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VERT Filter Test, Phase 3 with the DPF DINEX DiSiC catalysed on the Liebherr D 934 S Engine

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

Ordered by:

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Projekt leading:

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*) Abbreviations see at the end of report

CONTENTS

1. SUMMARY

This report summarizes the investigations with the Diesel Particle Filter DINEX DiSiC catalysed 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.

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 this filter material is the same as the DPF DINEX which was previously tested according to the VERT test procedure VFT1 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 catalytic coating.

The results can be summarized as follows:

- with the investigated DPF in the used condition the filtration based on number count reached 99.4 % and as average of the 4 operation points 99.15%
- the used DPF eliminates very well the opacimetric acceleration smoke
- the regeneration of the DPF with the catalytic coating worked very well
- due to the catalytic activity of the DPF system, there are influences on the gaseous components: reduction or elimination of CO & HC. There is no change of NO_x but the engine-out-NO_2 is increased up to the average value Δ NO_2 / NO_x = 34%.
- 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 and can be recommended to the users.

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].

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.

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

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.

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.

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

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

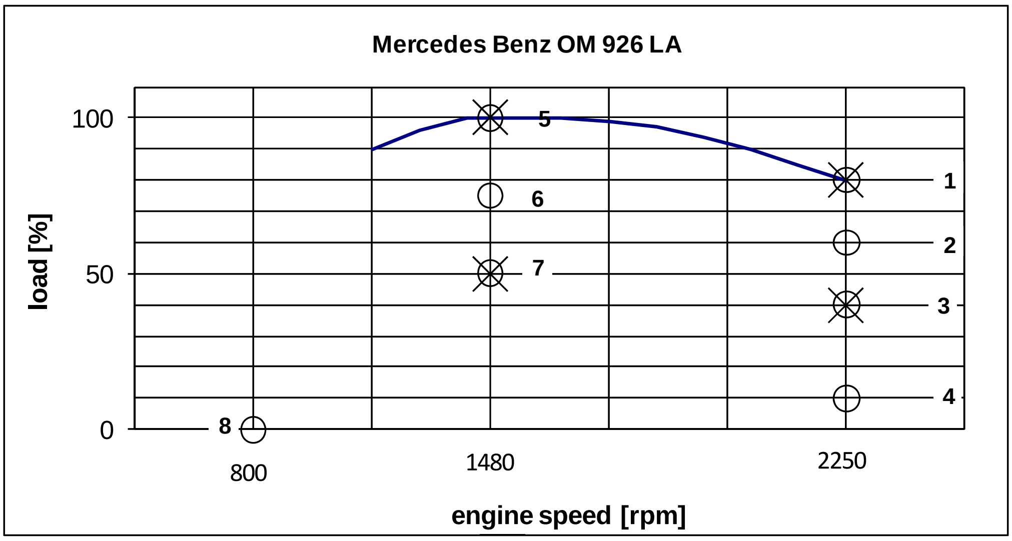


Fig. 1: Operating points of the VERT-Filter-Test

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)

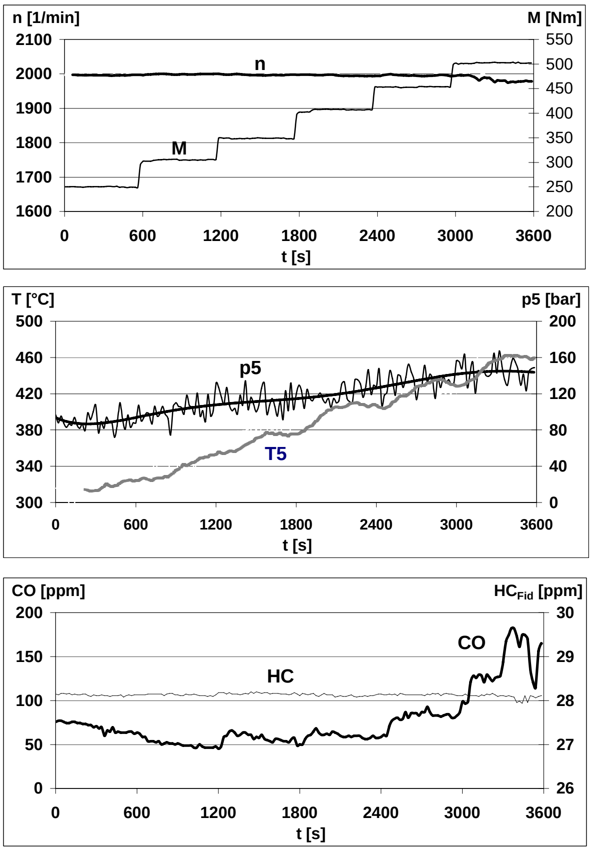


Fig. 2: Regeneration of a trap with an Fe-additive, (on engine dynamometer).

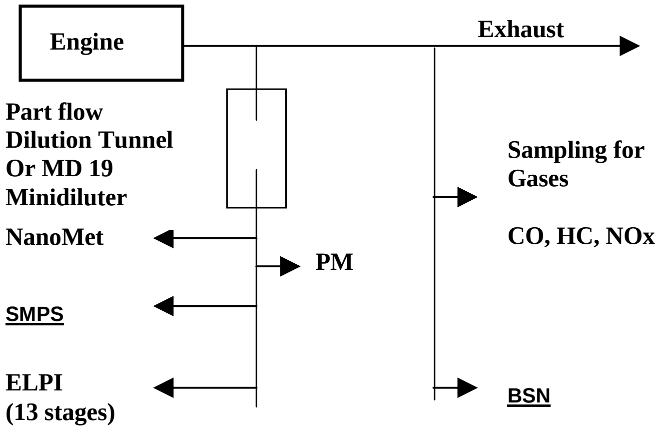


Fig. 3: Principal sketch of the sampling lines and test arrangement.

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.

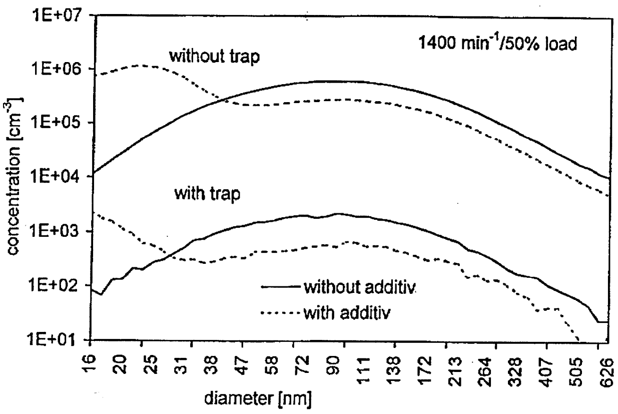
For details of the sampling, and analysis of nanoparticulates see annex A1 and for the off-line optional analytical methods see annex A2.

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.



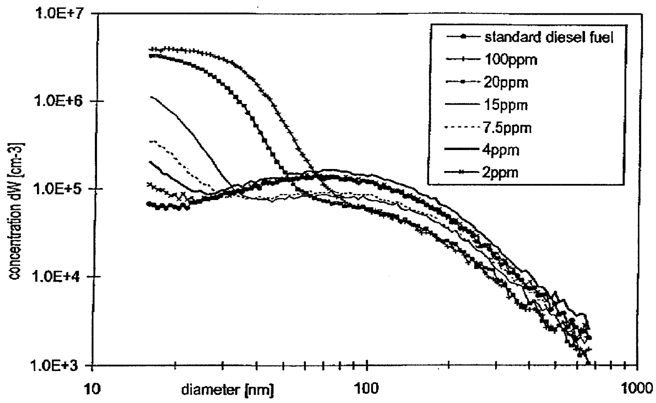


Fig.4: Particle size distribution with/without Additive

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:

<u>Fig. 6</u> 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

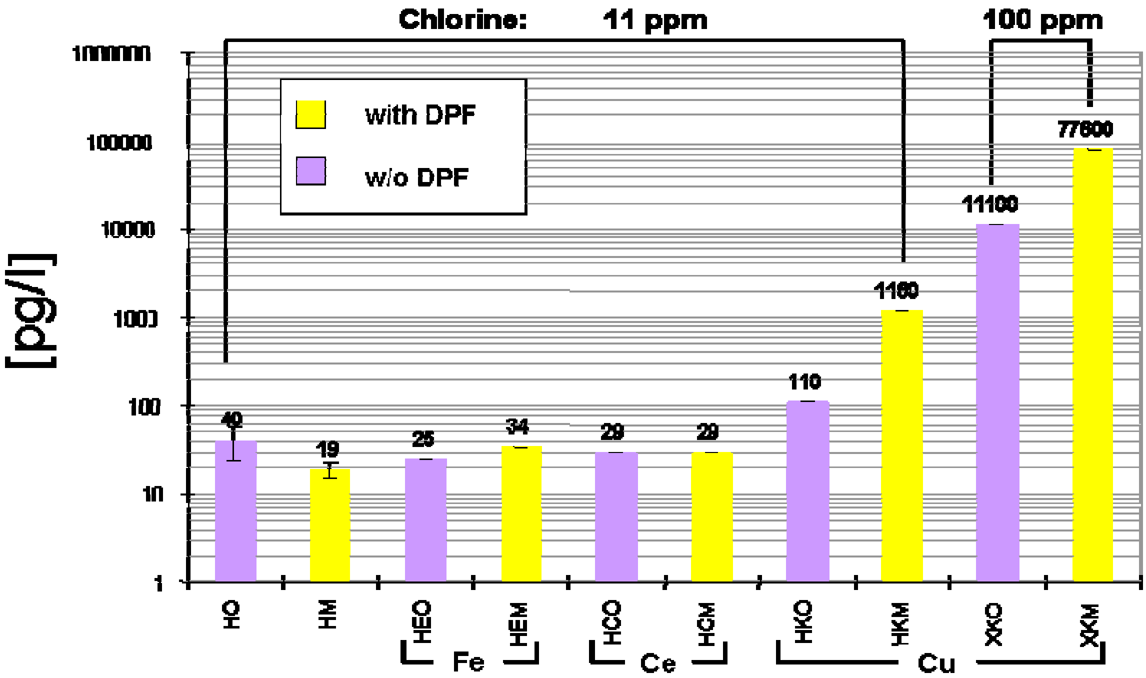


Fig. 6: Formation of Dioxins in a catalytic active particulate trap

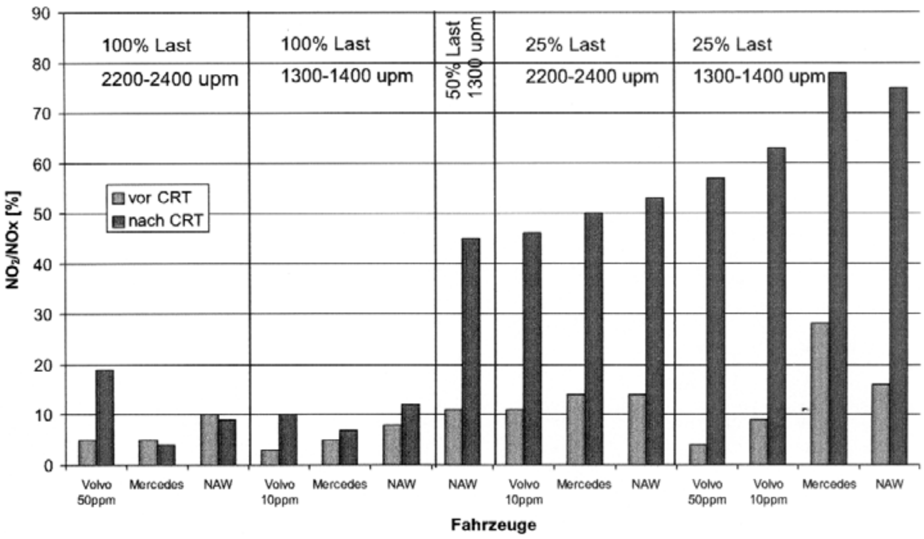
When using the copper additive the trap immediately became active, increasing the PCDD/F-emission by about one order of magnitude at limited chlorine content but by more than 3 orders of magnitude for increased chlorine whereas in the case of the Fe- and Ce-additives the PCDD/F-concentration was not 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, <u>Fig. 7</u>. 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.



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

<u>5.4. Results with the same DPF material</u>

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

The DINEX SiC monolyths with the same pore size showed a very good filtration efficiency of solid nanoparticles (up to 99,7 % count filtration efficiency) and a total elimination of the acceleration smoke. (VFT1, [14]).

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.

<u>6. PARTICIPATING INSTITUTIONS and RESPONSIBLE PERSONS</u>

The tests were performed at DINEX engine laboratory, Middelfart DK, with the participation and contribution of some measuring systems from the Swiss VERT team.

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. Th. Hilfiker, 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.
- DINEX engine laboratory, Middelfart, DK
  (Measurements on engine test rig)
  Mr. Lars Chr. Larsen, Mr. S. Gjerlev

7. TEST-ENGINE, FUEL and LUBRICANT

7.1. Test engine data

SNR 277205, Tab. D.3

Manufacturer / type	Mercedes Benz / OM 926 LA
Maximum emission level (legal exhaust level)	97/68/EG step 3A; EPA/CARB Tier 3
Cylinder number and configuration	6 cylinders in-line
Bore / stroke	106 x 136 [mm]
overall displacement	7.20 [dm^3]
Compression ratio	17.5 [-]
Serial number / year of manufacture / operating hours	926929-00-667522 / 2007 / 200
Cooling medium (air, water, etc.)	water
Combustion process (direct injection, prechamber, etc.)	direct injection
Fuel system type	solenoid-controlled single unit pumps
Speed governor	EDC
Method of air aspiration	turbocharging
Charge air cooling system	intercooler
Measures to reduce emissions	-
Rated power / Rated speed	220 [kW] @ 2200 [min^{-1}]
Low idle speed / high idle speed	600 [min^{-1}]; 2750 [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}]	2252	2252	1484	1484
Torque [Nm]	1005	492	1308	648
Power [kW]	237.1	116.0	203.3	100.7

7.2. Fuel data according to SN EN 590

SNR 277205, Tab. D.4

Base fuel (without additive)			
Type	Diesel fuel Danish market quality		
Manufacturer	YX Energi A/S		
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

YX Energi Texaco Ursa Ultra X, Low SAPS, 10W-40

Property		
Viscosity kin 40°C	-	mm^2/s
Viscosity kin 100°C	13.5	mm^2/s
Viscosity index	154	(--)
Density 15°C	860	kg/m^3
Pourpoint	-33	°C
Flamepoint	238	°C
Total Base Number TBN	9.8	mg KOH/g
Sulfur ashes	1.0	%w

8. TEST METHODS AND INSTRUMENTATION

8.1. Engine dynamometer and standard test equipment

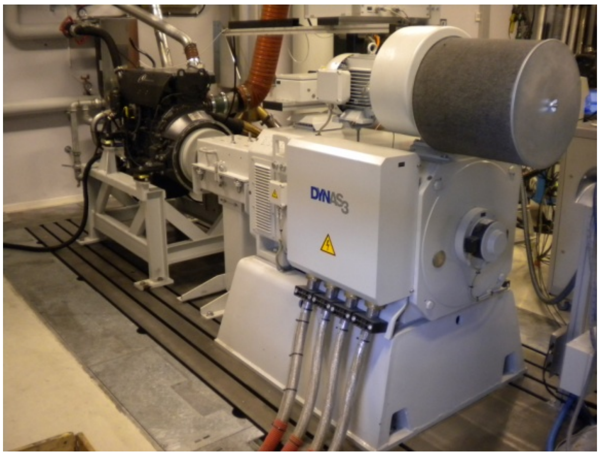


Fig. 8-1: Horiba Schenck dynamometer Dynas 3 HD 600

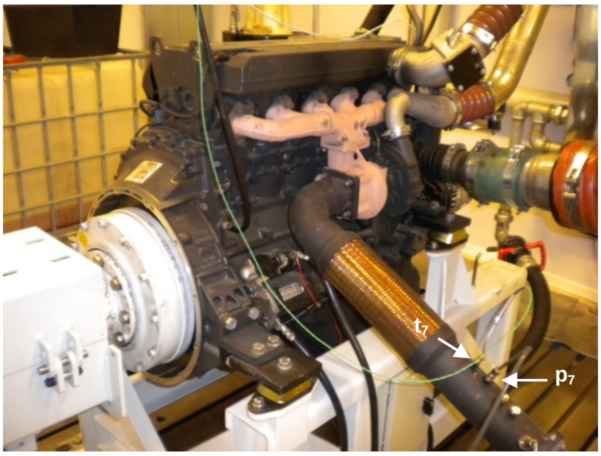


Fig. 8-2: sensors p_7, t_7

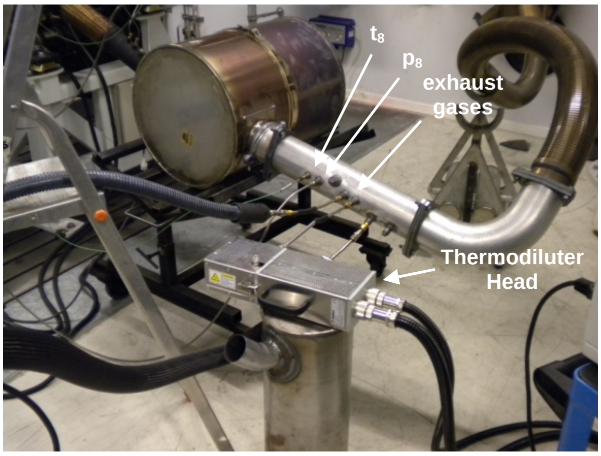


Fig. 8-3: sensors p_8, t_8 and TSI 379020A Thermodiluter Head (MD19-3E)

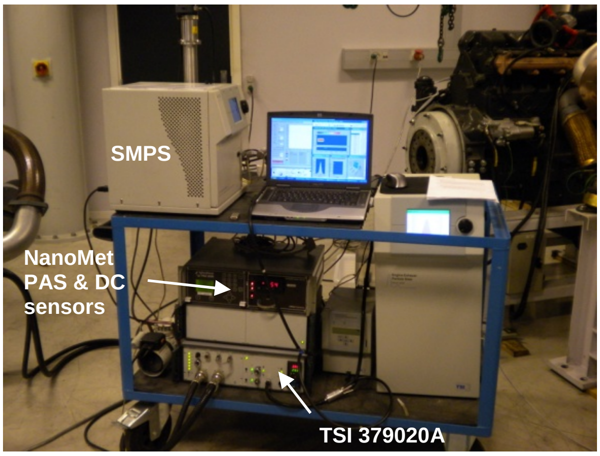


Fig. 8-4: NanoMet, SMPS and TSI 379020A apparatus

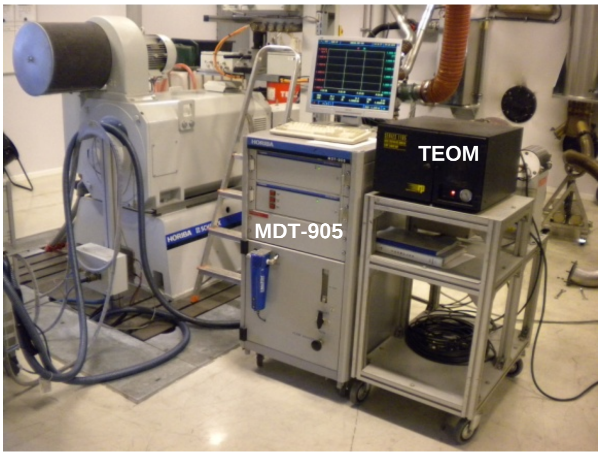


Fig. 8-5: Horiba MDT-905 and TEOM series 1105

Fig. 8-6: FTIR Horiba MEXA 6000FT

Following laboratory equipment was employed:

Horiba Schenck Engine Test Stand Titan D 600 with:

- Dynamometer Dynas 3 HD 600 with torque measuring flange
- Fuel flow measuring and conditioning unit KMA 4000
- Air flow measuring unit Sensycon Sensyflow P DN 150
- Pressure transducers Schenck CANSAN-SP8
- Thermo-couples Type K, Pt 100
- Intake air conditioning: mixing valve outside / inside air

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 device
    Type MEXA 6000FT, Fourier Transform Infrared Spectrometer (FTIR)
- Measurement of the particulate emission:
  - Sampling and dilution:
    Horiba Micro-Dilution Sampling System MDT-905
    Diesel particulate mass monitor Tapered Element Oscillating Microbalance (TEOM)
    Series 1105 (Rupprecht & Patashnick Co., Inc.)
  - Opacimetry:
    Bosch BEA mobile

Calculations are done with the user-software MS Excel 2007. 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 3081, CPC TSI 3010)
- NanoMet – System consisting of:

  - PAS – Photoelectric Aerosol Sensor (Eco Chem PAS 2000)
  - DC – Diffusion Charging Sensor (Matter Eng. LQ1-DC)
  - MD19 tunable minidiluter (TSI 379020A Thermodiluter Head respectively Matter Eng. MD19-3E)
  - 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: last 5 min. of 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: online with TEOM
- Free acceleration with opacimetry

Monitoring of the test conditions

- Ambient temperature: default value (mixing valve outside / inside air)
- Barometric pressure: default value
- Ambient humidity: default value
- CO_2 content of the ambient air: not measured
- Temperature in the test cell: mixing valve outside / inside air, set to 22°C
- Air inlet temperature after the filter: 20°C 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

SNR 277205, Tab. D.1

Manufacturer of filter system		Dinex A/S, Fynsvej 39 5500 Middelfart, Denmark
Type / serial number		Catalysed Silicon Carbide / PN 984703, SN 121613
Designation of particle filter family		$DiSiC_{CATALYSED}$
Filter medium (particle filter element)		
Manufacturer of filter medium		Dinex A/S
Type		Silicon carbide
External dimensions / weight		11.25" x 12" / 19.5 kg
Material		Silicon carbide
Porosity	[%]	42-45
Pore size	[μm]	15-17
Number of cells per square inch	[CPSI]	150, 7 segments
Wall thickness	[mm]	0.5
Maximum flow-through rate	[m^3/s]	0.8125 @ 470°C / 0.71 *)
Maximum space velocity	[s^{-1}]	36.4 *)
Maximum operating temperature	[°C]	600 cont. / 750 peak
Storage capacity for soot/ash	[g]	ca. 234
Regeneration		
Regeneration procedure		NO_2 - oxidation
With additive (FBC = fuel borne catalyst)		
Manufacturer and specification of additive		
Catalytically active substances		
Treat rate recommended / standard		
Additizing procedure		
Specification of dosage device		
With catalytic coating		
Catalytically active elements / concentration of catalytically active substances		Pt 20 g/ft^3
OBC (electronic on board control unit)		
Manufacturerer and specification		Dinex DiNLOG
Serial number		PN 41005, SN 08100215

The tested filter Dinex DiSiCcatalysed on the engine stand is represented in annex A5. Technical information from manufacturer – is represented in annex A6.

*) see annex A12 (at bottom)

10.2 Field Test VFT2

The DPF Dinex DiSiCcatalysed was installed on a Volvo B10 bus with Euro II engine DH 10A 245, 180 kW, operated by Arriva Denmark, Gladsaxe, Denmark.

Description of the field test from the operator:

Description	**Date**	**Operating km of the bus**	**Cumulated km of DPF 121613**
Installation	10.02.2009	577'418	0
1000h control measurement	02.06.2009	Odometer dysfunctional	24'500 *)
Removal	24.09.2009	Odometer dysfunctional	49'000 *)
Total working km			49'000 *)
Total working hours (with $\bar{v}$ = 24 km/h)			**2'042**

*) according to Arriva

There were continuous controls of backpressure by means of datalogger (examples see annexes A7).
The distribution-plots of pressure and temperature before DPF (from datalogger) show that the average backpressure rarely exceeds 50 mbar and the temperature before trap is mostly between 150 and 300°C.
The first control measurement was performed by the Danish Technological Institute, see annex A8.
There is a catalytic influence of the measured DPF system on the gaseous emission components: reduction of CO and HC and increasing of the NO_2/NO_x-ratio up to approx. 8% at low idle and 38% at high idle.
Annex A9 (after 1000h) shows the same influence, there is an increasing of the NO_2/NO_x-ratio up to approx. 34% at low idle and 19% at high idle.
The measurements after 2000 operating hours showed a reduction of CO and a decreasing of the NO_2/NO_x-ratio down to approx. 9% at high idle. NO_2/NO_x-ratio at low idle was equal, see annex 10.

11. RESULTS

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 DINEX DiSiC catalysed 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 catalytic influence of the measured DPF-system on the gaseous emission components: reduction or elimination of CO, HC and no influence on NO_x. The engine-out-NO_2 is increased up to the NO_2 / NO_x - ratio of 60%.

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 0.01 and 0.001. (An exception is the operation points 5, 1st performance in state of delivery).

Fig. 16 – the integrated numbers of particles in the size spectrum 20-300 nm show differences with/without DPF, which are generally of 2 orders of magnitude. The smallest differences are at pt. 5 (1st performance).

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 0.01 and 0.001.
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 DPF DINEX DiSiC catalysed. The average filtration efficiency for counts PCFE = 99.31%, is very good and sufficient for VERT.

Fig. 20 shows the regeneration attempt, which followed at 2200 rpm with the stepwise increased torque. A first backpressure drop is visible in the 7th step at approx. t_7 = 500°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 DPF DINEX DiSiC catalysed increases NO_2-concentration at all steps. The average increase ratio Δ NO_2 / NO_x is 34%.

12. CONCLUSIONS

The results can be summarized as follows:

- with the investigated DPF in the used condition the filtration based on number count reached 99.4 % and as average of the 4 operation points 99.15%
- the used DPF eliminates very well the opacimetric acceleration smoke
- the regeneration of the DPF with the catalytic coating worked very well
- due to the catalytic activity of the DPF system, there are influences on the gaseous components: reduction or elimination of CO & HC. There is no change of NO_x but the engine-out-NO_2 is increased up to the average value Δ NO_2 / NO_x = 34%.
- 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 and can be recommended to the users.

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

16. APPENDICES

17. ABBREVIATIONS

AFHB	Abgasprüfstelle FH Biel, CH
AKPF	Arbeitskreis der Partikelfilterher steller, 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 Pro gram, 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 Abgasnachbehand ungs –technologien für Dieselmo toren, Germany
FBC	Fuel Borne Catalyst = Fuel Addi tive = 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 Administra-tion, 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
TEOM	trapping element oscillating microbalance
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