25th ANNUAL MDEC CONFERENCE
Toronto Airport Hilton Hotel, Canada

MDEC DIESEL WORKSHOP
Diesel Particulate Filter (DPF) Technology and Engine Technology Deployment

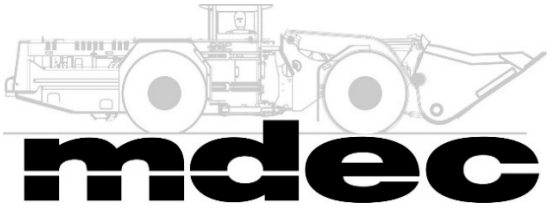
PRESENTED BY:

Andreas C.R. Mayer,
Chris Burrei (DPF Alternatives) and Ralph Deayton (Mammoth)
Matt Roth (Caterpillar)
Bob Deprez (AirFlow Catalyst Systems)
Evelynn Stirling (Cummins)
Vahid Hosseini (University of Alberta)

COORDINATED BY

David Young (Natural Resources Canada) and
Jozef Stachulak (Mirarco)

October 8 - 10, 2019



MDEC Diesel Workshop

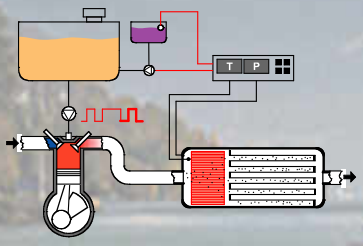
Hilton Toronto Airport Hilton
Ontario, Canada

Thursday, October 10, 2019

WORKSHOP Diesel Particulate Filter (DPF) Technology and Engine Technology Deployment

MDEC Toronto - VERT-Workshop on DPF Technologies – 10.Oct.2019

Part 1
DPF System Design



A.Mayer / TTM-VERT

A.Mayer - TTM
Independent Consultant
Emission Reduction of IC-Engines

- graduaded from Karlsruhe Institute of Technology, Germany
- Brown Boveri Switzerland Steam- and Gas-Turbines Researach
- Supercharging Diesel Engines aand Emission Technology
  founded TTM 1990
- **founded VERT 1994** Verification of Emission Reduction Technology
- Research and Development in International Projects
- Implementation of Emission Reduction Measures
  (Germany, Austria, Italy, California, Canada, Chile, China,Iran, Israel)
- Organization of Seminars and Conferences: HDT and ETH-NPC
- 3 books 2004/5/8 on “Elimination of Comb. Gen. Particles”
- Member of Swiss DPF-Standard Group SNR 277205
- Member of 2008 EU-Expert Group for DPF-Retrofit
- SAE Fellow 2005
- Dr.med h.c. University Bern 2009

CONTENTS

as requested by MDEC Conference Organizers

- **History and Evolution of DPF systems**
- Modern DPF design
- Expected changes in near future
- Pros and Cons of different designs
- How to select a DPF-system for a given application

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This is not a new story

but we only started late to learn our lessons

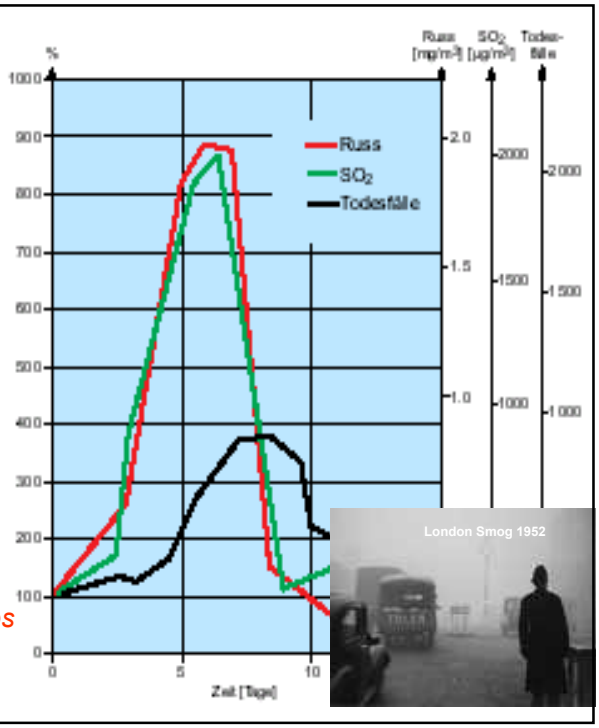
- 1775: Percival Pott proves the correlation between cancer and soot at chimney sweeps scrotum
- 1928: Lawther proves correlation between traffic in London/Wales and lung cancer
- 1936: first assumption in the German journal “DUST” correlates deseases to particles < 1 µm
- 1959: OSH Convention in Johannesburg defines the submicron fraction which penetrates bronchi and alveoli
- 1978: John J.Mooney introduces aftertreatment for the petrol engine, the TWC – three way catalyst
- 1981: CANMET: First Report Dainty/Mogan
- 1982: CARB introduces the first limit value for Diesel PM
- 1989: WHO declares Diesel exhaust probably carcinogenic
- 1993: Dough Dockery: Mortality due to PM2.5 quantified in the Six Cities Study USA 1978-1993

London Smog 1952

during one week died
6'000 persons
6'000 more next month

London had replaced the electric tram by Diesel buses 6 month before

The famous medical doctor Sir Percival Pott found 1775 that soot is the reason for carcinoms in chimney sweeps



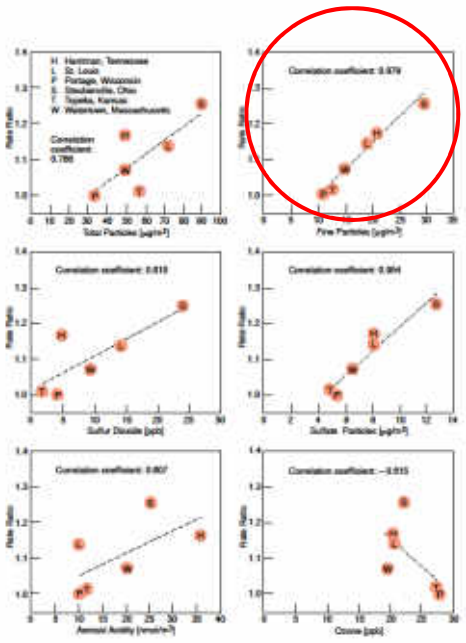
Which TOC correlates to Mortality ?

6-Cities-Study
USA 1978-93
15'000 cases

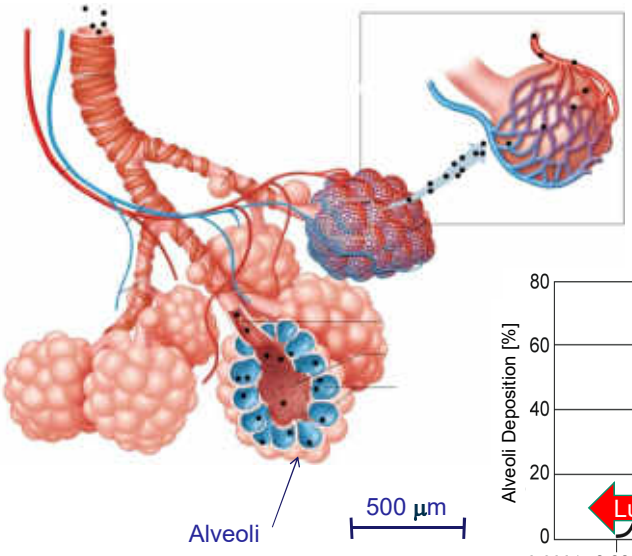
Correlation with fine particles only:
soot + sulfate + nitrate + minerals + water

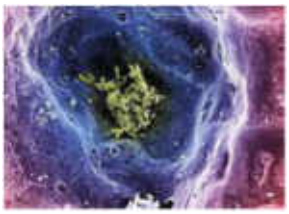
(Sulfate particles is not an independent result since sulfate is just part of PM – same sampling)

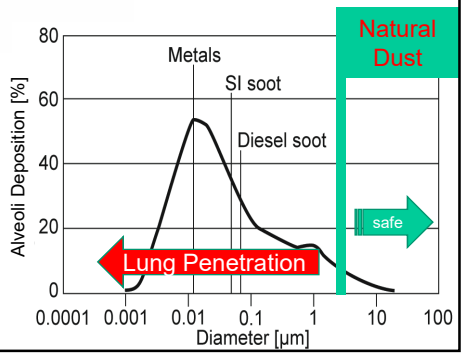
Source: Dockery NEJM 1993



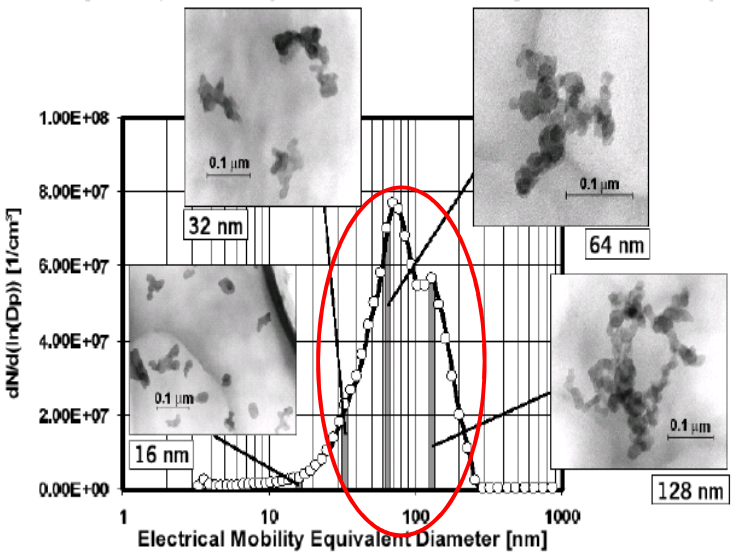
Translocation into blood circulation
is only possible for solid particles < 500 nm







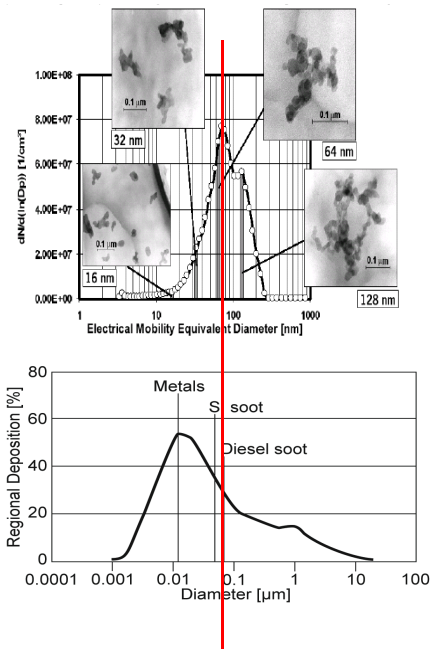
Particles emitted by combustion engines
are solid and smaller than 500 nm (0.5 µm)



A very strange coincidence

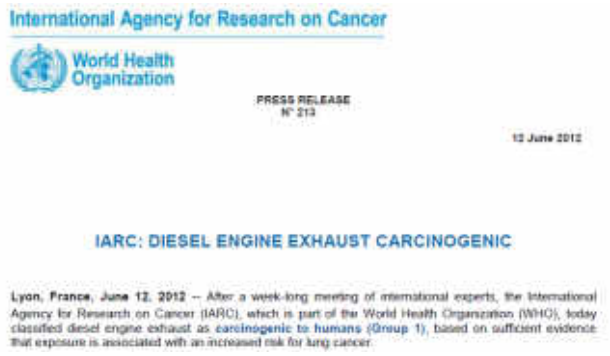
The most sensitive size range of the Lungs is the most intensive emission range of the Engines

The Lung is an open door for engine emitted particles



Diesel Exhaust Carcinogenic

1988 class 3, 2012 class1



International Agency for Research on Cancer

World Health Organization

PRESS RELEASE N° 213

12 June 2012

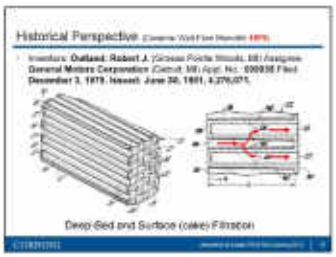
IARC: DIESEL ENGINE EXHAUST CARCINOGENIC

Lyon, France, June 12, 2012 – After a week-long meeting of international experts, the International Agency for Research on Cancer (IARC), which is part of the World Health Organization (WHO), today classified diesel engine exhaust as carcinogenic to humans (Group 1), based on sufficient evidence that exposure is associated with an increased risk for lung cancer.

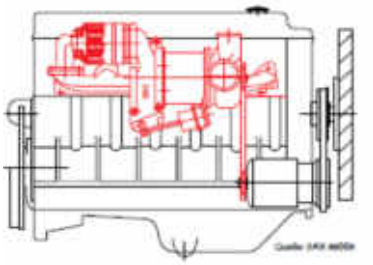
Based on epidemiologic evidence in 8 US metal mines
with 2 lung cancer victims in 100 workers – after 10 years work
exposed to Diesel particle concentration of 100'000 P/cc

But we had a perfect Solution pretty early available

1979
GM



Corning 1982



TTM 1984 with DB

Canada started very early in Mines

Energy, Mines and Resources Canada | Energie, Mines et Ressources Canada
CANMET
Canada Centre for Mineral and Energy Technology | Centre canadien de la technologie des minéraux et de l'énergie

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SUMMARY OF DIESEL EXHAUST EMISSIONS FILTER DEVELOPMENT AT CANMET

E.D. Dainty and J.P. Mogan
Canadian Explosive Atmospheres Laboratory

September 1981

A SUMMARY OF UNDERGROUND MINE INVESTIGATIONS OF CERAMIC DIESEL PARTICULATE FILTERS AND CATALYTIC PURIFIERS

E.D. Dainty, M.K. Gangal, D.H. Carlson,
H.C. Vergeer and E.W. Mitchell

February 1986

Limit Values based on Mining Evidence

Diesel Engine Exhaust

Health-based recommended occupational exposure limit

No. 2019/02, The Hague, March 13, 2019

Executive summary

Advice to the minister

The Committee estimates that the exposure concentrations of respirable elemental carbon in the air, which serve as parameter for exposure to diesel engine exhaust powered by petroleum-diesel fuels, and which corresponds to:

- 4 extra death cases of lung cancer per 100,000 (target risk level), for 40 years of occupational exposure, equals to 0.011 µg REC/m³,
- 4 extra death cases of lung cancer per 1,000 (prohibition risk level), for 40 years of occupational exposure, equals to 1.03 µg REC/m³.

The exposure levels are 8-hour time-weighted average concentrations.

Health Council of the Netherlands

Long-Term Health Impacts

ETH-Nanoparticle Conference
Zurich, Switzerland, June 2019

Heart Failure/Myocardial In

Dr. Scott Weichenthal
Department of Epidemiology, Biostatistics, and Occupational Health
McGill University

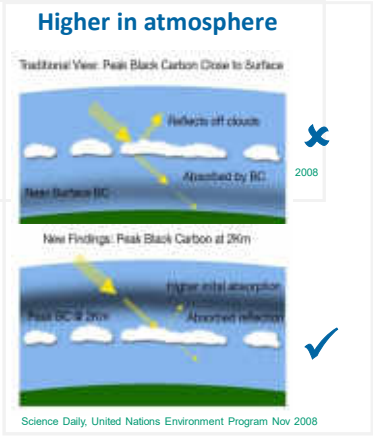
ONPHEC Cohort (1.1 million adults, Toronto, Canada)

- **2-5% Increased risk per 10,000/cm³** independent of $PM_{2.5}$ and NO_2

Table 3. Hazard Ratios for Incident Congestive Heart Failure and Acute Myocardial Infarction According to Long-Term Exposure to Ultrafine Particles and Nitrogen Dioxide, Toronto, Ontario, Canada, 1996–2012

Model[a]	Incident CHF		Incident AMI	
	HR	95% CI	HR	95% CI
UFP_0				
Stratified by age and sex	1.06	1.04, 1.07	1.06	1.04, 1.08
Adjusted for neighborhood-level covariates[b]	1.04	1.02, 1.05	1.05	1.03, 1.07
Adjusted for comorbidity[c]	1.03	1.02, 1.05	1.05	1.02, 1.07
Adjusted for $PM_{2.5}$	1.03	1.02, 1.05	1.04	1.02, 1.06
Adjusted for nitrogen dioxide	1.02	1.00, 1.03	1.05	1.03, 1.07
Adjusted for $PM_{2.5}$ and nitrogen dioxide	1.02	1.00, 1.03	1.05	1.02, 1.07

Awareness of black carbon's role on GW



BC on snow decreases albedo, turning to water.. further lowering albedo

Journal of Geophysics Res.2007

Global Warming by BC-Particles

CONTENTS

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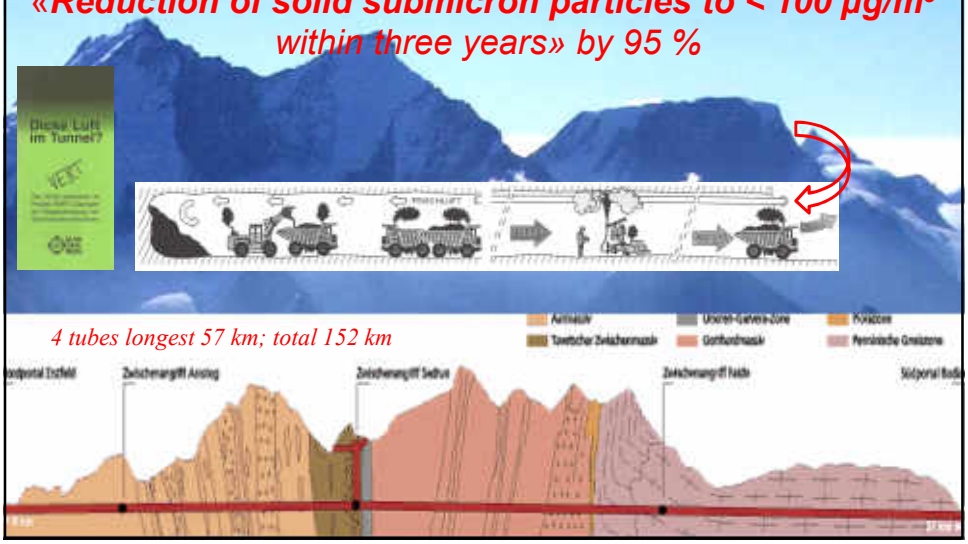
VERT 1993 the NEAT-Tunnel

Switzerland + Germany + Austria

Occupational Hygiene Requirement

«***Reduction of solid submicron particles to < 100 µg/m³***
within three years» by 95 %



Tunneling is the extreme challenge

„VERT-Filter for each Diesel“

Switzerland (VERT) 1996

Based on this physiological and toxicological findings (mostly from occupational health, see Johannesburg convention 1952) a first definition was proposed

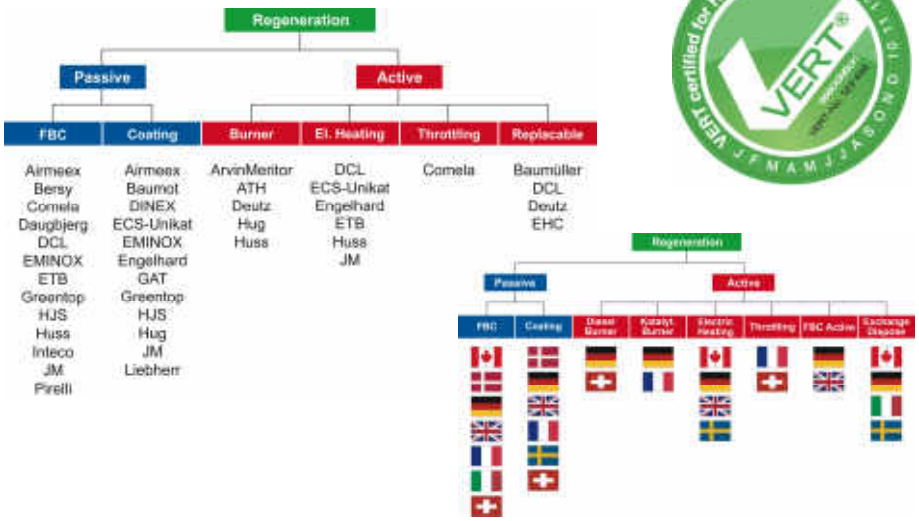
„Solid, **insoluble** particles in the mobility **size range** of 20-500 nm“

→development of new instrumentation
→ BAT-particle filters
→ start of the ETH-NPC

7 reasons why we need PN count replacing PM

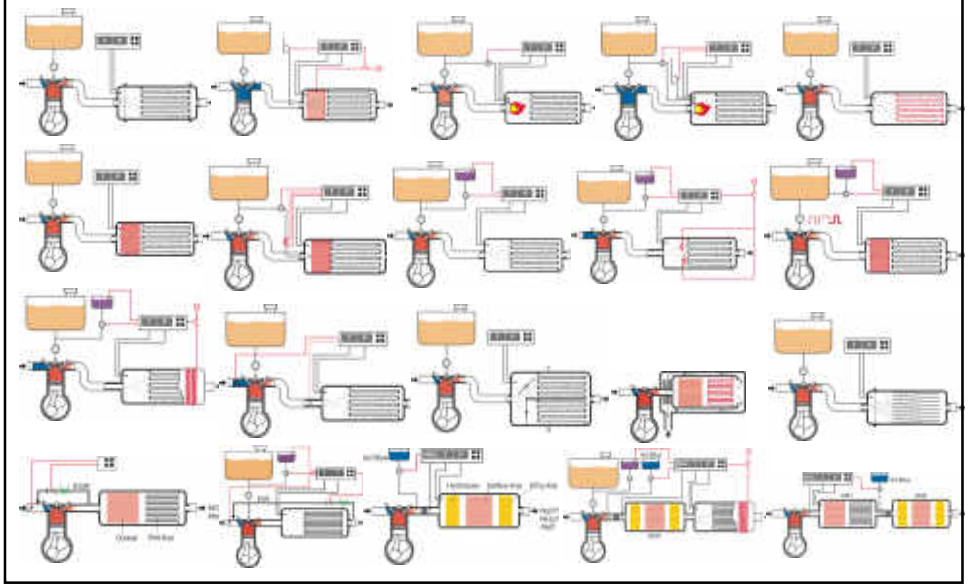
- PM detection limit is 5 mg/kWh – PN DL is 1000 times lower
- Filtration depends on particle size → only size specific PN count can define size depending filtration efficiency
- Only particles < 500 nm can penetrate alveoli membranes, their mass is 1 fg = 10^{-15} g! Can not be weighed but counted
- Only PN-measurement is sensitive enough to permit dynamic roadside quality control of DPF
- PN measurement is also more accurate, dynamic, easy to handle and cheaper than PM-monitoring (NIOSH 5040) and supplies more information
- Only PN monitoring in ambient air can confirm the effect of DPF on ambient air quality
- Only PN permits to monitor soot particles **and** metal oxide particles – BC or TC is unsufficient

VERT–certified DPF Systems

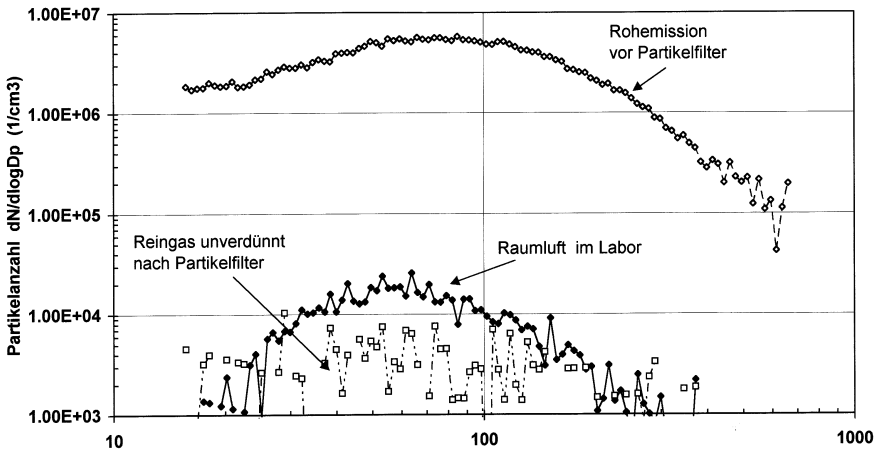


VERT–certified DPF Systems

for different targets and applications

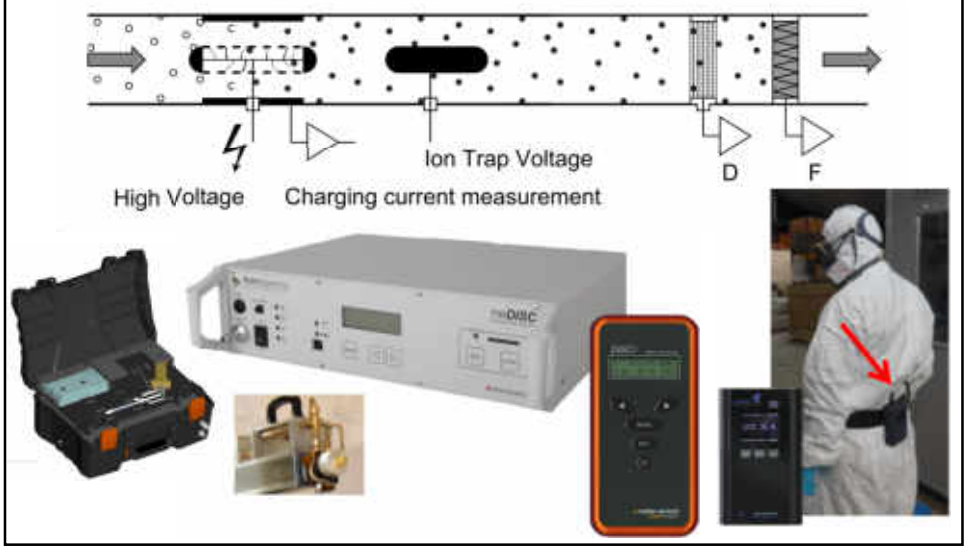


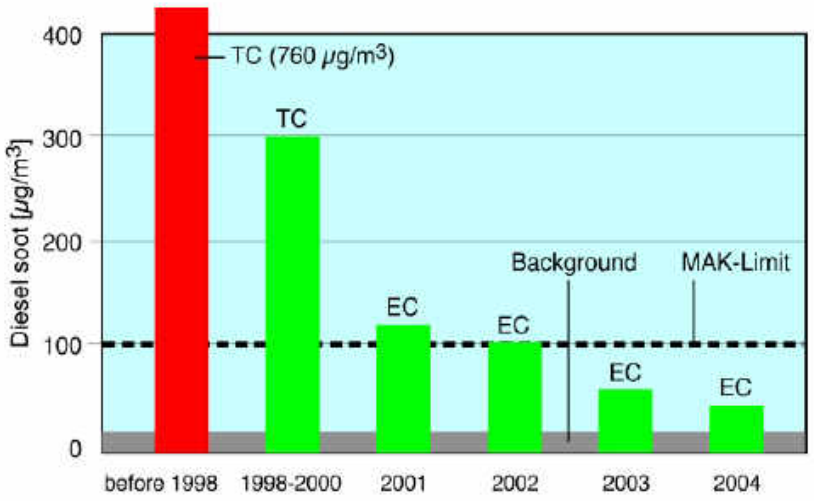
Filtered Diesel-Exhaust is cleaner than Ambient Air (Quelle VERT 1998)



Metrology Development became decisive

for Particle Counting by CPC and DC -Instruments
for Laboratory, PEMS, Maintenance and Personal Sampling



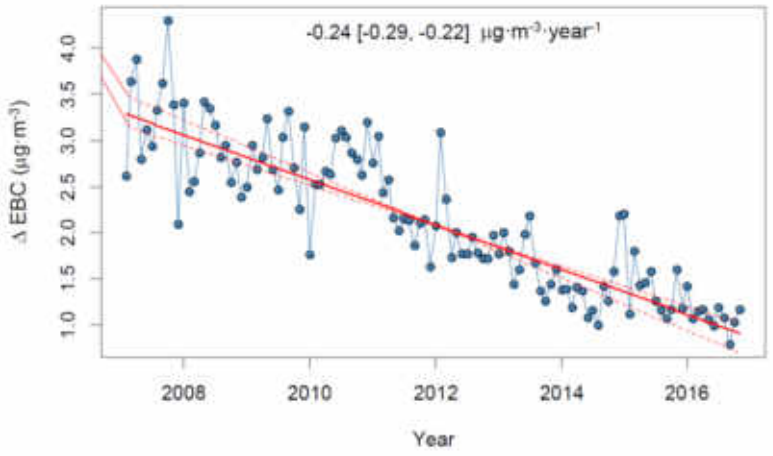


Improvement of Air Quality in Swiss Tunneling

"no Diesel without filter" since 1997

Proof of Success: PN and BC reduced by 60% at a very busy motorway in Switzerland

although traffic increased by 30 %



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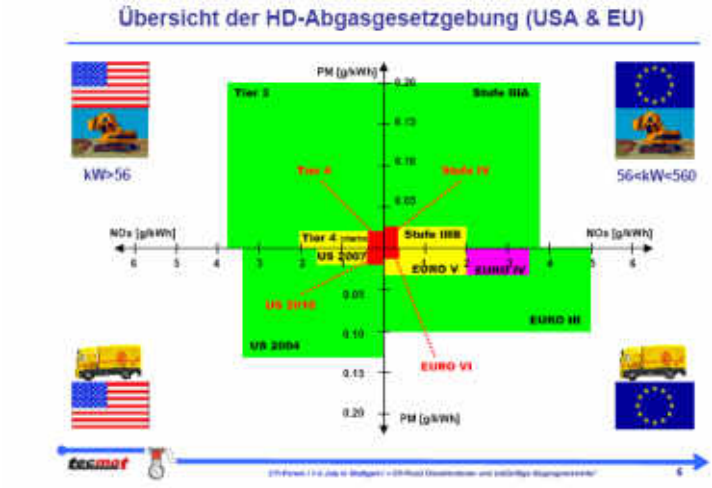
Peugeot mit FAP – 2 Mio Fahrzeuge erfolgreich im Einsatz !

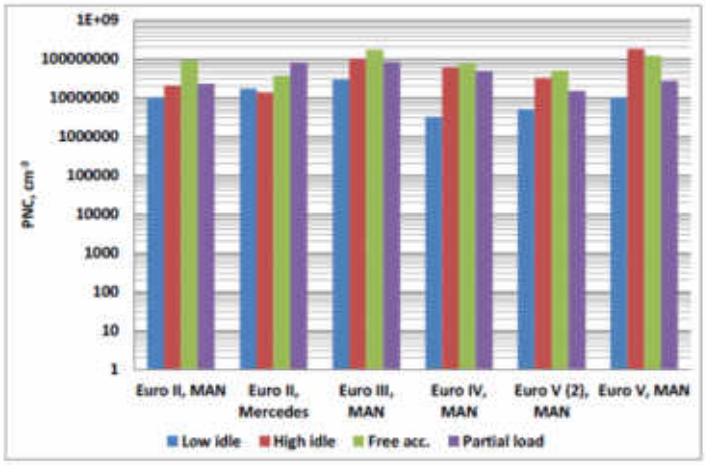
Roll out May 2000

Response of International Legislation ?

→ Impressive reduction of PM Mass
but is this the solution ?

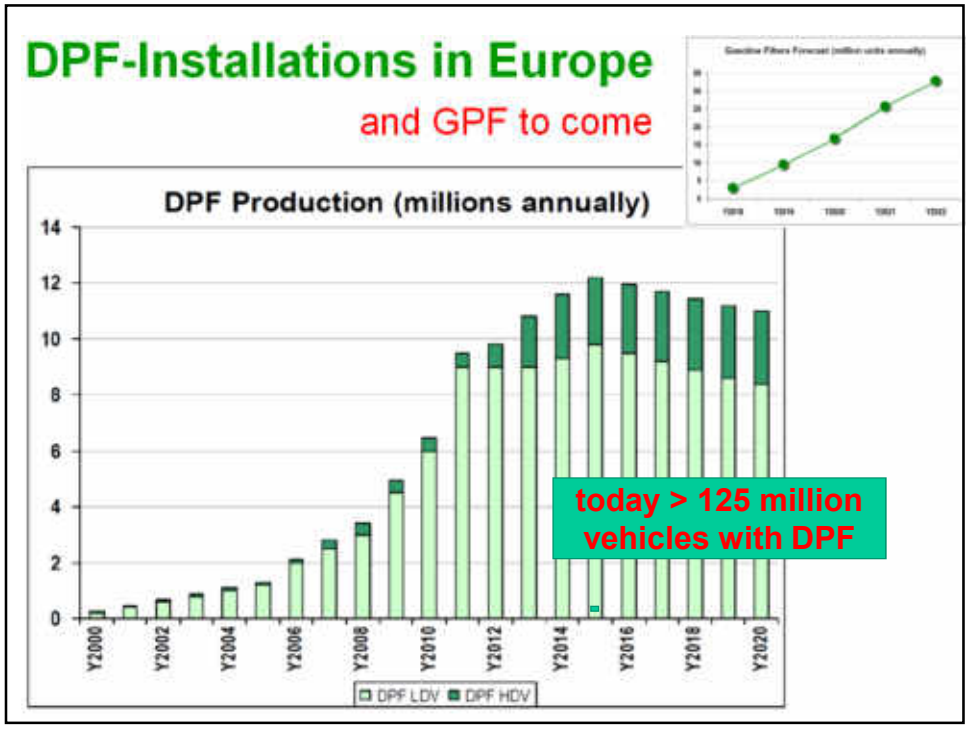


Nanoparticle number concentrations



EU adopts VERT Criteria in 2006 for Euro 6 - EU Co-Decision (Art.12, Rec.15)

- In order to achieve these environmental objectives it is appropriate to indicate that **particle number limits** are likely to reflect the highest level of performance with **particle filters** using best available technology
- .. the commission shall introduce particle number based limit values at a level appropriate to the technologies actually being used.



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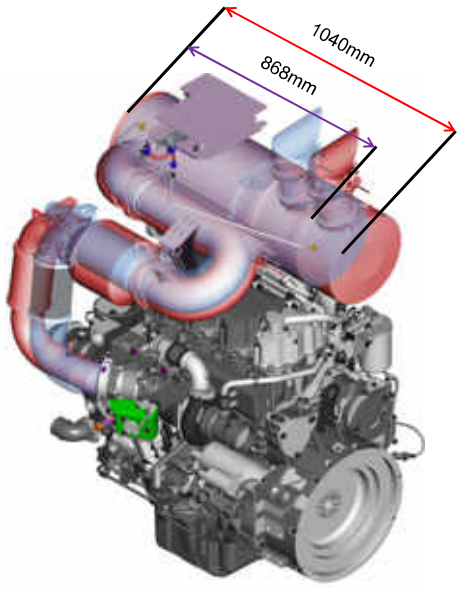
SCR on DPF



Liebherr
Red → SCRoF (1040mm)
Purple → SCR-only (868mm)

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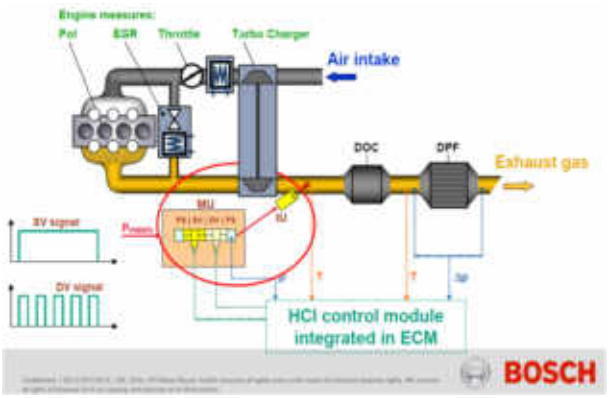
Thermomanagment
Tools are available in all modern vehicles
for DPF-Regeneration, SCR-Support, Deposit Cleaning



- Intake Throttle
- HC-injection
- Catalyt Combustion
- Retarded injection
- Multiple Injection
- TC-Management
- EGR Managment
- Cooler Managment
- Electric Load

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Structures

- **Porous Ceramic Extrusion**
- Metallic Sinter Structure
- Ceramic Foams
- Metal Foams
- Ceramic Wire Structures
- Glas Fibre Cartridges
- Metal Wire Structures
- Deep Filtration and Membrane Structures
- Low Temperature Paper Filters

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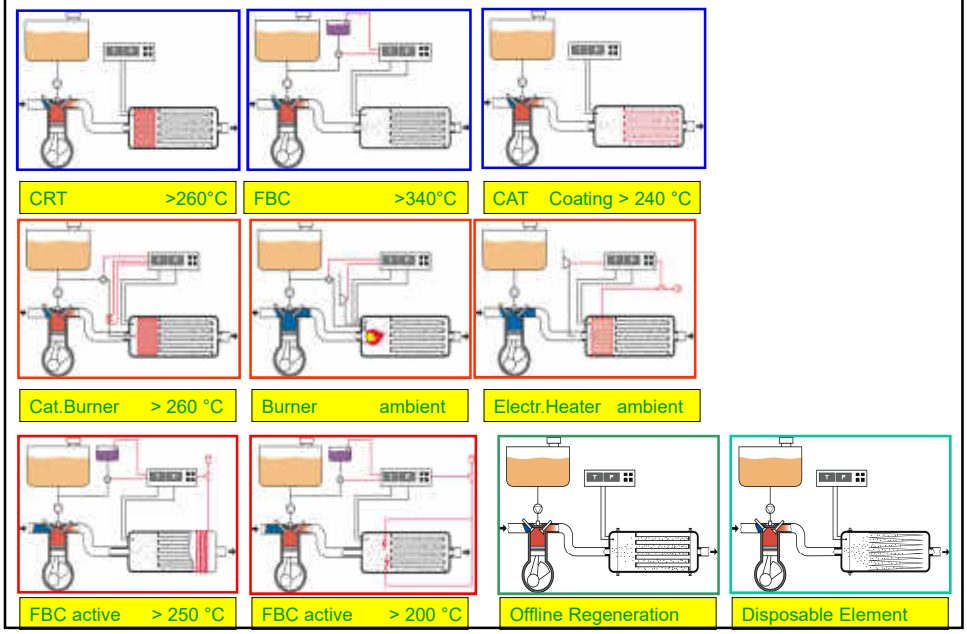
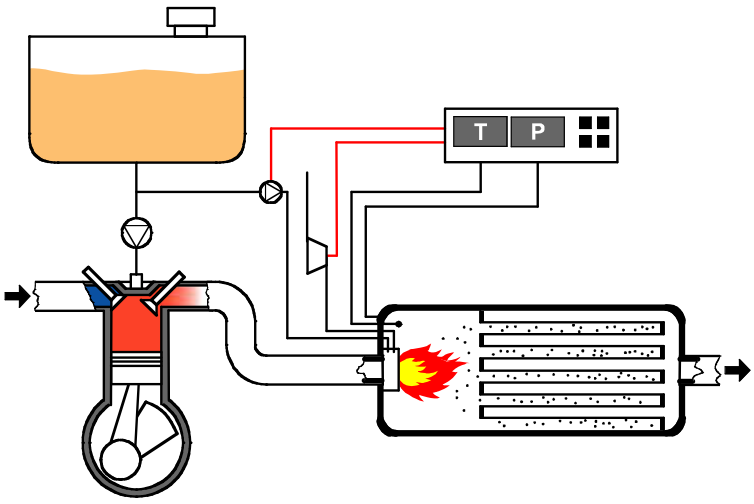
VERT-DPF-Systeme für Retrofit (passiv & aktiv)



Full flow Burner



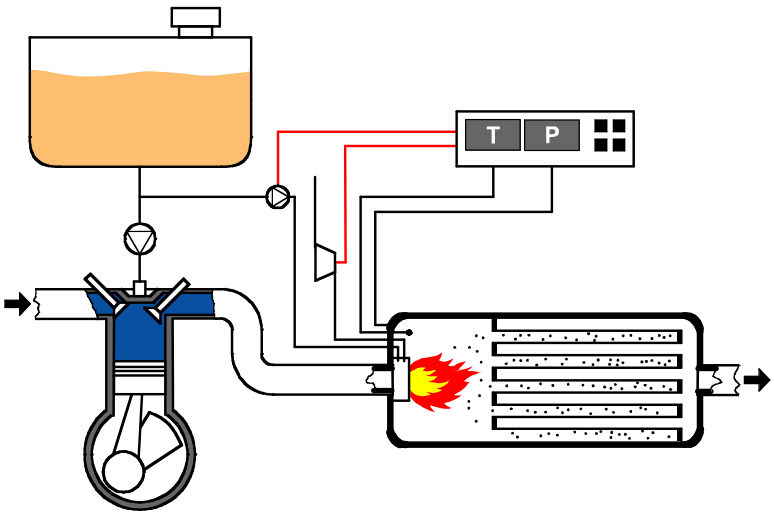
Full Flow Burner combined with Base Metal-Catalyst - Sulfur tolerant

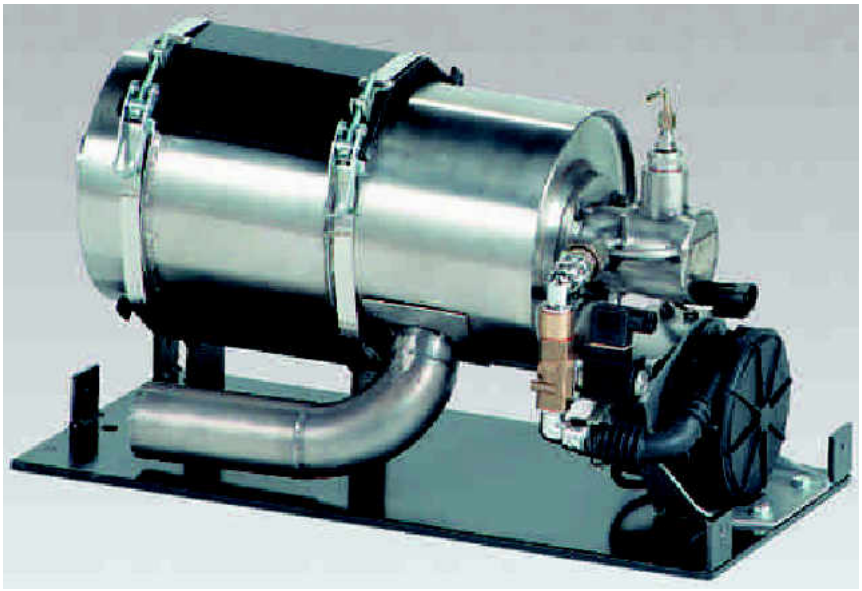
Standard Filtermodul

Restsauerstoff im Abgas:	> 8%
Heizleistungen:	30 – 400 kW
Druckluft > 5 bar:	20 Nm^3/h
Dieselkraftstoff:	3 – 40 l/h
Stromversorgung:	24 VDC

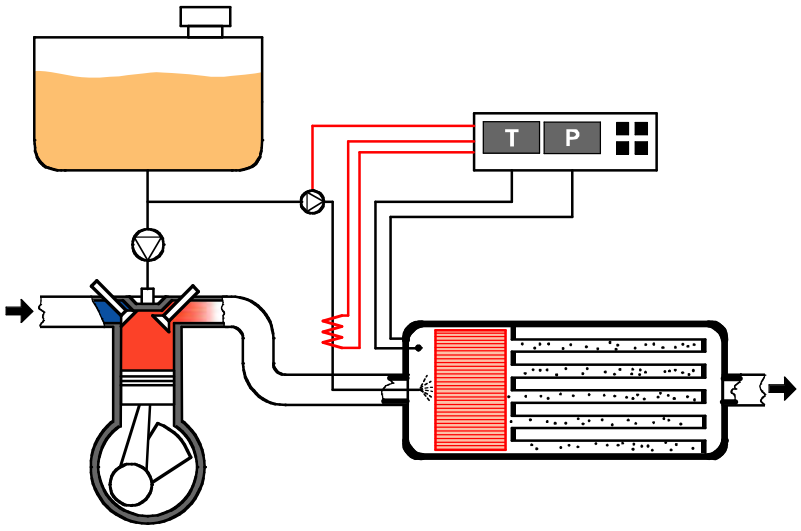
FS26 spezial

Diesel-Burner at Engine Idle or Standstill

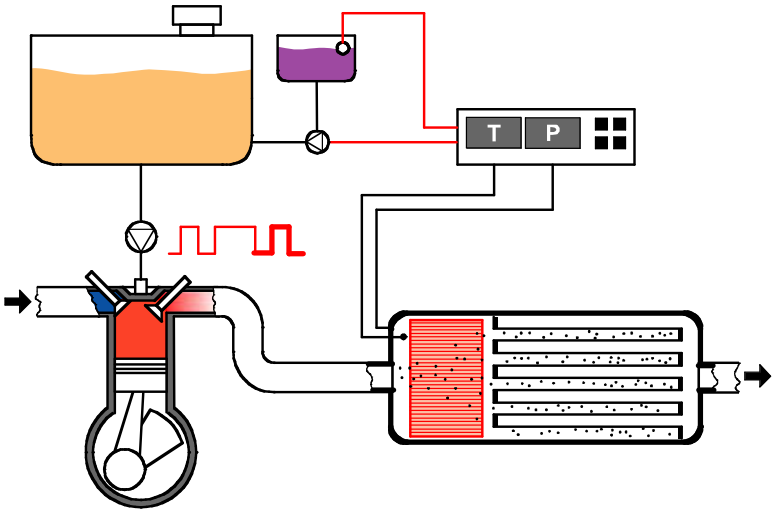




Catalytic Combustion



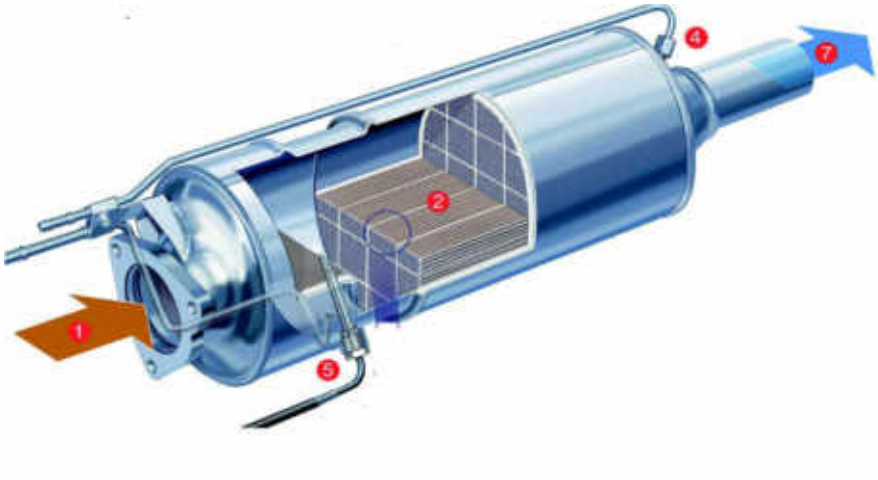
Late Injection and Fuel Borne Catalyst combined



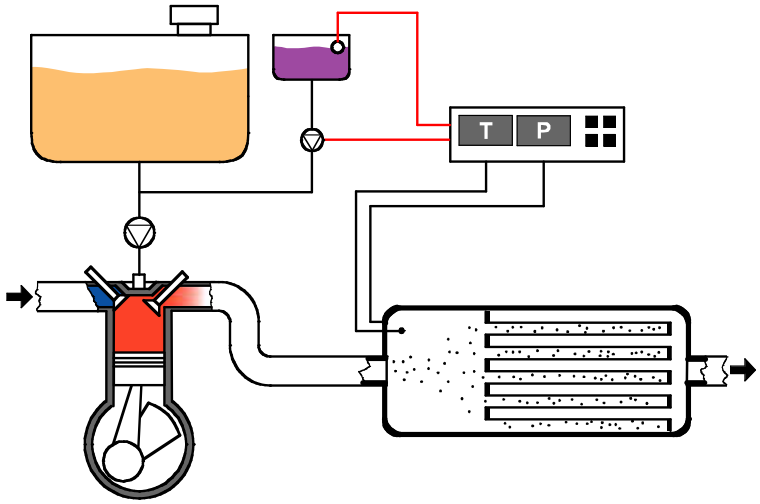
Electric triggered FBC supported Combustion

CRT-Filter System

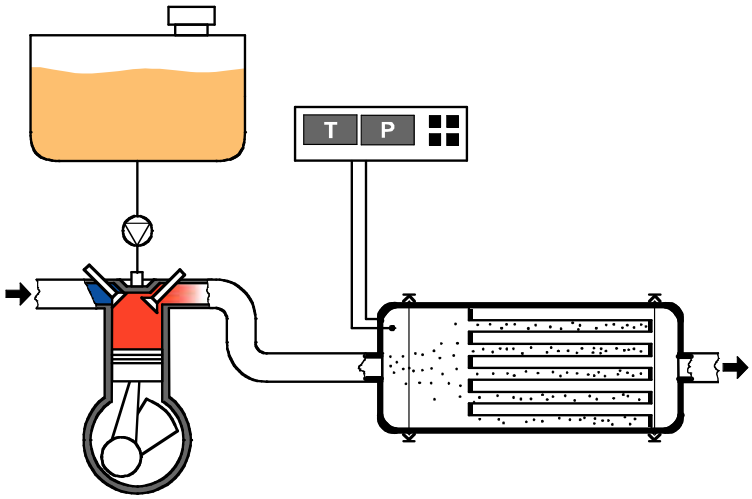
Johnson Matthey Patent 1988



Passive Regeneration with FBC (360 °C)



Filters for external Regeneration and disposable Filters



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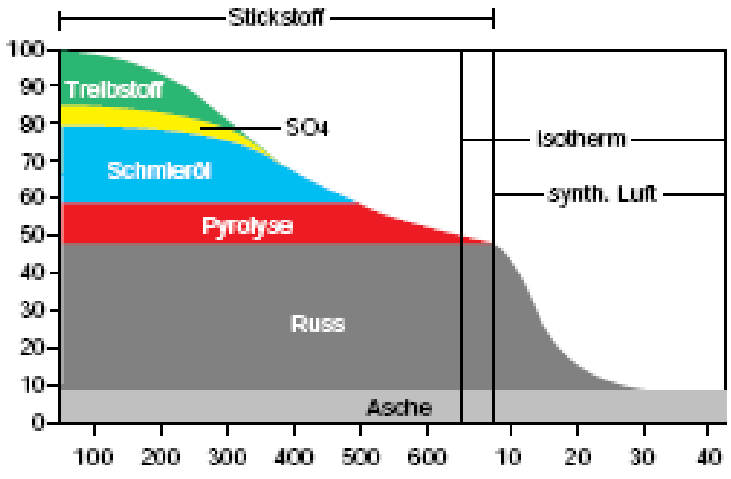
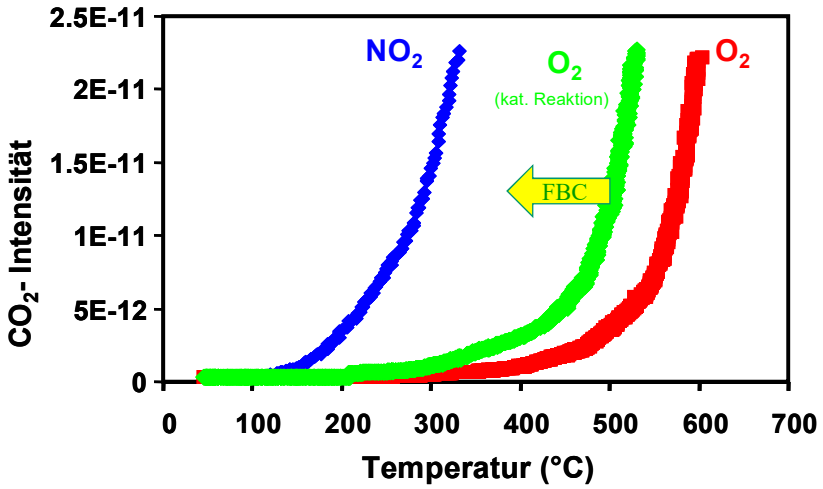
All VERT-certified filters guarantie particle elimination, toxic gas reduction, no secondary emissions, low noise, long life …..

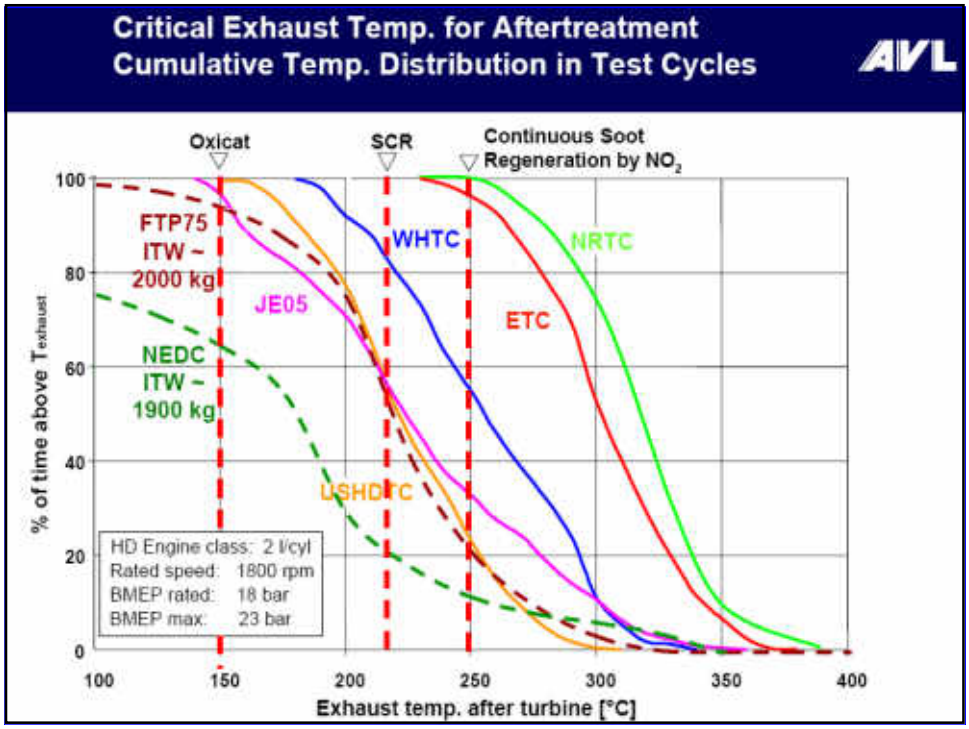
But which one
will regenerate properly
under the given operation conditions ?

Soot burns above 600 °C



Soot combustion with mit O_2 or NO_2



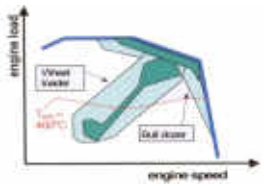


Operation Profiles can be very different

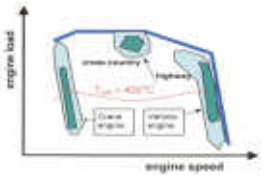




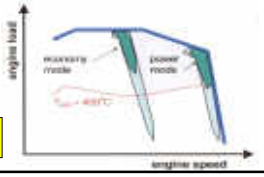

Wheel loader



Mobile Crane

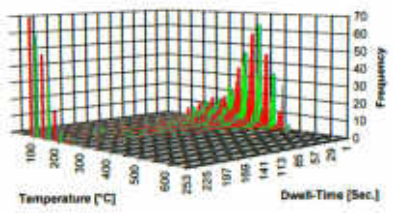


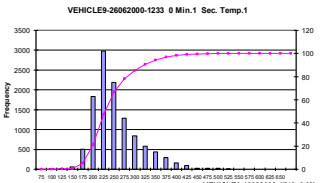
Excavator

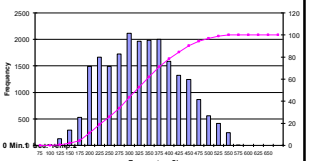


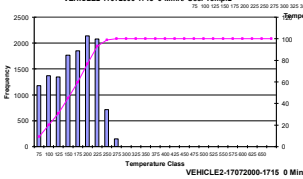
Welche Temperatur steht zur Verfügung für die Regeneration ?

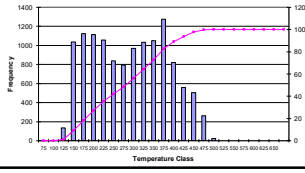
Sometimes individual Measurement is required



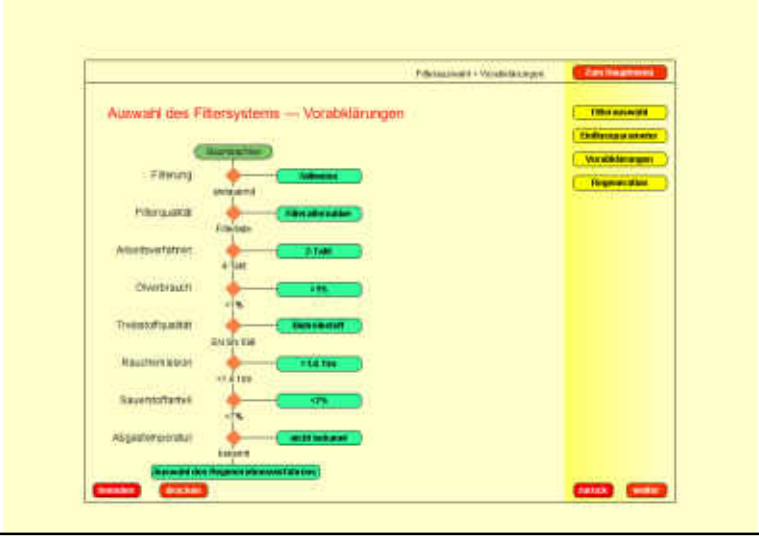




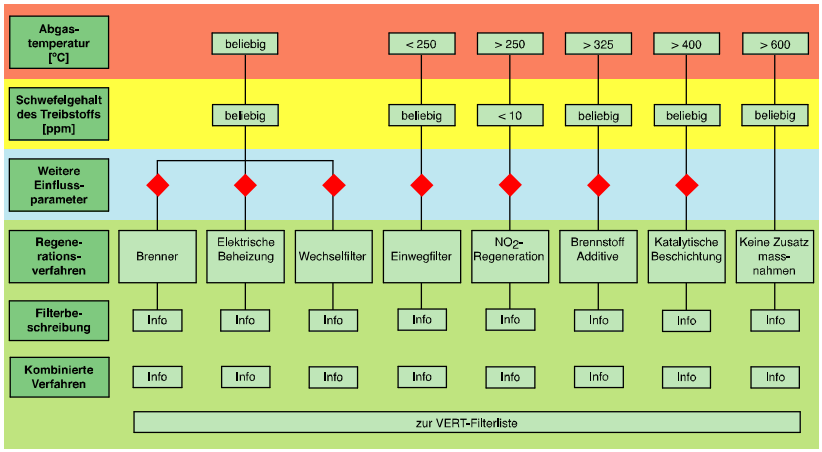




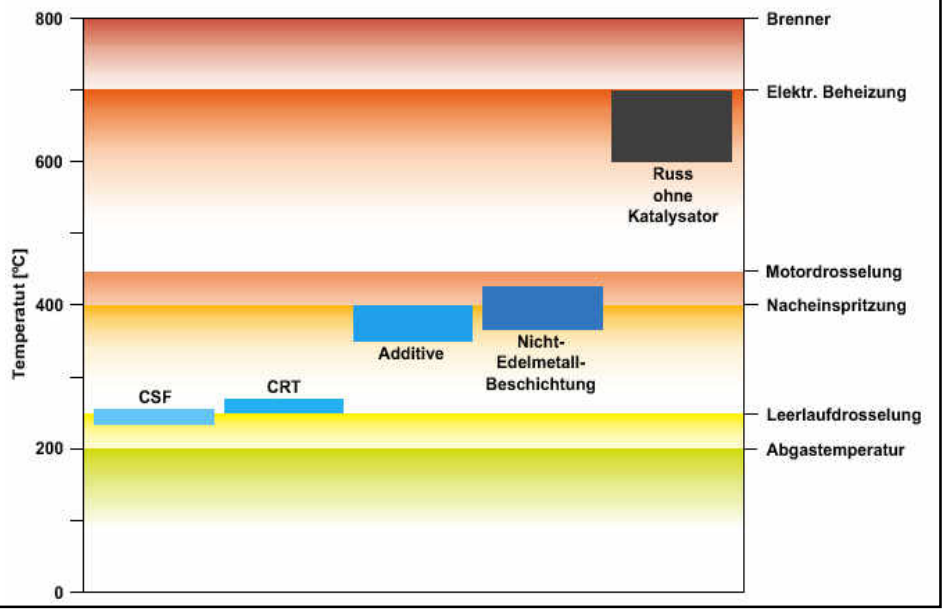
VERT interactive CD-Rom
→ Tool for Filter Selection



VERT interactive CD-Rom
→ respecting all boundery conditions



Passive and Active Regeneration

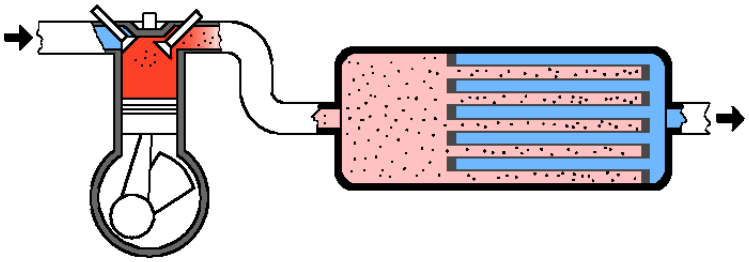


But in addition look for

- Backpressure Requirement - might be very different for different engine types
- Fuel Quality - might have high sulfur content
- Lube Oil Quality – Ash, Sulfur, Calcium +++
- Installation: Vibration, Heat
- Safety Aspects: Visibility, Fire Risk
- Variation of operation Conditions
- Continuous Monitoring

which might influence the Filter Type Selection

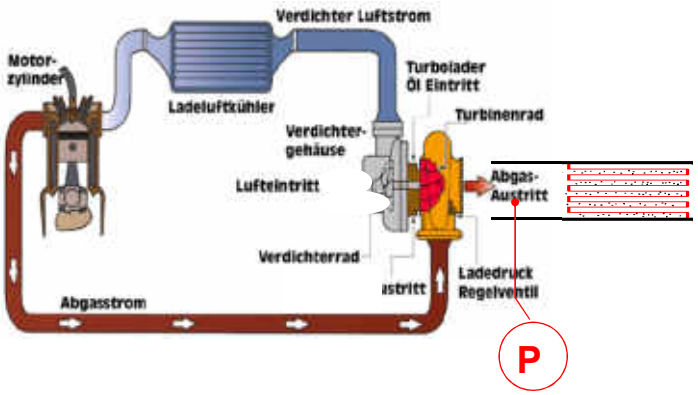
Backpressure required OBD



- Exhaust Flow
- Soot Emission
- O_2- & NO_X- Content
- Exhaust Temperature

- Filter Loading = f (Time); max 10g/l
  max 200 mbar
- Filter Regeneration
- FILTER-BACKPRESSURE

Some Engines are more sensitive



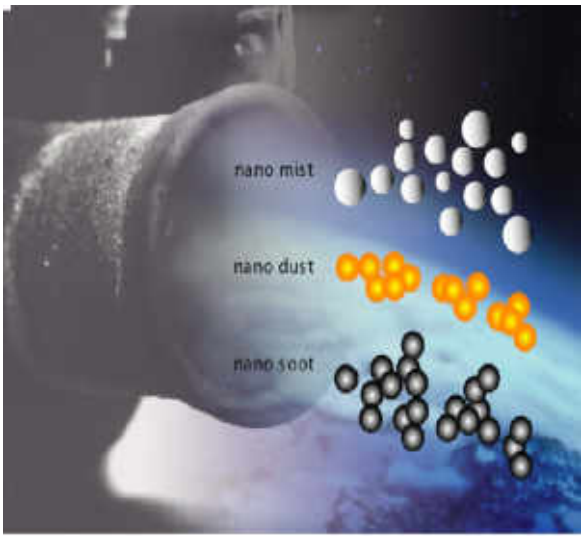
If Backpressure increases ↑ → Charging Pressure Air Excess and Performance Decrease ↓ → Soot Generation Increases ↑

Engine Exhaust Gas contains

Soot Particles
Ash Particles
Liquid Droplets

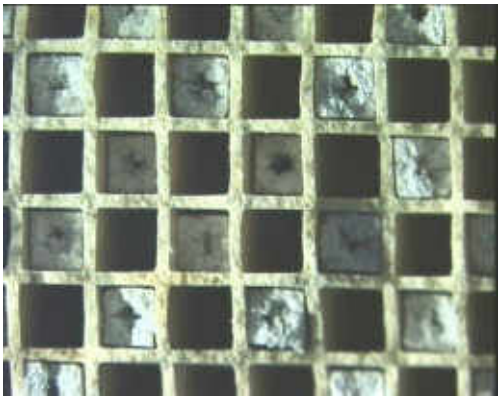
Gases:
CO, HC, NOx
PAH, Nitro-PAH

and many trace substances

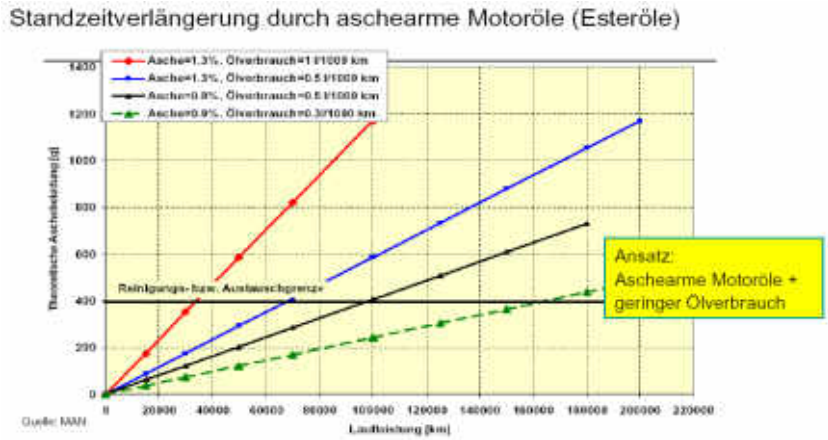


Filter Cleaning

- Ash cleaning every 1000-2000 operation hours must be well organized to protect workers from toxic dust and clean filters efficient to reach long filter life



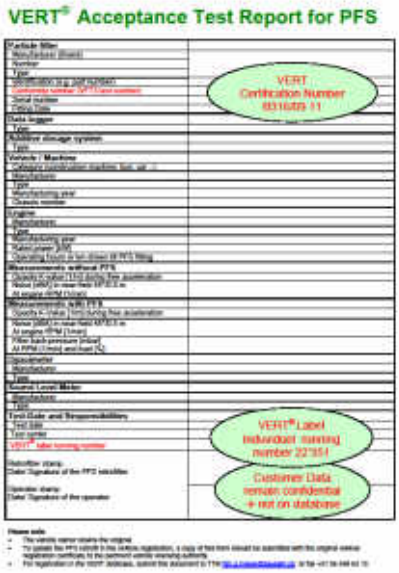
Minimize Ash-Deposit by use of LowSAPS Lubricants



And insist on Acceptance Test

- for each Retrofit

Warranty-Document
VERT-Label with
individuel Number



Conclusions

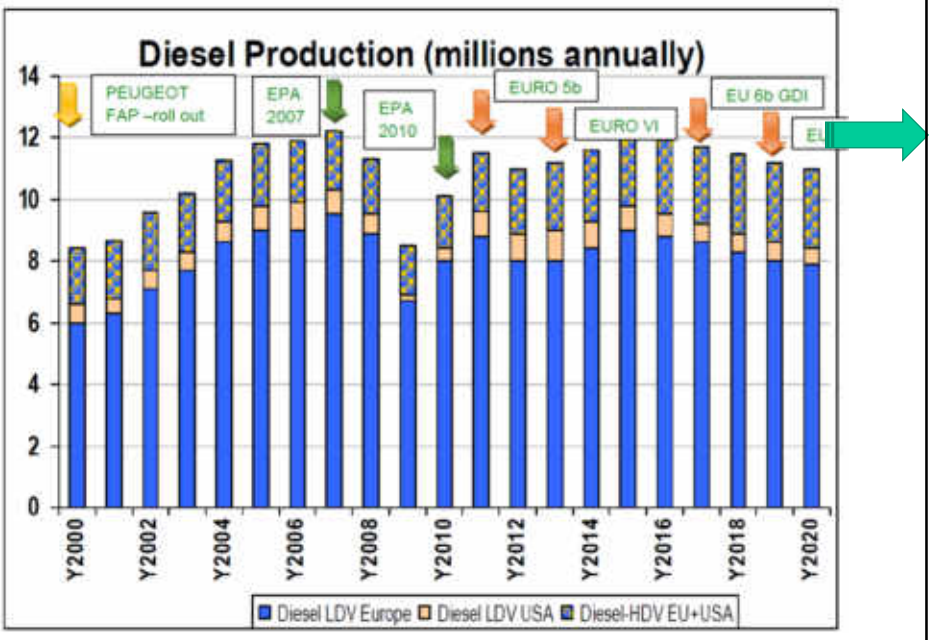
- Select only certified filters – VERT-Filterlist
- Check the operation conditions carefully
- Ask for experience → VERT database
- Install remote control Monitoring
- Implement Inspection & Maintenance Rules
- Require 2 Years Guarantee

Learning Curve in Switzerland

Success need a Vision and Persistance
Inspiration & Transpiration

Year	Fuel Sulfur ppm	Retrofit total	Retro-Fitters	Failures % p.a.	VERT Certified
1988	2'000	100	2	>10	-
1992	2'000	350	2	>10	-
1995	500	500	3	>10	5
1998	500	900	8	10	16
2000	350	2'500	12	8	23
2002	50	4'900	7	3	8
2003	50	6'500	11	2	22
2005	10	11'500	21	2	30
2007	10	17'500	26	2	50
2010	10	25'000	30	<2	71
2012	10	35'000	30	<2	75
2015	10	46'000	32	<2	80
2020	10	55'000	35	<1	85

Y 2000: failure rate too high, 15 manufacturer deverified, 2000 hrs endurance introduced



DPF Retrofit worldwide

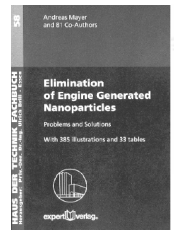
- **EUROPE: 540'000 (2001-2015)**
- **USA : 120'000**
- **ASIA : 545'000 mainly Korea and Japan**

	Y2001-Y2005			Y2006-Y2010			Y2011-Y2015			Y2016-Y2020			Total
	Bus	Truck	NR	Bus	Truck	NR	Bus	Truck	NR	Bus	Truck	NR	x 1000
Switzerland	3	1	7	2	1	11	3	2	16	-	1	8	55
Germany	20			25	50		5	50				40	190
Italy	10			20			15						45
France	7			3			2					10	22
G.Britian	9	11			12			10	1			5	48
EU-Rest	15			15			15						45
EU Indoor			50			75			75			50	250
USA	20	10		12	22	2	20	28	7	10	20	10	161
Latin Amer.				3			1			10	40	10	64
Iran										8	35	2	45
Israel										4	5	2	11
Korea	10	20		20	130		20	80		20	70		370
Japan	30	30		30	30		30	30		-	-		180?
China				4	4		15	10	1	50	30	50	164?
Asia-Rest	15			15			15			25			70
Sum	139	72	57	149	349	88	141	210	100	127	201	187	
Total		268			486			451			515		
Total					1'205 (Europe: 541)								1'720

Table 2: Retrofits worldwide (x 1000)

Technology Transfer

Much educational material available



3 books published > 300 papers

Safety is possible.

Checklist

Particulate filters for diesel engines used underground

SUMMARY

- Worldwide > 9 million death per year by pollution
- Mortality by Air Pollution is 95% by EC-Particles
- Main source of EC particles are vehicle engines
- LDV & HDV / Diesel & Petrol / on-road & off-road
- EC-particle emissions eliminated by DPF/GPF
- DPF/GPF are applicable for in-use vehicles and OE
- EU enforces DPF/GPF for all new vehicles
- > 100 million DPF/GPF guarantee reliability

IRAN has already an excellent policy
and will succeed to clean the air within 10 years

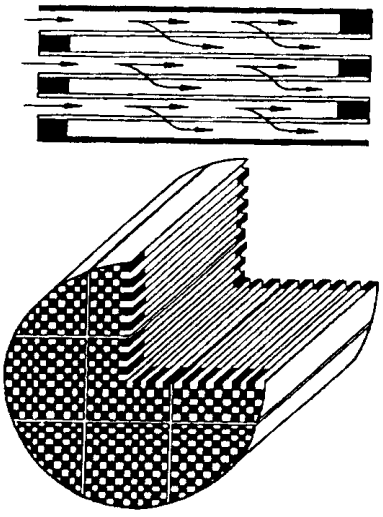
70

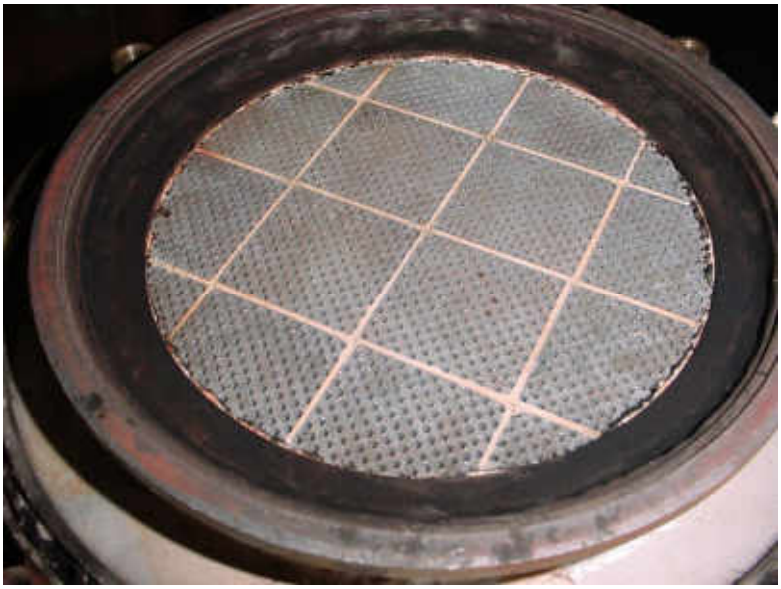
Exhaust End Pipe stays clean !

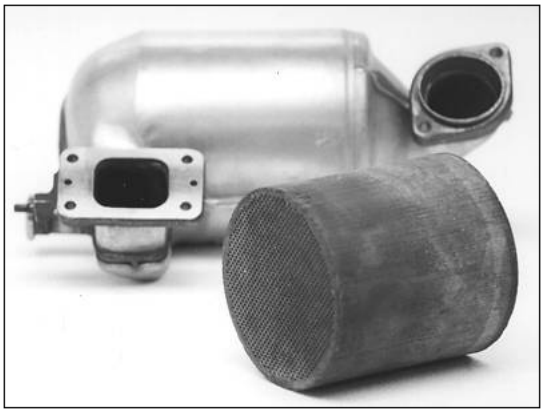
onroad > 85‘000 km **offroad > 1000 h**

The classic Wallflow Filter = *Full Flow*

CORNING 1982







EU adopts VERT Criteria in 2006

EU Co-Decision (Art.12, Rec.15)

- *In order to achieve these environmental objectives it is appropriate to indicate that **particle number limits** are likely to reflect the highest level of performance with **particle filters** using best available technology*
- *.. the commission shall introduce particle number based limit values at a level appropriate to the technologies actually being used.*

DPF introduced via PN-Regulation with new vehicles Euro-6 2011 and Euro-VI 2014

US-EPA stays far behind

Standard	PM requ.	PN eff.	PN requ	PM eff	Comment
Euro-I	700	$3x10^{14}$			No real progress
Euro-II	150	$2x10^{14}$			No real progress
Euro-III	100	$1x10^{14}$			No real progress
Euro-III DPF	-	$1x10^{10}$	-	0.02	Retrofit 99.99%
Euro-V	20	$6x10^{13}$			No real progress
EPA 2010	10	$3x10^{13}$			DPF not required PFF suficient
„Euro VI“ w/o filter	10	$3x10^{13}$			Scania 2007
Euro VI (2013)	10	$3x10^{13}$	$6x10^{11}$	0.2	50x below EPA DPF required

PM [mg/kWh] CVS Particles < 2.5 µm
PN [PNC/kWh] CVS-PMP 23-2500 nm
PN converted to PM with particle diameter 70 nm

The new EU-NRMM-Regulation

Type approval 2018-21; Sales 2019-22

Is based on Particle count PN < 10^{12} P/kWh

Which guarantees introduction of highly efficient DPF

NRE (19≤P≤560) – *Construction*

+ NRMM general

NRG (P>560) - *Gensets*

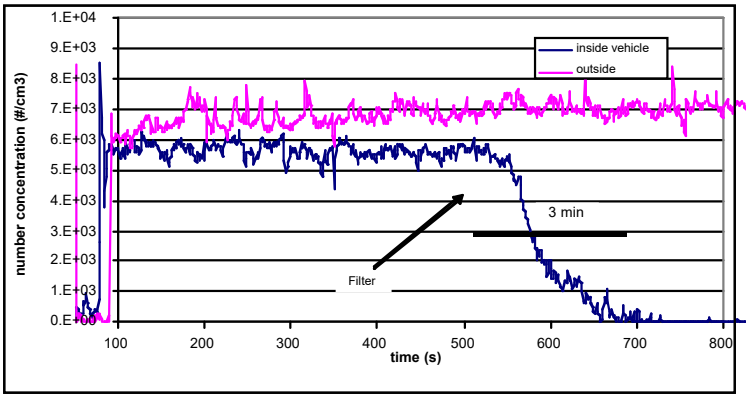
IWP (P≥300) – *Ship propulsion*

IWA (P≥300) – *Ship Auxiliary*

RLR (P>0) - *Railcars*

Cabin Filter: "NanoCleaner"

Doors shut, Filter ON...



HJS Fahrzeugtechnik GmbH & Co KG

SMF® – Design-Alternativen

Satelliten-Filter

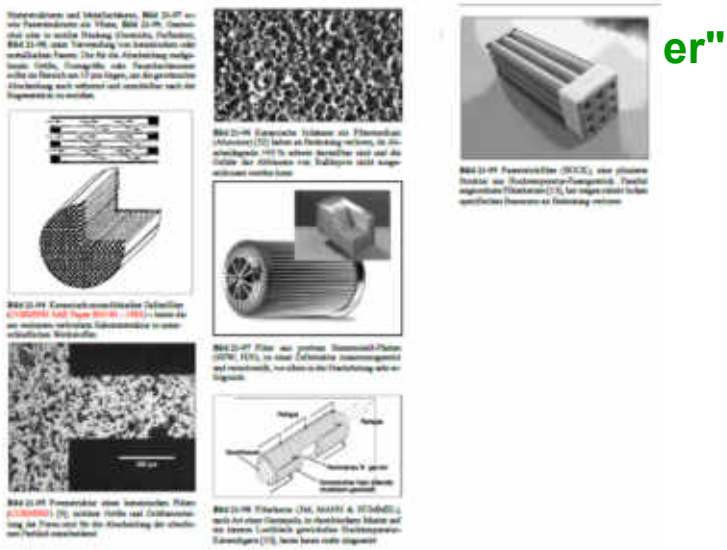
Filtertasche

Filter-Box

Jetfilter®

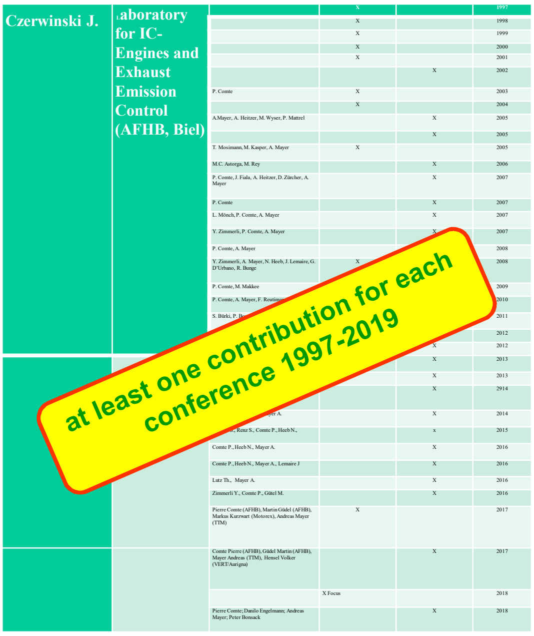
DPF-Efficiency can be very high

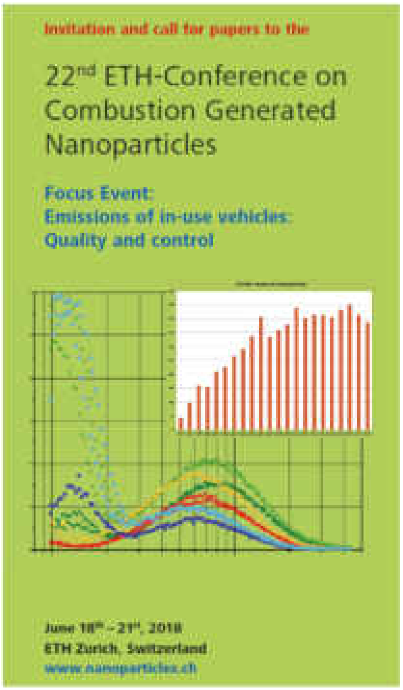
Just 7 m^3 exhaust (3 min operation of a 3.0 L Euro-3 engine (100 kW)



er"

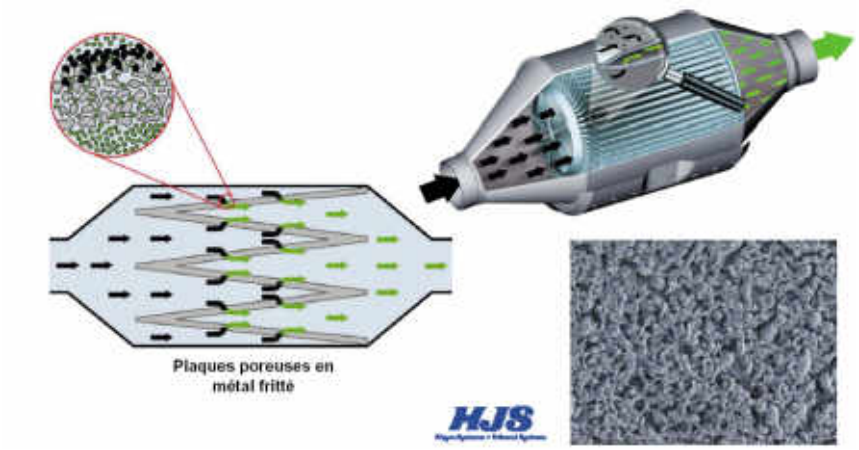
ETH-NPC from 1997



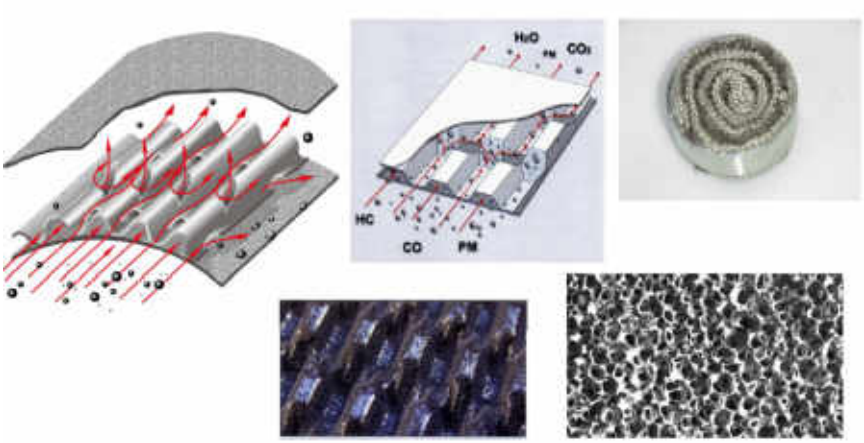


>100 SAE-Papers
> 300 publications

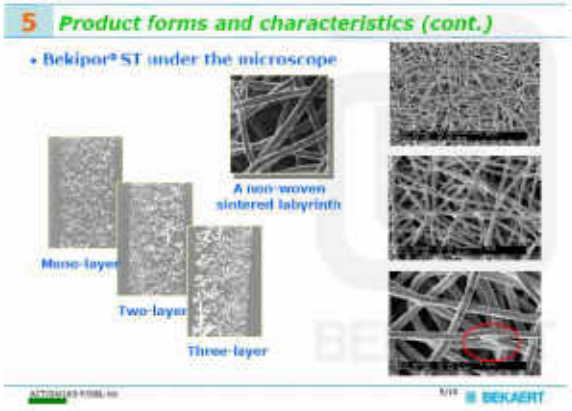
Überschrift



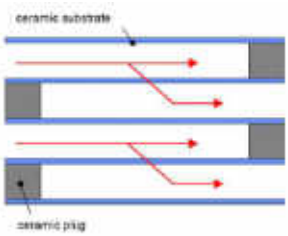
Überschrift



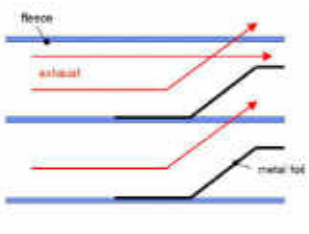
Überschrift



Überschrift



- **ceramic substrate** (e.g. silicon carbide, cordierite, alumina titanate) as **wall flow** monolith, possibly coated
- soot is stored inside the channels
- regeneration is necessary in regular intervals, depending on e.g. exhaust gas backpressure, exhaust gas temperature, soot loading of DPF
- **particulate reduction: > 90%**



- corrugated, helical **metal foils** with open channels, catalytically coated
- should the **fleece** be plugged with soot, exhaust flows through open channels (particulate reduction is then zero)
- **thermal regeneration** is not necessary
- typ. average **particulate reduction: 30%**
- Manufacturers: e.g. Emitec, Oberland Mangold, Ecocat

Regeneration is controlled by the Availability of Oxygen and Temperature

$$\frac{dM}{dt} = k_o \cdot M^m \cdot p_{O_2}^n \cdot e^{\frac{-E}{RT}}$$

M = relative Russmasse
p_{O2} = Partialdruck des Sauerstoffs
R = Gaskonstante
T = absolute Temperatur
E = Aktivierungsenergie

- plenty of **Oxygen** is available in Diesel Engine Exhaust Gas – particularly at light load 12-16 %
- but **Temperature** is often to low to support regeneration at light load conditions if the NO_2-Process is to be avoided

→ Adding Energy (fuel burner, electr.heater ? is properly speaking not needed

→ **Available Energy can be used to lift the Temperature to the required Level**

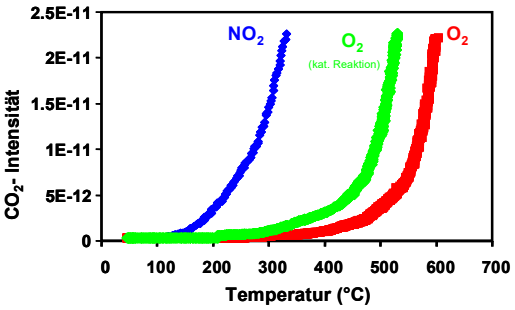
Soot-Reactions with O_2 und NO_2

- $C+O_2 = CO_2$

and the CRT-Process (JM)

- $C+2\ NO_2 = CO_2+2\ NO$

this CRT-process needs NO_2 which is not available in engine exhaust but can be provided by catalysis



NO2-Rection is very attractive because of low temperatur

→ but requires Pt-Catalysis, which is not Sulfur-tolerant

Backpressure must be under Control

Electronic Datalogging

Sensors for Backpressure and Temperatures

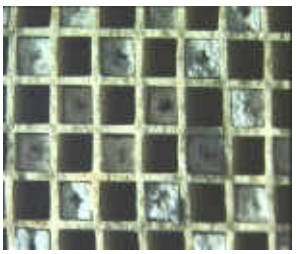
Anzeige von Messwerten der ECU, z. B.
- Gegendruck
- Temperaturen
- Betriebsspannung
- Drehzahl
- Kraftstoffdurchsatz
- Additivverbrauch

Auslesemöglichkeit aktive Fehlerliste

Warnung des Fahrers bei
- Zu hohem Gegendruck (VERT)
- Additivreserve

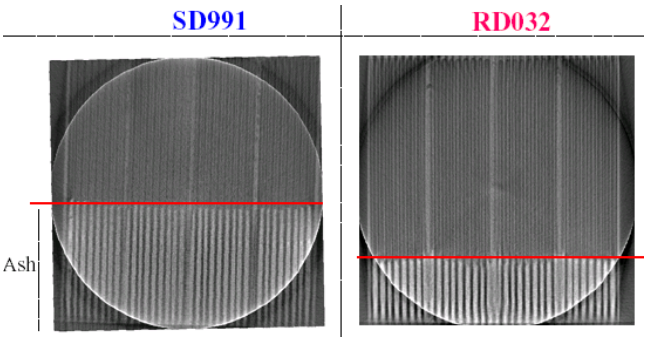
Alarm Indicator at the Drivers Seat

or remotely controlled



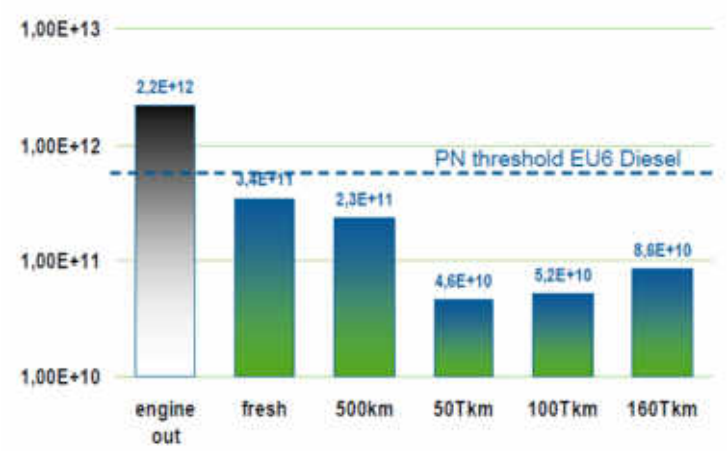
Ash Deposits

filters must be cleaned professionally 1-2 times per year



3WC and Filter harmonized

Umicore 2012



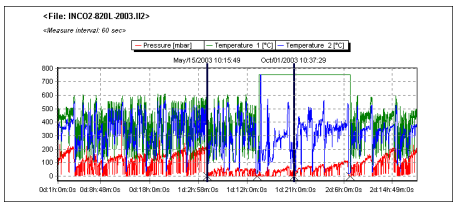
\+ = 1. Local Download

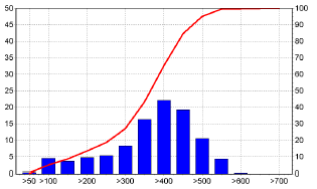
2. Remote Download

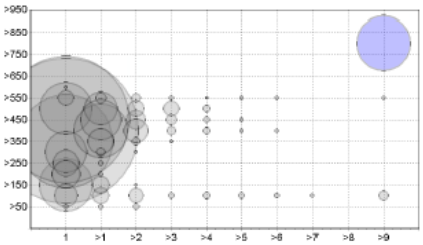
- Data will be transferred to an independent internet server
- Alarms at critical levels Automatic notification of 3 phones by SMS

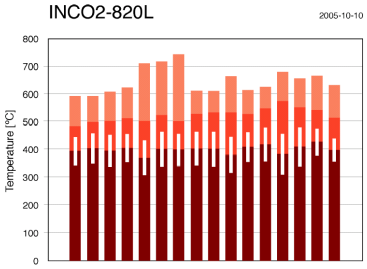
Results of Monitoring

online, frequency profiles, episode structures, variability

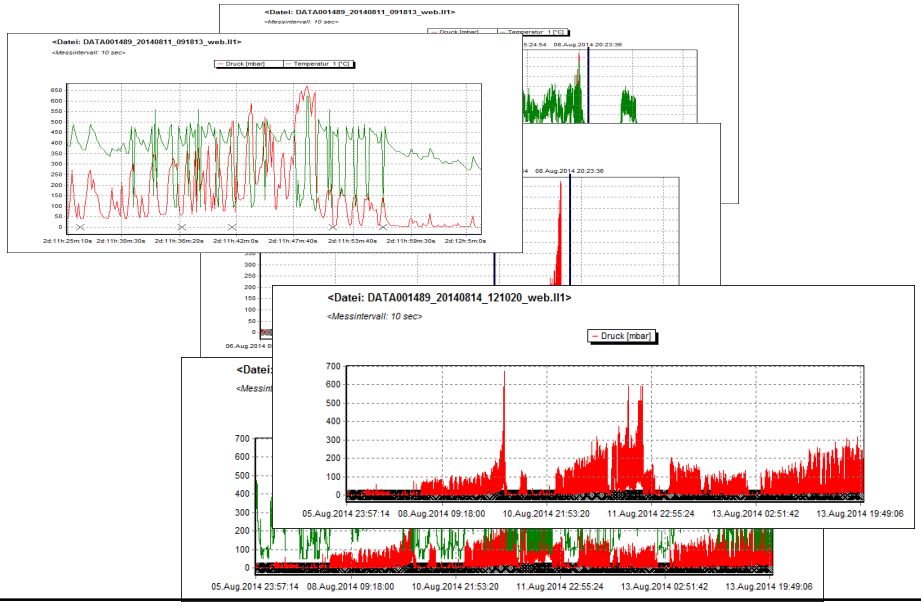




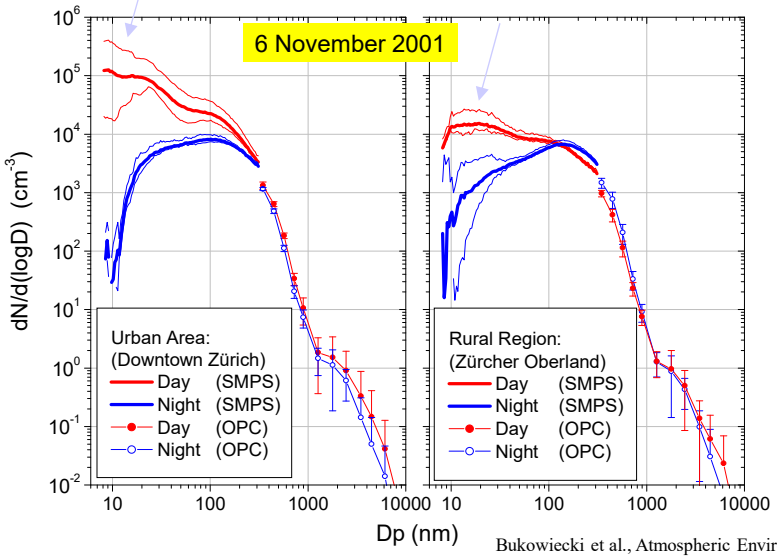




Monitored History with Particle Filter

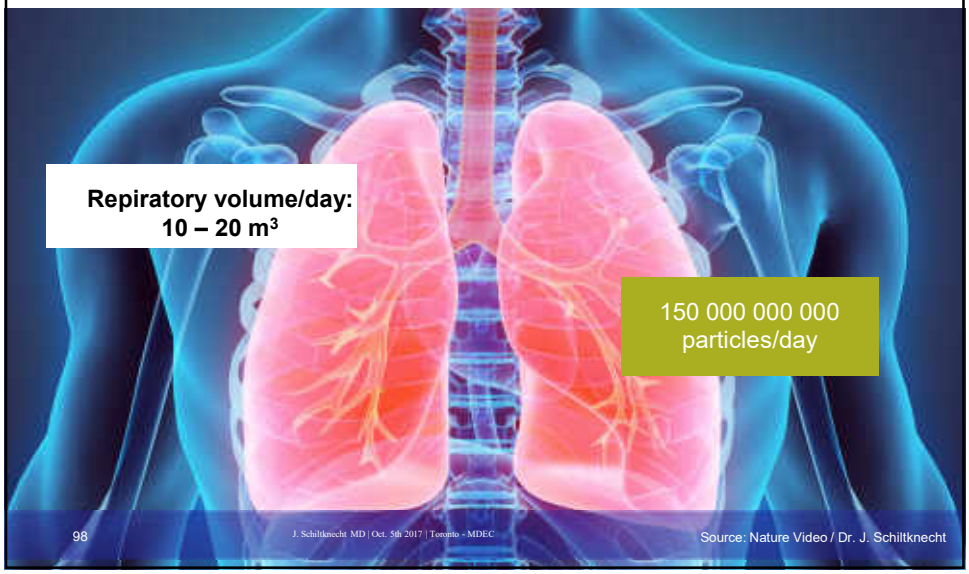


Aerosol Number/Size – Distribution
City (Zürich) and Coutry (Zürcher Oberland)



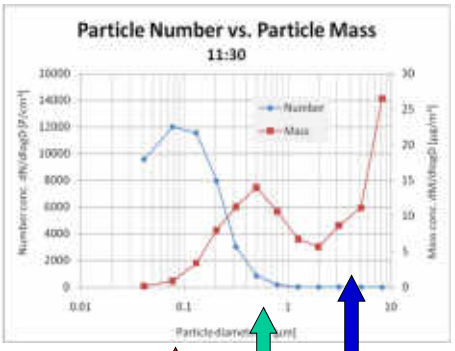
Bukowiecki et al., Atmospheric Environment, 2002

The Lung are an open door for toxics
to enter our body since we cannot stop breathing



Size Distribution at Curbside Zürich

would BC be the right parameter ?



- Engine emitted (EC+metal oxides) particles have very little mass but high numbers
- Tire wear (BC) has low numbers but higher mass
- Resuspended material (also BC ?) has even higher mass

resuspended
Road Dust

Tire wear ?
Break wear ?
Wall deposited particles

Engine
Exhaust

Mortality and Health Cost global 2012

due to traffic [per year]

	Inhabitants Mio	*Mortality Traffic x1000*	Related Health Cost Mio €	Mortality per 1 Mio and year	Cost €/Pers
USA	313	200	?	638	?
California	38	9	?	236	?
London	8.1	4	23.4	493	2800
Schweiz	7.8	4.5	6.5	576	833
EU28	501	400	650	798	1390
World	7000	4500	?	642	100?

Chronicle of DPF-Introduction and reasons why PN was and is that importan

From 10 VERT-Pilots 1996 to 100 Millions of vehicles with VERT-Quality Filters

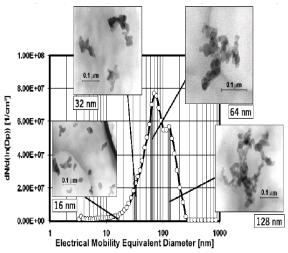
1775	**Percifal Pott established clearly a correlation between soot and cancer of chimney sweeps – first epidemiologist** ***Nobilitation, knighthood, for his merits, however no further reverberation***
1910	English MD's in occupational health suspect besides pneumo-coniosis and silicosis serious lung damage due to much smaller not visible particles; they begin both, to classify according to seize and to count particles → conimetry
1928	Lawther establishes correlation between lung cancer and traffic growth in London and in Wales – at that time there was no lung cancer in Swiss Canton Tessin, which is nowadays no. 1 (Cavalli)
1936	First edition of occupational health journal "STAUB" brings conjecture of serious illness via lung due to particles of seize < 1µ; improvements of measuring methods are requested.
1936	Asbestos is recognized as causing cancer; US-insurance companies deny life insurance for asbestos miners and handlers; first reactions in Switzerland: the criterion of number of broken fibres is introduced, because determination by weight (mass) is not feasible. *No notice is taken of this change in paradigms for measuring harmful sub-stances. Apparantly, a lack of communication in medical disciplines of environment public and occupational health.*
1951	Occupatonal Health Medicine Conference of Johannesburg: The early suspicion of British MD's in mining is confirmed: particle are classed into three fractions, adhesion whether to thorax, or bronchi or to alveoli (< 1µ); measures are requested, excellent proceedings are published one year later.

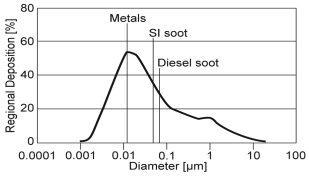
Aerosol Research

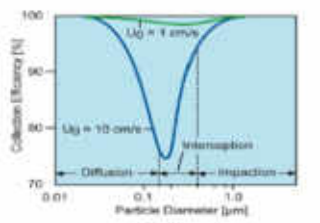
strange coincidence

The most sensitive size range
of the Lungs
is the most intensive emission range
of the Engines
and the weakest size range of
Filtration

The Lung is an open door for
engine emitted particles

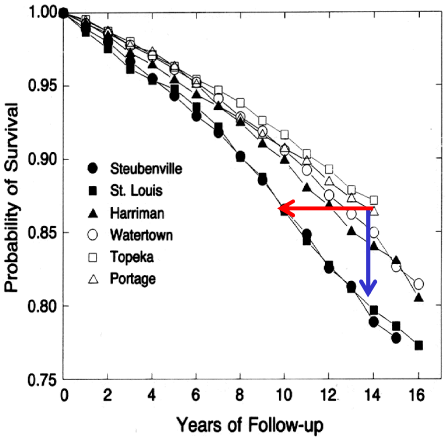






1993 Six Cities Adult Mortality Study

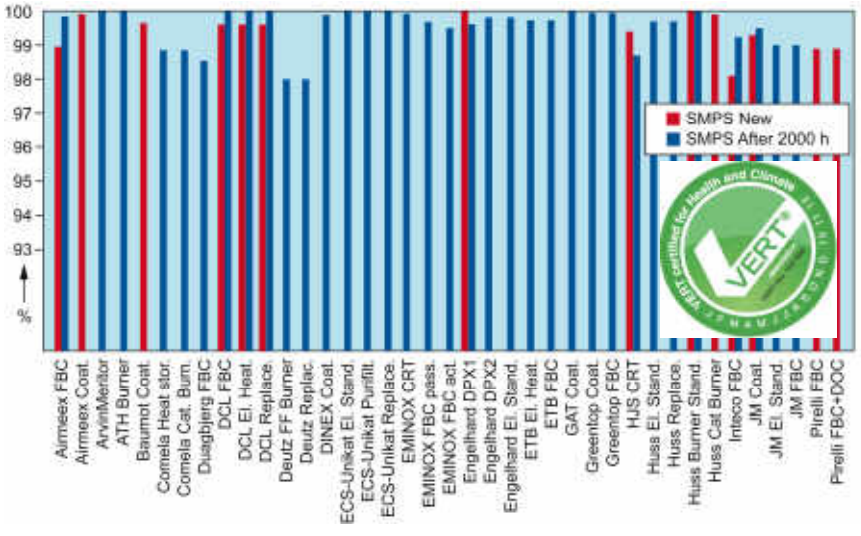
- Random sample of 8411 adults in six cities
  - Dirty: *Steubenville, OH & St. Louis, MI*
  - Moderate: *Watertown, MA & Harriman, TN*
  - Clean: *Topeka, KS & Portage, WI*
- Enrolled 1974-77
- 14-16 years of mortality follow-up



Dockery et al, NEJM 1993;329:1753

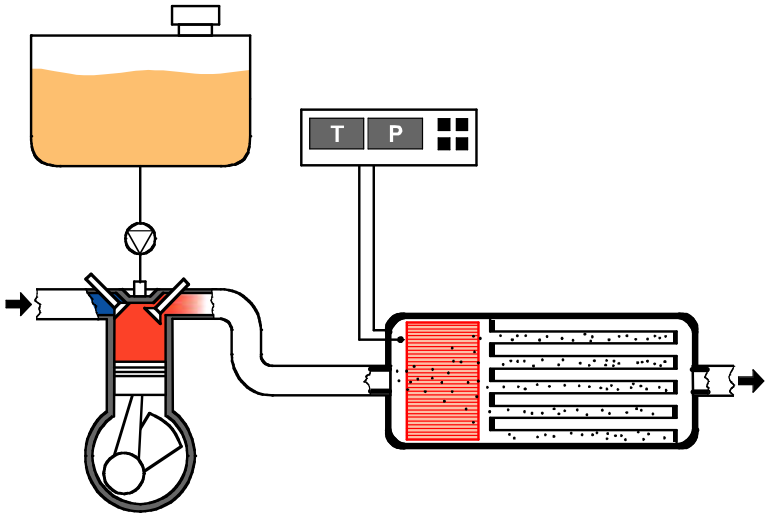
Filtration - 65 DPF VERT tested

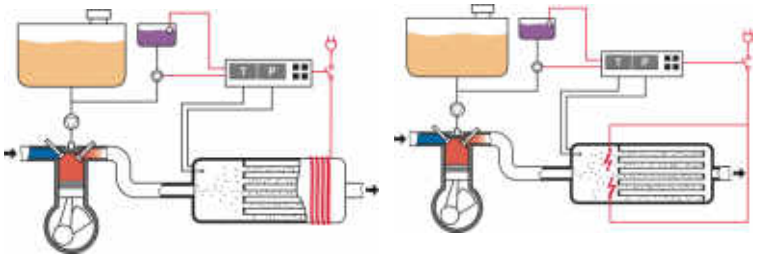
25 % > 99.8 % within size range 20-300 nm



CRT: FAP à régénération continue par NO_2

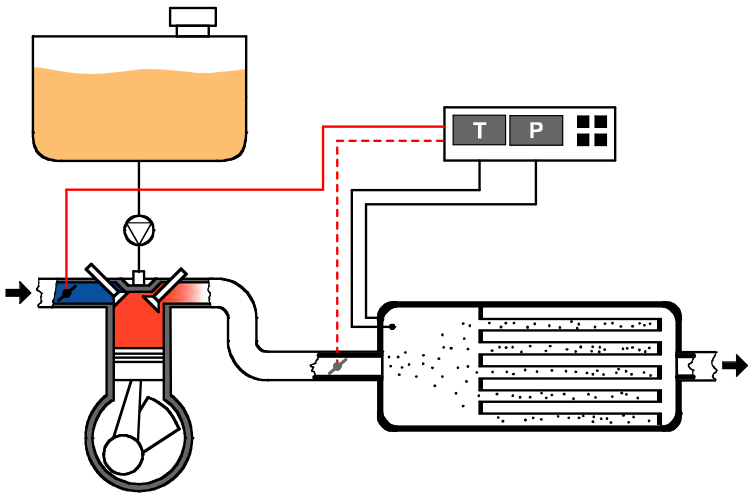
Johnson Matthey 1988





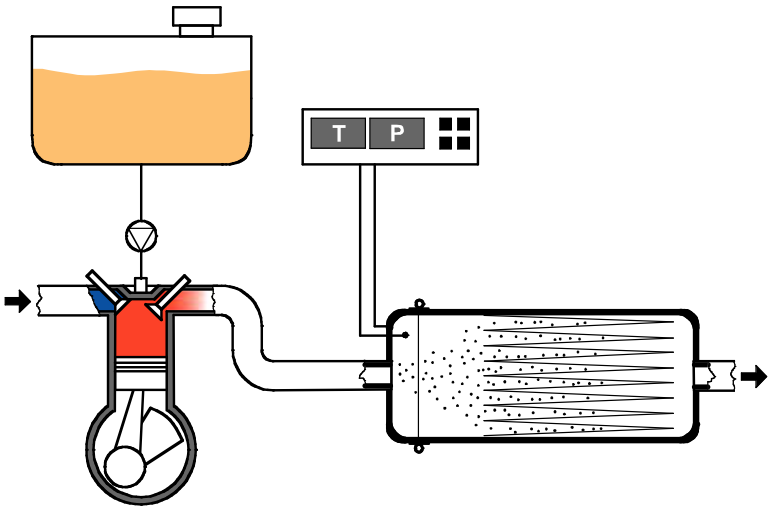
Wärmemanagement mit Gas-Drosselung

MAN, ENWA, LOGLINK, DAIMLER-BENZ, ISUZU, XXX, YYYY

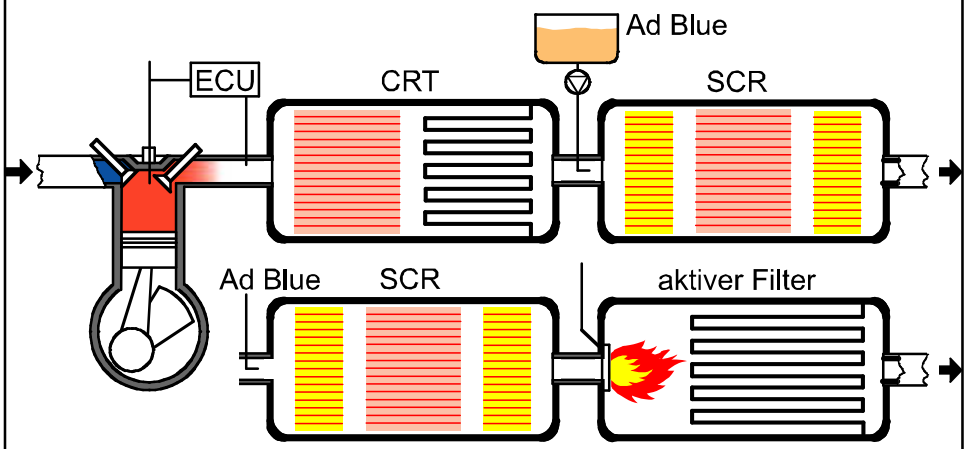


Einweg-Filter →Hausmüll

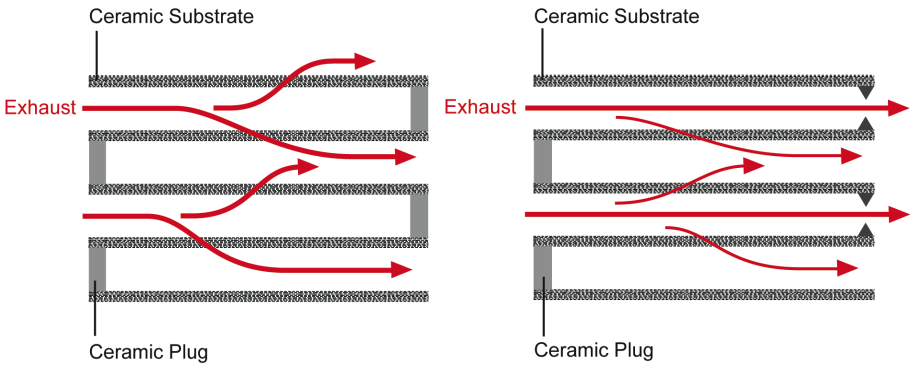
ENDEAVOUR / TSH / DONALDSON / EHC / BAUMÜLLER



Kombination von SCR und Partikelfilter



Schematic of full-flow filters FFF (left) and partial flow filters PFF (right)

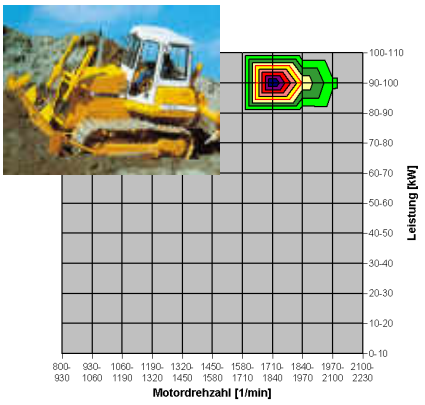


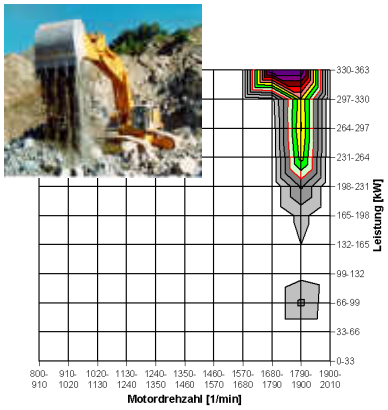
Messung von Abgaskomponenten im Feld

CO, CO_2, O_2
NO, NO_2, HC, SO_2

Careful Selection for each Application

since operation modes can be very different



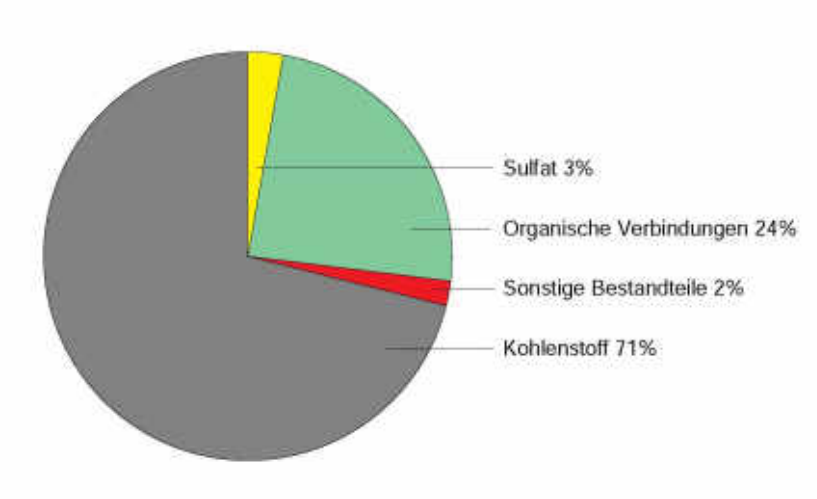


Quelle: Liebherr

Elektronische Onboard Filterkontrolle

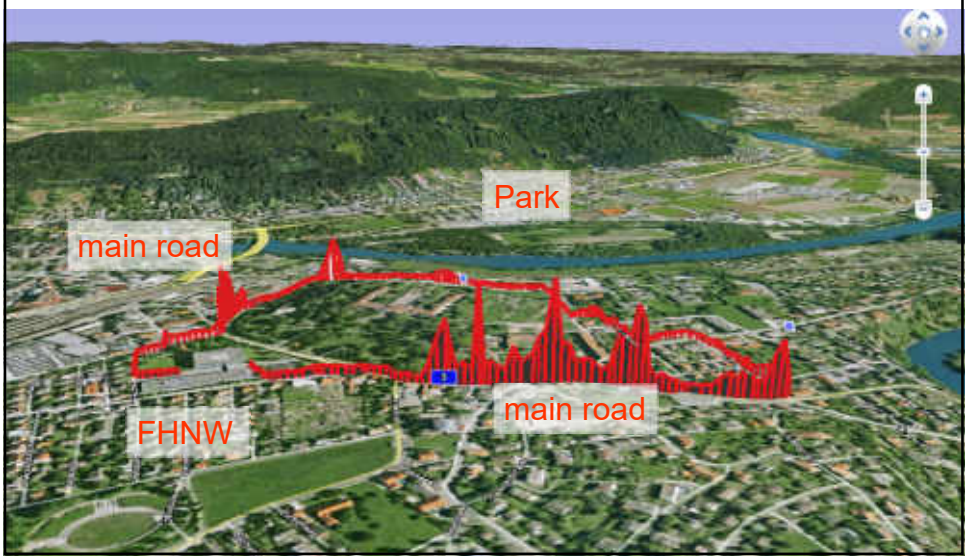
zwingender Bestandteil des Filtersystems

Chemical Composition of Diesel-Particles



VERT: Interactive CD for Filter Selection

Walk through the city and monitor pollution by PN



Evaluation of Diesel Particulate Filter Systems at Stobie Mine

March, 2006

Diesel
Emissions
Evaluation
Program

INCO

Prepared by: Bruce R. Conard

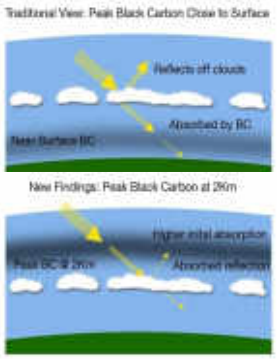
Assisted by: Jozef Stachulak, Andreas Mayer, George Schnakenberg, Aleksandar Bugarski, Mahe Gangal, Gregory Nault, Rick Mayotte, Robert Coppal, Gilles Bedard

Awareness of black carbon's role on GW

BC on snow decreases albedo, turning to water.. further lowering albedo

Journal of Geophysics Res.2007

Higher in atmosphere



2008

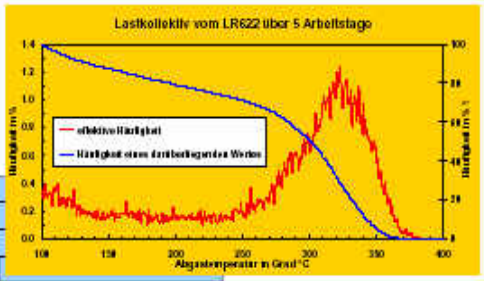
Science Daily, United Nations Environment Program Nov 2008

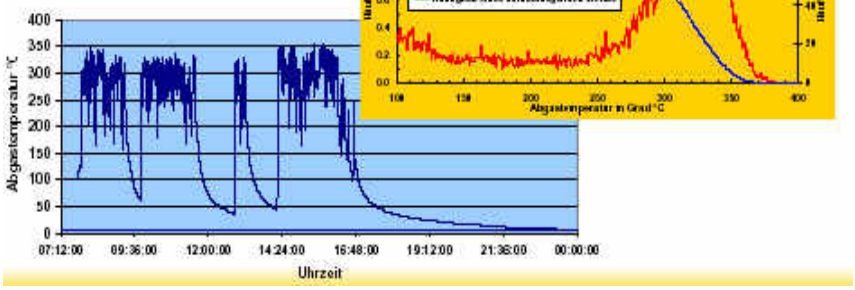
Global Warming by BC-Particles

Datalogging Driving Cycle Parameters for proper PFS-Selection

Abgastemperaturaufzeichnung mittels Datalogger im Praxiseinsatz

➤ PFS-Wahl (für Systeme mit Passiv-Regeneration unerlässlich !)





MDEC Toronto – VERT Workshop on DPF Technologies – 10.Oct.2019

Part 2

VERT DPF Type Approval with respect to physical and chemical properties

A. Mayer, TTM-VERT

What is VERT ?

- 1. **VERT** =
- Verification of Emission Reduction Technologies
- **2. VERT** is a Diesel Particle Filter Testing, Certification and Quality Control System
- **3. VERT** is a Trade Mark
- for Particle Filters of Best Available Technology
- **4. VERT** is a non-profit Association (based in CH) of Filter Manufacturers, Engine Builders and Associates – 24 members

CONTENTS

as requested by MDEC Conference Organizers

- **Why is Filter Type Approval needed ?**
- Filtration with resp. to particle size and number concentration
- Emission of limited gaseous emission THC, NOx, CO
- Secondary Emissions
- Further Requirements: Endurance, Fuel Economy, Noise …
- Standards and the VERT Filter List
- What does measured engine emission mean with regard to exposure or exceedance ?

123

Anzahl und Oberfläche von kugelförmigen Partikeln mit einer Massenkonzentration von 10 µg/m³ (hypothetisch)

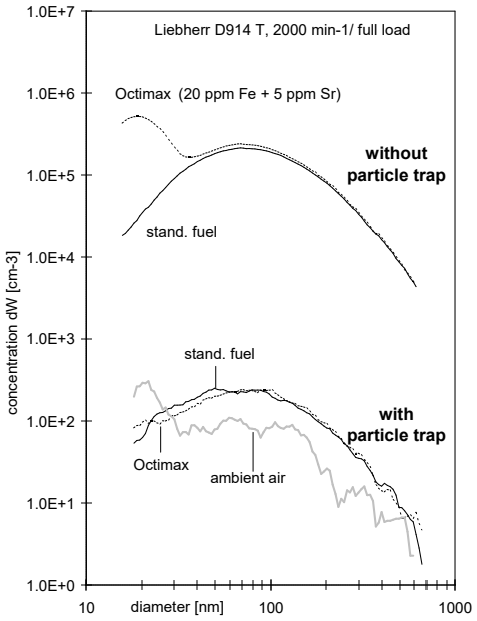
Durchmesser	Anzahl [cm^{-3}]	Oberfläche [cm^{-3}]
20 nm	2.400.000	3.016 µm²
500 nm	153	120 µm²
2.5 µm	1	24 µm²

- Institut für Epidemiologie

Oberdörster et al., 1994

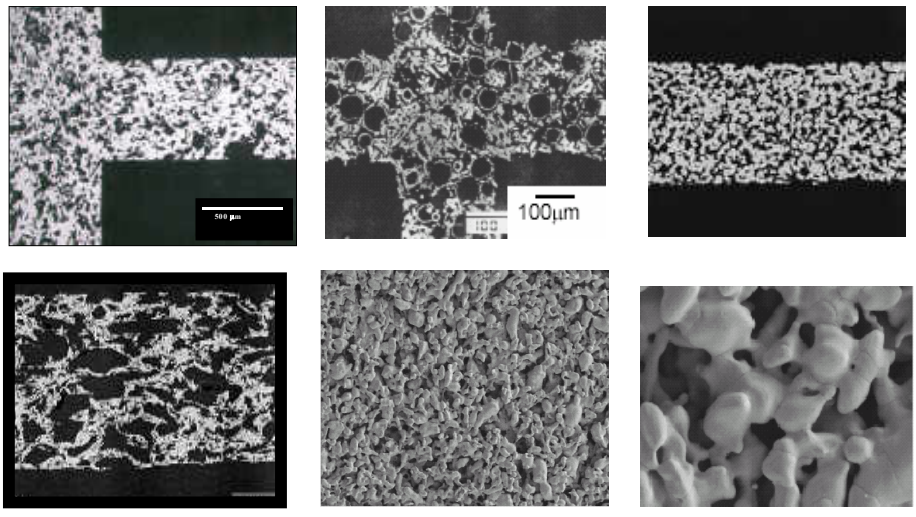
Measurement must be by Number and Size

to show that Filtration Effectiveness is > 99 %

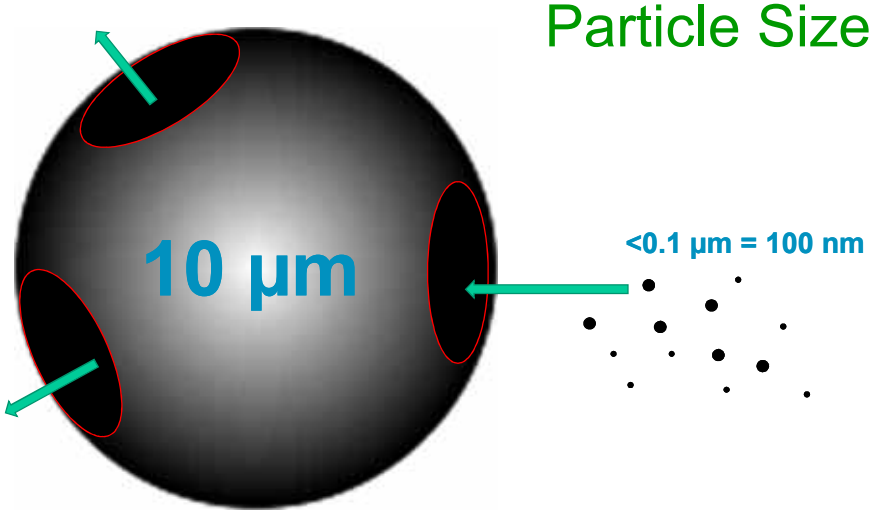


Filtering Structures must be porous

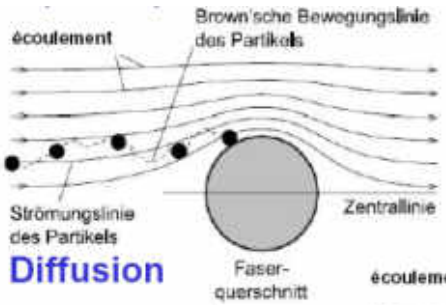
which makes them brittle and weak



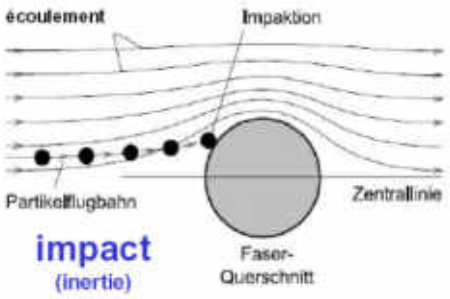
Pore Size
Particle Size



Filtration Mechanisms



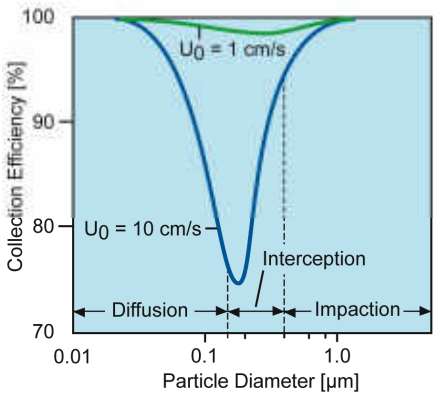
Diffusion

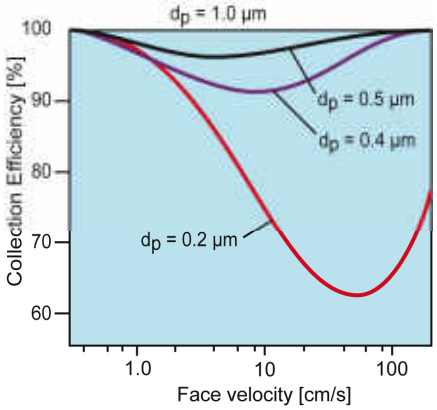


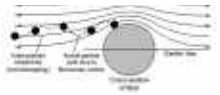
impact
(inertie)

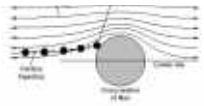
Filtration Risk in the Middle Size Range

Source: Hinds: Aerosol Technology





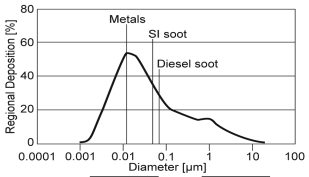


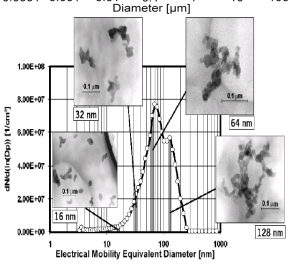


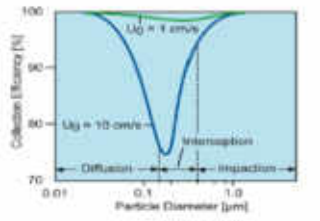
Strange Coincidence

The most sensitive size range of the Lungs is the most intensive emission range of the Engines and the weakest size range of Filtration

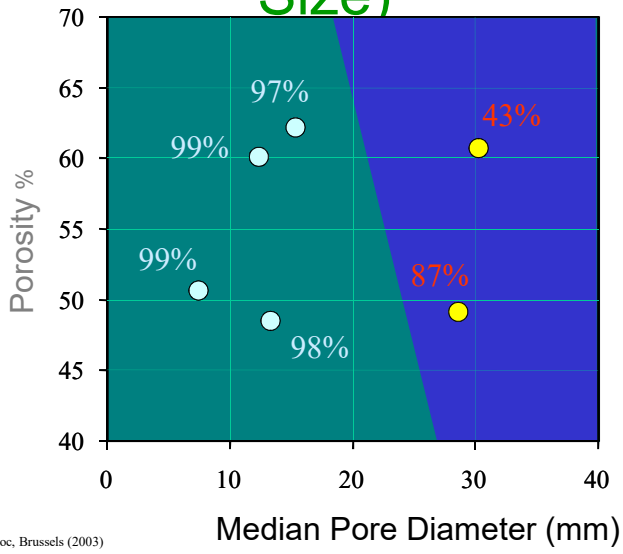
The Lung is an open door for engine emitted ultrafine particles in this size range







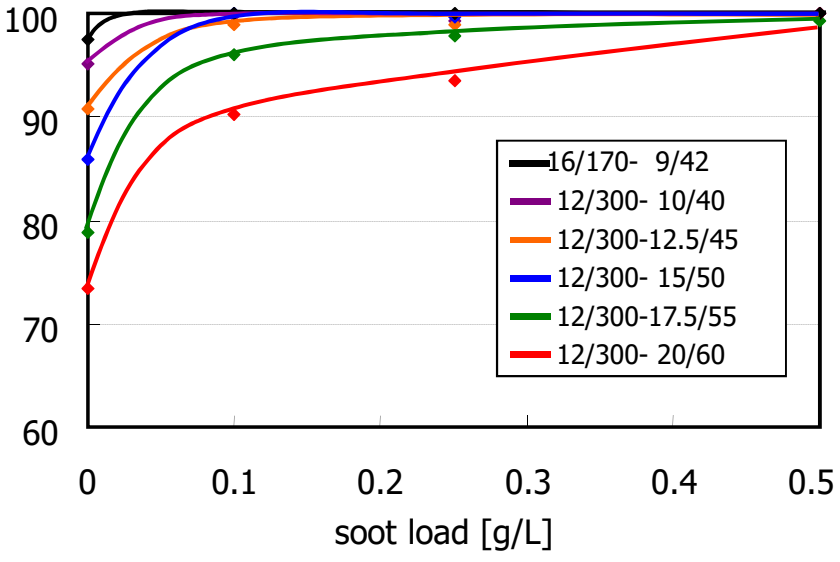
Filtration Efficiency = f (Pore Size)



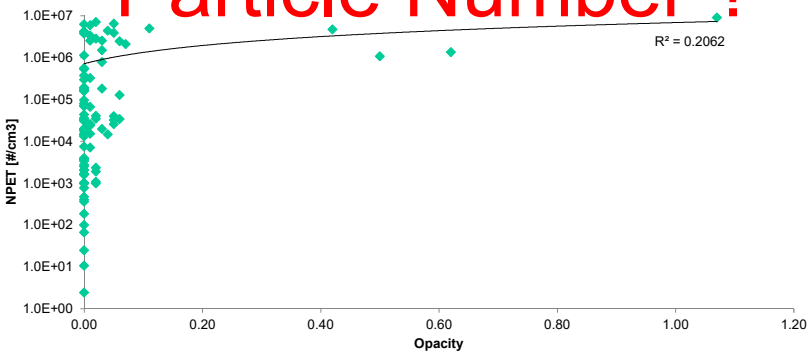
Source: Merkel et al.; CaPoc, Brussels (2003)

Filtration [%] = f (Time, Soot-Loading)

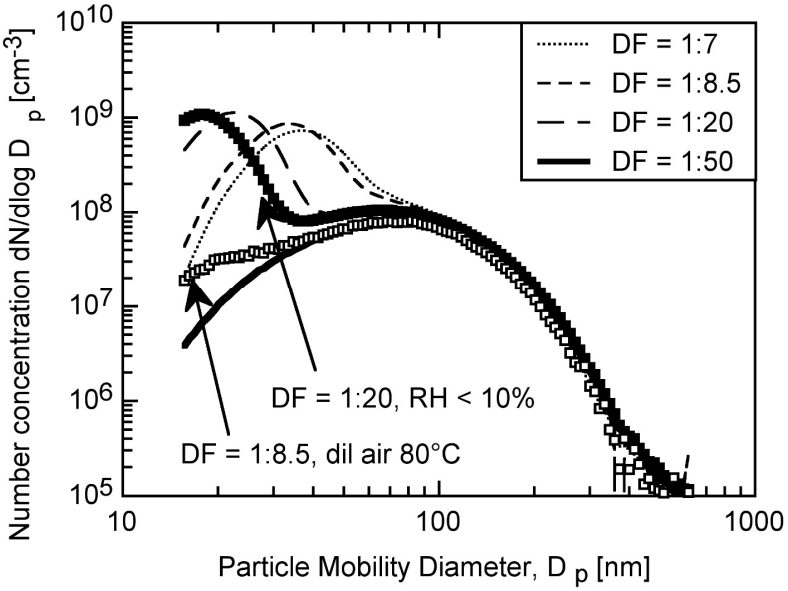
Source: IBIDEN HDT-Seminar 2006



Correlation Opacity / Particle Number ?



Solids or Volatiles?

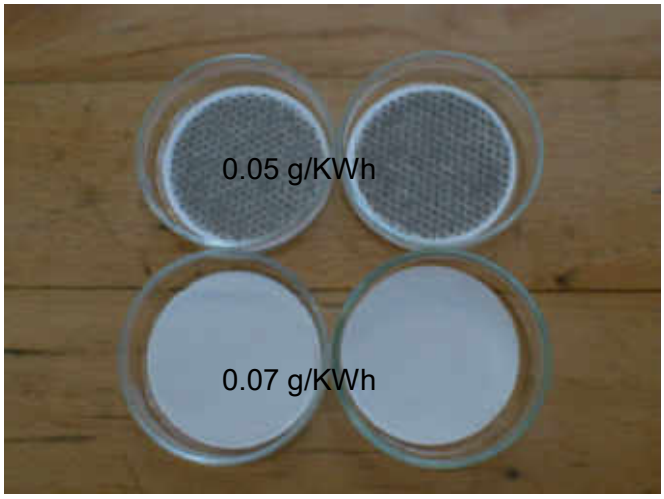


Particulate Mass Samples upstream and downstream of a Particle Filter in a Bus

Hansen, Jensen, Ezerman (2001) Report 270-1-0019, Engine Technique Aarhus

Without Filter

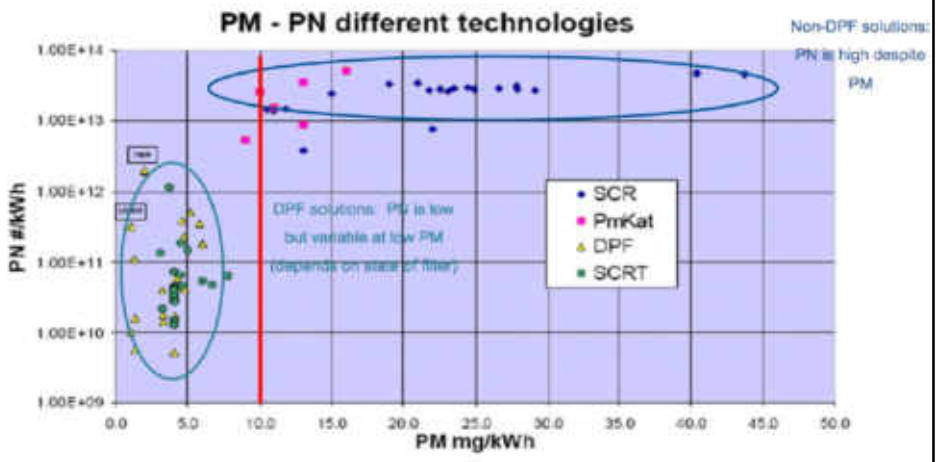
With Filter



Conclusion Daimler

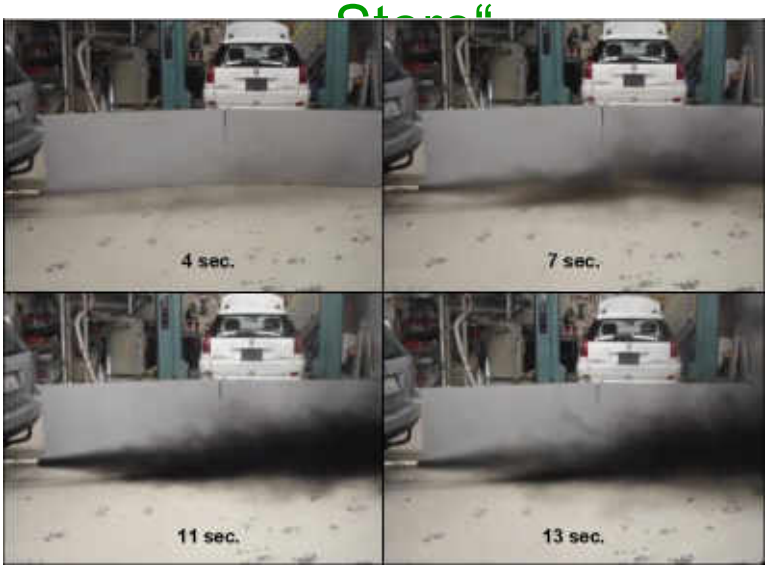
→ SCR is not reducing PN

→ DPF reaches reduction of 100-1000



Source; Daimler, SAE HD Emissions Symp, 9/14

„Release“ after 4000 km Stops“



Switzerland (VERT) 1996

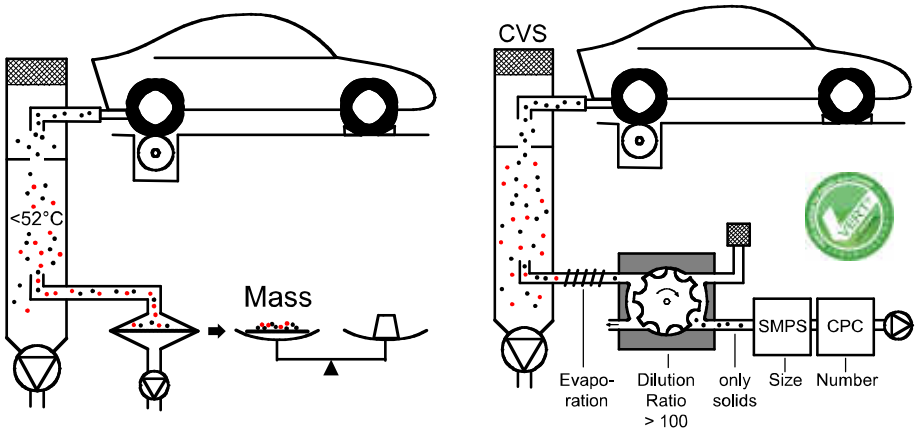
Based on this physiological and toxicological findings (mostly from occupational health, see Johannesburg convention 1952) a first definition was proposed

„Solid, insoluble particles in the mobility size range of 20-500 nm“

→development of new instrumentation
→ BAT-particle filters
→ start of the ETH-NPC

Change from unspecified PM to solid Particle number PN and size

In Switzerland 10 years before EU-PMP



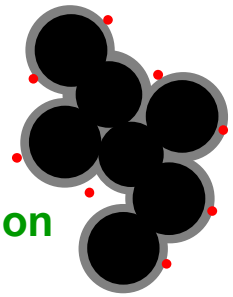
ME

Volatile Particle Remover + CNC

The Golden Instrument

What is the toxic Element ?

The Carbon core ?
Coatings ? Deposits ?
→ A new
Concept for Toxicology Evaluation



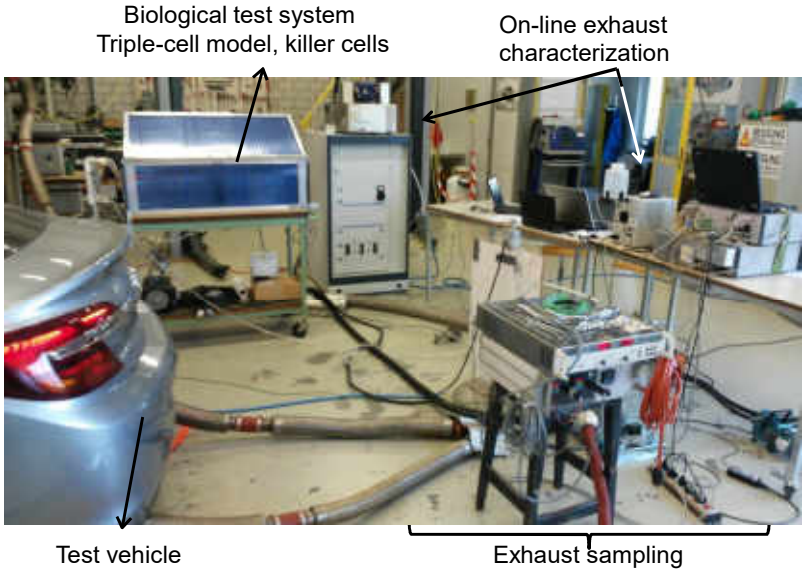
Two important conditions:

1. Expose to fresh aerosols
2. Expose human lung cells - epidermic, macrophages, dendritic – the triple cell model

Biologic endpoints

- Cytotoxicity: amount of death cells
- Oxidative stress ROS
- Damage in the DNA - Mutagenicity
- Inflammation + pre-inflammation gene reactions

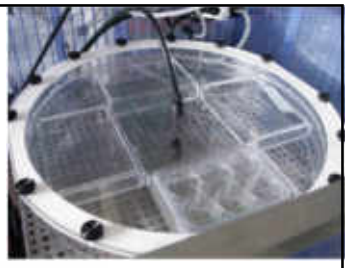
To learn more requires biologic testing in the engine lab: exposure of cell cultures to exhaust aerosol

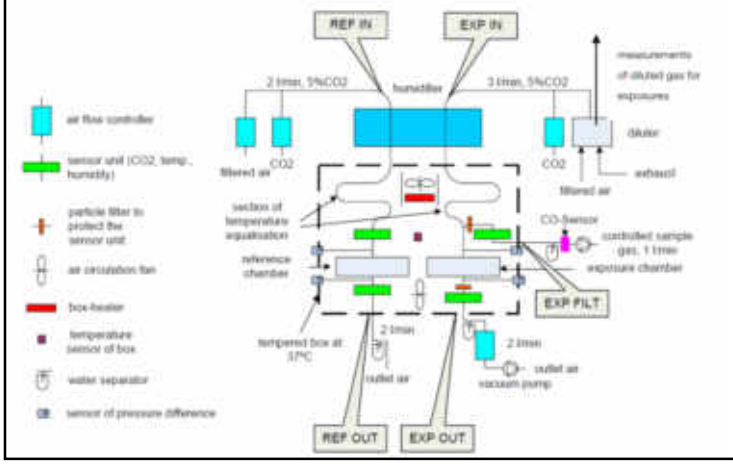


Exposure of triple cell model

lung epithelial, dendritic, macrophages

to engine out diluted and conditioned aerosol

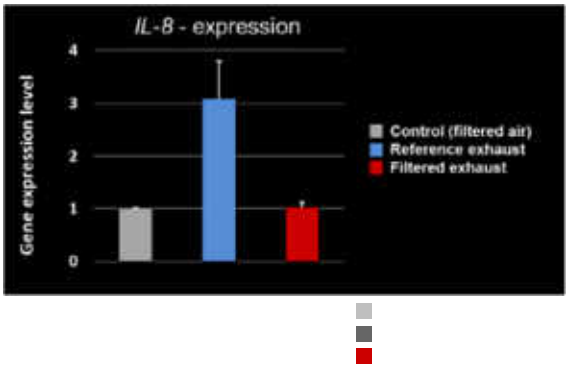




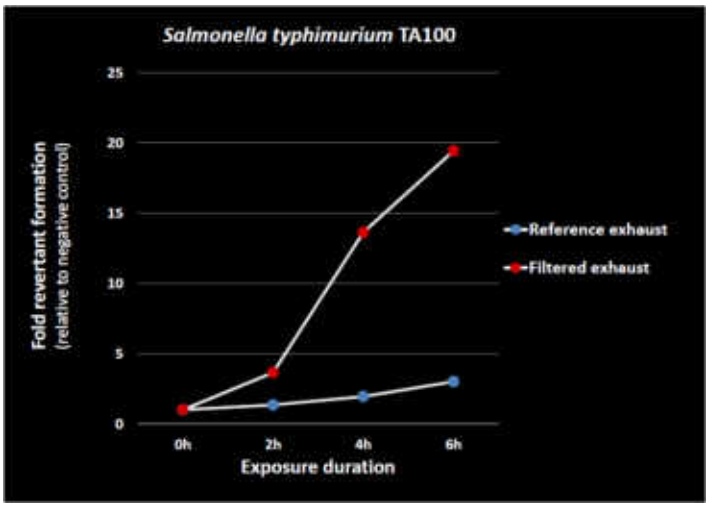
Particles are eliminated
Effects on gases weaker

Exhaust comp.	REF	DPF	% change
Particles	4.0E+08	1.0E+03	-99.999%
CO (ppm)	33.2	32.6	-1.7
HC (ppm)	11.5	8.8	-23.0
NO_x (ppm)	10.7	11.0	2.8

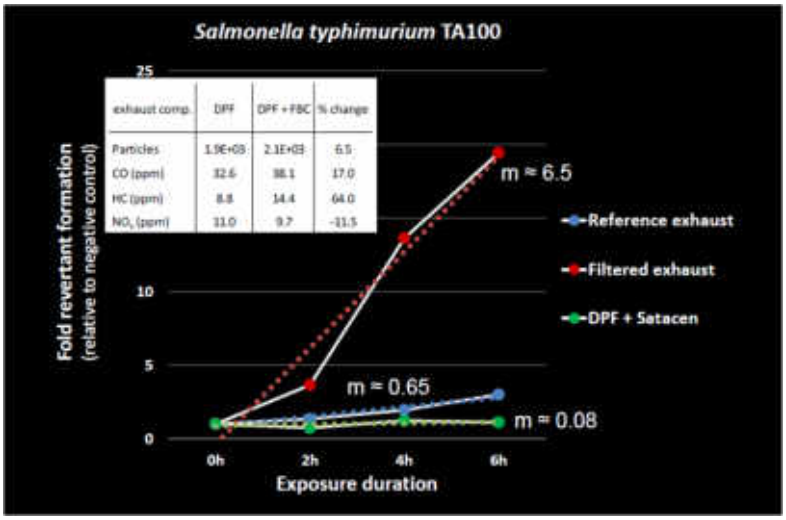
Testing Inflammation with non-catalysed DPF



Testing Mutagenicity (Ames Test) with non-catalysed DPF

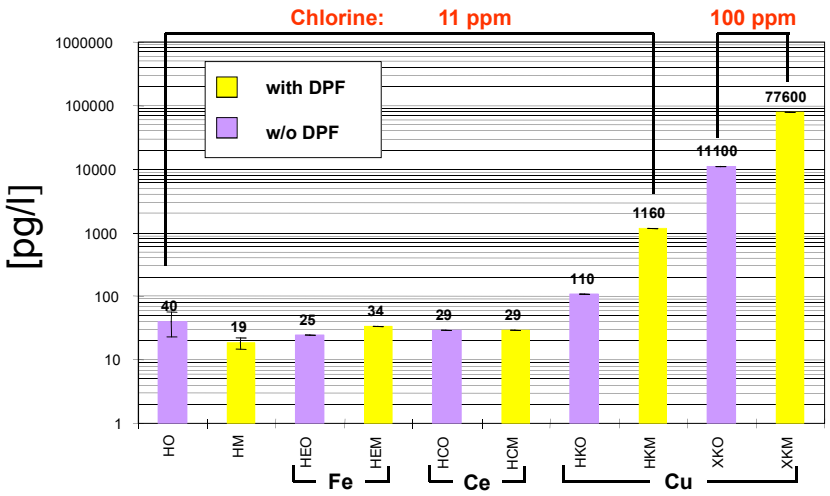


Testing Mutagenicity (Ames Test) with catalysed DPF

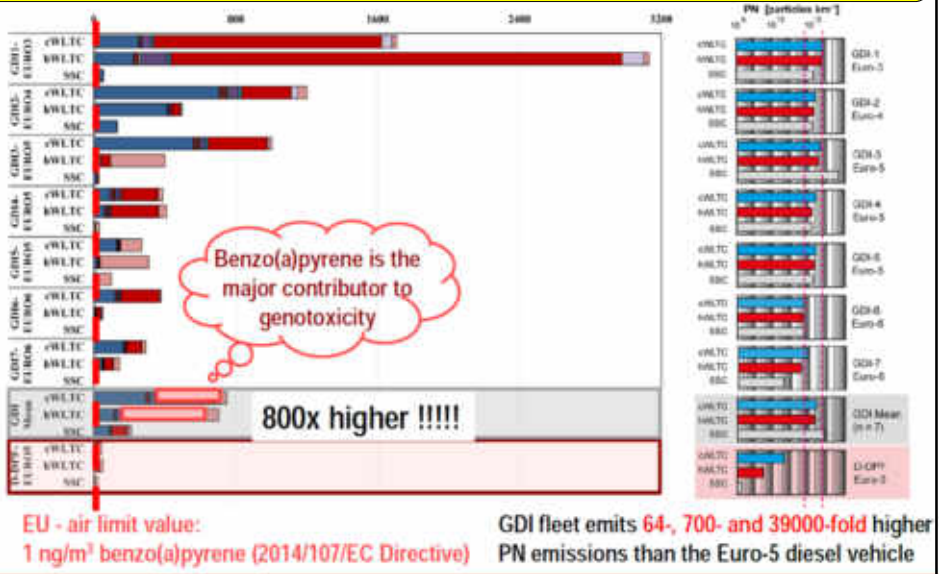


exhaust comp.	DPF	DPF + FBC	% change
Particles	1.9E+03	2.1E+03	6.5
CO (ppm)	32.6	38.1	17.0
HC (ppm)	8.8	14.4	64.0
NO_x (ppm)	11.0	9.7	-11.5

But then we observed Formation of Dioxins in a Filter System using Cu-FBC



And extremely toxic Polycyclic Aromatic Hydrocarbons PAH even in the exhaust of gasoline engines



Maria Muñoz, Empa
VERT-Focus Event: Effect- and toxicity-based assessment of exhausts, March 16, 2018, Empa 16

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as requested by MDEC Conference Organizers

- Why is Filter Type Approval needed ?
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- Emission of limited gaseous emission THC, NOx, CO
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- Standards and the VERT Filter List

- What does measured engine emission mean with regard to exposure or exceedande ?

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→

all this must be covered
by a Type Approval Process
which clearly favors sytems
which
- provide best available filtration,
- eliminate all toxic substances
contained in the engine exxhaust
gas - and suppress any generation of
new toxics in the filtration system

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Traditional DPF Certification Protocols

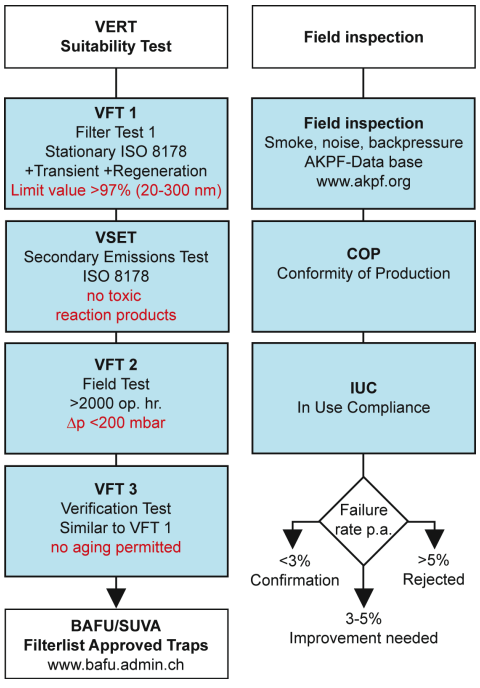
	Metric	Setup	Filtration
CARB	PM	Engine+Filter	30/50/80
US-EPA	PM	Engine+Filter	30/50/80
Germany	PM	Engine+Filter	50/80
Italy	PM	Engine+Filter	80
Beijing	PM	Engine+Filter	80
VERT	PN	Filter only	97 (99)

VERT, focussing on Particle Number + Size, is health-oriented, reaches 99% provides much more in-depth phys.+chem. Information and tests application robustness – but is less costly because it focusses on DPF properties and supplies information which is be valid for any engine application.

UN-ECE-REP is actually developing a new retrofit regulation based on PN, Filter only, > 95 % .. following VERT. EU will adopt the result

VERT

Filter Testing Certification and Quality Control



Concept of VERT-Filter Testing

- In Depth Testing of Exhaust Gas Filter Structures for Nanoscale Filtration (Physical Properties)
- In Depth Testing Chemical Phenomena in Exhaust Gas Filter Structures
- Testing a complete DPF system
- Type Approval of one filter per filter family
- Endurance Testing on Typical Vehicle Application
- Testing is Worst Case oriented
- Best Available Technology is the moving Target

Testing the Combination Filter + Engine not required

VERT targets are BAT dynamic

Filtration

Filtration between Regenerations

	A	B	C
From year	2010	2012	2015
New state	≥97%	≥98%	≥99%
2000 hrs.	≥97%	≥98%	≥99%

Filtration during Regeneration

	1	2	3
From year	2010	2012	2015
New state	≥ 60%	≥ 70%	≥80%
2000 hrs.	≥ 60%	≥ 70%	≥80%

Secondary Emissions

$\Delta NO_2/NOx$ ratio for newly certified systems

before	2012
No limit	< 20 %

Swiss Standard
(Techn.Norm)

How to measure and characterize Nanoparticle Filtration systems for Combustion Engines


INB

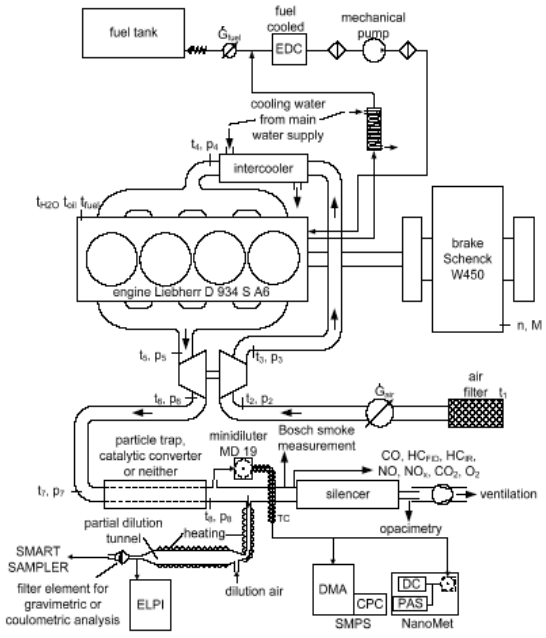
SN 277206

Internal Combustion Engines – Exhaust Gas After-treatment – Particle Filter Systems – Testing Method

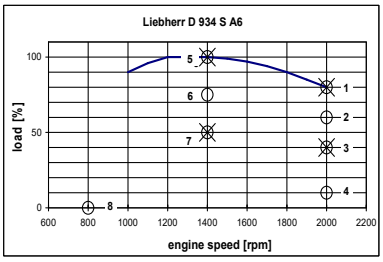
Verbrennungsmotoren – Abgasnachbehandlung – Partikelfiltersysteme – Prüfverfahren

Moteurs à combustion – Post-traitement des gaz d'échappement – Systèmes de filtres à particules – Méthode de test

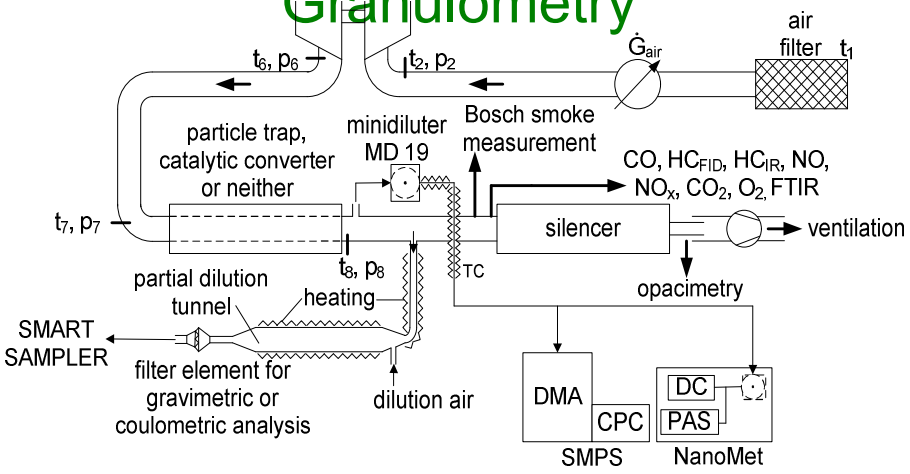
Motori a combustione – Post-trattamento dei gas di scarico – Sistemi di filtri antiparticolato – Metodo di collaudo



• Test Setup

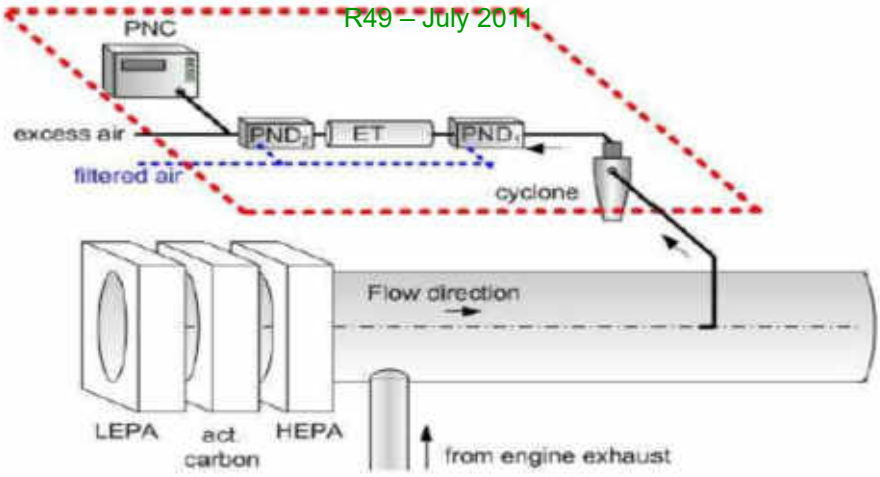


Test Setup Detail Granulometry

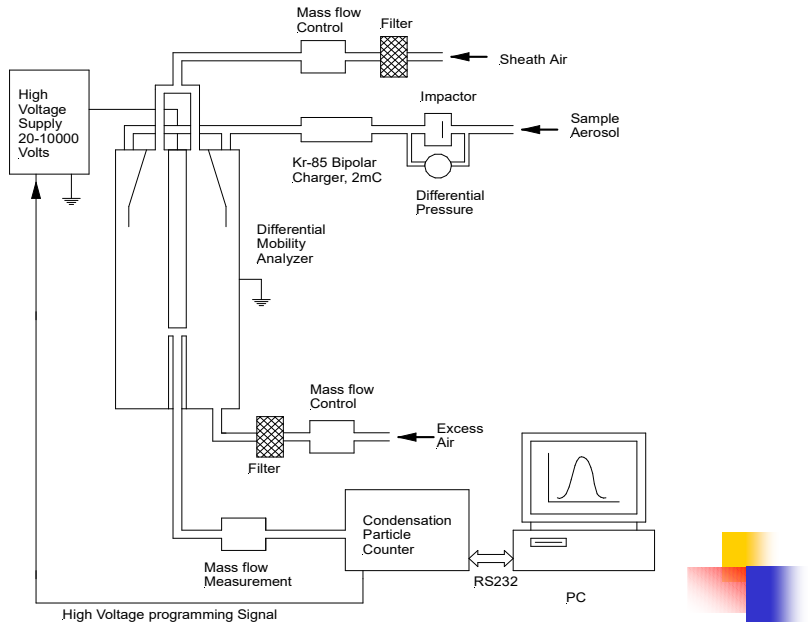


Compatible to EU-PMP PMP-Set-up for solid particle counting

PNC 23-2500 nm; ECE/324/ Add.48, R49 – July 2011

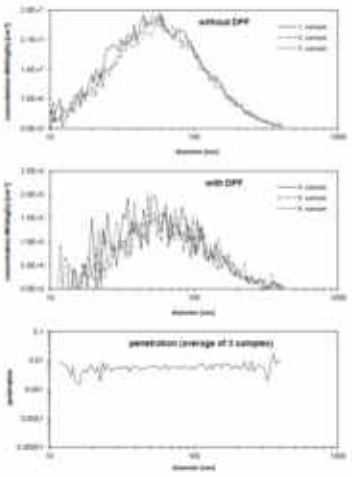


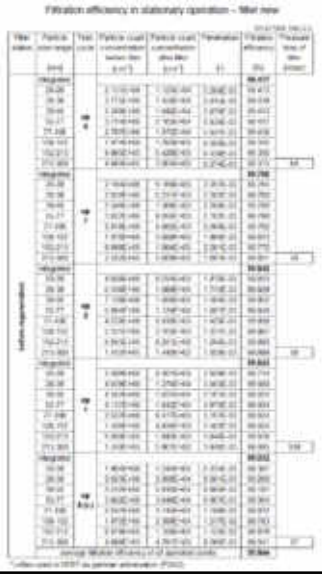
SMPS = Scanning Mobility Particle Sizer

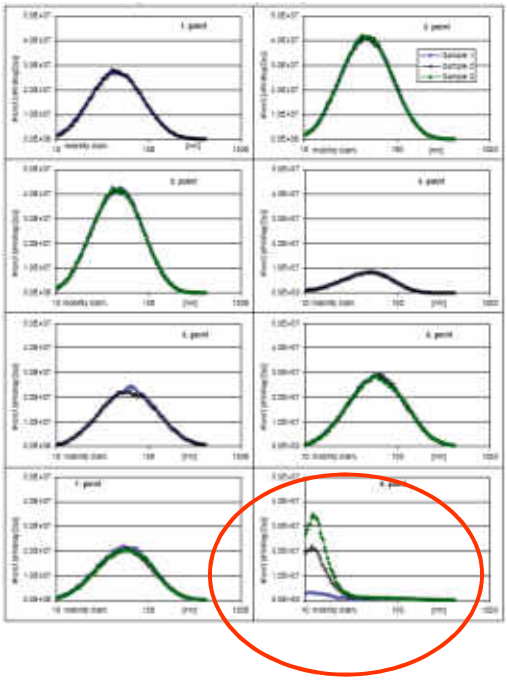


good DPF

Measuring Particle Size, Surface, PN Number, EC/OC, PM Mass and Gases NO, NO2, HC, CO, CO2, O2 + FTIR-Analysis..
before, after and during Regeneration
new Filter and after 2000 operation hours



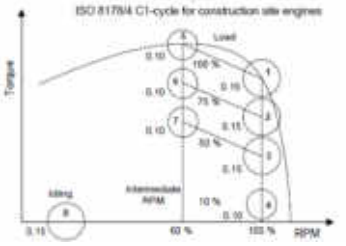




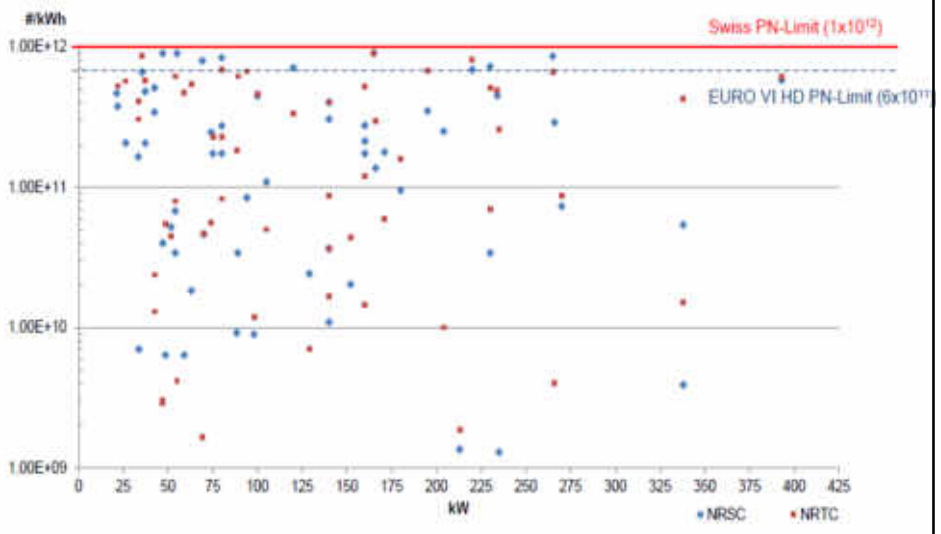
Size distributions

Liebherr Diesel

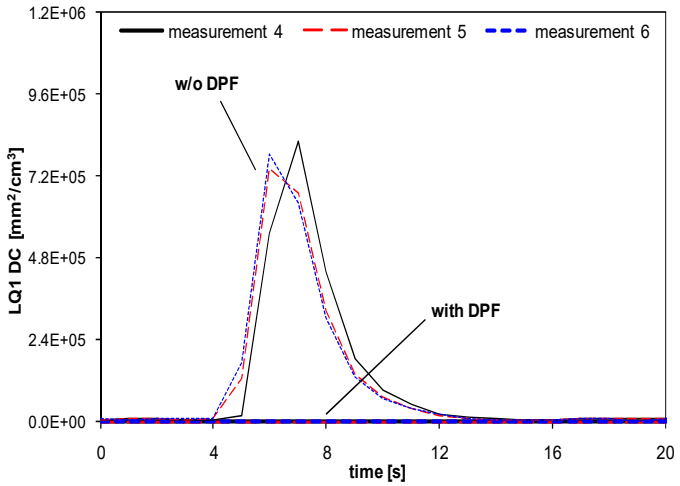
110 kW
8 operation points of
ISO 8178/4 C1 test cycle
OP 8 = idle
Sampling: 300°C,
Dilution Ratio DR=100



PN-Test results

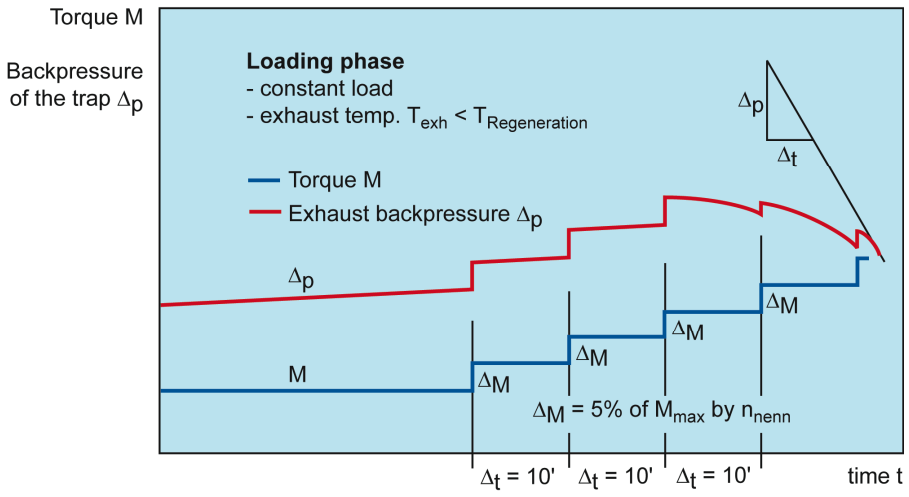


Extreme Transients « free acceleration » with DC-signal, with / without DPF

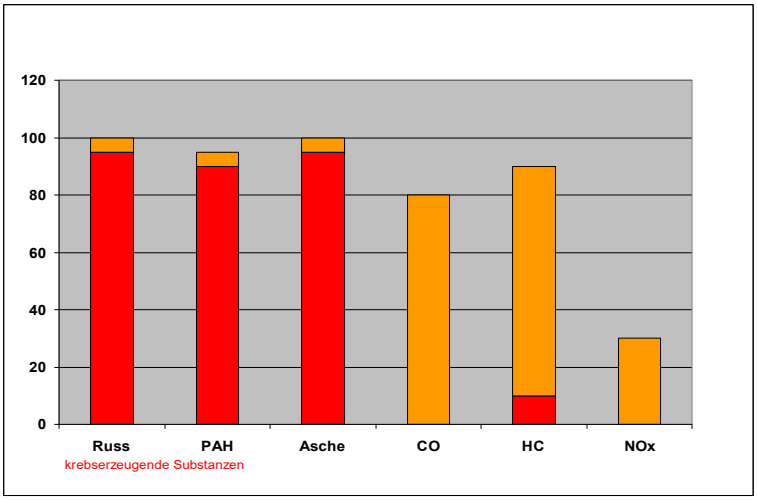


Regeneration Test

Find Balance Point and Regeneration Gradient



Emission Reduction by DPF



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Secondary Emissions

Toxics generated in the Filter/Catalyst system

- NO_2, Dioxins/Furans, PAH, Nitro-PAH etc.
- Sulfuric acid aerosols
- Metal oxide (Ash) particles, mineral fibers etc.

The Legal Basis for secondary pollutants analysis

Why should we care on secondary emissions?

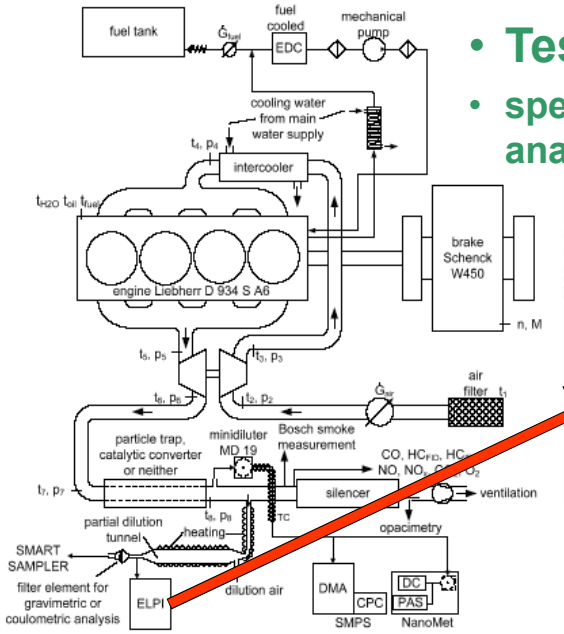
Legal Aspects

US Clean Air Act (Section 220):

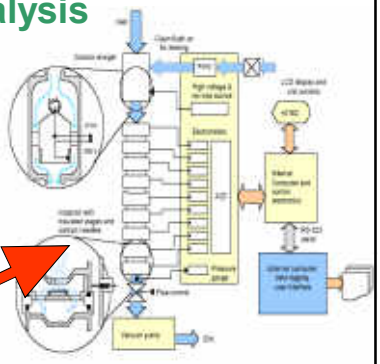
- "Effective with respect to vehicles and engines manufactured after model year 1978, no emission control device, system or element of design shall be used if such a devise will cause or contribute to an unreasonable risk to public health, welfare, or safety. The administrator shall consider, among other factors, whether and to what extent the use of any device, system, or element of design, causes, increases, reduces, or eliminates emissions of any unregulated pollutants".

CH EJPD 8/1990:

- " In Verkehr stehende und neue, ohne Partikelfilter typengeprüfte Fahrzeuge, können nachträglich mit Partikelfiltern ausgerüstet werden.... .beim Einsatz von additiv- oder katalytischunterstützte Regenerationsverfahren ist nachzuweisen, dass eine Gefährdung von Gesundheit und Umwelt durch die zusätzlichen entstehenden Reaktionsprodukte ausgeschlossen ist"



- **Test Setup for size-**
- **specific particle analysis**

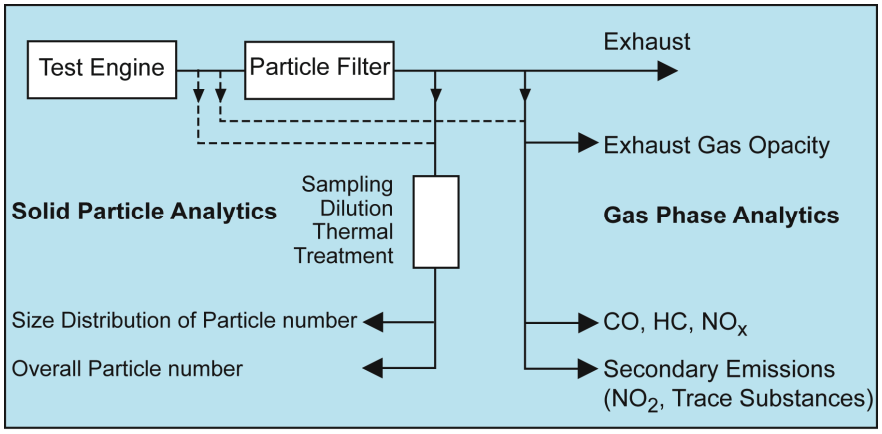


ELPI – Impactor

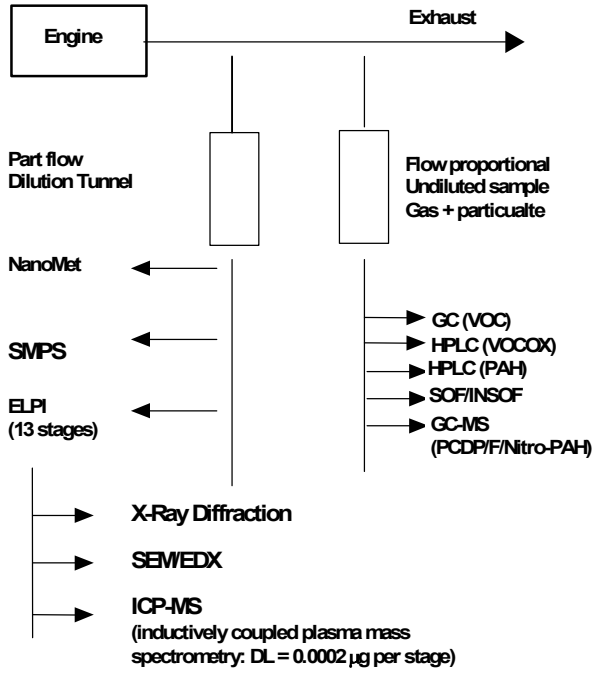
13 size classes

30 nm – 10 µm

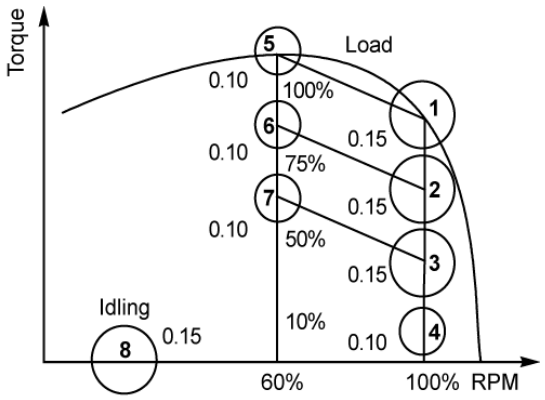
Sampling during VERT-Filter Test



VSET Test set-up and Metrology

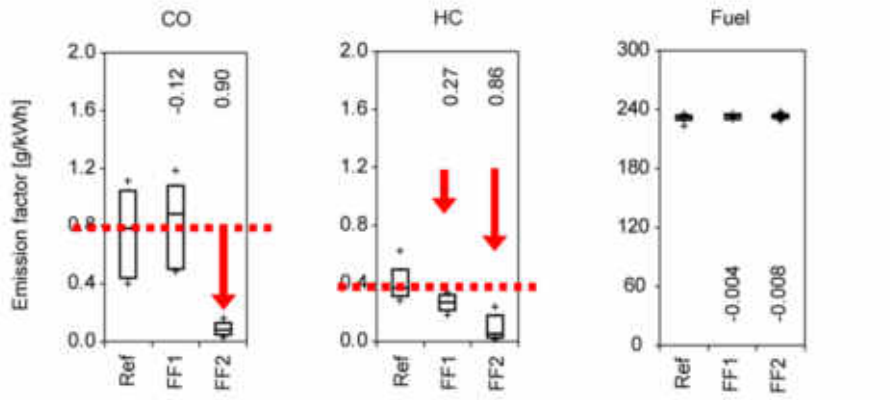


ISO 8178 continuous for VSET

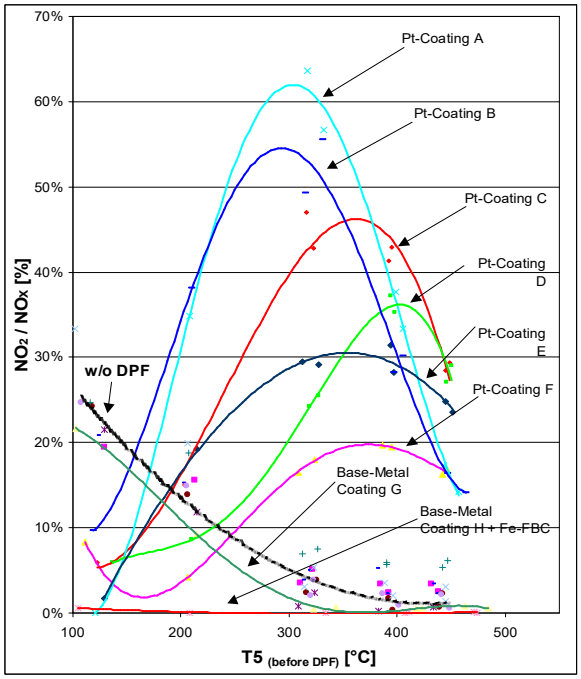


No significant effects on fuel consumption

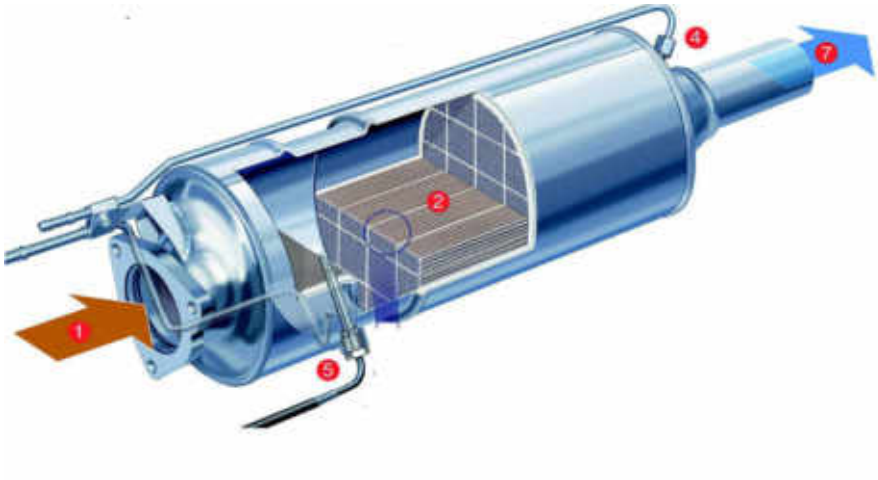
Carbon monoxide, hydrocarbons, fuel

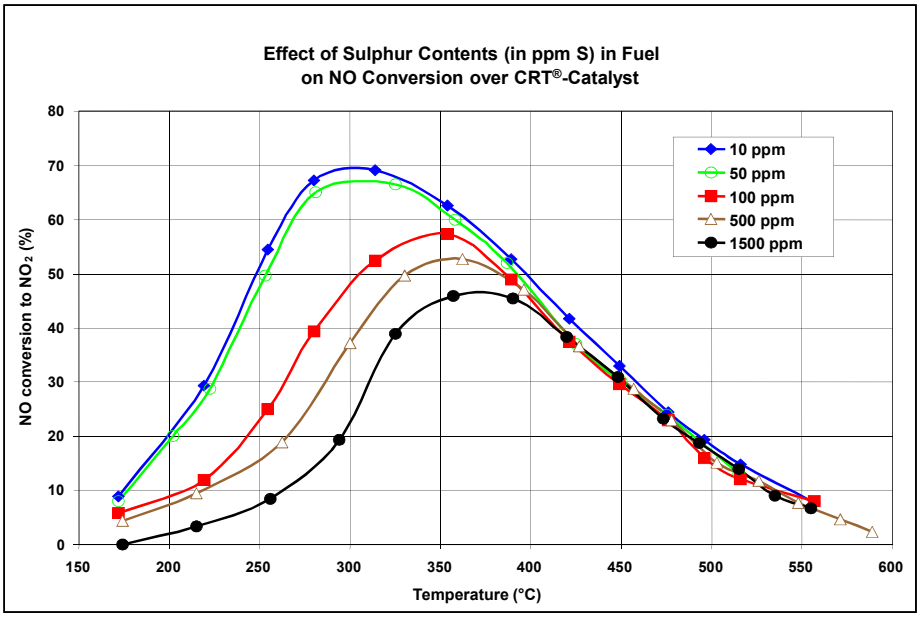


$NO \rightarrow NO_2$ conversion with catalytic coatings and NO_2-reduction with FBC



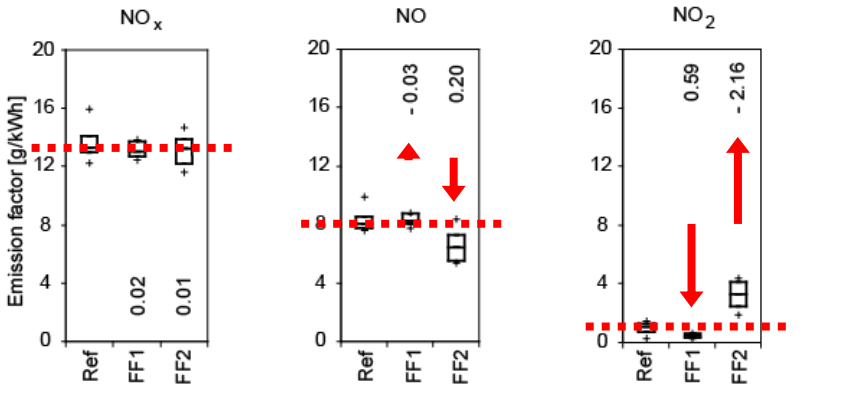
CRT-Filter System
Johnson Matthey Patent 1988





Nitrogen oxide emissions

Two filter families: one converts NO_2 the other form NO_2!

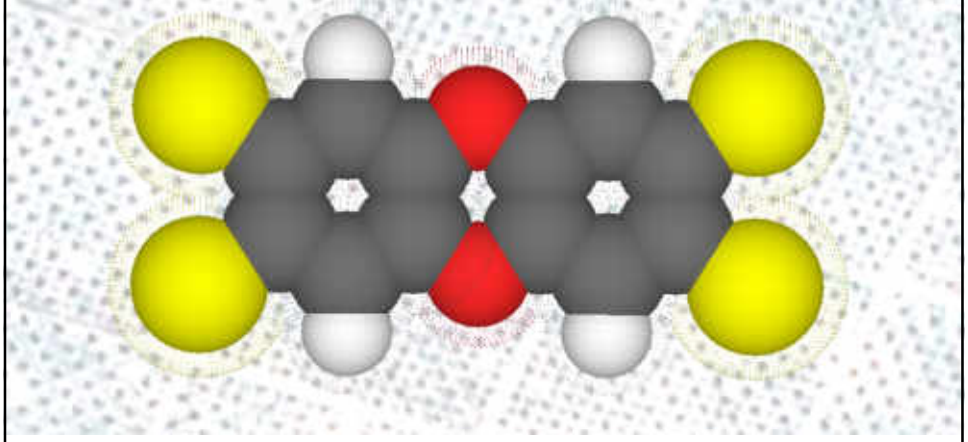


Heeb et al. ES&T, **2010**, 42, 3773-3779

PCDD/Fs: toxic at pg-quantities

What are PCDD/Fs?

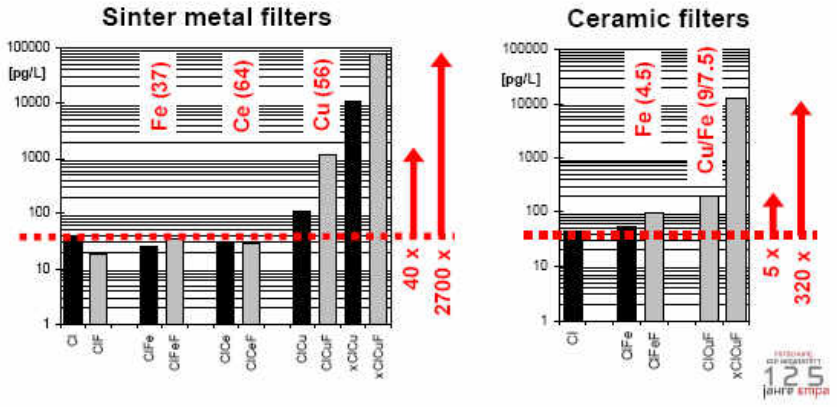
2,3,7,8-Tetrachlorodibenzodioxin - the so-called Seveso-dioxin



Copper-induced *de novo* PCDD/F-formation

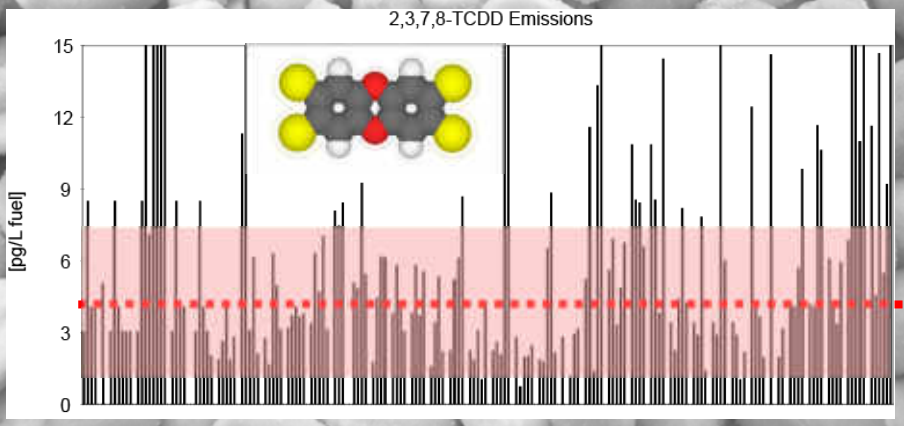
What happens if traces of chlorine enter the system?

2,3,7,8-chlorinated PCDD/F (TEQ-Sum)



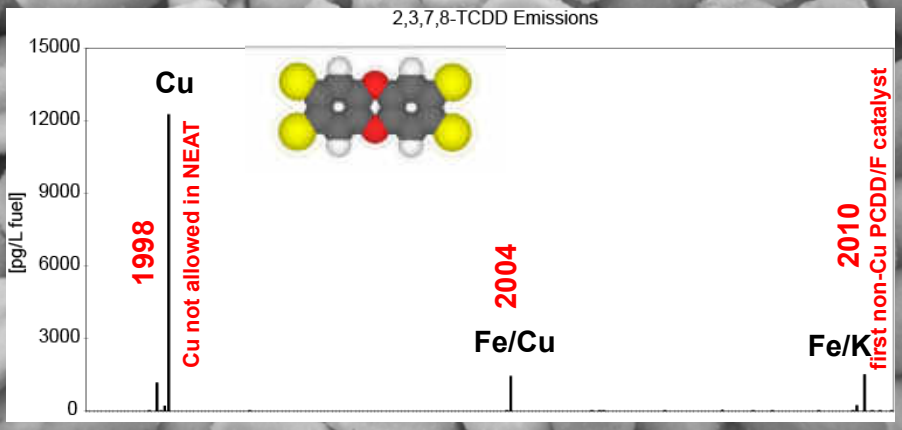
Assessment of the PCDD/F-formation potential

We just have to pick the right ones



Assessment of the PCDD/F-formation potential

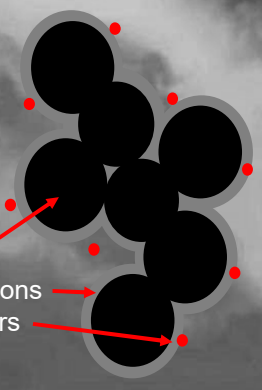
These 3 DPFs exceed the MWI emission limit of 100 pg/m3 exhaust



PAH and Nitro-PAH transported with Particles

- Nanoparticles penetrate cell membranes (alveoli, placenta, blood cells, brain)

transport like a **Trojan horse** toxic compounds



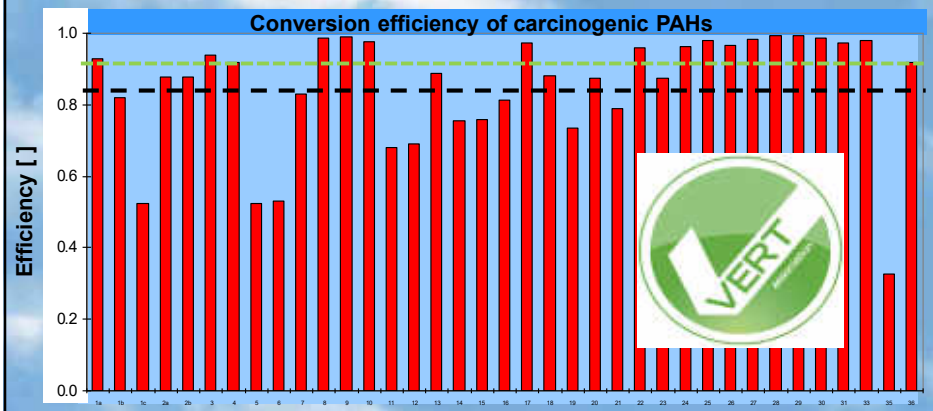
Elementel Carbon
Polycyclic Hydrocarbons
Metal Oxides Clusters

into cells

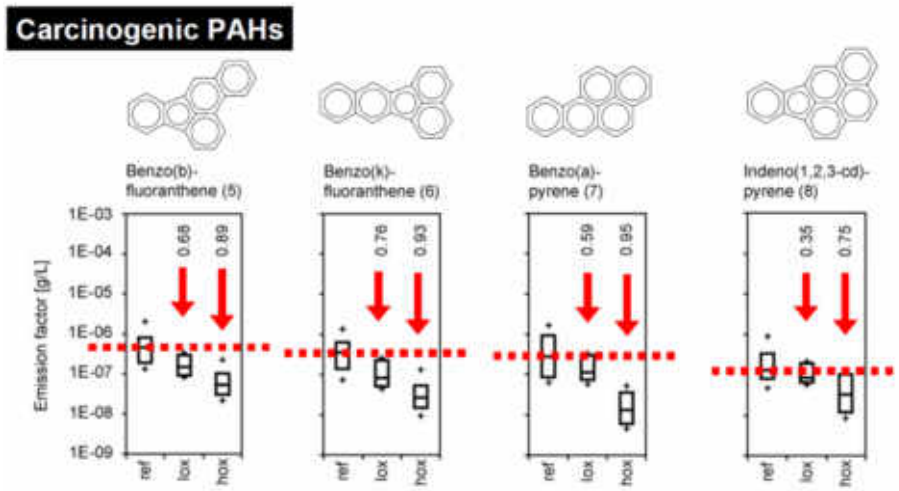
Trojan horse, Harbour of Canakkale, Turkey

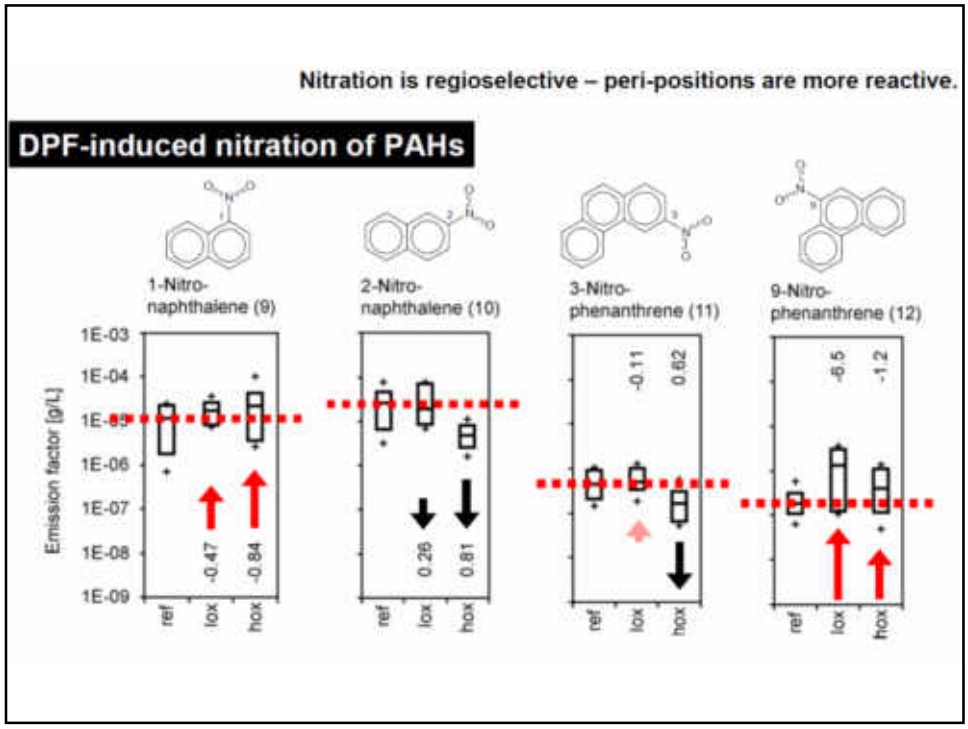
PAH Conversion

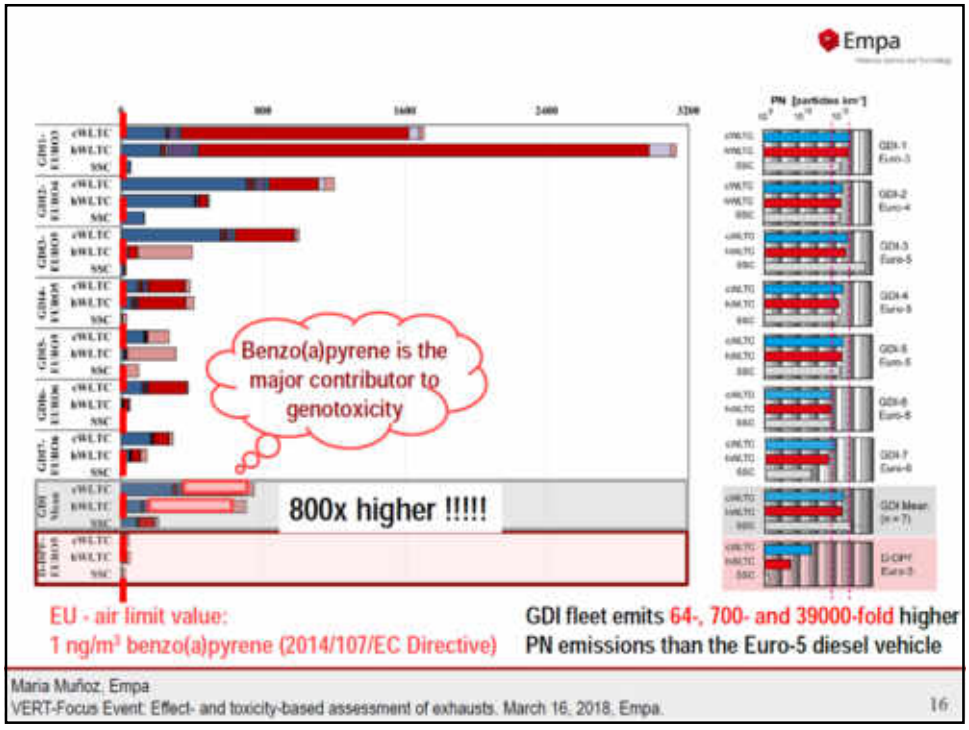
What is BAT today?



Conversion of all carcinogenic PAHs!




Nitration is regioselective – peri-positions are more reactive.
DPF-induced nitration of PAHs
1-Nitro-naphthalene (9)
2-Nitro-naphthalene (10)
3-Nitro-phenanthrene (11)
9-Nitro-phenanthrene (12)
Emission factor [g/L]
1E-03
1E-04
1E-05
1E-06
1E-07
1E-08
1E-09
-0.47
-0.84
0.26
0.81
-0.11
0.62
-6.5
-1.2
ref
lox
hox


Empa
Benzo(a)pyrene is the major contributor to genotoxicity
800x higher !!!!!
EU - air limit value:
1 ng/m³ benzo(a)pyrene (2014/107/EC Directive)
GDI fleet emits 64-, 700- and 39000-fold higher PN emissions than the Euro-5 diesel vehicle
Maria Muñoz, Empa
VERT-Focus Event: Effect- and toxicity-based assessment of exhausts. March 16, 2018, Empa.
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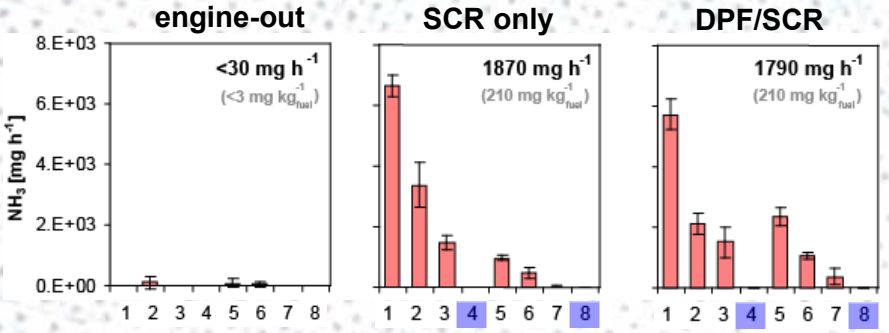
Secondary pollutants of DeNOx-technologies

Substantial ammonia emissions with active SCR!

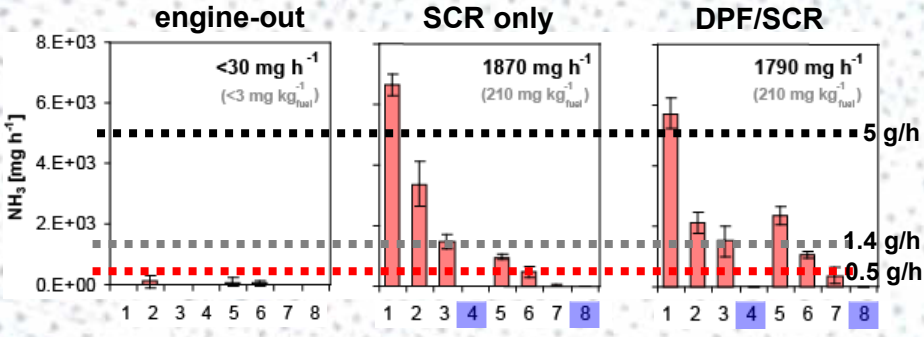
Ammonia (NH_3)



Secondary pollutants of DeNOx-technologies

Substantial ammonia emissions with active SCR!

Ammonia (NH_3)



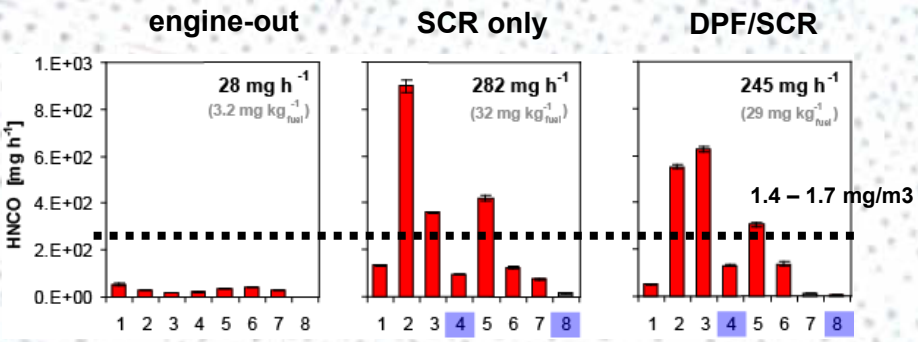
Heeb et al. Atm. Env. 40 (2006) 3750-3763
Heeb et al. Atm. Env. 40 (2006) 5986-5997

Livingston et al. Atm. Env. 43 (2009) 3326-3333
Heeb et al. Atm. Env. 42 (2008) 2543-2554

Secondary pollutants of DeNOx-technologies

Isocyanic acid emissions 70-85 x above MAK

Isocyanic acid (HNCO)



Heeb et al. Atm. Env. 40 (2011) 3203-3209

Metal Analysis in 13 size 10 nm – 10 mm classes per HR- ICP-MS

- For all catalytic coating metals
- For all fuel borne catalysts
- For metals from oil packages
- For engine wear metals

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Size Specific Pt-Emission-Analysis (CDT-FBC)

ELPI Stage	Diameter D50 [nm]	upstream Trap [µg]	downstream Trap [µg]	Trapping eff. [%]
1	30	0.002	-	
2	63	0.006	-	
3	109	0.007	-	
4	173	0.005	0.001	
5	267	0.015	0.001	
6	407	0.022	0.002	
7	655	0.022	0.001	
8	1021	0.013	0.0005	
9	1655	0.007	0.0005	
10	2520	0.004	0.0002 DL	
11	4085	0.003	0.0002 DL	
12	6560	0.002	0.0002 DL	
13	9999	0.002	0.0002 DL	
	Sum:	0.117 µg	0.0068 µg	93%

Durability Test (Field test) 2000 hrs

VERT approved DPF systems must undergo a field test of **at least 2000 operating hours**

Do be done in a typical application of the specific DPF system (i.e. stationary or mobile application resp.)

With periodic tests of filter performance, back pressure, regeneration, control and alert systems, mechanical construction etc.

Followed by a full filter test on bench VFT3
no aging or deterioration permitted

Effect of Backpressure on Fuel Consumption

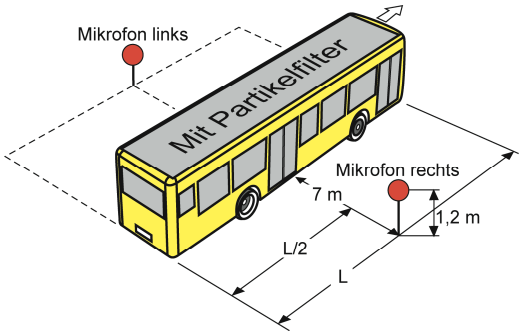
$$\frac{\Delta be}{be} = \frac{\Delta p}{pe + pr}$$

Where be is the specific Fuel Consumption [g/kWh] Δbe the Increment due to the Backpressure Increment Δp in relation to the overall Engine Work, expressed by effective pressure + friction pressure

This linear Relationship is valid for natural aspirated engines without EGR up to about 300 mbar, above we find a nonlinear increase.

Noise

Filter is replacing Silencer
Noise must be controlled for each Retrofit Case
Noise usually 1-2 dB(A) lower – see VERT-database



Drehzahl [rpm]	Ohne Filter links [dB]	Ohne Filter rechts [dB]	Mit Filter links [dB]	Mit Filter rechts [dB]
600	63	65	62	62
1000	66	70	66	65
1500	74	78	69	69
1700	77	81	71	71
Mitelwert	71,7		66,8	

CONTENTS

as requested by MDEC Conference Organizers

- Why is Filter Type Approval needed ?
- Filtration with resp. to particle size and number concentration
- Emission of limited gaseous emission THC, NOx, CO
- Secondary Emissions
- Further Requirements: Endurance, Fuel Economy, Noise …
- **VERT Filter List**
- What does measured engine emission mean with regard to exposure or exceedande ?

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VERT-Certificate

1.VERT-testing successfully completed
2.Application per System duly signed - directed to VERT coordination office
3.Examination by VERT Scientific Committee - ananimity required
4. Stamp “Valid” VERT-CEO
5. Filter listed
6. Certificate to manufacturer


VERT®-Certificate

VERT Filter List

65 Certifications
First Publication 1998
Published on VERT-homepage
www.VERT-certified.eu
Updated whenever modified
Responsible:
VERT-Scientific Committee
Language: English only

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- Standards and the VERT Filter List
- **What does measured engine emission mean with regard to exposure or exceedance ?**

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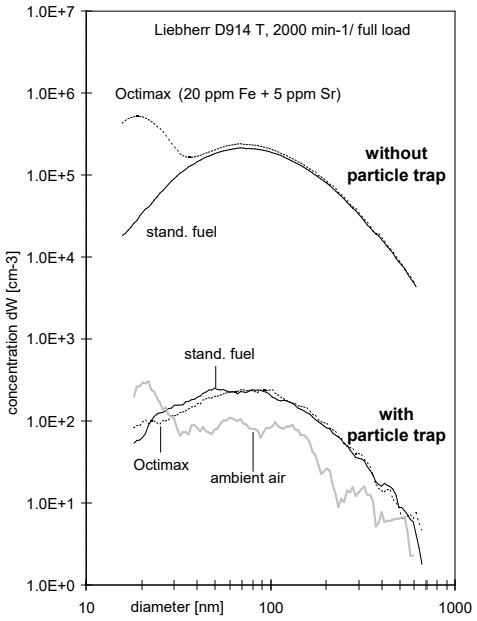
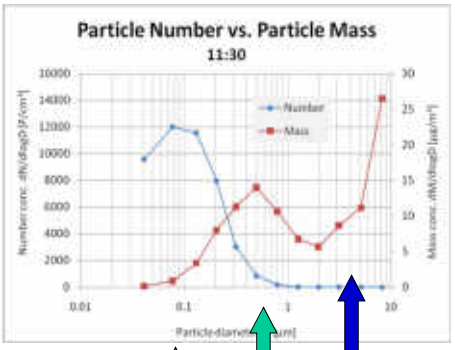
Measurement must be by Number and Size

to show that Filtration Effectiveness is > 99 %



Size Distribution at Curbside Zürich

would BC be the right parameter ?



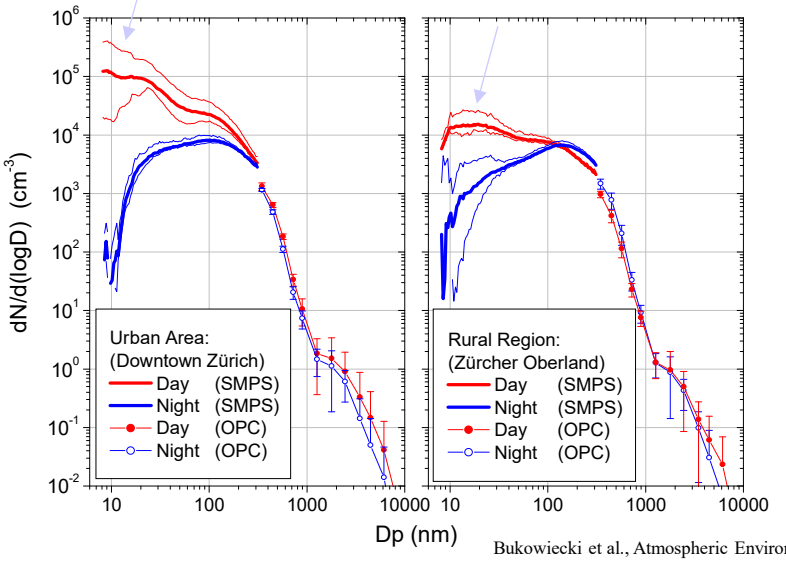
- Engine emitted (EC+metal oxides) particles have very little mass but high numbers
- Tire wear (BC) has low numbers but higher mass
- Resuspended material (also BC ?) has even higher mass

resuspended Road Dust

Tire wear ?
Break wear ?
Wall deposited particles

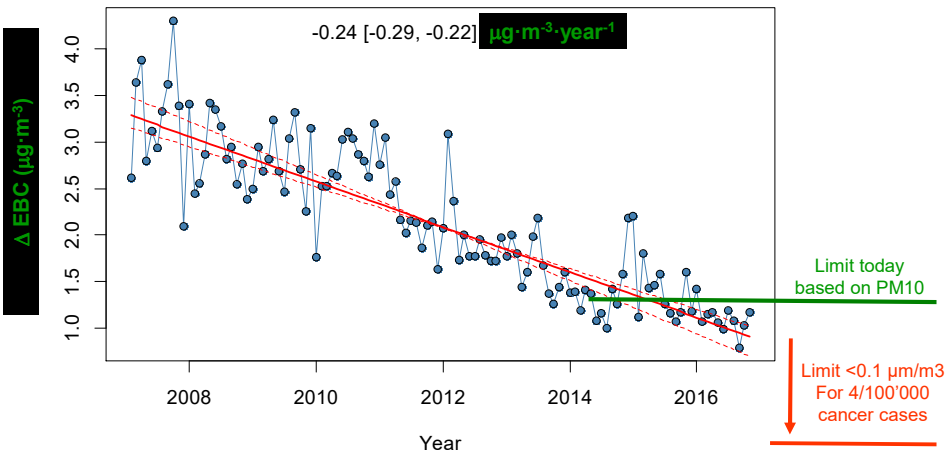
Engine Exhaust

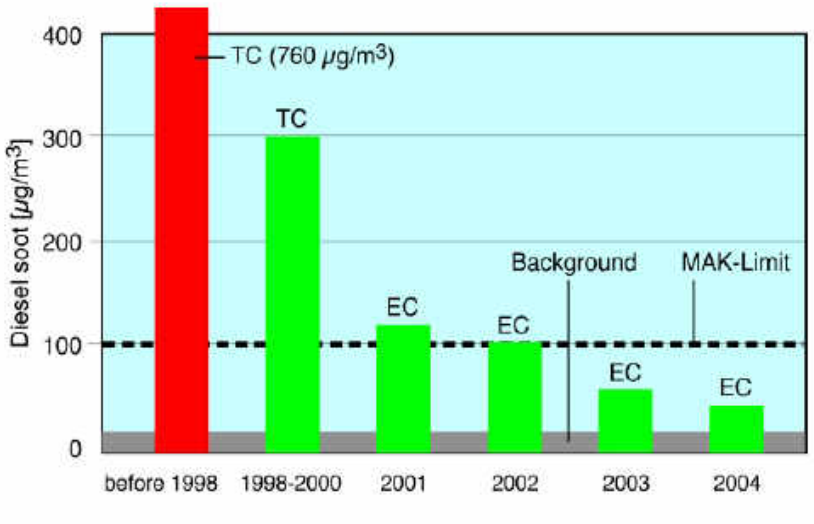
Aerosol Number/Size – Distribution
City (Zürich) and Coutry (Zürcher Oberland)



Bukowiecki et al., Atmospheric Environment, 2002

And the Result:
Cleaning the Air by DPF in Switzerland
Monitoring BC





Improvement of Air Quality in Swiss Tunneling

Health Cost Reduction Zürich

due PM/PN-reduction by vehicle exhaust filtration

450 million CHF less annually = 300 CHF per Person

published April 2018

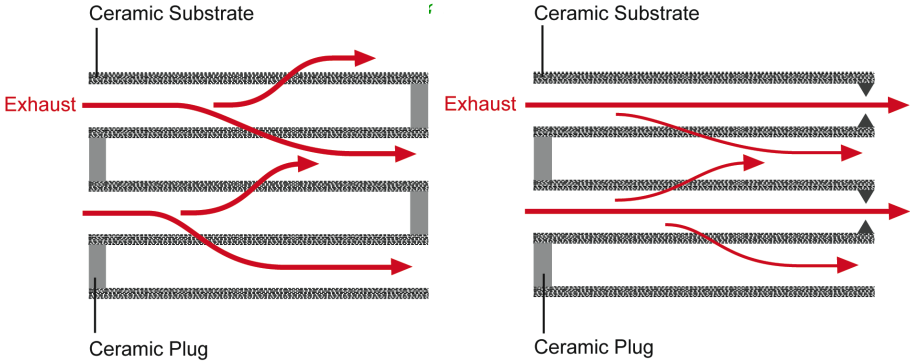
VERT was there before 1993
and may stay after 2018

- 1984 BBC/ETH-DPF with DB tested successful in USA
  → Corning-Degussa-DPF desaster, 2000 engines failed in USA
- 1993 DPF the only solution for building NEAT
  → 1994 Filtertest at AFHB following the PN-standard
  → 1997 First ETH-Nanoparticle Conference
  → 1998 First VERT-Filterlist
  → 1999 Nanomet «the golden nstrument» at Hannover fair
  → 2000 DPF mandatory in Swiss tunneling
  → PSA FAP roll out
- 2002 DPF mandatory in Swiss construction
- 2011 DPF mandatory for Euro 6 only possible due to PN-standard
- 2020 DPF offroad and GPF for DI-Petrol
- 2029 EV produce all PM10, ICE eliminate all PN < 500 nm
- 2038 Sun-Fuel CO2 neutral for ICE - EV becomes a niche application

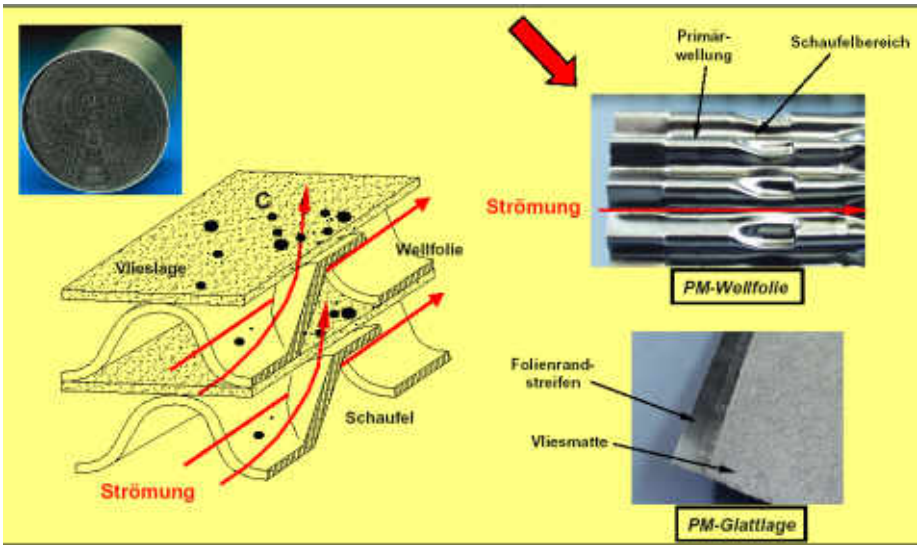
Main requirements of VERT filter test

- **High filter efficiency 97 %:**
  highest space velocity,
  highest temperature,
  clean,loaded,regenerated and during regeneration
  new and aged,
  all particle sizes 20-500 nm
- **No secondary emissions**
- **Durability of filter quality**
- **Regeneration of the filter**

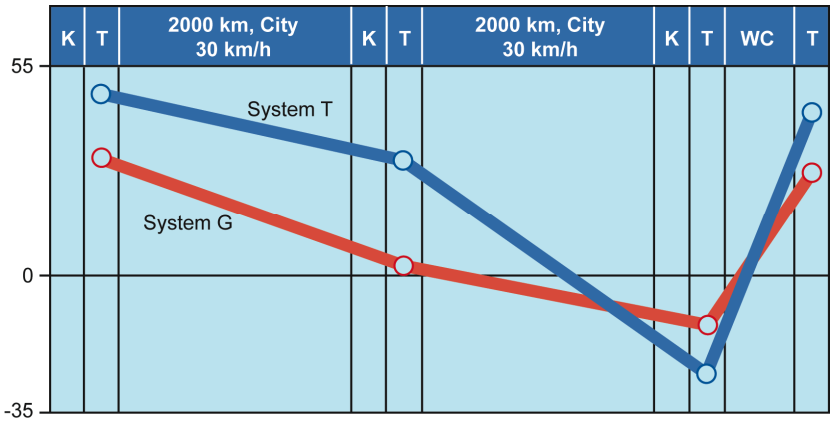
Full Flow versus Partial Flow Filters



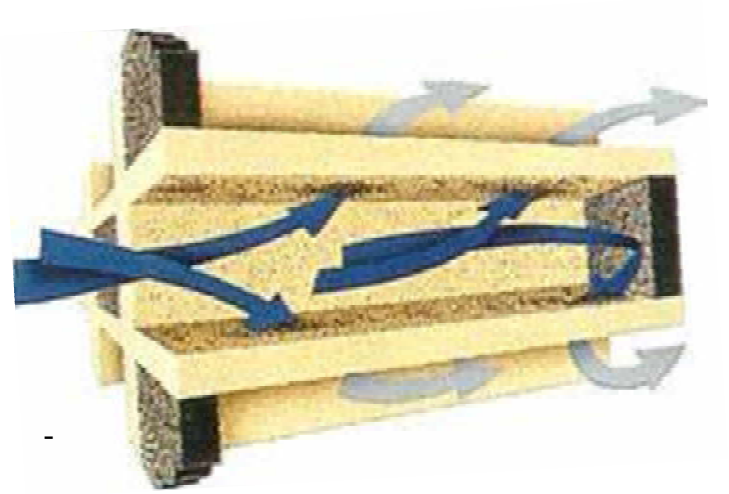
Partial Flow System A : EMITEC



Soot „*Store and Release*“-Effects

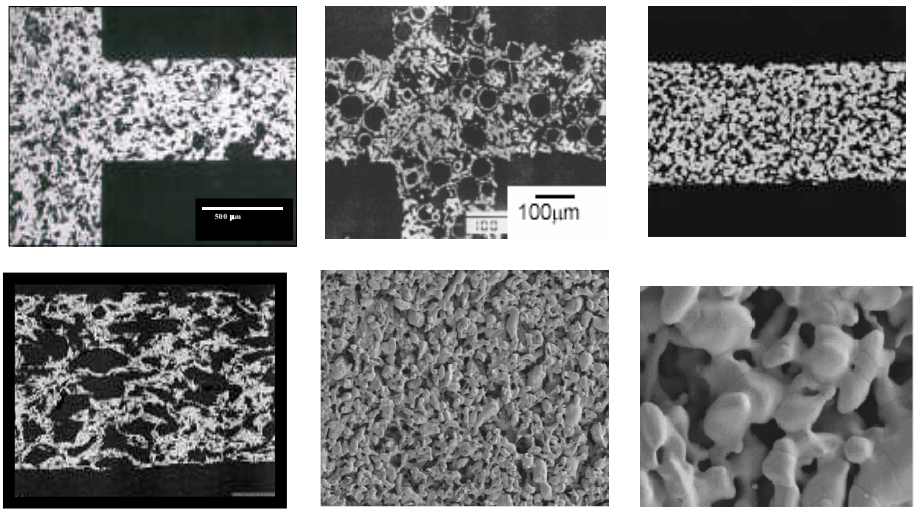


The Wall Flow Filter

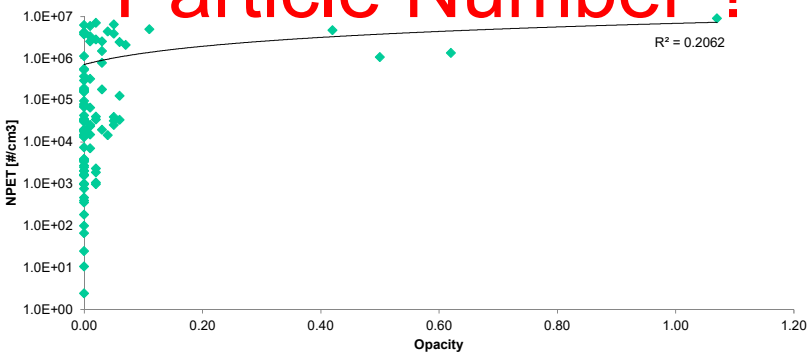


Filtering Structures must be porous

which makes them brittle and weak

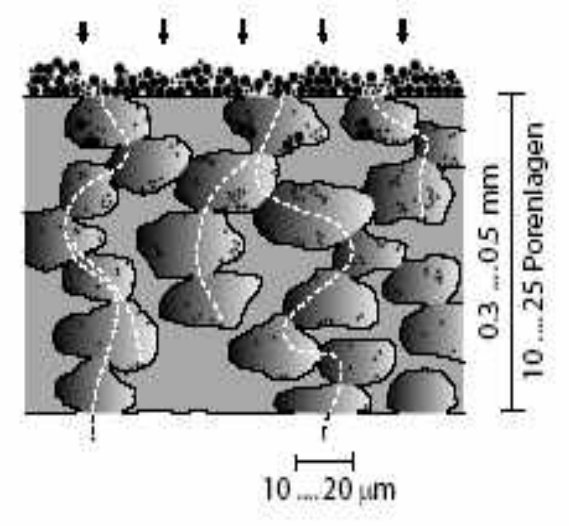


Correlation Opacity / Particle Number ?

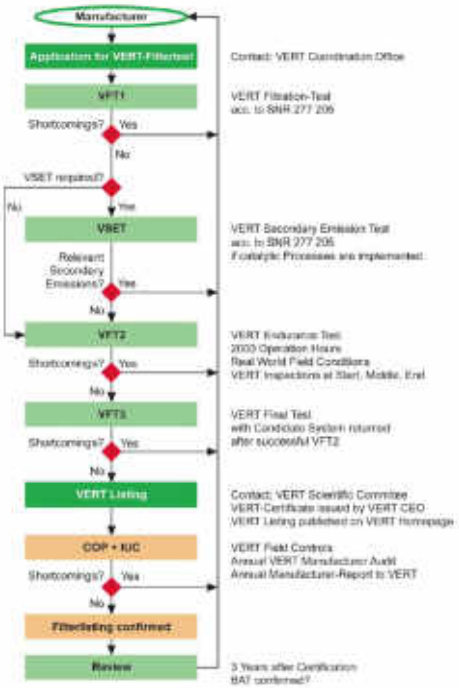


Wall-Flow-Filtration by Diffusion only !

Size Ratio
of Particle/Pore
10nm / 10‘000nm
equals the ratio
of a fly to a room
→Not acceptable is filtration after soot cake formation only
→Not acceptable is low cycle migration



VERT-Test for BAT



VERT-Conformity Criteria 1998

the Golden Standard

VERT-Pflichtenheft für Partikelfiltersysteme bei Baumaschinen Stand 15.4.98

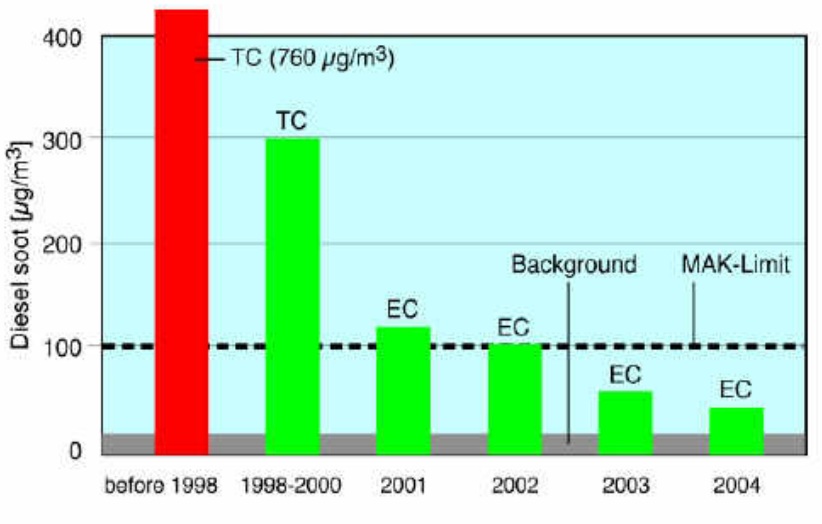
Abscheidegrad (am Referenzmotor Liebherr 914 T)

- Gesamtpartikel, gravimetrisch (ISO 8178 C1, 4 Testpunkte) > 90%
- Elementarer Kohlenstoff, coulometrisch > 95%
- Russstoss bei freier Beschleunigung: Opazität < 10%
- Penetration von Feststoff-Feinpartikeln im Grössenbereich10-500 nm < 5% (Anzahlkonzentration)

Zusatzanforderungen Emissionen

Es ist keine messtechnisch eindeutig nachweisbare und relevante Erhöhung folgender Emissionen gegenüber dem Ausgangszustand des Motors zulässig, insbesondere:

- Sulfatbildung, Schwefelsäure-Aerosole
- Sekundäremissionen durch Brennstoff-Additive
- Sekundäremissionen durch Dioxinbildung
- Erhöhung der Grundemission CO, HC, NO, NO_2 (Summe Zyklus)
- Mineralfaser-Emission



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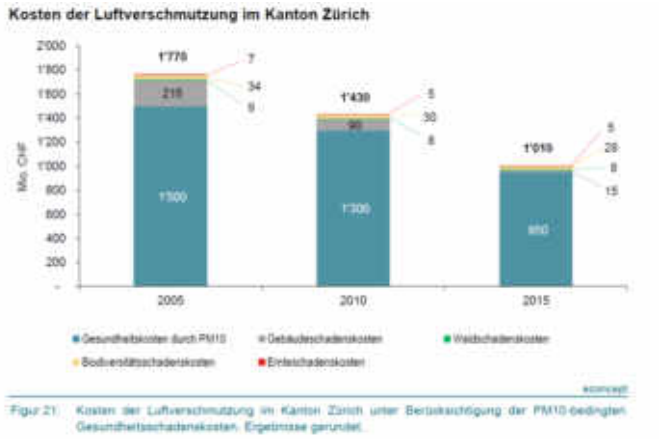
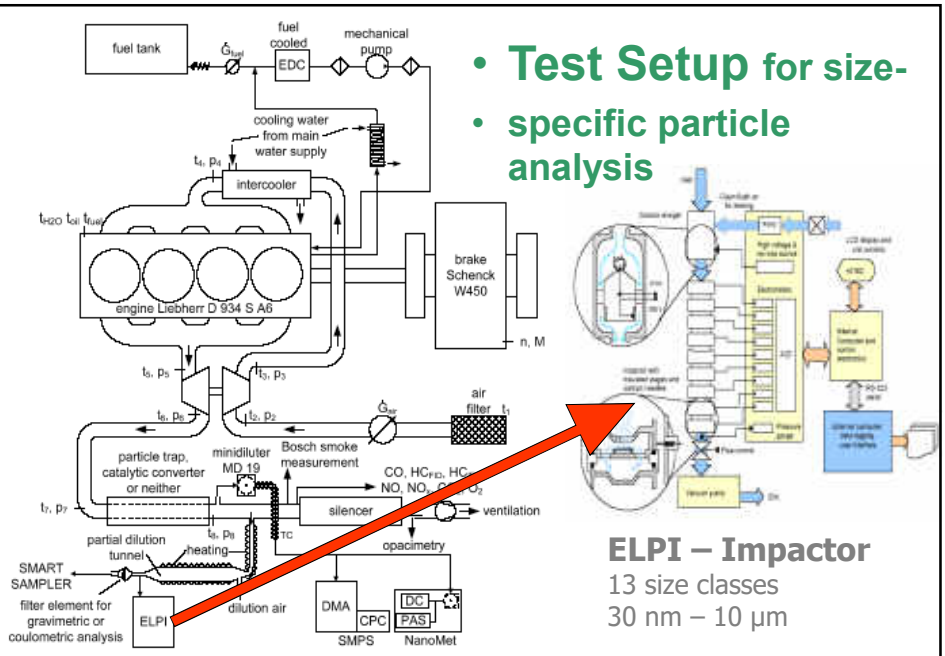


Figur 21: Kosten der Luftverschmutzung im Kanton Zürich unter Berücksichtigung der PM10-bedingten Gesundheitsschadenkosten. Ergebnisse gerundet.

450 million CHF less annually = 300 CHF per Person

published April 2018



- **Test Setup for size-**
- **specific particle analysis**

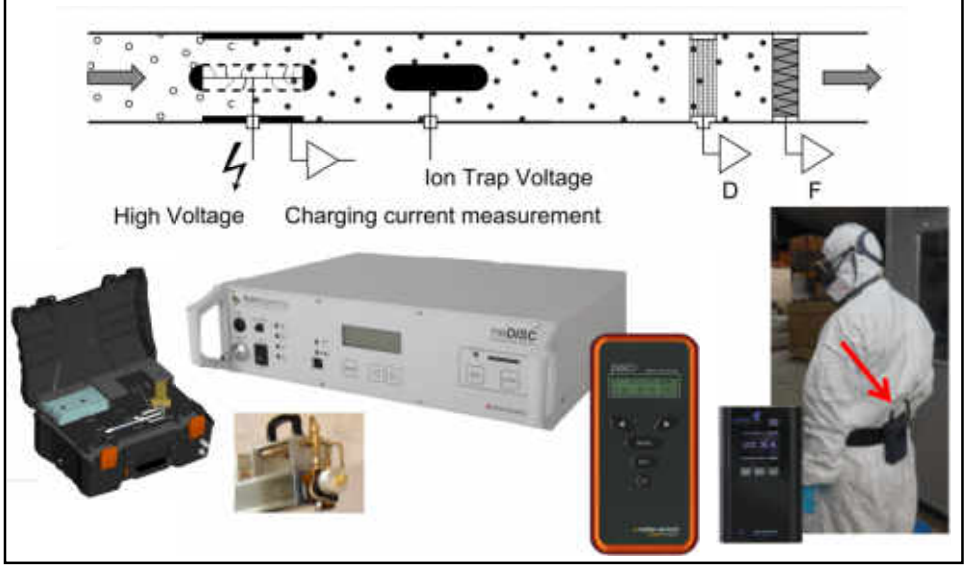
ELPI – Impactor

13 size classes

30 nm – 10 µm

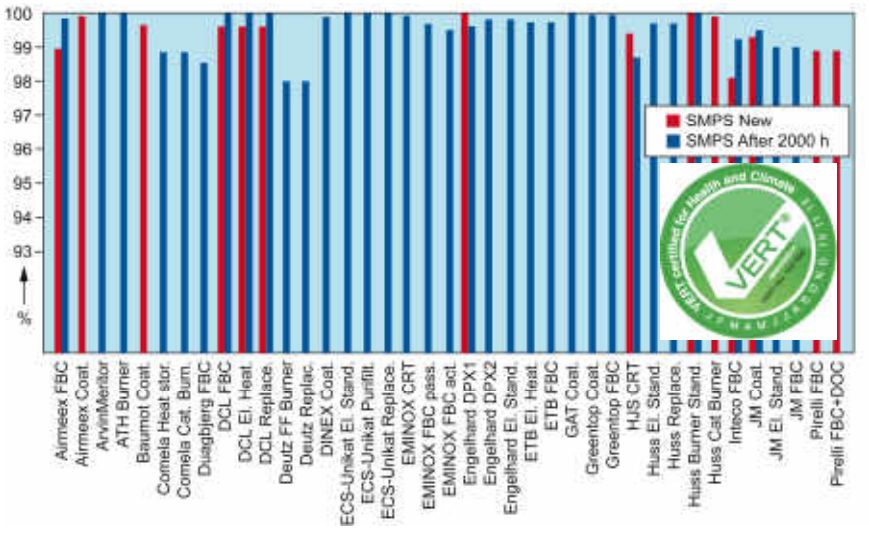
Diffusion Charging by TESTO and NANEOS

for Laboratory, PEMS, Maintenance and Personal Sampling

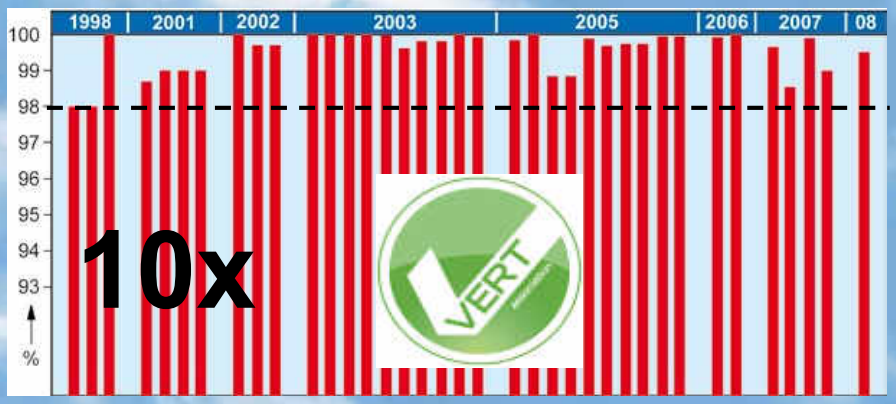


Filtration - 65 DPF VERT-tested

average 98.4 %; 25 % > 99.8 %



You have to zoom in to see differences



Mayer et al. MTZ, **2009**, 70, 72-79

World Health Organization, IARC
Diesel engine exhaust: a group 1 carcinogen

Diesel engine exhaust cause cancer in humans

The Diesel Exhaust in Miners Study: A Nested Case–Control Study of Lung Cancer and Diesel Exhaust

Debra T. Silverman, Claudine M. Samanic, Jay H. Lubin, Aaron E. Blair, Patricia A. Stewart, Roel Vermeulen, Joseph B. Coble, Nathaniel Rothman, Patricia L. Schleiff, William D. Travis, Regina G. Ziegler, Sholom Wacholder, Michael D. Attfield

Manuscript received February 16, 2011; revised June 3, 2011; accepted October 21, 2011.

Correspondence to: Debra T. Silverman, ScD, Occupational and Environmental Epidemiology Branch, Division of Cancer Epidemiology and Genetics, National Cancer Institute, Rm 8108, 6120 Executive Blvd, Bethesda, MD 20816 (e-mail: silvermd@mail.nih.gov).

Background Most studies of the association between diesel exhaust exposure and lung cancer suggest a modest, but consistent, increased risk. However, to our knowledge, no study to date has had quantitative data on historical diesel exposure coupled with adequate sample size to evaluate the exposure–response relationship between diesel exhaust and lung cancer. Our purpose was to evaluate the relationship between quantitative estimates of exposure to diesel exhaust and lung cancer mortality after adjustment for [illegible] confounders.

Methods We conducted a nested case–control study in a cohort of 12315 workers in e[illegible] which included 198 lung cancer deaths and 562 incidence density–sampled [illegible] subject, we selected up to [illegible] control subjects, individually matched on mining [illegible] birth year (within 5 years), from all workers who were alive before the day the [illegible] diesel exhaust exposure, represented by respirable elemental carbon (REC), by [illegible] based on an extensive retrospective exposure assessment at each mining facili[illegible] ical and continuous regression analyses adjusted for cigarette smoking and ot[illegible] ables (eg, history of employment in high-risk occupations for lung cancer and [illegible] to estimate odds ratios (ORs) and 95% confidence intervals (CIs). Analyses were both unlagged and lagged to exclude recent exposure such as that occurring in the 15 years directly before the date of death (case subjects)/reference date (control subjects). All statistical tests were two-sided.

Results We observed statistically significant increasing trends in lung cancer risk with increasing cumulative REC and average REC intensity. Cumulative REC, lagged 15 years, yielded a statistically significant positive gradient in lung cancer risk overall (P_{trend} = .001); among heavily exposed workers (ie, above the median of the top quartile [REC ≥ 1005 μg/m³-y)), risk was approximately three times greater (OR = 3.20, 95% CI = 1.33 to 7.69) than that among workers in the lowest quartile of exposure. Among never smokers, odd ratios were 1.0, 1.47 (95% CI = 0.29 to 7.50), and 7.30 (95% CI = 1.46 to 36.57) for workers with 15-year lagged cumulative REC tertiles of less than 8, 8 to less than 304, and 304 μg/m³-y or more, respectively. We also observed an interaction between smoking and 15-year lagged cumulative REC ($P_{interaction}$ = [illegible]) such that the effect of diesel exhaust was attenuated in the presence of high levels of the [illegible]

Conclusion Our findings provide further evidence that d[illegible] exh[illegible] represent a potential public health burden.

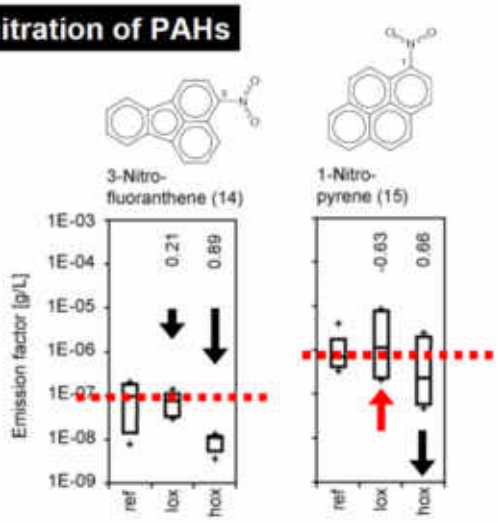
J Natl Cancer Inst 2012;104:1–14

12315 workers cohort, 198 lung cancer death (16 in 1000)

diesel exhaust exposure: a potential public health burden

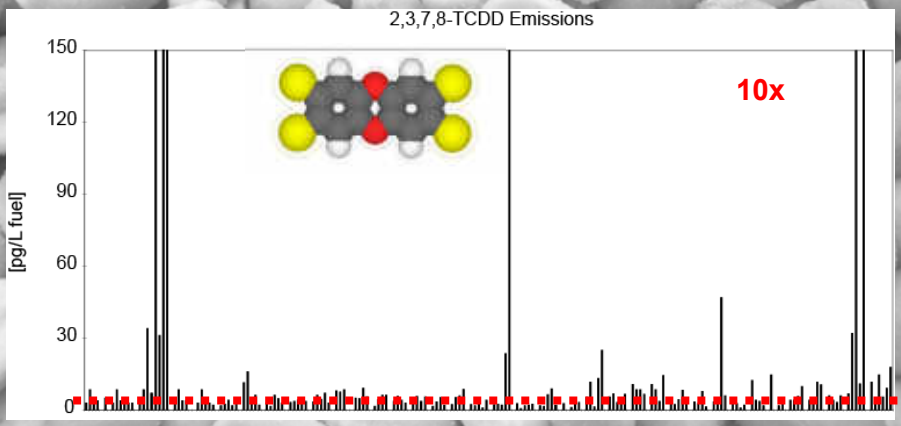
What about mutagenic Nitro-PAHs?

DPF-induced nitration of PAHs



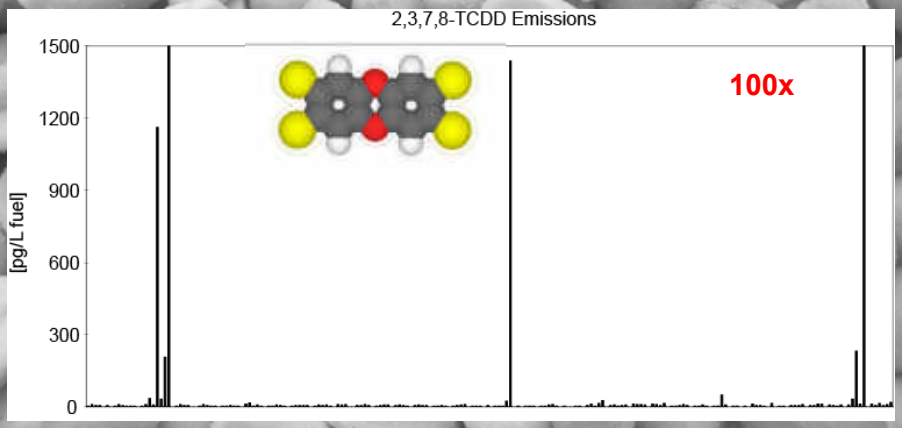
Assessment of the PCDD/F-formation potential

The dioxin formation potential of the respective DPFs?



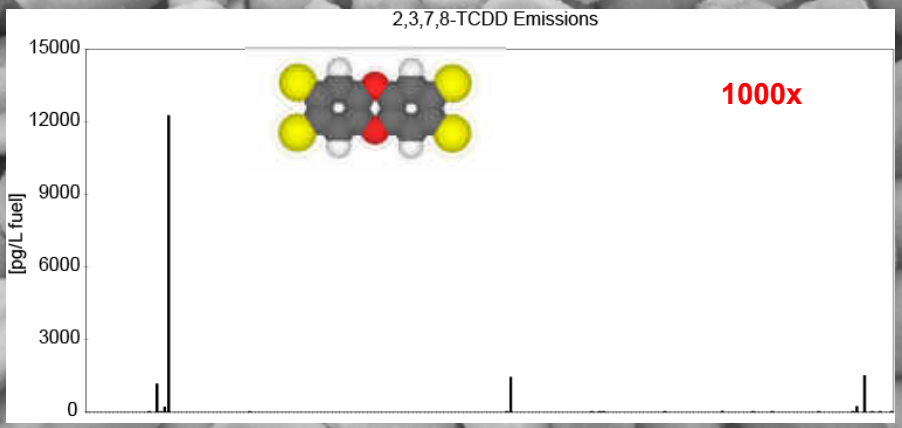
Assessment of the PCDD/F-formation potential

So far only 3 of the 37 tested DPFs induced a PCDD/F formation?



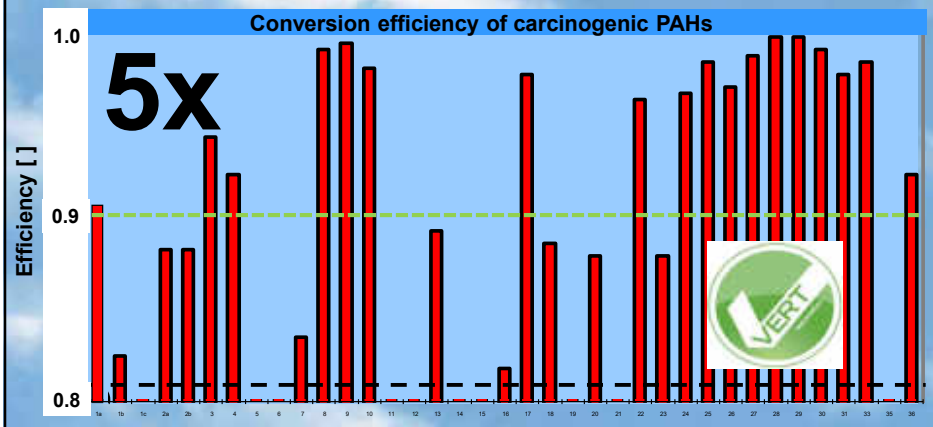
Assessment of the PCDD/F-formation potential

These 3 DPFs exceed the MWI emission limit of 100 pg/m3 exhaust



PAH Conversion

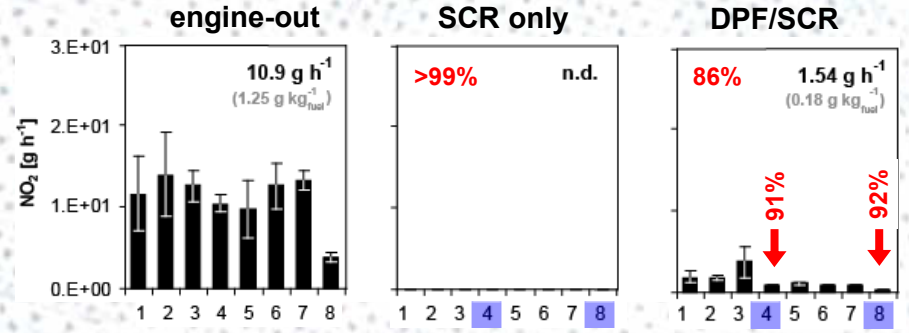
Is 90% conversion BAT today?



DeNO$_x$ Efficiencies

High deNO$_2$ efficiencies can be achieved!

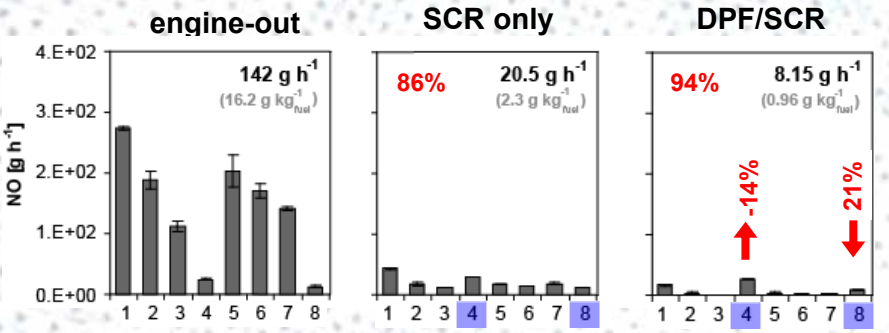
Nitrogen dioxide (NO$_2$)



DeNO$_x$ Efficiencies

High NO conversion efficiencies can be achieved!

Nitric oxide (NO)



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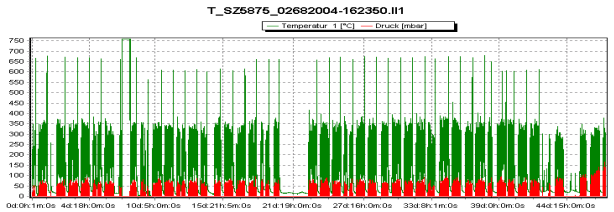
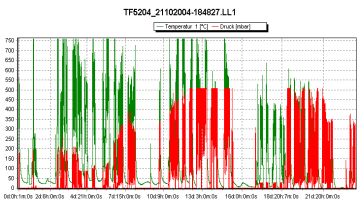
Filter Regeneration

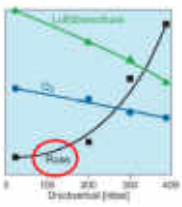
- During filter operation, the filter fills with filtered soot which must be removed
- Soot is carbon, i.e. can be burnt in the filter
- This so called „regeneration“ of the filter is very important for a good functioning
- Filter regeneration is carefully tested in the VERT filter test
- Emission during Regeneration is measured online and limited

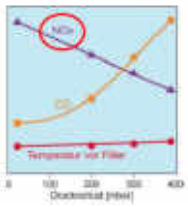
Electronic Control of each VERT-Filter



IS







Conflicts of Targets

Filtration	Pressure Loss
Small Pores	Large Pores
Labyrinth Character	Streight Channals
Cake Formation	Loose Deposition
High Filter Depth	Thin Walls
Low Regeneration Frequency	High Regeneration Frequency
Gas Velocity high > 500 nm low < 300 nm	Gas Velocity low
Gas should be hot	Gas should be cold

Fuel Consumption be = f (Backpressure Δp)

		Bus	Truck	Construction Machine	Passenger Car
Δp		100	100	100	100
pe + pi	bar	6	8	10	3
Δbe/be	%	1.6	1.2	1.0	3.3

acc. to VERT-Rules
- backpressure of the new filter shall be < 50 mbar
- max backpressure must be < 200 mbar
- average backpressre will be in the range of 100 mbar

VERT–Reports for DPF Systems

are confidential

VERT Filter Test, Phase 3 with the
Diesel Particle Filter
ARK STARFILTER
on the Liebherr D 934 S Engine

according to the VERT measuring procedure (VFT 3)

Ordered by:
ARK Holding AG, Artherstrasse 34, CH-6300 Zug

Project leading:
TTM, Technik Thermische Maschinen, Niederrohrdorf / Schweiz

Report:
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Gwerdtstrasse 5, CH-2560 Nidau / Switzerland

M. Kasper, Dr. sc. nat. ETH
Th. Mosimann, Dipl. Ing. HTL
A. Hess , MSc. ETH
Matter Engineering AG, 5610 Wohlen

May 2010

*) Abbreviations see at the end of report

VERT-Label

- Public Awareness of BAT-Filter Quality
- Used with each retrofit internationally
- Carries the individual running VERT-Number
- Issued to VERT-certified manufactureres only
- Languages: D, E, I, F,SN

VERT Association stands for BAT-Filtration

see www.VERT-certification.eu

and provides Best Practice Guidance

- Filterlist
- Filter-Video
- Retrofit-Label
- Filterselection-CD
- VERT-Events
- VERT-Forum
- VERT-Database
- Acceptance Test
- 300 Publications
- 3 Books






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Maintaining Mining Diesel Engine Exhaust After-treatment Systems – New Technologies for Better Performance and Increased Equipment Uptime

2019 MDEC Conference

Prepared By:

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Prepared By:

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DPF Alternatives
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Presentation Overview

1. Mammoth overview
2. DPF Alternatives overview
3. Why do DPF's require cleaning?
4. Benefits of a clean DPF
5. History of DPF cleaning/restoration
6. DPF cleaning options available today
7. What is ultrasonic technology
8. DPF Cleaning Myth busting
9. Findings – R&D
10. Benefits & limitations of the options available
11. Common Questions
12. Availability of services

Company Overview

A family owned & operated company established in 1974

Specialists in developing & manufacturing standard and customized replacement exhaust components for all brands of marine, transport, earth moving and mining equipment.

Constantly develop products for exhaust and emission solution

Global reputation for industry proven products.

Innovative solution provider to the industry

divisions of MEIGroup P/L

Mammoth

PyroGard

Zero

Emitech




DPF Alternatives was created as the development and international business expansion arm of its predecessor; Diesel Doc.

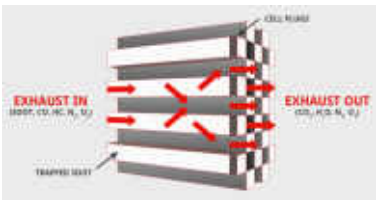
Diesel Doc was founded as a research and service company with the sole purpose of developing the most effective DPF and related component “restorations”.

Upon the perfection of our proprietary process and equipment design we branded ourselves DPF Alternatives to communicate that as a brand **we offer people and companies an “Alternative” to deleting their DPFs (breaking the law in many cases) or costly unnecessary DPF replacements (provided the DPF is capable of performing its function).**

Why do DPF's require cleaning?

There is 2 main causes for a DPF to require cleaning:

1. Though the process of continual thermal cycling in the DPF (Regeneration), with each soot burn off there is a residue of inert ash. When this gets mixed with humidity and heat from the exhaust this ash gets baked and impacted into the filter. Over a period of time, by performing the simple 'pin test', it will be found that the filter is filling and back pressure is increasing
2. There has not been sufficient regeneration and the filter has become plugged with soot



Benefits of a clean DPF / DPF Maintenance

- Improved vehicle performance
- Increased fuel economy
- Less downtime
- Extended DPF life
- Experience fewer regenerations
- Lower maintenance costs
- Control over scheduled downtime

History of DPF cleaning/restoration

Timeline of events:

- DPF technology began as early as the 1970's but didn't really begin to take off until the mid-2000's.
- For many years the only means to service/clean these filters was to bake at high temperature to effectively force a regen and then blow out using a pneumatic air knife - filters left 66% clean
- 3-5 years ago concerns were appearing that filters weren't getting a full clean with the bake and blow method and some experimentation done in some regions with flush station to try and wash the filters. Filters left 85% clean
- Recognizing that there was still something missing with getting DPF's clean. DPF Alternatives set about experimenting with ultrasonic technology beginning in 2015. Perfecting this in 2017 there is now multiple locations set up across the USA servicing many large fleets – Full filter restoration process leaving filters 98% clean

DPF cleaning options available today

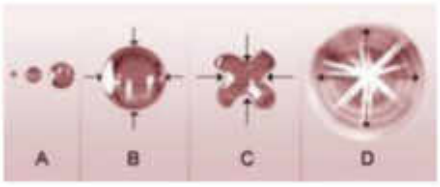
1. On the Vehicle Regen
2. Pneumatic Air Knife and Kiln Baking (Shake-N-Bake)
3. Water Flush With and Without Pressure
4. DPF Alternatives Stage Three "Cleaning"
    1. Test
    2. Pneumatic Air Knife
    3. Water and Air Purge Flush
    4. Kiln dry
5. DPF Alternatives Stage Three "Restoration"
    1. Test
    2. Pneumatic Air Knife
    3. Ultrasonic Treatment
    4. Water and Air Purge Flush
    5. Kiln Dry or Quick Dry (1 Hour Turnaround Time)

What is ultrasonic technology?

Ultrasounds are sound waves with frequencies above the human auditory range (20 – 100 kHz). The ultrasound applications are based on the physical phenomenon of cavitation

which may be induced in any liquid medium

The sound waves cause the microscopic bubbles present in the natural liquids to expand (during phases A and B of low pressure) and contract until they implode (during phases C and D of high pressure). The formation and implosion of bubbles (cavitation process) is produced thousands of times per second



Traditional cleaning equipment

DPF restoration equipment incorporating Ultrasonic

- Flow station
- Ultrasonic tank
- Flow station
- Kiln

DPF Cleaning Myth busting

Here Are Some Common Myths We Have Found In The Industry

1. Regen = Clean
2. Baking fails a filter
3. If a filter gets wet it is ruined
4. Green (Tag) = Clean
5. You should be able to see through a DPF if it is clean
6. Deleted filters = Better running engines…
7. All “cleaning” is the same
8. Bigger filters = Longer life (but also more impacted ash; fact)
9. When Check Engine light comes on you must replace the DPF because it has reached the end of its useful life – False
10. A remanufactured filter is same as a new filter – only a traditional clean. Not really a true restoration
11. Reman cleaning process = like new filter
12. We cannot service Ford, Dodge, Chevy, Mercedes, BMW, Volkswagen (all unitized systems)

Our Findings – Results of R&D

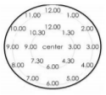
1. With proper maintenance a DPF can last indefinitely
2. Maintenance cycles cannot be determined solely on miles driven due to excessive idle times
3. As a DPF begins to collect contaminants it's performance impact on the engine increases – so the longer you postpone proper maintenance the greater the inefficiencies of the engine become
4. To improperly clean a DPF during a scheduled maintenance cycle reduces the DPFs ability to perform properly until its next scheduled down time, and in many cases prevents the equipment from operating as long as necessary
5. A DPF that is not properly "restored" has between 2 and four "cleaning" cycles before it is fully impacted with ash and only recoverable by using Ultrasonics
6. Soot-to-ash conversions = a fine powder within the DPF, moisture from the exhaust turns the ash to a paste that locks itself into the DPF. The operating temperature of the engine bakes the moisture our leaving an immovable dense plaque/concrete substance forever in the DPF

Benefits & limitations of the options available

1. On the Vehicle Regen – No Benefit to Risk of Ruining the DPF
2. Pneumatic Air Knife and Kiln Baking (Shake-N-Bake) – This just buys the filter more time with very little time required to perform the service, but much short filter life and performance – leaves filter around 66-70% clean
3. Water Flush With and Without Pressure – Get more out of the filter than air, but must be dried to re-test the filter. And water alone will not break up the plaque/concrete.
4. Stage 3 or 'Silver' level cleaning – Leaves filter 85% clean
    1. Test
    2. Kiln
    3. Pneumatic Air Knife
    4. Water and Air Purge Flush
5. DPF Alternatives Stage Four/Gold service "Restoration" – Restores filter to 98% clean
    1. Test
    2. Pneumatic Air Knife
    3. Ultrasonic Treatment
    4. Water and Air Purge Flush
    5. Kiln Dry or Quick Dry (1 Hour Turnaround Time)

Common Questions

1. Do I need to clean my DOC's?
   - Yes – Periodic cleaning of DOC's required otherwise these can become soot loaded and their effectiveness compromised – especially if the DOC has been exposed to high-sulfur and poisoned.
2. Will cleaning my DOC with ultrasonic have an effect on the stability of the wash coat on my DOC?
   - No – study by Tech Sonic International showed no loss in weight of filter/DOC as a result of cleaning
3. How do I tell how clean my DPF is after cleaning?
   - Combination of flow test and pin test. With the Pin test, a thin wire is inserted into the clean side of the filter and a measurement taken. The Pin is then inserted into the 'dirty' side of the filter and a 2nd measurement taken. If the filter has been properly cleaned/restored then the 2 measurements should be equal. Cleaning provider should provide written report showing status of filter/cleanness.



Availability of Services

The truth is: most service shops can use compressed air to perform blow-out of a DPF to get slightly more life out of the filter as long as the DPF was not damaged due to over Regeneration

The use of a Kiln does help reduce the density of the soot, however it does not address impacted ash. There are many options including some dealerships that offer this service.

Some companies are just now experimenting with water, so more of these options will be seen in the next 12 months.

DPF Alternatives currently offers Ultrasonic restorations, and any other level of cleaning requested –

30+ locations across the USA – 1 location in Canada (Winnipeg) with locations in Sudbury, Edmonton, Toronto opening soon….


Mammoth
Equipment and Exhausts
DPF
ALTERNATIVES
Thank you for your time

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Cat® Tier 4F / Stage v

Technology and Deployment

Matt Roth

October 2019

Cat Engine Product Line

5.7 - 4920 kW (7.6 - 6600 bhp)

Highly Regulated and Lesser Regulated offering the **most comprehensive range** in the industry

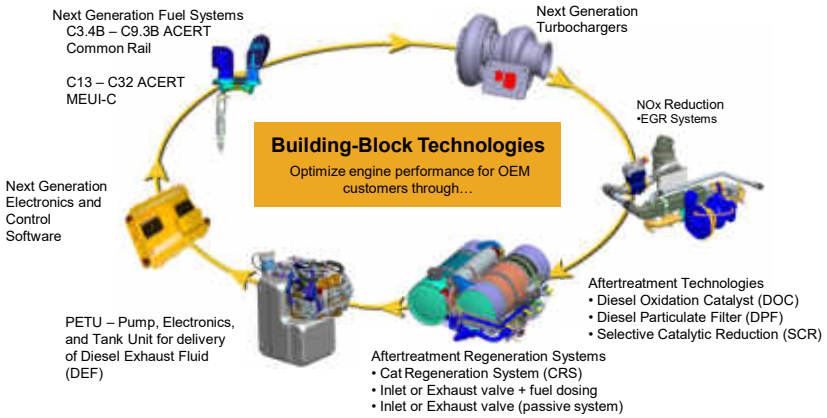
T4F / Stage V engines –

Tier 3 equivalents

NOx and PM Reduction Technology Added

US EPA Tier 4 Final
EU Stage V

T4F / Stage V Technology Suite

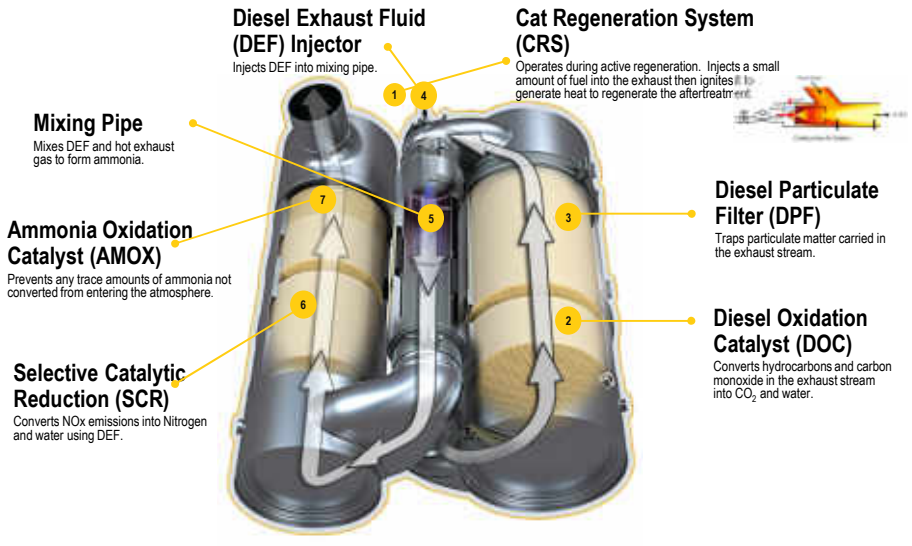


EPA T4F / EU Stage V Technology Overview – 9.3 to 18L

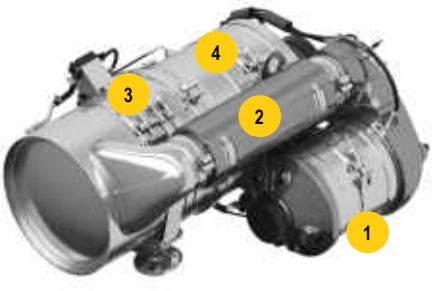
Product	PM After Treatment	Turbocharger	EGR	Fuel System	Regen System	SCR
						
C9.3	DOC + DPF	Single	Yes	Common Rail (CR)	Cat Regeneration System (CRS)	Yes
C9.3B	DOC + DPF	Single	No	Common Rail (CR)	Intake Throttle, In-cylinder Dosing	Yes (high efficiency)
C13B	DOC + DPF	Single	No	Mechanical Electronic Unit Injector (MEUI)	Intake Throttle, 7th inj Dosing	Yes (high efficiency)
C13 C15 C18 < 560 kW	DOC + DPF	Single	Yes	Mechanical Electronic Unit Injector (MEUI)	Cat Regeneration System (CRS)	Yes
C18 > 560 kW	DOC	Twin Turbo	Yes	Mechanical Electronic Unit Injector (MEUI)	-	-

KEY
DOC=Diesel Oxidation Catalyst
DPF= Diesel Particulate Filter
EGR= Exhaust Gas Recirculation
SCR= Selective Catalytic Reduction

Clean Emissions Module (CEM) – C9.3 / C13 / C15 / C18



Clean Emissions Module (CEM) – C9.3B / C13B



1. DOC reduces Carbon Monoxide (CO) and Hydrocarbon (HC)
2. Diesel exhaust fluid (DEF) injector / mixing pipe
3. DPF for soot capture
4. SCR NOx reduction + Ammonia oxidation (AMOX) for Ammonia reduction
   – High Efficiency SCR formulation

* CRS system replaced with Engine Intake Throttle + Fuel Dosing regeneration system

Innovative technology delivers a compact, lightweight package and efficient performance

C9.3B and C13B Regeneration Technology and Functionality

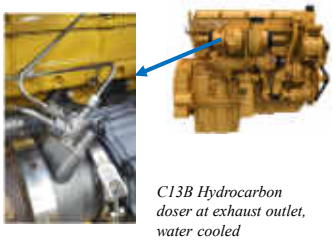
Regeneration Air Management

- Intake throttle valve (ITV) used for all regeneration management
- Delivers transparent regeneration, without operator distraction or impact to machine performance

Regeneration Fuel Management

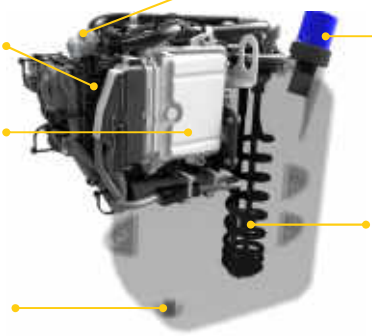
•C9.3B: Common rail fuel system / in-cylinder dosing (ICD) used for high temperature regeneration

•C13B: Hydrocarbon dosing at turbine exit used for high temperature regeneration



C13B Hydrocarbon doser at exhaust outlet, water cooled

DEF Pump and Tank Unit



Heated Lines
Warms up when necessary to thaw any DEF left in lines and to prevent freezing.

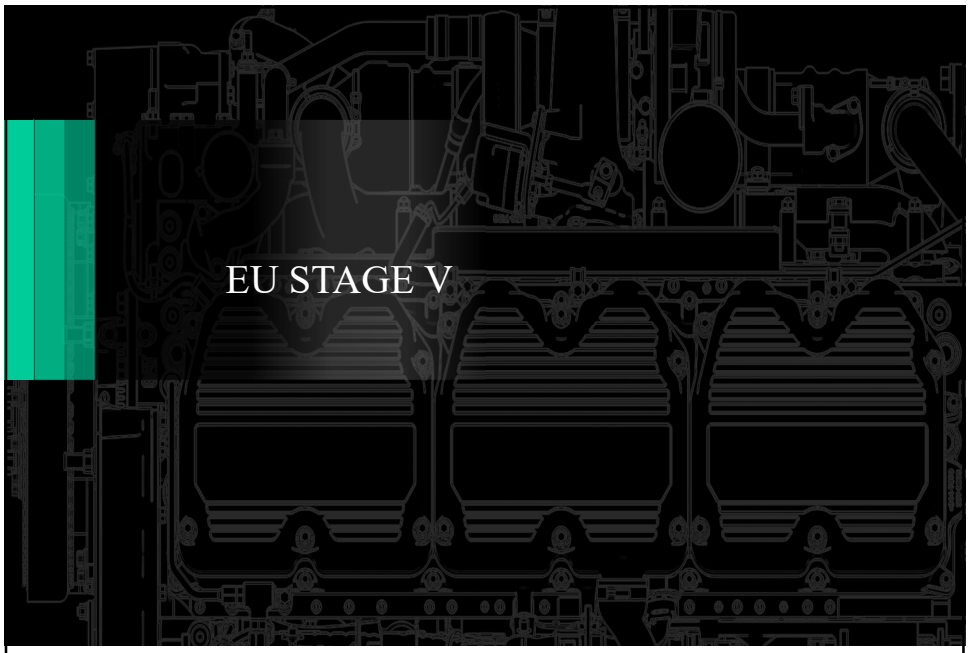
Pump Assembly
Supplies DEF to the injector and purges line at shutdown.

Controller
Ensures the correct amount of DEF is supplied to the injector.

Fill Adapter & Cap
Blue cap is the industry standard for easy identification.

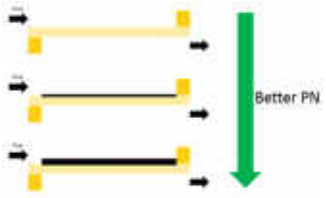
Tank Heater
Thaws DEF when needed so there's no lost time on cold jobsites.

Drain Plug



Particle Number (PN)

- EU Stage V implemented Particle Number (PN) regulations for first time in non-road applications (Jan 2019)
  - Particle Number (PN): $1x10^{12}$ #/kW-hr
  - Particle Mass (PM): 0.015 g/kW-hr
- Sources for PM and PN include both tailpipe exhaust and crankcase fumes
- PM regulation achievable w/o DPF, but PN regulation drives wall-flow DPF technology
- PN filtration efficiency of DPF impacted by:
  - substrate physical characteristics
  - soot loading
- PN managed through DPF selection, engine calibration, and crankcase filtering



EU Stage V Updates

- Certified all existing EU Stage IV / U.S. EPA Tier 4 Final ratings to EU Stage V
- Hard Rock vehicle product line offers Stage V certified option (by-passed Tier 4 Final)
- Updates for EU Stage V (vs Tier 4 Final)
  - Upgraded DPF technology on Clean Emissions Module (CEM) for C9.3, C13 and C15 (up to 354kW). New DPF is reverse compatible and used for Tier 4 Final and equivalent emission standards.
  - Open Crankcase Ventilation (OCV) Filter is required for C9.3, C13 to meet EU Stage V emissions requirements
    - optional for U.S. EPA Tier 4 Final and equivalent emission standards
  - Emissions system failure indicator (ESFI) lamp included on C18 > 560kW
- No impact to:
  - Customer connection points
  - Lug curves
  - Engine performance
  - Heat loads
  - Wiring (*exception for C18 > 560kW, see above)
  - Service intervals

Engine Development for Underground – Stage V and Lesser Regulated

Development consideration taken into account for underground

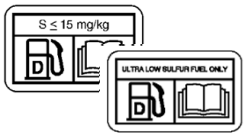
- Peak cylinder pressure
- Emission compliance at negative and positive altitudes
- Vent rate effects
  - Limiting factors
  - Target vent rate
- Component robustness
  - Electrical system
- Targeted Emission reduction
  - DPM , Gaseous (NO/NO2)
- Fluid consumption
  - Fuel and DEF (if required)

R2900G Stage V engine testing

Proper Fluid Use is Critical

Low Ash Oil

- Ash is a permanent deposit and cannot be removed by normal A/T regeneration process.
- Low Ash oil = no issues.
- High Ash build up will shorten product life.



Ultra Low Sulphur Diesel (ULSD)

- ULSD = No aftertreatment issues.
- High Sulphur content in fuel will de-activate A/T
- A/T can be recovered by regeneration provided it identified early enough and ULSD fuel is used.

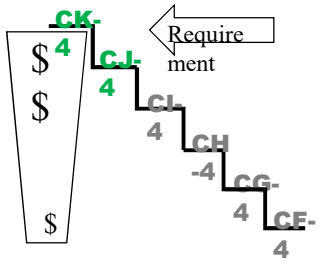
Diesel Emissions Fluid (DEF)

- De-Ionized Water (67.5 %) + Urea (32.5%) mix
- Improper storage temperature and/or exposure to sunlight decreases shelf life.

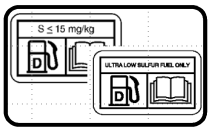
Lube Oil Specification

Incorrect oil may lead to:

- Significantly Reduced DPF Filter Service
- Core Engine Component Durability



Fuel Specification



Former Fuel >5000ppm

Low Sulphur Fuel 50ppm

Requirement → ULSD 15ppm ✓

Incorrect fuel may lead to:

- Rapid Failure & Machine Downtime
- High Aftertreatment Replacement Cost
- Risk of Unintentional Sulphur Contamination

DEF Quality & Handling

- New Concept for Machine Operators
- Significant Storage & Handling Education
- Poor DEF Storage & Contamination Damages
- Significant Change Management Exercise

DEF Storage

Follow recommended storage requirements.

Any commercial **DEF** meeting **ISO 22241** specifications can be used.

Optimal temperature for storage is -9°C to 25°C.

Improper storage temperature and/or exposure to sunlight decreases shelf life.

- Rate of decay significantly accelerates when stored in temperatures above 32ºC
- Freezes at -11ºC

DEF Contamination Control

Dirty jobsite conditions a reality; must clean around cap at refill.

These "before" pictures highlight just how dirty the area surrounding the blue DEF cap can become during normal operation.

That's why it is important that you clean around the cap with every refill to avoid aftertreatment system component failures that result from contamination.

DEF Contamination Control

Avoid internal contamination; use proper tooling and fittings.

DEF is corrosive to most materials. That's why it's important to use proper dispensing equipment and procedures to avoid contamination.

If even one of the fittings is incorrect, it could contaminate the entire DEF supply, leading to emission system faults and engine shutdown.

DEF Contamination Control

Avoid internal contamination; use proper materials.

Only approved materials such as High Density Polyethylene (HDPE) may be used in DEF storage and dispensing. The use of non-approved material for DEF storage and dispensing equipment can result in corrosion that will system failure in machine.

The following is a list of approved and un-approved materials:

Approved DEF Materials	**Materials to Avoid**
Stainless Steel (304, 304L, and 316)	Carbon Steels, Zinc coated Carbon Steels, mild iron
High Density Polyethylene	Non-ferrous Metals, copper, brass, zinc, lead
Titanium	Solder containing lead, silver, zinc, or copper
Polypropylene	Aluminum and aluminum alloys
Poly-isobutylene	Magnesium and magnesium alloys.
Epoxy Resins	
Polytetrafluoroethylene (PTFE) free of additives	

Maximize Uptime with Proper Fluids

Incorrect Fluids
- High Sulphur diesel
- High ash Oil
- Poor quality DEF
- DEF mis-fill
- Airborne harmful gas

$$$ Replacement Cost

A/T Failure :
- SCR/DOC de-activated
- DEF System plugged
- Low NOx Conversion
- White smoke during Regen
- Inducement & 100% de-rate
- Machine down

Operator Interface

Enhancements help protect the aftertreatment and engine components.

- **DEF Level Gauge** indicates the level of DEF in the tank
- **Automatic systems to protect your investment**
  - **DEF Purge:** Purges DEF from the lines to prevent freezing
  - **Delayed Engine Shutdown:** Engine idles briefly after key off if cool down needed
  - **Wait to Disconnect Lamp:** Illuminates until the product is safe and ready for complete shutdown
  - **Regeneration:** Warms up aftertreatment if needed

Transparent emissions systems your operators won't need to manage.

How Caterpillar Can Help with Customer Education

Stickers

Brochures

E-Learning

Videos

CAT®

Experiences with Enabling Technologies

Evelynn Stirling

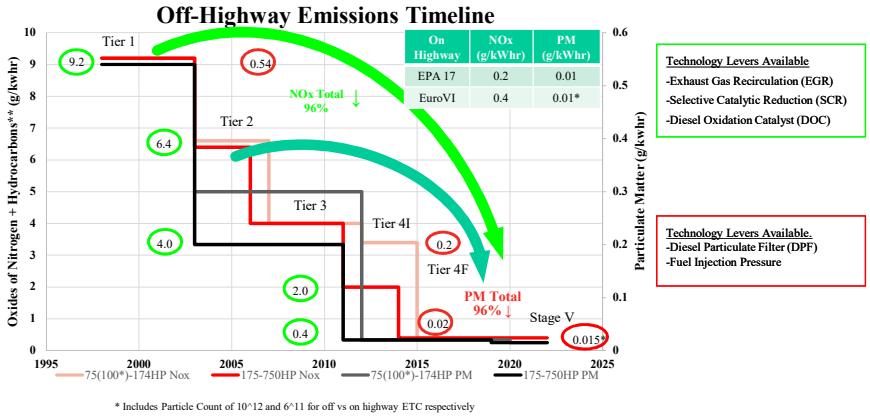
October 2019

Enabling technology

Definition
An **enabling technology** is an invention or innovation, that can be applied to drive radical change in the capabilities of a user or culture. Enabling technologies are characterized by rapid development of subsequent derivative technologies, often in diverse fields. Equipment and/or methodology that, alone or in combination with associated technologies, provides the means to increase performance and capabilities of the user, product or process.

https://educalingo.com/en/dic-en/enabling-technology

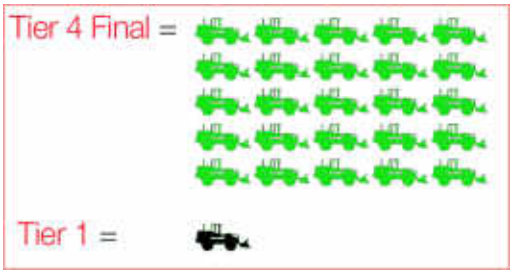
Significant Reduction in Emissions Over Time



* Includes Particle Count of 10^12 and 6^11 for off vs on highway ETC respectively

Meeting 'Near-Zero' Emissions

Emissions from 25 Tier 4 Final machines equivalent to just one Tier 1 machine!



Technology Introduction - Recent Tiers

Tier 4i (Stage 3B) Emissions

Stage V Emissions (2019/20 CMI Products)

2006 — 2011 — TPEM Effect — 2014 — 2019 — 2027+

Tier 3 (Stage 3A) Emissions

Tier 4F (Stage IV) Emissions

TBD Emissions Standards
-NA Tier5 potential remains gray.
-Likely to see an increase in the availability of new technologies such as hybrid, start/stop, electrification, etc.

Evolution of CMI Off-Hwy Aftertreatment

2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2019 2020 2021 2022

T4 Interim / Stage IIIb
DOC-DPF for MD and HD
- On-Hwy derived DPF system ruggedized for demands of off-hwy
- DEF not required
- 5k hours DPF filter cleaning interval

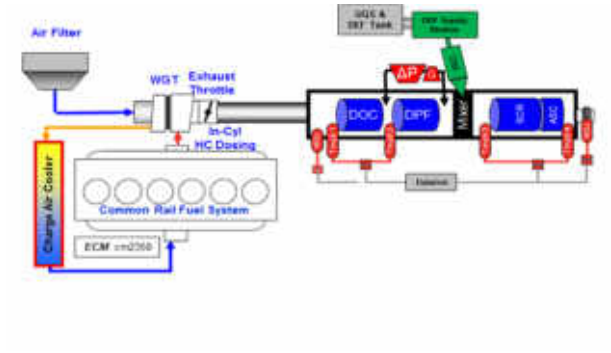
T4 Final / Stage IV
DOC-SCR for MD
- SCR technology leveraging millions of miles of global on-hwy experience
- Bosch DEF dosing system
- Optimized combustion eliminates need for DPF to control PM

T4 Final / Stage IV / Stage V
DOC-DPF-SCR for HD
- Parented from industry leading EPA 2013 on-hwy product to maximize DPF ash capacity
- Utilizing Bosch(15L) and UL2 (12L) DEF dosing systems

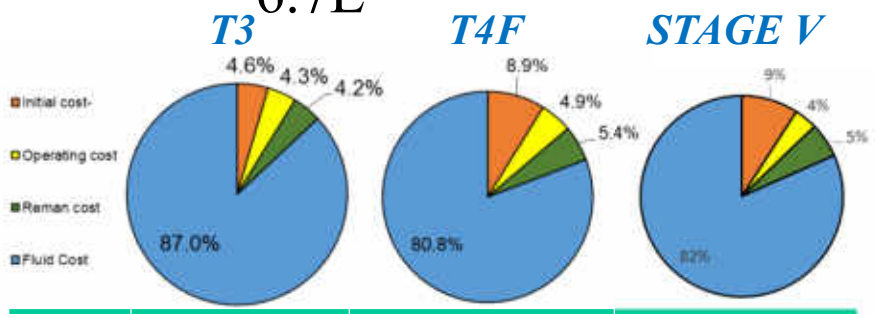
Tier 4 Final / Stage V
Single Module for MD
- Revolutionary design combines DOC-DPF-SCR into single unit for optimized total installed cost
  - Eliminate 2-4 exhaust joints per installation
  - Reduced installation labor, freight, and bracketry required
- UL2 DEF dosing system
- Optimized catalyst allow >5K ash cleaning intervals*

* Cleaning interval is duty cycle dependent, not based on fixed time period – clean only as required.

Simplified Stage V System Architecture



Operating TCO Comparison: 6.7L



Total Cost	*1*	*0.93*	*0.91*
Maint Cost	*1*	*1.08*	*.78*

**TCO savings realized with newer products is highly duty cycle dependent.*
**Regional diesel & DEF pricing have direct affects on the above.*

Stage V Operational Considerations

Tier 3 Baseline	F3.8-L9 Representative
Fuel Efficiency	+8-10% +8-12%
Aftertreatment Maintenance	None Minimal
Diesel Exhaust Fluid	3-5% of Fuel 8-10% of Fuel
Operator Notifications	Minimal Optional
Power Density	+7% +15%
Peak Torque Capability	+6% +38%

Tier 4 Final (vs Tier 3)
Stage V (vs Tier 3)

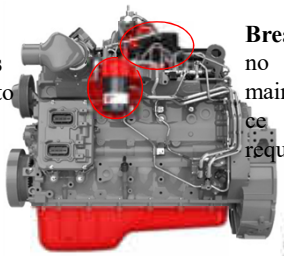
Major Maintenance Interval Comparison

Maintenance	QSB6.7 T3	QSB6.7 T4F	2019 B6.7
Oil & Filter Change	500 hours	500 hours	1000 hour options
Fuel Filter Change	500 hours	500 hours	1000 hours
Crankcase Filter Change	Service Free	2000 hours	Service Free
Overhead Adjust	5000 hours	5000 hours	5000 hours
Drive Belt Check	250 hours	1000 hours	2000 hours
DEF Dosing Pump Filter	N/A	4500 hours	4500 hours
DPF Ash Cleaning	N/A	N/A	Variable (5K+)*

*Duty cycle dependent, minimum planned to be 5,000 hours but many customers could see significantly longer.

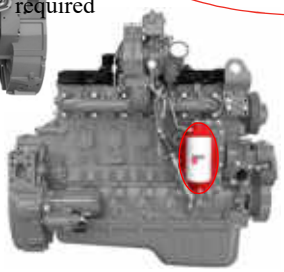
Lower ownership cost via reduced maintenance

Fuel Filters (both): Up to 1,000 hours change interval



Breather: no maintenance required

1,000 hours maintenance intervals achievable *



Oil Filter: Up to 1,000 hours change interval

Oil: Up to 1,000 hours drain interval

*Application Dependent

Stage V & DPF Regeneration Capability

Historical Experience

- In production with DPF equipped engines since 2007.
- Automotive learnings continuously leveraged in off-highway.
- Off-Highway DPF experience since 2011.
- Millions of validation hours/miles with aftertreatment systems.

Stage V The Right Architecture

- Non-EGR engines run naturally higher exhaust temps that assist with keeping the aftertreatment passively clean.
- Combination of VGT+IntakeThrottle enhances thermal management capability.
- Single canister aftertreatment mitigates temperature losses thereby keeping more heat in the system.

Extensive Validation

- Over 110k Stage V specific field test hours achieved to date.
- Team of engineers have consistently monitoring field test data to make calibration and tuning optimization to support regen capability.

Result: Confidence & Optional Regen Interface

Maintaining Aftertreatment

- **Diesel Particulate Filter Cleaning**
  - Newer Products (Stage V) No Longer Require a DPF Maintenance Interval
  - Product is Designed to go >5k Hours Without Needing Cleaned, diagnostic based
  - Cummins ReCon Exchange Program Allows Over the Counter Exchange at a Cummins Distributor
  - Clean DPFs Could be Stocked for Quick Change-Out if a Plug Occurs

- **Diesel Exhaust Fluid (DEF)**
  - 32.5% urea and 67.5% de-ionized water
  - Clear, non-toxic, safe to handle
  - Has a 2 Year Shelf Life
  - Should be Stored Between 13F and 85F
  - DEF freezes at -11C (12 F)
  - Consumption is Usually 2%-6% of Fuel Usage

Start-Stop delivers value through superior idle management

Start/Stop Technology

- **Fuel Savings**: improved operating cost by reducing fuel burned and urea consumed
- **Less Maintenance**: fewer engine run hours means reduced preventative maintenance and downtime
- **Machine Resale**: fewer run hours results in higher machine residual value

- Integration flexibility:
  - OEM choice of Cummins-supplied or 3rd-party system

Cummins Field Test:
16-25% total fuel saved!
Fuel savings will vary based on application and duty cycle

Field testing has covered a wide range of applications

F3.8
- Irrigation Pump
- Wheel Loader
- Material Handler
- Forklift
- Water Pump
- Excavator
- Telehandlers

B4.5
- Power Screen
- Road Roller
- Excavator
- Hauler
- Travel Lift
- Water Pump
- Telescopic Forklift
- Wood Chipper
- Forklift

B6.7
- Fellerbuncher
- Water Pump
- Wheel Loader
- Yardspotter
- Air Compressor
- Material Handler
- Log Skidder
- Excavator
- Snowblower
- Tractor

L9
- Fellerbuncher
- Water Pump
- Wheel Loader
- Mine Truck
- Material Handler
- Excavator
- Snowblower
- Snowgroomer

Engine Longevity Article Link (Useful?)

https://www.hyster.com/north-america/en-us/announcements/press-releases/manufacturer-evaluation-proves-long-term-performance-and-durabilty-of-hyster-tier-4-engines/

This article was a joint CMI / Hyster teardown on a T4i L9 with 10K hours, installation was a downsize form a T3 M11 so has a couple angles. The overall message is that when properly maintained the durability is not compromised on T4+ products compared to more simple T3 legacy systems.

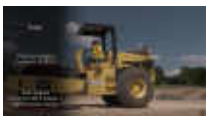
Customer testimonials

Cummins In Action: B4.5 Performance Series Chipper

Cummins In Action: B4.5 Performance Series Forklift

Cummins in Action: B.7 Performance Series Excavator

Cummins In Action: B4.5 Performance Series Screener



Cummins In Action: B4.5 Performance Series Roller

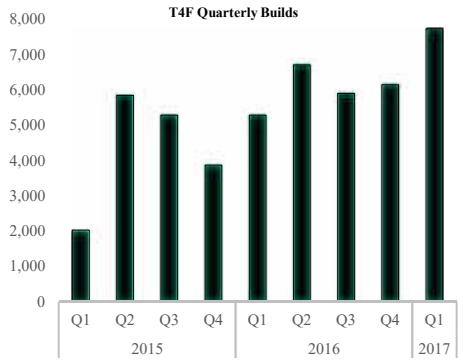
Cummins in Action: B6.7 Performance Series Irrigation Pump

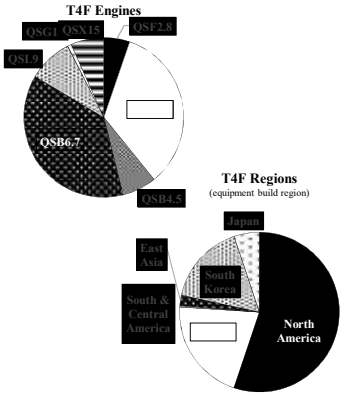
Cummins In Action: B4.5 Performance Series Excavator

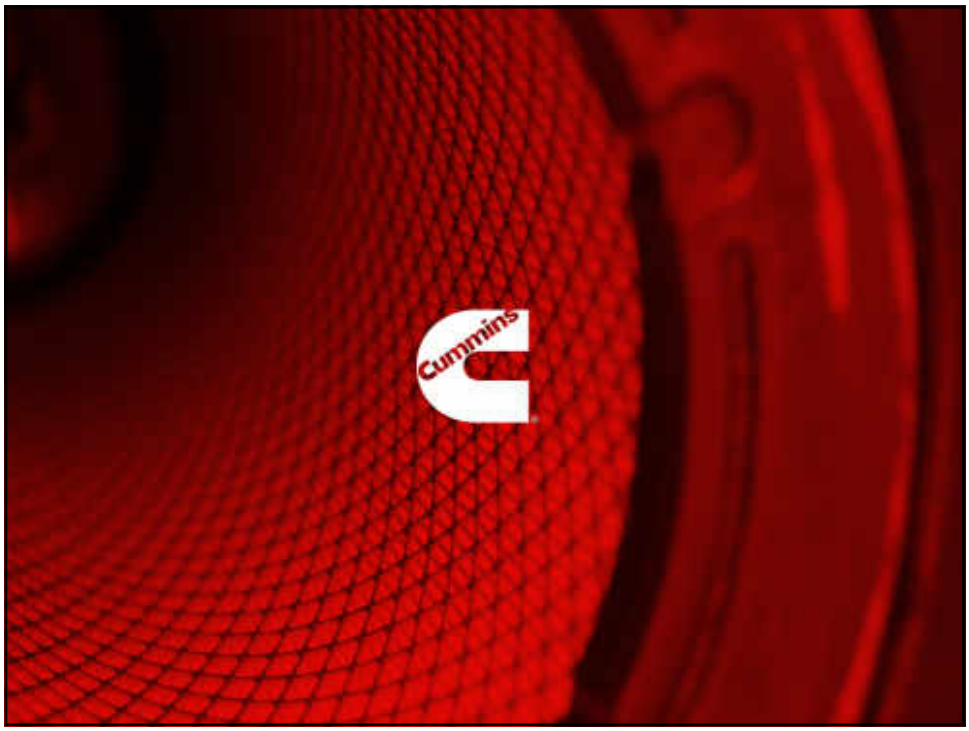
Cummins In Action: F3.8 Performance Series Telehandler

Cummins in Action: B6.7 Performance Series Backhoe Loader

Over **50k** Tier 4 **Final** engines produced







Diesel Particulate Filters (DFFs) in Both New and Retrofit

Bob Deprez
AiorFlow Catalyst Systems
2019 MDEC Workshop
October 10, 2019

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Key Points

- No one type of filter (DPF or other) is always the best answer for all applications
- A filter is not a substitute for proper engine maintenance
- Take advantage of available resources – ask questions
- Don’t turn a DPM problem into a worse problem

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Terminology

DPF	Diesel Particulate Filter
CDPF	Catalyzed Diesel Particulate Filter
DPM	Diesel Particulate Matter (Official Name for Soot)
Regeneration	Filter burning soot faster than it is coming in. Two types:
	Active Something needs to happen to cause the regeneration
	Passive Regeneration occurs on its own
T-30	Temperature exhaust is at or above 30% of the time
MSHA	Mine Safety & Health Administration – Part of U. S. Department of Labor

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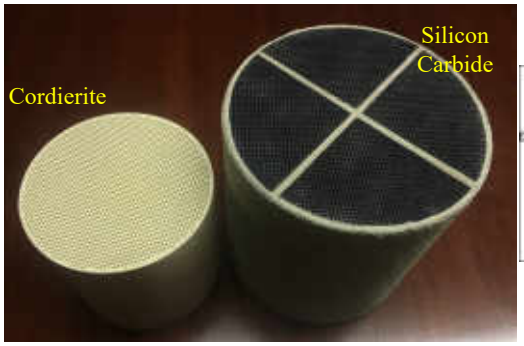
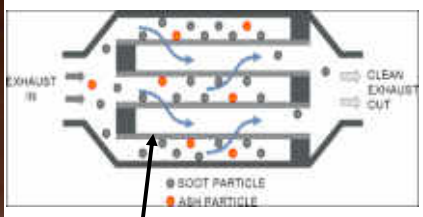
Substrate Materials





Porosity of walls generally
15 – 25 microns

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Other Technologies

Paper Filter

- Removes DPM
- Simple
- Low initial cost
- Limited duration between changes
- Ongoing expense
- No reduction in gaseous pollutants
- Temperature limited
- Need to dispose of spent filters

Water Scrubber

- Removes DPM and some gaseous pollutants
- Cools exhaust
- Adds humidity to air
- Ongoing cleaning & maintenance
- Requires source of water
- Need to dispose of sludge / dirty water

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Why Should You Use a DPF?

Two identical diesel generator, one with a DPF, one without

308

Rules of Thumb

A DPF works much like a burn barrel

A 10 ° C increase in filter temperature will roughly double the rate of DPM combustion in a DPF.

A DPF can hold approximately 10 grams per liter of DPM before it should be regenerated.

Size matters! Goldilocks had the right idea.

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A DPF Works Much Like a Burn Barrel

- Collects & stores combustible waste materials (DPM)
- Burns combustible waste materials
  - Could be slow & steady
  - Could be rapid & episodic
- Accumulates noncombustible material
- Needs to be emptied when full of ash & noncombustible materials

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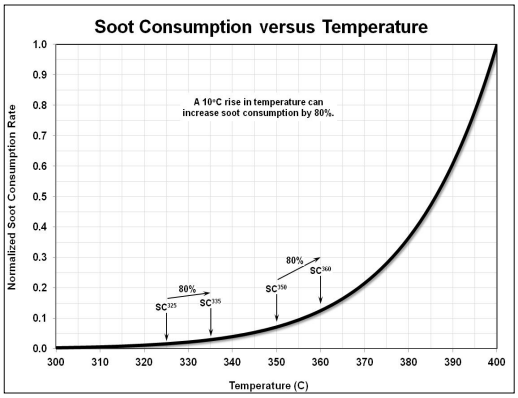
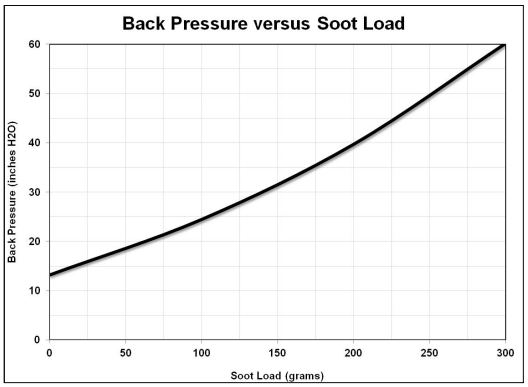
A 10 ° C Increase in Filter Temperature Will Roughly Double the Rate of DPM Combustion in a DPF.



311

A DPF Can Hold Approximately 10 Grams per Liter of DPM Before it Should Be Regenerated



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Size Matters!

Too Small

- High backpressure
- Insufficient soot / ash storage capacity
- Insufficient surface area for combustion
- Insufficient catalysis of gaseous materials (if catalyzed)

Too Large

- Takes up too much space
- Costs too much
- Slower to heat up
- Lower max temperature

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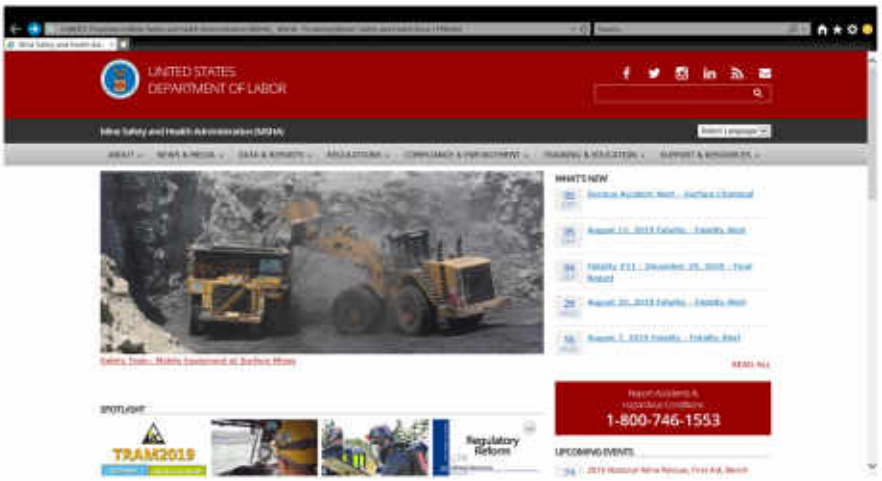
Resource: MSHA Home Page



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Resource: MSHA Approved Engine List

Approval Number	Engine Manufacturer	Model	HP @ RPM at 1000ft Elevation	Ventilation Rate CFM	Particulate Index CFM	DPM grams/hr weighted	DPM grams/hp-hr weighted	Filter Eff. for 5.0 grams/hr	Filter Eff. for 2.5 grams/hr	Date Issued	EPA Compliant per 72.502	Exhaust BP Max Limit, in.H2O
7E-B001	DEUTZ	MWM 916	94 @ 2300	4000	11500	19.54	0.42	74	87	7/10/1997	N	40
7E-B002	DEUTZ	BF6M 1015C	402 @ 2100	18500	17500	29.74	0.14	83	92	7/15/1997	Y	30
7E-B004	CATERPILLAR	3304 PCNA	100 @ 2200	5000	15000	25.49	0.48	80	90	12/19/1997	N	34
7E-B005	GENERAL MOTORS	L57, 6.5L - 1994	160 @ 3400	7500	9500	16.14	0.19	69	85	12/24/1997	Y	75
7E-B006	ISUZU	QD 100-301 *RETIRED*	75 @ 2400	5000	7500	12.74	0.31	61	80	1/15/1998	N	41
7E-B011	DEUTZ	BF4M 1012EC	113 @ 2500	6500	4000	6.8	0.12	26	63	3/13/1998	Y	30
7E-B011	DEUTZ	BF4M 1012C	99 @ 2500	6500	4000	6.8	0.12	26	63	3/13/1998	Y	30
7E-B012	CATERPILLAR	3176 ATAAC	310 @ 2100	13500	7500	11.9	0.07	58	79	4/15/1998	Y	27

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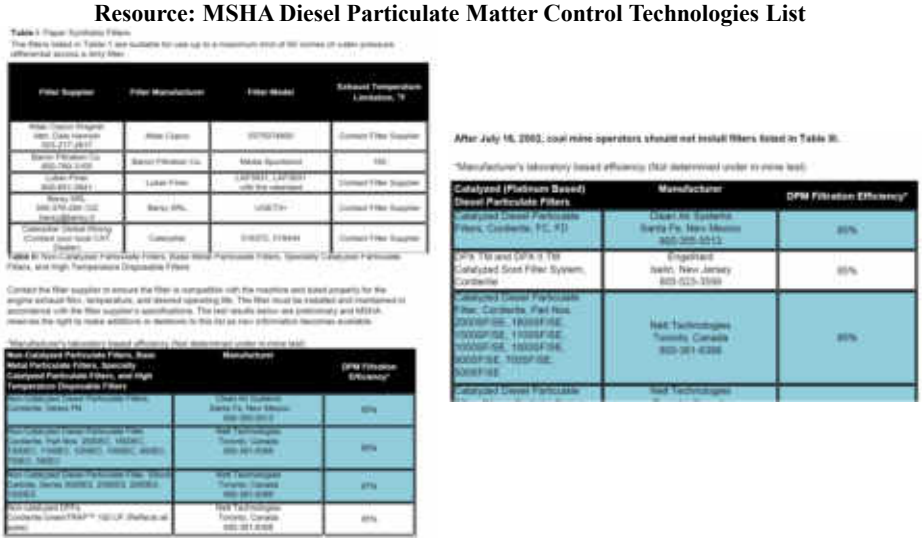
Resource: MSHA Diesel Particulate Matter Control Technologies List



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A Few Words About NO_2

Any engine, with or without a catalyzed device (either a DOC or CDPF) can produce NO_2

Be careful not to create a worse problem when trying to reduce DPM – check performance specifications before choosing equipment.

Tier IV Engines – may have lower NO_x, but higher NO_2

Catalyzed filters can be a problem – see Table III of MSHA Filter Efficiency List

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Exposure Limits Summary From Dieselnet

Exposure Limits for Gases

The exposure limits for selected gaseous pollutants found in diesel exhaust are listed in Table 1. Limits set by OSHA are known as Permissible Exposure Limits (PEL). Both OSHA PELs and MSHA TLVs are legally enforceable limits. Limits shown in the column OSHA 88 were adopted as a final rule in 1988, but were later remanded by court and have no legal significance. The TLVs by ACGIH are industrial hygiene recommendations. All limits are 8 hour time weighted averages (TWA), unless marked as ceiling values.

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Table 1. Exposure Limits for Gaseous Pollutants (ppmv, TWA, 8 hr)

Substance	CAS#	OSHA PEL	OSHA 88*	MSHA TLV	ACGIH TLV
CO	630-08-0	50	35	50	25
CO_2	124-38-9	5000	5000	5000	5000
NO	10102-43-9	25	25	25	25
NO_2	10102-44-0	(C) 5	1[d]	5	3
HCHO	50-00-0	0.75			(C) 0.3 A2
SO_2	7446-09-5	5	2	5[a] / 2[b]	2

* - not legal limits (PELs adopted in 1988 were later remanded by court)
a - for metal/nonmetal mines
b - for coal mines
d - 15-minute short term exposure limit (STEL)
(C) - Ceiling value
A2 - Suspected human carcinogen

Passive VS Active Regeneration

Passive – Regeneration occurs on its own
- Usually catalyzed filter, so may also address CO & gaseous hydrocarbons
- No fuel penalty
- No downtime for regeneration
- Requires sufficient exhaust temperature / duty cycle

Active – Something needs to happen to cause the regeneration
- May use electrical heating, engine management, fuel injection, or be off-line
- May require work stoppage
- Usually also requires DOC to address CO & gaseous hydrocarbons
- Often larger / more expensive / more complicated than passive system
- Less dependent on exhaust temperature / duty cycle / engine DPM rate
- Additional operating cost / fuel penalty

Both types require periodic ash removal & proper engine maintenance

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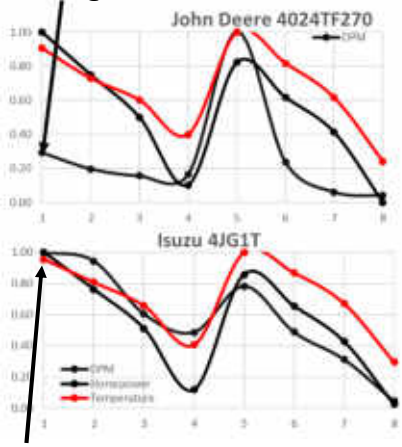
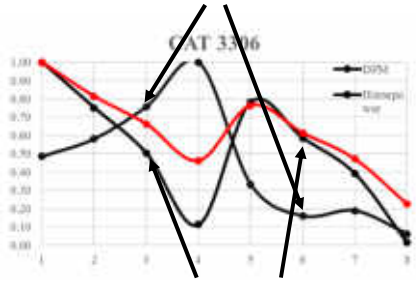
Engine Operating Points Impact DPF Performance

Low DPM @ Full Power



High DPM @ Full Power

Very Different DPM Rates



Similar HP

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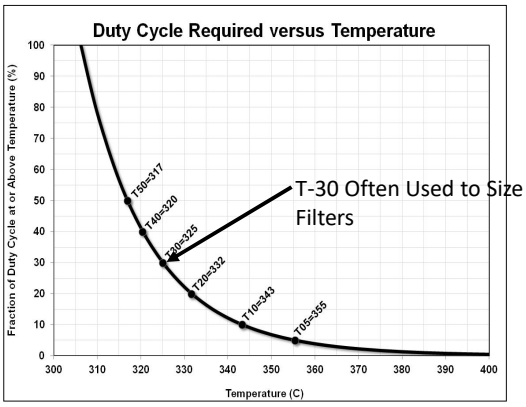
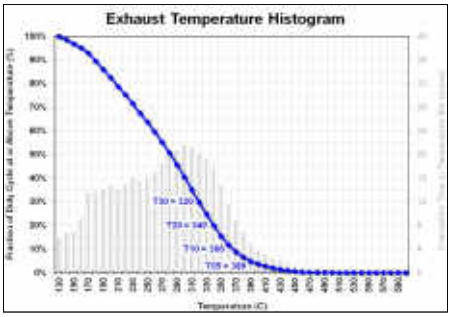
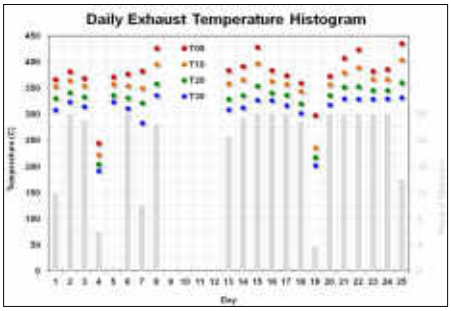
DPM Rate, Temperature, Backpressure, & Regeneration



322

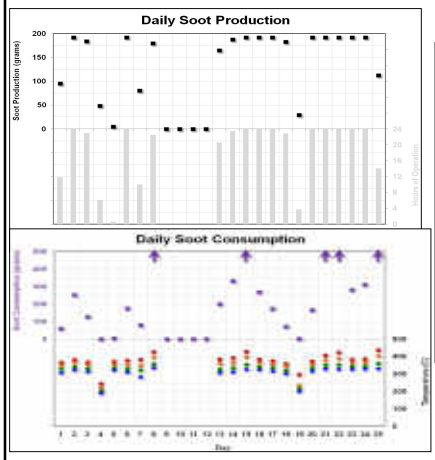
DPM Rate, Temperature, Backpressure, & Regeneration

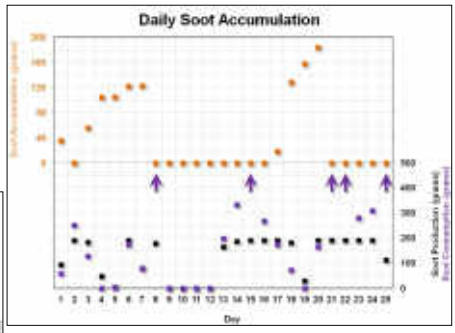




323

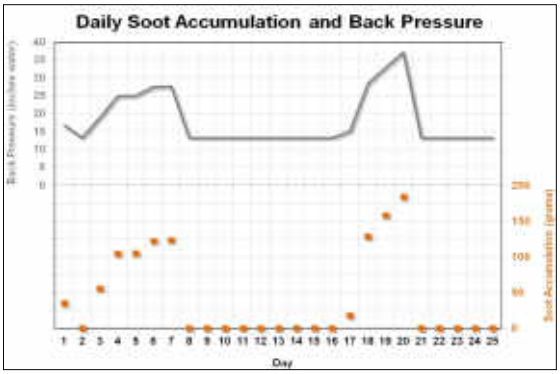
DPM Rate, Temperature, Backpressure, & Regeneration





324

DPM Rate, Temperature, Backpressure, & Regeneration



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Fuel & Oil Additives and Contaminants

Ferrocene (organometallic iron compound) usually not too bad

- Reduces capacity to hold DPM & ash
- May negatively impact active systems that use radio waves to measure ash / dpm load
- Generally not harmful to the filter

Zinc can be a problem

- Melts at 420° C
- Often in form of zinc dialkyldithiophosphate (ZDDP) which can poison catalyzed filters

Sodium is a flux for silicon carbide, and will cause a silicon carbide (melting point 2730° C) substrate to melt at standard exhaust temperatures.

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In Summary

- No one type of filter (DPF or other) is always the best answer for all applications
- A filter is not a substitute for proper engine maintenance
- Take advantage of available resources – ask questions
- Don't turn a DPM problem into a worse problem

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Useful Links

MSHA Homepage:

https://www.msha.gov/

MSHA Engine List:

https://lakmshaegov01.msha.gov/ReportView.aspx?ReportCategory=EngineAppNumbers

MSHA Diesel Particulate Matter Control Technologies:

https://arlweb.msha.gov/TECHSUPP/ACC/lists/00DPM-FilterEfflist.pdf

U. S. Diesel Emission Standards:

https://www.dieselnet.com/standards/us/nonroad.php#tier4

U. S. Occupational Exposure Standards

https://www.dieselnet.com/standards/us/ohs.php#gas

Generator video:

Exilator

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MDEC Toronto – VERT Workshop on DPF Technologies – 10.Oct.2019

PART 3
Risks, Failures, Challenges Monitoring and Maintenance

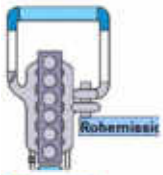
A. Mayer / TTM-VERT

Contents

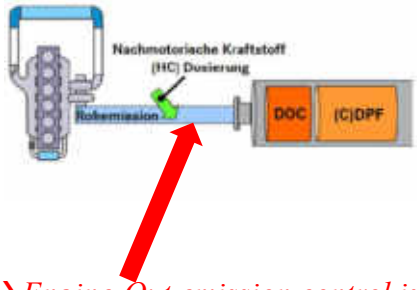
- How does the Filter effect the Engine
- How does the Engine effect the Filter
- Effect of Backpressure on
  - Engine Performance
  - Fuel Consumption
- Effect on Noise
- Operation Conditions
- Typical Failures
- Trouble Shooting
- Not all Filters are good Filters
- Why only use VERT-certified filtes
- Why local approval is required
- Conclusions

Aftertreatment masks the Engine

→ **tailpipe control alone might be misleading**



Old engine: raw emission permits engine-diagnosis by noise, smoke, smell, colour
Free acceleration revealed all problems

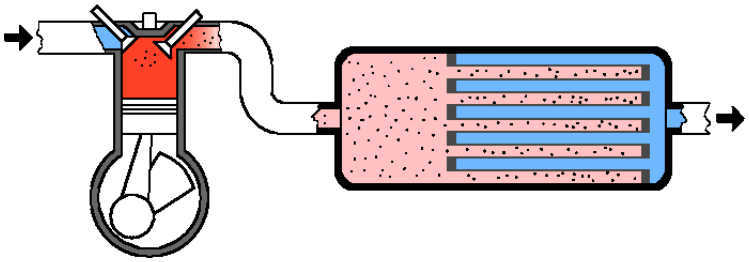


DPF and DOC mask smell and smoke, change noise and colour →engine diagnosis impossible

→ *Engine-Out emission control is important for Engine protection and preventive maintenance*

How does the Engine influence the Filter ? and how does the Filter influence the Engine ?

Mutual Effects Engine ←→ Filter



- Exhaust Flow
- Soot Emission
- O_2- & NO_X- Content
- Exhaust Temperature

→ • Filter Loading = f (Time); max 10g/l
max 200 mbar

→ • Filter Regeneration

→ • FILTER-BACKPRESSURE

Effect of Backpressure on Fuel Consumption

$$\frac{\Delta be}{be} = \frac{\Delta p}{pe + pr}$$

Where be is the specific Fuel Consumption [g/kWh] Δbe the Increment due to the Backpressure Increment Δp in relation to the overall Engine Work, expressed by effective pressure + friction pressure

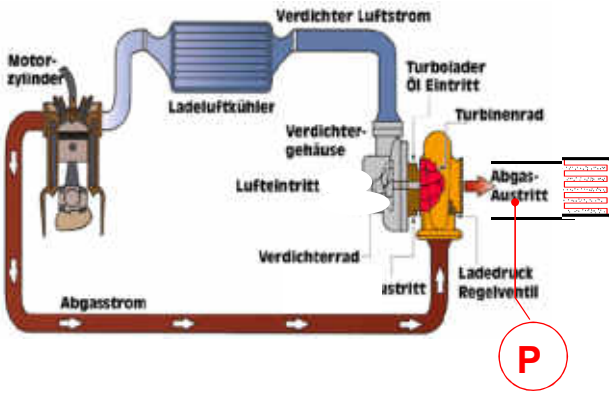
This linear Relationship is valid for natural aspirated engines without EGR up to about 300 mbar, above we find a nonlinear increase.

Fuel Consumption be = f (Backpressure Δp)

		Bus	Truck	Construction Machine	Passenger Car
Δp	mbar	100	100	100	100
pe + pi	bar	6	8	10	3
Δbe/be	%	1.6	1.2	1.0	3.3

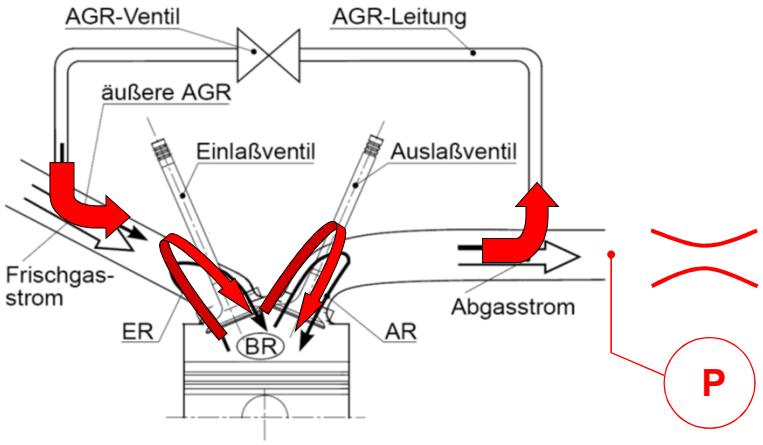
acc. to VERT-Rules
- backpressure of the new filter shall be < 50 mbar
- max backpressure must be < 200 mbar
- average backpressre will be in the range of 100 mbar

Turbocharged Engines are more sensitive



If Backpressure increases ↑ Charging Pressure Air Excess and Performance Decrease ↓ Soot Generation Increases ↑

EGR (AGR) – makes Engines also more sensitive to Backpressure



Engines with uncontrolled EGR

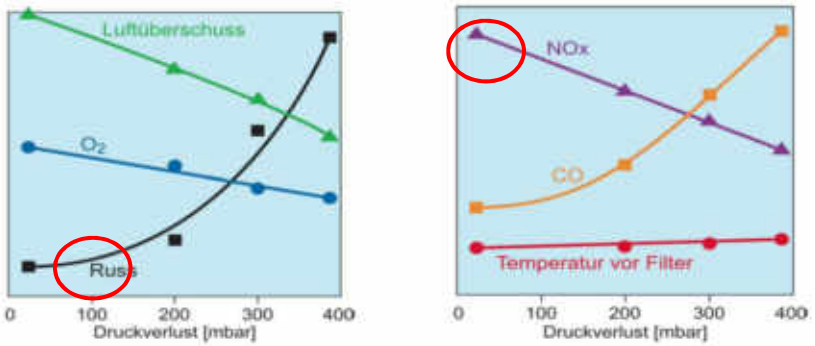


Fig. 3: Auswirkung der Gegendrucksteigerung bei einem MAN Euro 3 - Motor mit ungeregelter Abgasrückführung

Reaction is Non-Linear from beginning - Backpressure should remain below 120 mbar

Backpressure must be under Control

Electronic Datalogging

Sensors for Backpressure and Temperatures

Anzeige von Messwerten der ECU, z. B.
- Gegendruck
- Temperaturen
- Betriebsspannung
- Drehzahl
- Kraftstoffdurchsatz
- Additivverbrauch

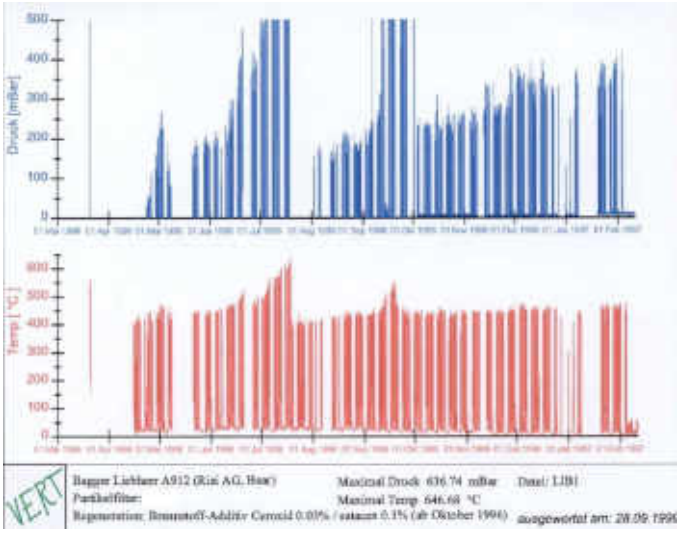
Auslesemöglichkeit aktive Fehlerliste

Warnung des Fahrers bei
- Zu hohem Gegendruck (VERT)
- Additivreserve

Alarm Indicator at the Drivers Seat

or remotely controlled

Backpressure Exceedence must be detected and the trained Driver must be alarmed

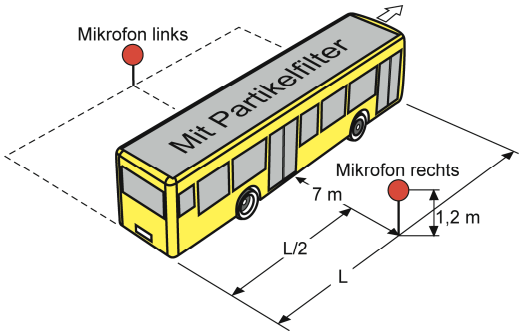


Because of limited installation space, the filter must replace the muffler

→ What about Noise

Noise

Filter is replacing Silencer
Noise must be controlled for each Retrofit Case
Noise usually 1-2 dB(A) lower – see VERT-database



Drehzahl [rpm]	Ohne Filter links [dB]	Ohne Filter rechts [dB]	Mit Filter links [dB]	Mit Filter rechts [dB]
600	63	65	62	62
1000	66	70	66	65
1500	74	78	69	69
1700	77	81	71	71
Mitelwert	71,7		66,8	

Categories of Failures

1. Thermal and thermomechanical stress
2. Canning Failures
3. Vibration Failures
4. Result of engine and turbo failures
5. Failures due to ash deposits and ash sintering
6. FBC-dosing mistakes
7. Overheating during cleaning
8. Maintenance mistakes
9. Quality of fuels and lubricaion oils
10. Short term and long term failures
11. Risks for the environment and people
12. Failure statistics
13. Trouble-Shooting

VERT

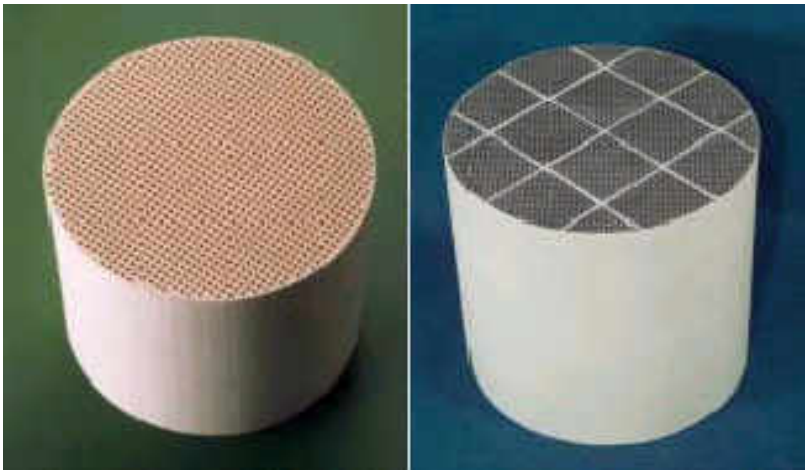
Brief history of scientific findings

NGK , Corning, Ibiden SHW, Buck	Industrialisation	Field problems due to wrong coatings



- **1988:** WHO declares diesel soot conditional carcinogenic
  SUVA introduces MAK limits for black carbon (BC) – <100µm since 1995)
  Johnson Matthey patent „CRT"-Filter systems (continuous regeneration traps)
- Corning, NGK, 3M, MANN+HUMMEL
- **1988/1989 Industrial disaster – due to ceramic destroying coatings thousands of destroyed engines -> Industry distances itself from DPF**

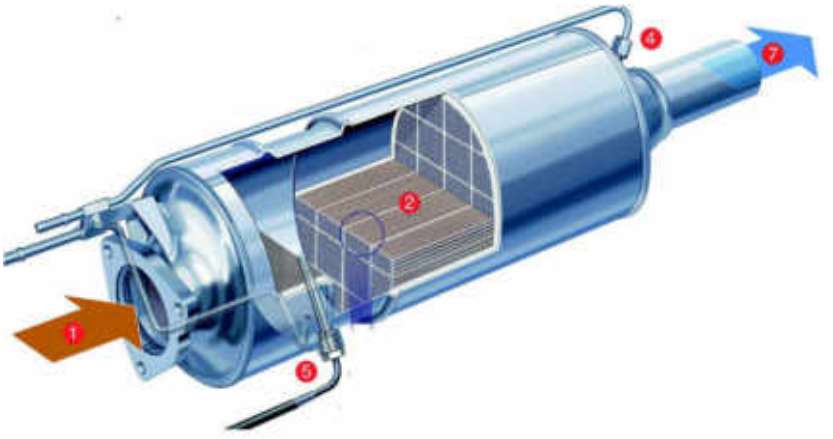
Porous Brittle Ceramics in a Hostile Environment at High Temperatures and Vibrations



Material Data of ceramic filter substrates

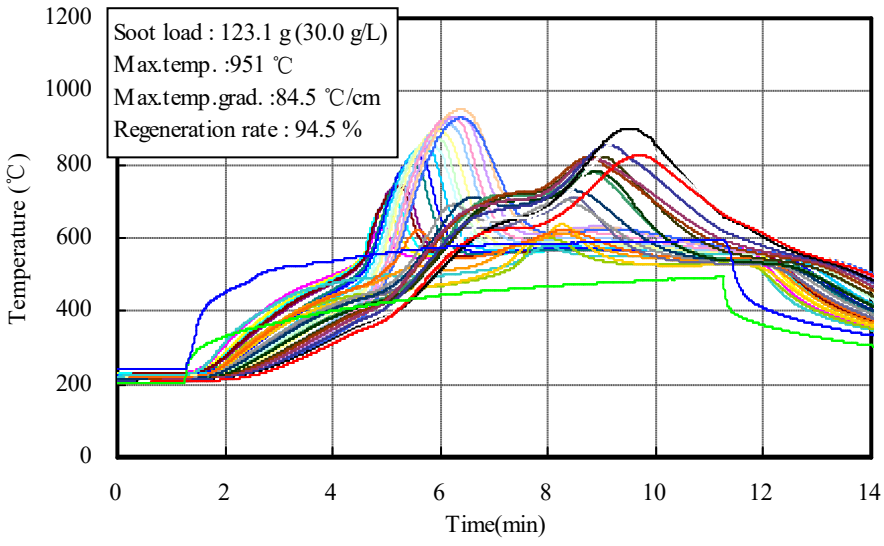
	Si-SiC	Recrist. SiC	Cordierit
Porosity [%]	46 (40-62)	36-45	60 (53-70)
Pore Size [µm]	20 (8-33)	8-10	25 (15-35)
Youngs modulus E [Mpa]	18	49	11
Bending Strength [Mpa]	**21**	**53**	**1-8**
Heat Expansion CTE X10^6 (40-800°C)	**4.1**	**4.3**	**0.3**
Thermoshock resistance [°C] (cold water test)	1200	800	> 1200
Heat conductivity [W/mK]	**31**	**53**	**0.8**

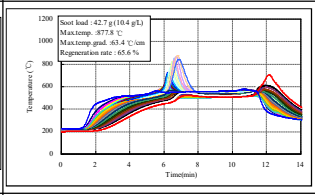
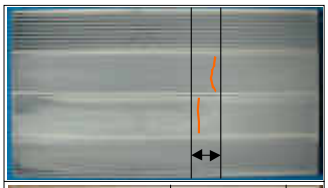
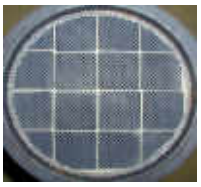
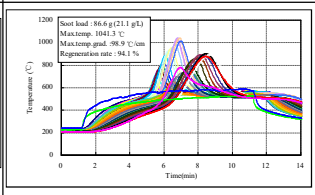
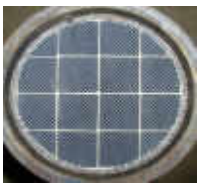
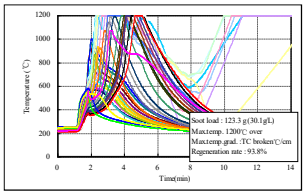
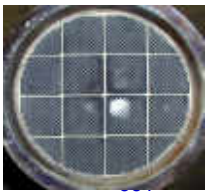
Ceramic Particle Filter Systems require careful shock absorbing canning and insulation



Typical Failures
Thermal Stress during Regneration

Origin of Failures: Local Temperature Peaks during Regenerations (source IBIDEN)

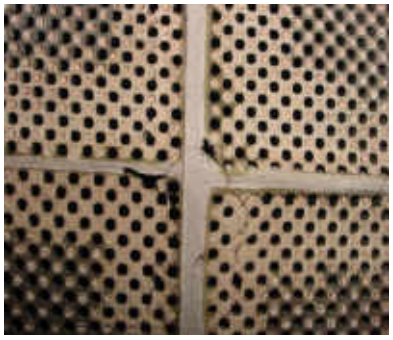


	Regeneration chart	Cross section photo	Outlet surface photo
•10 g/L			
•20 g/L			
•30 g/L			

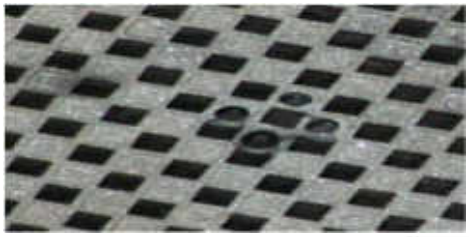
Cracking and Melting

a very rear case

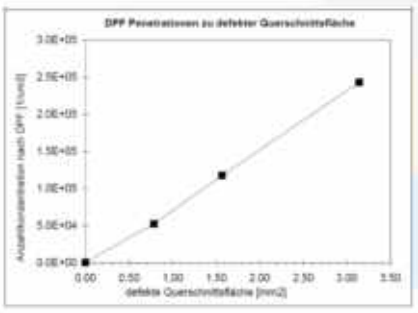
But this shows, how it starts and filtration efficiency is lost even with small cracks



Can we detect Small Failures?

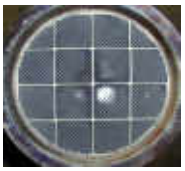


Yes, we can with particle number measurement



Repair Small Failures by ceramic cement

W.Haldenwanger
Technische Keramik GmbH
Teplitzer Strasse 27
D-84478 Waldkraiburg
WH Feuerfestkitt Teil A und B
www.haldenwanger.de



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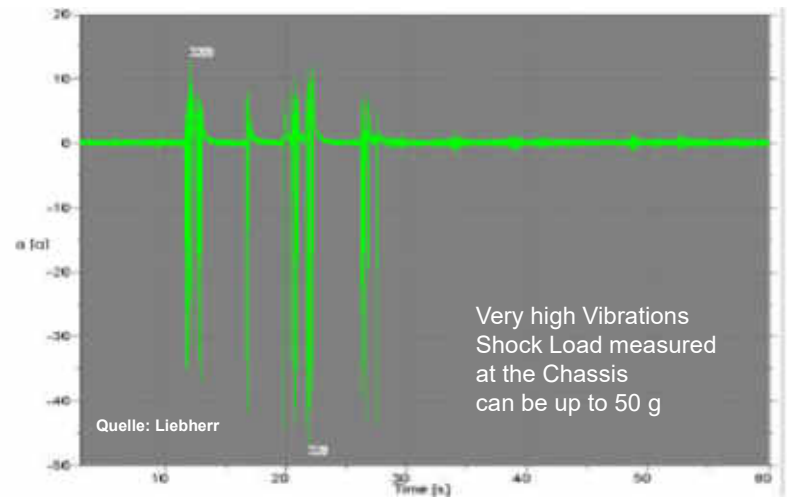
Typical Failures

Canning problems due to wrong materials, excessive thermal expansion or humidity

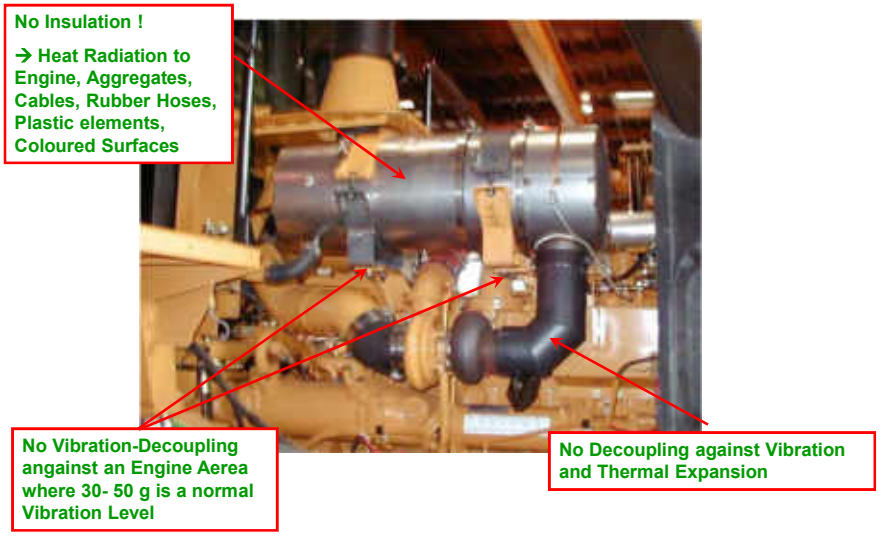
Canning-Gap leaking due to low cycle fatigue (thermomechanic, vibrations, design mistake , manufacturing defect)

Double-Wall-Insulation without Pressure Release

Vibration up to 50 g



Mechanical Problems to be Expected ?



Lose Catalysts and Filter Substrates




Segment Cement Breakdown and Loss due to Vibrations and/or Overheating?

Vibration finds every weak Point of a Design

Typical Failures due to Deposits

Deposits lead to fast Plugging and rapid Increase of Back Pressure

High Lube Oil Consumption (due to Turbo Failure ?)

Nozzle – Deposits A Risk with FBC Overdosing

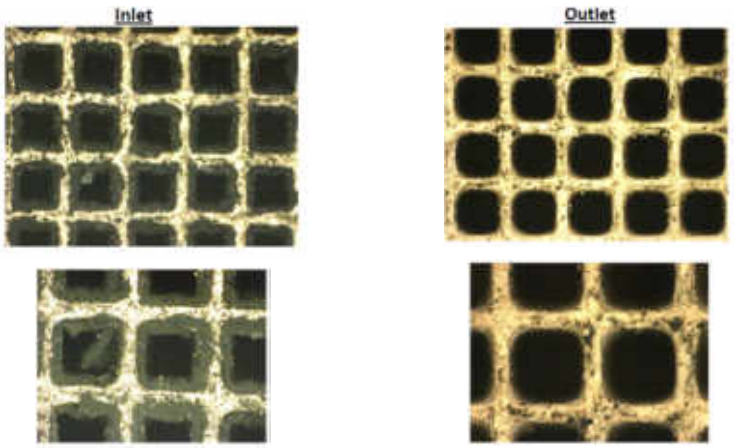
light

strong

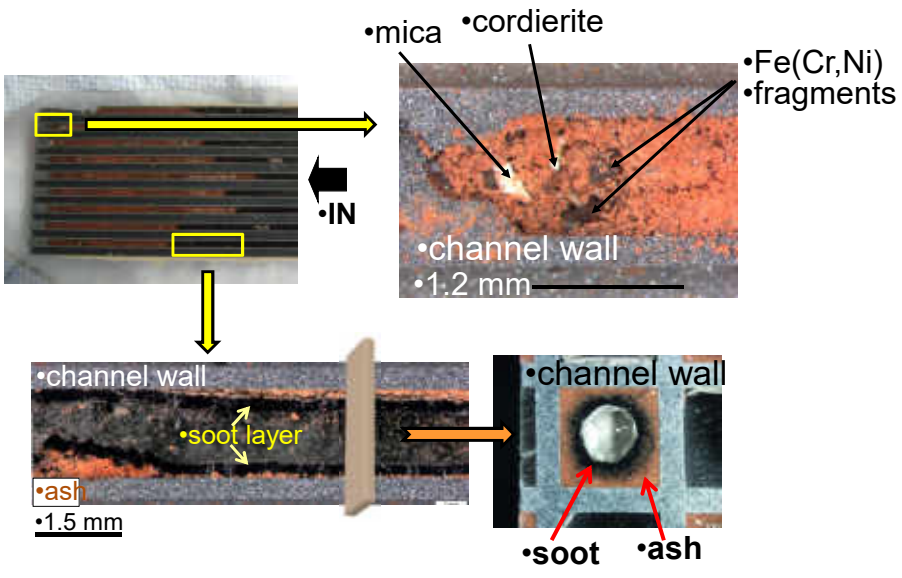
middle

very strong

DOC might be covered by soot or poisoned or destroyed or aged or just not adequately coated



Ash Deposits in a Particulate Filter Cell

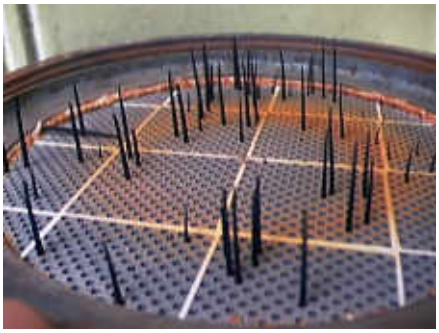


•17th ETH-Conference on Combustion Generated Nanoparticles

•370

Regeneration interrupted

→ Pyrolysis, Soot Densification, Gaphitisation →
Soot Combustion Temperature climbs up



Eisen – Additiv (FBC) – normales Bild

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Typical Failures due to unprofessionel Installations

DPF-Installation „Check-List“

DPF-Installation:

- ✓Location:
  - -Visibility ?
  - -Safety ?
  - -Noise ?
  - -Cooling ?
- ✓Close to Engine and insulate Ducts
- ✓Insulate Filter (Safety & Heat Loss)
- ✓Decouple Filter against Vibrations (Engine and Chassis !)
- ✓Install On-bord Control and Alarms

Installation too tight (close to plastic wall)

Mechanical Elements: avoid Notches and provide sufficient Elastic Pretension

Engine-Failures due to Filter-Regeneration Failures

Influence factors

- **Backpressure extremely high**
- **Alarms neglected**
- **Engine maintenance neglected (filter masking)**
- **EGR too high**

→ **Solution: backpressure monitoring < 200 mbar**
→ **With EGR below 120 mbar**
→ **Diagnose access upstream filter**

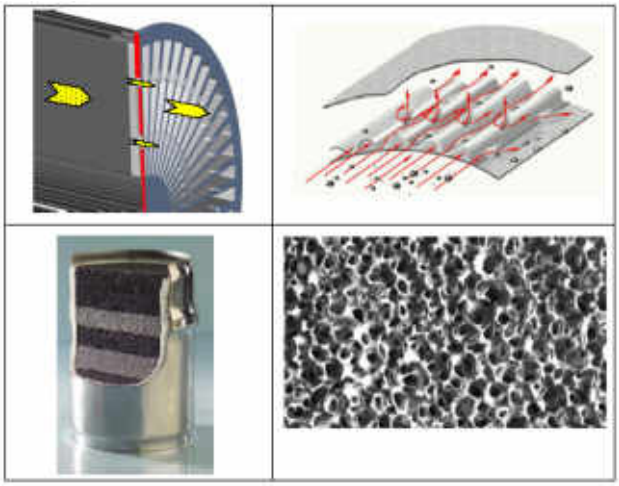
Trouble Shooting → see VERT materials TA

Disorder	Cause	Remedy
Pressure indicated persistently and unexpectedly low.	Connection or pipe is clogged, iced or leaky; Pipe diameter too small.	Clean pipe ar Verify leak tig Fit larger pipe Condensate t Condensate f
	Defective pressure sensor.	Compressed reduction valv
Pressure indicated high. Does not revert to zero at standstill.	Connection or pipe is clogged.	Clean pipe ar Verify leak tig
	Defective pressure sensor.	Pipe sloping Condensate t Compressed reduction valv
Black smoke emission visible and high back-pressure.	Filter extremely overburdened.	Regenerate fi load operatio
	Regeneration ineffective.	Adapt regene procedure to Clean filter (b residues exte

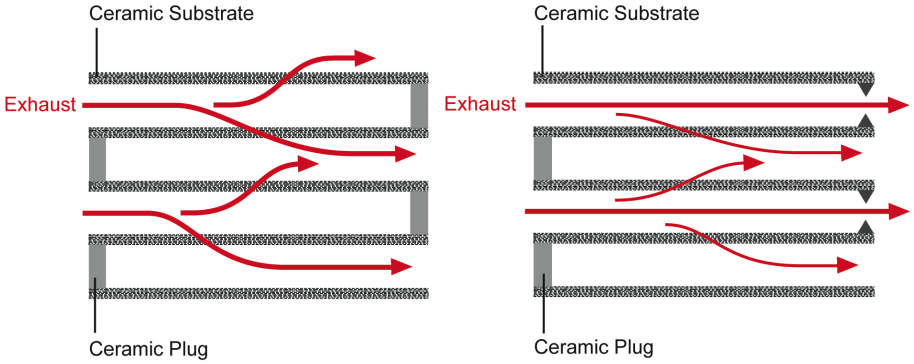
Not all DPF offered on the market are good filter

Many don't fulfil the BAT requirements

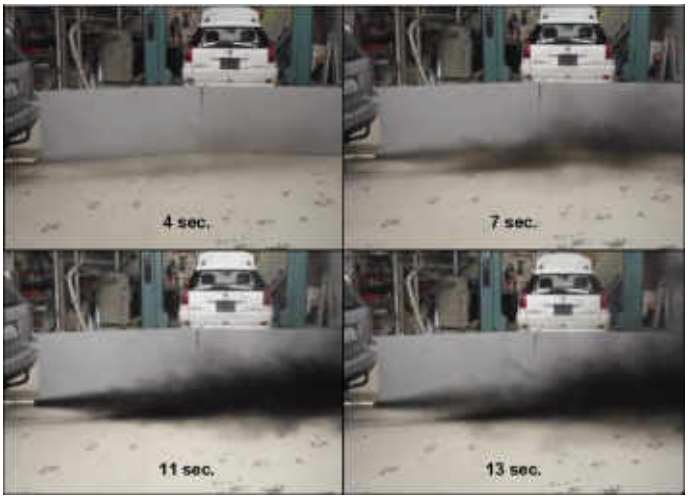
2 partial flow systems and large pore systems



•Schematic of full-flow filters FFF (left) and partial flow filters PFF (right)



Typical blow-off during full load acceleration after city driving



Exclusive use of VERT certified Filters

Durability Test (Field test) 2000 hrs

VERT approved DPF systems must undergo a field test of **at least 2000 operating hours**

Do be done in a typical application of the specific DPF system (i.e. stationary or mobile application resp.)

With periodic tests of filter performance, back pressure, regeneration, control and alert systems, mechanical construction etc.

Followed by a full filter test on bench VFT3 **no aging or deterioration permitted**

Swiss Standard
(Techn.Norm)

How to measure and characterize Nanoparticle Filtration systems for Combustion Engines

INB

SN 277206

Internal Combustion Engines – Exhaust Gas After-treatment – Particle Filter Systems – Testing Method

Verbrennungsmotoren – Abgasnachbehandlung – Partikelfiltersysteme – Prüfverfahren

Moteurs à combustion – Post-traitement des gaz d'échappement – Systèmes de filtres à particules – Méthode de test

Motori a combustione – Post-trattamento dei gas di scarico – Sistemi di filtri antiparticolato – Metodo di collaudo

Automatic Cleaning Machines available

- hermetically closed
- 2-stage process
- success control

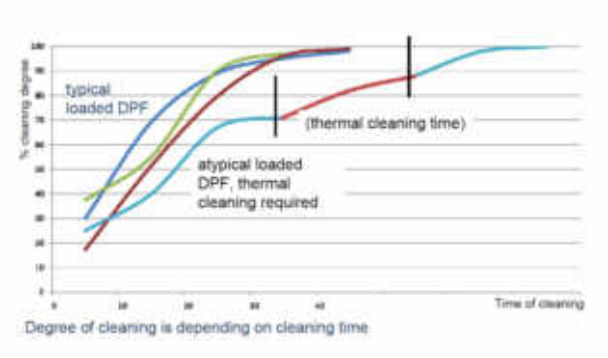
Comparison of Cleaning Technologies

Source: H.P:Mayer, Puritech

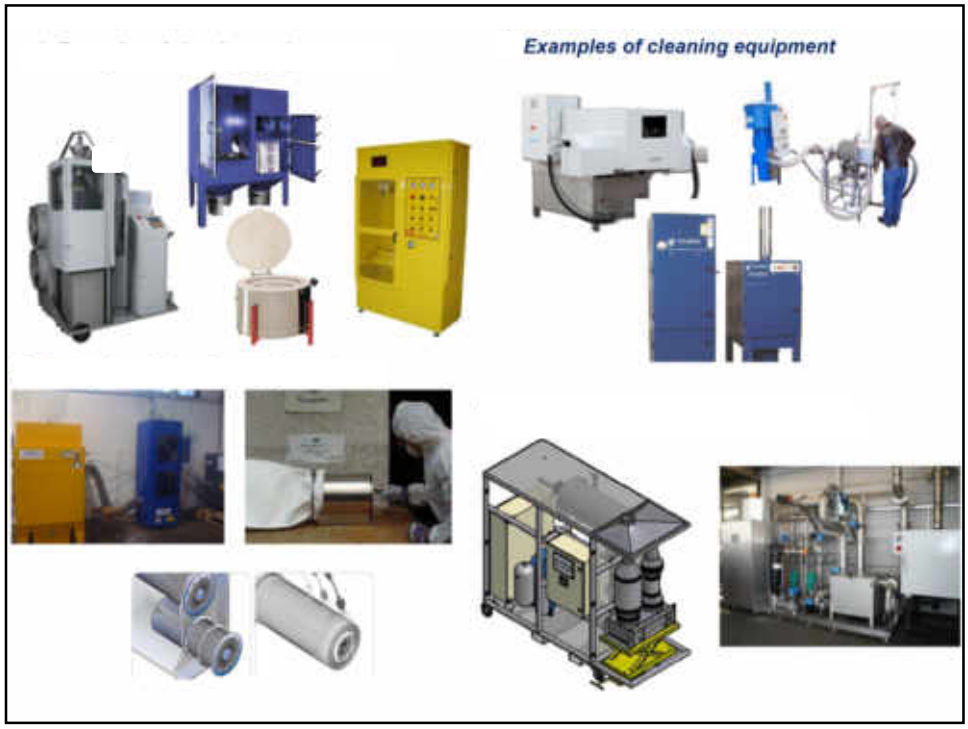
How	Advantages	Disadvantages
1) Air - air gun - air shot - compressed air	➢ process capability ➢ automated ➢ soft cleaning ➢ recyclable ➢ cost ➢ dry cleaning	➢ high air impulse required ➢ efficiency > 90 %
2) Water - steam jet - steam impact	➢ metallic substrates ➢ no dust ➢ min. media speed ➢ no thermal cleaning	➢ wet matt (interam) ➢ drying of ceramic substrates ➢ water filtration needed
3) Dry Ice Cleaning	➢ dry cleaning ➢ high Impulse	➢ abrasive effect on catalytic coating
4) Thermal - oven - compressor	➢ soot oxidation	➢ faster aging of catalytic coating

Automatic Cleaning Machines available

Source: H.P:Mayer, Puritech



Automatic Cleaning Machines available



Maintenance and periodic emission check for all vehicles

Maintenance Sticker for Engines < 18 kW

Emission Sticker for Engines > 18 kW

Reliability of DPF in Switzerland

1990: 230 Filters installed in Buses (DB/M&H-System)
1998: still 200 in Operation

2000: 2400 PFS in Operation, > 6% Failures per year
→ too many Failures → VERT-Test 2 introduced

2003: > 6500 PFS in Operation
Failures 2-3 % per year
- PFS > 800‘000 km Trucks and Buses
- PFS > 10‘000 op.hrs Construction Machines
- PFS > 45‘000 op.hrs Ferry Boat
- PFS > 60’000 op.hrs Genset

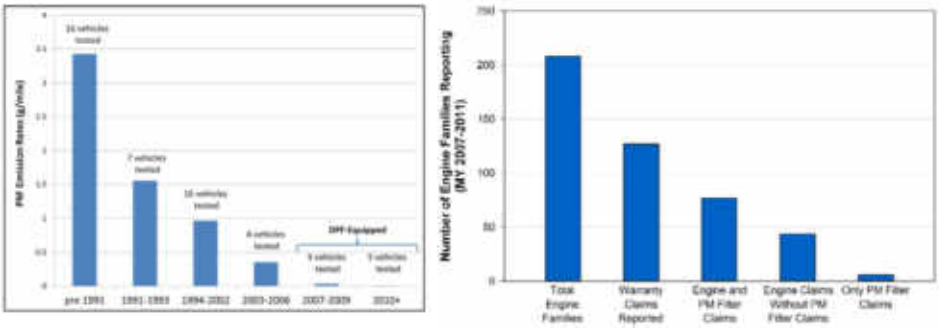
2010> 25’000 PFS in Operation
Failures 2-3 % per year; some companies < 1 %

2012 < 1 % - some large fleets < 0.3

CARB investigated 587 trucks (OE and Retrofit) for engine and DPF problems (report May 2015)

As discussed in Section 3, staff conducted 621 roadside truck inspections, 587 of which were trucks equipped with PM filters. The resulting sample of paired truck inspections and operator surveys was representative of the California fleet. Appendix V provides a table showing the number of trucks inspected by body type relative to statistical sample targets.

Based on responses from truck operators, about 2 percent (11 of 587 trucks) reported a past problem with the PM filter on their truck that required service to resolve the

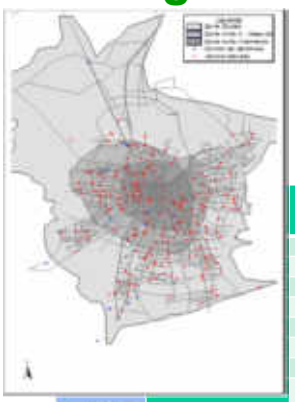


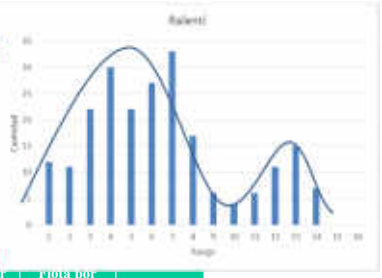
How to avoid Failures

- **Use only VERT-certified filters –VERT-Filterlist**
- **Evaluate vehicle operation → VERT Guide**
- **Select filter acc.VERT and prefer active regeneration**
- **Design installation carefully → VERT-Guide**
- **Install datalogger and alarms – remote download**
- **Set alarms to max 200 mbar; for EGR lower**
- **Training for mechanics, drivers and management**
- **Acceptance test of each retrofit → VERT-Guide+Label**
- **Control emission once a Year → VERT-Guide**
- ***Be proud cleaning the air of your environment***

Bus Fleet of Berlin (1200 vehicles) respecting these rules has 1-2 failures per year – 0.1 %

•Santiago Studie zu Filt





Sobre Referencia	Medidos	Tasas por modelo	Flota por modelo	Flota
0	26	0,0%	215	0
9	127	7,1%	1466	104
6	32	18,8%		
10	14	71,4%		
11	11	100,0%		
3	13	23,1%		
39	223	17,5%		

Tasa Gene

Fleet

Implementation Stage	Number of Abnormal Emissions	Buses Tested	Rate of Abnormal Emissions	Average DPF Milage [km]
2005-2009	21	25	84%	524,341
2010-2013	18	198	9%	297,084
Total	39	223	17,5%	325,920

VERT
Type Approval

VERT
Suitability Test

VFT 1
Filter Test 1
Stationary ISO 8178
+Transient +Regeneration
Limit value >97% (20-300 nm)

VSET
Secondary Emissions Test
ISO 8178
no toxic
reaction products

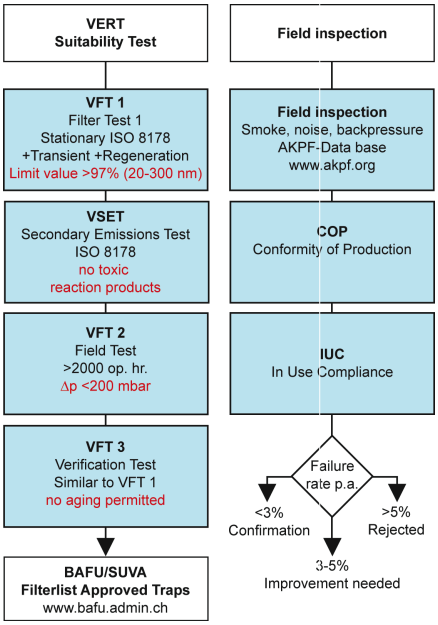
VFT 2
Field Test
>2000 op. hr.
Δp <200 mbar

VFT 3
Verification Test
Similar to VFT 1
no aging permitted

BAFU/SUVA
Filterlist Approved Traps
www.bafu.admin.ch

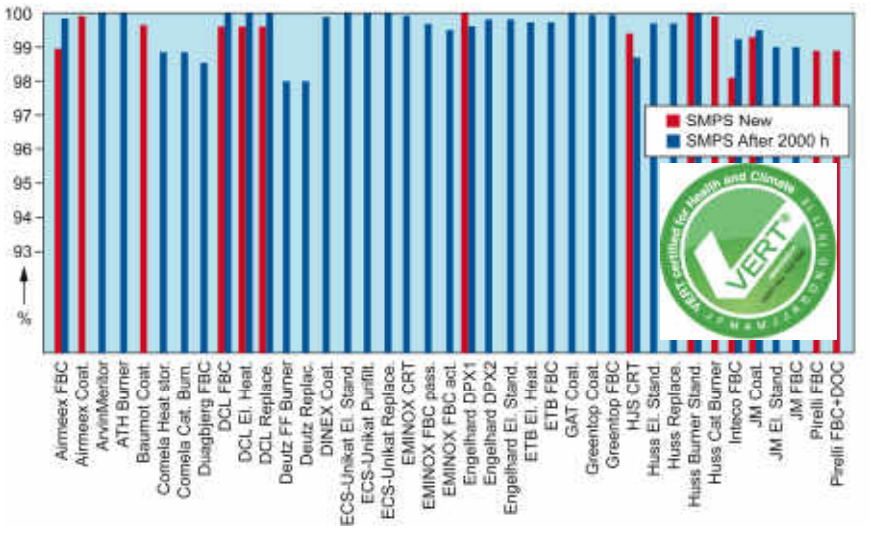
+

VERT Field Control



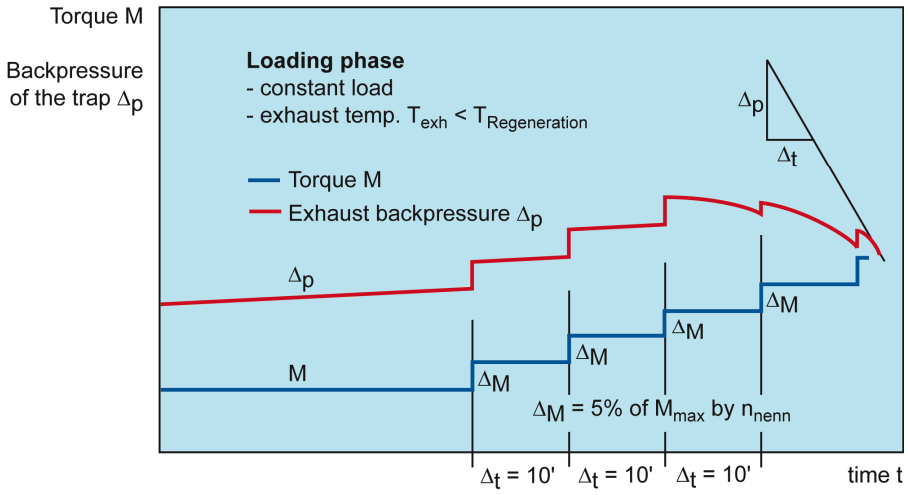
Filtration - 65 DPF VERT tested

25 % > 99.8 % within size range 20-300 nm



Regeneration Test

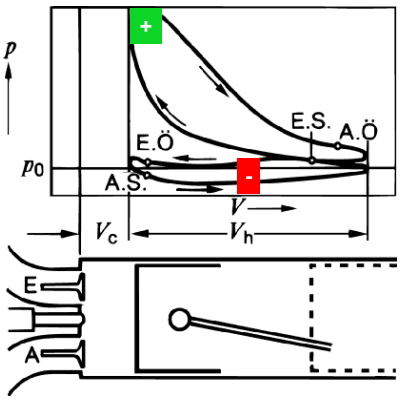
Find Balance Point and Regeneration Gradient

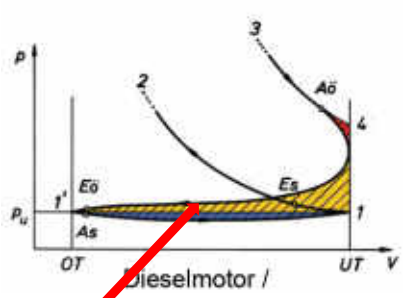


Exhaust End Pipe stays clean !

onroad > 85‘000 km offroad > 1000 h

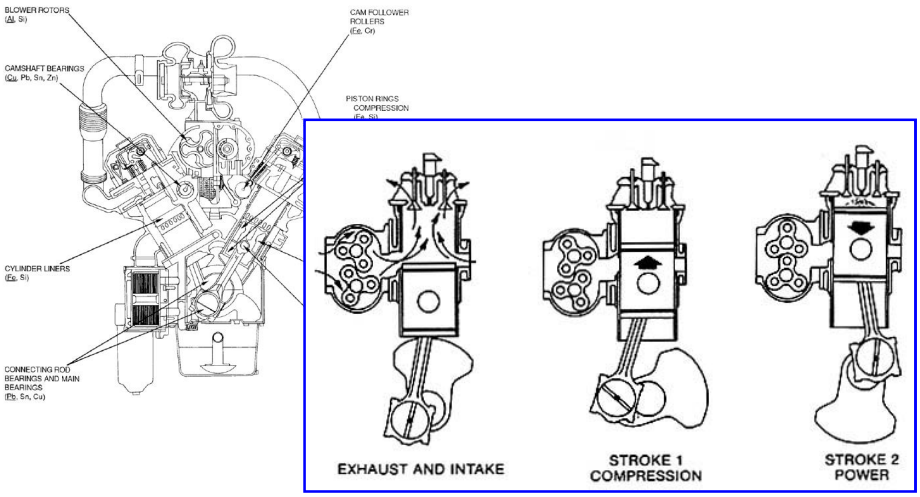
Effect of Backpressure on Performance and Fuel Consumtion





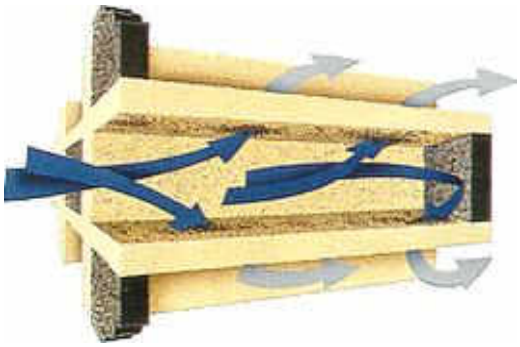
If the Flow Resistance of the Filter is higher than the Flow Resistance of the replaced Silencer the actual Engine Pumping Work will increase.
Performance and Fuel Economy will be influenced proportional to the Pumping Work Increment – which will be in the Range of 2-3 %.

Very Special Case « 2-Stroke Diesel »: very sensitive to Backpressure but VERT has developed Solutions for CARB and Detroit Diesel



DPF : Wall-Flow Particle Filters

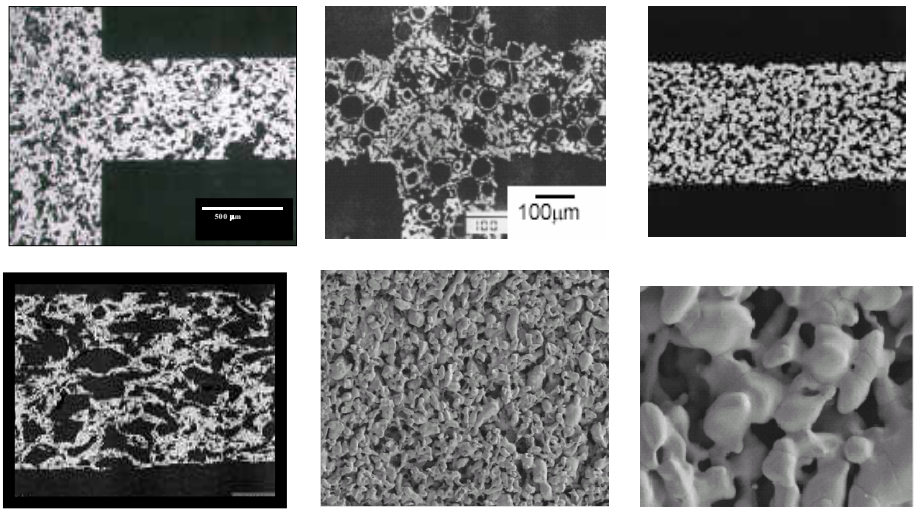
available since 1982



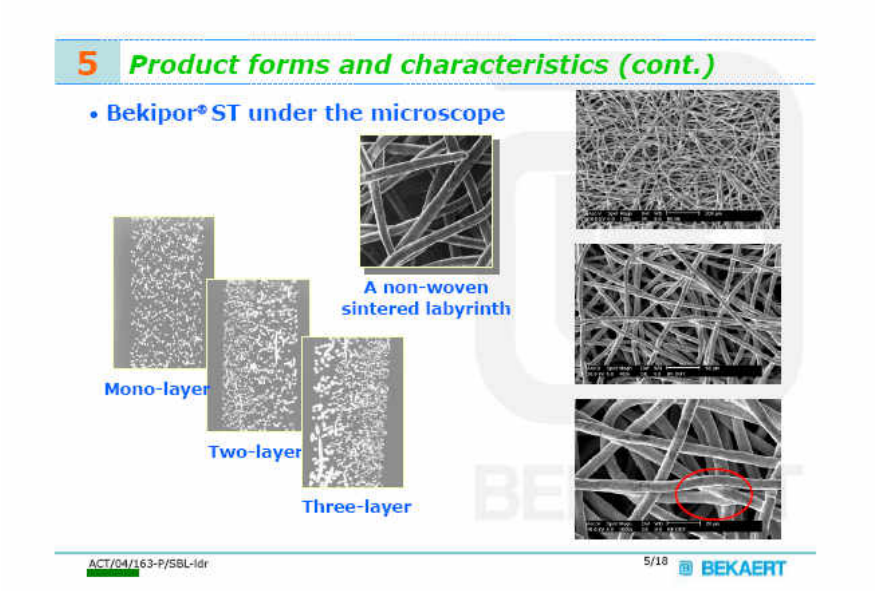
- - Filtration Effectiveness > 99.9 % if pore size < 15 µm
- can be used for all Diesel Engines – new and in-use

Filter-materials need to be porous

→ necessarely weak and brittle

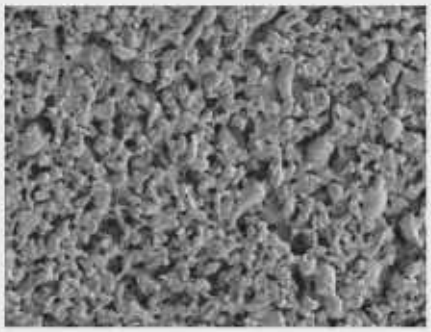


Also Sinter metal substrate undergo high vibrational stress



HJS Fahrzeugtechnik GmbH & Co KG

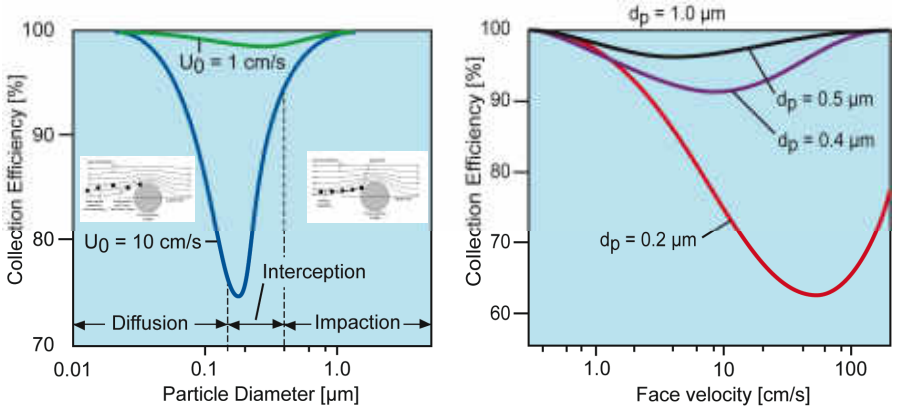
Filter-Material



REM-Bild, Anströmseite

REM-Bild, Detail

Filtration Risk in the Middle Size Range

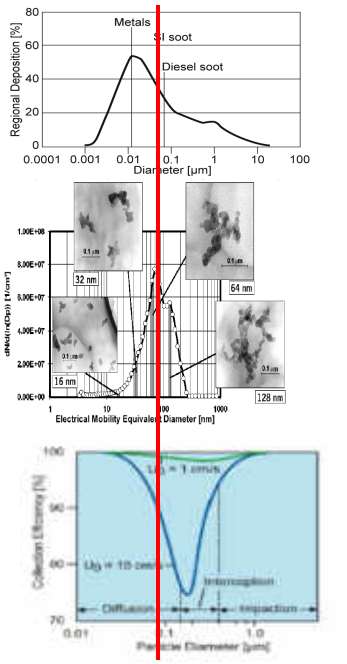


Large pores and high flow velocity lower efficiency

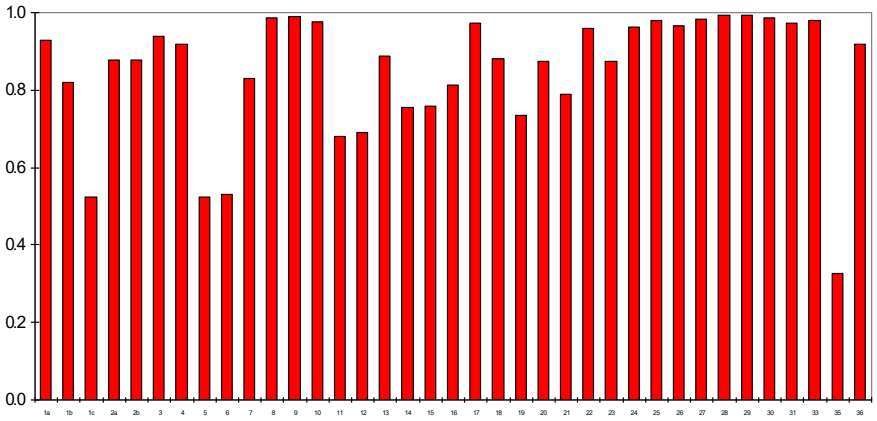
Strange Coincidence

The most sensitive size range of the lungs is the most intensive emission range of the engines and the weakest size range of filtration

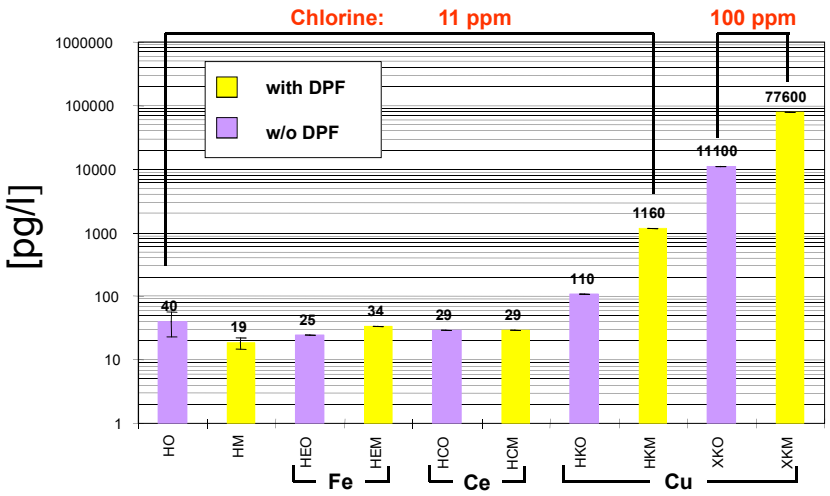
The lung is an open door for engine emitted ultrafine particles in this size range



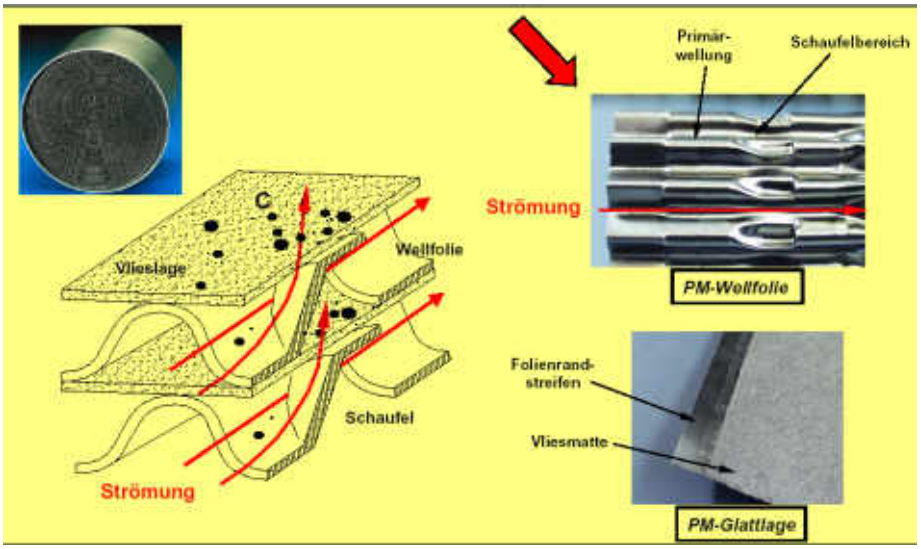
PAH are very effectively reduced in most filter systems



Formation of Dioxins in a Filter System using Cu-FBC

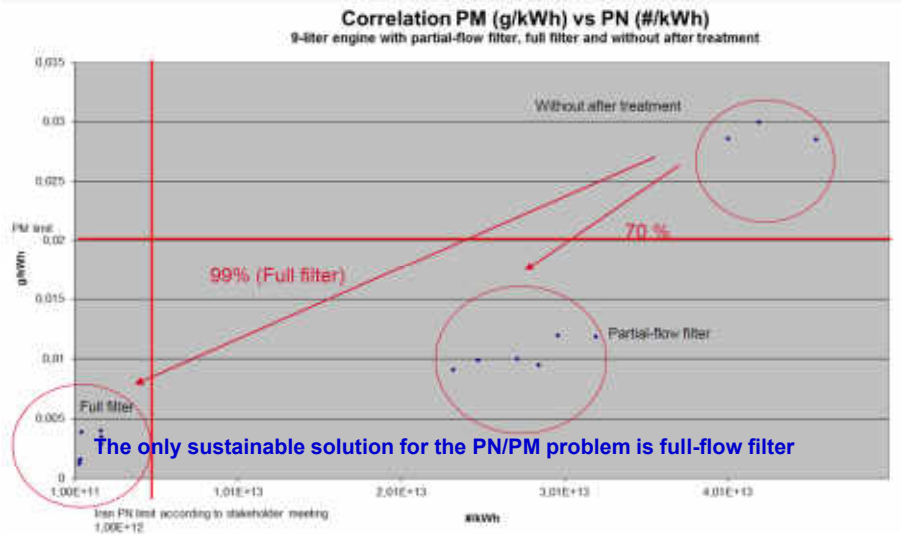


Partial Flow System A : EMITEC



Partial-flow filter (EEV) vs Full-flow filter (Euro IV + DPF)

415



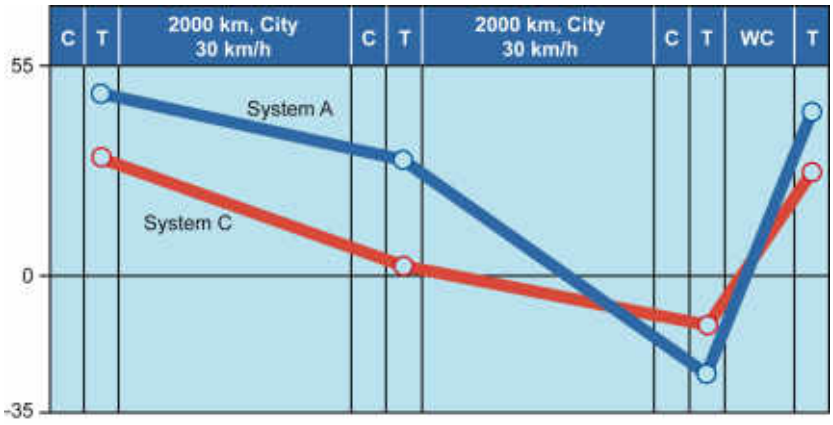
Soot-free Tehran - September 7th, 2016

System A and C during a city driving test

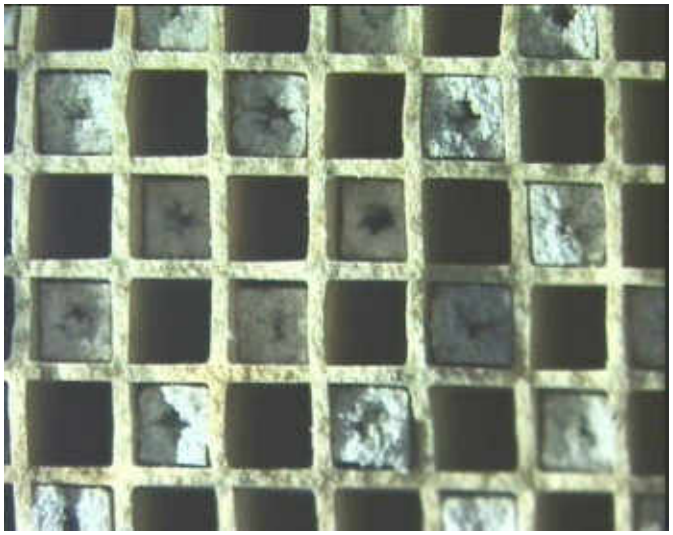
of 2 x

2000 km < 70km/h, < 300°C (homologation test App. 26)

„C" = conditioning= 3x NEDC, „T"= NEDC-test; „WC"= worst case;



Too late - No Cleaning possible anymore !



VERT-Certificate

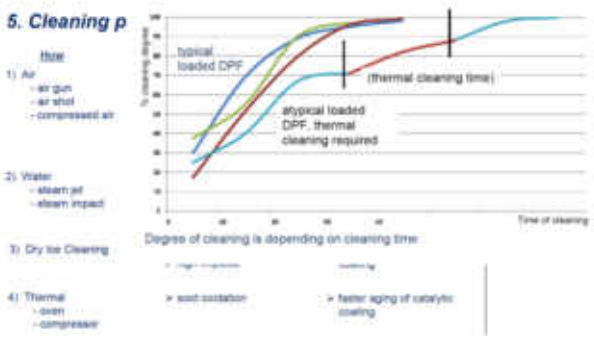
1.VERT-testing successfully completed
2.Application per System duly signed - directed to VERT coordination office
3.Examination by VERT Scientific Committee - ananimity required
4. Stamp “Valid” VERT-CEO
5. Filter listed
6. Certificate to manufacturer


VERT®-Certificate

VERT Filter List

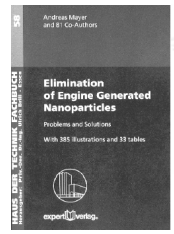
65 Certifications
First Publication 1998
Published on VERT-homepage
www.VERT-certified.eu
Updated whenever modified
Responsible:
VERT-Scientific Committee
Language: English only

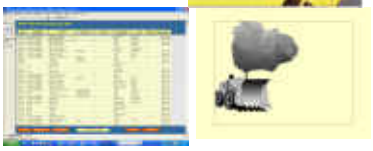
Automatic Cleaning Machines available



Training

- Much educational material available
  translation needed





•3 books published > 300 papers

Safety is possible.

Checklist

Particulate filters for diesel engines used underground

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MDEC Toronto – VERT-Workshop on DPF Technologies – 10. Oct 2019

Part 4

DPF Application Worldwide

Milestones and Keys for Clean Air

A.Mayer / TTM - VERT

Summary of Worldwide Underground Mine Diesel Regulations

Mahe Gangal

NRCan, CanmetMINING

Report #12-037 (OP)

18th MDEC Conference
Toronto, Ontario, Canada
October 2-4, 2012

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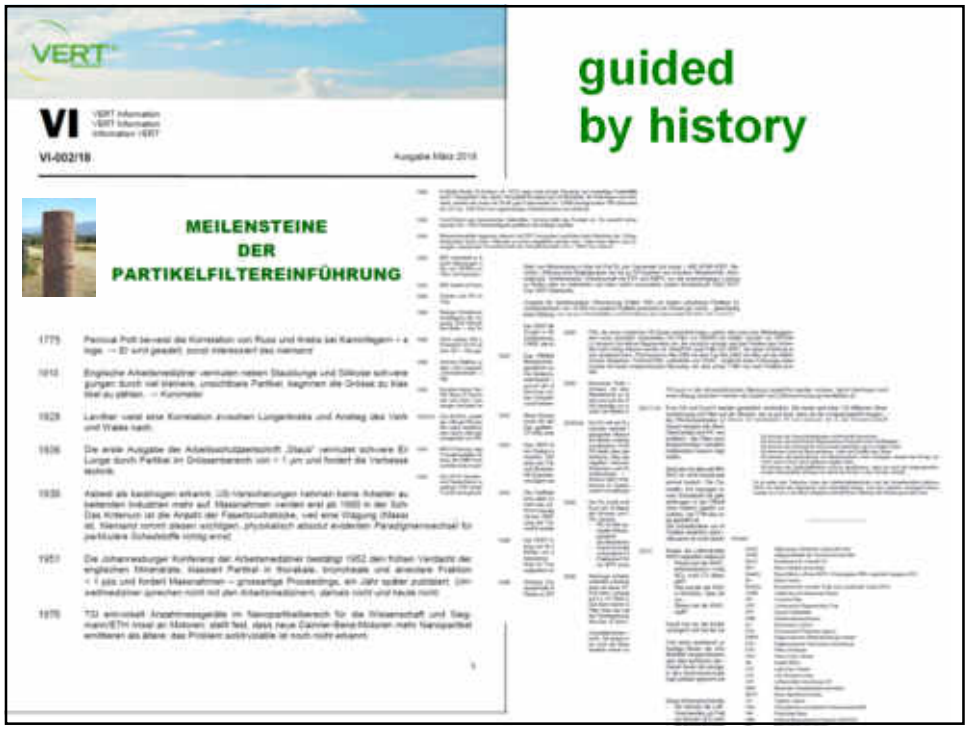


guided by
worker protection

starting aerosol science in mines had defined Particles Sizes deposited in Lung Compartments in 1959

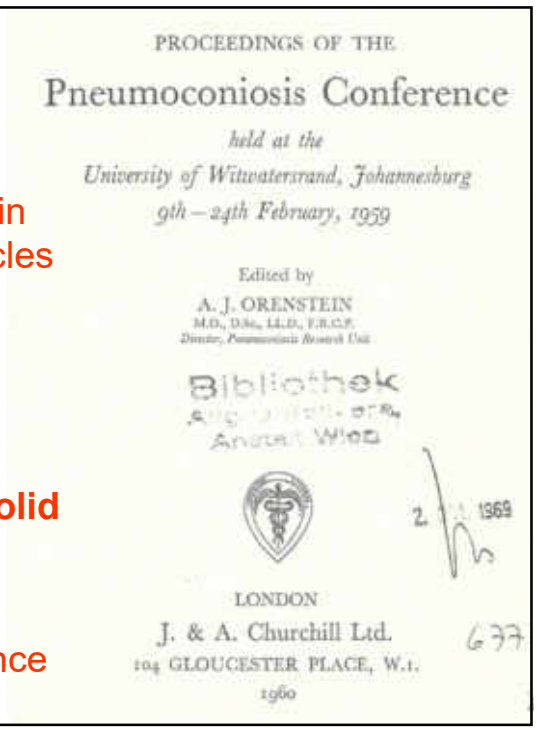
VERT:

SUVA, AUVA, TBG

required elimination of **solid insoluble particles**

< 500 nm

and to limit each substance individually


PROCEEDINGS OF THE

Pneumoconiosis Conference

held at the

University of Witwatersrand, Johannesburg

9th–24th February, 1959

Edited by

A. J. ORENSTEIN

M.D., D.Sc., LL.D., F.R.C.P.

Director, Pneumoconiosis Research Unit

Bibliothek

1969

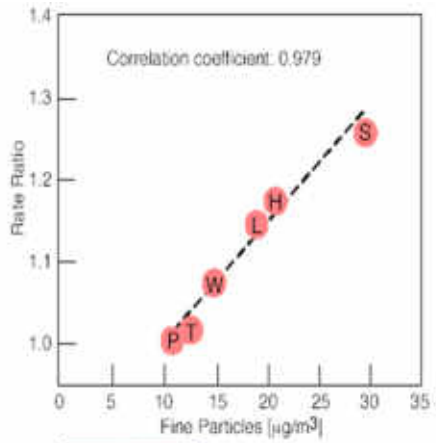
LONDON

J. & A. Churchill Ltd.

104 GLOUCESTER PLACE, W.1.

1960

guided by Epidemiology

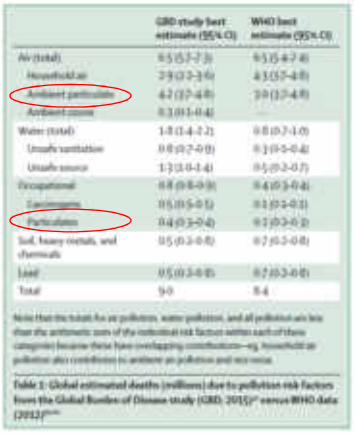


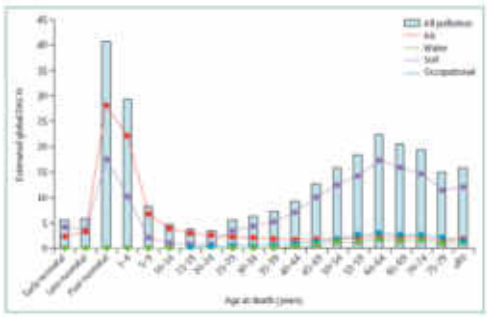
Dock Dockery
6 cities study
1978-1993

- 1976: TSI develops measurement devices for nanoparticle counting Application in sciences – Kittelson and Siegmann (ETH) start to measure engines
- 1980: Mortality due to PM2.5 quantified in 6-Cities-Study USA 1978-1993
- 1980: CARB announce first PM limits for light duty vehicles

guided by Health Research

The *Lancet*-Commission on pollution & health published a very large meta study Oct 2017





The study does not even mention health effects by NO2

3 x more death by pollution than from AIDS, tuberculosis and malaria combined

15 x more than from all wars - in Iran 1 death in four

Financial Losses due to pollution are estimated 6 trillion US$

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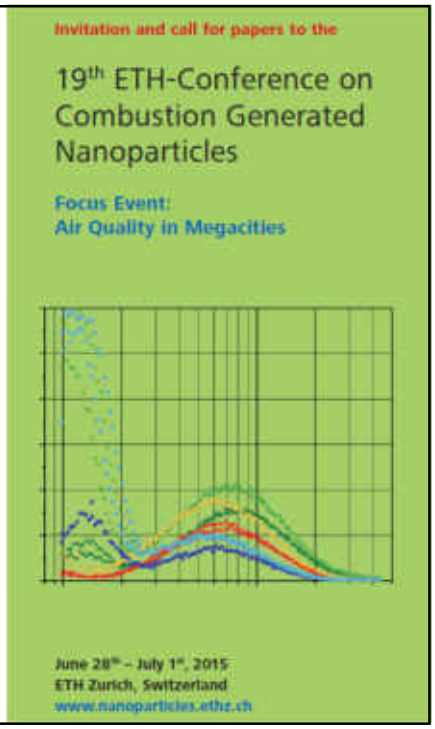
Guided by a scientific network worldwide

- 1997 first international ETH-NP-workshop - 40 participants
- Today ETH-NPC is the annual event of UFP experts from science to technology > 400
- 20th conference June 2016 13th to 16th – no participation fee



guided by Metrology

Develop Nano-Metrologie → The Golden Instrument

Table 1 Air pollution cost factors in EUR/ton of pollutant (€2008 values)

Pollutant	$PM_{2.5}$ (exhaust)			PM_{10} (non-exhaust)			NO_x	NMVOC	SO_2
Region type	Metropolitan	Urban	Non-urban	Metropolitan	Urban	Non			
Source	HEATCO	*UBA/ HEATCO	HEATCO	*UBA/ HEATCO			NEEDS	NEEDS	NEEDS
Country									
Austria	482,200	155,900	80,700					1'600	10'000
Belgium	483,400	156,000	104,400					2'600	10'900
Bulgaria	70,500	22,700						400	6'200
Czech Republic	355,400	114,5						1'100	9'500
Denmark	436,4						20,500	5'300	1'200	5'700
Estonia	2				4,000		17,700	2'800	600	4'500
Finland	432				55,800		14,400	2'600	600	3'500
France	438,6			175,500	56,500		35,100	10'500	1'400	9'900
Germany	430,300			172,100	55,500		33,600	12'700	1'400	10'900
Greece	338,600		,700	135,400	43,600		19,100	2'700	600	5'800
Hungary	288,900		74,100	115,600	37,200		29,600	12'400	1'000	9'100
Ireland	537,200		56,200	214,900	69,300		22,500	4'400	1'100	5'400
Italy	Switzerland		498,700		160,500		82,400	00		8'700
Latvia								'00		5'000
Lithuania	266,300	86,500	53,300	106,500	34,600		21,300	5'600	800	5'700
Luxembourg	877,100	282,400	125,000	350,800	112,900		50,000	12'700	2'400	10'300

Switzerland	498,700	160,500	82,400
Poland	248,900	79,900	74,700

and never forget the money involved
Benefit/Cost > 10

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Switzerland startet with Tunneling 1993

„VERT-Filter for each Diesel“

Public Transport in Switzerland
> 90 % BAT-DPF




Construction Machines in Switzerland
> 90 % BAT-DPF



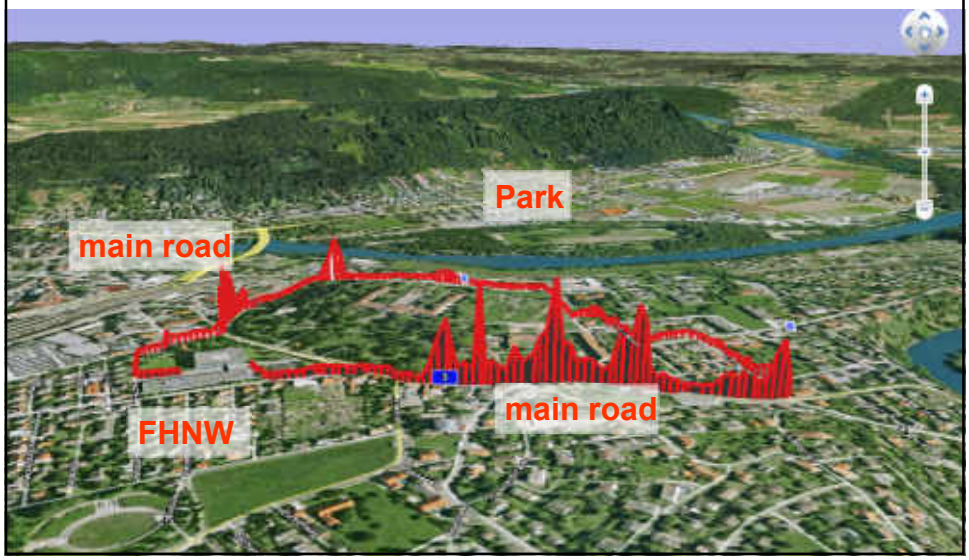

Locomotives and Ships in Switzerland
> 60 % BAT-DPF

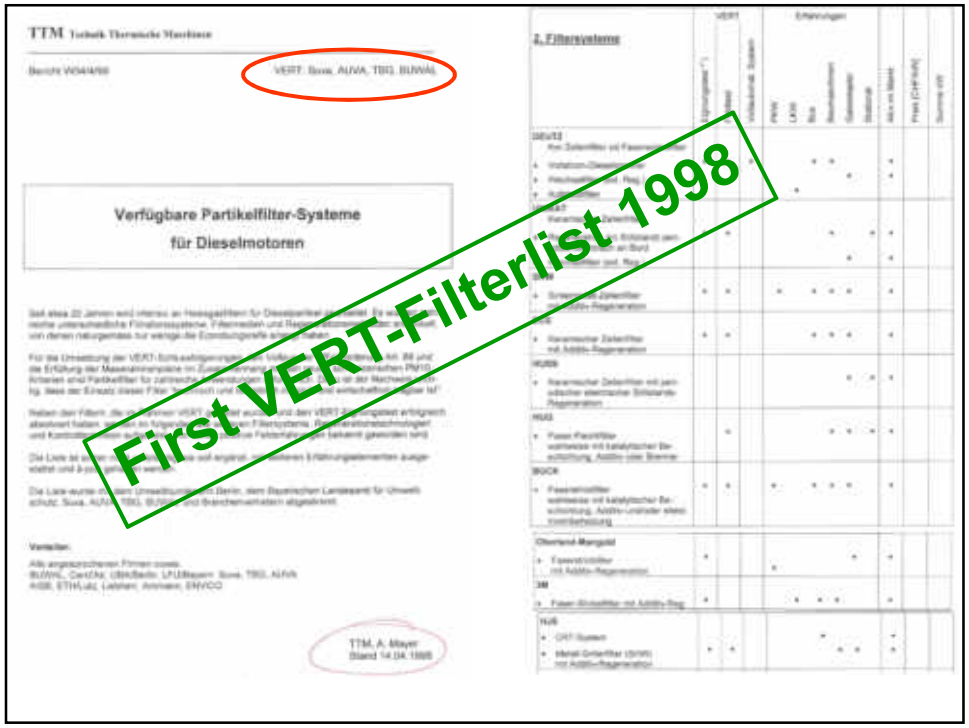
Learning Curve in Switzerland
Success need a Vision and Persistance
Inspiration & Transpiration

Year	Fuel Sulfur ppm	Retrofit total	Retro-Fitters	Failures % p.a.	VERT Certified
1988	2'000	100	2	>10	-
1992	2'000	350	2	>10	-
1995	500	500	3	>10	5
1998	500	900	8	10	16
2000	350	2'500	12	8	23
2002	50	4'900	7	3	8
2003	50	6'500	11	2	22
2005	10	11'500	21	2	30
2007	10	17'500	26	2	50
2010	10	25'000	30	<2	71
2012	10	35'000	30	<2	75
2015	10	46'000	32	<2	80
2020	10	55'000	35	<1	85

Y 2000: failure rate too high, 15 manufacturer deverified,
2000 hrs endurance introduced

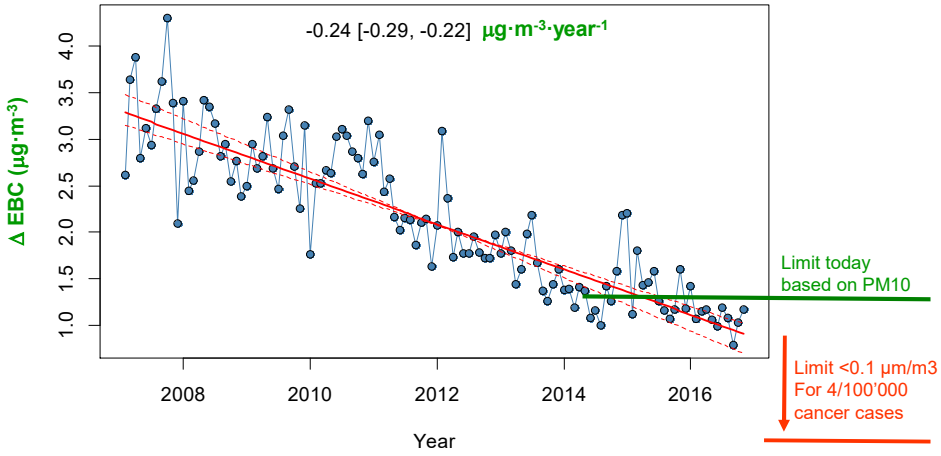
Importance of number counting metrology
walk through the city and monitor PN pollution





and the Result:
Cleaning the Air by DPF in Switzerland

Monitoring BC at the motorway crossing Härkingen



Followers worldwide

- **EUROPE: 540'000 (2001-2015)**
- **USA : 120'000**
- **ASIA : 545'000 mainly Korea and Japan**

	Y2001-Y2005			Y2006-Y2010			Y2011-Y2015			Y2016-Y2020			Total
	Bus	Truck	NR	Bus	Truck	NR	Bus	Truck	NR	Bus	Truck	NR	x 1000
Switzerland	3	1	7	2	1	11	3	2	16	-	1	8	55
Germany	20			25	50		5	50				40	190
Italy	10			20			15						45
France	7			3			2					10	22
G.Britian	9	11		12				10	1			5	48
EU-Rest	15			15			15						45
EU Indoor			50			75			75			50	250
USA	20	10		12	22	2	20	28	7	10	20	10	161
Latin Amer.				3			1			10	40	10	64
Iran										8	35	2	45
Israel										4	5	2	11
Korea	10	20		20	130		20	80		20	70		370
Japan	30	30		30	30		30	30		-	-		180?
China				4	4		15	10	1	50	30	50	164?
Asia-Rest	15			15			15			25			70
Sum	139	72	57	149	249	88	141	210	100	127	201	187	
Total		268			486			451			515		
Total					1'205 (Europe: 541)								1'720

Table 2: Retrofits worldwide (x 1000)

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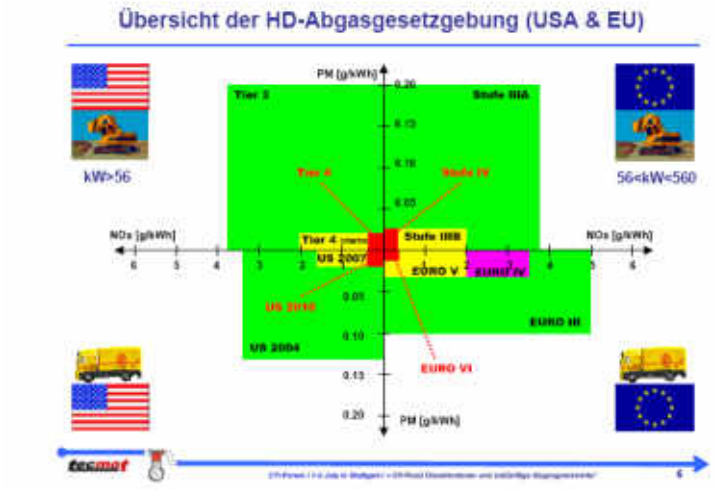
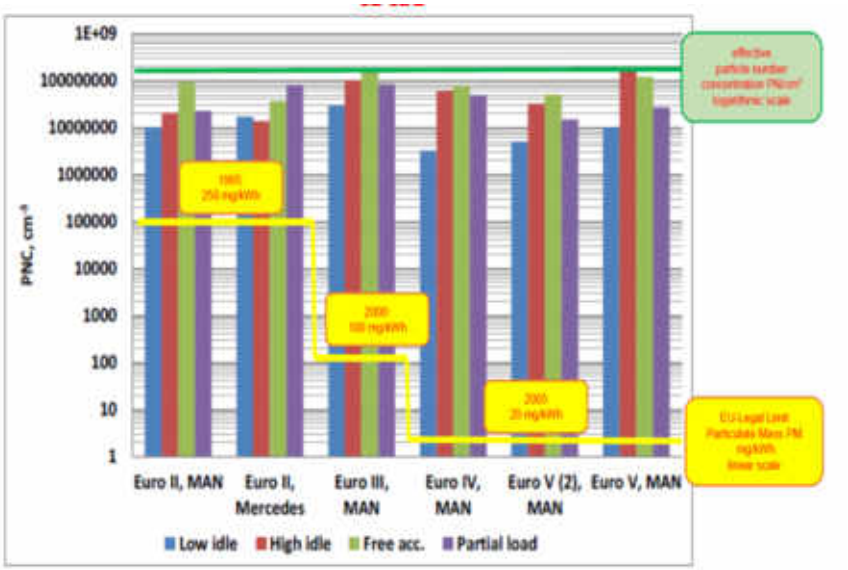
Response of International Legislation ?

→ Impressive reduction of PM Mass
but is this the solution ?

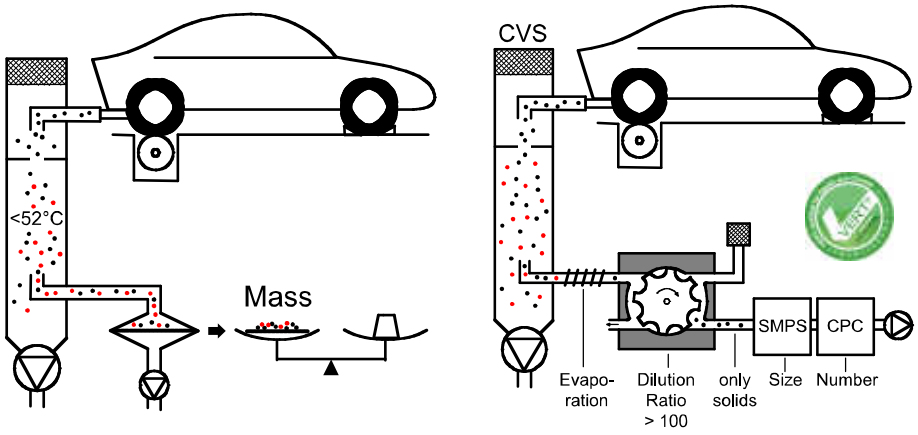


No Change of PN Concentration < 500



Change from unspecified PM to solid Particle number PN and size

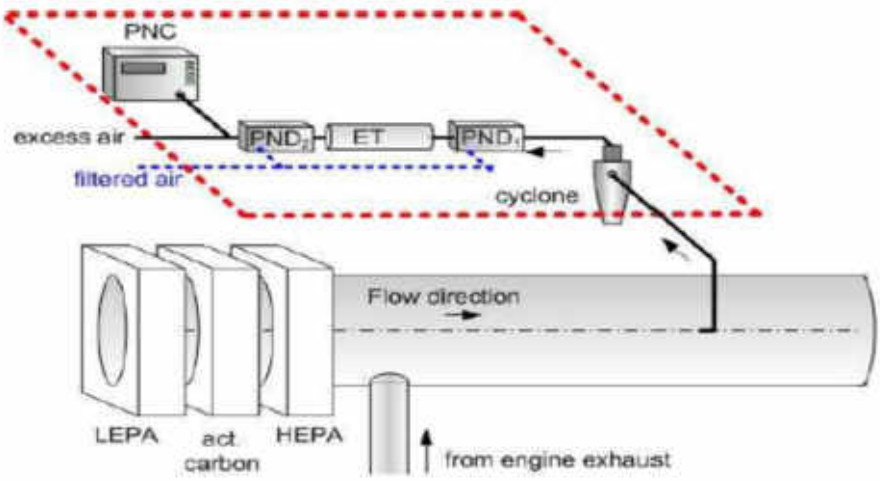
In Switzerland 10 years before EU-PMP



EU-PMP

PMP-Set-up for solid particle counting

PNC 23-2500 nm; ECE/324/ Add.48, R49 – July 2011

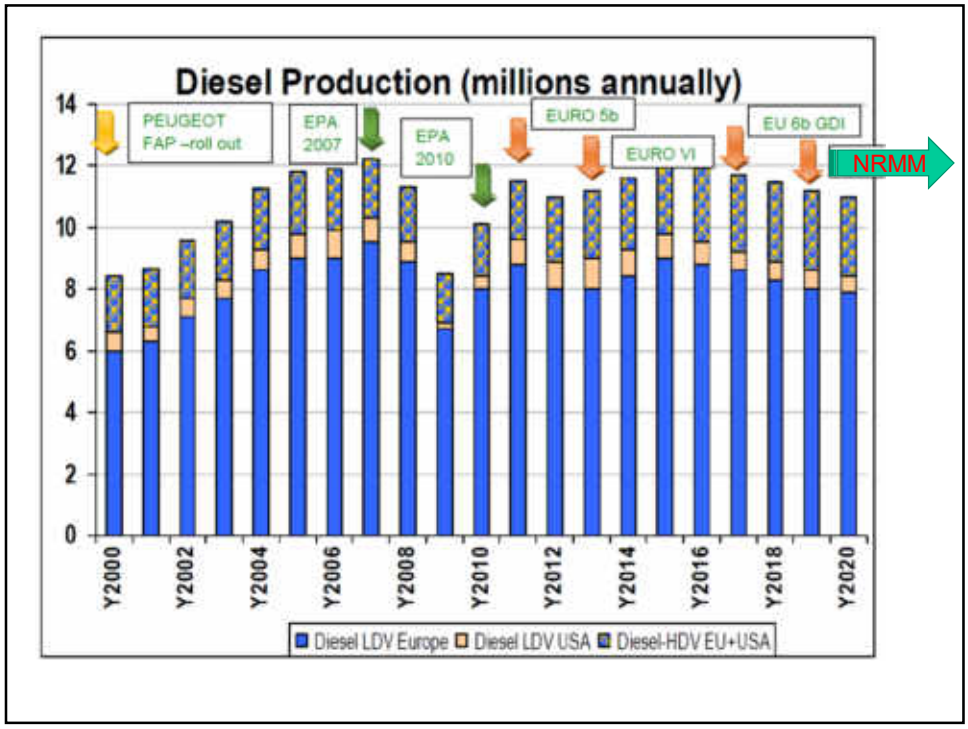


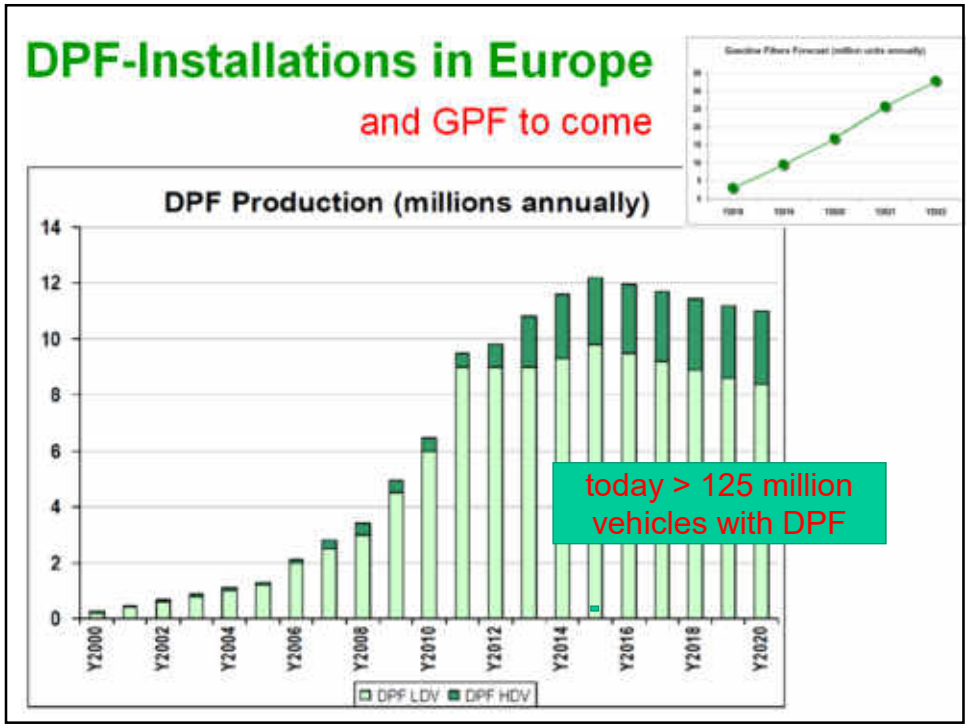
EU adopts VERT Criteria in 2006

EU Co-Decision (Art.12, Rec.15)

- *In order to achieve these environmental objectives it is appropriate to indicate that* ***particle number limits*** *are likely to reflect the highest level of performance with* ***particle filters*** *using best available technology*
- *.. the commission shall introduce particle number based limit values at a level appropriate to the technologies actually being used.*

but introduces DPF only with Euro 6/VI 2011

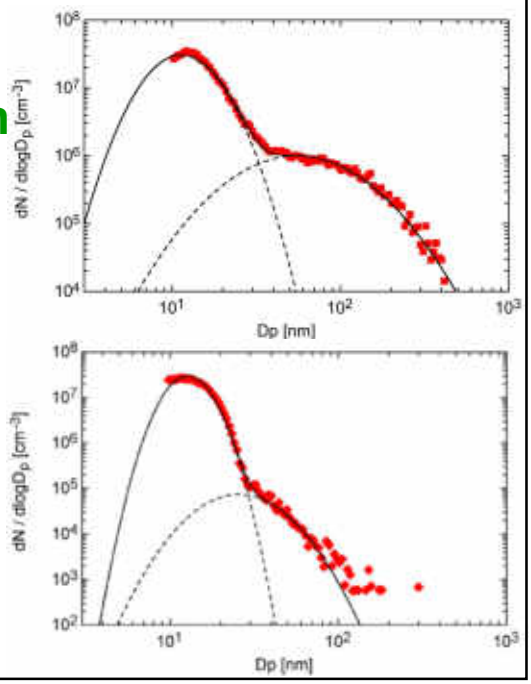

Diesel Production (millions annually)
PEUGEOT FAP –roll out
EPA 2007
EPA 2010
EURO 5b
EURO VI
EU 6b GDI
NRMM
14
12
10
8
6
4
2
0
Y2000
Y2002
Y2004
Y2006
Y2008
Y2010
Y2012
Y2014
Y2016
Y2018
Y2020
Diesel LDV Europe
Diesel LDV USA
Diesel-HDV EU+USA


DPF-Installations in Europe
and GPF to come
DPF Production (millions annually)
14
12
10
8
6
4
2
0
Y2000
Y2002
Y2004
Y2006
Y2008
Y2010
Y2012
Y2014
Y2016
Y2018
Y2020
DPF LDV
DPF HDV
today > 125 million vehicles with DPF

Particle Emission by all combustion engines

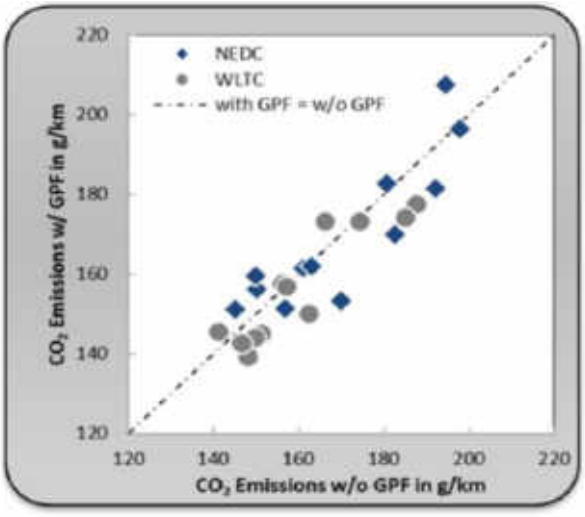
Diesel
Sootpeak: 80 nm; 10^6
Ashpeak: 10 nm; 10^7

Petrol
Sootpeak: 40 nm; 10^5
Ashpeak: 10 nm; 10^7



No Degradation of fuel consumption or CO_2 by use of Filters

Source: Integer Summit Dresden 2017



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and ambient Air Criteria?

Measurements in China:

20.12.2012 — **90-120.000 PN/cm³ at reported PM2.5>300µg/m³ → unhealthy air**

18.12.2013 — **200.000-500.000 P/cm³ at reported PM2.5<50µg/m³ → healthy air ??**

Apparent disconnect between PN number concentrations and PM concentrations in highly polluted atmospheres which metric characterizes pollution best ?

China

Cooperation Project Switzerland-China 2009-2015

VERT coordinated DPF Certification


Technical Guide for Diesel Vehicle Particulate Emissions Treatments in Beijing

Compiled by: Beijing Automotive Research Institute Co., Ltd.
December 2007


SZDB/Z 200-2017

Technical Regulation of Retrofitting In-use Diesel Vehicle and Non-road Mobile Machinery with Particulate Filter in China

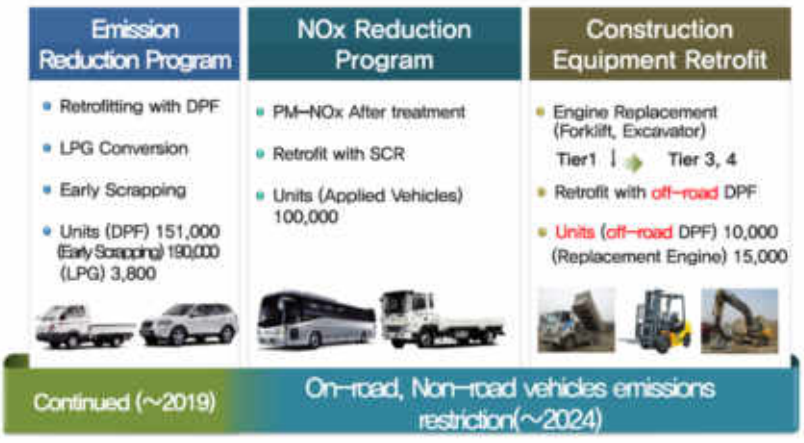
CAEPI

中国环境保护产业协会标准

KOREA

Cooperation VERT since 2004

VERT coordinated DPF Certification



Latin America

VERT coordinated DPF Certification

LEY N° 1972 18 JUL 2019

"POR MEDIO DE LA CUAL SE ESTABLECE LA PROTECCIÓN DE LOS DERECHOS A LA SALUD Y AL MEDIO AMBIENTE SANO ESTABLECIENDO MEDIDAS TENDIENTES A LA REDUCCIÓN DE EMISIONES CONTAMINANTES DE FUENTES MÓVILES Y SE DICTAN OTRAS DISPOSICIONES"

EL CONGRESO DE COLOMBIA

DECRETA:

ARTÍCULO 1°. *Objeto.* La presente ley tiene por objeto establecer medidas tendientes a la reducción de emisiones contaminantes al aire provenientes de fuentes móviles que circulen por el territorio nacional, haciendo énfasis en el material particulado, con el fin de resguardar la vida, la salud y goce de ambiente sano.

ARTÍCULO 2°. *Definiciones.*

Euro VI: La norma Euro 6 está recogida en el reglamento 715/2007 adoptado por la UE (cuyo objeto establece requisitos técnicos para la homologación de tipo de los vehículos de motor). Se establecen las disposiciones sobre las emisiones de los vehículos de las categorías M1, M2, M3, N1, N2 y N3. El Euro 6 es una normativa de protección medioambiental que entró en vigor en septiembre de 2015. Su propósito es limitar las emisiones de ciertos gases contaminantes que emiten los vehículos.

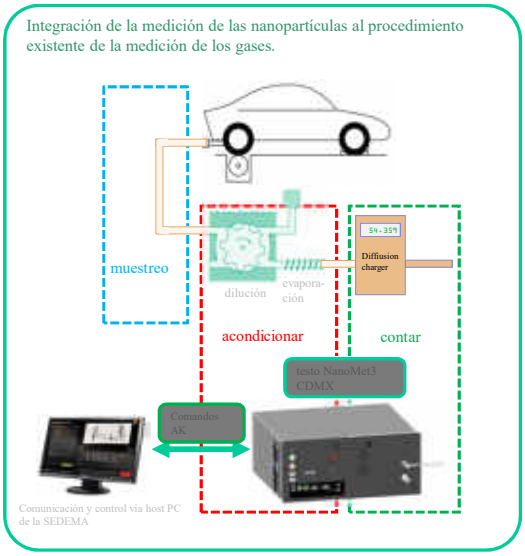
Sistema de Autodiagnóstico a Bordo (OBD): Dispositivos o sistemas instalados a bordo del vehículo y conectados al módulo electrónico de control, que tiene como objetivo identificar el deterioro o el mal funcionamiento de los componentes del sistema de control de emisiones, alertar al usuario del vehículo para proceder al mantenimiento o a la reparación del sistema de control de emisiones, almacenar y proveer acceso a las ocurrencias de defectos y/o fallas en los sistemas de control y contar con información sobre el estado de mantenimiento y reparación de los sistemas del control de emisiones.

Vehículo Ciclo Diésel: Vehículo que opera con un motor de combustión interna cuya función se basa en un ciclo termodinámico, en el cual se inyecta en la cámara de combustión el combustible después de haberse realizado una compresión de aire por el pistón. La relación de compresión de la carga del aire es lo suficientemente alta como para encender el combustible inyectado, es decir, el calor se aporta a presión constante. Para efectos de esta Ley, se incluyen los vehículos ciclo Diésel que operen con combustible diésel y sus mezclas con biodiésel, gas natural o gas licuado de petróleo.

MEXICO

VERT Particle Number measurement

in all 60
test centers
each vehicle
once per year



Iran, Israel and India

VERT coordinated DPF Certification

Bloomberg BNA Environment & Energy Report

Israeli Plan Could Snuff Out Heavy-Polluting Diesel Vehicles

INDIA BHARAT STAGE VI EMISSION STANDARDS

Iran legislation to protect the environment

from April 2014

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as requested by MDEC Conference Organizers

- The Worldwide Guidelines
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- Engine Strategies for decoupling and EAS optimization
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- Benefit / Cost for Health, Global Warming and Economy

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US-EPA stays far behind

Standard	PM requ.	PN eff.	PN requ	PM eff	Comment
Euro-I	700	$3x10^{14}$			No real progress
Euro-II	150	$2x10^{14}$			No real progress
Euro-III	100	$1x10^{14}$			No real progress
Euro-III DPF	-	$1x10^{10}$	-	0.02	Retrofit 99.99%
Euro-V	20	$6x10^{13}$			No real progress
EPA 2010	10	$3x10^{13}$			DPF not required
Euro VI (2013)	10		**$6x10^{11}$**	0.2	50x below EPA DPF required

PM [mg/kWh] CVS Particles < 2.5 µm
PN [PNC/kWh] CVS-PMP 23-2500 nm
PN converted to PM with particle diameter 70 nm

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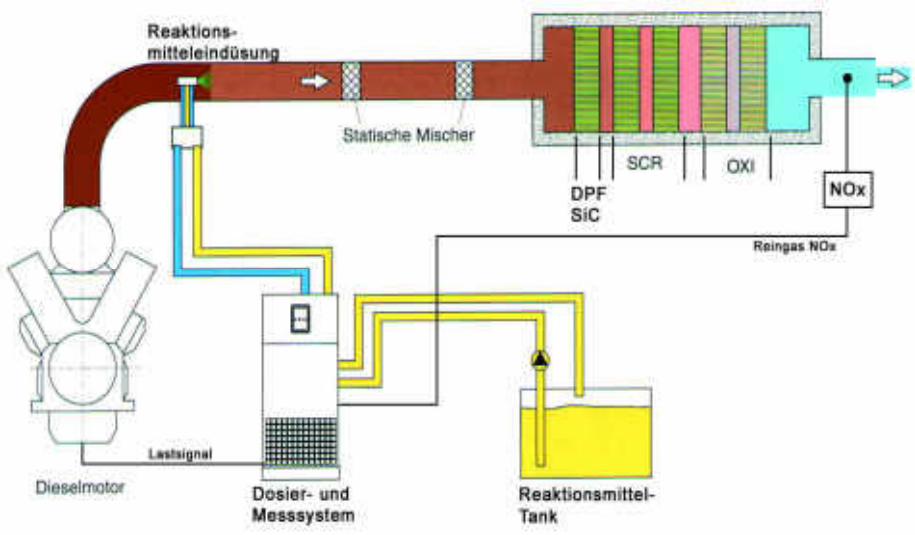
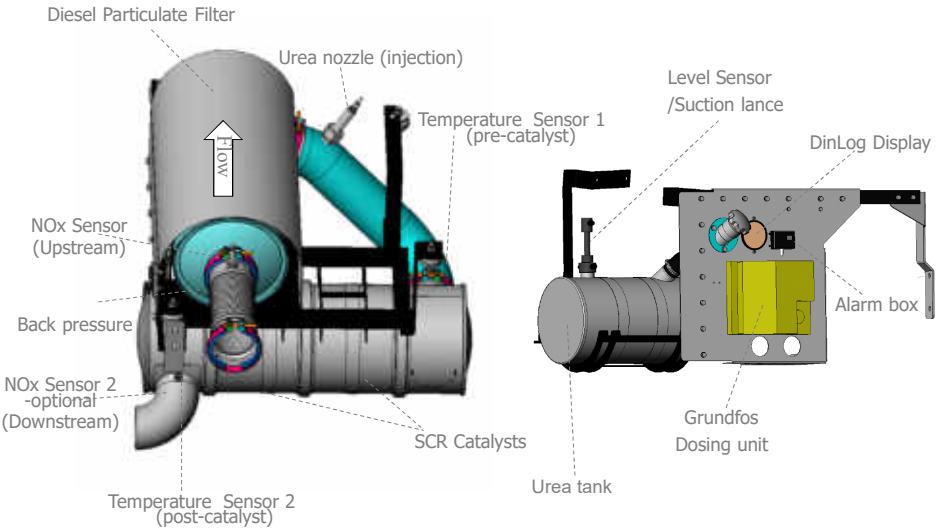
HUG stationär PFS + SCR-DeNOx 1988



DINEX 2010 VERT certified

available + effective > 250 °C but complex and bulky



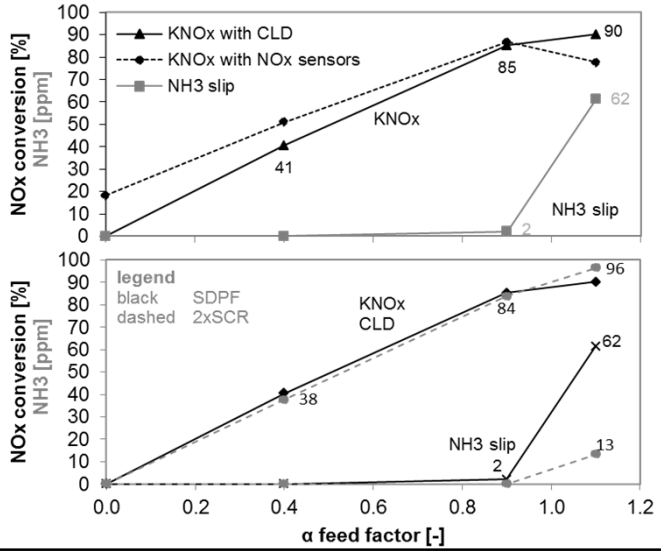
VERT-Research → SDPF 2012

(Dinges, NGK VERT-Forum 2012)

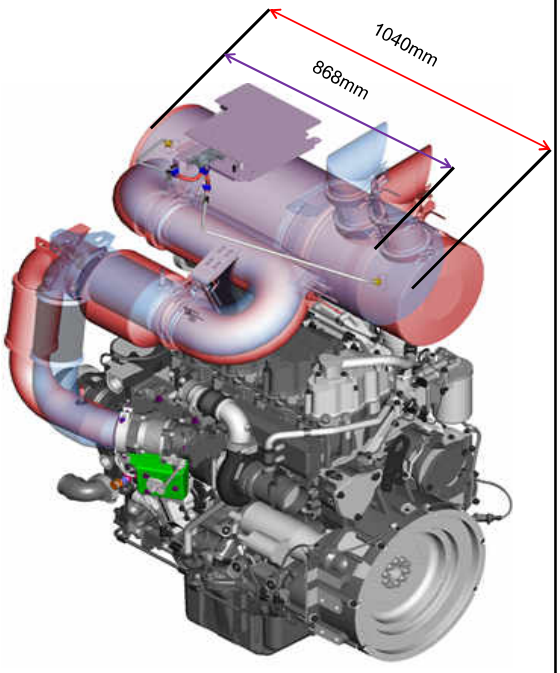
on-road: reduction of space and costs

off-road: introduction of PN regulations

VERT-Research: SCR-efficiency of SDPF at stationary OP 2200 rpm / 175 Nm &



SCR on DPF



Liebherr
Red → SCRoF (1040mm)
Purple → SCR-only (868mm)

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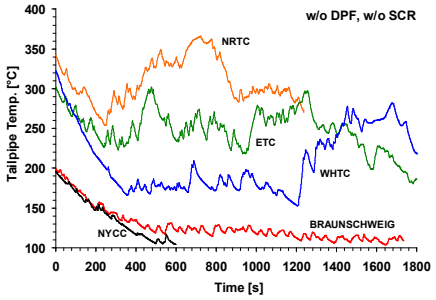
The Problem

Under normal operating conditions, the exhaust temperatur is usually too low for regeneration. Lifting the temperature by late fuel injection, HC-dosing, burners or heaters **consumes energy!**

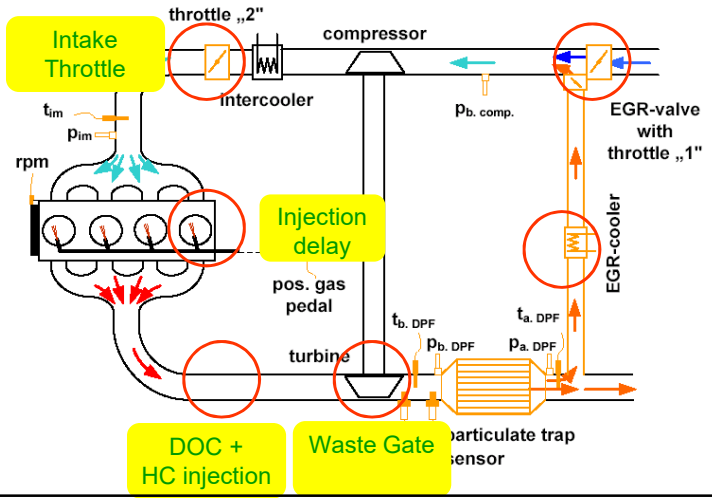
Exhaust temp.in different test cycles



Increase the temperature without adding energy ?

VERT-Research: Toolbox for Retrofit

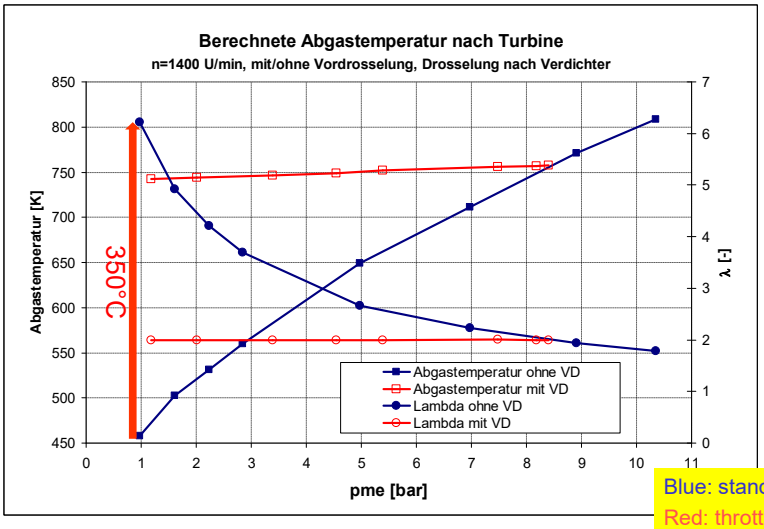
EGR clean gas, Lambda controlled combined with Intake Thottle, Waste Gate, HC injection



Hardware is available

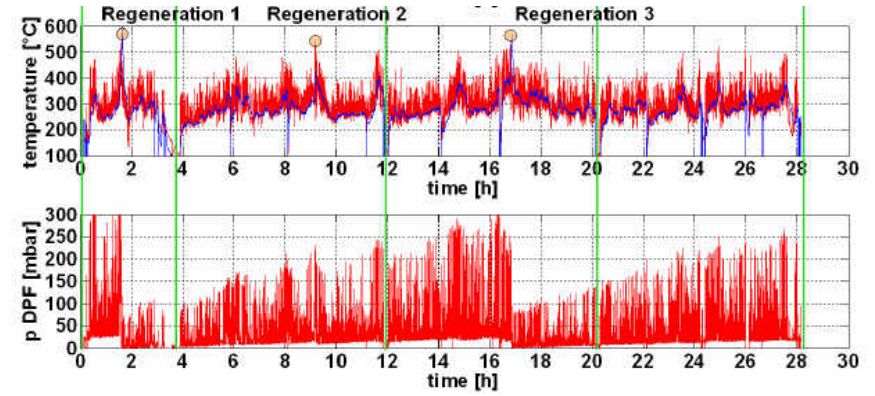
Computer Simulation

if Lambda is kept constant over load
exhaust temperature will stay nearly constant



Blue: standard
Red: throttled

Regeneration at Vehicle Operation



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Biggest Mistake of EU-Policy
Independent Control „delegated“ to OBD
invited car makers to fraudulent hard-and software

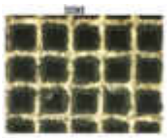
Quality Control (USA)
- **Type Approval**
- **COP** Conformity of Production
- **IUC** In Use Compliance
- **PTI** Periodic Techn. Inspection

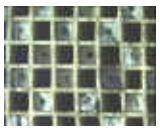
EU Quality Control 2014/45
- **Type Approval**
- **COP**
- **IUC not implemented**
- **PTI abandoned** (CH:2013)

Control for Public Health must be independent

Montesquieu: De l'esprit des lois 1748 → la séparation des pouvoirs

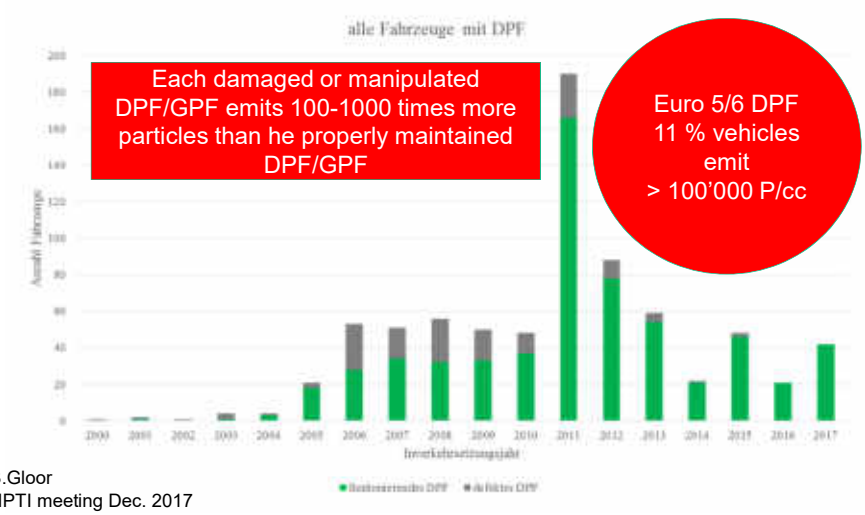
and this is what we are finding – why?





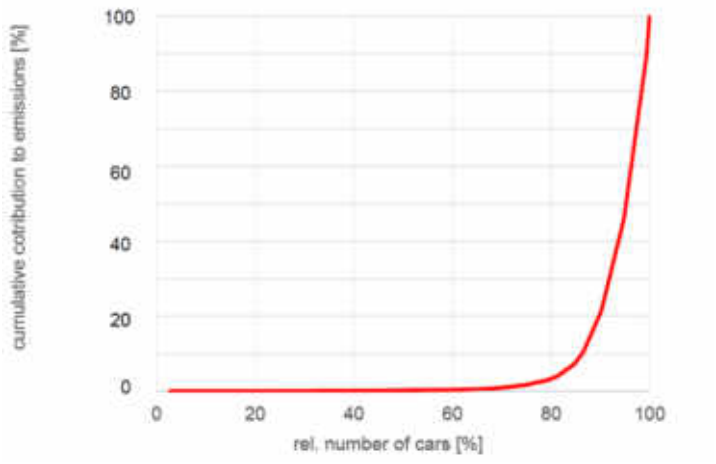
because they want to avoid cost for proper repair or cleaning

DPF Failure Statistics in Switzerland



B.Gloor
NPTI meeting Dec. 2017

Cumulative contribution of High Emittors to fleet emission

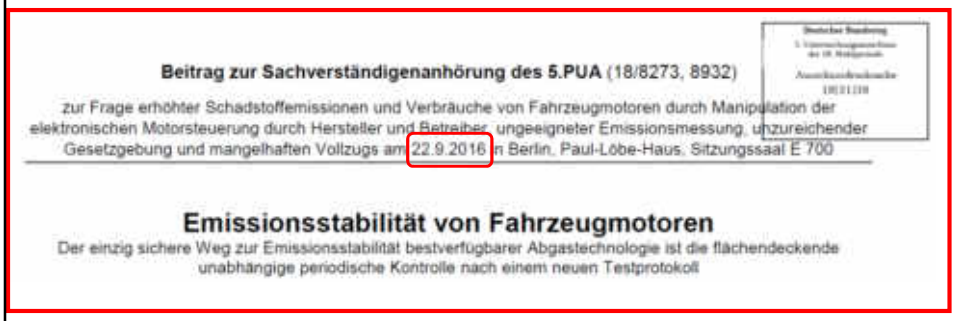


H.Burtscher / FHNW
VERT-Forum March 2019

VERT at Expert Hearing Bundestag 5 PUA Berlin 22. Sept. 2016 on Dieselgate

→ **This must be reversed and Emission PTI must become EU-Regulation**

and here is my recommendation to the German government 9/2016



Beitrag zur Sachverständigenanhörung des 5.PUA (18/8273, 8932)

zur Frage erhöhter Schadstoffemissionen und Verbräuche von Fahrzeugmotoren durch Manipulation der elektronischen Motorsteuerung durch Hersteller und Betreiber, ungeeigneter Emissionsmessung, unzureichender Gesetzgebung und mangelhaften Vollzugs am 22.9.2016 in Berlin, Paul-Löbe-Haus, Sitzungssaal E 700

Emissionsstabilität von Fahrzeugmotoren

Der einzig sichere Weg zur Emissionsstabilität bestverfügbarer Abgastechnologie ist die flächendeckende unabhängige periodische Kontrolle nach einem neuen Testprotokoll

→ Germany Road Authority reacted immediately by re-activation of AU January 2017

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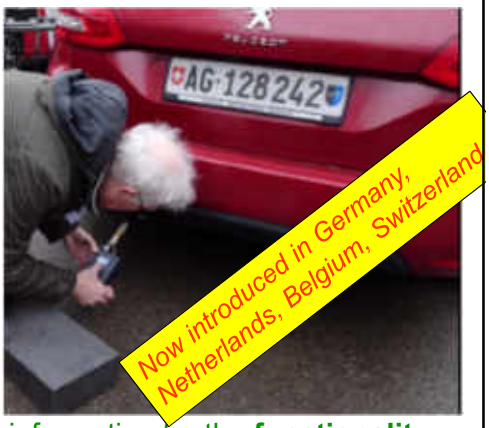
Concept of the VERT-NPTI-Group

for a very efficient and cost effective 100% in-use periodic emission control for DPF equipped vehicles

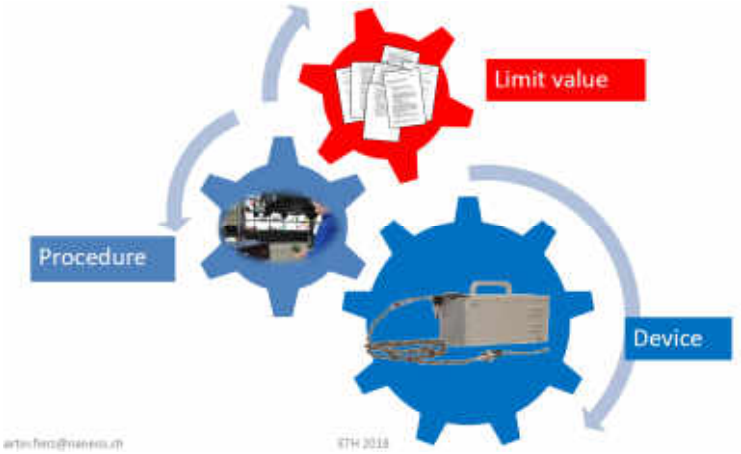
- **PN-Test at low idle**
- **PN with DPF < 10^3**
- **PN with failure > 10^6**
- **Pass/Fail: 100'000 1/cc**



This Test is more than Pass/Fail

It supplies **quantiative diagnostic** information for the **functionality** of each emission control component and the engine as well and permits **preventive repair and maintenance.**

New Periodic Technical Inspection PTI is a package with 3 elements



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Availabe Technology
Diesel DPF compared to Gasoline

Source: EU Commission Joint Research Center

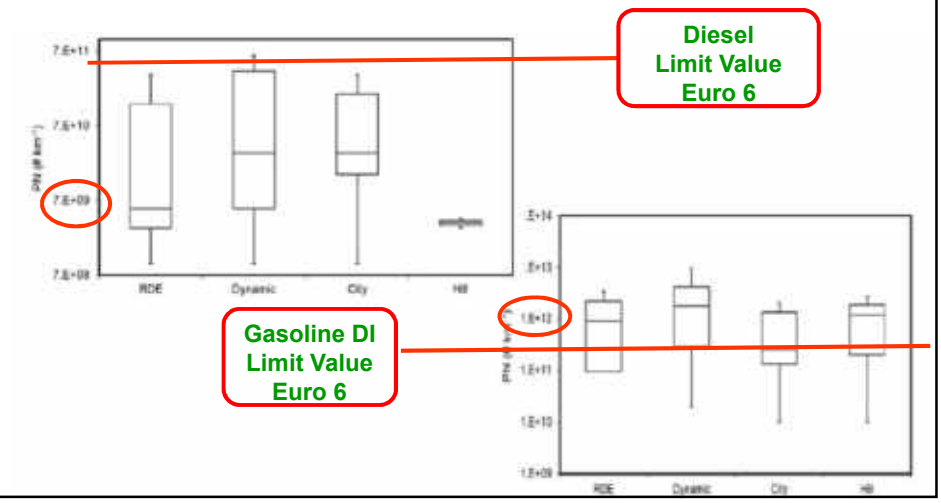

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Table 1 Air pollution cost factors in EUR/ton of pollutant (€2008 values)

Pollutant	$PM_{2.5}$ (exhaust)			PM_{10} (non-exhaust)			NO_x	NMVOC	SO_2
Region type	Metropolitan	Urban	Non-urban						
Source	HEATCO	*UBA/ HEATCO	HEATCO	HEATCO	HEATCO	HEATCO			
Country									
Austria	482,200	155,900	80,700	192,900	62,400	32,300	13'600	1'600	10'000
Belgium	483,400	156,000	104,400	193,400	62,400	41,700	8'700	2'600	10'900
Bulgaria	70,500	22,700	18,100	28,200	9,100	7,200	7'100	400	6'200
Czech Republic	355,400	114,500	88,200	142,200	45,800	35,300	10'600	1'100	9'500
Denmark	436,400	140,700	51,300	174,500	56,300	20,500	5'300	1'200	5'700
Estonia	261,700	85,000	44,200	104,700	34,000	17,700	2'800	600	4'500
Finland	432,600	139,400	36,100	173,000	55,800	14,400	2'600	600	3'500
France	438,600	141,200	87,70						00
Germany	430,300	138,800	83,90						00
Greece	338,600	109,100	47,70						00
Hungary	288,900	93,000	74,10						00
Ireland	537,200	173,400	56,20						00
Italy	397,400	128,400	72,30						00
Latvia	245,300	78,900	45,60						00
Lithuania	266,300	86,500	53,30						00
Luxembourg	877,100	282,400	125,000	350,800	112,900	50,000	12'700	2'400	10'300
Switzerland	498,700	160,500	82,400						
Poland	248,900	79,900	74,700						

Emission monetized

Switzerland
498 € / kg PM2.5
>1200 € / kg Soot

Source:
EU research study NEEDS 2008 [485]

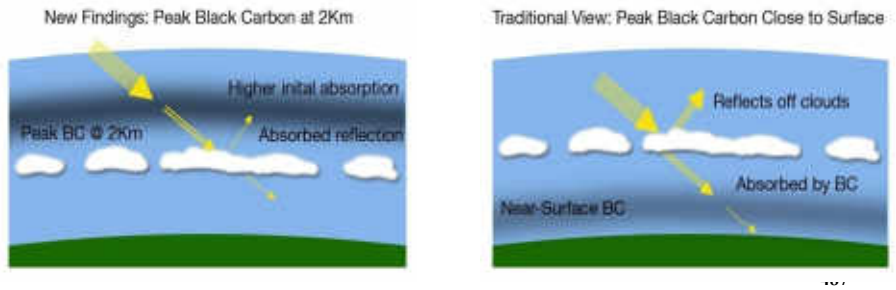
Health Benefit in case of a typical Retrofit DPF-Application

	HDV+FFF	
PM-Emission (Euro III / 3)	0.1 g/kWh	
Mileage	1000 hrs/yr	
Average Performance [kW]	100	
PM Emission [kg/year]	10	
Overall vehicle life [year]	15	
Emission [kg/vehicle life]	150	
Filter type	wall flow	
Filter efficiency [%]	99.9	
Health Cost [€/kg Soot]	1'200	
Total prevented soot [kg/life]	150	
Health Benefit [€]	**180'000**	

Health Benefit of DPF is about the investment for a vehicle [486]

and we have a co-benefit FOR GLOBAL SURVIVAL

since DPF can contribute to lower global warming by eliminating Black Carbon Particles, which are Number 2 GW-substance after CO_2



Benefit /Cost by EAS Truck Application

Combustion soot is carcinogen, triggers heart attacks and strokes
Health benefit is 498 € /kg PM 2.5 but 1 kg of PM2.5 only contains only < 20% of soot particles, so the monetary value of 1 kg of engine emitted soot particles might be as high as 1'200.- Euro. → 180'000 €

Combustion soot is also a very strong global warming substance
and the CO_2-equivalent of 1 kg combustion soot is 4400 kg CO_2
Assuming a "price" for CO_2 of 50 Euro per ton CO2, the GW damage of 1 kg soot comes to 220 Euro → 33'000 €

EAS permits efficiency increase (CO2 reduction) by decoupling
with 10% efficiency gain which is state of the art → 40'000 €

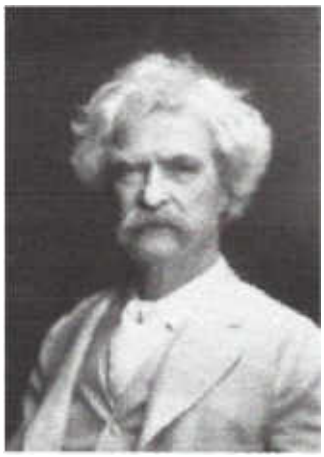
Overall Benefit: 253'000 €
Overall Cost: 10'000 €
Benefit / Cost 25

Monetärer Nutzen:

Kanton Zürich spart
550 Mio CHF
extern. Gesundheitskosten
durch Partikelfilter – 4/2018

Luftschadstoffe beeinträchtigen die Gesundheit und verursachen hohe volkswirtschaftliche Kosten.

Luft
ZUP Nr. 90 April 2018



Mark Twain

Keep in mind

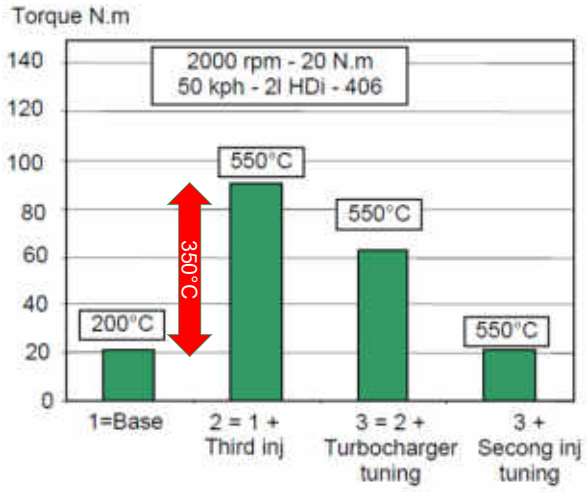
«What gets us into trouble is not what we don't know It's what we know for sure that just ain't so»

Test Cycle on a Floor Chassis Dyno

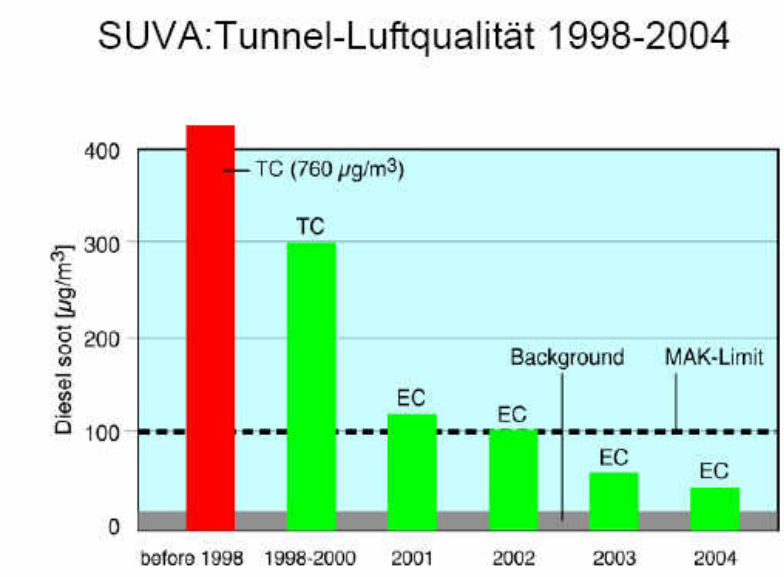
(Quelle: MAHA)

20 years old result from Peugeot

using multiple injection and catalytic combustion



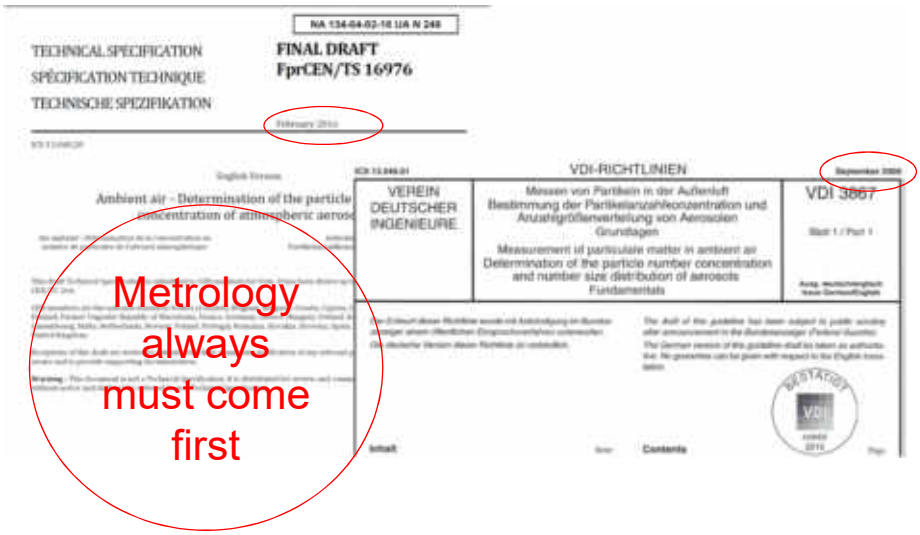
SAE 2000-01-0473
Belot et al



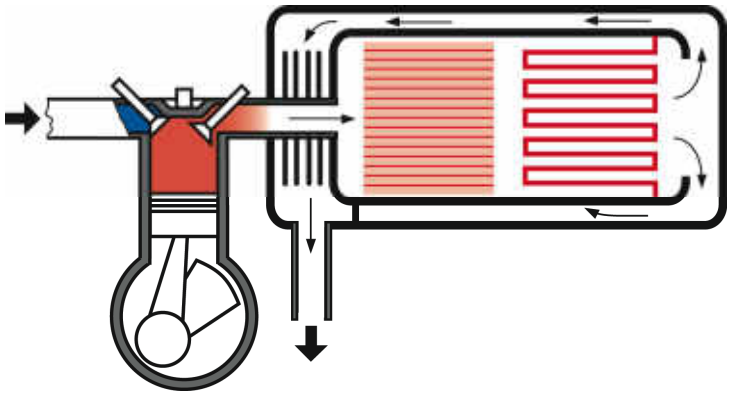
Improvement of Air Quality in Swiss Tunneling

"no Diesel without filter" since 1997

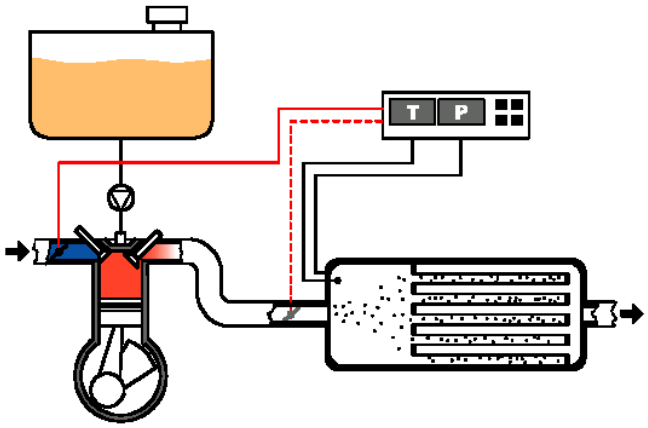
Aerosol Society is preparing the Standards



Heat Recuperation



Temperature Managment for Regeneration by Throttling



VERT-Team *power on demand*

A. Mayer

Schweizerische Eidgenossenschaft
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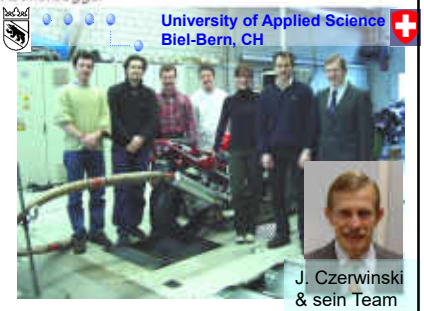


Matter Engineering AG

M. Kasper
& sein Team

H. Burtscher

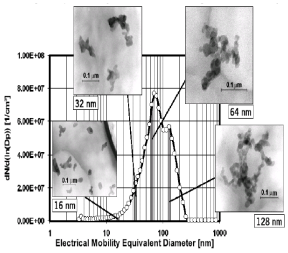
J. Czerwinski
& sein Team

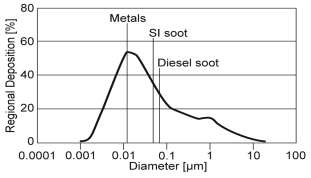
guided by
Aerosol Research

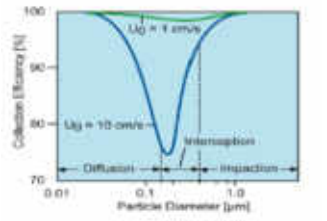
strange coincidence

The most sensitive size range
of the Lungs
is the most intensive emission range
of the Engines
and the weakest size range of
Filtration

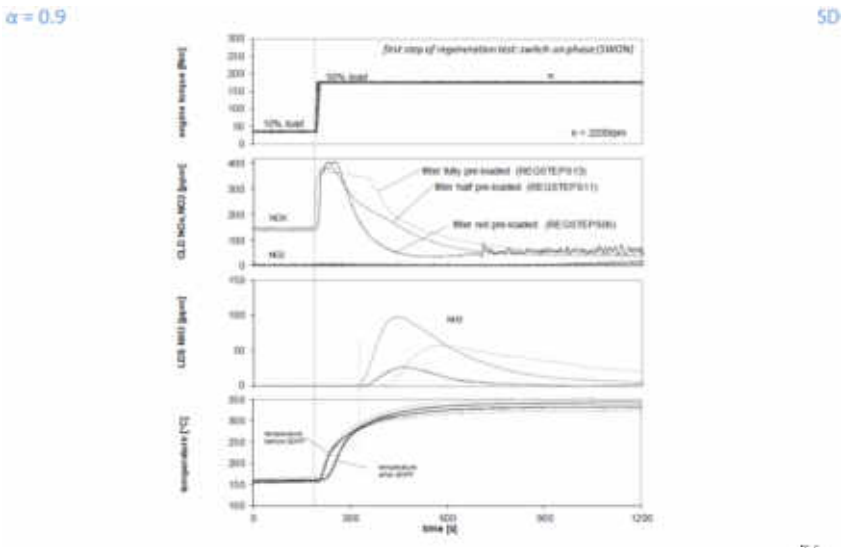
The Lung is an open door for
engine emitted particles



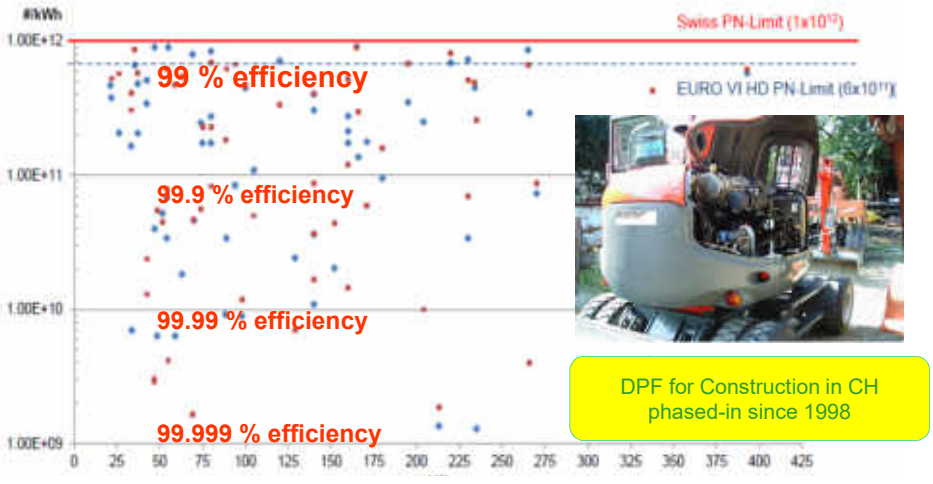




VERT-Research SDPF – Dynamics



PN-Test results

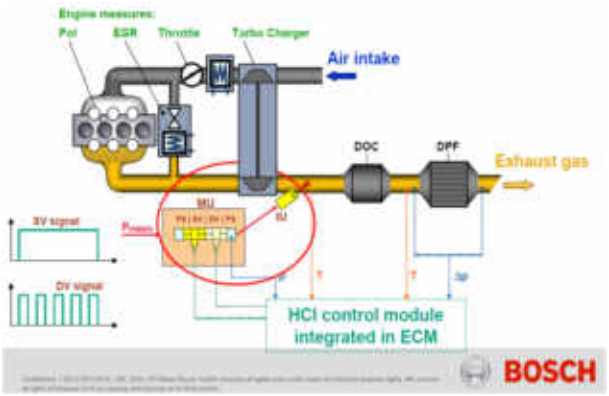


DPF for Construction in CH
phased-in since 1998

Type approval of imported construction machines
in stationary and transient cycle In function of engine power [kW]
DPF Technologies permit limit strengthening by one order of magnitude

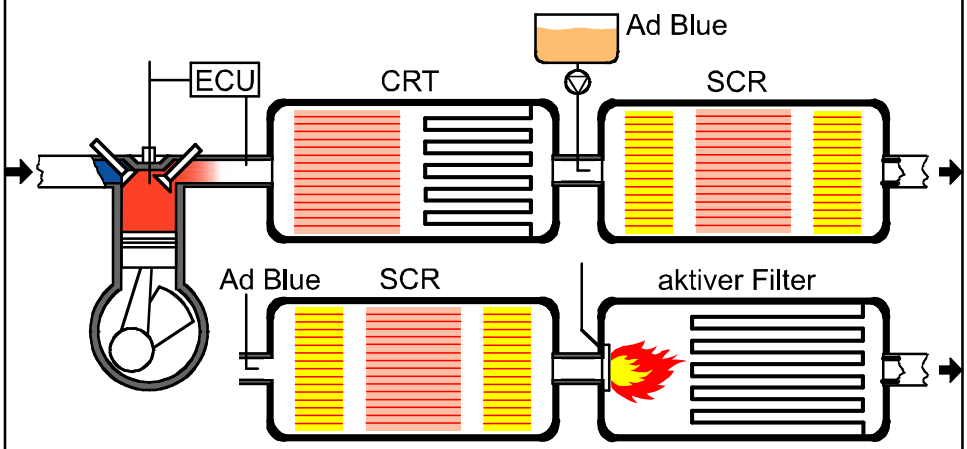
And now: Thermomanagment Tools are available in all modern vehicles

for DPF-Regeneration, SCR-Support, Deposit Cleaning



- Intake Throttle
- HC-injection
- Catalyt Combustion
- Retarded injection
- Multiple Injection
- TC-Management
- EGR Managment
- Cooler Managment
- Electric Load

Combination of SCR and Particle Filter



VERT-Conformity Criteria 1998

VERT-Pflichtenheft für Partikelfiltersysteme bei Baumaschinen Stand 15.4.98

Abscheidegrad (am Referenzmotor Liebherr 914 T)

- Gesamtpartikel, gravimetrisch (ISO 8178 C1, 4 Testpunkte) > 90%
- Elementarer Kohlenstoff, coulometrisch > 95%
- Russstoss bei freier Beschleunigung: Opazität < 10%
- Penetration von Feststoff-Feinpartikeln im Grössenbereich10-500 nm < 5% (Anzahlkonzentration)

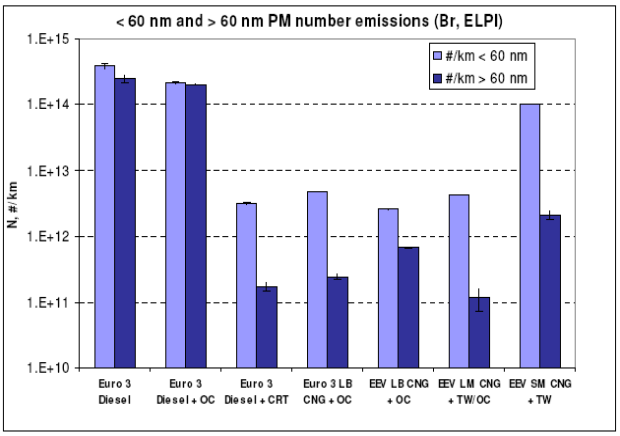
Zusatzanforderungen Emissionen

Es ist keine messtechnisch eindeutig nachweisbare und relevante Erhöhung folgender Emissionen gegenüber dem Ausgangszustand des Motors zulässig, insbesondere:

- Sulfatbildung, Schwefelsäure-Aerosole
- Sekundäremissionen durch Brennstoff-Additive
- Sekundäremissionen durch Dioxinbildung
- Erhöhung der Grundemission CO, HC, NO NO_2 (Summe Zyklus)
- Mineralfaser-Emission

Partikelanzahl Erdgas/Diesel

< 60 nm und > 60 nm



Quelle: VTT-Studie, 2004

Feasibility study of diesel particulate filter (DPF) retrofit solutions

Vahid Hosseini[1,2], Mahdi Doozandegan[2]

1- Mechanical Engineering Department, University of Alberta, Edmonton, AB, Canada
2- Mechanical Engineering Department, Sharif University of Technology, Tehran, Iran

25th MDEC annual conference
October 8-10 , Toronto, Canada

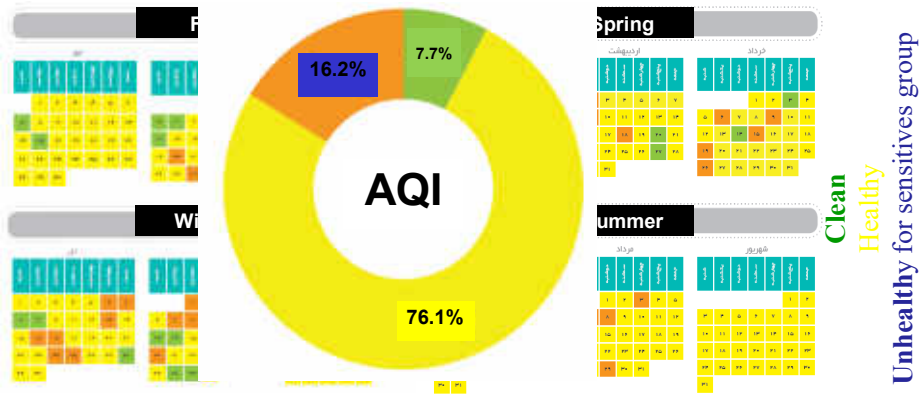
Table of content

- The case of a mega-city air pollution: Tehran
- Feasibility study of DPF retrofit solution for diesel buses
  - Technology evaluation on the engine dynamometer
  - Durability and practical considerations
- Results and cost-benefit ratio calculations
- Conclusions

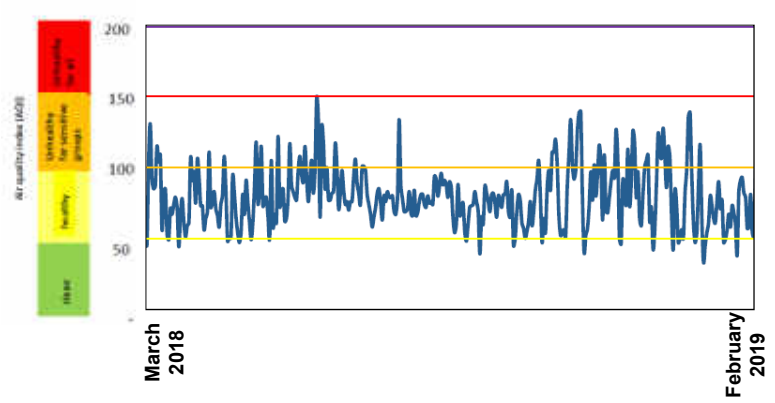
Pictures from Tehran

- Population: 8.5 million
- 4 million LDVs and motorcycles all gasoline and CNG
- 130,000 HDVs, all diesel

Air quality index (During March 2018 to February 2019)

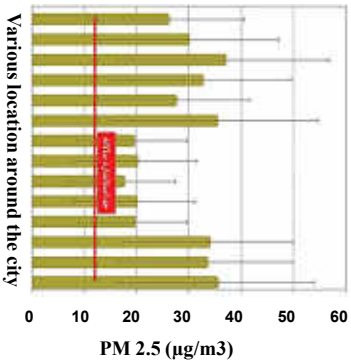


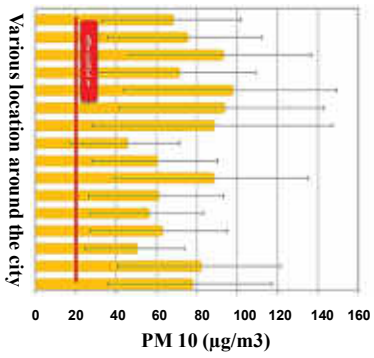
AQI during March 2018 to February 2019- Iranian 1397



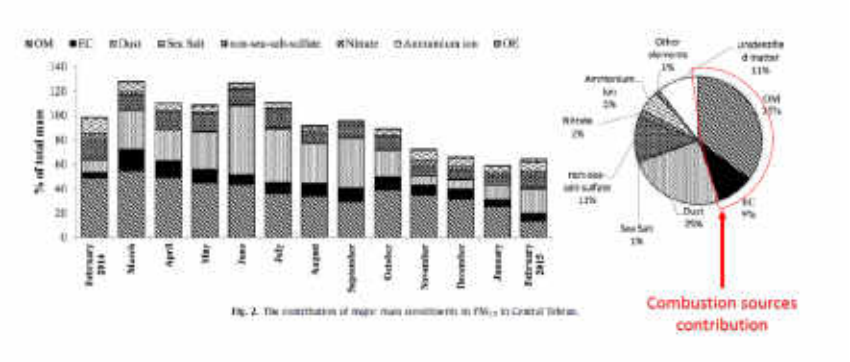
Annual Concentration of PM2.5 in AQCC Station in the City of Tehran
During March 2018 to February 2019

The red lines are national standard level (the same as WHO recommendation)

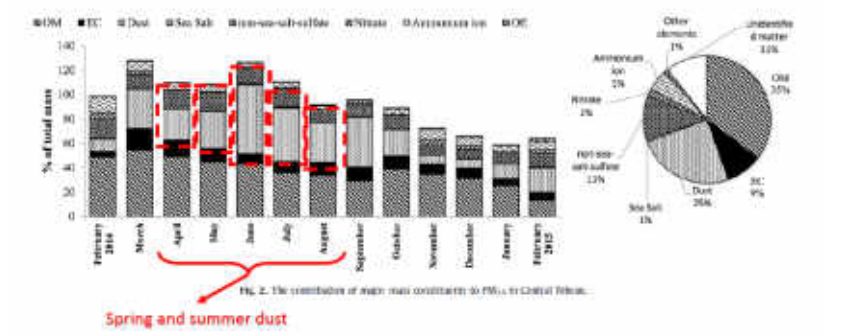




PM2.5 source apportionment study

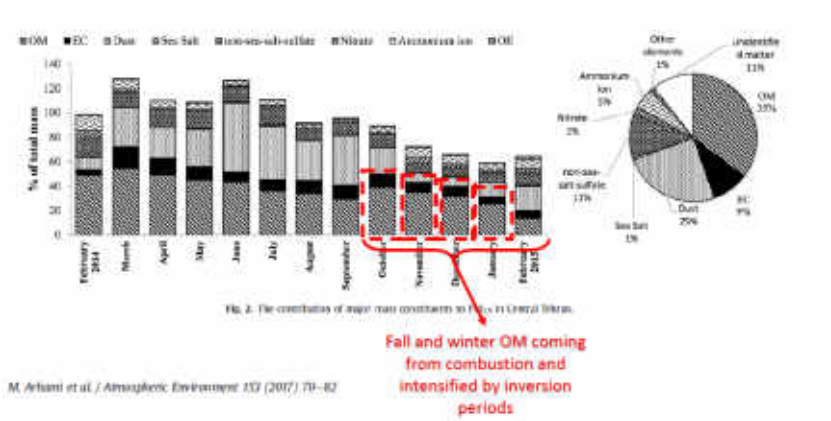


PM2.5 source apportionment study

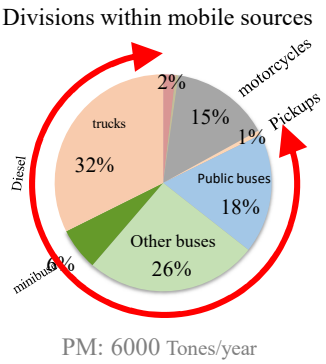


M. Arhami et al. / Atmospheric Environment 153 (2017) 70–82

PM2.5 source apportionment study

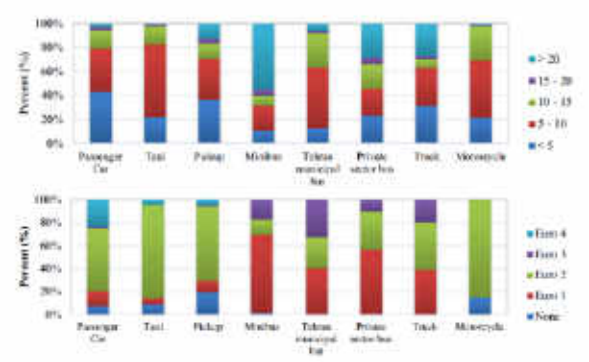


Mobile source fleet composition effects on PM contribution

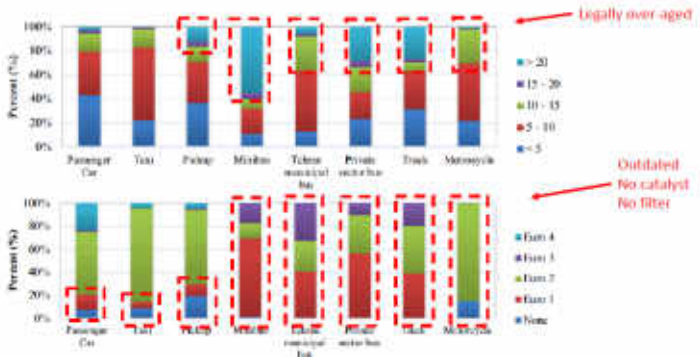


Shahbazi H, Reyhanian M, Hosseini V., et al., The Relative Contributions of Mobile Sources to Air Pollutant Emissions in Tehran, Iran: an Emission Inventory Approach, Emission Control Science Technology, vol 2, No. 44

Tehran fleet age and emission standards



Tehran fleet age and emission standards



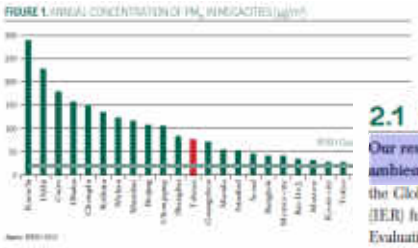
The World Bank discussion paper regarding air pollution on Tehran

DETAILS

Document Date	2018/04/01 14:09:03
Document Type	Working Paper (Numbered Series)
Report Number	126402
Volume No	1
Total Volume(s)	1
Country	Iran, Islamic Republic of
Region	Middle East and North Africa
Disclosure Date	2018/05/22 14:09:32
Disclosure Status	Disclosed
Doc Name	Air Pollution in Tehran : Health Costs, Sources, and Policies Discussion Paper

See More +

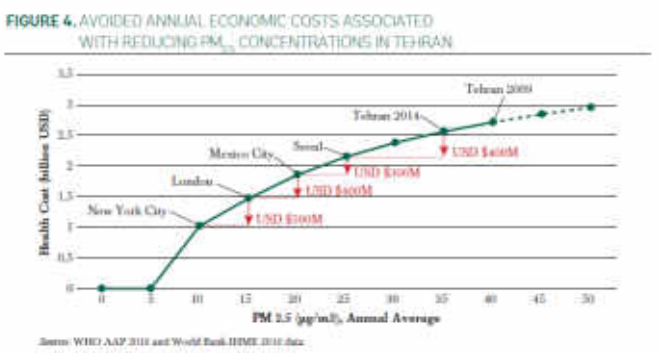
The World Bank discussion paper regarding air pollution on Tehran



2.1 MORTALITY

Our research indicates that slightly more than 4000 people die prematurely from ambient $PM_{2.5}$ air pollution in Tehran per year. We arrived at this measure using the Global Burden of Disease (GBD) methodology and Integrated Exposure-Response (IER) functions, as outlined by the recent World Bank-Institute for Health Metrics and Evaluation (IHME) publication (Narain and Sall 2016). The GBD methodology predicts premature mortalities based on relative risk functions drawn from the epidemiological literature. The reference provided gives more information about the methodology.

The World Bank discussion paper regarding air pollution on Tehran



economic burden of 2.6 Billion USD per year

Legislation

- DPF was first introduced to nation in 2014 by VERT activities, establishing an office in Iran in 2014
  - Feasibility study project
  - 50 buses retrofitted with DPF in Tehran during 2016-2017 (first retrofit project)
  - 60 DPFs were purchased for second retrofit project (for Tehran)
- Since then, there is a national legislation for Euro IV+DPF for new diesel vehicles starting Sep 2016
  - Approx. 5000 VERT-approved DPFs and more than 6000 other DPFs have been already installed in the market (newfit, option-fit and retrofit)
- European OEMs lobbied for Euro V EEV to be added to legislation.
  - This is planned to scrapped one old diesel vehicle for every new EEV vehicle by manufacturers. This encourage manufacturer to produce EU IV+DPF instead of EEV.

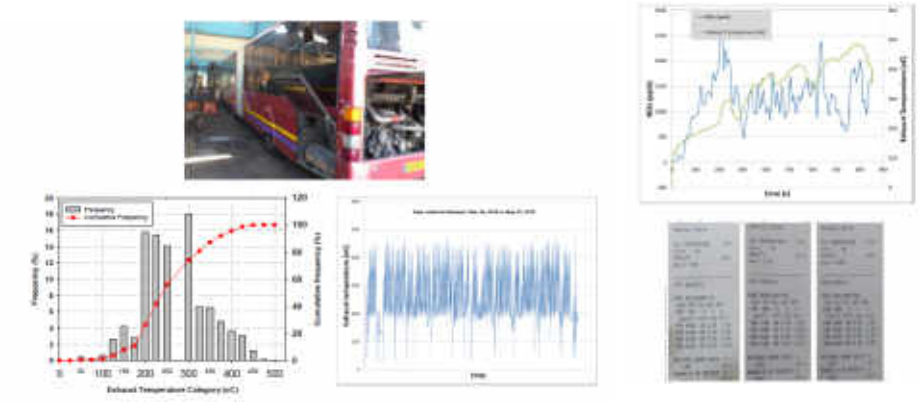
DPF retrofit of public transit city buses in Tehran: Main concerns

- Low exhaust temperature
- High fuel sulfur content or unstable distribution
- High sulfate ash lube oil
- High smoke number and low NOx

DPF Retrofit feasibility study program

- Selection of candid engine and vehicles, exhaust data gathering
  - MAN articulated buses with Euro II and Euro III engine
- Engine dynamometer tests
  - Daimler OM 457 Euro II engine
  - Fuel sulfur content: 50 ppm, 229 ppm and 7000 ppm
- Year-long durability tests on buses
  - Hot and cold exhaust gas's line

Baseline data collection campaign



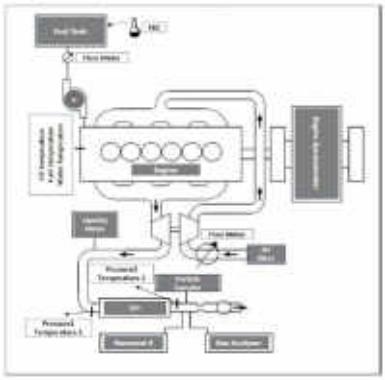
Engine dynamometer tests

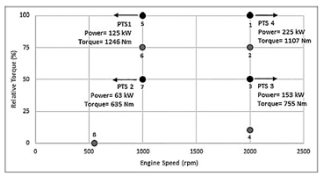
- Test procedure: VFT 1
- Tested engine: Daimler OM 457
- Tested fuel: LSD (50 ppm), MSD (229 ppm), HSD (7000 ppm)
- Number of tests: more than 7 DPFs with different fuel
- Evaluation criteria:
  - DPF performance (PM & PN efficiency, gaseous emission)
  - Safety issues
  - Regeneration quality and soot capacity
  - Sulfur tolerances

Test cell preparation

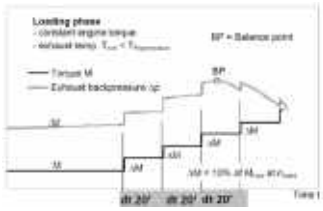



Engine test layout and test procedures





4-point stationary test, efficiency tests

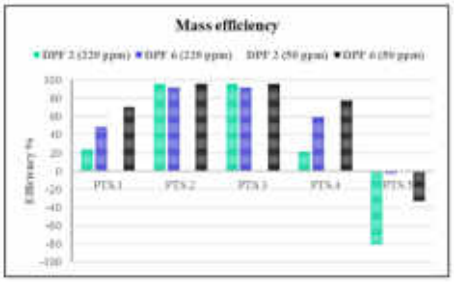


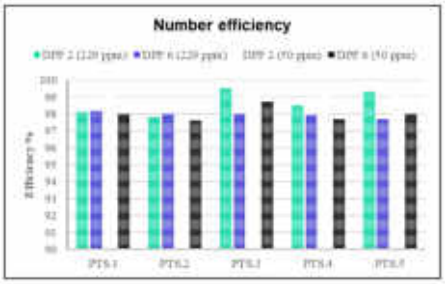
Ramp up test, regeneration test

Engine test cell results

DPF type and technology				Tested fuel sulfur content			Cause of failure
DPF No.	Active/Passive	Regeneration method	Core type	50 ppm	229 ppm	7000 ppm	
1	Active	Electrical heater + FBC	Sintered metal	-	✓	✓	-
2	Passive	DOC upstream of filter (CRT)	Sintered metal	✗	✗	-	Fuel sulfur content Low PM efficiency
3	Passive	FBC	Silicon carbide	-	✓	✓	-
4	Passive	FBC + Catalyst upstream of DPF	Cordierite	-	✓	✓	-
5	Passive	Catalyzed DPF (CDPF)	Cordierite	-	✓	-	-
6	Passive	DOC upstream of filter (CRT)	Silicon carbide	-	✗	-	Fuel sulfur content Low PM efficiency
7	Passive	DOC upstream of filter (CRT)	Silicon carbide	-	✗	-	Fuel sulfur content Low PM efficiency
8	Passive	FBC	Silicon carbide	-	✗	-	Filter cracking
9	Active	diesel burner technology	Silicon carbide		✗	✗	Safety issue
10	Passive	FBC	Silicon carbide	-	✓	-	-

Mass and number filtration efficiency of CRTs with 50 ppm and 229 ppm sulfur diesel

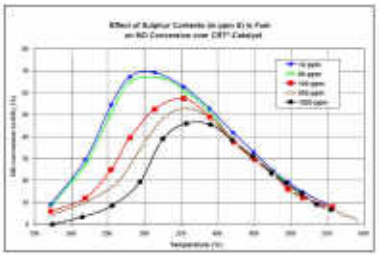




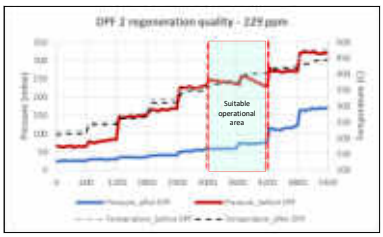
Point No.	Engine rotational speed (rpm)	Load (%)	Average temperature (°C)
PTS.1	1000	100	470
PTS.2	1000	50	327
PTS.3	2000	50	330
PTS.4	2000	100	415
PTS.5	1000	100	480

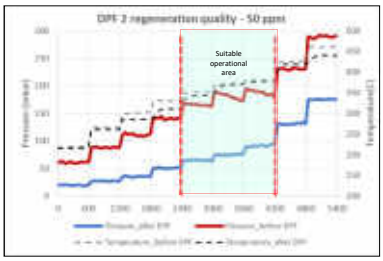
DPF No.	DPF 2 (229ppm)	DPF 6 (229ppm)	DPF 2 (50 ppm)	DPF 6 (50 ppm)
Average	98.6	97.9	98.8	98

Regeneration quality of CRTs

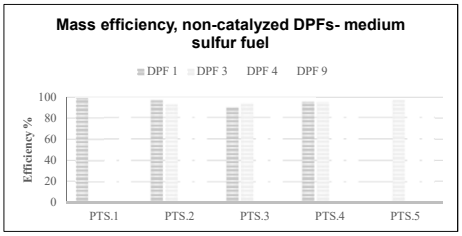


Warren 1998

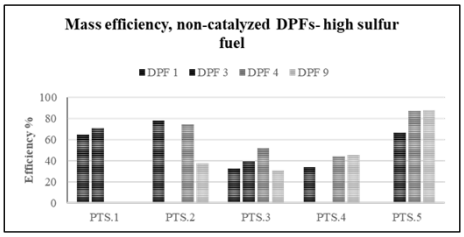




Mass filtration efficiency of non-catalyzed DPF with 229 ppm and 7000 ppm sulfur diesel

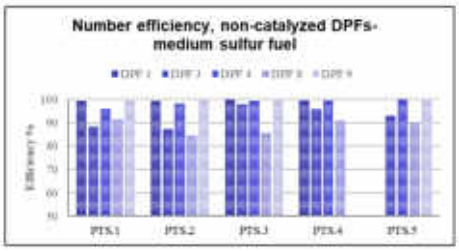


DPF No.	DPF 1	DPF 3	DPF 4	DPF 9
Average	94.5	93.7	78.34	95.48

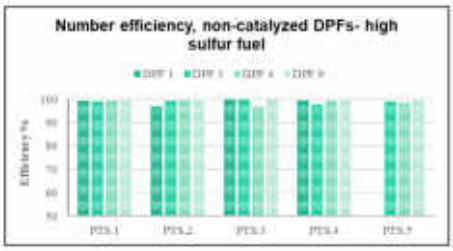


DPF No.	DPF 1	DPF 3	DPF 4	DPF 9
Average	52.3	58.7	64.6	50.4

Number filtration efficiency of non-catalyzed DPF with 229 ppm and 7000 ppm sulfur diesel

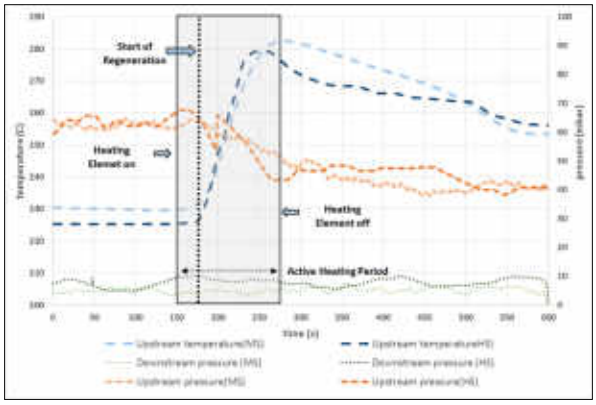


DPF No.	DPF 1	DPF 3	DPF 4	DPF 8	DPF 9
Average	99.5	92.36	98.64	88.46	99.7

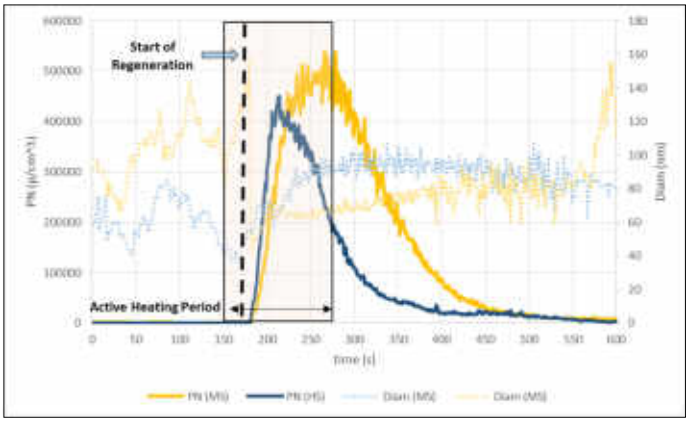


DPF No.	DPF 1	DPF 3	DPF 4	DPF 9
Average	99	99.02	98.74	99.56

Exhaust gases' back-pressure and temperature during regeneration of non-catalyzed quasi-active DPF with 229 ppm and 7000 ppm sulfur diesel



Particle count and diameter during regeneration of non-catalyzed quasi-active DPF with 229 ppm and 7000 ppm sulfur diesel



Outcome of engine dynamometer tests

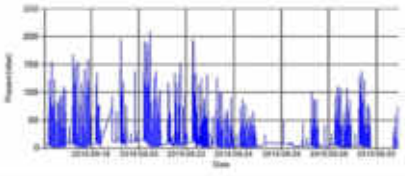
- Full report of engine tests' results
- Determination of candidate DPFs for field tests
- Several scientific papers and presentation

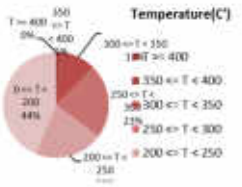
DPF durability tests in the field

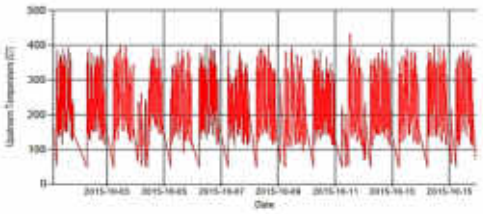
- Vehicles: Tehran BRTs
- Engine: MAN Euro III diesel
- Fuel: mostly LSD (50 ppm) and occasionally MSD (229 ppm)
- Procedure: 50,000 km at low- and high-exhaust temperature lines
- Evaluation criteria:
  - Durability
  - Appropriate regeneration regime
  - Reasonable cleaning interval

Online monitoring

Online monitoring





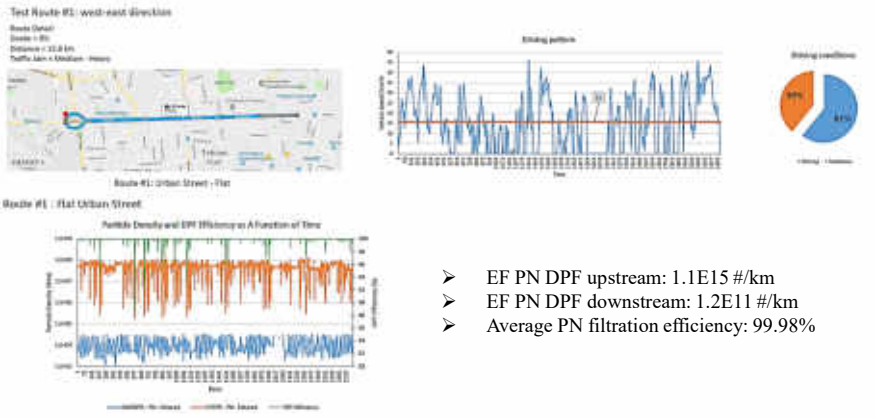


PEMS/RDE for selected buses

PEMS for CO, CO2, NOx, HC, O2

Particle counter

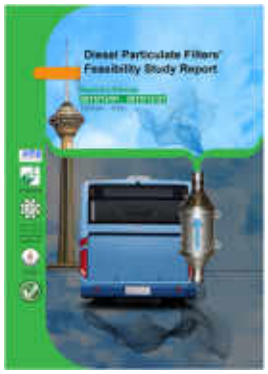
PEMS/RDE sample test results



- EF PN DPF upstream: 1.1E15 #/km
- EF PN DPF downstream: 1.2E11 #/km
- Average PN filtration efficiency: 99.98%

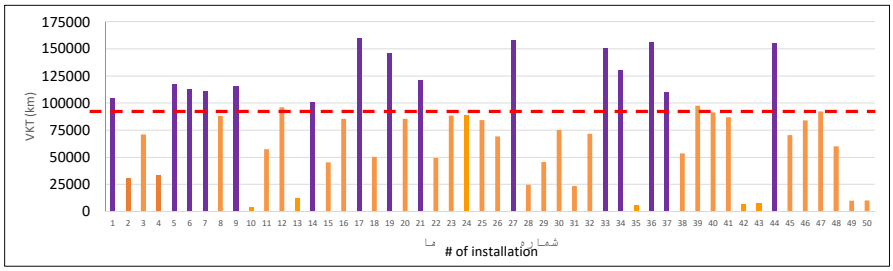
DPF durability test results

- Total installed DPFs: 14
- Acceptable operation at high and low temperature lines: 6
- Acceptable operation only at high temperature lines: 3
- Rejected filters: 3
- Ongoing : 2
- Total vehicle kilometers travelled > 1,000,000 km.



DPF durability test

- Target vehicles: Tehran city buses
- Installed DPFs: 50 pieces
- VKT: **4,008,789 km**



DPF retrofit projects, costs and benefits

- Total investments: 300,000 USD
- Approx. soot collection: 1,202 Kg
- Health costs of 1 Kg soot in Iran: 1,000 USD
- **Approx. Benefits within 3 years: 1.2 Million USD**

60 DPFs is being installed in 2019

World Bank cost-benefit analysis for DPF retrofit solutions

- Retrofit effects for 4577 diesel buses in the City of Tehran will reduce annual PM2.5 mean by 14%.
- The project estimated for 7 years period of 2019 to 2025.
- The cost depends on technology, USD 22.32 million for buses retrofitted with CDPF or CCRT, USD29.47 million for metal CRT, and USD 44.05 million for active DPF+FBC. Estimated annual benefits outweigh costs by a factor of around 8:1 to 16:1.

World bank report
Cleaning the Air of Tehran, One Bus at a Time: retrofit solutions for the ageing diesel bus fleet in Tehran Technological Assessment, Economic Analysis, and International Best Practices
Available at: http://documents.worldbank.org/curated/en/267071563886365000/Technological-Assessment-Economic-Analysis-and-International-Best-Practices

Conclusions

- Despite of advances in diesel engine technologies and recent emission certification levels for PM/PN, DPF retrofit solution still is much needed for many places around the world.
- Low exhaust temperature, high idling time, variable sulfur content, and high ash lub oil are challenges to overcome for most cases, but there are technologies available.
- For the case of Tehran, it was shown that DPF retrofit solution is available, technically possible, and economically feasible to protect people' health and exposure.

Thanks for your attention
Questions?

vhosseini@ualberta.ca