Diesel Particle Filter Systems in Tunneling in Switzerland. Filtration Efficiency, Secondary Emissions and Overall Effect on Ambient Air

A. Mayer / TTM, Technik Thermische Maschinen
M. Kasper / ME, Matter Engineering
J. Czerwinski / AFHB, Abgasprüfstelle Fachhochschule Biel
W. Scheidegger / SUVA, Schweiz Unfallversicherungsanstalt, Bereich Bau

ABSTRACT

The VERT project 1993 -1998 laid the technical foundation for curtailing the emission of fine particles from Diesel engines at Swiss underground workplaces. The targeted maximum was 100 µg/m3 EC. Extensive Lab and field investigations demonstrated that this specification is only attained with modern DPF (Diesel Particle Filter) systems that almost eliminate particles in the entire lung penetrating size range from 20 nm to 2.5 µm.

In January 2000, Switzerland mandated compulsory particle filters at underground workplaces, particularly in tunneling, irrespective of engine age, size and type. After complete implementation of the imperative, the particle concentration in the respiratory air is now below 40 µg/m3 EC, compared to earlier values of up to 750 µg/m3 EC. Deployed DPF have proven filtration rates of 99% in the entire size range of alveoli intruding particles. The DPF are as durable as the engine, suffer no aging and require minimal maintenance. The failure rate is below 3% annually. Of the 6000 retrofitted construction machines in Switzerland, about 400 are deployed underground. Prerequisites for this quality are a sophisticated certification procedure, electronic monitoring of DPF operation and meticulous periodic exhaust-gas inspection of the engines.

1. INTRODUCTION

The planning of the Swiss New Alpine Transit Railway NEAT (AlpTransit, 1994) in 1993 motivated a comprehensive scrutiny of Diesel engine particle emissions and possible curtailment. The total length of all tunnels on the new railway line is 160 km, of which the basis tunnel (dual tunnels) is itself 57 km. The tunnel cross-section is large to facilitate high-speed trains. The NEAT tunnels were a challenge in many technical aspects. Healthy air quality, at the tunnel sites, was the responsibility of the SUVA (Swiss National Accident Insurance Organization). The SUVA had classified Diesel particle emissions as carcinogenic and set the total carbon limit TC < 200 µg/m3 , which was subsequently (SUVA Report No. 1903/1994) corrected to elementary carbon EC < 100 µg/m3. Swiss environmental legislation requires all carcinogenic substances be curtailed using the best available technology (BAT).

A preliminary estimate based on the 1993 Swiss off-road emissions inventory (SAEFL 1995, Report 23 (1994) is shown in Table 1.

	Gases				Aerosols	
mg/Nm3	CO	NO	NO2	SO2	PM/TC/EC	H2SO4
Construction machine emissions	1000	2700	300	100	250 (–90%EC)	25
Exposure lim. Switzerland 94 Switzerland 00	35	30	6	5	0.2 (EC+OC) 0.1 (EC)	1 1
Required dilution	> 26	> 90	> 50	> 20	> 1000	> 25

Table 1: Comparison diesel emissions and respiratory air quality limits

The concentrations of gaseous emissions and sulfuric acidic aerosols are easily restricted at the workplace with the prescribed dilution of about 1:40 (SUVA-rule is 4 m3/kW/min). However, the particle emissions brutally exceed the limits. Curtailment by a factor 50, i.e. at least 98% filtration efficiency is essential.

Occupational health requires (Staub, 1936 (!); Johannisburg 1959; Birgerson B.,1998; BIA, 1998) that this curtailment must also comprise the alveoli intruding and almost insoluble fraction of solid particles, leading to the definition "solid particles in the size range of 20-500 nm". The objective was clear and the time available short, not to jeopardize the beginning of the NEAT construction.

2. THE PROJECT VERT

To solve the problem, the project VERT (Curtail Diesel Engine Emissions in Tunneling) was initiated under the auspices of the Safety and Occupational Health Agencies of Switzerland (Suva), Austria (AUVA) and Germany (TBG). The project scope was obvious: within 3 years evaluate and test retrofit devices to curtail the fine particle emissions to below 2% of the raw emissions.

The VERT project plan comprised the extensive test-rig investigations of exhaust-gas emission-curtailment technology; on at least two typical construction-site Diesel engines. This implied pertinent aerosol measurement methods, which were not yet developed. Further tasks were field-testing DPF (Diesel Particulate Filters) on at least 10 construction-site machines during 2 years, and the validation and evaluation of field test methods. Finally, the expertise had to be formulated as guidelines and directives for implementing the particle curtailment.

The VERT project team was then completed by UBA and BUWAL, the environment protection agencies of Germany and Switzerland, Swiss national laboratories for engine research AFHB, aerosol physics at ETH and chemistry EMPA and reinforced through an industrial consortium of fuel refiners and manufacturers of engines, catalytic converters, DPF and instrumentation. Thus pragmatic and rapidly implemented equipment was developed. During the project, altogether 11 different engines, 4 fuels, 33 DPF-systems and DOCs (Diesel oxidation catalytic converters), 5 fuel additives and numerous other emission curtailment methods were investigated.

New fuel formulations, even pure synthetic blends without sulfur and aromatics, insignificantly improved solid particle emissions and only for the largest size fractions (Mayer et al, SAE 1999-01-0116). DOCs did not diminish solid particle emissions but generated supplementary toxic components, particularly more NO_2 from NO and more SO_3 from SO_2

Engine management, including new developments such as common-rail systems with high pressure injection, sophisticated injection schemes and oxygenated fuels (Aufdenblatten et al, MTZ 11/2002) enabled a relatively minor curtailment of the particle emissions, restricted to the larger agglomerated particles.

DPF proved to be much more effective. Even the early DPF dependably curtailed the count of alveoli-intruding solid fine-particles by > 98%, the EC mass by > 90% and the carcinogenic PAH (Polycyclic Aromatic Hydrocarbons) by > 90%.

DPF became the answer. The best available technology was defined. The foundation was laid for quickly implementable specifications (Mayer et al, 1998, Gefahrstoffe Jg. 58 No.1/2; Mayer, 2000, VERT Final Report).

3. TECHNICAL REQUIREMENTS OF DPF SYSTEMS

The first specification for DPF systems was the product of the VERT project data and consultations with the collaborating industrial consortium. The specifications were subsequently refined in stages. Table 1 documents the latest status.

The technical requirements are further specified in the SAEFL/Suva Filter List (SAEFL, 2004, VERT Filter List) and also in the check list for DPF on Diesel engines deployed underground (Suva, 2002, Checklist).

Filtration efficiency “Concentration count“ in the particle size range 20-300 nm	> 95%
Filtration efficiency “EC mass concentration“	> 95%
Opacity during free acceleration	< 0.12 m-1
No increase of the limited emissions CO, HC, NOx and PM	
No relevant secondary emissions Pressure loss, max	< 200 mbar
On-road monitoring with alarming + logging functions	
Noise attenuation equivalent to muffler	
Durability:	min.5’000 op.hrs
Identification Flow direction marked	
Safety: Compliance with Swiss legislation on safety STEG	
Diagnosis access for exhaust gas sampling upstream trap	
Concept for ash cleaning and ash disposal	

Table 2: VERT specifications for particle trap systems

It is a technical challenge to achieve high filtration rates at very low back-pressure and yet have a compact DPF. The answer is finely porous microstructures in surface-rich macro-structures. Porous ceramic materials and finely cellular honeycomb configurations are basically suitable. However, these porous structures are vulnerable to thermo-mechanical stresses. From 1996, silicon carbide SiC and stronger cordierites facilitated durable substrates (Figures 1 and 2).

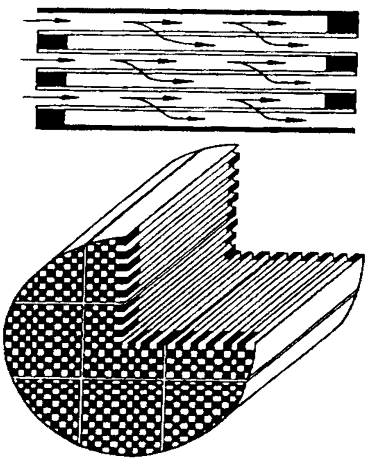

Fig. 1: Ceramic cell filter (Corning 1982)

The biggest technical hurdle is the reliable filter regeneration despite varying operating conditions. Limiting the permissible back-pressure and secondary emissions only indirectly specifies this criterion. It is the DPF manufacturers' responsibility to assure dependable regeneration through a system suitable for a particular deployment. They must develop the necessary expertise and provide a two-year guarantee. The methodology (Mayer et al. SAE 2001-01-0187) developed during the VERT project is a suitable basis for selecting DPF (SAEFL, 2004 interactive CD) and their regeneration.

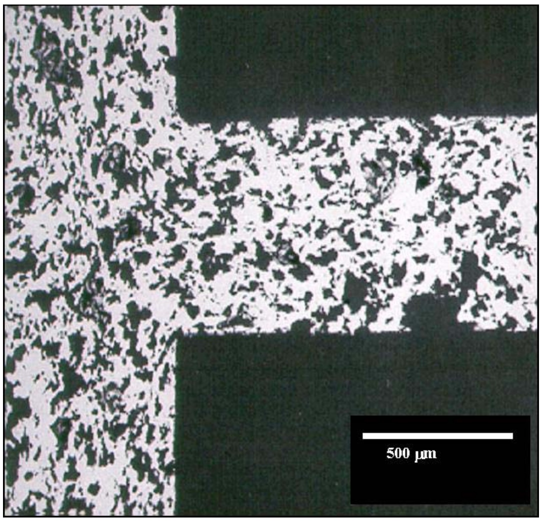

Fig. 2 Pore structure of the ceramic cell filter (Corning)

4. LEGAL BASIS

Switzerland mandated (Swiss Federal Government Ordinance, EJPD 1990) the criteria for DPF deployment, at the time of the first wave of retrofitting which included mainly public buses. The Swiss directive is similar to the US Clean Air Act (U.S.Clean Air Act 2002). It permits retrofitting with catalytic converters and DPF. Concurrent requirements are that neither the noise level nor toxic reaction products, i.e. secondary emissions shall increase. Exhaust gas emissions shall not contain toxic substances, which before retrofitting were either absent or only detectable in substantially lower concentrations.

Diesel engine emission, defined as TC = EC+ OC in particulate form, was declared as carcinogenic and included in the MAK list in 1994 by the Swiss occupational health agency (SUVA Report No. 1903). Further, in 1998, Diesel soot was included in the list of carcinogenic substances of the OAPC (Ordinance Air Pollution Control) (SAEFL, LRV 1985, revised 1998). In addition to the compliance with limit values, carcinogens must be curtailed using the best available technology BAT. The limit for the particle content in respiratory air at workplaces was prescribed in 1994 as TC < 200 µg/m3 and later redefined as EC < 100 µg/m3.

The Swiss OAPC 1998 prescribes two additional limits for emissions of stationary Diesel engines. These are: dust < 50 mg/m3 and EC < 5 mg/m3. Subsequently, SUVA mandated DPF for underground workplaces (Suva, 2000, Partikelfilter-Obligatorium). Then the Swiss Federal Government (SAEFL 2002, Guideline) issued the ordinance on air quality at construction sites.

The two last mentioned directives do not specify tailpipe emission limits nor ambient concentration limits. Instead, there is a simple requirement to retrofit Diesel engines with DPF. The DPF must fulfil the VERT criteria in Table 2, i.e. must be approved in the VERT Filter List and periodically verified.

5. VERT SUITABILITY TEST FOR DPF SYSTEMS

The VERT suitability test is a generic certification, i.e. tests a representative sample of a particular filter technology. A feature of the VERT test procedure is the intensity of testing, rather under worst-case deployment conditions on a typical Diesel engine than during standard driving cycles.

The authorized test labs have a responsibility to the end-users. Hence, all health relevant attributes of the filter system are scrutinized. These include the filtration characteristics for fine particles, changes in the engine raw emissions and any formation of toxic secondary emissions.

The tests are done at severe temperature, space-velocity and filter-burden conditions. The aging is observed during 2000 operating hours. The emissions at extreme transient states are investigated during free acceleration of the engine. Regeneration is verified in a stage test, with step-wise increasing exhaust gas temperatures, and transients measured. Secondary emissions are determined in the trace level concentration range and metallic emissions are quantified including their particle size dependence. All main and subsidiary functions of the DPF system, particularly the alarm functions are verified.

After successfully completing the entire VERT tests, the pertinent DPF type is approved and can be deployed on any Diesel engine for any duty. Experience fully substantiates the filter theory, (Hinds, 1982) which states that filtration in the diffusion range solely depends on the particle mobility-diameter, velocity and temperature. The particle density and composition are irrelevant. Hence, respecting the maximum space velocity and temperature is sufficient to equally efficiently filter solid fine particles on all other engines.

With type approval, the manufacturer accepts responsibility for appropriate deployment and correct retrofitting of the DPF. The manufacturer must also guarantee reliability and durability. DPF approval is retracted if the annual failure rate exceeds 5%.

Switzerland insists on regular periodic verification of each and every DPF during the so-called "exhaust gas inspection“, which must be repeated every 24 months. The data recorded in the inspection document is a further possibility to assess the quality of retrofitted filter systems.

Ultimately, the operator is legally bound to perform the periodic exhaust gas maintenance and have the prescribed exhaust-gas inspection document. Thus, the responsibility for the specified functioning and reliable operation of the DPF system is defined between the authorities, the vendors and the engine operators.

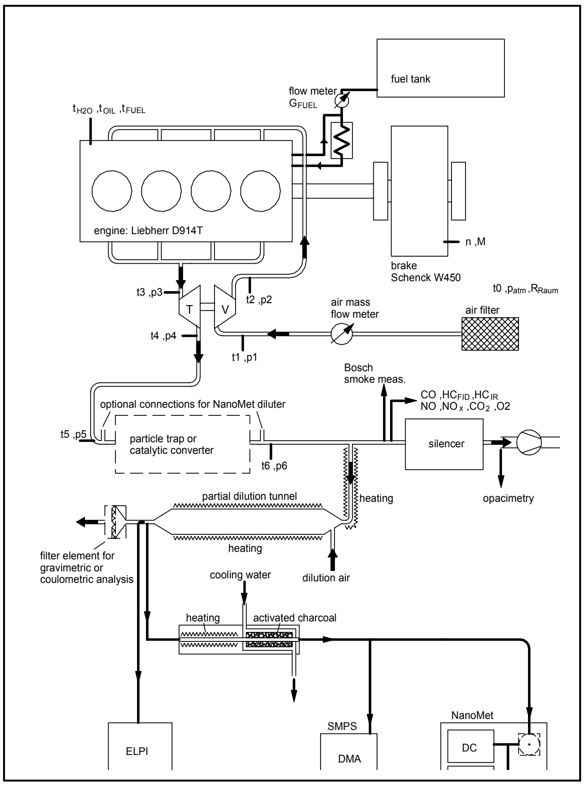

Fig 3: Overview of VERT tests

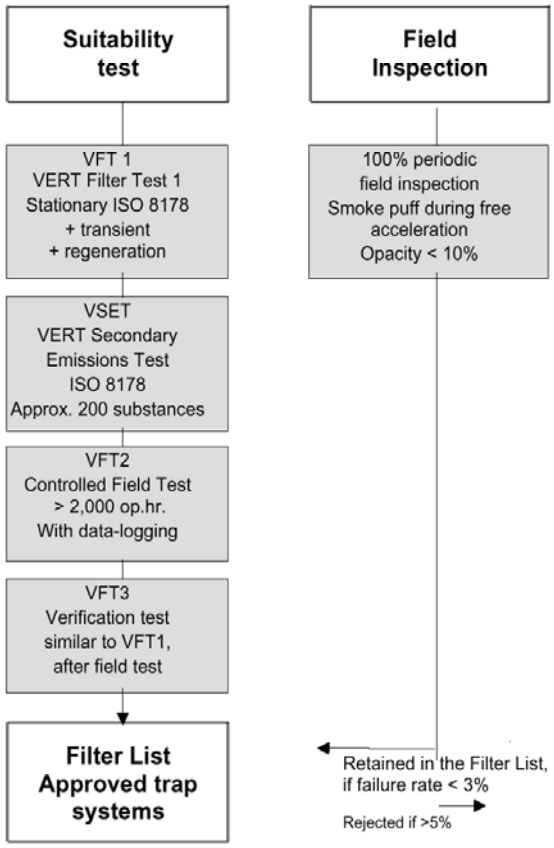

Fig. 4: Schematic VERT test of DPF

The VERT tests are a 4-stage procedure that is schematically shown in Figure 3:

VFT1: Testing the DPF on the engine test-rig. The DPF is measured at 4 operating points of the ISO 8178 cycle till the manufacturer-specified limits of space-velocity and operating temperature. The measurements are done on a new DPF after conditioning or "degreening“ following the manufacturers' instructions. The measurements are repeated at maximum soot burden. Subsequently, DPF regeneration is initiated and the 4 test points repeated with the regenerated DPF. All limited gaseous toxic components, i.e. CO, HC, NOx as NO and NO2, are measured both with and without DPF. Moreover, the particle mass PM, the carbon mass EC+OC, the fine particle count in the size range 20 - 300 nm, and the fine particle surface using the DC (Diffusion Charging) and the PAS (Photoelectric Aerosol Sensor) instrumentation. Gaseous emissions and fine-particle surface are also measured during the regeneration. The tests are enhanced with transient measurement during free acceleration from low-idling until high-idling, another worst-case operating condition for highly supercharged Diesel engines with respect to emission .

VSET, Verify the secondary emissions : The test repeatedly traverses all operating points of the ISO 8178 C1 cycle. About 150 toxic substances, including polychlorinated dibenzodioxins/furans (PCDD/F) , PAH and Nitro-PAH are measured applying an integral sampling procedure to collect gaseous, liquid and particle bound compounds. Additionally any metallic emissions are measured and categorized in particle sizes.

VFT2: Controlled field test of a sealed system with continuous monitoring of pressures and temperatures in a typical deployment, during at least 2000 operating hours, with final field measurements. Recommended are 3 such tests performed in parallel.

VFT3: Verification of the DPF. After successful completion of the VFT2 duration test, the filter comes back to the lab and a simplified version of the VFT1 is repeated.

The occupational health agencies of Austria, Germany and Switzerland together developed the original VERT suitability tests. The tests are now the standard for the 3 Swiss Federal departments of Environment, of Roads, and of Health. Similarly, VERT is the standard for the corresponding German Environment Ministry and German organizations responsible for construction, workplace safety, etc. Several other national authorities have adopted the VERT procedures. These include the Canadian DEEP (Diesel Engine Emission Project for underground deployment), the US MSHA (Mine Safety and Health Authority), the Californian ARB (Air Resources Board), the Chilean 3CV (Centro de Control y Certificación Vehicular) and the Danish DTI (Danish Technology Institute). Harmonization projects are proceeding with Sweden, Korea and Japan.

6. CHARACTERIZING PARTICLE EMISSIONs

The Diesel engine exhaust gas contains three categories of substances, which, depending on sampling and analytical techniques, may be considered as particulate matter:

Solids, mainly soot (elementary carbon EC) but also substantial amounts of ash particles (metal oxides from abrasion and lube oil) and mineral particles (from fuel, lube oil and intake air).

Semi-volatile substances, which during high-temperature combustion are deposited on the particles and bound to those, e.g. polycyclic aromatic hydrocarbons (PAH).

Volatile substances, which depending on the exhaust-gas sampling conditions (temperature, dilution, cooling, dwell-time) may form condensates, e.g. sulfuric acid, volatile organic compounds (VOC), residues of lube oils or water

The road-traffic legislation worldwide uses an encompassing PM (Particle Mass) definition. It includes all substances, which after slight (6-10 fold) dilution in the CVS (Constant Volume Sampling) tunnel are deposited at 52°C and can be weighed. This procedure to determine PM does not yield any information about the chemical composition or particle size distribution of the sample. Hence, it is not suitable to assess toxicity. Nevertheless, PM was also measured in the VERT test, because it is a key parameter in all conventional specifications.

For occupational safety considerations, SUVA defines particle as Elementary Carbon. Hence, the VERT test analyses the particle sample using coulometric instrumentation (VDI 1996, German Standard VDI 2465)

The VERT criteria are based on the German occupational health definitions (BIA, 1998, German Institute for Occupational Safety). These demand exhaust-gas after-treatment to eliminate the insoluble solid particles in the alveoli intruding size range 20 - 300 nm. The analytical procedures must therefore provide data on these particles, i.e. their size, number, composition and other attributes. Aerosol physics has several methods (Burtscher, 2004, Hinds, 1982), which the VERT project used to develop dependable metrology.

	2000 rpm full load	1400 rpm full load	2000 rpm half load	1400 rpm half load	aver-age
PMAG	-118.4	29.7	81.4	62.3	13.7
PZAG 20-200	21.9	76.1	100.0	98.4	36.1
PZAG 50-200	99.8	95.3	99.9	99.8	98.7
ECAG	-	98.5	-	-	98.5
PASAG	99.9	99.9	99.9	99.8	99.9
DCAG	98.5	99.5	96.0	97.2	97.8

Table 3: CRT (Continuous Regeneration Trap) filtration rate measured using 6 different metrics

PMAG: Gravimetric as legislated

PZAG: Particle count (SMPS with CPC) integrated from 20-200 nm and 50-200 nm, respectively.

ECAG: Coulometry of elementary carbon mass

PASAG: PAS (surface area of all combustion particles,

PAS photoelectric aerosol sensor of the NanoMet technology)

DCAG: DC measurement (surface area of all particles,

DC diffusion charging sensor of the NanoMet technology).

Table 3 shows large variations when DPF efficiencies are evaluated using various methods. The most pronounced discrepancy is given by the gravimetric method compared to other techniques. The explanation is solely the stated condensation processes. Condensates occur during sampling. These artifacts are weighed in the sample, despite actually passing through the DPF in the gaseous state, together with the exhaust gas. Spontaneous condensation causes the discrepancies in the PMAG data. The condensates are not discriminated from genuine solid particles and falsify the data. This error is frequently observed and is illustrated in Figure 5:

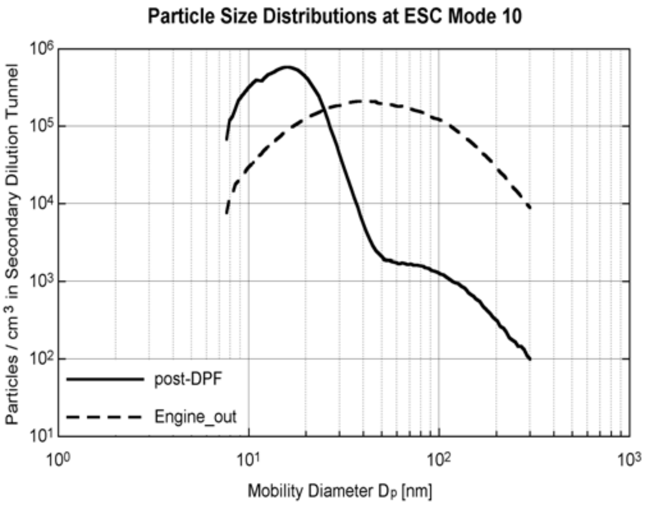

Fig. 5: Particle size distribution at engine-out and post DPF, both measured without temperature control during dilution. Post DPF, solid particles are curtailed 99%, but a large nucleation mode peak is observed.

Clearly, careful sampling is very important in measuring fine particles. The two important criteria are:

Avoid particle agglomeration and particle loss

Prevent the formation of condensates.

Hence, the particle composition in the sample must be "conserved", as extracted from the exhaust gas, and delivered unchanged to the instrumentation. Many international teams worked on developing suitable sampling technology within the European Particle Measurement Program (Dunne, 2003, PMP-Program). Their efforts led to a wide consensus.

The best method is to heat the exhaust gas after dilution.

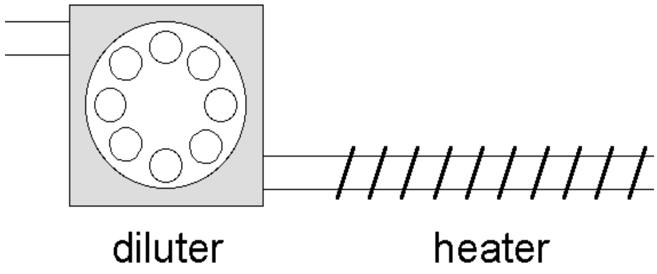

Fig: 6: Principle of post-dilution thermo-conditioning

A rotating diluter (Kasper, SAE 2004-01-0960) enables dilution rates exceeding 1: 1000. Then a short heating stretch raises the sampled exhaust-gas temperature until 400°C. This elegant and compact device is commercially available (Matter Engineering ThC1). It can vaporize > 99% almost non volatile compounds, e.g. Tetracontane ($C_{40}H_{82}$), and restrict thermo-diffusion losses below 10% of solid particles .

This sampling method is now consistently used in the VERT test procedure. It ensures accurate data acquisition on solid particles. Moreover, selecting the heating temperature facilitates a fractionated observation, from which a specialist can draw conclusions about the composition of the volatile substances.

Another important aspect is the instrumentation sensitivity. Only very low particle concentrations are present in the exit from a DPF. The necessary dilution further lowers the concentrations. Hence, the instruments must be very sensitive.

Figure 7 (Kasper, SAE 2004-01-0960) is a good overview of measurement methods. The gravimetric method PM and the coulometric EC determination are compared with more modern methods. These determine the active particle surface through DC (Diffusion Charging) and PAS (Photoelectric Aerosol Sensor).

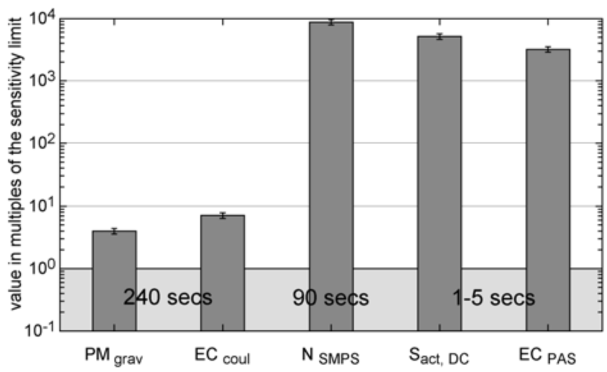

Fig 7: Measured particle concentrations as multiples of the sensitivity limit of the pertinent method. Nanoparticle methods are more sensitive and faster too.

Figure 7 normalizes the particle data, from an EURO 3 automobile at 50 km/h, as a multiple of the detection threshold of each instrument. The sensitivity of the gravimetric method and the coulometric method are constrained, i.e. offer no scope for more stringent emission standards. In comparison, the on-line aerosol instrumentations, both the counting and surface determination, are a thousand-fold more sensitive. Hence, these can not only measure the high raw emissions of present-day engines but also the low emissions exiting a DPF, and indeed the particle concentration in ambient air.

Figure 7 also indicates the time-constants of these instruments. The DC and PAS have time-constants in the seconds range, i.e. are suitable for tracking transients.

Typical measured data is shown in Figure 8:

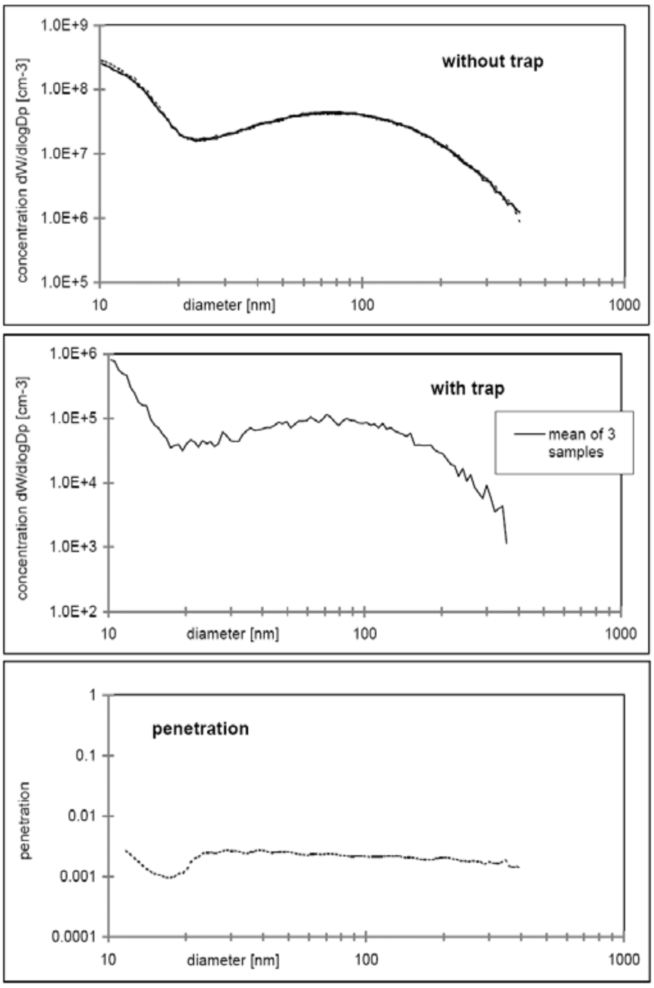

Fig 8: Size distribution of the particle emissions from a 28 kW DI Diesel engine at rated RPM and full load.

The bimodal raw-emissions curve has a noticeable second peak in the range of the finest particles. The cause is the fuel additive used to promote filter regeneration. It is a very fine iron-oxide, formed from a metal-organic compound during combustion.

The middle diagram shows the particle concentration of this highly emitting engine downstream of the DPF. The lower diagram charts the penetration, calculated per size class from the particles numbers measured upstream and downstream of the filter, which is close to 0.001, corresponding to a filtration rate 99.9%. The VERT procedure does not only yield a filtration rate, but includes the measurement of size resolved filtration spectra. Thus, the efficiency of trapping the very toxic fine particles is evident.

These measurements are supplemented with metrics of the total particle count and the total surface area of the fine particles. The DC and PAS instruments can also investigate transient phenomena. They can record the particle concentration before and after the DPF, during a free acceleration. This simple field test accurately establishes the filtration efficiency (Kasper, SAE 2004-01-0960).

The comprehensive investigations of sampling and measurement, as implemented in the VERT procedure, are documented (SAEFL, 2004, VERT Filter List). Specialized instrumentation is now commercially available (Kasper 2005, SIA Pune).

7. CERTIFICATION DATA: THE VERT FILTER LIST

Until today over 40 DPF have been tested as per the VERT procedure. Of those, 21 DPF are approved for unrestricted deployment. Further 6 are approved for short deployment as snap-on or disposable filters, or for specific applications. All approved DPF systems, i.e. successfully passed all VERT tests, are published on the Internet (SAEFL, 2004, VERT Filter List). The Filter List is regularly updated with the test specifications and other DPF requirements.

Table 4 contains all DPF systems approved for unrestricted deployment. The filtration data is the particle count PZAG averaged for all particle sizes and all operating points. Also recorded for comparison are the filtration rates ECAG and PMAG, which are based on the analysis of EC and PM respectively.

The values for the total filtration rate, based on the particle count, are remarkably good both for the new DPF and after the 2000 hour field test. The filtration rates from the EC analysis correlate well with the particle count. However, a large set of measurements again indicates that the PMAG data is misleading.

8. SECONDARY EMISSIONS

Figure 9 shows the test cycle and Figure 10 the sampling schema.

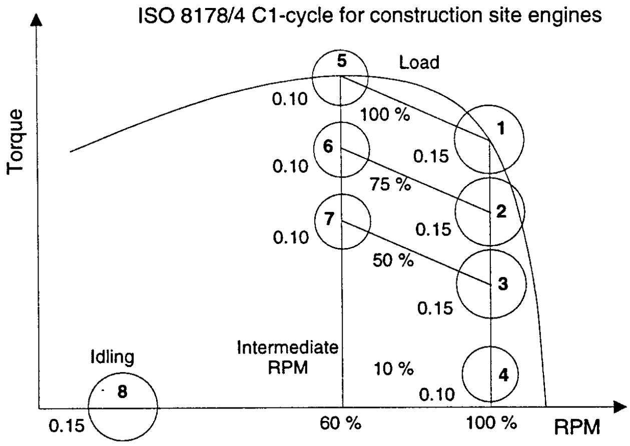

Fig 9: Test cycle for VSET Test according to ISO 8178/4 C1

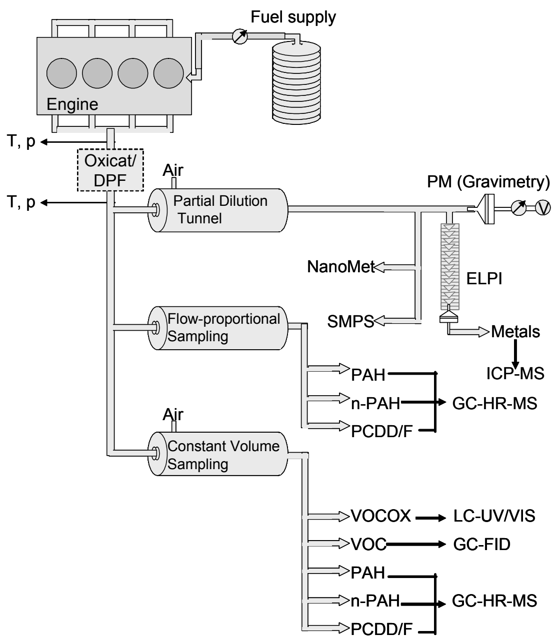

Fig 10: Schematic of sampling and analytical techniques in VERT secondary emissions test (VSET).

Table 5 lists all the parameters and the sampling conditions for each analysis method.

Filter Manufacturer			**Applications with manufacturer references**						**certification year**	**Trapping Efficiencies**					
										VFT1 (filter new)			**VFT3 (after 2000h)**		
R: regeneration			Truck	Bus	Construction site	Fork lift	Ship / Rail	Stationary		PMAG	**PZAG**	**ECAG**	PMAG	**PZAG**	**ECAG**
ECS (UNIKAT)	K18	IBIDEN SiC							2002		**100.0**	**------**	90.5	**100.0**	**------**
R1: Electric in situ / standstill			●		●	●	●	●							
R2: Replaceable filter			●		●	●									
ECS (UNIKAT)	Purifilter	IBIDEN SiC							2003	89.6	**100.0**	**98.4**	73.4	**100.0**	**99.0**
R1: Catalytic coating			●	●	●	●	●	●							
HJS	CRT®	CORNING DuraTrap™CO after oxidation cat.							1998 2002	83.8	**99.4**	**------**	13.7	**98.7**	**98.5**
R: NO_2 from oxidation cat. converter			●	●	●	●									
JOHNSON-MATTHEY	DPFi/DPFiS/ DPF-CRT™	IBIDEN SiC cell filter							1999 2001	84.5	**99.3**	**------**	85.3	**99.5**	**------**
R1: NO_2 from oxidation cat. converter			●	●	●	●									
R2: Electric in situ / standstill					●	●		●							
R3: Fuel additive satacen (Fe)					●	●	●	●							
R4: Fuel additive EOLYS (Ce)			●	●	●	●	●	●							
JOHNSON-MATTHEY	DPFi/DPFis/ DPF-CRT™	CORNING DuraTrap™CO.							2002	------	**99.0**	**------**	------	**99.0**	**------**
R1: NO_2 from oxidation cat. converter			●	●	●	●									
R2: Electric in situ / standstill					●	●		●							
R3: Fuel additive satacen (Fe)					●	●	●	●							
R4: Fuel additive EOLYS (Ce)			●	●	●	●	●	●							
HUSS-Umwelttechnik	FxxS-Serie	IBIDEN SiC cell filter							2002	**------**	**99.7**	**------**	88.8	**99.7**	**98.9**
R1: Electric in situ / standstill			●		●	●	●	●							
R2: Replaceable filter					●	●									
HUSS-Umwelttechnik	FS Filter-Series	IBIDEN SiC cell filter							2002 2003	91.7	**100.0**	**99.8**	73.6	**100.0**	**98.1**
R: Diesel burner at standstill			●		●	●	●	●							
DCL	Titan™ and BlueSky™	IBIDEN SiC							2000 2003	77.7	**99.6**	**------**	80.9	**100.0**	**95.6**
R1: Replaceable filter					●	●									
R2: Electric in situ / standstill					●	●									
R3: Fuel additive satacen (Fe)						●		●							
R4: Fuel additive EOLYS (Ce)						●		●							
INTECO	ECOPUR Kxx yy	Metal fiber fleece BEKIPOR® ST							2000 2003	88.9	**98.1**	**90.2**	88.5	**99.2**	**98.8**
R: Fuel additive satacen			●		●	●		●							
ARVINMERITOR	B-30	CORNING DuraTrap™RC.							2002 2003	79.3	**99.0**	**96.3**	90.2	**99.8**	**99.0**
R: Full-flow Diesel burner			●	●	●	●									
ENGELHARD	DPX1	CORNING DuraTrap™CO							2003	87.2	**100.0**	**99.0**	80.9	**99.6**	**98.0**
R1: Catalytic coating			●	●	●	●	●	●							
R2: Electric in situ / standstill				●	●	●									
ENGELHARD	DPX2	CORNING DuraTrap™CO							2003	**------**	**99.8**	**------**	85.1	**99.8**	**------**
R1: Catalytic coating			●	●	●	●									
R2: Electric in situ / standstill			●	●	●	●									

Table 4: List of all DPF systems approved since 1998, excepting snap-on filters and special applications

Parameter	Sampling type	Analytical method
Opacity	Directly from exhaust gas	Method of free acceleration according METAS instrument norm, SAE J 1667
EC mass	Partial flow or full flow dilution tunnel	Coulometry according to VDI 2465
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	Thermo-dilution and SMPS
Particle surface	Partial flow dilution or full flow or directly from exhaust gas	NanoMet including thermo-diluter
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

Table 5: Parameters tested in VERT static test including sampling + analytical method

Mayer et al. (SAE 2003-01-0291 and Heeb and al. (SAE 2005-26-14) comprehensively describe analytical methods and results of the secondary emissions investigations.

The VSET, part of the VERT procedure scrutinizes all substances that the WHO (World Health Organization) has classified carcinogenic, among others VOC and PAH, Nitro-PAH, and the toxic PCDD/F. Specially investigated are all DPF systems that employ catalytic coating and/or fuel borne metallic additives. In addition the emissions from such DPF are size-specific analyzed at trace level in the following, 3 examples of toxic secondary emissions are given (Heeb et al, SAE 2005-26-14):

PCDD/F-formation from copper containing fuel additives

Most fuel additives do not increase the concentration of polychloninated dibenzodioxins/furans (PCDD/F) in the exhaust gas. Indeed some catalytic systems diminish these toxic substances. However, in two cases, where copper containing fuel additives were used, a massive increase of the hazardous PCDD/F was induced. Fig 11 indicates, that in presence of copper PCDD/F emissions increased by 4 orders of magnitude when chlorine becomes available at trace levels (10-100 ppm).

i

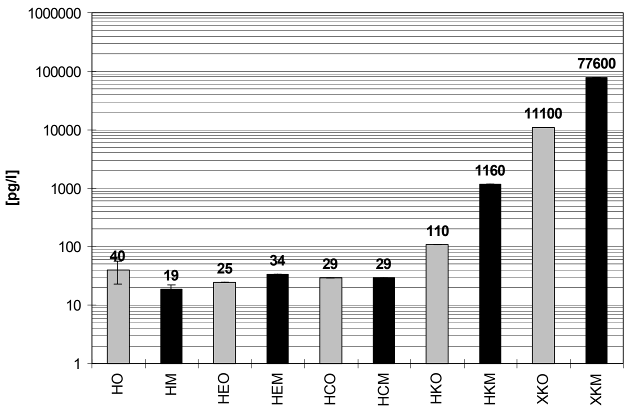

Fig 11 The presence of copper PCDD/F emissions increased by 4 orders of magnitude when chlorine becomes available at trace levels (10-100 ppm)

H: 10 ppm Chlorine
E: Iron additive
X: 100 ppm Chlorine
C: Cerium additive
O: without DPF and additive
K: Copper additive
M: with DPF

The formation of chlorinated dioxins and furans is normally not anticipated in the exhaust gas. The usual engine dwell time is too short for the slow process of de-novo-synthesis. The situation in the DPF is completely different. Reaction products from the exhaust gas are deposited on the exceptionally large surface of the filter substrate (up to 1000 m2/kW) and dwell a long time. This chemical reactor can induce formation of substances that do not normally occur in the engine exhaust gas. Hence, DPF must be carefully investigated. Culprits are not only intentional catalysts but also substances from the lube oil or engine abrasion, because the combustion process transforms them into very fine particles which will be trapped in the DPF as well.

Such catalytic conditions can also occur in other exhaust gas after-treatment systems. The formation of secondary emissions can therefore not be excluded a priori and the potential has to be investigated, e.g., for oxidation catalysts or DeNOx systems such as selective catalytic reduction systems (SCR) as well.

NO2 formation:

Normally, Diesel engine exhaust gas in the medium and higher load ranges, i.e. temperature > 250 °C, contains very little NO2, usually less than 10%. However, in catalytic converters with precious metal components, typically in the DOC (Diesel Oxy Cat), a significant conversion of NO→ NO2 occurs, particularly when the sulfur content of the fuel is low. Some passive DPF systems use this effect, to oxidize soot with NO2, at astonishingly low temperatures of 250 °C. NO2 slip is then inevitable. Figure 12 shows this in the VSET results of pertinent systems.

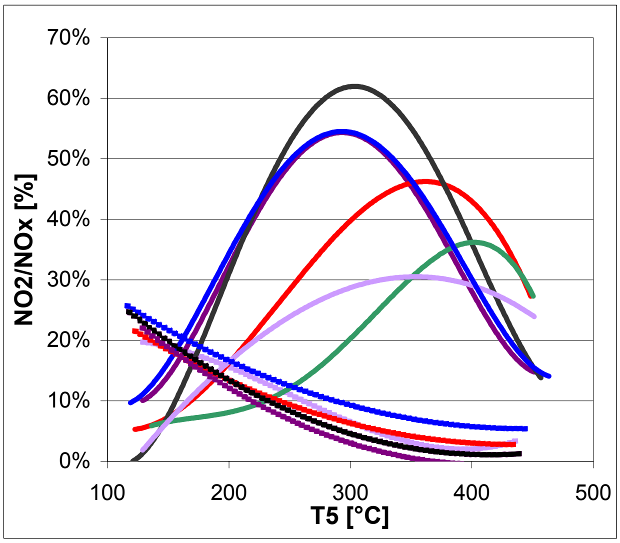

Fig 12: Conversion of NO, from engine combustion, into NO2 in DPF with precious metal catalyst coating

These technically elegant and maintenance-free DPF systems are popular. However, excessive NO2 emissions are a threat at workplaces and may exceed the occupational health limits. This technology is not ideal for underground workplaces where fresh air is often scarce.

Emissions of metal oxide nanoparticles:

The toxicity of metal oxides formed in the combustion chamber is not yet well understood but significant health effects have to be expected when metal oxide nanoparticles are released, particularly in particle sizes that are alveoli intruding (Costantini, 2000, 4.ETH-Conference). The source of metal emissions is either engine abrasion, or the lube oil, or fuel additives. After vaporization during combustion, such substances nucleate in the range 5-10 nm and subsequently agglomerate to about 20 nm in the exhaust gas. Particularly hazardous are so-called regeneration additives intended to lower the soot ignition temperature in the DPF. These fuel additives are mostly transition metals but precious metals are also used. VERT permits such additives, useful in many applications, only in combination with DPF, which are proven to reliably intercept the metal oxide particles. Figure 13 is an exemplary illustration of such an analysis. It pertains to a Cu/Fe additive dosed at 20 ppm to the fuel. Compared to a reference fuel, 100fold more copper nanoparticles are measured in engine-out exhaust gas but they could be removed completely when applying a DPF. The deduced filtration rate for these metal particles is 99.9%, compared to a soot filtration rate of 98.2%.

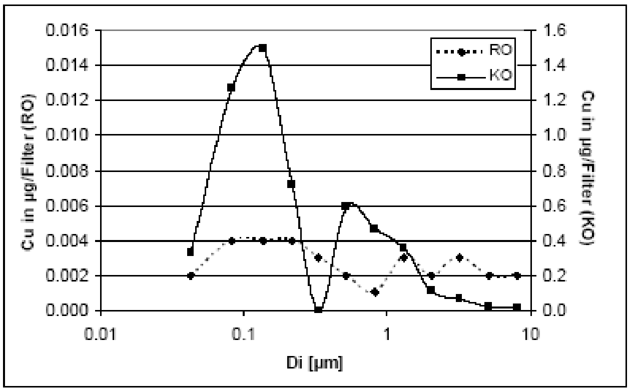

Fig 13: Size classified copper content in diesel soot for a Cu/Fe additive fuel (KO) and an additive-free reference diesel (RO)

The VERT secondary emission testing is now only performed on new DPF and only for systems using catalytic coating or fuel additives. These catalysts could deposit in the DPF and trigger undesirable chemical reactions. Under these circumstances, the restricted VSET testing may be insufficient. There is some evidence that non-catalyst DPF may acquire catalytic attributes during operation. Metallic substances from the lube oil or from the engine may be finely deposited in the filter matrix. Moreover, catalytic coatings may alter their response during operation. Unforeseen reactions may occur, as increasing amounts of fuel additives are deposited. These long-time effects need not exclusively be due to weakening, so-called aging. Instead, additional effects can occur that cause formation of further toxic substances. Hence, it would be advisable to repeat this test after the DPF is deployed for a while.

9. MEASUREMENTS AT TUNNEL SITES

The DPF imperative was progressively implemented at Swiss underground sites. Starting 1st April 2000, 29 measurements of EC and TC emissions were performed at 13 different underground sites and 180 averaged data points collected. The comparative baseline was the emissions data from the years 1998 until 2000. The valid legal limit in those years was 200 µg/m3 TC. Further comparisons were made with emission data until December 1998, from 30 underground sites, where Diesel vehicles were deployed without DPF.

µg/m3 EC or TC	Peak values	90% Per-centile	Aver-age	Avg / MAK [%]
Data 98-2000 (N=47)	987 TC	N/A.	300 TC	150
Data 2001 (N=28)	444 EC	202 EC	121 EC	121
Data 2002 (N=54)	384 EC	194 EC	105 EC	105
Data 2003 (N=33)	139 EC	124 EC	60 EC	60
Data 2004	210 EC	79 EC	45 EC	45

Table 6: Soot content in respiratory air at Swiss underground workplaces 1998 - 2004

The comparisons (Table 6) demonstrate a substantial improvement in the air quality at tunnel sites. At some sites, the recommended dilution of 4 m3/kW/min could be lowered to 2 m3/kW/min. The limit values are so well met that a further lowering of the limits to below 100 µg/m3 EC is being discussed. This conforms with the legislated intention to curtail carcinogenic substances to the extent feasible.

The progress to improved air quality is shown in the emissions data charted in Figures 14, 15, 16 and 17.

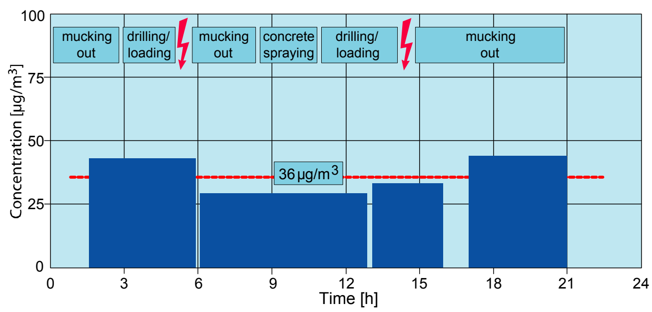

Fig. 14: EC-mass concentration measured inside a tunnel site 200 m from tunnel face. Sampling with GSA SG-10 (PGP FSP-10 acc. to BIA No.3020 with filtration characteristic EN 481). EC-determination by Coulomat acc. to SUVA SAA No.4.006. All engines are fitted with DPF. Emissions during a tunneling sequence (drilling, charging, mucking out, concrete spraying, except blasting). Assumed that the dilution air contains about 10 – 15 µg/m3 EC. Then the tunneling increments about 20 µg/m3. This is a factor 20 times lower than prior to DPF imperative and corresponds to an average filtration efficiency of 95% .

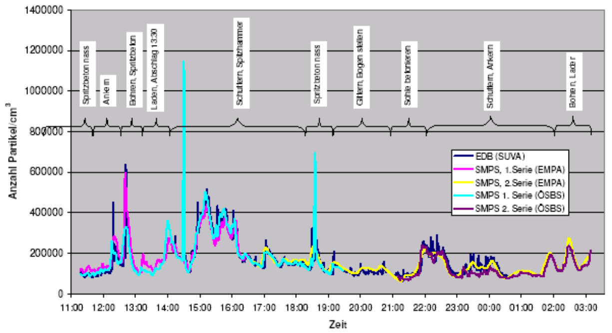

Fig 15 : Particle concentrations over time for conventional tunnelling (drilling/blasting)

New particle number metrology was used to characterize particle size and number:

SMPS Model 3034: particle size range 10 –500 nm / scanning time 180 sec

SMPS Model 3936: particle size range 14 –673 nm / scanning time 120 sec

EDB Electrical Diffusion Battery : size range 10 – 1000 nm; size analysis at 10 Hz (Fierz, 2002, 6.ETH-conference)

EC-Mass concentration in this tunnelling site was measured at different positions: 32-126 µg/m3.

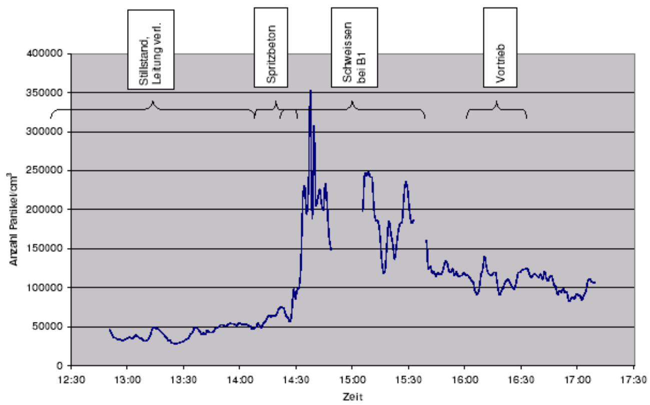

Fig. 16 : Particle concentration measured with ETB for operation with tunnelling-machine. Peaks are most probably due to welding.

EC-Mass concentration in this tunnelling site was measured to 22-36 µg/m3, which is very close to background pollution of the ventilation air.

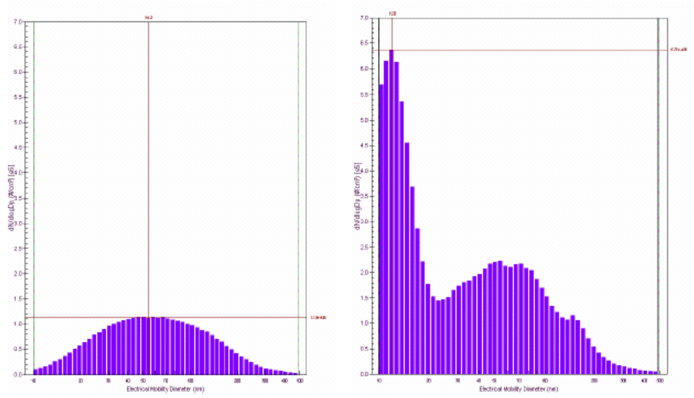

Fig 17: Particle size distributions during conventional tunnelling (drilling / blasting / mucking) – all Diesel engines are equipped with VERT-certified particle filters.

Usually pure Diesel soot size distributions are visible (left), sometimes bimodal distributions consisting of the soot mode and a nucleation mode of volatile particles.

10. DPF FAILURES AND THEIR CAUSES

A DPF failure analysis was done in October 2003. Table 7 shows the results.

Manu-facturer	Number of retrofits			Failures 2001-03	Total failures
	2001	2002	2003		%
A	280			5	1.8
B	420			10	2.4
C	225			5	2.2
D	400	600	320	20	1.5
E	200	250	370	12	1.5
F	134	195	340	18	2.6
G	-		18	1	5.5
H	< 10	< 10	< 10		?
I	< 10	< 10	< 10		?
K	?	?	?		?
L	-	< 10	< 25		?
	Number of retrofits 2001-03 > 3848			Failure rate 2001-2003 1.8% (< 1 % per annum)	
Total numbers	6231				

Table 7: Failure statistics (as of October 2003) for DPF retrofits in Switzerland

The analysis indicates a total annual failure rate much below 1%. The data for these statistics came from the DPF manufacturers, and may be somewhat optimistic. A simultaneous polling of the operators indicated twice as many DPF failures. Hence, a more realistic failure rate is in the range 2 – 3% per annum. This is unacceptable. Steps will be taken to decrease the annual failure rate below 1%.

11. IMPROVING DPF DURABILITY

From 2000 onwards, various efforts were made to improve the DPF technical quality. These efforts yielded rapid success (Mayer et al. SAE 2004-01-0076):

Expelled one DPF family from the VERT approved list.

- Incorporated the 2000 hour duration test as VFT2 of the VERT suitability test suite.
- Implemented electronic OBC (On-Board Control), which has at least 2 alarm levels. These are DPF blockage (indication is back-pressure exceeds 200 mbar) and filter rupture (very low back-pressure). Three months' data must be stored.
- Deployed more active DPF systems.
- Mandated exhaust gas inspection for all construction site machines and instructions on engine maintenance.
- Located diagnosis access-point for exhaust-gas measurement ahead of the DPF.
- Propagated uniform methods for DPF selection based on exhaust-gas temperature measured in the typical load collective, exhaust-gas measurements and checklists.

Requested the AKPF (Association of DPF Manufacturers and Retrofitters) to collect and analyze failure statistics. Therefore, improve DPF reliability and durability.

Other supporting measures to further improve DPF durability would be early availability of sulfur-free fuels, sooner than legally required, and a wider selection of low-ash lube oils from reputed vendors. Moreover, the DPF vendors and retrofitters should provide more information and teach operators on possible failure causes and their avoidance.

12. CONCLUSIONS

The experience with DPF retrofitting, at Swiss construction sites, is encouraging. It substantiates the claim that this exhaust-gas after-treatment, for better air quality, is technically and operationally feasible. It is also economically acceptable. There are no impediments to large scale DPF retrofitting of existing Diesel engines.

The filtration efficiency of modern DPF generally exceeds 99%, and applies to the entire size range of alveoli intruding 20-500 nm particles. The field failure rate of below 3 % is adequate to justify higher manufacturing volumes and extension to other deployment duties. Neither adverse aging phenomena nor other recurring durability limitations are noticed. Recommendations should be respected, e.g., careful exhaust-gas inspection, restricting oil consumption and monitoring back-pressure. Consequently, for retrofitting small numbers of similar design, a durability exceeding 5000 operating hours can be expected at 1% annual failure rates. Some DPF have successfully operated for more than 25 000 operating hours.

It is particularly easy to determine the respiratory air quality in tunnels. The data clearly prove the DPF efficacy in curtailing emissions. The tailpipe particle content is close to the concentration in the dilution, i.e. almost attained the background levels. The US NIOSH (National Institute of Occupational Safety and Health) confirms this result (Bugarski, 2004, 8.ETH Conference) in underground deployment.

Due to this effective emission curtailment at source, the tunnel ventilation rate can be lowered and operating costs saved. The cost/benefit ratio is very favorable. Moreover, the health benefits are substantial. A Swiss study (SAEFL, 2003, Report No.148) deduced that the health benefits are fourfold the DPF retrofitting costs.

Sustaining the substantial emission curtailment, and the reliability of the retrofitted DPF, is conditional on the sophisticated certification procedure. It ensures the trapping of alveoli intruding fine particles and the absence of secondary emissions. Moreover, periodic inspection and strict enforcement including punishment are essential.

13. ACKNOWLEDGMENT

Reaching the challenging targets of the VERT-project was only possible by very close cooperation of may organizations and individuals and by open discussion of all findings at an early stage in the scientific, engineering and occupational health communities of the partner countries. The authors would like to express their sincere thanks to all those who supported this task in particular H.Egli / SUVA, J.Weidhofer/AUVA, D.Kieser/TBG, A.Stettler/BUWAL, H.C.Siegmann / ETH.

14. LIST OF ABBREVIATIONS

3CV Centro de Control y Certificación Vehicular, Chile

AKPF Association of DPF Manufacturers and Retrofitters

AUVA Austrian National Accident Insurance

BAT Best Available Technology

BIA German Institute for Occupational Safety and Health
http:// www.hvbg.de/e/bia/

CARB Californian Air Resources Board

CVS Constant Volume Sampling Tunnel

DC Diffusion Charger

DEEP Canadian Diesel emission Evaluation Project for underground application

DME Diesel Engine Emission (Diesel Motoren Emissionen)

DPF Diesel Particle Filter

EC Elemental carbon

ECAG Filtration efficiency based on the mass of the Elementary Carbon (coulometric method)

ELPI Electrical Low Pressure Impactor

MAK Lists limiting toxic concentrations at Swiss workplaces
http://wwwitsp1.suva.ch/sap/its/mimes/waswo/99/pdf/01903-d.pdf

MSHA Mine Safety and Health Authority

NEAT Swiss Rail Project: New Alpine Transit

Nitro-PAH Nitrated Polycyclic Aromatic Hydrocarbons

OAPC Ordinance on Air Pollution Control

OC Organic carbon

PAH Polycyclic Aromatic Hydrocarbons

PAS Photoelectric Aerosol Sensor

PCDD/F Polychlorinated Dibenzodioxins/furans

PM Particulate matter

PMAG Filtration efficiency based on PM

PMP Particle Measurement Program

PZAG Filtration efficiency based on particle count

SAEFL Swiss Agency for the Environment, Forests and Landscape SAEFL/BUWAL, www.umwelt-schweiz.ch/buwal/eng/

SMPS Scanning Mobility Particle Sizer

STEG Swiss legislation on safety of technical equipment
http://www.admin.ch/ch/d/ff/1999/8864.pdf

SUVA Swiss National Accident Insurance Organization; www.suva.ch

TBG Tiefbau-Berufsgenossenschaft
(German Construction Association)

TC Total Carbon

TRGS German Technical Rules for Toxic Substances

UBA Umweltbundesamt (German Environmental Agency)

VOC Volatile Organic Compouds

VERT Austrian/German/Swiss project to Curtail Diesel Engine Emissions Verminderung der Emissionen von Real-Dieselmotoren im Tunnelbau

WHO World Health Organization

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