and the volume flow for sampling was 3 L/min. Two glass fibre filters are located between the sampling and the optical cell for removing



FIGURE 4 Cone calorimeter set-up at the BAM Lab.

particles which a filter fineness of 2 μm (particle pre-filter) or 0.1 μm (particle filter). The filters were heated up to 180°C. FTIR was calibrated with a test gas mixture of carbon monoxide and dioxide as well as methane, ethylene and nitrogen. The cone calorimeter was calibrated using a test gas composed of carbon monoxide, carbon dioxide and nitrogen. Test specimens made of foams and textiles were conditioned applying ISO 5660-1 to 23°C and 50% relative humidity. The foams were tested as 10 × 10 × 50 mm cuboids. For the textiles, several layers were placed on top of one another until a height of approximately 10 mm. Before the start of the experiment, all samples were photographed, weighed and the lower part was wrapped in aluminium foil.

Due to the special fire behaviour of the textiles and their property of pulling together and shrinking when exposed to heat, the fabrics were additionally clamped with a self-made wire mesh. The experiments were performed according the test procedure describes in the standard ISO 5660-1 applying an irradiance of 25 kW/m² and a

distance between upper sample surface and base plate of the cone heater of 25 mm. Data were recorded using the Cone Calorimeter software ConeCalc 5 (Fire Testing Technology). For each sample three specimens were tested and the arithmetic means of the collected data were calculated. The Cone Calorimeter set-up at the BAM Lab is shown in Figure 4.

3.4 | DIN tube furnace with FTIR spectroscopy

In the experimental studies on the DIN tube, various foams, upholstery materials (PE-based textiles) and foams combined with textiles were thermally decomposed. The material samples of the foams and textiles meet the prescribed fire protection requirements for bus interior materials. The use of the DIN tube is one of the test methods for determining the smoke development of building materials in Germany. With the DIN tube, a building material can be decomposed under smouldering conditions so that the percentage of light attenuation by the smoke can be determined. The thermal oxidative decomposition without flame formation was investigated using the DIN tube method. For each examined sample, at least three specimens were tested

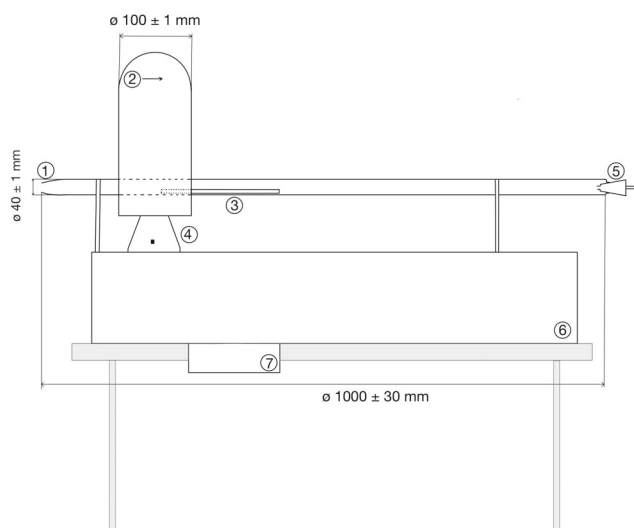


FIGURE 6 Schematic structure of the DIN tube furnace test with (1) quartz glass tube, (2) ring furnace with direction control, (3) specimen holder (glass cuvette), (4) lever for moving the (5) connection for air supply, (6) metal assembly including motor and feed speed control (7) temperature control.

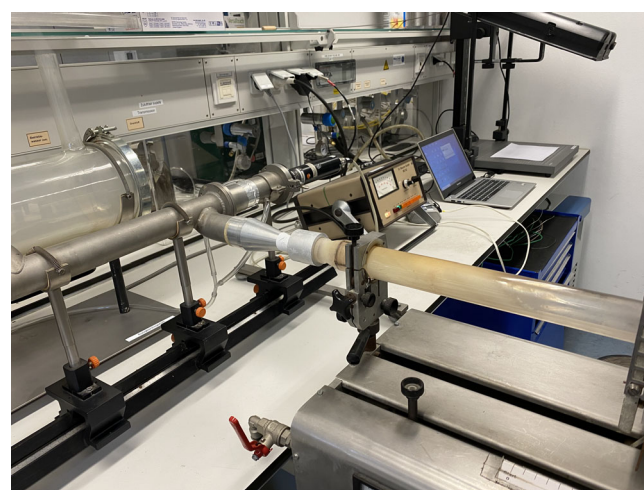
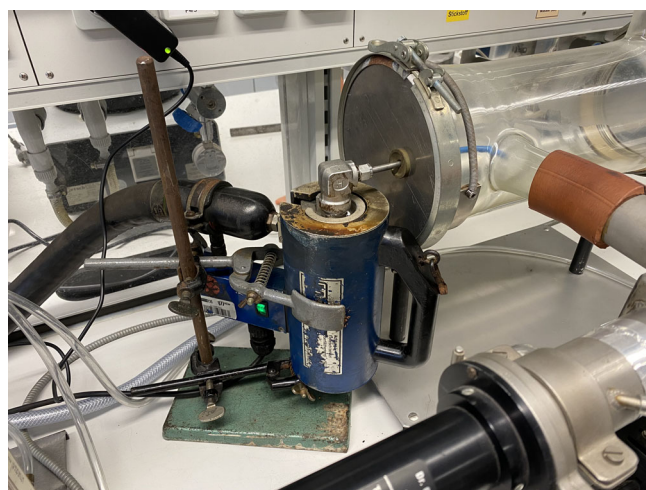
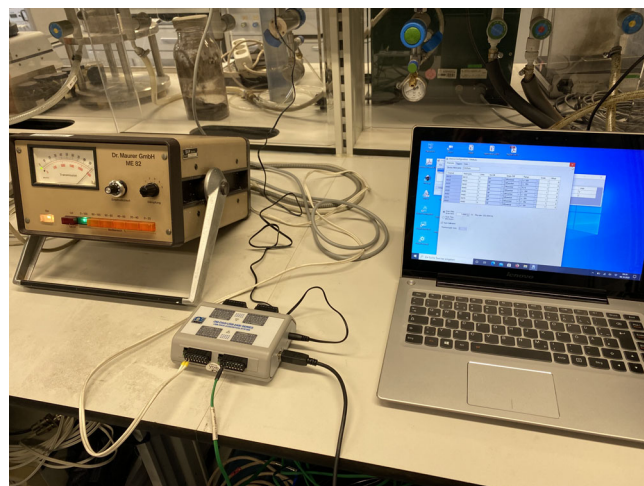


FIGURE 5 Laboratory set-up of the DIN tube furnace with connected light extinction measurement system and FTIR spectrometer at the compensation vessel.

and the arithmetic means of the collected data were calculated. Laboratory set-up of the DIN tube furnace with a connected light extinction measurement system and a FTIR spectrometer (Ansyco DX4000)²⁷ at the compensation vessel is shown Figure 5. Similar studies can be found in the literature by Löhnert et al.²⁸

According to the German standard DIN 60695-6-1, oxygen concentrations between 5 and 21 vol% by volume and temperatures between 500°C and 600°C are characteristic of thermal oxidative decomposition. This temperature range corresponds to a radiance of less than 25 kW/m² and can be assigned to a self-sustaining smouldering fire. A schematic structure of the DIN tube furnace test is shown in Figure 6.

For the generation of thermal decomposition products of materials for their analytical-toxicological test, a reference body temperature must be determined in order to be able to determine the actual to the temperature on the sample using the DIN tube procedure. The reference body consists of a strip of stainless austenitic steel with the dimensions 200 mm × 5 mm × 2 mm, on the centre of which a NiCr-Ni or Chromel-Alumel sheathed thermocouple with an outer diameter of 1 mm is brazed with high-melting silver solder in a groove of 10-mm length.

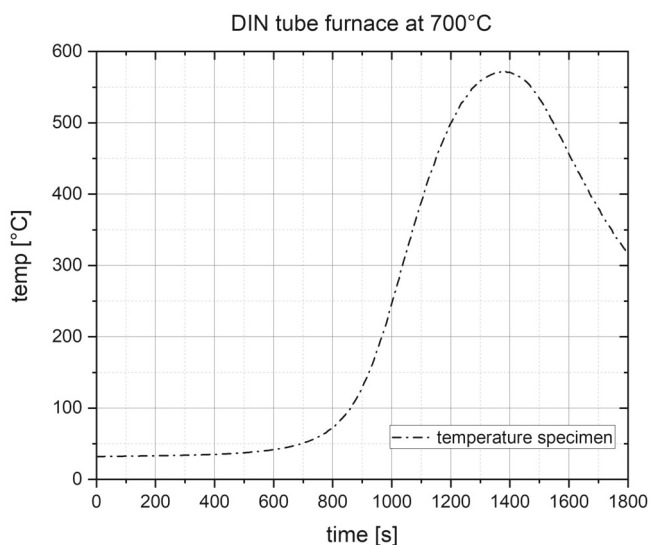


FIGURE 7 Course of reference body temperature in the DIN tube furnace (ring furnace temperature = 700°C).

TABLE 1 Overview of test results for peak heat release rate, total heat release, total smoke production and MARHE for the investigated textiles and the polyurethane foam

Material	Peak HRR (kW/m ²)	Total heat release (MJ/m ²)	Total oxygen consumed (g)	Total smoke production (m ²)	MARHE (kW/m ²)
RC	270.61 ± 7.50	32.82 ± 0.17	22.20 ± 0.18	8.79 ± 0.57	87.02 ± 2.59
CD	167.25 ± 6.08	37.12 ± 1.96	24.71 ± 0.86	7.98 ± 0.75	96.86 ± 3.61
MB	146.62 ± 11.23	15.20 ± 3.77	11.46 ± 2.53	16.95 ± 0.98	58.26 ± 9.09
LW	208.39 ± 2.91	37.41 ± 3.18	25.34 ± 1.68	6.20 ± 0.88	100.42 ± 3.66
PUR green	345.25 ± 7.94	50.25 ± 0.45	32.00 ± 0.29	6.33 ± 0.14	245.76 ± 18.32

The reference body temperature can be determined at different furnace temperatures. This relation can be displayed in a reference curve to check the test device, from which the controller setting for the furnace temperature for a given air flow can be used to receive a reference body temperature between 200°C and 600°C. If a constant temperature of 700°C is set-up for the DIN tube ring furnace, a temperature of approximately 560 ± 20°C on the sample surface is expected (Figure 7).

After the sample has been weighted and photographed, it is placed on a cuvette in the quartz glass tube. The ring furnace is set to a temperature of 700°C and to a moving speed of 1 mm/min. The test gas is turned on and a continuous flow rate of 5 L/min can be adjusted with a flow meter. The measurement software of the FTIR, the temperature recording and the measurement of the transmittance are triggered. After about 1800 s (30 min) the experiment is finished. The sample is removed from the quartz glass tube and the post-processing of the furnace experiment can be carried out.

4 | RESULTS OF THE EXPERIMENTAL STUDIES AND DISCUSSION

4.1 | Gas concentrations from cone calorimeter experiments

In the following, a detailed evaluation is first presented as an example using two selected samples, the PUR green foam and the textile CD. In the further explanations, only the summarised results of the investigated materials are shown in Table 1. The application of literature limits for toxicity assessment is not easily applicable with the concentration curves obtained from the cone calorimeter tests. Measurements were made according to standard procedure and an extraction rate of 24 L/s was selected. This could have been the cause of the gases undergoing a strong dilution. Further test series could show that a reduced extraction rate of 12 L/s has a favourable effect on the gas extraction and the subsequent FTIR analysis and that this approach is preferable.²⁸ Nevertheless, a schematic approach was taken and tested according to the standard. The materials will be tested again under conditions of reduced extraction volume flow. Nevertheless, the material investigations under flaming combustion conditions show differences to smouldering conditions, for example, in the production of CO₂. In the smouldering tests in the DIN tube

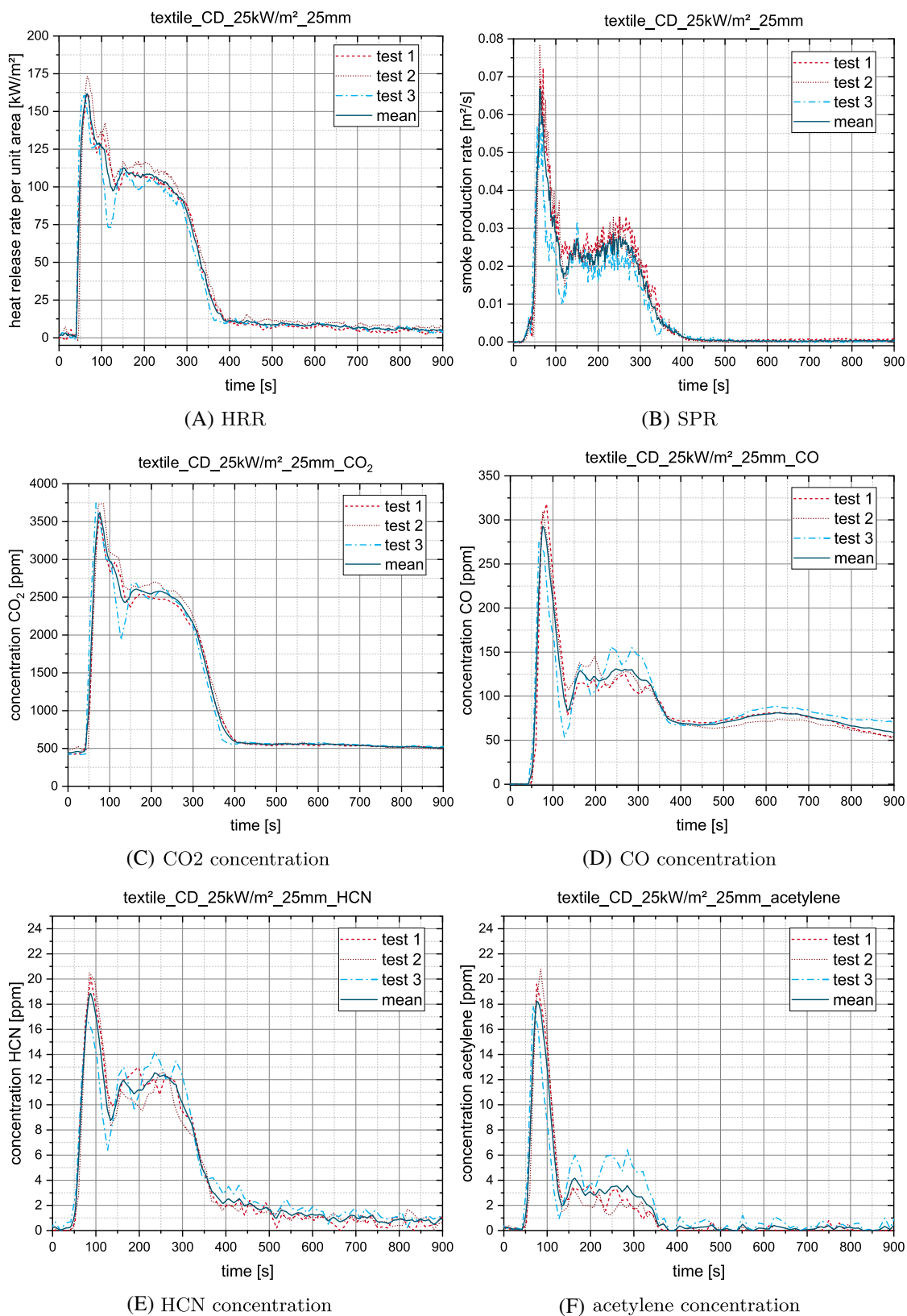


FIGURE 8 Selection of measured gas concentrations, heat release rate (HRR) and smoke production rate (SPR) for the textile CD in the cone calorimeter for three tests. (A) HRR. (B) SPR. (C) CO₂ concentration. (D) CO concentration. (E) HCN concentration. (F) Acetylene concentration.

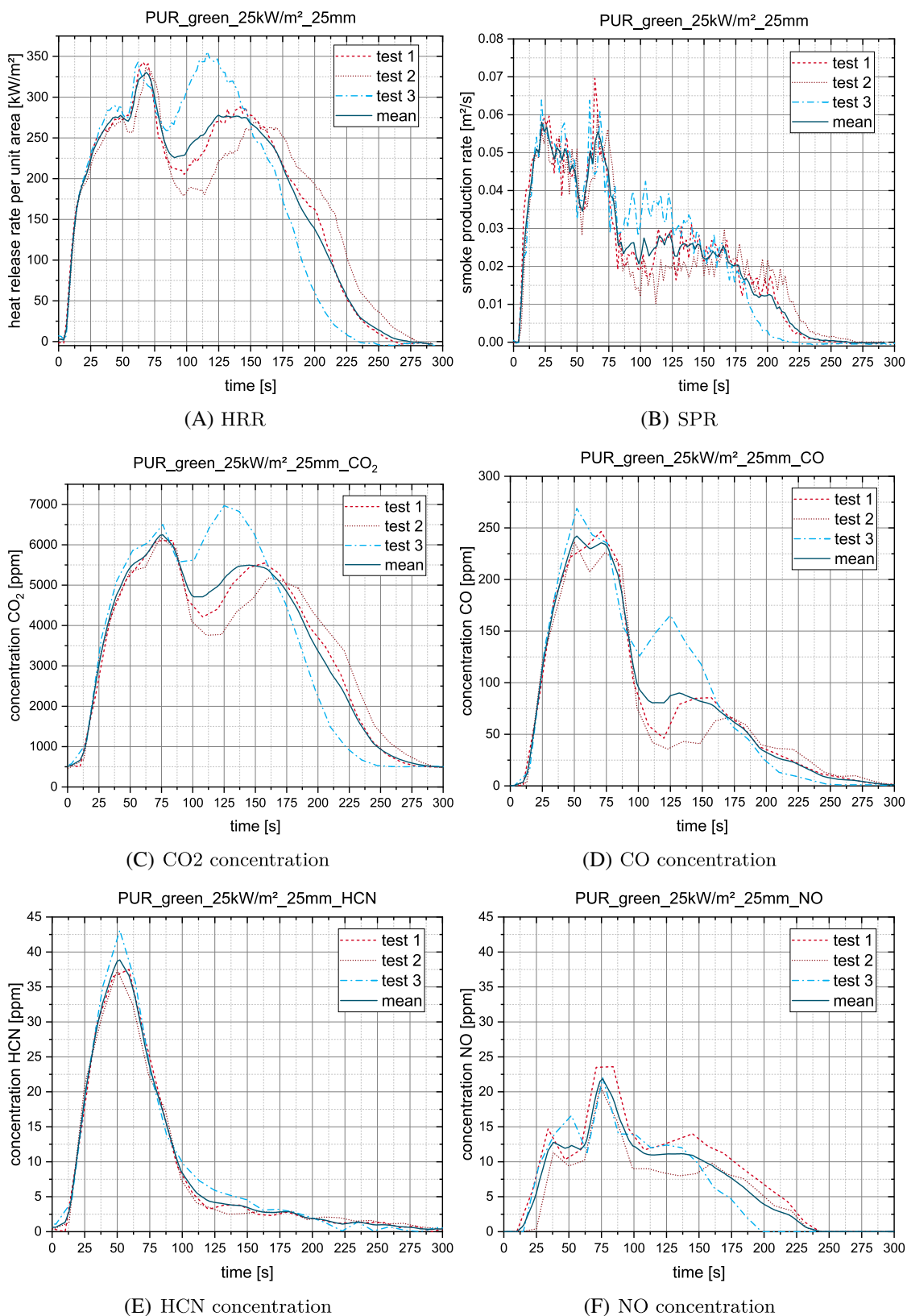


FIGURE 9 Selection of measured gas concentrations, heat release rate (HRR) and smoke production rate (SRP) for the PUR green (polyurethane foam) in the cone calorimeter for three tests. (A) HRR. (B) SPR. (C) CO₂ concentration. (D) CO concentration. (E) HCN concentration. (F) NO concentration.

TABLE 2 Experimental set-up of the bench-scale test apparatuses for toxicity assessment

	Bench-scale test apparatus	
	Cone calorimeter	DIN tube furnace
Test conditions	Well-ventilated flaming Open test	Oxidative thermal decomposition, non-flaming Steady-state tube furnace
Conical radiator	25 kW/m ²	-
Furnace temperature	-	700°C
Furnace speed	-	10 mm/min
Air supply	-	5 L/min air
Specimen size		
Textiles	100 mm × 100 mm	5 mm × 270 mm
Foams	100 mm × 100 mm	10 mm × 270 mm
Specimen thickness		
Textiles	3–5 layers of fabric, wear layer on top	1 mm
Foams	50 mm	10 mm
Specimen mass		
Textiles	22–29 g	1 g
Foams	17–27 g	1 g
Measured quantities	HRR, MARHE, TSR, TSP, MLR, COY, CO ₂ Y, gas concentrations etc.	Gas concentrations, transmittance
Toxicity assessment FTIR spectroscopy	Yes	Yes
Standard	ISO 5660-1	DIN 4102-1:1998-05 DIN 53436-1:2015-12
Advantages	Standardized procedure that is already used for the assessment of rail vehicle materials, can also be used vitiated	Reproducible/controllable burning conditions
Disadvantages	Control of supply air	Apparatus only available in Germany, only absolute mass loss measurable

furnace, CO₂ could only be detected in negligible concentrations in the smoke gas, which can be attributed to the temperature conditions during the test.

The following Figures 8 and 9 shows the time curves for the measured HRR, the SRP and gas concentrations for CO₂, CO, HCN and acetylene for the textile CD and PU foam in the cone calorimeter for three experiments.

The following observations were made during the cone calorimeter tests: In the case of the foam, almost the entire weight of the samples is completely burned. They all ignite after 4–5.5 s. The textiles ignite later: after 37–103 s. The textiles approved for buses ignite after 37–46 s. The fabric RC, which is approved for rail vehicles, ignites later: after 103 s. In the cone calorimeter, the ventilation is sufficient due to the discharged volume flow of 24 L/s, there is a dilution of the flue gases in the fume hood. But both heat release, smoke production and toxic or asphyxiating components such as CO, HCN and CO₂ show high values in the first 300 s. CO reaches maximum values of 300 ppm and HCN approximately 40 ppm. It is imperative to note that the well-ventilated conditions in the cone calorimeter leads to a strong dilution of the gases.

The MARHE determined in the cone calorimeter for the foam is approximately 245 kW/m². In these tests, the material showed a

significantly different—lower—fire development than in the other tests. For the textiles, the MARHE was between 58 and 100 kW/m².

Table 1 shows the measured values for the parameters given in the Table 2 for all samples, averaged from three tests in each case. The deviation from the mean value is also given. The foam and textiles were tested individually and in combination. The testing of the combined materials will be published in Part 2 of the publication series. The repeatability of the tests was satisfactory, the deviations being values up to a maximum of 12%.

4.2 | Gas concentrations from DIN tube furnace experiments

In the following, concentration-time diagrams, Figures 10 and 11 for measured species and for the transmittance are shown as examples for a textile cover material (CD) and for the foam (PUR green) during the DIN tube tests. The diagrams contain plots of all individual experiments and an averaged over all experiments for the respective species. The concentration-time curves for CO, HCN, formaldehyde and ammonia are shown for the textile CD. In the DIN tube, 1 g sample

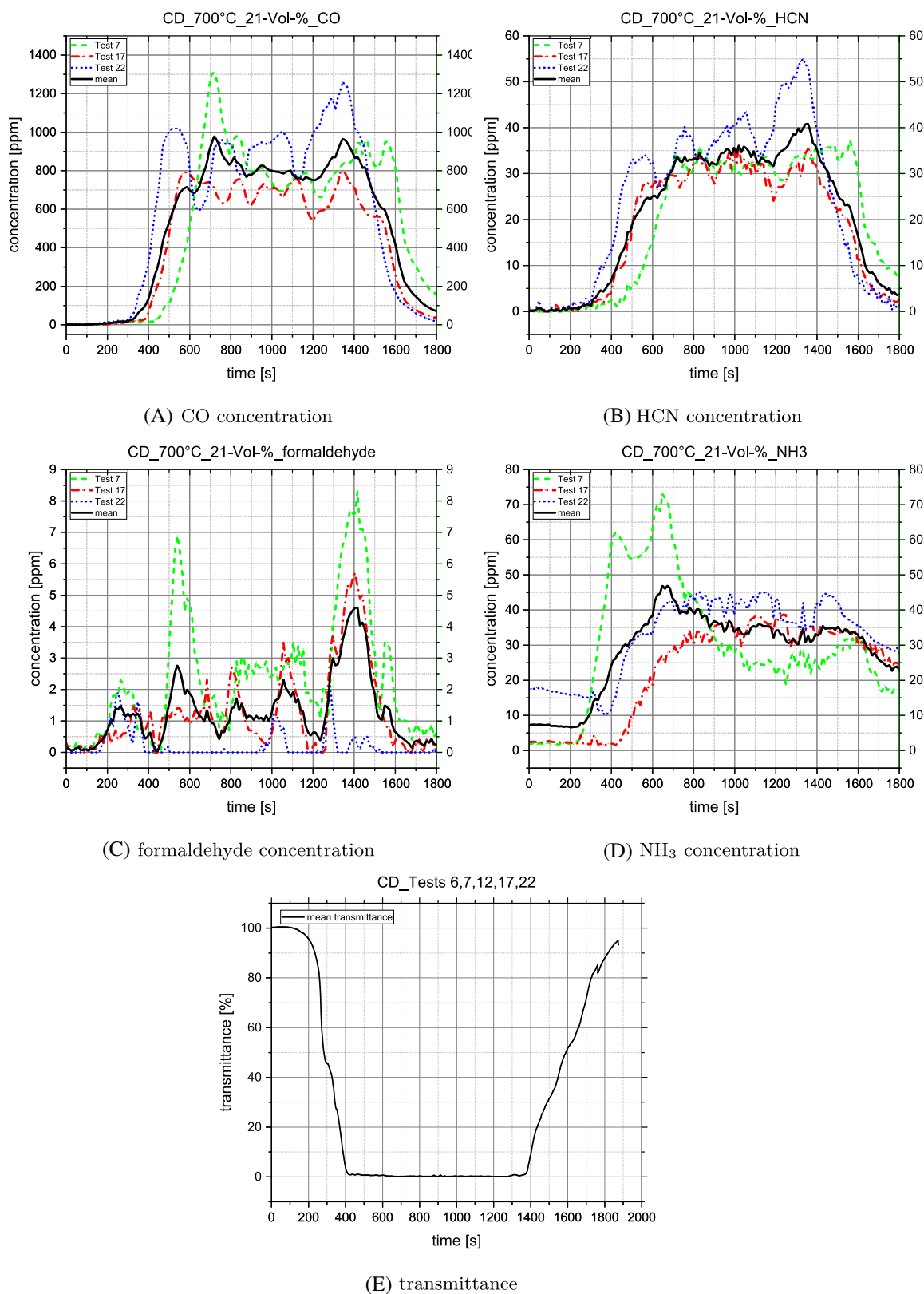


FIGURE 10 Selection of measured gas concentrations during the thermal decomposition of textile CD in the DIN tube furnace. (A) CO concentration. (B) HCN concentration. (C) Formaldehyde concentration. (D) NH₃ concentration. (E) transmittance.

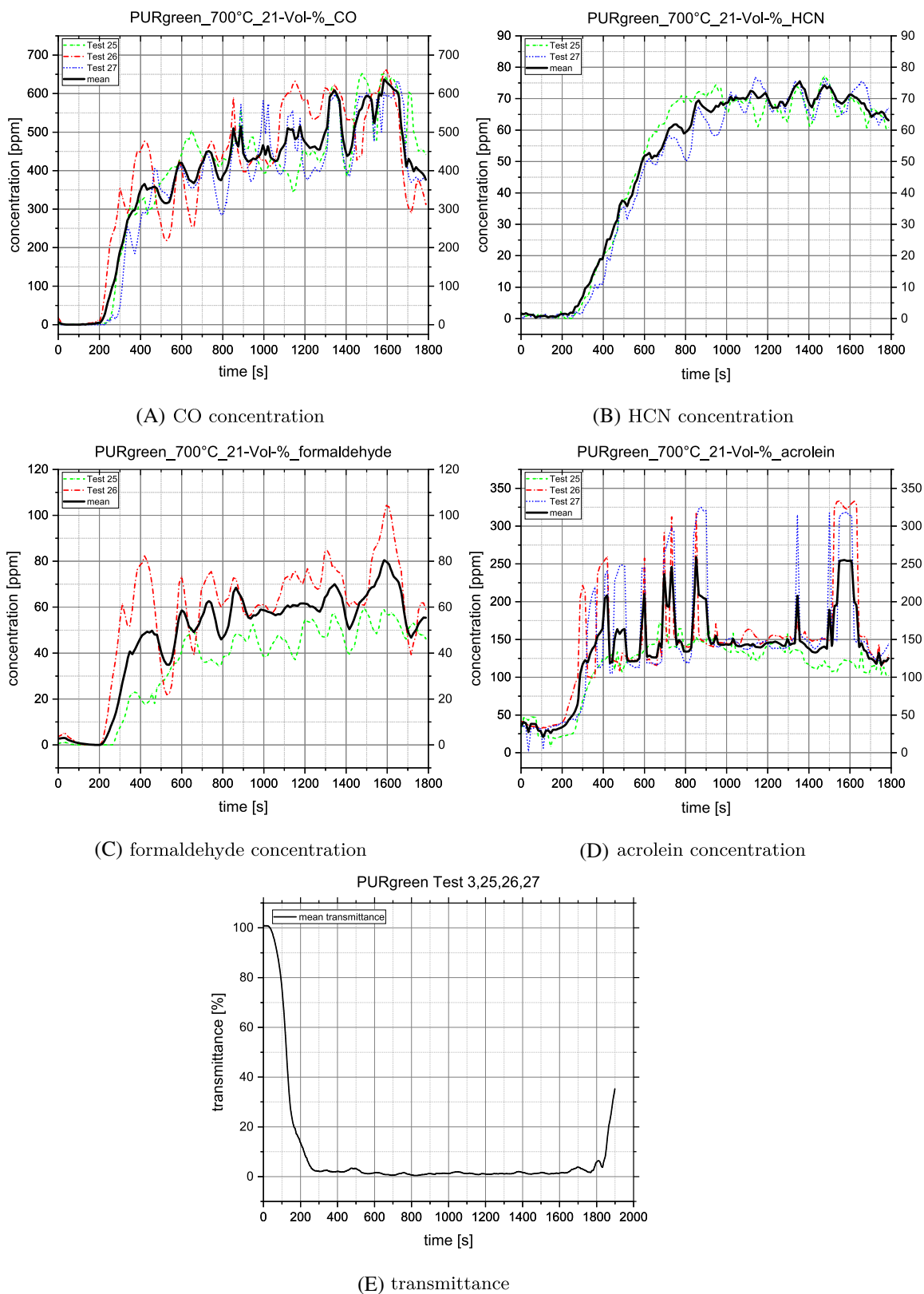


FIGURE 11 Selection of measured gas concentrations during the thermal decomposition of the green polyurethane cushion in the DIN tube furnace. (A) CO concentration. (B) HCN concentration. (C) Formaldehyde concentration. (D) Acrolein concentration. (E) Transmittance.

TABLE 3 Maximum concentrations of various measured fire smoke components in the DIN tube furnace averaged over the number of tests per configuration in comparison with IDLH values and AEGL-2 values for 10- and 30-min exposure

	Carbon monoxide CO (ppm)	Hydrogen cyanide HCN (ppm)	Nitrogen oxide NO _x (ppm)	Acrolein C ₃ H ₄ O (ppm)	Sulphur dioxide SO ₂ (ppm)	Methanol CH ₄ O (ppm)	Nitrogen dioxide NO ₂ (ppm)	Formaldehyde CH ₂ O (ppm)	Acetaldehyde C ₂ H ₄ O (ppm)	Benzene C ₆ H ₆ (ppm)
First symptoms of intoxication	200	18	10	1.8	10-20	160-1000	-	10-20	-	4
AEGL-2 10 min	420	17	NR ^a	0.44	0.75	11 000	20	14	340	2000
AEGL-2 30 min	150	10	NR ^a	0.18	0.75	4000	15	14	340	1100
IDLH	1,200	50	100	2	100	6,000	13	20	2,000	500
RC	843	37	7	27	567	4	7	3	140	48
CD	978	41	5	10	307	5	4	5	137	55
MB	1,237	12	7	18	558	10	7	22	27	54
LW	618	138	15	34	259	3	5	1	38	22
PUR green	637	76	94	259	177	65	88	80	306	89

^aNot recommended due to insufficient data.

mass is decomposed over 30 min, with resulting HCN concentrations of over 40 ppm, in Figure 10B. This clearly exceeds tolerable concentrations at which the first signs of poisoning are likely. The transmission decreases to zero after 400 s.

When measuring the PU foam in the DIN tube furnace, measurable concentrations of CO, HCN, acrolein and formaldehyde were particularly noticeable. Especially formaldehyde and hydrogen cyanide with approximately 80 ppm clearly exceed tolerable concentrations for the assessment of the hazards from fire smoke. In addition to the this components, the PU tests also showed measurable concentrations of methane, carbon dioxide, hydrogen fluoride, acetylene, nitrogen dioxide, acetone, hydrogen chloride, ammonia, ethene, ethane, nitrous oxide and methanol. The transmission drops to values almost zero after just 240 s.

An analysis and evaluation of the measured concentrations from the DIN tube tests for all decomposed textiles and for PU foam can be found in the Table 3 below. The table shows the maximum concentrations of selected species averaged over the respective number of tests in the DIN tube for all textiles and foam tested: CO, HCN, nitrogen oxide, acrolein, sulphur dioxide, methanol, nitrogen dioxide, formaldehyde, acetaldehyde and benzene. The maximum concentrations are compared with the IDLH values specified in the literature¹⁴ and threshold values that are related to the first symptoms of poisoning or intoxication¹ as well as with the AEGL-2 values for 10- and 30-min exposure. All measured maximum concentrations exceeding the IDLH values or AEGL values were marked in color.

For acrolein and sulphur dioxide, the IDLH limit values have been exceeded for all materials. The limit concentration of acrolein is exceeded 130 times with PUR (green). All examined materials show high concentrations of HCN during the thermal decomposition and clearly exceed the IDLH. The evaluation of the PU tests show very high concentrations of HCN, nitrogen oxide, acrolein, sulphur dioxide, nitrogen dioxide as well as formaldehyde. With regard to the evaluation of the smoke toxicity, the PU foam must be classified as rather insufficient. The examination of the textile MB showed particularly high CO values and also the highest SO₂ concentration. It is also the only textile examined that had exceeded the limit values for formaldehyde.

5 | CONCLUSIONS AND RECOMMENDATIONS

The results of the bus interior tests in the cone calorimeter and the DIN tube show clearly that evaluating bus interior materials need to take three key parameters into account: HRR, smoke gas production and toxicity of the smoke gases. These three parameters allow assessment of different hazards for bus passengers: high rates of heat release lead to a rapid spread of fire within the passenger compartment, thermal tenable conditions will deteriorate more quickly as well, both limiting the time for escape. High rates of smoke production lead to reduced visibility which prevents passengers to escape. Toxicity of smoke gas components lead to reduced mobility through smoke gas inhalation which prevents escape as well.

Test results show that limiting one or two of the parameters does not ensure reducing values for the third parameter. Therefore, limiting all three parameters for the use of materials in bus interiors is important. The investigations have also shown that for the evaluation of smoke toxicity and the measurement of SRP different combustion conditions should be taken into account: the experiments in the DIN tube showed much higher smoke concentrations compared to the experiments under flaming combustion conditions in the cone calorimeter when testing the same materials (textile and foam).

The fire development in buses is rapid in a lot of cases. Passengers have to evacuate before fire service arrives. That means that rescue of mobility reduced persons is not possible and is accepted when travelling by bus. The test results in the cone calorimeter tests with FTIR accordingly show high values for heat and smoke release rates as well as for toxic smoke gas components in the first 300 s of each test.

Therefore, limiting HRRs, SRPs and toxicity of smoke gas components of bus interior materials is important to allow more time for escape and enable fire service to rescue passengers.

As possible tests for an assessment of bus interior materials the cone calorimeter with FTIR and the DIN tube with FTIR have been investigated. The cone calorimeter allows the measurement of all three key parameters to assess the burning behaviour of bus interior materials. However, in the used version of the cone calorimeter according to ISO 5660-1 it allows only the assessment of flaming combustion. The MLC allows to measure two of the three parameters as the smoke production was not measured in the used approach. However, it would be possible to realise flaming and smouldering conditions in using the box (according to ISO 5660-5) to control the incoming oxygen. The DIN tube allows the assessment of the two parameters smoke gas production and smoke gas toxicity under smouldering combustion conditions. In the cone calorimeter values for all three parameters showed good reproducibility and provided evaluable test results.

The DIN tube allowed assessment of the bus interior materials under smouldering combustion conditions. The experimental results show very high values of toxic smoke gas components for these conditions.

That leads to the conclusion that the three parameters HRR, smoke gas production and toxic smoke gas components have to be assessed under both, flaming and smouldering combustion conditions.

In this project bus interior materials have been investigated which fulfil the newest regulations for bus interior materials, namely, the newly introduced requirement of a pass of the test for vertical burning behaviour according to Annex 8 of UNECE R 118 for vertical mounted materials. However, results of the bus interior materials tested in this research project were very similar to those in the previous project FE 82.0377/2009 'Investigation of the origin, spread and toxicity of smoke in bus fires examined samples' for the values for heat release, smoke production and toxicity of the smoke gases although most materials did not need to fulfil the test for vertical burning behaviour according to Annex 8 of UNECE R 118 at the time.

To increase safety for bus passengers in the event of fire, it is recommended to introduce limits for the rate of heat release and smoke production as well as for the toxicity of smoke gas components. One way to achieve that is to use materials which are used in trains according to EN 45545-2 as these regulations already limit these three parameters.

Operating conditions of buses and trains are comparable, at least city buses and trams and coaches and long distance trains. However, it has to be noted that the regulations for trains take the size and conditions of train carriers into account. The volume of bus cabins tend to be smaller than train carriers.

As a conclusion an approach for buses has to consider that bus cabins are normally smaller than train compartments and would have to limit all three parameters (rate of heat release, smoke production and toxicity of smoke gas components) under flaming and smouldering conditions. These conclusions are also supported by past work in this environment.^{29–33} This is possible either in a combination of the DIN tube with the cone calorimeter. For this case the cone calorimeter has to be used with a box according to ISO 5660-5³⁴ to control the oxygen supply.

For the establishment of limits of the three key parameters and as a holistic approach, bench and additional large scale experiments are required to evaluate the fire safety of interior bus materials. Bench-scale tests with seats have been already performed and are to be discussed in a following paper as well as the use of numerical calculations to assess the situation in a bus cabin by using data from small scale and bench-scale tests.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available on request from the corresponding author [AK].

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REFERENCES

- Hofmann A, Dülens S. Study on Smoke Production, Development and Toxicity in Bus Fires (Bericht Zum Forschungsprojekt Fe 82.0377/2009). 2014. Accessed March 15, 2022. <http://bast.opus.hbz-nrw.de/volltexte/2015/840/pdf/F99b.pdf>
- Huczek JP, Blais MS. Motorcoach Fire Safety (Final Report). National Highway Traffic Safety Administration. 2015.
- Göransson U, Lundqvist A. Fires in Buses and Trains. Fire Test Methods (SP Report 1990:45). 1990:63.
- Tewarson A, Quintiere JG, Purser DA. Post Collision Motor Vehicle Fires (Technical Report). Motor Vehicle Fire Research Institute. 2005.
- Digges KH, Gann RG, Grayson SJ, et al. Human survivability in motor vehicle fires. *Fire Mater*. 2008;32:249–258.
- Sundström B. Comparison of product evaluation systems in Europe for road and rail vehicles. Paper presented at: Proceedings from 1st International Conference on Fire in Vehicles. SP Technical Research Institute of Sweden. 2010.
- Hofmann A, Dülens S, Försth M, Brandt J. What can we learn from European train fire safety regulations for fire safety regulations for busses? Paper presented at: 5th International Conference on Fire in Vehicles - FIVE 2018. RISE Sweden. 2018.
- UNECE. Status of the 1958 Agreement (and of the annexed regulations).
- Publications Office of the EU. UNECE Regulation No 107 of the Economic Commission for Europe of the United Nations (UNECE)—uniform provisions concerning the approval of category M2 or M3 vehicles with regard to their general construction. 2015.
- UN Regulation No. 118. Uniform technical prescriptions concerning the burning behaviour and/or the capability to repel fuel or lubricant of materials used in the construction of certain categories of motor vehicles. 2012.
- International Organization for Standardization. ISO 13943:2017. Fire Safety—Vocabulary. 2018.
- Office of Response and Restoration. Emergency Response Planning Guidelines (ERPGS). 2019.
- Office of Response and Restoration. Acute Exposure Guideline Levels (AEGLS). 2019. Accessed May 27, 2022. <https://response.restoration.noaa.gov/oil-and-chemical-spills/chemical-spills/resources/acute-exposure-guideline-levels-aegls.html>
- Centers for Disease Control and Prevention. National Institute for Occupational Safety and Health (NIOSH). Table of IDLH Values. Accessed May 27 2022. <https://www.cdc.gov/niosh/idlh/intrid4.html>
- Purser DA, McAllister JL. Assessment of hazards to occupants from smoke, toxic gases and heat. In: Hurley MJ, Gottuk D, Hall JR, et al., eds. *SFPE Handbook of Fire Protection Engineering*. Vol 5. 5th ed. Springer; 2016:2308–2428.
- Purser DA. The application of exposure concentration and dose to evaluation of the effects of irritants as components of fire hazard. Paper presented at: Interflam 2007 Conference Proceedings. 2007.
- Purser DA. Toxicity assessment of combustion products. In: DiNenno PJ, ed. *SFPE Handbook of Fire Protection Engineering*. Springer; 1995:85–146.
- Babrauskas V, Gann RG, Levin BC, et al. *Toxic Potency Measurement for Fire Hazard Analysis*. Vol 827. NIST Special Publication; 1991.
- Babrauskas V, Gann RG, Levin BC, et al. A methodology for obtaining and using toxic potency data for fire hazard analysis. *Fire Saf J*. 1998;31:345–358.
- Stec AA, Hull TR. *Fire Toxicity*. Woodhead Publishing; 2010.
- International Organization for Standardization. ISO 13571:2012. Life-Threatening Components of Fire—Guidelines for the Estimation of Time to Compromised Tenability in Fires. 2012.
- Blomqvist P, Simonson-McNamee M. Large-scale generation and characterisation of fire effluents. In: Stec A, Hull R, eds. *Fire Toxicity*. Woodhead Publishing; 2010.
- International Organization for Standardization. ISO 5660-1:2015. Reaction to Fire Tests—Heat Release, Smoke Production and Mass Loss Rate—Part 1: Heat Release Rate (Cone Calorimeter Method) and Smoke Production Rate (Dynamic Measurement). 2015.
- Deutsche Institut für Normung e.V. *DIN 4102-1:1998-05: Brandverhalten von Baustoffen und Bauteilen, Teil 1: Baustoffe Begriffe, Anforderungen und Prüfungen*. Beuth Verlag GmbH; 1998.
- Deutsche Institut für Normung e.V. *DIN 53436-1:2015-12: Erzeugung thermischer Zersetzungsprodukte von Werkstoffen für ihre analytisch-toxikologische Prüfung – Teil 1: Zersetzungsgerät und Bestimmung der Versuchstemperatur*. Beuth Verlag GmbH; 2015.
- Wakefield JC. A toxicological review of the products of combustion. 2010. Accessed June 15, 2021. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/458052/HPA-CHaPD-004_for_website.pdf

27. Gasmnet.de. Fourier-Transform-Infrarot - Gasmnet.de. Accessed June 21, 2021. <https://www.gasmnet.com/de/produkte/fourier-transform-infrarot/>
28. Löhnert A, Monreal N, Knaust C, Hofmann A. CFD modeling approach of smoke toxicity and opacity for flaming and non-flaming combustion processes. *Fire Mater.* 2016;40:759-772.
29. Hofmann A, Dülsen S, Klippel AP. Problems in bus fire safety—Recent developments and possible solutions. Paper presented at: Fire and Materials 2013: 13th International Conference. 2013.
30. Hofmann A. What can we learn from European train fire safety regulations for fire safety regulations for busses? Paper presented at: 5th International Conference on Fire in Vehicles—FIVE 2018. 2018.
31. Grayson S. Letter to fire journal editors on materials identification in comparison of results among fire scaling and flammability studies. *Fire Mater.* 2018;42:581-582.
32. Försth M. Bus fires—presentation of a large nordic research project. Paper Presented at: Proceedings from 1st International Conference on Fire in Vehicles. SP Technical Research Institute of Sweden. 2010.
33. Johansson P, Axelsson J. Fire Safety in Buses—WP2 Report: Fire Safety Review of Interior Materials in Buses (Technical report). SP Technical Research Institute of Sweden. 2006.
34. International Organization for Standardization. ISO/TS 5660-5:2020. Reaction-to-Fire Tests—Heat Release, Smoke Production and Mass Loss Rate—Part 5: Heat Release Rate (Cone Calorimeter Method) and Smoke Production Rate (Dynamic Measurement) under Reduced Oxygen Atmospheres. 2020.

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