Control of DPM and Diesel Emissions Through Technology Retrofit

Dr. Lauretta Rubino

CEO VERT Association

MDEC WORKSHOP: INTRODUCTION TO DIESEL EXHAUST OCCUPATIONAL EXPOSURE: HEALTH EFFECTS, MEASUREMENT AND CONTROL

October 24th,2024 Sudbury Ontario, Canada

mdec
MINING VEHICLE POWERTRAIN

AGENDA

- Introduction
- VERT & Activities
- Diesel & Gasoline Particle filters – BAT
- Particle Filters overview
- Diesel & Gasoline Retrofit
- Typical Particle Filters failures
- VERT Filter Certification
- Summary

INTRODUCTION

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.

Lung Cancer death in exposed DPM workers

From 198 lung cancer death to now 409 (in additional 18 y)

In a cohort of 12'315 workers

From 16'000 lung cancer death / million to 32'000 / million (compared to a target value of the Swiss LRV of 1 / million!

Miners study II - 18 years later

(health impact of diesel exhaust exposure in miners, new findings from a extended cohort study, (Ron Kappeler)

Research

The Diesel Exhaust in Miners Study (DEMS) II: Temporal Factors Related to Diesel Exhaust Exposure and Lung Cancer Mortality in the Nested Case–Control Study

Aug., 2023

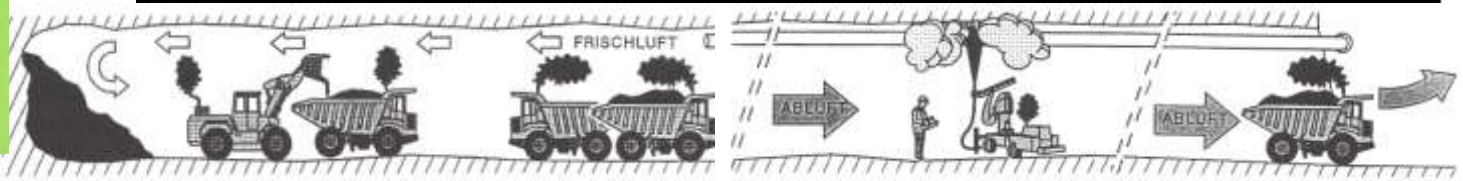
- **From Sept 2023, Ontario, Canada, has introduced new rules** lowering the permissible **exposure limit for diesel particulates to 0.12 mg/m³ one of the strictest in North America**
- **Using technologies like DPFs** & improving ventilation in mines is extremely important to meet the new safety standards
- **Retrofitting DPFs to mining equipment significantly reduces harmful emissions,** particulate emissions by up to 84% and particle numbers by > 97%, leading to a sharp **decrease in miners' exposure to dangerous pollutants like** elemental carbon

What is VERT?

- **VERT is a Non-Profit International Association** of **filter, catalyst manufacturers, instrument, engine manufacturers, universities and research associates**, founded in 1993 in Switzerland
- **VERT stands for Verification of Emission Reduction Technologies** & it is a Particle Filter Testing, Certification & Quality Control System, a Trade Mark for Particle Filters of **Best Available Technology (BAT)**
- **The VERT® Association, originated during the NEAT New Transalpine Railways Program**, which was one of the biggest tunneling projects in Europe at the time
- **Since then, VERT® has developed some of the most important particle filter testing procedures,** supported various international partners with **retrofit programs** and retrofit consulting and **established a worldwide scientific network of manufacturers** of **components, systems, engines, vehicles and PN measurement devices** as well as environmental, medical and technical research facilities **specialized in the field of "air quality" and nanoparticle emissions control**
- **VERT organizes international conferences** every year (i.e. the **VERT Forum**) and the **ETH Nanoparticle Conference in Zurich**
- **VERT has over 35 members** including universities and research centres as associate partners

Tunneling is the extreme challenge

„VERT-Filter for each Diesel“



4 tubes longest 57 km; total 152 km

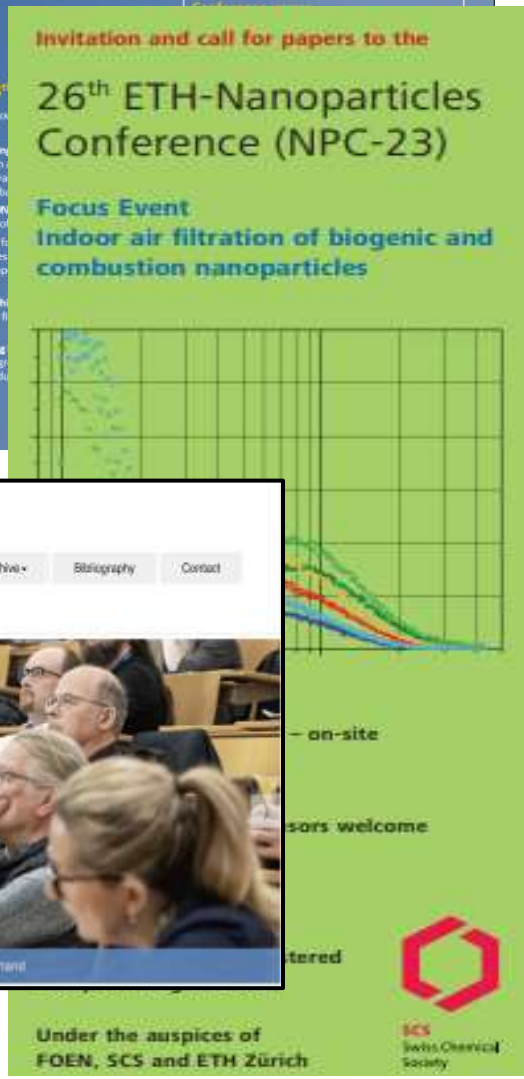
VERT scientific network

- **1997 first international ETH-NPC workshop - 40 participants**
- Today ETH-NPC is the annual event of UFP experts from science to technology
- **VERT Forum every year:**

- 14th VERT Forum on 22nd March 2024
- **15th VERT FORUM on 20 March 2025**

!! Save the date!! Location TBC

- www.vert-dpf.eu/



VERT Milestones / Activities

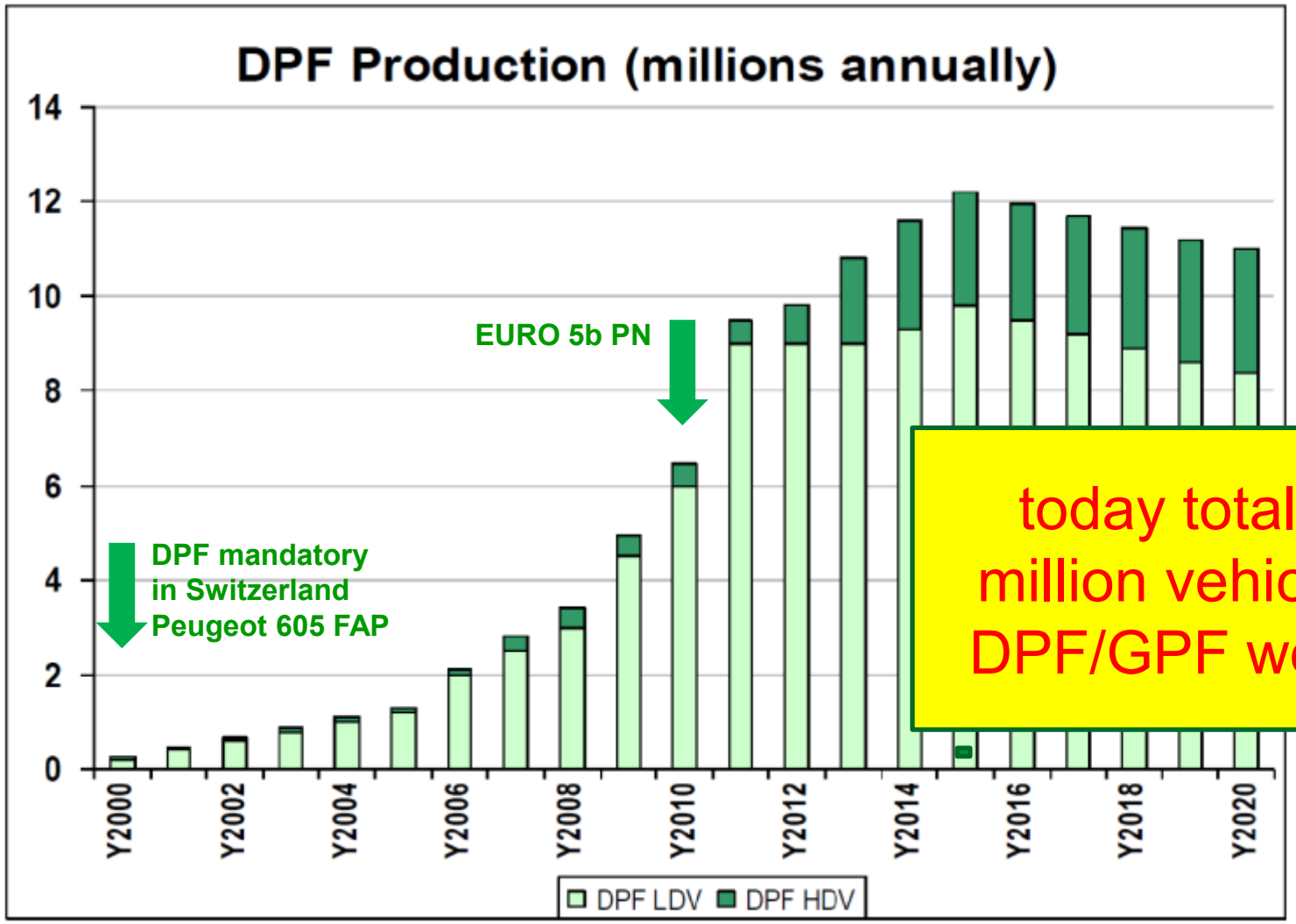
- 2023 & 2024 DPF for Global Warming Mitigation
- 2022-2025 GPF Retrofit within EU-AeroSolfd-Projekt based on earlier VERT research
- 2022 DPF-Membrane for Marine heavy fuel oil application
- 2020 DPF for Virus Filtration
- 2016-2019 NPTI- the introduction of PN-count at idle for DPF-PTI control
- 2016-2018 High Emitter Analysis with Mexico Ciudad and EU-JRC
- 2015 Start of stakeholder process for Iranian national emission legislation to eliminate UFP
- 2015 Legislation for construction equipment with DPF for public projects in Berlin
- 2014 Euro VI legislation in Europe and Retrofit programs in China and Iran
- 2013 Retrofit programs in Bogotá/Colombia
- 2010 First VERT Forum Dübendorf with >60 participants
- 2010 Cooperation between Switzerland and China to introduce Low Emission Zones
- 2009 Legislation for construction equipment in Switzerland with DPF
- 2008 Retrofit programs in the Netherlands and Italy; Low Emission Zones in London, Berlin and Munich
- 2006 Low Emission Zones in all major Cities in the Netherlands
- 2005 DPF Retrofit program in Chile
- 2002 DPF duty for Diesels in all metal mines in the USA
- 2000 California Show Case Diesel Risk Reduction Program (Program to reduce diesel PM emissions in California by 75% by 2010 and 85% by 2020; London/United Kingdom starts to retrofit the transport system
- 2000 VERT-certified DPF for tunneling in Switzerland, Germany and Austria mandatory
- 1998 Boston: DPF duty for construction machines (“Big Dig”)
- 1997 First VERT Filter List published, based on PN and secondary emissions
- 1996 Retrofit program of 20,000 city buses in Germany
- **1994 VERT-Project started: DPF developed for Swiss Tunneling NEAT**

International Diesel Particle Programs worldwide: Santiago del Cile, Bogota, China, Iran, Israel, Berlin

DPF-Production in Europe

+ GPF from 2015

+ China,
+ India,
+ Israel,
+ Iran
+ Latin America
+ USA HDV



today total > 300 million vehicles with DPF/GPF worldwide

*Source VERT

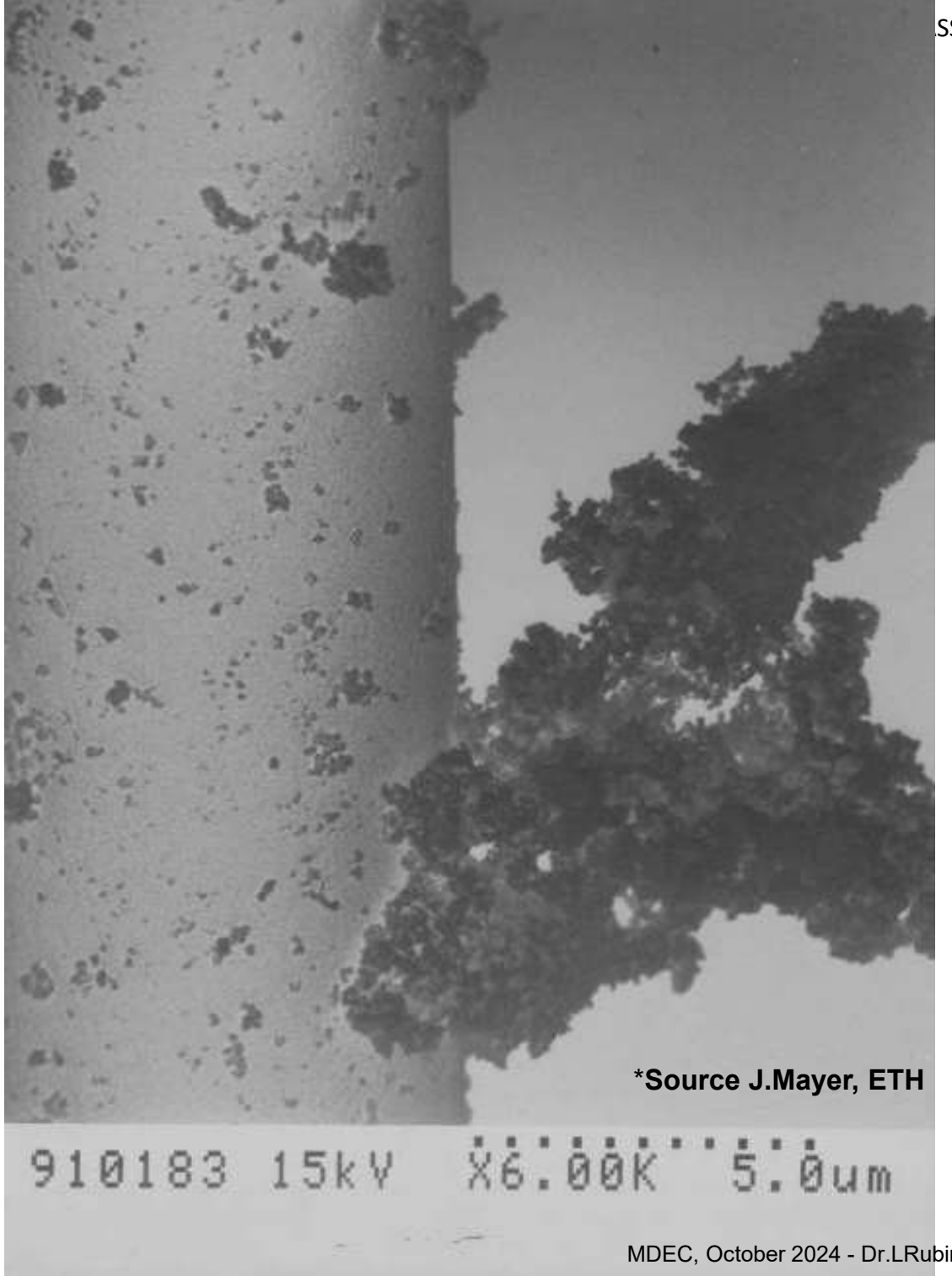
Soot Particles a double Risk because of

- **very small <100 nm**
- surface **> 100 m^2/g**
- carrying toxics
- persistent in organism
- carcinogenic
- **black colour**

→long life toxic aerosol

weeks to month up tp 3500 m

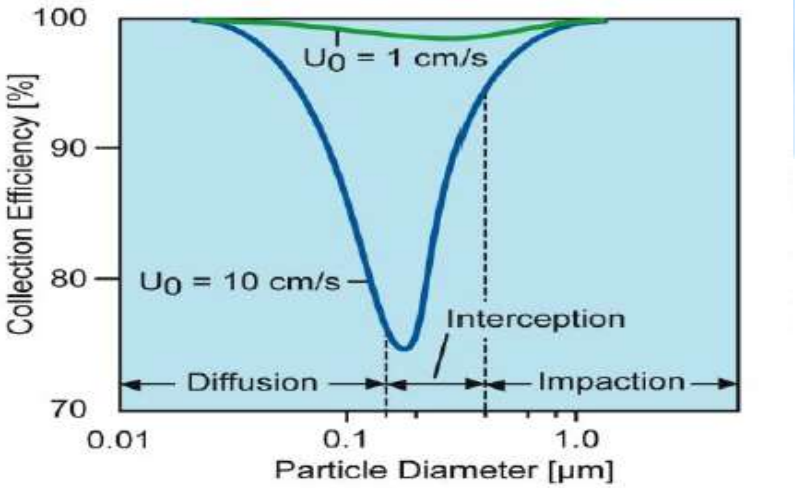
(→Jungfraujoch-Laboratory)

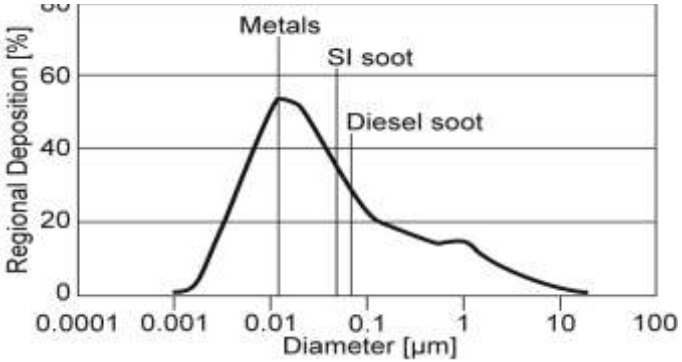


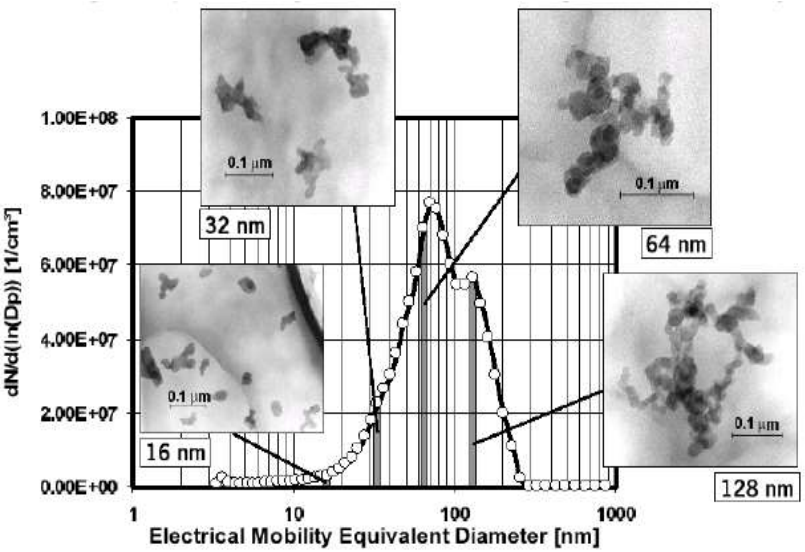
*Source J.Mayer, ETH

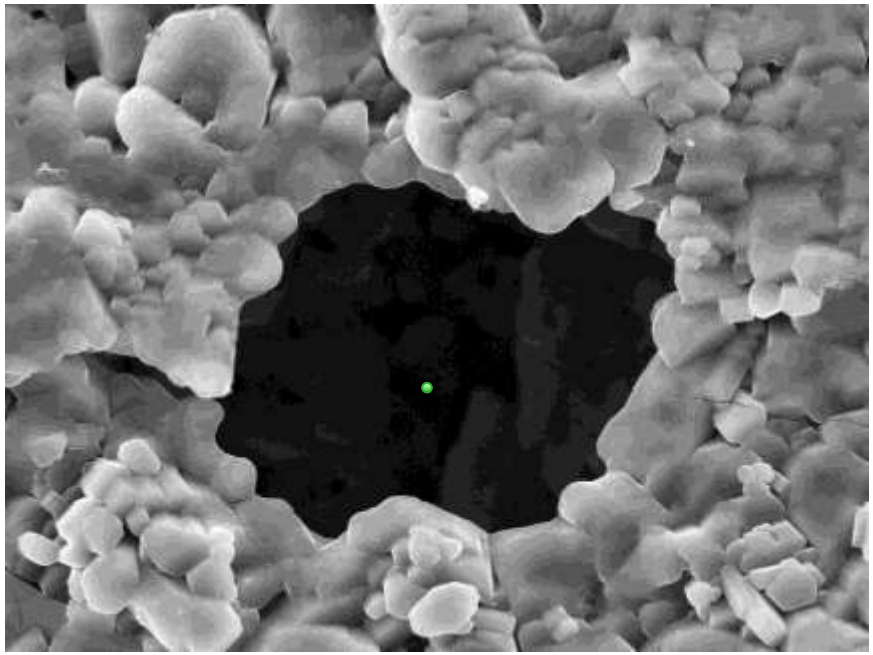
Particle Size matters….

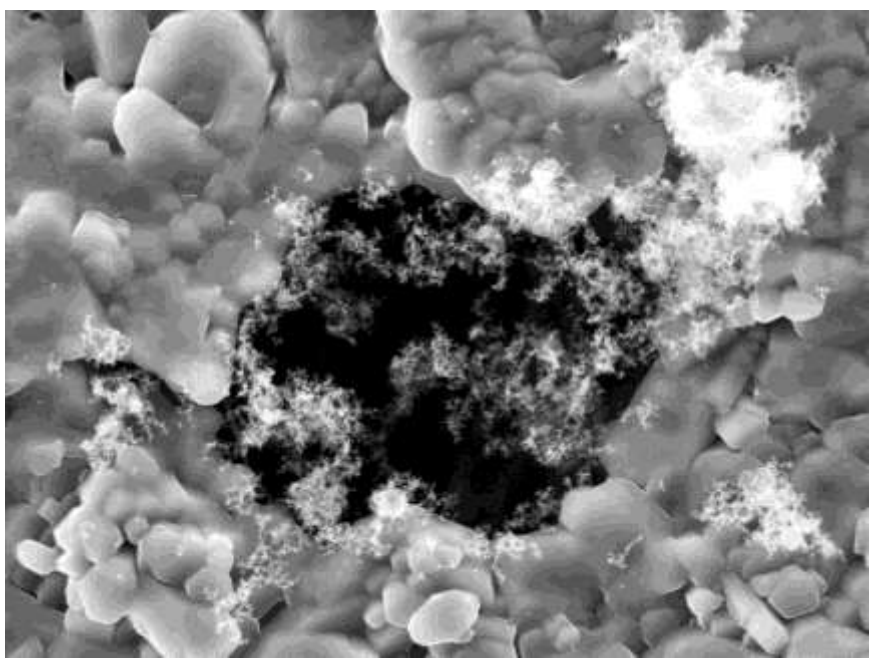
- *the weakest size range of filtration, the gap between diffusion and impaction*
- *…is the most sensitive size range of the lungs*
- *….the most intensive emission range of engines and the typical size range of viruses*











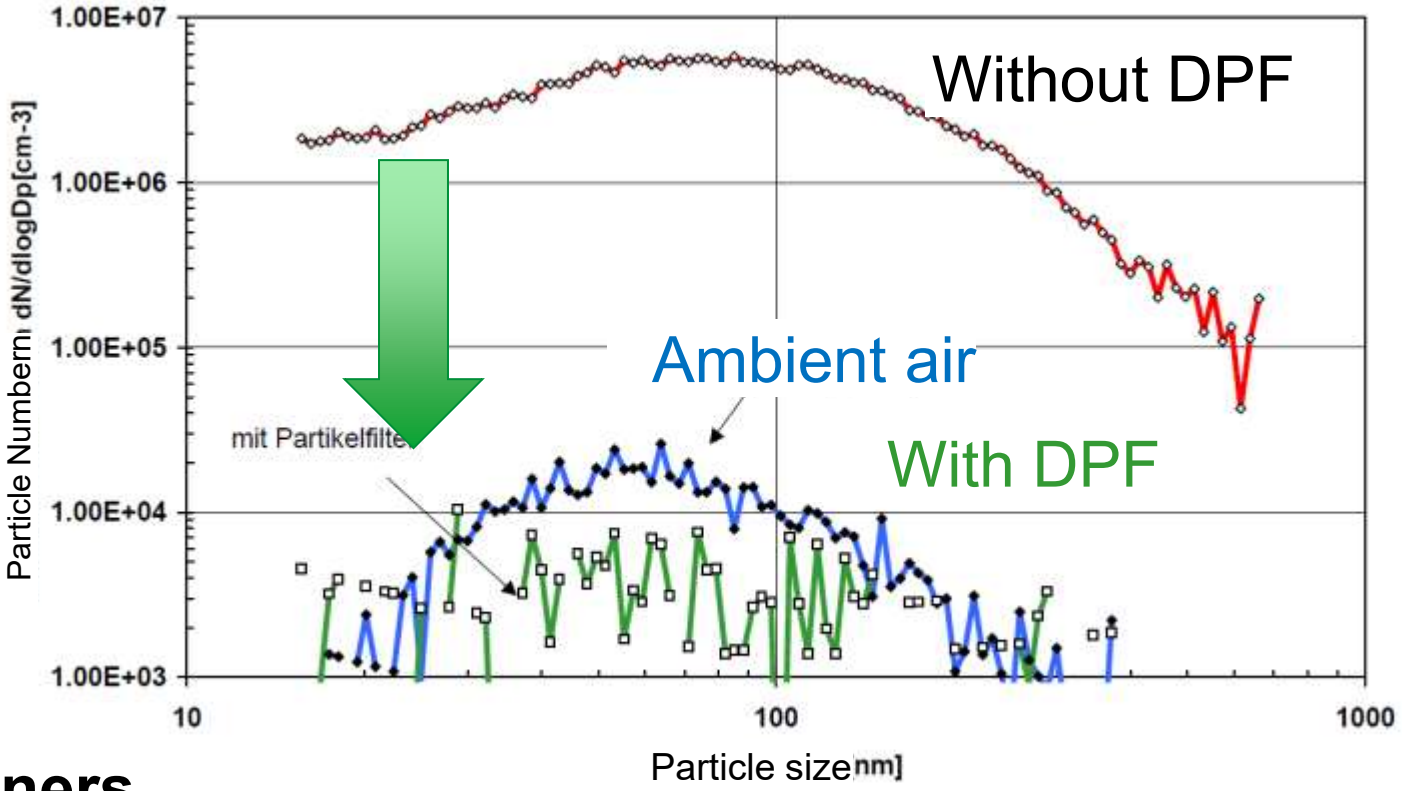
Particles 10-100 nm are 100 - 1000 x smaller than filter pores 10-20 µm

With ultrafine particle structures we can stepwise build a “membrane” covering the pore

*Source: Payne S. /Uni. of Cambridge; Study of diesel particulate bridging behavior with SEM; ETH-NPC 2012

Diesel particles are in the diffusion range

that makes them
so dangerous



VERT Research Partners

- Engine Emission Laboratory at Uni Biel AFHB
- Aerosol Laboratory at Uni FHNW
- Toxicology Laboratory Uni Bern –Fribourg
- Bioerosol (Virus) Laboratory AMI Uni Fribourg
- ETH

PN Emissions from ICE

Diesel

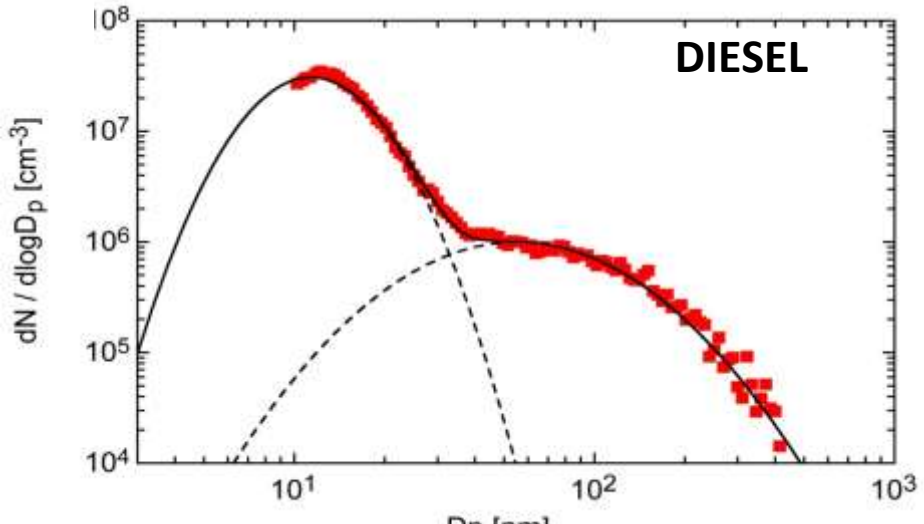
Soot peak: **~80 nm**; 10^6 -10^7

Ash peak: 10 nm;

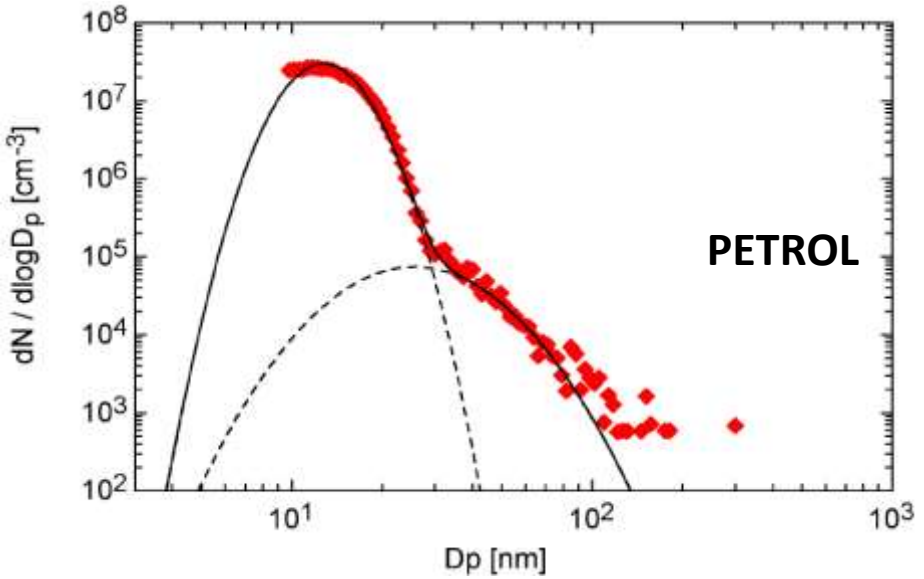
Petrol

Soot peak: **~40 nm**; 10^5-10^8

Ash peak: 10 nm;



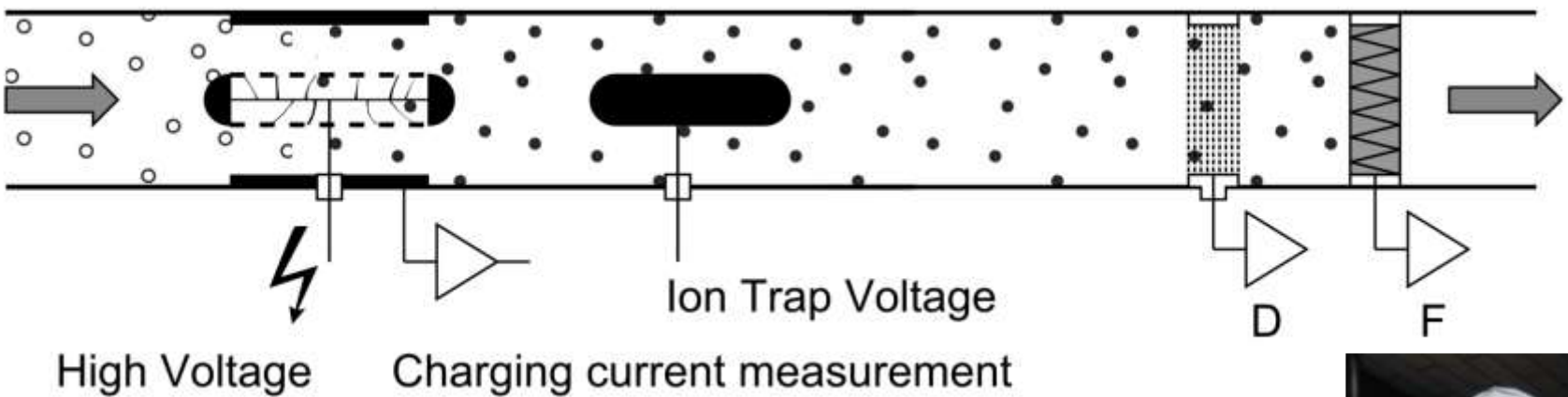
*Source SAE 2012-01-841 Mayer et al



*Source Dr. LRubino et Al.- SAE Paper 2023-24-0114

Metrology Development became decisive

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



Particle Filters Structure

Porous Ceramic Extrusion

Metallic Sinter Structure

Ceramic Foams

Metal Foams

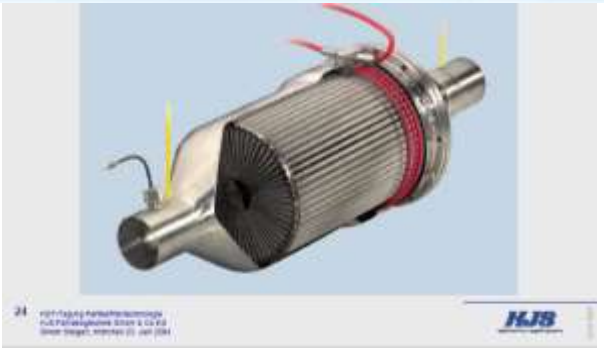
Ceramic Wire Structures

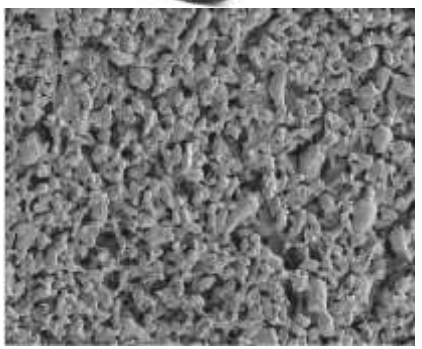
Glas Fibre Cartridges

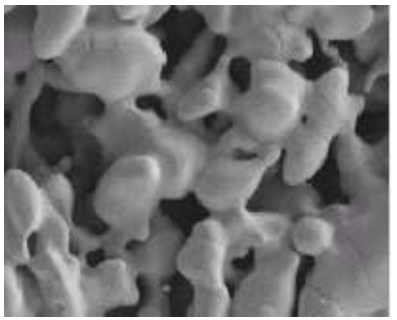
Metal Wire Structures

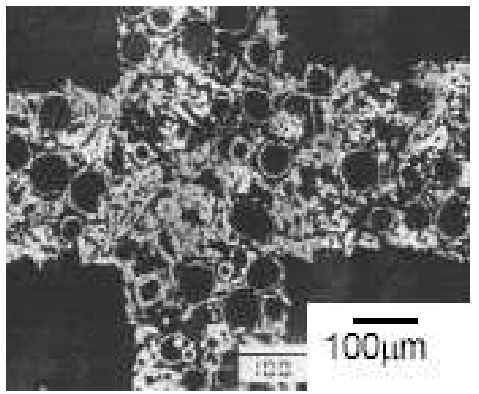
Deep Filtration and Membrane Structures

Low Temperature Paper Filters





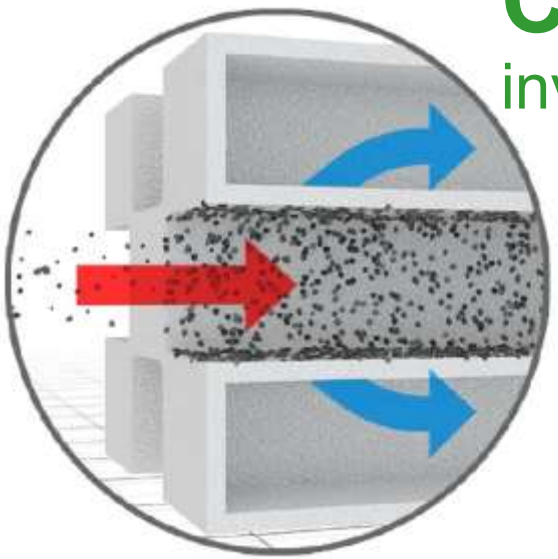


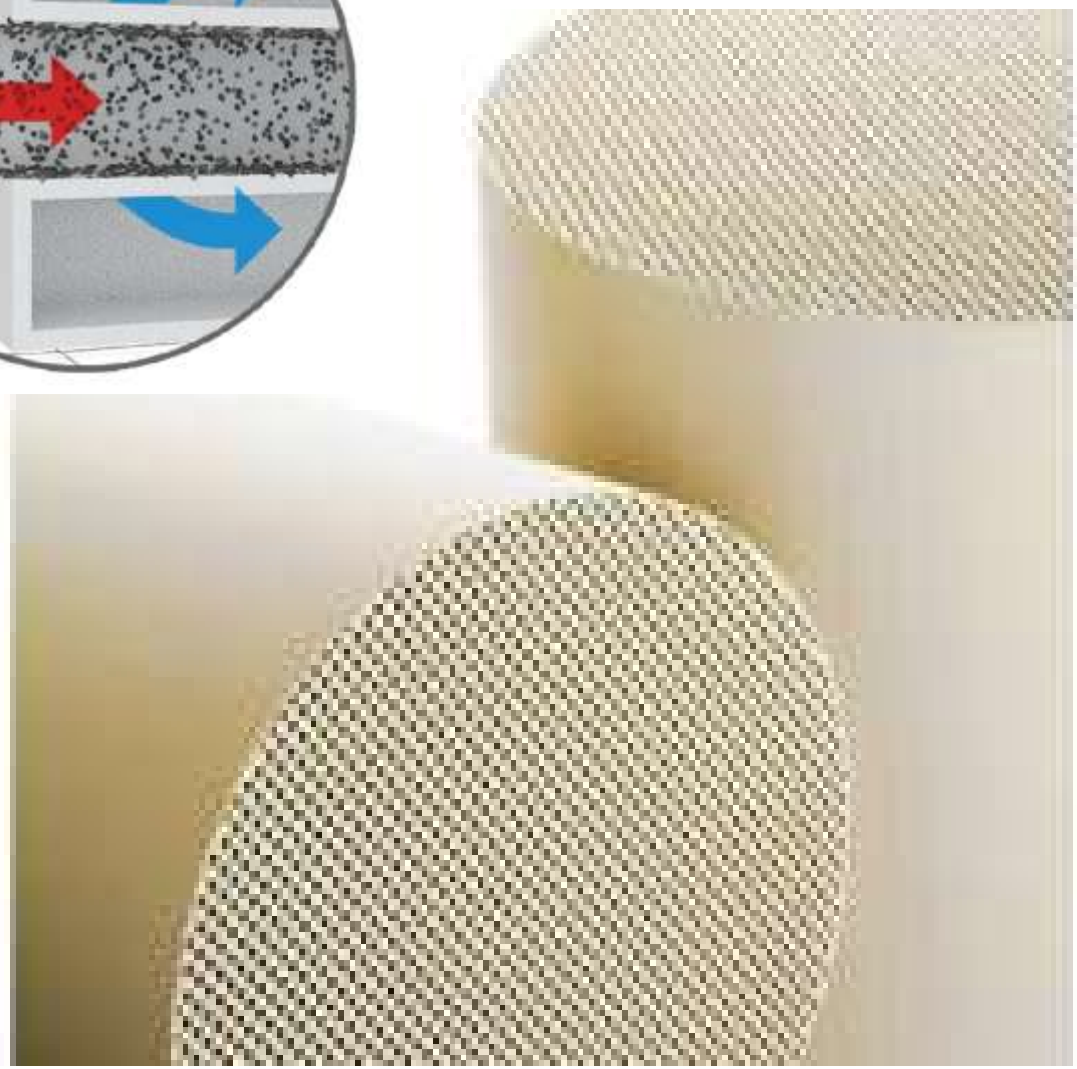


REM, HJS

Ceramic wall flow multicell filter

invented 1979, now > 200 Mio in Diesel cars

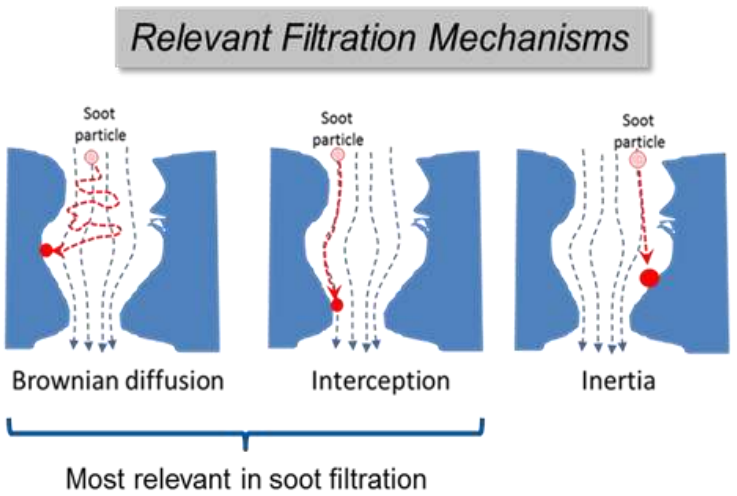




- pore size 10-20 µm
- porosity 45-65%
- 200 cpsi
- >1 m^2 per 1 ltr bulk volume
- High in-flow speed but low face velocity some cm/s
- filtration efficiency >99%
- particle size 10 – 500 nm
- soot storage 10 g/ltr
- any shape and size
- temperature > 1000°C
- no aging over vehicle life
- no vibration problem
- easy to clean

Diesel vs Gasoline Particle Filters

	PM	Engine out Gas T (deg. C)	O2 Conc.
GDI	LOW PN (1-10x10E+12 #/Km) PM (2-10 mg/Km)	HIGH (up t 800) deg. C)	LOW (0-20%)
Diesel	HIGH PN 10-100x10E+12 #/Km PM (10-50 mg/Km)	LOW (Max 400 deg. C)	HIGH (10-20%)

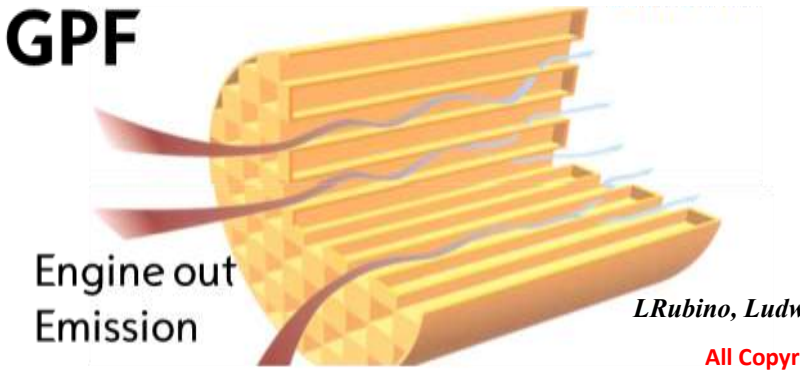


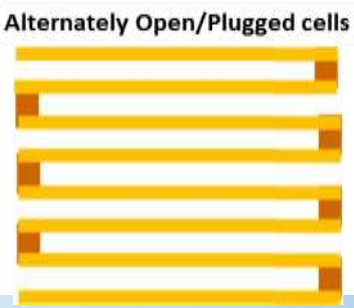
- Fast soot accumulation (Diesel) vs. Slow soot accumulation (Gasoline)
- Higher impact on back pressure (Gasoline)
- Since gasoline engines exhibits very dynamic exhaust heating & cooling - Thermal Shock Resistance is critical for GPF

Cordierite best option material so far for GPF

- ✓ Superior thermal shock performance (low CTE*)
- ✓ Better light off performance
- ✓ Isostatic strength & weight similar to substrate

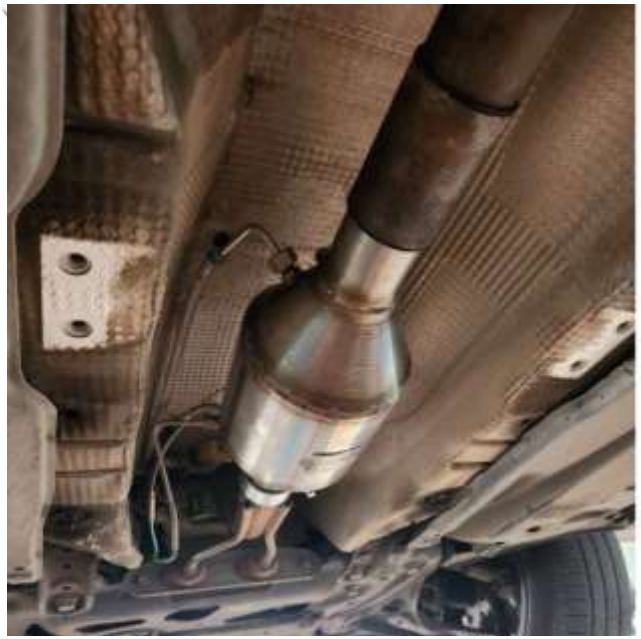
*CTE= Coefficient of Thermal Expansion

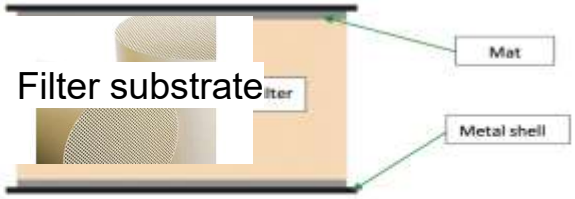




➢ **GPF filtration is dominated by the filter material vs. the soot cake in case of a DPF**

Engine Exhaust Gas / DPF Retrofit

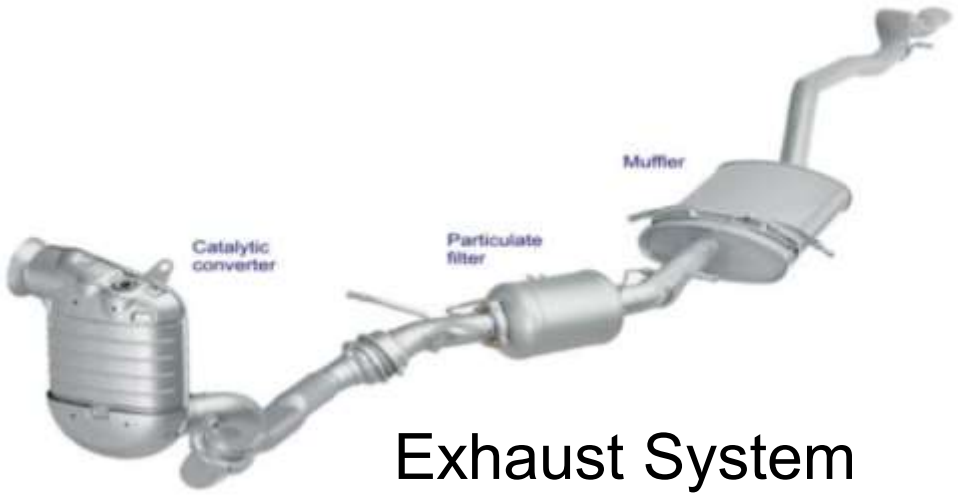




Filter substrate

Illustration sub assembly

Illustration filter assembly (substrate, mat, metal shell incl. cones, sensor sockets and pipes)

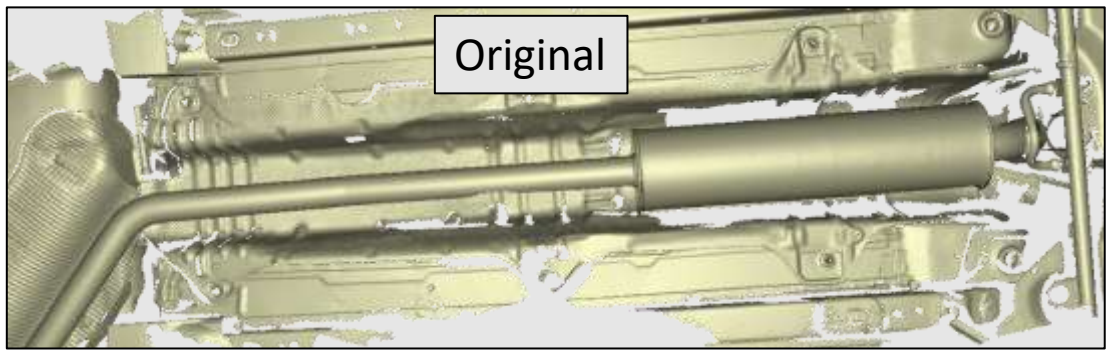


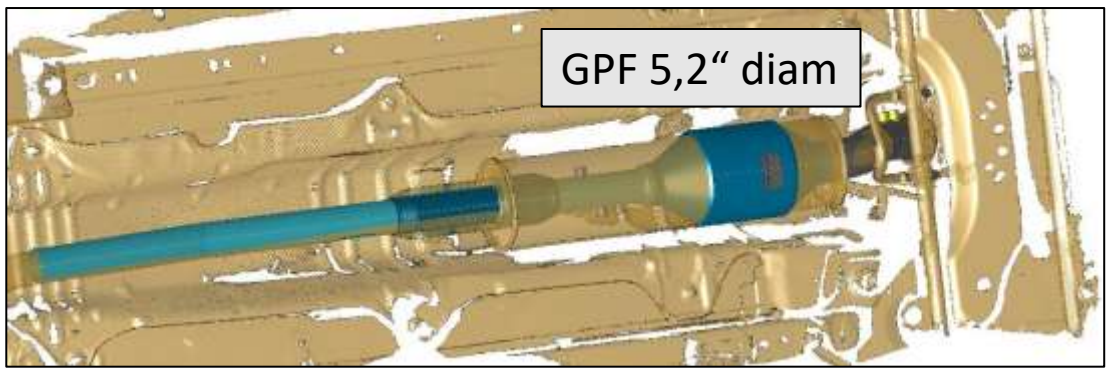
Exhaust System

4 Engine Families – GPF Retrofit

AeroSolfd
filtration devices

HJS Tailpipe GPF retrofit (example)





Peugeot 3008, DI ,1,6L

VW Golf

DI, 1,4L

FIAT, 500X

PFI, 1,6L

OPEL Corsa

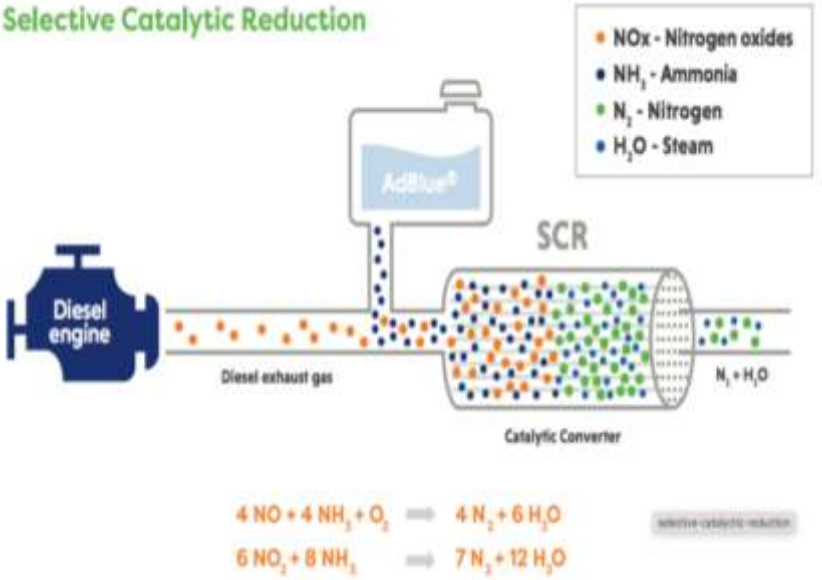
PFI , 1,2L

Co-funded by the European Union

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

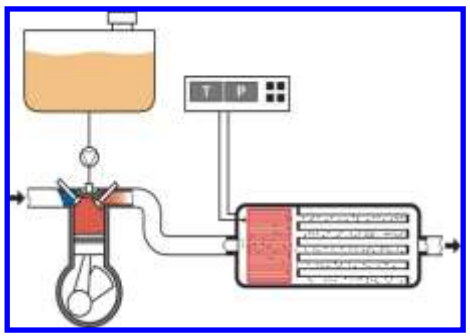
Engine Exhaust Gas / SCR Retrofit

SCR-Installation, ACU and AdBlue Tank

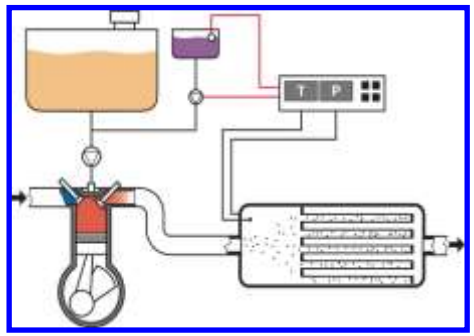


Exhaust System

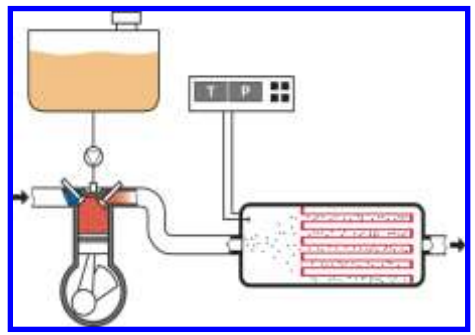
VERT-DPF Systems for Retrofit - passive & active



CRT >260° C



FBC >340° C

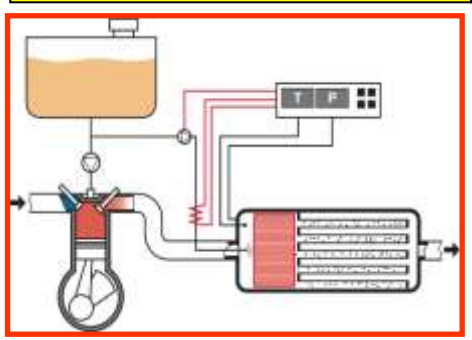


CAT Coating > 240 ° C

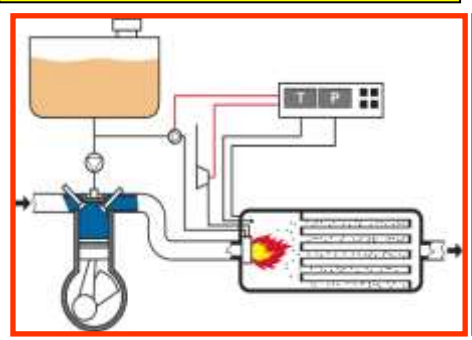
Passive systems are favoured, particularly for retrofit applications, because they require no integration with the engine, no source of energy other than the exhaust gases themselves, and no complicated control systems.

All active filter regeneration techniques operate **by raising the temperature of the filter to around 600°** C. This is the temperature at which the particulate matter (PM) collected in the filter, will combust in oxygen.

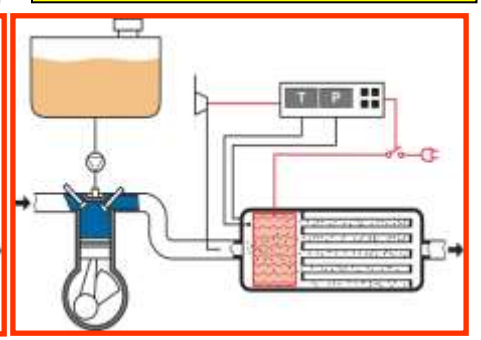
The **CRT** system is able to function in a wider range of conditions as passive system. Its advantage is most clearly seen in applications with low exhaust temperatures.



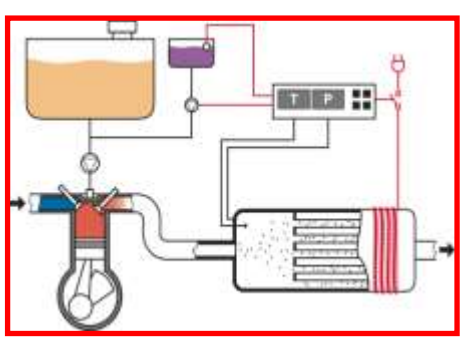
Cat.Burner > 260 ° C



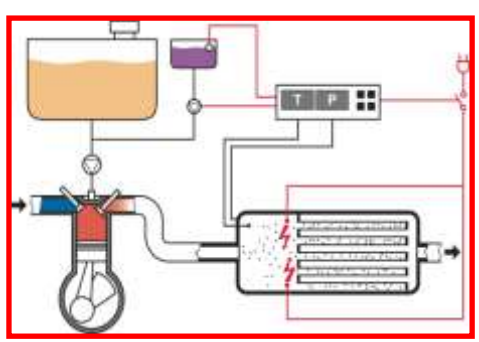
Burner ambient



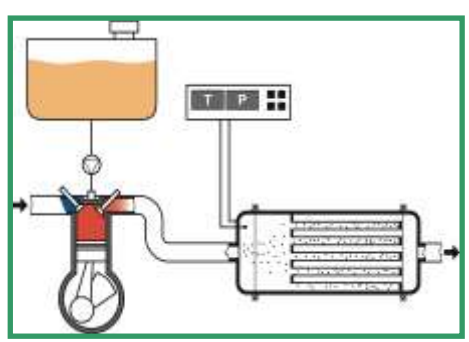
Electr.Heater ambient



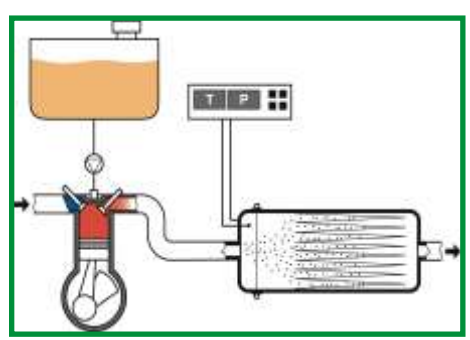
FBC active > 250 ° C



FBC active > 200 ° C

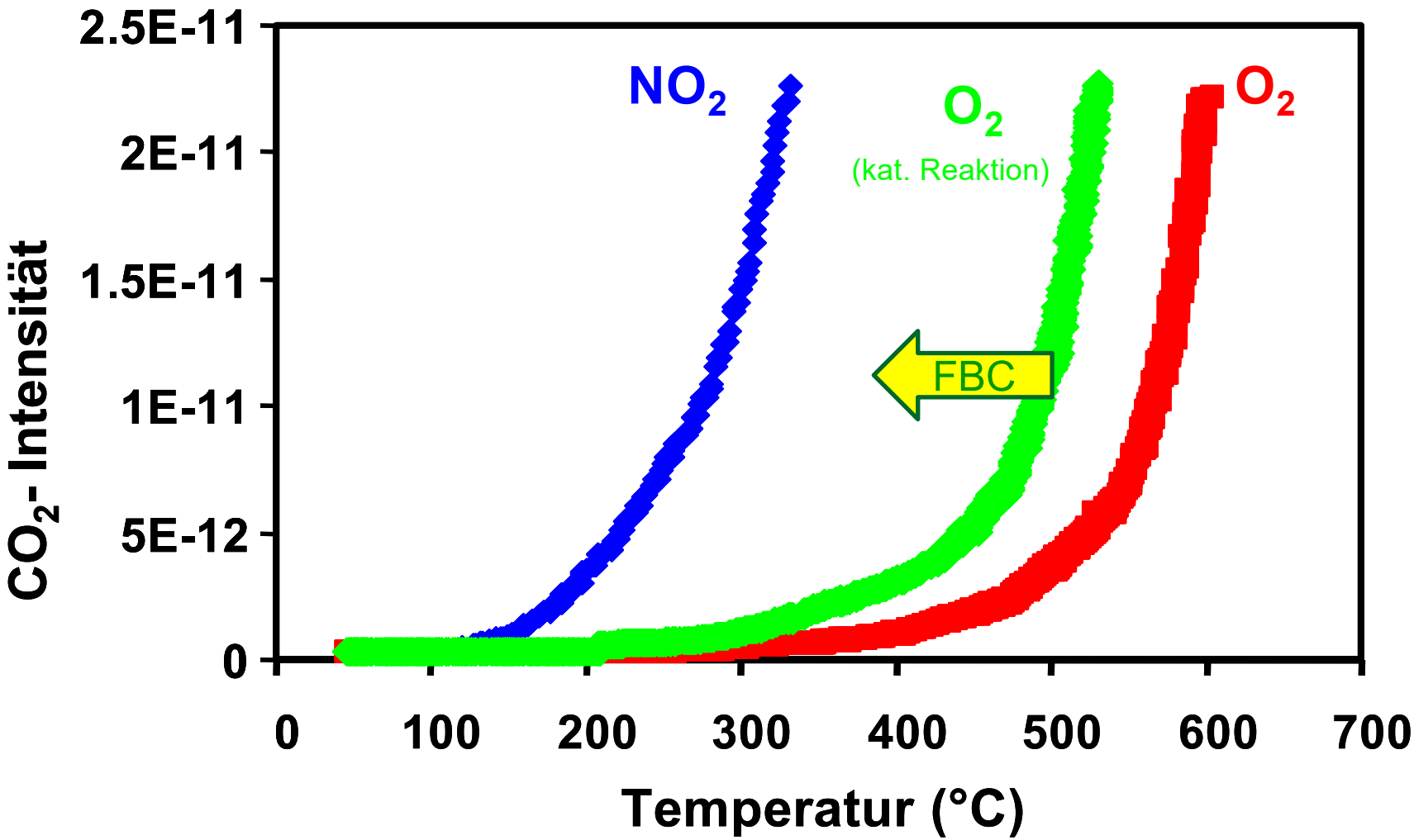


Offline Regeneration



Disposable Element

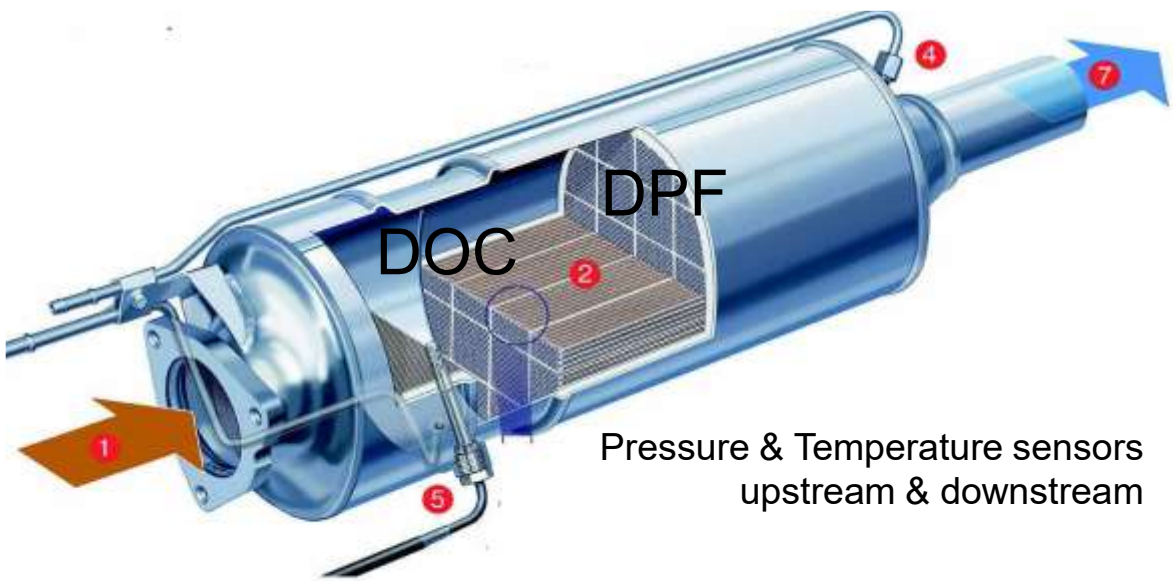
Soot combustion with O_2 or NO_2



CRT-Filter System

Johnson Matthey Patent 1988

NO &
CO2

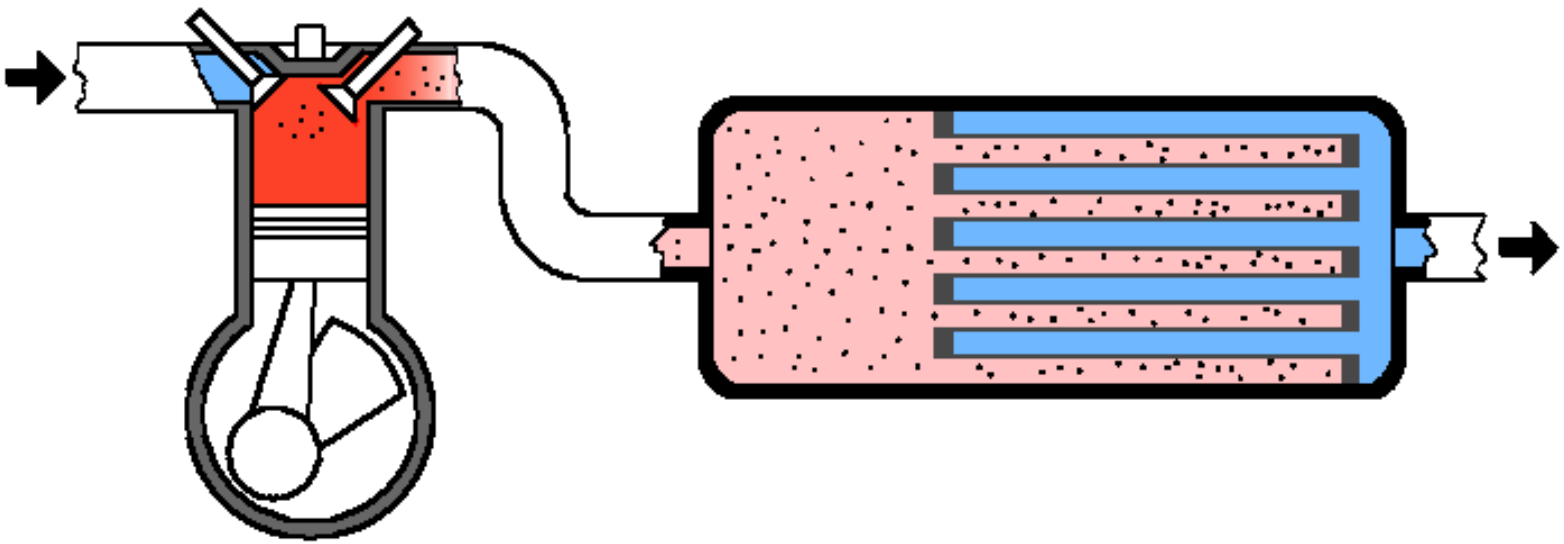


PM
CO & HC..

Pressure & Temperature sensors
upstream & downstream

- **Passive Regeneration** - The Continuously Regenerating Trap (**CRT®**) system is the **most widely used diesel particulate filter (DPF) system in the world** and is a patented Johnson Matthey technology
- It comprises an **oxidation catalyst (DOC)** followed by a **diesel particulate filter** (DPF)
- The **oxidation catalyst removes CO and HC and oxidises some of the NO** in the exhaust gasses to **NO_2**. **This NO_2 then reacts with the particulate matter (PM) trapped in the filter**, producing NO and CO_2 and cleaning the filter

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

Backpressure must be under Control

Electronic Datalogging

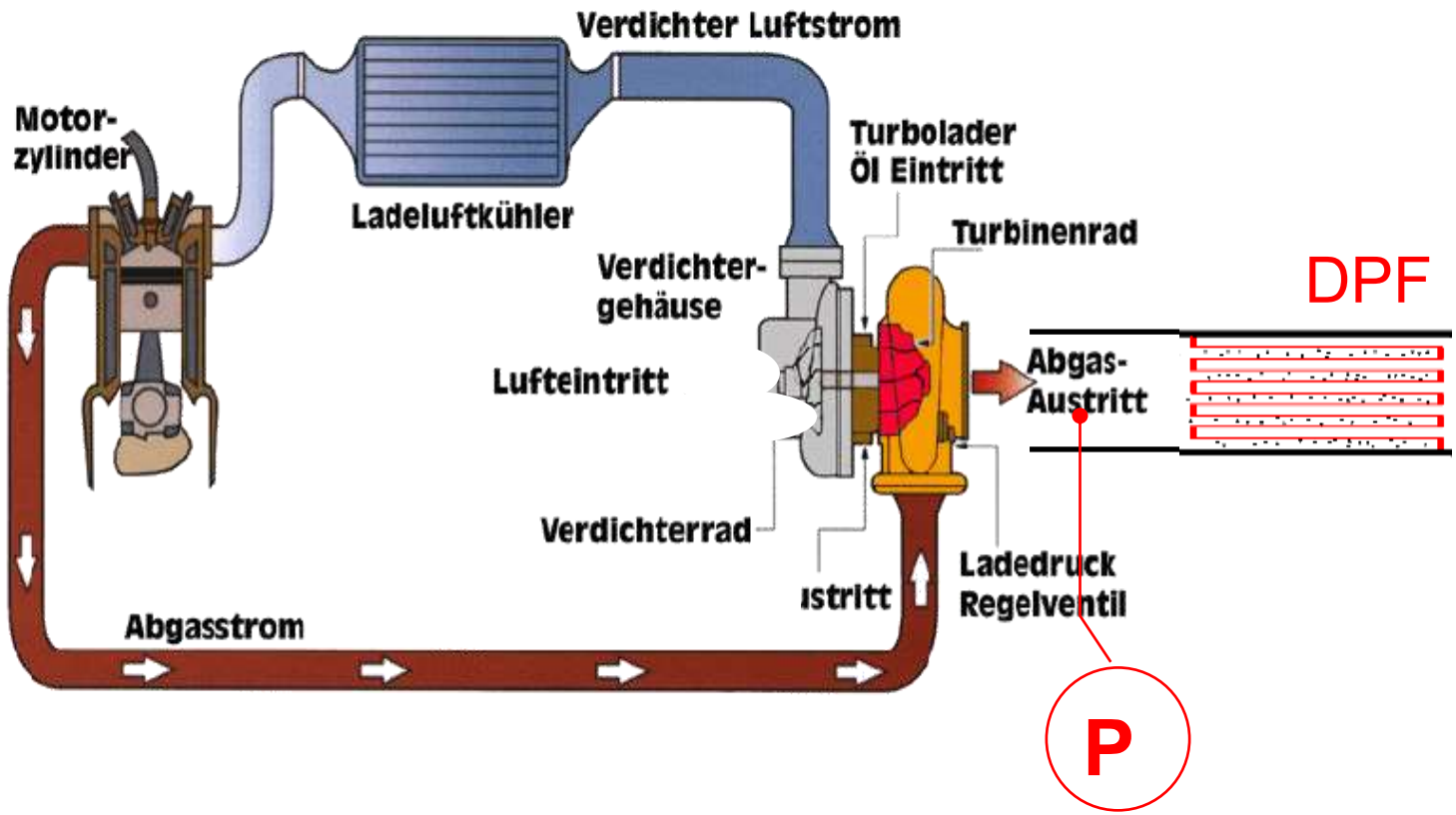
Sensors for Backpressure and Temperatures

BP & Temperature monitoring

Alarm Indicator at the Drivers Seat

or remotely controlled

Some Engines are more sensitive



If Backpressure increases ↑

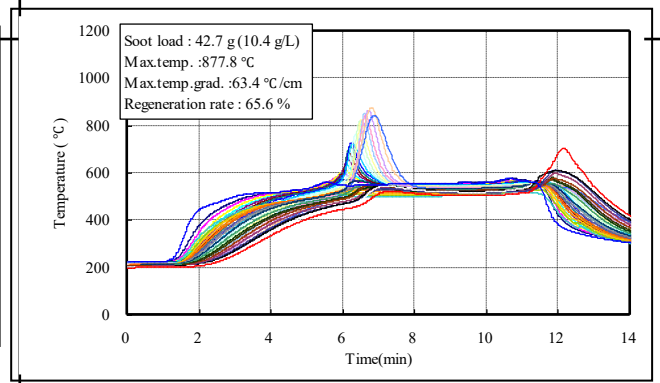
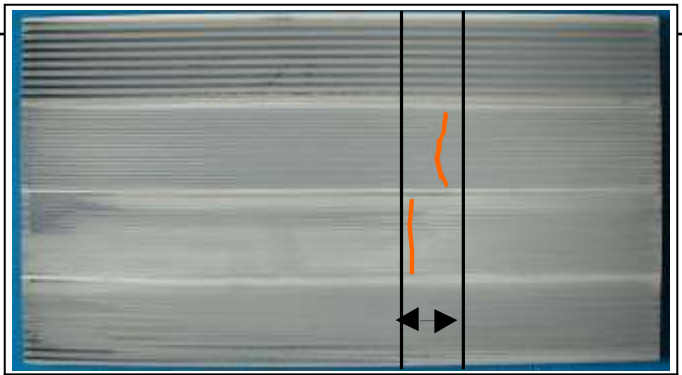
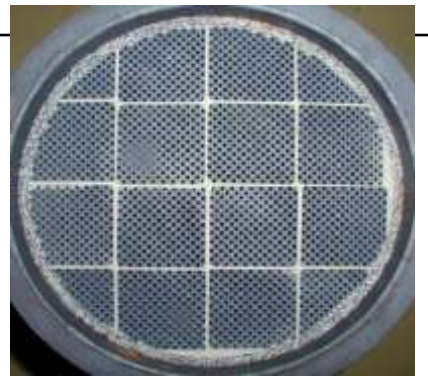
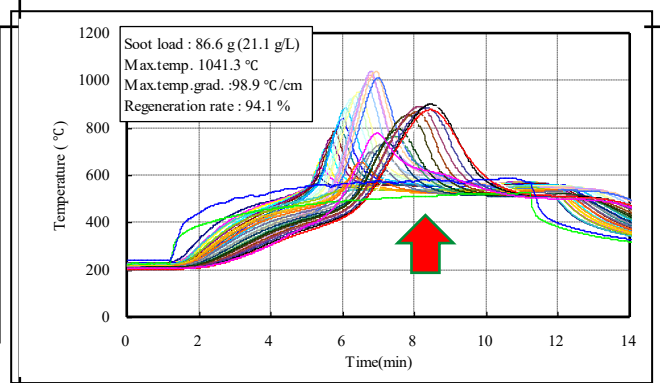
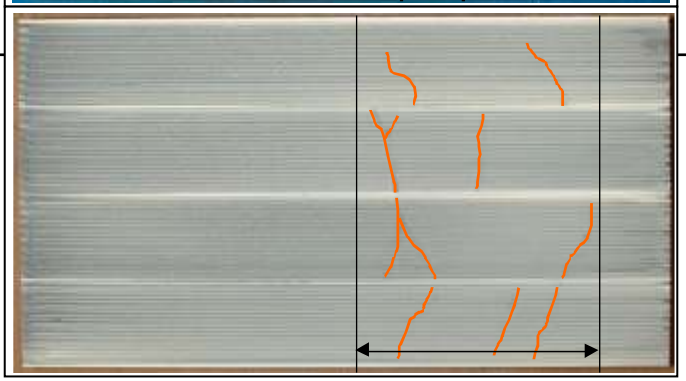
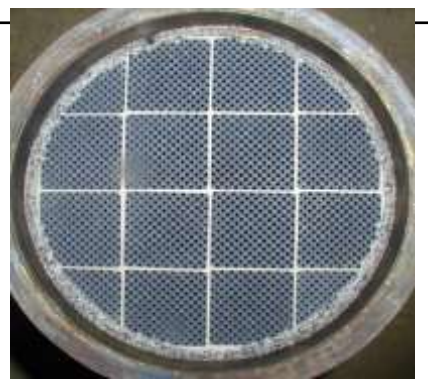
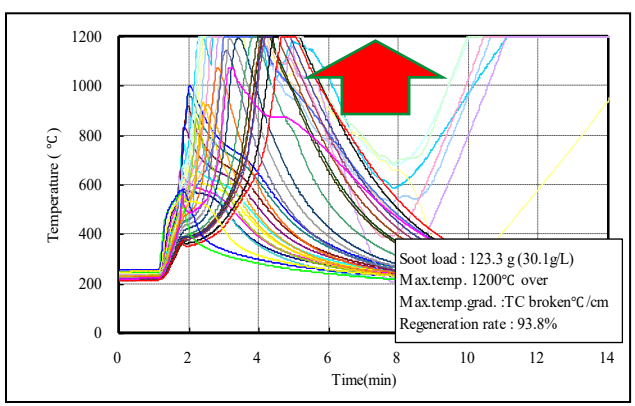
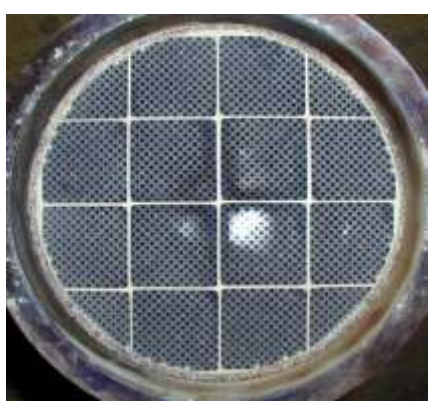
Charging Pressure Air Excess and Performance Decrease ↓

Soot Generation Increases ↑

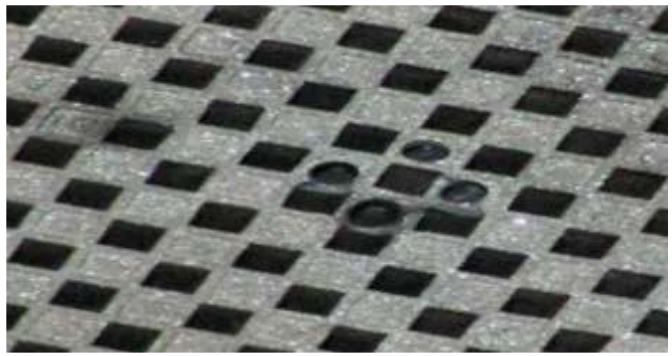
Typical DPF Failures

- Thermal and thermomechanical stress
- Canning Failures
- Vibration Failures
- Result of engine and turbo failures
- Failures due to **ash deposits** and ash sintering
- FBC-dosing mistakes
- Overheating during cleaning
- Maintenance & Installation mistakes
- Quality of fuels and lubricaion oils
- Short term and long term failures
- Failure statistics
- **Trouble-Shooting**
- ….

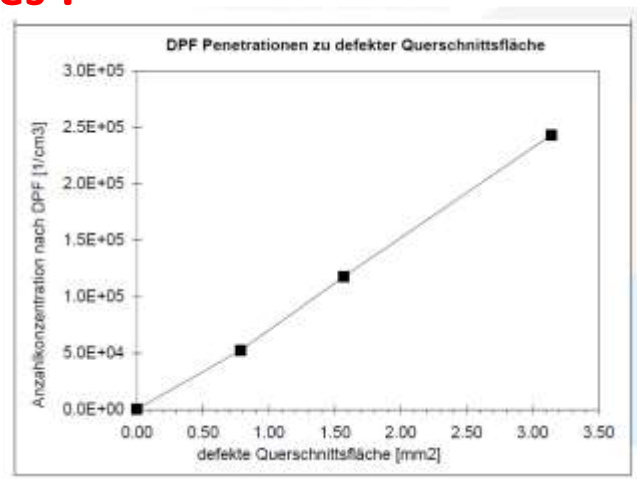
DPF Failure during Regeneration

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

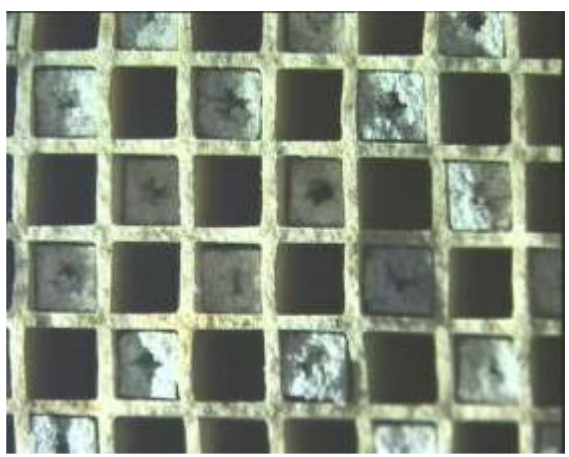
Cracking and Melting



Particle number measurement can detect also small DPF failures !

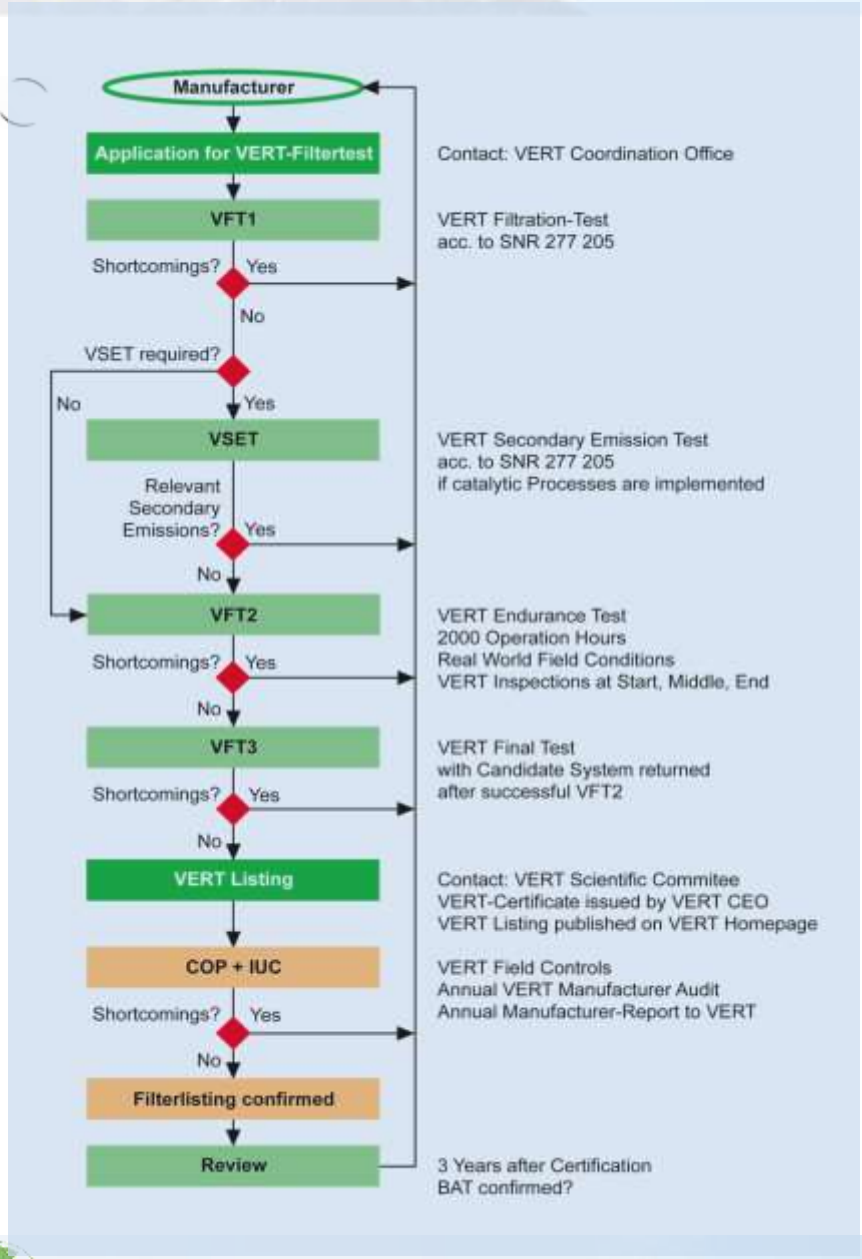


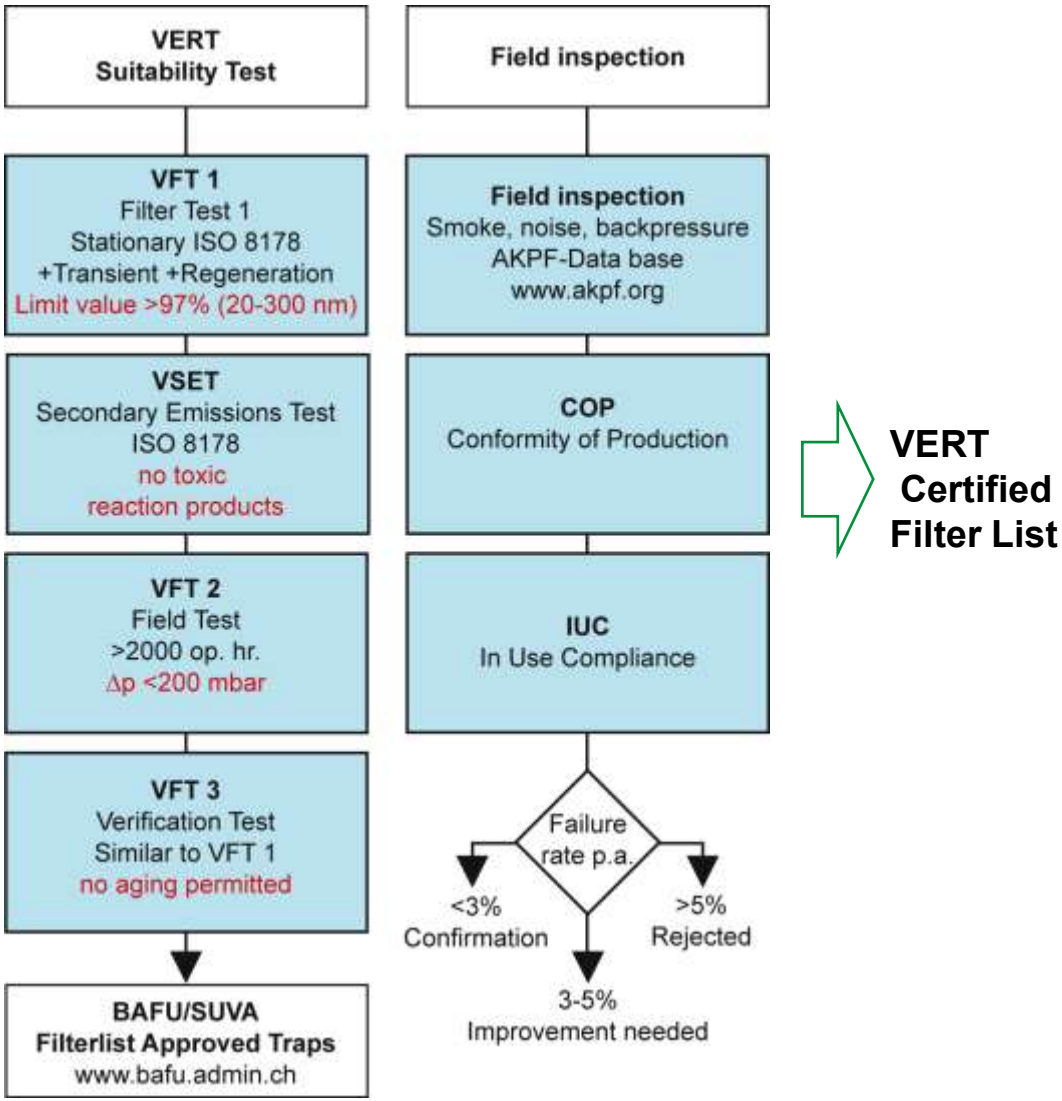
Ash Accumulation during operation /DPF Blockage



- **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

VERT Filter Testing Certification & Quality Control





VERT® testing of particle filter systems

VERT Filter Testing Certification & Quality Control

VERT CONCEPT:

- 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 (BAT)

Measuring Particle Size, Surface, PN Number, EC/OC,

PM Mass & Gases NO, NO2, HC, CO, CO2, O2 + FTIR-Analysis..

- Before, After & during DPF Regeneration
- New Filter and after 2000 operation hours

VERT APPROVAL CRITERIA FOR PARTICLE FILTERS

Filtration Rate by Particle Count PC

- Filtration rate for solid particle number PCFE as defined by UN-ECE PMP according to EC-regulation 715/2007 [10], must be attained in average of all operating points, throughout the particle size range 20-300 nm.

From year	A	B	C
	2000	2007	2016
New state	≥95%	≥97%	≥98%
2000 hrs.	≥90%	≥97%	≥98%

- PCFE during regeneration
  the criterion is the ratio of averaged values during the whole regeneration process as specified by SN-277206
  Regeneration time < 3 % operation time

	1	2	3
From year	2010	2012	2016
New state	≥ 60%	≥ 70%	≥80%
2000 hrs.	≥ 60%	≥ 70%	≥80%

- Overall PN-peak reduction during free acceleration ≥ 95%
  The criterion is the ratio of the peak values
  Measurement as specified by SN 277206

SUMMARY

- **Retrofitting machinery with DPFs**, is one of **the key strategies for protecting miners from harmful diesel particulate exposure**
- For Health protection, **All combustion engines** must have Particle Filters to reduce particle number emissions
- **Retrofit** of all in-use Diesels with DPF
- **Retrofit** of all in-use Petrol Engines with GPF
- **Select only VERT certified filters – VERT- Filterlist**
- **All VERT-certified filters ensure particle elimination, toxic gas reduction, no secondary emissions, low noise, long life, but …it is important** to check the engine operation conditions carefully (i.e. engine Backpressure requirement, Fuel Quality, Lube Oil Quality, Installation, Vibration, Heat etc.)
- Important is to install remote control Monitoring and Implement Inspection & Maintenance Rules

→ **This will generate Health Protection, Global Warming Mitigation, fast & cost effective solutions to Clean urban mobility ….and above all in developing countries, where extremely dirty engines will be used for many years to come….**

Acknowledgement

Co-authors – VERT Association Scientific Committee

https://www.vert-dpf.eu/

Dr. A. Mayer

Prof. J. Czerwinski

Mr. T. Lutz

THANK YOU FOR YOUR ATTENTION!

aerosolfd-project.eu

https://www.vert-dpf.eu/

Questions?

Lauretta.Rubino@vert-dpf.eu

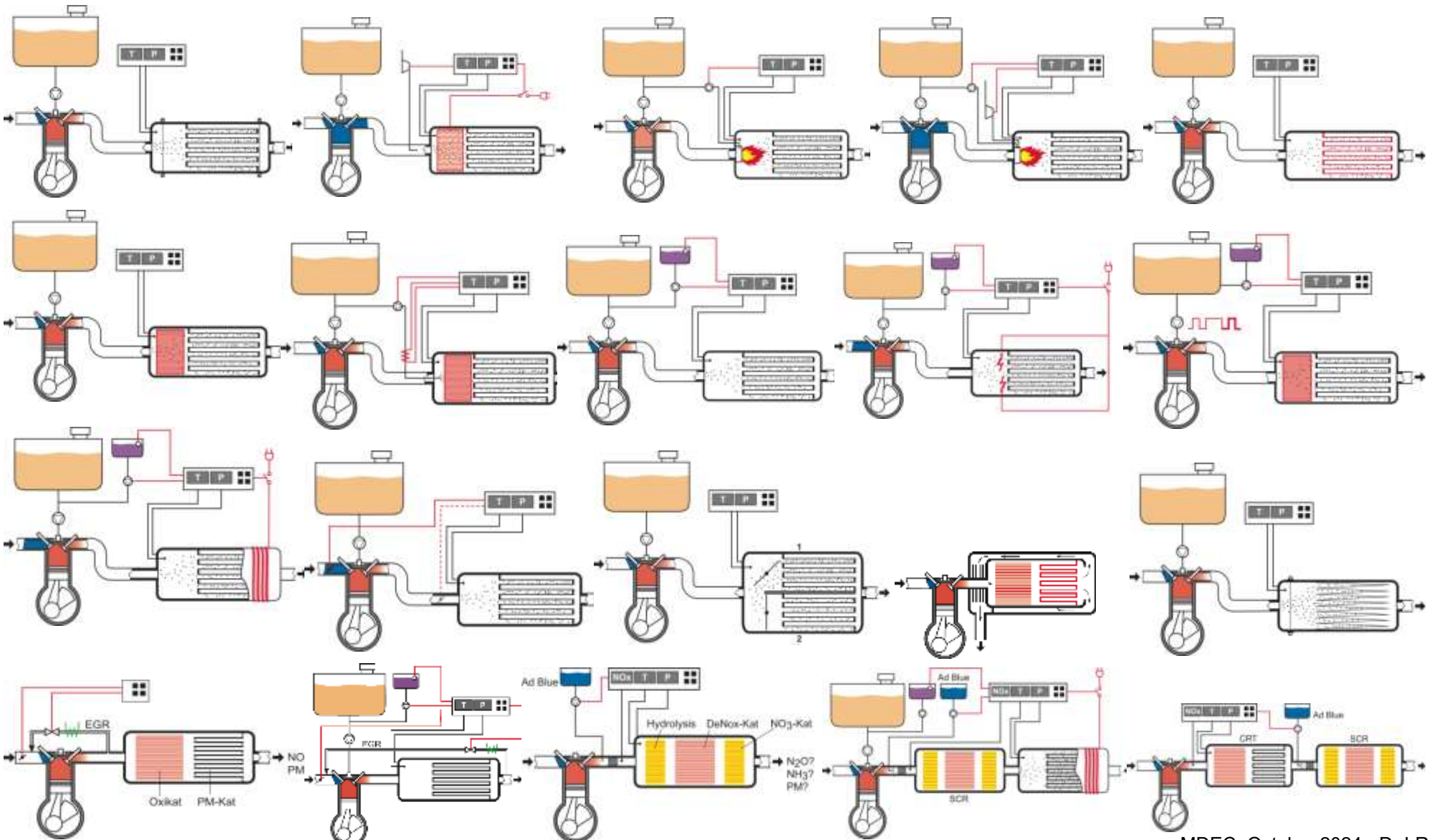
BACKUP

Material Data of ceramic filter substrates

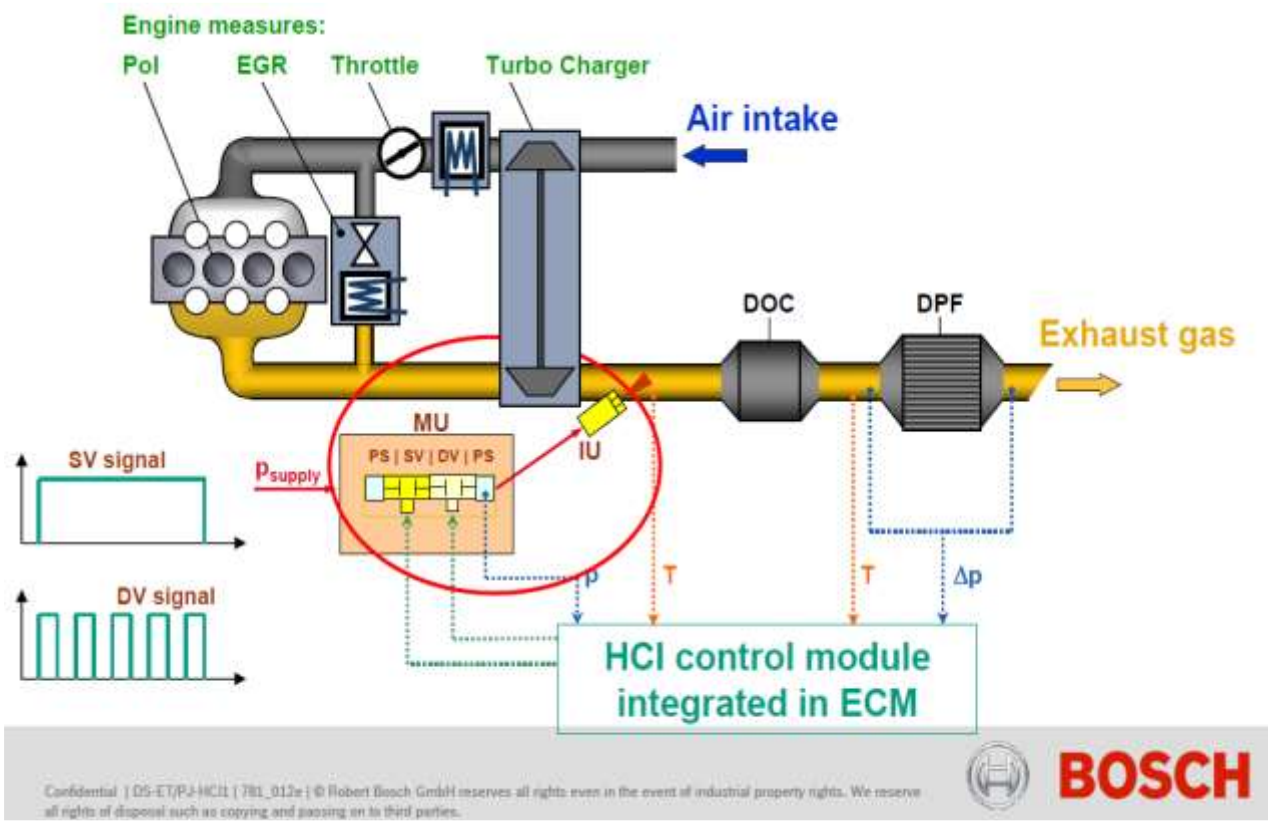
	Si-SiC	Recrist. SiC	Cordierite
Porosity [%]	46 (40-62)	36-45	60 (53-70)
Pore Size [µm]	20 (8-33)	8-10	25 (15-35)
Youngs modulus E [Mpa]	18	49	11
Bending Strength [Mpa]	**21**	**53**	**1-8**
Heat Expansion CTE X10^6 (40-800°C)	**4.1**	**4.3**	**0.3**
Thermoshock resistance [°C] (cold water test)	1200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

VERT–certified DPF Systems

for different targets and applications



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

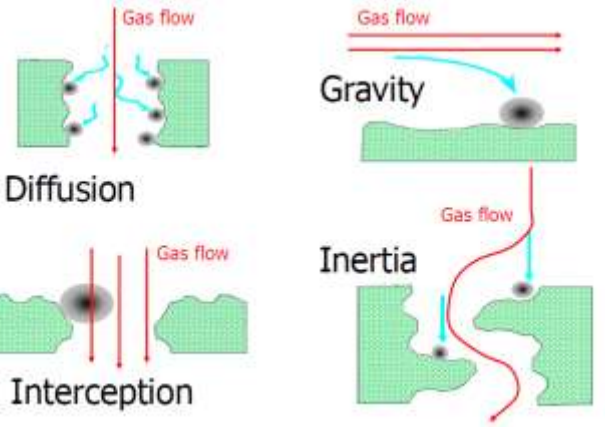


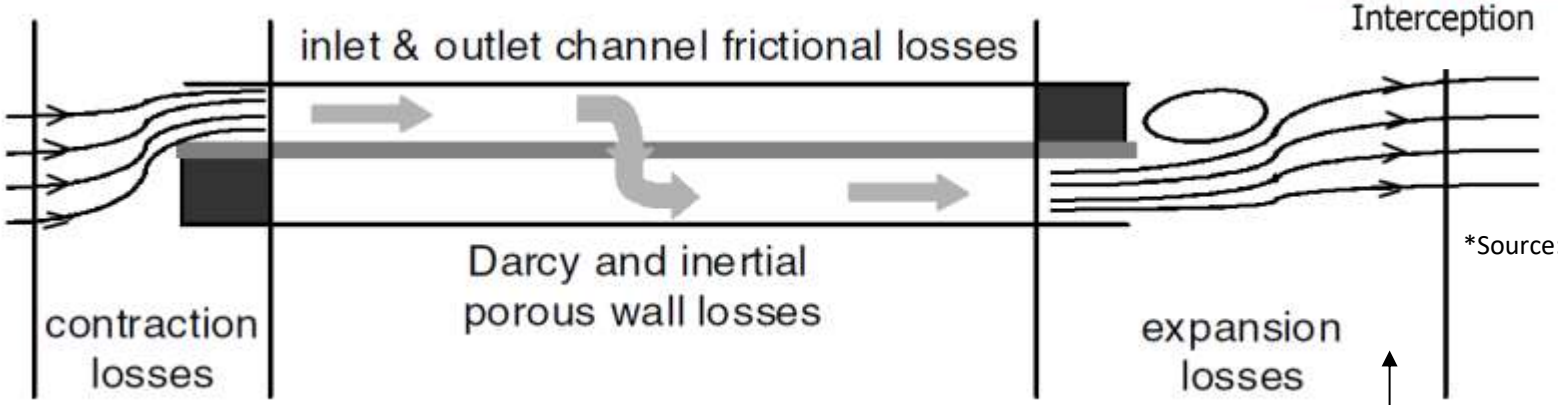
- Intake Throttle
- HC-injection
- Catalyt Combustion
- Retarded injection
- Multiple Injection
- TC-Management
- EGR Managment
- Cooler Managment
- Electric Load

Particle Filter Filtration & Backpressure

Backpressure drivers:

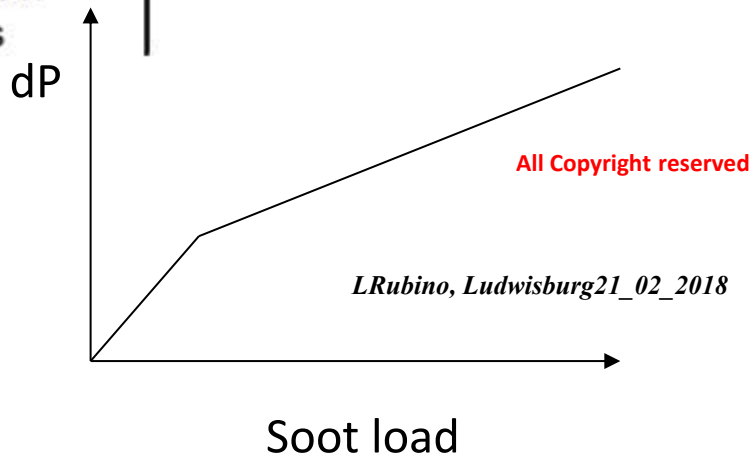
- **Deep bed filtration**
- **Soot cake**





*Source: SAE 2001-01-0909

- Flow contraction when entering the filter channel
- Friction within channel
- Flow trough soot cake
- Flow trough (soot loaded) filter wall
- Expansion losses when leaving the channel



LRubino, Ludwisburg21_02_2018