

Secondary emissions risk assessment of diesel particulate traps for heavy duty applications

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ABSTRACT

Most particulate traps efficiently retain soot of diesel engine exhaust but the potential hazard to form secondary emissions has to be controlled. The DPF regeneration is mainly supported by metal additives or metallic coatings. Certain noble or transition metals can support the formation of toxic secondary emissions such as dioxins, PAH, Nitro-PAH or other volatile components. Furthermore, particulate trap associated additive metals can penetrate through the filter system or coating metals can be released from coated systems. The VERT test procedure was especially developed to assess the potential risks of a formation of secondary pollutants in the trap. The present study gives an overview to the VERT test procedure. Aspects of suitability of different fuel additives and coating metals will be discussed and examples of trap- and additive induced formation of toxic secondary emissions will be presented.

INTRODUCTION

Particulate traps are very efficient to minimise soot emission of heavy duty diesel engines. Metal additives or metallic coatings can be used to enhance soot combustion in both, the engine and the particulate trap. Transition or noble metals, used as fuel additives or catalytic coatings on the filter system, decrease the soot ignition temperature to values that are obtained in most heavy duty applications.

Diesel soot is a complex mixture of elemental carbon and organic compounds. Therefore, a loaded particle trap with added catalyst has to be considered as a chemical reactor with potential to form toxic secondary

emissions such as dioxins, PAH, Nitro-PAH or other volatile components. Furthermore, metal additives may penetrate the filter system or be released from its coating.

The VERT test procedure was developed in Europe to guarantee the efficiency and real-world suitability of particulate traps used on heavy-duty diesel engines. The VERT secondary emission test (VEST), which is the main focus of this publication, was designed to avoid the potential risk of particulate traps for the formation of secondary pollutants. The VERT procedure is now mandatory for trap certification in Switzerland, Germany and Austria. Only particulate trap systems which passed this VERT test procedure are included in the VERT filter list^[1] and officially recommended for retrofitting. Up to now, about 20 different particulate trap systems for heavy duty applications have been evaluated with respect to secondary emissions of toxic organic compounds as well as for trace metal penetration.

In this study aspects of suitability of different additive elements or coatings will be discuss. Moreover, correlations between specific metal species used as additive or coating and the potential formation risk of specific secondary pollutants have been investigated.

EXPERIMENTAL

VERT TEST PROCEDURE

The abbreviation VERT is a synonym for „Verminderung der Emissionen von Real-Dieselmotoren im Tunnelbau“, which means reduction of real diesel engine emissions at tunnel construction sites.^{[1][2][3]} While tunnel construction was the main focus during the very first test development, the VERT procedure (Figure 1) is now

applied in a more general way to diesel particulate traps for other heavy duty applications and even to private traffic diesel vehicles. The secondary emissions test (VSET) is designed to identify traces of unwanted toxic secondary emissions. Hence, it must fulfil the following conditions: The test must

- be representative for typical operational deployment of the DPF system.
- contain worst case conditions in terms of the formation of secondary toxic emissions.
- ensure a representative sampling for the analysis of trace and ultratrace compounds.
- cover all possible DPF operation conditions, including loading and regeneration.
- include adequate sampling procedures for trace analysis of particulates, metals and organic compounds.

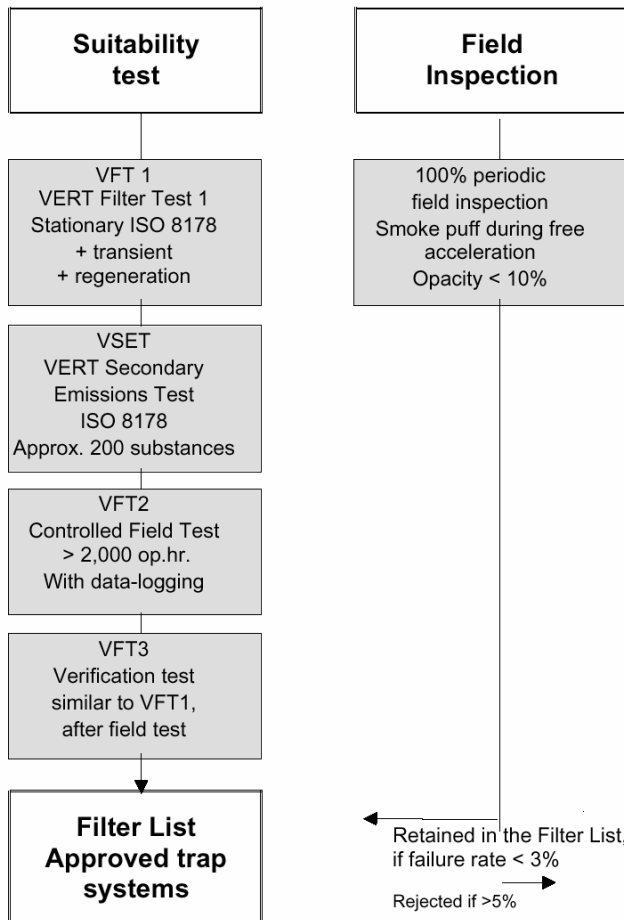


Figure 1: VERT suitability test

VERT Test Conditions

A ISO 8178/4 C1 cycle (Figure 2) is driven two times in sequence to provide sufficient sampling time for inorganic analysis (200 minutes) and four times (400 minutes) for appropriate sampling for organic analysis. The cycle is an industry-wide consensus

considered as representative for common operation conditions of construction site machinery. It ensures that all characteristic conditions for the formation and emission of toxic substances are simulated during the VERT test. This is especially important for the temperature, which covers a wide range from idle to full load.

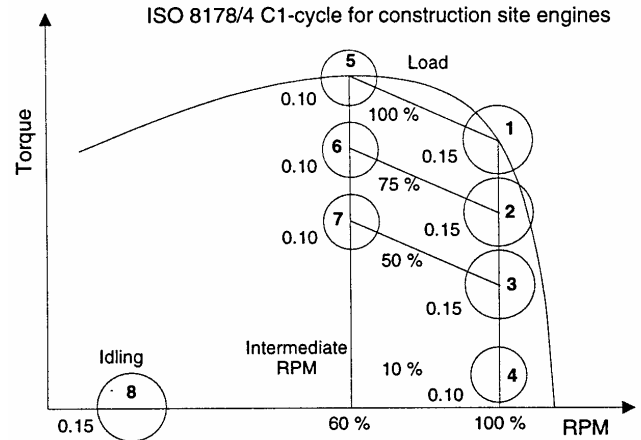


Figure 2: Test cycle for VSET Test according to ISO 8178/4 C1

The cycle covers both, the accumulation and the regeneration phase during which catalytic soot combustion takes place.

VERT Test Equipment

The test described here were performed either at the University of applied sciences in Biel (FH Biel) or at the Swiss Federal Laboratories for Material Testing and Research (EMPA). Characteristics of the engines used are given in Table 1. The engines were run with diesel fuel according to EN SN 590. As particle traps require diesel with low sulphur content, the sulphur content of the reference diesel was always a low sulphur diesel. The actual state of the art diesel fuel for VERT testing has sulphur content below 50 µg/g.

Table 1: Test-engines used for VERT tests

Sampling Site	FH Biel	EMPA
Manufacturer:	Liebherr	Liebherr
Engine type	Liebherr 914 T	Liebherr 924 TI
Displacement:	6.11 litres	6.6 litres
Rated RPM:	2,000 RPM	2,000 RPM
Rated power:	105 kW	143 kW
Supercharging:	Turbocharger with vario turbine	Turbocharger with air intercooler and direct injection

An overview of the main sampling locations and analytical techniques used during the secondary emission test (VSET) is given in Figure 3.

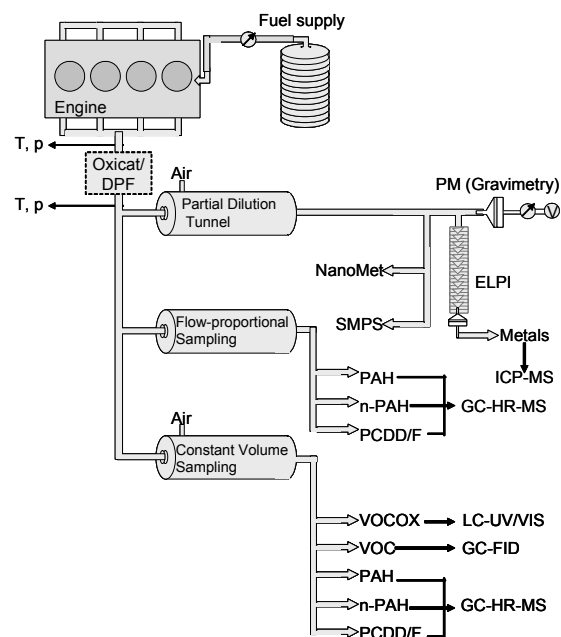


Figure 3: Schematic of sampling and analytical techniques in VERT secondary emissions test (VSET).

SAMPLING

Depending on the DPF system three to five test configurations are required. While all five configurations given below are tested for fuel additive supported DPF systems, for coated systems two configurations can be omitted. M is a synonym for a specific additive metal and will be replaced in the following graphs by synonyms for specific elements such as K for copper, C for cerium, E for iron.

- RO engine driven with reference diesel without fuel additives and without particle trap
- MO: engine driven with metal additivated diesel without particle trap
- MF: engine driven with metal additivated diesel with particle trap
- HMO: engine driven with metal and chlorine additivated diesel without particle trap
- HMF: engine driven with metal and chlorine additivated diesel with particle trap

Table 2 summarizes the parameters required according to the current VERT test regulation. The list covers besides regulated pollutants also potential unwanted toxic secondary emissions of serious health risk.

Table 2: Parameters tested in VERT static test including sampling and analytical method

Parameter	Sampling type	Analytical method
Opacity	Directly from exhaust gas	Method of free acceleration according METAS-instrument norm, SAE J 1667 ^[4]
EC mass	Partial flow or full flow dilution tunnel	Coulometry according to VDI 2465 ^[5]
PM mass	Partial flow dilution	Filter gravimetry according ISO 8178
PM size distribution	Partial flow dilution	ELPI + SMPS
Particle number (10-300 nm)	Partial flow dilution or full flow or directly from exhaust gas	Thermodilution and SMPS
Particle surface	Partial flow dilution or full flow or directly from exhaust gas	NanoMet including thermodiluter
CO	Condensation from exhaust gas	NDIR
HC	Flow proportional sampling from raw exhaust gas	FID
NOx NO2/NOx	Heated sampling line and permeation dryer from raw exhaust gas	CLD with converter
Metals (PM-bonded)	Flow proportional dilution, ELPI	ICP-MS
PCDD/F	Flow proportional from raw exhaust gas, sampling train	GC-HRMS
PAH	Flow proportional from raw exhaust gas, sampling train	GC-HRMS LC-UV / Fluorescence
Nitro-PAH	Flow proportional from raw exhaust gas, sampling train	GC-HRMS
VOC	CVS sampling from diluted exhaust	GC-FID
Aldehydes/ Ketons (VOCOX)	CVS sampling from diluted exhaust, chemisorption	LC-UV/VIS

ORGANIC ANALYSIS

For the analysis of organic traces, such as PCDD/F or PAH, it is necessary to sample large amounts of raw gas.^[6] To yield a representative sample, its volume has to be proportional to the total raw gas flow at any given time of the test cycle. This was achieved by pumping a partial flow of the exhaust out of the 100 mm ID tubing

directly after the engine or after the particulate trap. The raw exhaust flux was determined based on continuous measurements of gas velocity and temperature using a Pitot tube and a K-type thermo-element. The sample flow was continuously measured by a specially designed Venturi (Kalman Inc.) and the frequency controlled pump (Piccolino, Rietsch AG) adjusted accordingly by a dedicated software. Sampling was done by condensation and adsorption on XAD-2 in a condensation setup adapted from EN 1948-1. The total sample volume was about 10 Nm³.

INORGANIC ANALYSIS

The VERT test procedure combines the control of a potential penetration risk of the additive elements supporting DPF regeneration. Additives are usually added in form of organo-metallic components or in form of colloidal oxides. Coated particle filter systems have to be controlled for a potential release of the coating metals. Therefore the particulate emissions are sampled size classified from the partial dilution tunnel using an electrical low pressure impactor (ELPI) with 12 stages for a size classification in the range of 30 nm to 10 µm and an additional downstream backup filter to collect particles < 30 nm.

All filter samples are digested in a MLS 1200 Mega – High Performance Microwave Digestion Unit (MSL GmbH) upgraded with temperature control unit. To achieve the required low detection limits, only ultra pure quality acids (Merck) and high-purity water (18.2 MΩ cm), prepared by a Milli-Q Gradient A10 system (Millipore), are used for sample and standard preparation. Standards are prepared from single and multi-element standards in ICP-quality (Merck and Alfa Aesar). A specific digestion procedure was especially optimised to achieve best detection limits.^{[7][8][9][10]}

Depending on the elements of interest the aqueous digestion solutions are determined using a quadrupole-ICP-MS ELAN 6000 (Perkin Elmer/Sciex) or a magnetic sector field ICP-MS ELEMENT II (ThermoFinnigan) both operated under standard hot plasma conditions. The instrument detection limits of the ICP-MS are for most of the elements in the ng/L range.

The dosing of additive elements is also controlled. Sulphur and chlorine are directly determined in undiluted samples using a Philips PW-1400 wavelength dispersive x-ray fluorescence spectrometer (WD-XRF) with typical detection limits of 1 – 2 µg/g. Many elements can be determined directly in the diesel samples after dilution with xylene using an ICP-OES (radial VistaPro ICP-OES Varian) if oil-based calibration standards such as from Conostan are available. For the quantification of other elements the diesel samples have to be digested.

Further details about optimization of the metal sampling as well as development and optimization of the digestion procedure and analysis methods can be found in [7], [8], [9] and [10].

RESULTS AND DISCUSSION

As an example of the VSET, the emission characteristic of 4 sintered metal filter systems with respect to regulated and toxic organic compounds are discussed below. One sintered metal filter was operated with reference diesel and no additives. Three sintered metal filters (SHW) were run in combination with iron-, cerium-, and copper-based fuel additives. The additives were diluted to iron-, cerium- and copper-levels of 37, 64 and 56 µg/g, respectively.

REGULATED POLLUTANTS

In all test configurations the examined Euro-2 diesel engine (Liebherr, 924 TI, 6.6 l) fulfilled the valid EU off-road limits for construction engines (stage 1) with limitations for CO, THC, NOx and PM of 5.0, 1.3, 9.2 and 0.54 g/kWh, respectively. Figures 4-7 represent the conversion efficiencies of the 4 traps for THC, PM NOx, and CO.

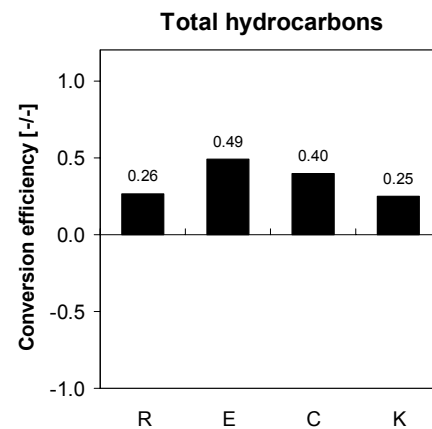


Figure 4: THC conversion efficiency of sintered metal filters with reference diesel (R), iron- (E), cerium-(C) and copper- (K)-additivated fuel

As shown in Figure 4, THC emissions are reduced by 25-49% when applying a trap in all tested configurations. Conversion efficiencies of 95-96% were obtained for particulate matter (Figure 5). As reported earlier, even higher filtration efficiencies above 98.6% are obtained for particulate number in the size range of 20-300 nm.^[11] These findings indicate that all investigated traps efficiently reduced particulate matter independent of the fuel additive used.

No significant effects of the applied traps were noticed for NOx emissions (Fig. 6) but as shown in figure 7 CO conversion efficiency was negative for all 4 trap

applications. This indicates that CO emissions increase by 15-45% due to the applied trap. It is unclear whether additional CO is formed via a trap-induced partial combustion of soot and adsorbed hydrocarbons, or if the increased CO emissions are the result of changed engine parameters, e.g. increasing exhaust gas back pressure.

It can be concluded that (i) an efficient filtration of particulate matter occurred, (ii) hydrocarbons were retained in all 4 investigated trap systems, (iii) the traps had no effects on nitrogen oxide levels and (iv) based on increased CO emissions a trap-induced soot combustion can be postulated.

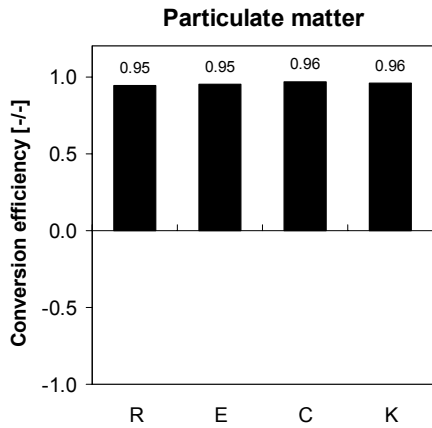


Figure 5: PM conversion efficiency of a sintered metal filter with reference diesel (R), iron- (E), cerium-(C) and copper- (K)-additivated fuel

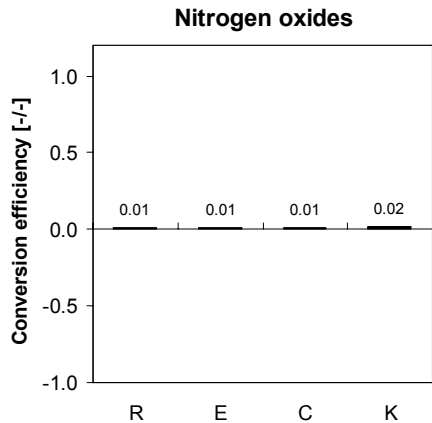


Figure 6: NOx conversion efficiency of sintered metal filters with reference diesel (R), iron- (E), cerium-(C) and copper- (K)-additivated fuel

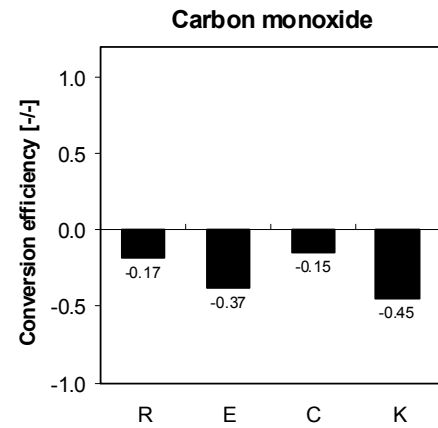


Figure 7: CO conversion efficiency of sintered metal filters with reference diesel (R), iron- (E), cerium-(C) and copper- (K)-additivated fuel

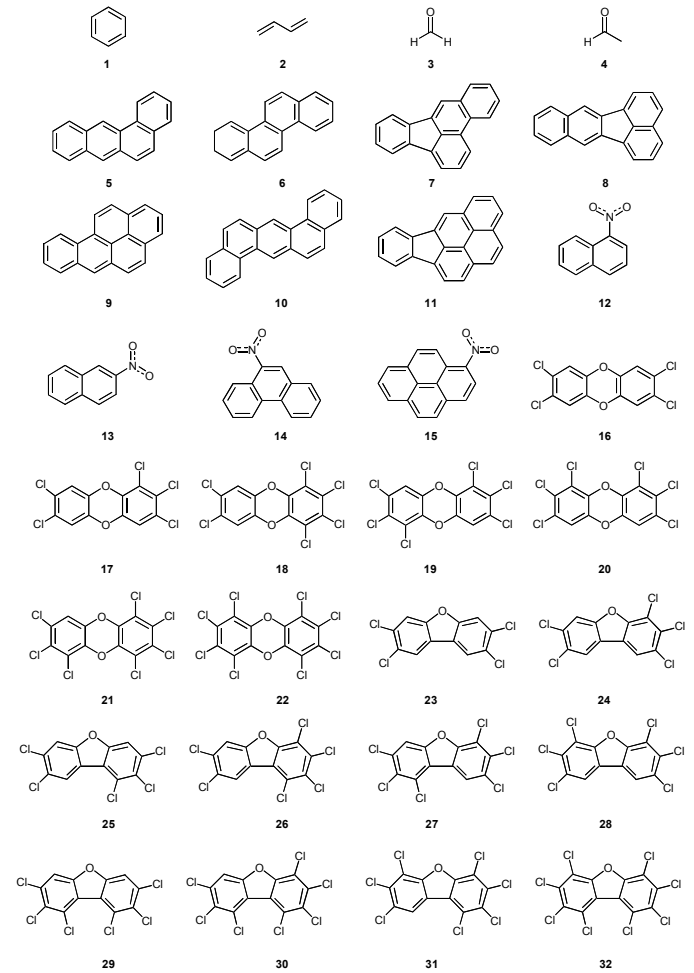


Figure 8: Chemical structures of toxic trace compounds. Investigated were carcinogenic VOC (1-4), carcinogenic PAH (5-11), nitro-PAH (12-15), toxic PCDD (16-22) and toxic PCDF (23-32).

TOXIC ORGANIC TRACE COMPOUNDS

Given the pronounced chemical transformation reactions observed for the regulated pollutants, it is of importance to also study effects of such combustion conditions on the emissions of hazardous compounds present at trace- and ultra-trace level. Therefore, the scope of the analysis was enlarged and the potential secondary emissions risks for toxic, carcinogenic or mutagenic compounds were investigated in detail.

Figure 8 displays the chemical structures of the most relevant toxic organic trace compounds investigated in the VERT secondary emission test (VSET). The focus is mainly on the carcinogenic compounds.

VOLATILE HYDROCARBONS

At trace level, hundreds of different hydrocarbons can be distinguished in diesel exhaust, all of them contributing to the THC signal. Four of them, their chemical structures are given in figure 8, are classified as human carcinogens, benzene (1), 1,3-butadiene (2), formaldehyde (3) and acetaldehyde (4).

Figure 9 indicates that no net benzene (1) conversion is occurring in the trap. On the opposite, negative conversion efficiencies were observed for all trap configurations indicating that benzene is formed to some degree upon soot combustion. Similar findings were obtained for 1,3-butadiene (2) another volatile carcinogenic hydrocarbon (data not shown).

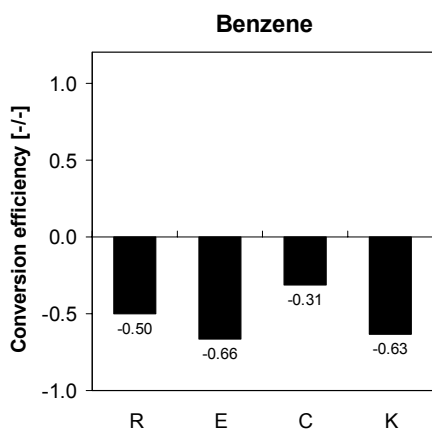


Figure 9: Benzene conversion efficiency of a sintered metal filter with reference diesel (R), iron-(E), cerium-(C) and copper-(K)-additivated fuel

This contrasts the findings of reduced overall hydrocarbon emissions (THC) as discussed above (Fig. 4). Benzene and 1,3-butadiene are highly volatile

and therefore not adsorbed on the trap material or the diesel soot, whereas other higher boiling hydrocarbons such as the saturated hydrocarbons characteristic for diesel fuel (C_xH_{2x-2} , $x>12$) are less volatile and therefore efficiently retained in the trap.

Formaldehyde (3) and acetaldehyde (4) are partially oxidised hydrocarbons classified as human carcinogens too. Figure 10 shows, that independent of the fuel formaldehyde emissions are reduced to some degree in the traps. Since both aldehydes are volatile enough to penetrate the trap, the overall reduction is less efficient than for less volatile hydrocarbons.

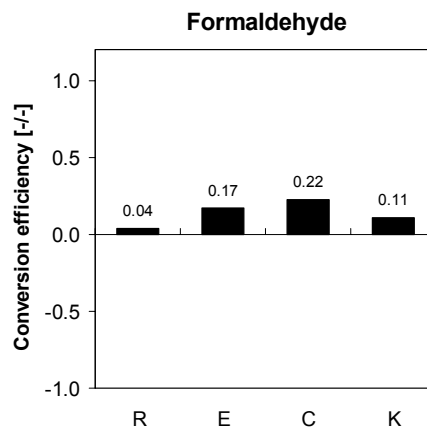


Figure 10: Formaldehyde conversion efficiency of a sintered metal filter with reference diesel (R), iron-(E), cerium-(C) and copper-(K) additivated fuel

POLYCYCLIC AROMATIC HYDROCARBONS

The analysis of polycyclic aromatic hydrocarbons was limited to 4- to 7-ring systems only. At room temperature, these PAH are mainly bound to particulates. Among these only the carcinogenic PAH (Fig. 8) benzo(a)anthracene (5), chrysene (6), benzo(b)fluoranthene (7), benzo(k)fluoranthene (8), benzo(a)pyrene (9), dibenzo(a,h)anthracene (10) and indeno(1,2,3-c,d)pyrene (11) were investigated.

Figure 11 displays the conversion efficiency for the sum of these carcinogenic PAH during trap application. All 4 trap configurations clearly reduced the emissions of carcinogenic PAH by 28-91%. Conversion efficiencies were even higher than those of the THC class of compounds (Fig. 4), but lower than for soot (Fig. 5).

These findings indicate that particulate traps significantly reduce the toxicity of diesel engine exhaust gas regarding carcinogenic PAH.

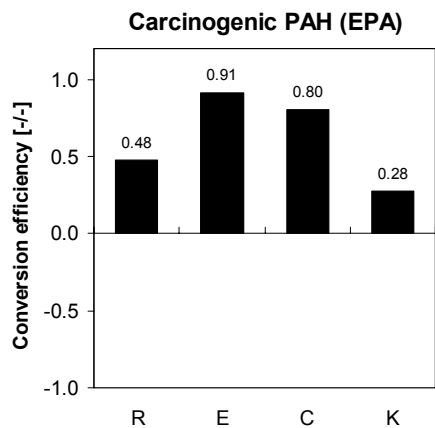


Figure 11: Carcinogenic PAH conversion efficiency of a sintered metal filter with reference diesel (R), iron- (E), cerium-(C) and copper- (K)-additivated fuel

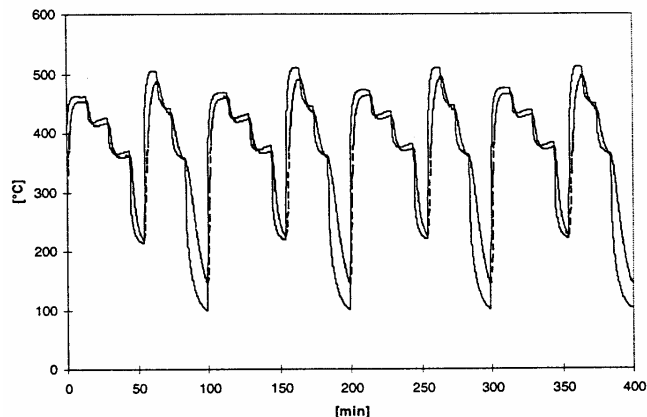


Figure 12: Temperature profiles before and after a sintered metal filter during four consecutive ISO 8178/4 C1 cycles.

POLYCHLORINATED DIBENZODIOXINS/FURANS

Compared to the regulated pollutants and to the individual hydrocarbons discussed so far, polychlorinated dibenzodioxins/furans (PCDD/F) are present only at ultra-trace levels ($\text{pg} = 10^{-12} \text{ g}$). Of the 75 different PCDD- and of the 130 individual PCDF-congeners only those 17 isomers with chlorine atoms at positions 2,3,7 and 8 are toxicologically relevant (Fig. 8). The overall toxicity of the PCDD/F-fraction (TEQ-sum) is therefore determined from the relative toxicity of the 2,3,7,8-substitued congeners and their respective concentration. The most toxic congener, the 2,3,7,8-tetrachlorodibenzodioxin (**16**), the so-called "Seveso-dioxin", is weighted with a factor 1, the least toxic octochlorodibenzodioxin (**22**) with a toxicity equivalent factor of 0.001.

Exhaust gas treatment in municipal waste incinerators (MWI) can induce a new formation of polychlorinated dibenzodioxins/furans. Especially during the filtration step a *de-novo* formation was observed in the critical temperature range of 260-440 °C. Figure 12 shows, that the examined particulate traps have been operated about 75-80% of the time in this critical temperature window.

The filter material itself as well as the trapped diesel nanoparticles offer a large surface for adsorption and therefore prolongate the residence time of potential PCDD/F precursor molecules in the trap. It is known that the presence of copper in the chlorine-rich flue gas of waste incinerators has a catalytic effect on the PCDD/F formation.^[12]

It can be concluded that all necessary conditions but one are given for an efficient *de novo* formation of PCDD/F in a particulate trap. Residence time, temperature, precursor levels and - in case of copper additives - also catalysts are optimal for an efficient PCDD/F synthesis. Only the chlorine levels are expected to be considerably lower than in MWI flue gas.

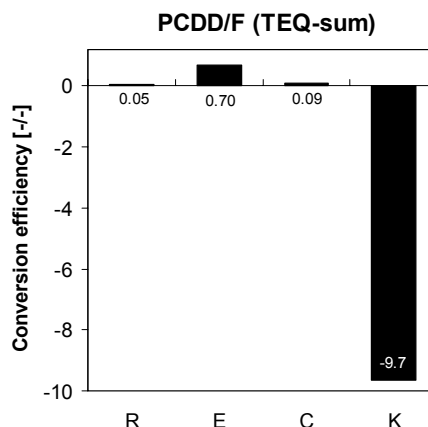


Figure 13: PCDD/F (TEQ-sum) conversion efficiency of a sintered metal filter with reference diesel (R), iron- (E), cerium-(C) and copper- (K)-additivated fuel

Therefore, the potential chlorine intake was examined. In the urban air of Zürich several $\mu\text{g}/\text{Nm}^3$ of chlorine-containing compounds, mostly chlorinated solvents, are present. Whereas no chlorine could be detected in the diesel fuel itself ($< 5 \mu\text{g}/\text{g}$), about 160 $\mu\text{g}/\text{g}$ chlorine was found in the applied lubricant oil. From these findings it can be concluded, that chlorine can accumulate in a particulate trap at μg -levels, representing a sufficient source for PCDD/F-formation at the pg -level. Nevertheless, to investigate the potential risk of a trap-induced PCDD/F formation at worst case conditions the

chlorine intake of the trap was increased via the application of chlorine-additivated diesel fuels.

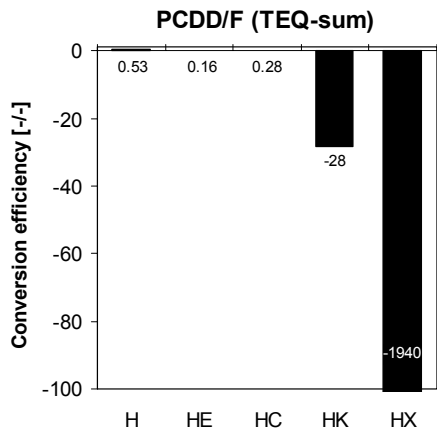


Figure 14: PCDD/F (TEQ-sum) conversion efficiency of a sintered metal filter with chlorine- (H, X = 10, 100 µg/g), iron- (E), cerium-(C) and copper- (K)-additivated fuel.

Figures 13 and 14 display the filter efficiency for PCDD/F (TEQ-sum) using commercial diesel fuel with no chlorine (< 5 µg/g) and chlorine-additivated diesel (H, X = 10, 100 µg/g). The chlorine level was increased via mixing with an aliquot of 1,6-dichlorohexane.

As shown in figure 13, the application of the sintered metal filter had no negative effect on PCDD/F emissions when using reference fuel as well as the iron- and cerium-based regeneration additives. But the copper-regenerated system clearly had a negative impact on the PCDD/F emissions. About 10 times more PCDD/F are emitted from the trap system than from the engine.

Even at increased chlorine levels (Fig. 14) the trap itself as well as the iron- and cerium-regenerated traps did not induce an increase of the PCDD/F emissions. In case of the copper-regenerated trap, PCDD/F emissions increased by about factors of 30 and 2000 when applying the chlorine-additivated fuels, respectively. These findings clearly prove that the presence of copper significantly increases the PCDD/F-formation potential of a particulate trap. This potential can be further increased by the presence of trace amounts of chlorine (µg-level) which can not be excluded at real world applications.

These findings also prove that particulate trap systems with different catalytic metals can promote very trap-specific chemical processes.

EFFECTS OF FUEL-ADDITIVES AND CATALYTIC COATINGS ON METAL EMISSIONS AND PARTICLE SIZE DISTRIBUTIONS

The additive must be well distributed in a stable mixture with the fuel. Usual additive doses range between 10 and 50 µg/g. The additives must mix perfectly with the diesel fuel and should be well distributed within each fuel micro-droplet during the combustion process. The stability of the additive-fuel mixture depends on the chemical form of the additive metal as well as on the fuel composition. Additives are usually added as organo-metallic-compounds (e.g. iron) or in form of colloidal oxide form (e.g. cerium).^[13] At first, single metal additives have been tested but mixtures of two additive metals become more common. According current knowledge, the additives form catalytically active metal oxides during combustion and exit the combustion chamber as ultra-fine solid clusters in the nano-meter range.

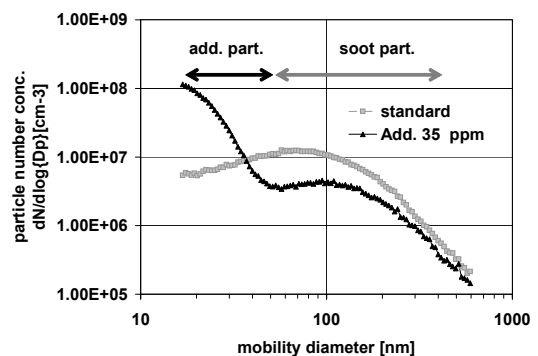


Figure 15: Particle size distribution of diesel emissions with and without cerium additivated fuel^[14]

Additives can change size distribution of the emitted particles.^{[15][16][17]} It might also be assumed that the chemical form of an additive has a significant effect on the size distribution, especially if it is taken into account that additives are often applied in form of colloidal oxides. Figure 15 gives an example of the particle size distribution of diesel soot generated with a non- and a cerium additivated fuel (35 µg/g cerium) by means of particulate number. The cerium additive seems to induce a shift to smaller particle sizes and shows a bimodal distribution in comparison to the non-additivated fuel.

Figure 16 displays the particle size distribution of a copper/iron additivated and a non-additivated reference fuel by means of metal content. The size classified metal content increased from less than 0.05 µg/filter for 10 µm particles to 1.6 µg/filter for 0.1 µm particles. A comparison of this pattern with the one of the reference diesel soot supports the above given hypothesis. The additivated diesel shows a bimodal distribution with a significant peak at smaller particle size whereas the non-additivated diesel shows a flat distribution.

assess the hazard of secondary emissions of aged particulate trap systems.

OUTLOOK

Current metal sampling technique with ELPI covers only particulate bounded metals. A flow proportional sampling directly from the raw gas can also enable to determine non-particulate bonded or volatile metals.^[18]

A further investigation of long-term stability of additive-fuel mixtures is necessary to guarantee stable solutions for general use. A clarification of the influence of additive form, fuel composition and other effects on the mixture stability is needed.

Specific changes of aged particulate trap systems might result in an increase of toxic secondary emissions. Therefore a long-term monitoring is desirable.

Secondary emissions during DPF accumulation and regeneration modes should be DPF distinguished and weighted according to the frequency of occurrence.

Secondary emissions risk assessment of DENOX-systems for heavy duty applications will be of future importance before the world wide application of this new exhaust gas treatment technology.

The influence and the contribution of the used lubrication oils to the formation of particulate matter should be investigated in a tracer study. First results will be published soon.^{[19][20][21]}

CONCLUSION

VERT is very valuable to discover insufficient systems which tend to form secondary emissions. Many tested filter systems gave promising results.

The VERT protocol, including the developed secondary emission test allows a comprehensive assessment of the benefits and risks of the current diesel particulate filter technologies.

The protocol was successfully applied up to 20 different trap systems so far, both to metal coated catalytic filters as well as to fuel-additive regenerated traps.

Among those traps two copper-regenerated systems had to be rejected because of a significant increase of polychlorinated dibenzodioxins/furans emissions.

In general, all trap systems clearly reduced the emissions of carcinogenic PAH and therefore had a positive effect on the toxicity of diesel exhaust gas.

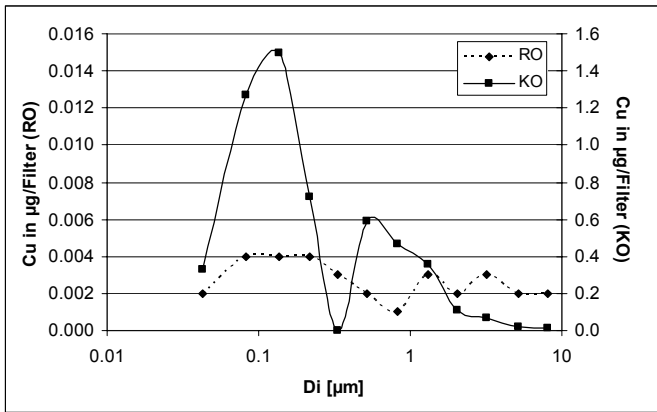


Figure 16: Size classified copper content in diesel soot for a Cu/Fe-additivated fuel (KO) and an additive-free reference diesel (RO).

Table 3 shows an example of a VERT tested DPF system operated with a cerium/iron fuel additive. The filter efficiency for particulate matter was determined to 98.2 %. The additive retaining efficiency, calculated based on the total amount of applied additive and on the cerium emissions found with the trap, can be amounted to 99.9 %. Therefore, the penetration for this specific system was rather low. However, the amount of cerium found in the test without DPF was also significantly lower than the originally dosed additive quantity. It can be assumed that the additive might be deposited in the system. A larger difference was also found in several tests, whereas this example showed a relatively huge discrepancy. A possible reason might be an insufficient stability of the additive-fuel mixture or additive deposition processes in the engine itself.

Table 3: Example of a VERT tested DPF system operated with a cerium/iron fuel additive

Additive metal	Cerium
Dosed additive amount	473 mg
PM ELPI without DPF	2.05 g
PM ELPI with DPF	0.04 g
Ce/PM in emission without DPF	15.4 mg
Ce/PM in emission with DPF	0.3 mg

The degree of penetration probably depends on pore size of the DPF and the chemical form of the additive. The metal penetration through metal regenerated DPF systems is usually higher than metal release of new, additive-free systems which operate with catalytic coatings. However, a release of the coating metals might increase with aging of the DPF. Therefore, a long-term monitoring of DPF systems in use is an urgent need to

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

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|--------------|--|
| VERT | Verminderung der Emissionen von Real-Dieselmotoren im Tunnelbau“, which means reduction of real diesel engine emissions at tunnel construction sites = Swiss, German and Austrian task force to reduce emissions of heavy duty diesel engines. |
| VFT | VERT Filter Test |
| VSET | VERT Secondary Emission Test |
| BUWAL | Bundesamt für Umwelt, Wald und Landschaft, Bern = SAEFL Swiss Agency for the Environment, Forests and Landscape, Bern |

SUVA Schweizerische Unfallversicherungsanstalt
= Swiss Accident Insurance Association

EMPA Eidgenössische Materialprüf- und
Forschungsanstalt = Swiss Federal
Laboratories for Material Testing and
Research

AFHB Abgasprüfstelle der Fachhochschule, Biel
CH = Laboratory for Exhaust Gas Control at
the University of Applied Sciences, Biel-
Bienne, Switzerland

TTM Technik Thermische Maschinen

DPF Diesel Particle Filter

CRT Continuously regenerating trap

CO Carbon monoxide

CO₂ Carbon dioxide

NO_x Nitric oxides = NO + NO₂

HC Hydrocarbons

VOC Volatile organic compounds

VOCOX Oxidized volatile organic compounds
(aldehydes, ketons)

PAHs Polycyclic aromatic hydrocarbons

Nitro-PAHs Nitro-Polycyclic aromatic hydrocarbons

PCDF Polychlorinated dibenzofurans

PCDD Polychlorinated dibenzodioxins

PCDD/F PCDD and PCDF

PM Particulate Matter or Particle Mass

DC Diffusion charging sensor

PAS Photoelectric Aerosol Sensor

NanoMet Thermodiluter + PAS + DC

ELPI Electrical Low Pressure Impactor

SMPS Scanning Mobility Particle Sizer

ICP-MS Inductively Coupled Plasma Mass
Spectrometry

GC-MS Gas Chromatography Mass Spectrometry

LC-UV/Vis Liquid Chromatography Ultraviolet/Visible
Detector

CLD ChemiLuminescence Detector

NDIR Non Dispersive Infrared

FID Flame Ionisation Detector