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VERT Filter Test, Phase 3 with the
DPF Physitron Physitec SiC-CB
on the Liebherr D 934 S Engine

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according to the VERT *) measuring procedure (VFT 3)

Ordered by:

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Projekt leading:

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November 2009 B 270

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*) Abbreviations see at the end of report

CONTENTS

1. SUMMARY

This report summarizes the investigations with the Diesel Particle Filter Physitron Physitec SiC-CB (coated) on a Liebherr engine according to the VERT*) Filter Test Phase 3 after the field test VFT2. The most important results of the field test are reported. Additionally a VFT with identical new filter element uncoated Physitec SiC-B was performed.

The investigations comprise all measurements and evaluations, which were performed on Diesel engines within the scope of the VERT*) project. The size distributions of the particulates were systematically measured besides the usual engine operating parameters, volatile pollution emissions and particulate mass emissions.

The technology of Physitron filter material is the same as the UNIKAT Puri Filter which was previously tested according to the VERT test procedure and yielded excellent filtration results, (see chap. 5.4.).

The analysis was performed at four operating points of the engine and during the attempt of charging and regeneration of the DPF by means of burner with catalytic coating (SiC-CB) and without catalytic coating (SiC-B).

The results can be summarized as follows:

- with the investigated DPF (SiC-CB) in the used condition the filtration based on number count reached 99.99 % and as average of the 4 operation points 99.99%
- the used DPF eliminates very well the opacimetric acceleration smoke
- the regeneration of the DPF with the burner at standstill of the engine worked very well
- due to the catalytic activity of the DPF system, there are influences on the gaseous components: CO & HC strongly reduced or eliminated; NO_2 increased up to the average ratio ΔNO_2 / NO_x of 13%.
- an inspection of the DPF before the tests revealed a perfect condition of the filter material.

The investigated DPF fulfils the criteria of the VERT filter test phase 2 and phase 3 can be recommended to the users.

For the uncoated filter element SiC-B similar statements can be made:
- particle count filtration efficiency PCFE: maximum 99.95% average 99.73%
- elimination of opacimetric and particulate acceleration emission
- satisfactory regeneration with burner
- no catalytic oxidation of CO & HC, but nearly elimination of the engine-out NO_2.

Also this DPF material can be recommended as an option in the investigated DPF system under the requirement of a further durability prove in retrospect.

2. INTRODUCTION

The occupational health authorities of Switzerland, Austria and Germany: SUVA, AUVA and TBG together with the Swiss clean air authority BAFU have performed the VERT project 1994-1999 to satisfy the increasingly stringent demands on air quality in underground workplaces and offroad [1].

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*) VERT… Verminderung der Emissionen von Realmaschinen im Tunnelbau
Verification Emission Reduction Technologies

Targets of VERT and LRV

- Evaluate aftertreatment systems for existing engines to reduce particulate emissions to < 3 % of engine-out emissions levels - with respect to total EC+OC-mass and particle number count in the size range 20-300 nm
- Define certification procedures for such aftertreatment systems
- Establish rules for monitoring field emissions of offroad engines
- Define application guidelines in consensus with engine manufacturers and operators.

VERT was concluded 3/2000 with application tools such as trap-system-specification, certification procedures and field monitoring standards and a list of VERT-approved trap-systems published in the SUVA/BAFU-Filter-List [2], yearly updated. Only traps systems which have successfully passed the VERT-Filter-Test VFT are listed in this document and they remain in this list only if they continue to prove their quality in the field.

The particulate trap system has proved to be the only available effective measure to curtail particulate emissions. Regeneration of such traps requires appropriate technical means such as burners, heaters, catalytic coatings or fuel additives. All such means must be certified together with the trap system and quality-monitored in the field. Continuous electronic OBD is a further requirement to control such systems, which need to perform automatically and safe for the engines and the environment.

Research on trap systems has revealed that traps can become highly active chemical reactors because of their extremely high specific surface. They can adsorb any substances offered by the exhaust gas, extent their residence time under high temperature conditions and thereby create products which did not exist in the exhaust before or in much lower concentrations. This chemical activity can be increased by the presence of catalysts originating from fuel or lube-oil, additives or coatings. It has been shown that extremely toxic substances can be created such as PCDD/F**) in very high concentrations [3]. This has prompted the introduction of a so-called VERT-Secondary-Emission-Test VSET which must be performed in all cases where such catalytic means are used.

Swiss legislation for the workplace [4] and offroad [5] where traps are now mandatory on all Diesel engines is based on VERT-results and requires exclusive use of systems which have successfully passed VFT and VSET. These test protocols are also approved by the German UBA , the Austrian AUVA, the German TBG, the Canadian DEEP, London LEZ, New York USA, Südtirol Italy, NL EPA Chile EPA, CARB, MSHA, INRS.
The VERT measuring procedures were carefully reconsidered and described in the Swiss Norm SNR 277205 (Sept. 2007), [6].

In the amendment to the Clean Air Ordinance (LRV) from Sept. 19th, 2008, (part 4a and appendix 4, paragraph 3) [5], the Swiss Federal Office of Environment established new legal base for the approval of construction machines and DPF systems for retrofitting.
These procedures, here simply called LRV are based on VERT test procedures and SNR 277205.. There are some simplifications of quality requirements and a change of administrative procedure, which became a conformity testing and conformity certification, like for different other products, according to the federal law.

LRV offers two options to control the emission quality of construction machines (both OEM and retrofit).

- fulfilling of nanoparticles counts limit value of 10^{12} 1/kWh in the NRSC and NRTC according to the guideline 97/68/EG (possibility for OEMs),
- using of DPF system, which fulfils the LRV-requirements.

**) PCDD/F... polychlorinated dibenzodioxins / furans (isomers)

Since January 2009, the Federal Office BAFU transformed the VERT Filter List in a LRV List, which recommends the DPF systems suitable for retrofitting.

The Association of Retrofit Manufacturers (AKPF) decided to create a VERT Association, which owns the legally protected label "VERT" and will continue to take the worldwide responsibility for BAT- VERT procedures and of VERT Filter List. In this way, a regular attention will be paid to: additional quality requirements (which are not included in LRV), activities of knowledge transfer, consulting and support for the users and for industry and a control of the aftermarket service.

There is a close and continuous collaboration between the committees of VERT verification procedures and LRV conformity.

3. LEGAL BACKGROUND and VFT-OBJECTIVES

Swiss legislation supports the use of particulate traps but in case of regeneration procedures using fuel additives or catalytic coatings it requires to proof that there will be no additional substances produced which can affect human health or the environment in general.
The first regulation issued by the EJPD (Swiss Ministery of Justice) on 7.August 1990, based on Art. 84 Abs.1 BAV states " In Verkehr stehende und neue, ohne Partikelfilter typengeprüfte Fahrzeuge, können nachträglich mit Partikelfiltern ausgerüstet werden.....beim Einsatz von additiv- oder katalytischunterstützten Regenerationsverfahren ist nachzuweisen, dass eine Gefährdung von Gesundheit und Umwelt durch die zusätzlichen entstehenden Reaktionsprodukte ausgeschlossen ist" [7].

Based on this the VERT trap-system specification requires under "additional constrains for emissions", that "there shall be no clearly detectable and relevant increase of emissions compared to the initial engine conditions", where "relevant" is defined by the SUVA MAK-threshold levels at the working place and the general BAFU (Swiss EPA) threshold levels for ambient air [6, 8].

Beside of these requirements particulate trap-systems installed and operating in offroad vehicles must comply with existing legislation in particular with respect to noise emission, safety aspects [9] and new-substance-regulations, [10].

VFT-Objectives:

Objectives of the three phases of the VERT-Filter-Test are:

Phase 1 (engine dynamometer tests):
- quality control of the filter material – filtration efficiency of counts and of mass at different soot loading
- functionality of regeneration system
- particle size analysis over 20-300 nm:
- monitoring of gaseous emissions during regenerations (part of VFT).

Phase 2 (field test):
- control of the long-term behaviour of the particulate trap system in field application

Phase 3 (engine dynamometer tests):
- shortened procedure of the trap quality control after a long field application (until 2000 h).

4. VFT TEST-PROTOCOL

4.1. Test-Cycle and procedure (on engine dynamometer)

In general 4 operating points of the ISO-cycle 8178 C/4 C1 designed for construction site engines are selected as the basis for all emission measurements, Fig. 1 (symbols ⊗):

- Operating point 5: full load, mean RPM (max. torque)
- Operating point 7: mean RPM, 50% load
- Operating point 3: rated RPM, 50% load
- Operating point 1: full load, rated RPM

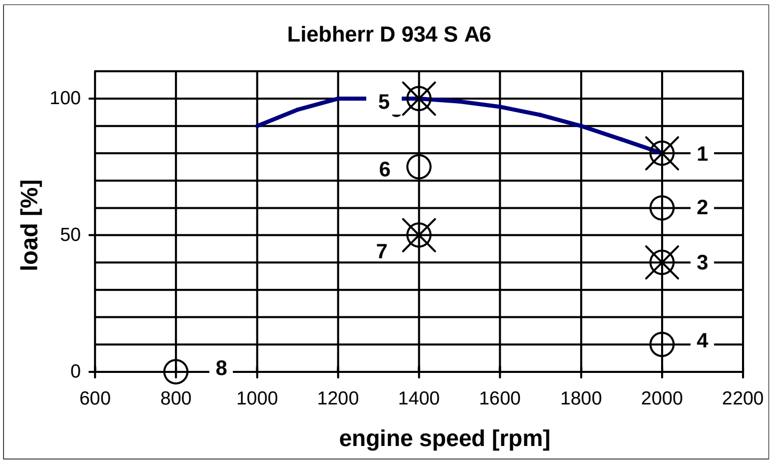


Fig. 1: Operating points of the VERT-Filter-Test

The test is driven in the fixed sequence after a warm-up phase until engine coolant temperature reached >83 °C and lube-oil > 90° (test routine see chap. 9).

VFT, Phase 1

The first quality control of the trap is the free acceleration with opacity measurement. The peak opacity has to be lower than 5%.

The following test sequences are:
- 4-point-test with a “trap new” (or in state of delivery),
- charging of the trap with soot
- 2-point-test with a “trap soot-loaded”,
- regeneration of the trap (Fig. 2 example with additive)
- 4-point-test with a “trap regenerated”.

According to the VERT-experiences the opacimetry at free acceleration furnishes analogous information, as at torque-converter acceleration.

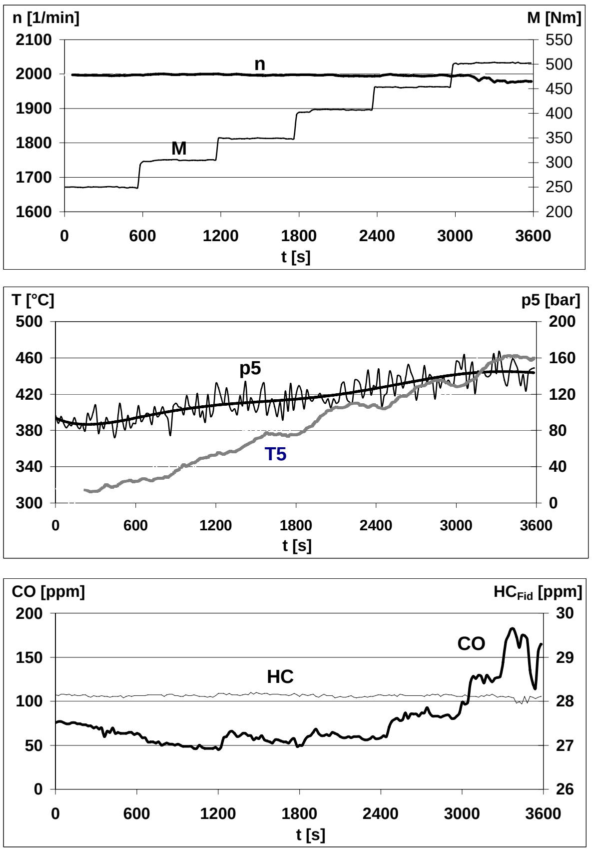
During the regeneration test the engine torque is increased at nominal (constant) speed. While the exhaust gas temperature increases the regeneration is indicated by means of the back-pressure, exhaust gas emissions and NanoMet-signals. All those parameters are on-line measured, Fig. 2.

In certain cases, e.g. if the filter material was already measured in another type of trap, a shortened test procedure of the VFT, phase 1, like in the phase 3 can be applied.

VFT, Phase 3 (after field test)

The performed measurements in this case are:

- free accelerations
- 4-points test procedure with the trap "delivery state".
- loading of the trap
- regeneration of the trap (Fig. 2 example with additive).



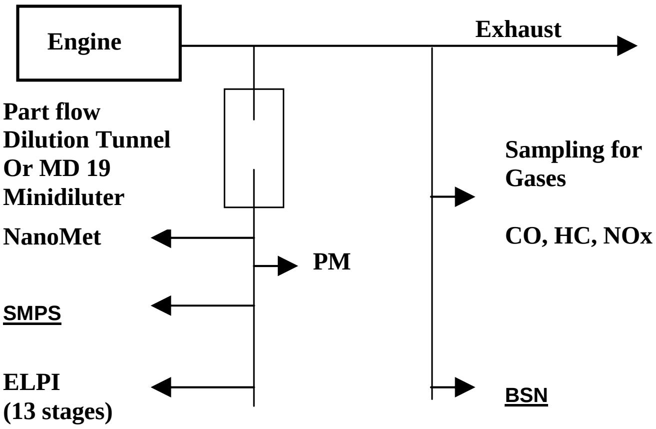


Fig. 3: Principal sketch of the sampling lines and test arrangement.

Fig. 2: Regeneration of a trap with an Fe-additive, (on engine dynamometer).

4.2. Sampling lines and test-arrangement (on engine dynamometer)

2 sampling lines are used, Fig. 3:

- sampling via Part-Flow-Dilution tunnel, or MD 19 Minidiluter
  for direct on-line size, count, and surface information using SMPS, NanoMet and ev. ELPI, as well as for gravimetric particulate mass (PM) measurement
- sampling of gas from the undiluted exhaust gas for the gaseous components and Bosch Smoke Number (BSN).

On-line measurements (for each operating point)

- Regulated pollutants total HC by FID , CO by NDIR, NOx by chemiluminescence detection (CLD)
- Particle count by SMPS in combination with thermoconditioner
- Size-specific particulate mass by ELPI (if desired)
- Particle surface and particle composition by NanoMet
- Control parameters: pressures and temperatures.

For details of the sampling, and analysis of nanoparticulates see annex A1 and for the off-line optional analytical methods see annex A2.

5. AVAILABLE INFORMATION

5.1. General information on emission with traps and fuel-additives

During the VERT project, experience was obtained regarding the properties of ultrafine particulates at engine-out conditions as well as downstream of the aftertreatment devices such as particulate traps or oxidation catalysts or combinations of both [1], [2], [11], [12], Fig. 4.

In particular, it was found that fuel additives (called regeneration additives, FBC) mostly reduce particulate mass but increase the number count of ultrafine particles in some cases by two orders of magnitudes forming a clearly pronounced bimodal size distribution of engine-out solid particles. It was proved in previous cases that these were solid non-carbonaceous particles presumably consisting of clusters of primary metal-oxide particles in the size range around 20 nm, Fig. 5.

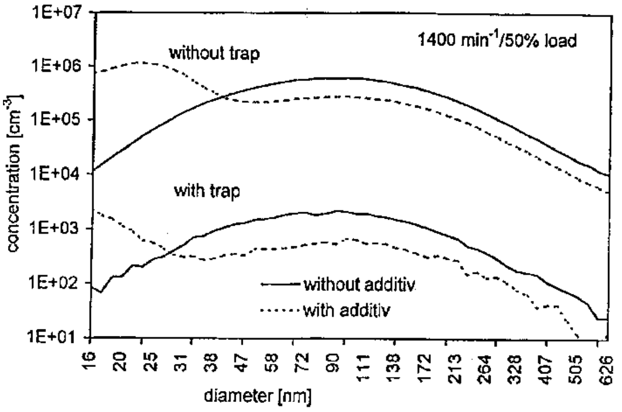


Fig.4: Particle size distribution with/without Additive

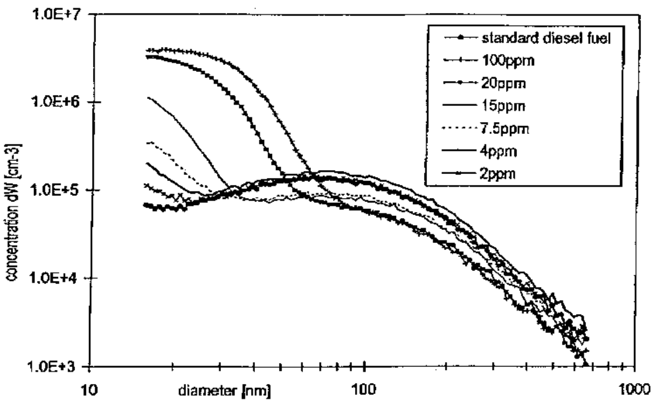


Fig. 5: Additive ash particle formation depending on concentration

It was also shown that this bimodal distribution was dependent on the additive concentration in the fuel, very pronounced with high concentrations and nearly disappearing with lower concentrations where the additive was still equally active catalysing soot combustion.

In certain configurations, e.g. with particulate traps but without fuel additive, the ultrafine particulate count is increased, too. This is mainly caused by the spontaneous condensation of volatile sulfate or HC. These particulates are mainly volatile and can be absorbed in the activated carbon trap. They are referred to as spontaneous condensate. They particularly occur under conditions where there is little condensation surface of solid particulates available and the pertinent substance is in a saturated state.

When a fuel additive is used with a particulate trap, the count of ultrafine particulates can increase due to a combination of both effects mentioned above.

Experience shows that the particulate traps have a very good filtration rate for carbon particulates and metal oxide particles.

5.2. General Information on secondary gaseous emissions with traps and fuel-additives

Since traps provide an ideal environment for generation of new substances from the many educts supplied by fuel, lube-oil, combustion and engine wear it must be expected, that such chemical processes can be accelerated by catalysis if catalytically active materials are also present. Fuel additive substances are by definition catalytically active. Examples from earlier VSET’s demonstrate how strong such effects may be thus supporting the need of this kind of test:

Fig. 6 represents the formation of Dioxins in a particulate trap with different fuel additives (FBC). The worst case is simulated by means of doping the fuel with chlorine.

Generation of PCDD/F when using a Copper-Additive

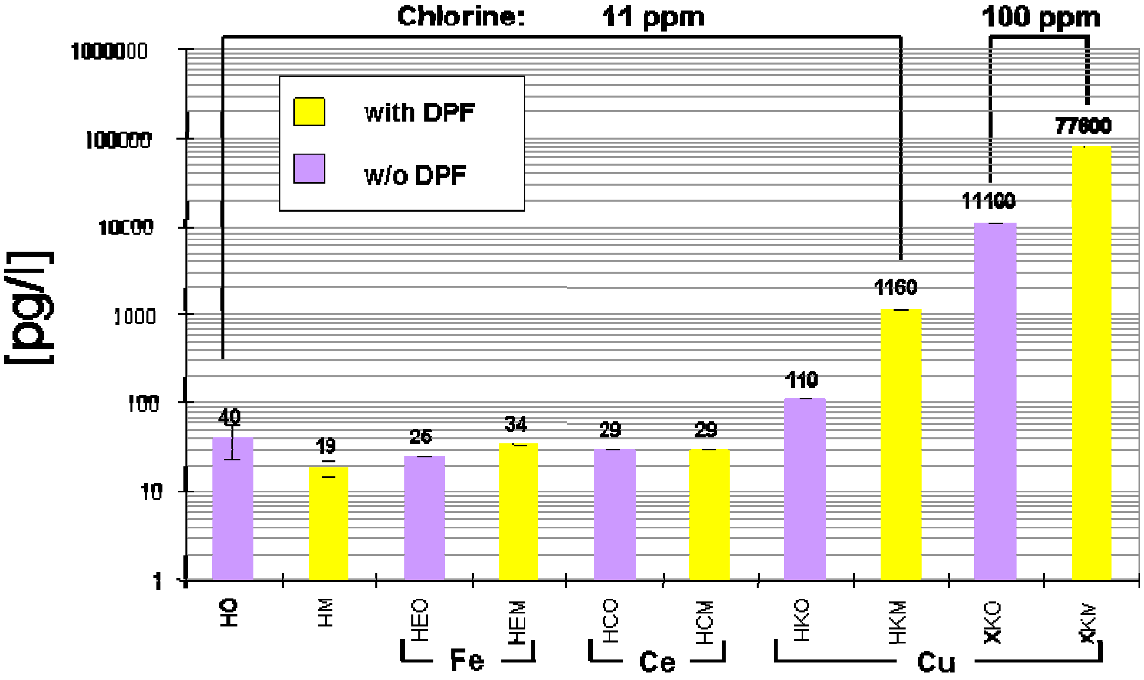


Fig. 6: Formation of Dioxins in a catalytic active particulate trap

When using the copper additive the trap immediately became active, increasing the PCDD/F-emission by about one order of magnitude at limited chlorine content but by more than 3 orders of magnitude for increased chlorine whereas in the case of the Fe- and Ce-additives the PCDD/F-concentration was not influenced with the trap-system.

5.3. Increase of NO2/NO-ratio when using noble metal coatings

The ratio of NO_2/NO where NO is the less toxic component of NO_x , is usually < 0,1 at engine-out conditions. When using noble metal coatings on high specific-surface substrates however NO can be oxidized to NO_2 which is 6 times more toxic based on MAK-threshold values.

In this case the conversion of NO to NO_2 is performed on purpose to support a soot oxidation process at very low temperatures. This process however is obviously not very well controlled, resulting in high NO_2-slip levels, Fig. 7. The same could happen with Pt-containing additives.

It was remarked during several investigations, that the fuel additives (FBC) and some special filter coatings don't produce the higher NO_2-level. More systematic clarifications of these effects were started in 2003.

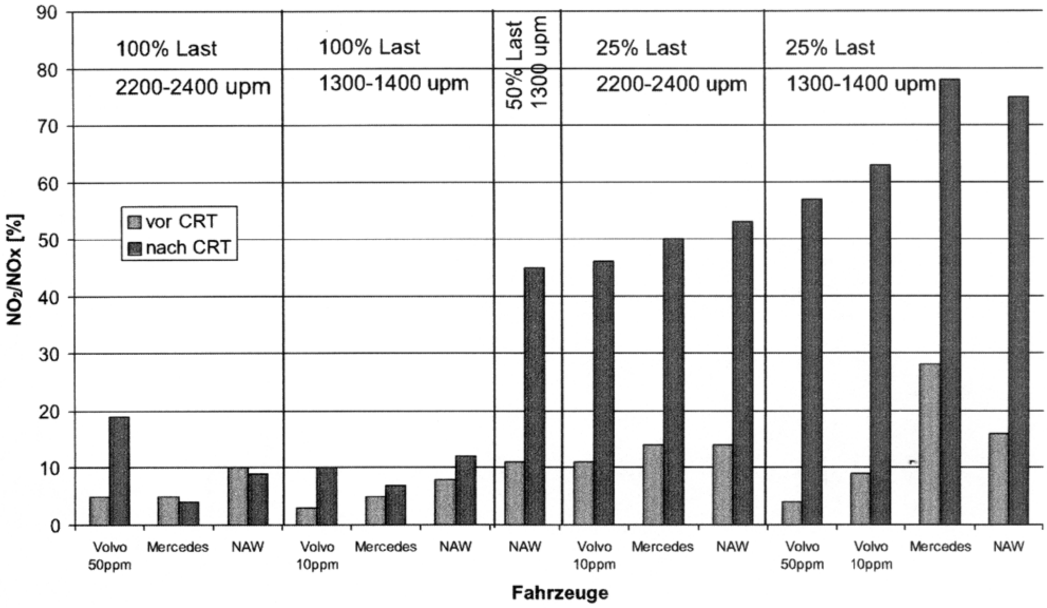


Fig. 7: NO_2/NOx for 4 city-buses using Pt-coated catalyst in combination with traps, [13]

5.4. Results with the same DPF material

Several DPF's with SiC as filtration material were investigated in the VERT verification procedure.

The Ibiden and LiqTech monolyths with the same pore size showed a very good filtration efficiency of solid nanoparticles (up to 99,96 % count filtration efficiency) and a total elimination of the acceleration smoke, (VFT1, [14] for SiC-CB Ibiden; VFT1, [15] for SiC-B LiqTech).

With the state of knowledge of today it is proven, that the effects of condensation, especially sulphates, overlap the gravimetric results and simulate a worse PM-filtration efficiency. In this situation the most useful parameter to qualify the trap is the particle count filtration efficiency.

Due to these effects lower particle mass filtration efficiencies are usually indicated.

6. PARTICIPATING INSTITUTIONS and RESPONSIBLE PERSONS

The following institutions participated in the measurements:

- Laboratories for Exhaust Emission Control of the University of Applied Sciences, Biel-Bienne, CH
  (Measurements on engine test rig, leading the test program);
  Prof. Dr. Jan Czerwinski, Dipl. Ing. P. Bonsack
- Matter Engineering AG / Wohlen, CH
  (Particle analysis)
  Dr. M. Kasper, Dipl. Ing. Th. Mosimann, MSc ETH A. Hess
- TTM Technik Thermische Maschinen, Niederrohrdorf, CH
  (Project management);
  Dipl. Ing. A. Mayer.

7. TEST-ENGINE, FUEL and LUBRICANT

7.1. Test engine data

SNR 277205, Tab. D.3

Manufacturer / type	Liebherr Machines Bulle S.A./ D 934 S
Maximum emission level (legal exhaust level)	97/68/E9 step 3A; EPA/CARB Tier 3
Cylinder number and configuration	4 cylinders in-line
Bore / stroke	136 x 122 [mm]
overall displacement	6.36 [dm^3]
Compression ratio	17 [-]
Serial number / year of manufacture / operating hours	2005 03 1341
Cooling medium (air, water, etc.)	water
Combustion process (direct injection, prechamber, etc.)	direct injection
Fuel system type	unit pump Bosch
Speed governor	EDC
Method of air aspiration	turbocharging
Charge air cooling system	intercooler
Measures to reduce emissions	internal EGR
Rated power / Rated speed (presend EDC setting)	111[kW] @ 2000 [min^{-1}]
Low idle speed / high idle speed	840 [min^{-1}]; 2170 [min^{-1}]

Test points of engine in accordance with ISO 8178-4, test cycle C1				
	Rated speed		Intermediate speed	
Test phase	1	3	5	7
Speed [min^{-1}]	2000	2000	1400	1400
Torque [Nm]	500	250	680	340
Power [kW]	104.7	52.4	99.7	49.8

7.2. Fuel data according to SN EN 590

SNR 277205, Tab. D.4

Base fuel (without additive)			
Type	Diesel fuel Swiss market quality		
Manufacturer	Shell Formula		
Property	**Method**	**Unit**	
Density (at 15°C)	ISO 3675	kg/l	0.820 – 0.845
Viscosity (at 40°C)	ISO 3104	mm^2/s	2.2 – 2.8
Cetane number	ISO 5165	-	52 - 54
Cetane index	ISO 4264	-	49 - 51
Sulphur content	ISO 4260 / 8754	mg / kg	max. 10
Cloud point	ISO 3015	°C	max. -10
Pour point (CFPP)	ISO 3016	°C	max. -20
Flash point	ISO 2719	°C	min 62
Heating value		MJ/kg	min 42.5
Aromatic hydrocarbons	ISO 3837	% vol	max. 2
Conradson at 10% test residue			max. 0.02 g/100g
Boiling analysis (at 1013 mbar, 340°C)			min. 98 vol%

7.3. Lubricating oil data

Lubrizol research oil OS No. 165108, blue, 15W/40

Property		
Viscosity kin 40°C	-	mm^2/s
Viscosity kin 100°C	13.98	mm^2/s
Viscosity index	-	(--)
Density 20°C	-	kg/m^3
Pourpoint	- 25	°C
Flamepoint	-	°C
Total Base Number TBN	8.4	mg KOH/g
Sulfur ashes	10 770	mg/kg
Sulfur	3 360	mg/kg
Mg	< 10	mg/kg
Zn	1 200	mg/kg
Ca	2 630	mg/kg
P	1 110	mg/kg

8. TEST METHODS AND INSTRUMENTATION

8.1. Engine dynamometer and standard test equipment

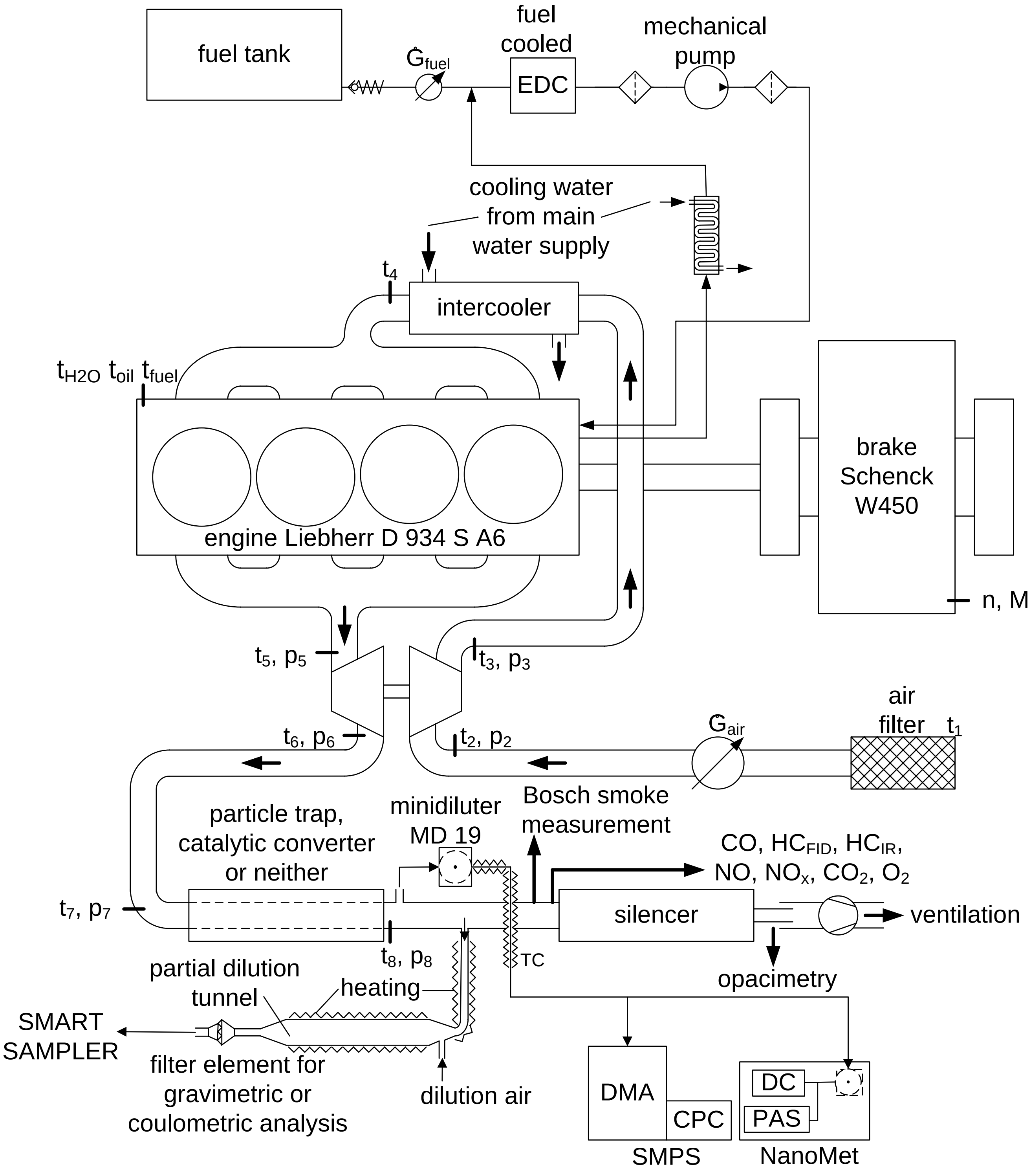


Fig. 8: Engine dynamometer and standard test equipment

Following laboratory equipment was employed:

- Eddy current brake Schenck W450 with force transducer HBM U2
- Fuel flow measurement AIC 2022 with through-flow meter FS-4/2400
- Air mass meter Sensycon Sensyflow P NW 150
- Pressure transducers Keller PAA-21-2, PD-4/8236
- Thermo-couples Type J, K
- Air filter Durulator P77-1558 (Duramont)
- Intake air conditioning: none (manual)
- Silencer: DINEX

The engine cell and the measuring cell are separated.

Different parameters are registered on-line via PC or on a chart recorder. The continuous registration of all parameters is possible.

8.2. Test equipment for regulated exhaust gas emissions

Measurement is performed according to the Swiss Regulation for Exhaust Emissions from Heavy Duty Vehicles, which responses to the directive 2005 / 55 / EC & ISO 8178.:

- Volatile components:
  - Horiba exhaust gas measurement devices
    Type VIA-510 for CO_2, CO, HC_{IR}, O_2,
    Type: CLA-510 for NO, NOx
  - Amluk exhaust gas measurement device Type FID 2010 for HC_{FID},
- Measurement of the particulate emission:
  - Sampling and dilution:
    partial flow dilution tunnel AVL Smart Sampler II, Model 472
    tunnel diameter 70 mm
    tunnel length 700 mm
    mass flow constant 2 g/s
    dilution air, purified, oil-free compressed air, usually 1.6 g/s (dilution 1:5)
    dilution factor DF is variable, determined by means of $CO_{2L/H}$-measurement
  - Gravimetry:
    filter material PALFLEX TX 40 HI 20-WW
    filter efficiency: 95% (300nm) until 99% (10 nm) (see SAE 950373, own measurements),
    filter temperature: $\leq$ 52 °C
    mass of filter residue usually about 1 mg
    accuracy of the scale ± 1 µg
    conditioning: 8 .. 24 h (20°C, rel. humidity 50%)
  - Opacimetry:
    AVL Dismoke 435

Calculations are done with the user-software MS Excel 8.0. All data are saved and are available for further evaluations.
The corrected exhaust emissions are calculated according to the Swiss Regulation for Exhaust Emissions from Heavy Duty Vehicles, which responses to the directive 2005 / 55 / EC & ISO 8178.
Formulae used for calculation are listed in appendix A3, nomenclature see A4.

8.3. Particle Size Analysis and optional analytical methods

In addition to the gravimetric measurement of particulate mass, the particle size and counts distributions are analysed with following apparatus:

- SMPS – Scanning Mobility Particle Sizer, TSI (DMA TSI 3071, CPC TSI 3025 A)
- NanoMet – System consisting of:

  - PAS – Photoelectric Aerosol Sensor (Eco Chem PAS 2000)
  - DC – Diffusion Charging Sensor (Matter Eng. LQ1-DC)
  - MD19 tunable minidiluter (Matter Eng. MD19-2E).
  - Thermoconditioner (TC) (i.e. MD19 + postdilution sample heating until 300°C)

A detailed description of those systems can be found in annex A1.

The optional analyses, which can be performed in external analytical laboratories (EMPA, SUVA and others) are:

- coulometric analysis of PM-filtrate residue, giving EC & OC,
- analysis of SOF / INSOF and sulfates in PM by solvent methods,
- analysis of PAH in gas phase and in PM.

Some further explanations about these methods see annex A2.

9. TEST ROUTINE

- Engine conditioning: with particulate trap 60 minutes; without particulate trap 40 minutes
- Conditioning program: 5 load points, equal duration, ascending load from idling to full load
- Start of the measurements: 5 min. after setting the operation point
- For size distributions: 30s after setting the operating point
- Time for complete test sequence: 10 min. per operating point
- Time for repetition measurement: 10 min.
- Sequence of operating points: point 5 – 7 – 3 – 1 – 5 rep.
- Particulate gravimetry: after the size distribution analysis (sampling 3 min.)
- Free acceleration with opacimetry

Monitoring of the test conditions

- Ambient temperature: one measurement per test sequence
- Barometric pressure: one measurement per test sequence
- Ambient humidity: one measurement per test sequence
- CO_2 content of the ambient air: one measurement per test sequence
- Temperature in the test cell: not regulated
- Air inlet temperature after the filter: 20°C-25°C, manually controlled by mixing with outside air (except for very high ambient temperatures)
- Oil pressure and oil temperature: continuous monitoring by test rig control
- Engine cooling water temperature: continuous monitoring as per manufacturer specifications

10. TEST OBJECTS

10.1. Particle filter after field test

SNR 277205, Tab. D.1

Manufacturer of filter system		Physitron GmbH, Am Merzenborn 6 56422 Wirges, Germany
Type / serial number		Physitron Physitec SiC-CB / 703136
Designation of particle filter family		Physitron Physitec SiC
Filter medium (particle filter element)		
Manufacturer of filter medium		Ibiden
Type		Wall Flow Filter
External dimensions / weight		11.25” x 12”
Material		SiC
Porosity	[%]	43 +/- 3%
Pore size	[µm]	11 +/- 2
Number of cells per square inch	[CPSI]	169
Wall thickness	[mm]	0.4 +/- 0.03
Maximum flow-through rate	[m^3/s]	0.85 / 0.60 *)
Maximum space velocity	[s^{-1}]	30.8 *)
Maximum operating temperature	[°C]	700
Storage capacity for soot/ash	[g/l]	5
Regeneration		
Regeneration procedure		Diesel burner
With additive (FBC = fuel borne catalyst)		
Manufacturer and specification of additive		
Catalytically active substances		
Treat rate	recommended / standard for test	
Additizing procedure		
Specification of dosage device		
With catalytic coating		
Catalytically active elements / concentration of catalytically active substances		Pt, 30g/ft^3
OBC (electronic on board control unit)		
Manufacturerer and specification		Physitron DNY ControlBox
Serial number		20103

The tested filter Physitron Physitec SiC-CB (Greentop 703136) on the engine stand is represented in annex A5. Technical information from manufacturer – is represented in annex A6.

*) see annex A10 (at bottom)

10.2. Particle filter new

SNR 277205, Tab. D.1

Manufacturer of filter system		Physitron GmbH, Am Merzenborn 6 56422 Wirges, Germany
Type / serial number		Physitron Physitec SiC-B / 08.35.06
Designation of particle filter family		Physitron Physitec SiC
Filter medium (particle filter element)		
Manufacturer of filter medium		LiqTech A/S
Type		Wall flow filter
External dimensions / weight		11.25” x 12” / -
Material		100% RE SiC
Porosity	[%]	43
Pore size	[µm]	12-15
Number of cells per square inch	[CPSI]	150
Wall thickness	[mm]	0.5
Maximum flow-through rate	[m^3/s]	1.2 @ 20°C, 1013.25 mbar / 0.42 *)
Maximum space velocity	[s^{-1}]	21.6 *)
Maximum operating temperature	[°C]	900
Storage capacity for soot/ash	[g/l]	18
Regeneration		
Regeneration procedure		Diesel burner
With additive (FBC = fuel borne catalyst)		
Manufacturer and specification of additive		
Catalytically active substances		
Treat rate	recommended / standard for test	
Additizing procedure		
Specification of dosage device		
With catalytic coating		
Catalytically active elements / concentration of catalytically active substances		-
OBC (electronic on board control unit)		
Manufacturerer and specification		Physitron DNY ControlBox
Serial number		20103

The tested filter Physitron Physitec SiC-B on the engine stand is represented in annex A11. Technical information from manufacturer – is represented in annex A6.

*) see annex A14 (at bottom)

10.3. Field Test VFT2

The DPF Physitron Physitec SiC-CB was installed on a Caterpillar M318C MH excavator with Tier 2 engine CAT 3056E ATAAC, 129 kW, operated by SITA Heinemann GmbH, Eschbach, Germany.

Description of the field test from the operator:

Description	Date	Operating hours of the loader	Cumulated hours of T40417
Installation	04.09.2006	16	
Removal	14.06.2007	2'648	2'632
Total working hours			**2'632**

There were continuous controls of backpressure by means of datalogger (examples see annex A7).
The distribution-plots of pressure and temperature before DPF (from datalogger) show that the average backpressure rarely exceeds 150 mbar and the temperature before trap is mostly between 150 and 350°C.
The measurement after 2000 operating hours was performed by TÜV Hessen GmbH, see annex A8. With no increase of gaseous emissions the DPF fulfilled the requirements. The TÜV field control was performed on a Greentop DPF, which is the previous name of the present Physitron DPF. (Physitron got the product and the rights for it from Greentop. New identification plates from Physitron for both investigated DPF materials are represented in annex A5-2.)

11. RESULTS

SiC-CB coated after field test

Inspection
When inspecting the filter supplied after the field test and before starting the VFT3 test procedure the filter element presented itself perfectly clean at the outlet side and without any signs of failures such as cracks, leakages or bondings.

The graphic representation of results is given in the attached figures, see chap. 15.

The results of measurements and calculated parameters are tabulated in annex, A11 & A12, see chap. 16.

Following tendencies can be seen:

Fig. 9 - the DPF Physitron Physitec SiC-CB shows a very good reduction of particle mass PM.

Nevertheless one of the most important statements of VERT is: gravimetry is not an appropriate parameter to characterize the DPF quality. The right metric is the nanoparticles count concentration.

There is a catalytic influence of the measured DPF-system on the gaseous emission components: elimination of CO, strong reduction of HC, increase of the NO_2 / NO_x-ratio up to approx. 45%.

Fig. 10 – the investigated DPF in state of delivery eliminates very well the black smoke during the free acceleration. Beside the standard opacimeter this is also documented by the very sensitive signals PAS & DC (about PAS & DC see comments to Fig. 18)

In the following Figures 11 - 15 the SMPS particle size distribution spectra (PSD) without and with DPF are represented. There is generally very good filtration efficiency with penetration values mostly between 0.001 and 0.00001.

Fig. 16 – the integrated numbers of particles in the size spectrum 20-300 nm show differences with/without DPF, which are of 3 to 4 orders of magnitude.

Fig. 17 – the integration of the particulate counts in partial size spectra confirms the findings: generally a very good filtration efficiency.

Fig. 18 – shows the results with the on-line measuring sensors at all operating points.
The signals of PAS and DC in this figure are converted to the values responding to the undiluted volume concentrations in the exhaust gas.
PAS (photoelectric aerosol sensor) is sensitive to the surface of particulates and to the chemical properties of the surface. It indicates the solid particles.
DC (diffusion charging sensor) measures the total particle surface independent of the chemical properties. It indicates the solids and the condensates.
Additional information about PAS and DC see annex A1.

With DPF the values of both signals are reduced generally yielding the penetration values mostly between 0.001 and 0.0001.
Penetration is a parameter representing the portion of particulates passing through the DPF, it is a ratio of down – to upstream concentrations.

penetration = 1 – filtration efficiency

The table in Fig. 19 summarizes the filtration efficiencies for mass (PMFE), or counts (PCFE) filtration of the used Physitron DPF. The average filtration efficiency for counts PCFE = 99.99%, is excellent and sufficient for VERT.

Fig. 20 shows the regeneration attempt, which followed at 2000 rpm with the stepwise increased torque. A first backpressure drop is visible in the 7th step at approx. 400°C.

Fig. 21 represents the results at load steps without DPF.
This measuring series were performed to demonstrate other emission components, in particular PAS, DC, NO_x, NO, NO_2 and compare the results with/without DPF.

In Fig. 22 some considerations of the NO_2-changes with / without DPF at load steps are represented. The Physitron DPF increases NO_2-concentration at all steps. The average ratio $\Delta NO_2 / NO_x$ is 13%.

Fig. 23 shows the time-plotts of the measured parameters during the burner regeneration at standstill of the engine. There is a good functionality of the burner and the attained temperatures in the DPF are sufficient to promote the regeneration.

SiC-B uncoated

The figures with results of this supplementary filter material have analogous numbering (with "a", "b", "c"), as the figures for the original filter material.

Generally the same statements can be made. Some little differences are:

- no catalytic activity, no influence on CO, HC, NO_x and reduction of engine-out-NO_2 (Fig. 9a).
- SMPS penetration values in the range of 0.001 (Figures 11a-15a), exception is the operating point 5, which was performed directly after the regeneration with burner at standstill.

  At the operating point 5, which was performed at first, the consecutive scans with DPF show lowering NP-level. This is the effect of discharging sulfates and ev. other NP, which were accumulated in the DPF during the regeneration procedure. Due to the higher exhaust temperature at OP5 the sulfates vaporize and create after the spontaneous condensates in nuclei mode. This effect is very common for many traps after field test and it has nothing to do with the filtration quality.

- PCFE values: max. 99.95%, average 99.73 % (Fig. 19a)
- Average reduction ratio Δ NO_2 / NO_x = 5% i.e. nearly elimination of engine-out-NO_2 (Fig. 21a).

12. CONCLUSIONS

The results can be summarized as follows:

- with the investigated DPF (SiC-CB) in the used condition the filtration based on number count reached 99.99 % and as average of the 4 operation points 99.99%
- the used DPF eliminates very well the opacimetric acceleration smoke
- the regeneration of the DPF with the burner at standstill of the engine worked very well
- due to the catalytic activity of the DPF system, there are influences on the gaseous components: CO & HC strongly reduced or eliminated; NO_2 increased up to the average ratio ΔNO_2 / NO_x of 13%.
- an inspection of the DPF before the tests revealed a perfect condition of the filter material.

The investigated DPF fulfils the criteria of the VERT filter test phase 2 and phase 3 can be recommended to the users.

For the uncoated filter element SiC-B similar statements can be made:

- particle count filtration efficiency PCFE: maximum 99.95% average 99.73%
- elimination of opacimetric and particulate acceleration emission
- satisfactory regeneration with burner
- no catalytic oxidation of CO & HC, but nearly elimination of the engine-out NO_2.

Also this DPF material can be recommended as an option in the investigated DPF system under the requirement of a further durability prove in retrospect.

13. DOCUMENTATION

The original data are confidential. They are archived at the Exhaust Gas Laboratory of the University of Applied Sciences, Biel.

14. LITERATURE

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15. LIST OF ATTACHED FIGURES

SiC-CB coated after field test

SiC-B uncoated

16. APPENDICES

A 1 Particle size analysis
A 2 Optional off-line analytical methods
A 3 Calculation formulae
A 4 Measured and calculated engine data, nomenclature

SiC-B coated after field test

A 5 Physitron Physitec on the test bench
A 6 Physitron DPF system with burner data from manufacturer
A 7 Examples datalogger screening with statistical evaluation of backpressure
A 8 Inspection report TÜV Hessen Nr. TÜH-TB 2007-113.00
A 9 Tables of measured and calculated values: w/o DPF, ULSD (10 ppm),
A 10 Tables of measured and calculated values: with DPF, ULSD (10 ppm), after field test,

SiC-B uncoated
A 11 Physitron Physitec SiC-B on the test bench
A 12 Tables of measured and calculated values: with DPF, ULSD (10 ppm), new
A 13 Tables of measured and calculated values: with DPF, ULSD (10 ppm), charged
A 14 Tables of measured and calculated values: with DPF, ULSD (10 ppm), regenerated

17. ABBREVIATIONS

AFHB	Abgasprüfstelle FH Biel, CH
AKPF	Arbeitskreis der Partikelfilterhersteller, Austria
AUVA	Austria Unfall Versicherung-Anstalt
BAFU	Bundesamt für Umwelt, (Swiss EPA)
BAT	best available technology
CARB	Californian Air Resources Board
CFPP	cold filter plugging point
CLD	chemoluminescence detector
CNC	condensation nuclei counter
CPC	condensation particle counter
CRT	continuously regenerating trap
CVS	Constant Volume Sampling: Dilution Tunnel for Regulated Emission Measurement
DC	Diffusion Charging sensor
DEEP	Diesel Engines Emission Program, Canada
DI	Direct Injection
DPF	Diesel Particle Filter
DMA	differential mobility analyzer
DME	Diesel Motor Emissions = EC (nomenclature of occupational health authority SUVA)

EC	Elemental carbon, European Community
ECU	electronic control unit
EDC	Electronic Diesel Control
EDX	Energy dispersive x-ray detection
EGR	exhaust gas recirculation
ELPI	Electric low pressure impactor
EMPA	Eidgenössische Material Prüf- und Forschungsanstalt, CH
EPA	Environmental Protection Agency
FAD	Förderkreis Abgasnachbehandlungs –technologien für Dieselmotoren, Germany
FBC	Fuel Borne Catalyst = Fuel Additive = Regeneration Additive
FE	filtration efficiency
FID	flame ionization detector
FL	full load
FOEN	Federal Office of Environment (BAFU), CH
GRPE	UN Groupe of Rapporteurs Pollution & Energie
HD	heavy duty
IARC	International Agency for Research of Cancer
ICE	internal combustion engines
ICP-MS	Inductively coupled plasma mass spectrometry
INRS	Institut National de Recherche sur la Santé, F
JRC	EC Joint Research Center
LEZ	low emission zones
LRV	Luftreinhalteverordnung, CH
ME	Matter Engineering, CH
MD19	heated minidiluter
MSHA	Mines Safety & Health Administration, US
NanoMet	NanoMetnanoparticle summary surface analyser (PAS + DC + MD19)
NDIR	nondispercive infrared
NP	nanoparticles < 999 nm SMPS – range)
NRSC	nonroad stationary cycle
NRTC	nonroad transient cycle
OBD	on board diagnosis
OC	Organic carbon
OEM	original equipment manufacturer
OP	operating point
PAH	Polycyclic Aromatic Hydrocarbons
PAS	Photoelectric Aerosol Sensor
PC	particle counts
PCDD/F	Polychlorinnated Dibenzodioxins / Furans
PCFE	particle counts filtration efficiency
PM	particulate matter, particle mass
PMFE	particle mass filtration efficiency
PMP	Particulate Measurement Program of GRPE
PSD	particle size distribution
RE	reduction efficiency
SEM	Scanning Electron Microscopy
SMPS	Scanning Mobility Particle Sizer
SUVA	Schweiz. Unfallversicherungs-Anstalt, CH
TBG	Tiefbaugenossenschaft, Germany
TC	thermoconditioner, Total Carbon
TEQ	Toxicity-Equivalent
TNO	Netherland National, Laboratories, NL
TTM	Technik Thermische Maschinen, CH
TÜV	Technischer Überwachungsverein, D
UBA	Umwelt Bundesamt, Germany
ULSD	ultra low sulfur Diesel
US-EPA	US – Environmental Protection Agency
VERT	Verminderung der Emissionen von Realmaschinen im Tunnelbau (Swiss – Austrian – German project, DPF retrofitting underground)
VFT1	VERT Filter Test Phase 1
VROM	Netherlands EPA
VSET	VERT-Sekundäremissionstest
WHTC	worldwide heavy duty transient cycle