

## Filtration of diesel soot nanoparticles and reliability in Swiss HDV retrofitting

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## INTRODUCTION

- Ambient PM10 - Limit exceeded all over Switzerland
- 60% Ultrafine Particles are emitted by Combustion Engines
- Diesel Particles are Lung Penetrating
- **Diesel Particles are Carcinogenic**
- Mortality by Air Pollution is **5 x Traffic Accident Mortality**

→ Minimization acc. to Best Available Technology BAT required

→ **Particle Traps are efficient and available = BAT**

## Health Effects in Numbers

### Mortality in Switzerland :

- 3'300 cases per year due to traffic air pollution

### Cost-Effectiveness of Particle Filters:

- Health Cost 3 x higher than Cost of Particle Filters

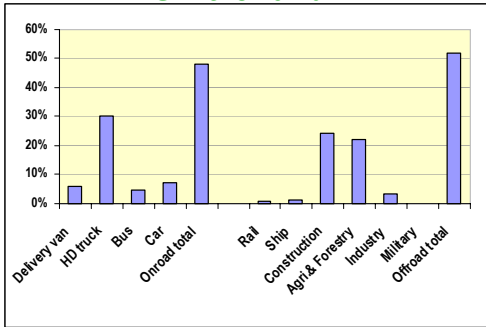
### Population Groups are at the highest Risk:

- **Children**
- Truck/Bus-Driver
- User of Diesel Buses
- People living in Cities, close to Highways

## High emissions from construction machines downtown



### Contribution of on-road and off-road Diesel engines to particle emissions in Switzerland.



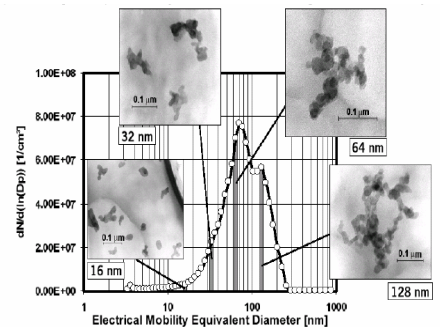
### Statements of the Swiss Government

- Application of PFS on Construction Machines is **technically and operationally feasible and commercially justified**
- Retrofit of PFS on Construction Machines is **in the paramount interest of public and occupational Health**
- Use of PFS is **economically beneficial** since Cost for Retrofitting (1,4 billion SFr till 2020) is 3 times lower than Health Cost (4 billion SFr) during the same Period

### Swiss Regulations to enforce PFS-Introduction

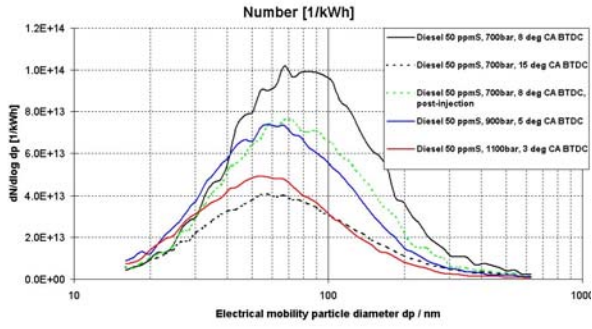
- 1990 (EJPD): Retrofit permitted under Condition:
  - no additional Noise Emission
  - no Formation of **secondary toxic Air Contaminants**
- 1994: SUVA: Diesel-Emissions DME **carcinogenic**
- 1998: LRV: Diesel-Soot **carcinogenic**
- 1998: Limit for steady state Engines < 5 mg/m<sup>3</sup>
- 2000: **SUVA: PFS mandatory underground**
- 2002: **BUWAL-BauRLL: PFS mandatory for general construction (B-type construction sites)**
- 2003: ASTRA: only VERT approved PFS for Vehicles

### Diesel Particles Morphology depends on Particle Size

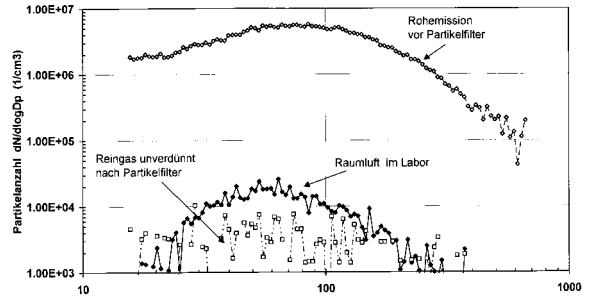


Quelle: METZ, BMW

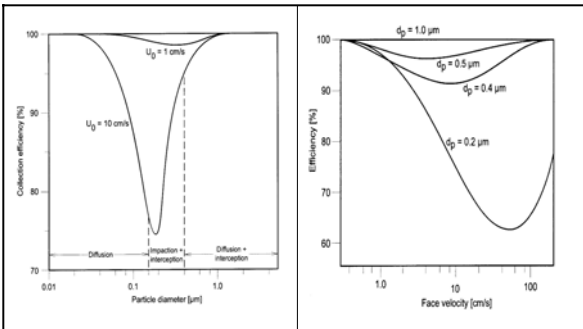
## Particle-Reduction by Injection Management – but NOx increases



## Filtered Diesel Exhaust cleaner than Ambient Air



## Weaknesses of Filters in the Size Range of Diesel Soot Particles



## Definitions for Filtration Efficiency

- PZAG: Filtration based on **Particle Number PZ**  
**PZAG:** 1 – PZ downstream Filter / PZ upstream Filter
- PMAG: Filtration based on **Particle Mass PM**  
**PMAG:** 1 – PM downstream Filter / PM upstream Filter
- ECAG: based on elemental **Carbon Mass EC**  
**ECAG:** 1 – EC downstream Filter / EC upstream Filter

## VERT specifications for particle trap systems (1)

	New	2000 operation hours
<ul style="list-style-type: none"> <li>▪ <b>Filtration efficiency</b> „Concentration count“ in the particle size range 20-300 nm</li> </ul>	> 95%	> 90%
<ul style="list-style-type: none"> <li>▪ <b>Filtration efficiency</b> „EC mass concentration“</li> </ul>	> 90%	> 85%
<ul style="list-style-type: none"> <li>▪ <b>Opacity</b> during free acceleration</li> </ul>	< 0.12 m <sup>-1</sup>	< 0.12 m <sup>-1</sup>
<ul style="list-style-type: none"> <li>▪ <b>No increase</b> of the limited emissions CO, HC, NOx and PM</li> </ul>		

## VERT specifications for particle trap systems (2)

- **No relevant emission** of secondary emissions
- **Rejection limit for field verification:**  $K > 0.24 \text{ l/m}$
- **Pressure loss** max. 200 mbar
- **On-road monitoring** with alarming + logging functions
- **Noise attenuation** equivalent to muffler
- **Durability:** Minimum 5,000 operation hours
- **Unique identification:** Flow direction marked
- **Safety:** compliance with legislation on safety of technical equipment
- **Diagnosis access** for exhaust gas sampling ahead of trap
- **Concept for cleaning and disposal**

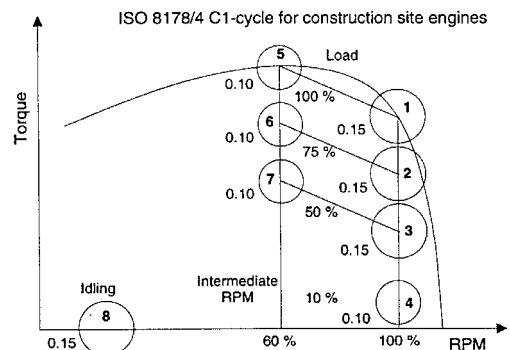
## VERT Filter Suitability Test

- **VFT1:** PFS new – degreening acc.to manufacturer
- **VSET:** Secondary Emissions Test (>200 Substances incl. PCDD/F and Nitro-PAH)
- **VFT2:** 2000 Operation Hours Field Test
- **VFT3:** Repetition of VFT1 after Field Test

**VERT-Approval → BUWAL Filter List**

**VERT-Approval is lost at a Failure Level > 5 % pa**

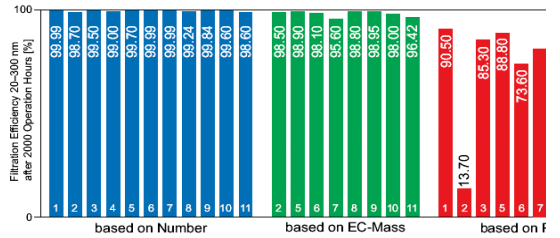
## Test Cycle for VERT Suitability Test



## VERT- tested PFS Status 8/2003

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	Active Regeneration	Passive Regeneration	Filtration-Efficiency
DEUTZ	Full Flow Burner		98 old data
ECS-UNIKAT	Electrical Heating	Catalyst Coating	99.99
HJS		CRT, FBC (Additives)	99.40
JOHNSON MATTHEY	Electrical Heating	CRT, FBC	99.50
HUSS	Electrical Heating Standstill-Burner		99.99
DCL	Electrical Heating Intake Throttling	FBC, Catalyst Coating	99.99
ARVINMERITOR	Full Flow Burner		99.84
ENGELHARD		CSF	99.60
HUG	Full Flow Burner	Catalyst Coating	98.60
INTECO		FBC	99.24
EHC	Exchangable		96.70
TSH	Electrical Heating	Catalyst Coating	98.90



VERT Particle Filter-Verification (all Systems after 1998)  
ISO 8178 Test-Cycle. Number by TD+SMPS+CPC. EC-Mass by Coulometry. PM as usual.

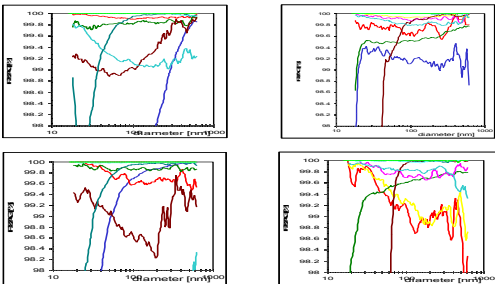
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## Filtration efficiency for 10 VERT-PFS

Nominal RPM; full load (top), half load (bottom)

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left: new right: after 2000 op.hrs

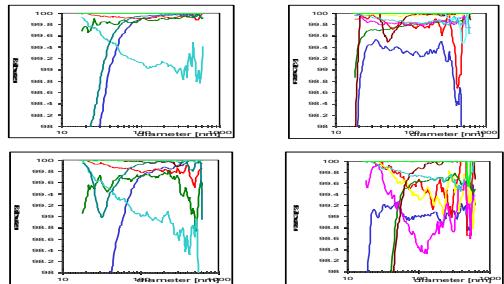


## Filtration efficiency for 10 VERT-PFS

60 % of nominal RPM; full load (top), half load (bottom)

20

left: new right: after 2000 op.hrs

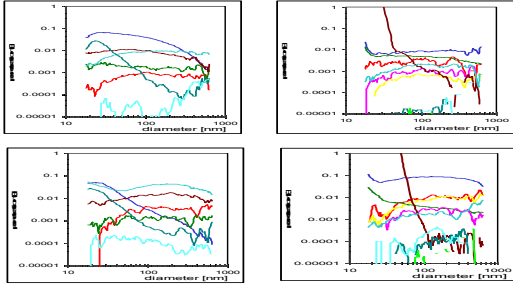


## Filter Penetration for 10 VERT-PFS

Nominal RPM; full load (top), half load (bottom)

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left: new right: after 2000 op.hrs

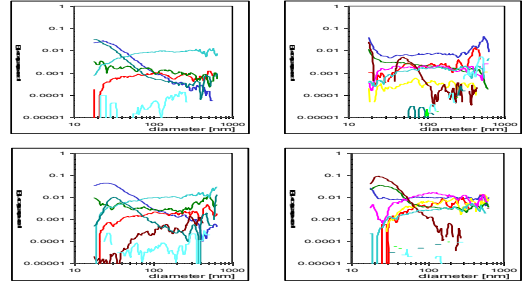


## Filter Penetration for 10 VERT-PFS

60 % of nominal RPM; full load (top), half load (bottom)

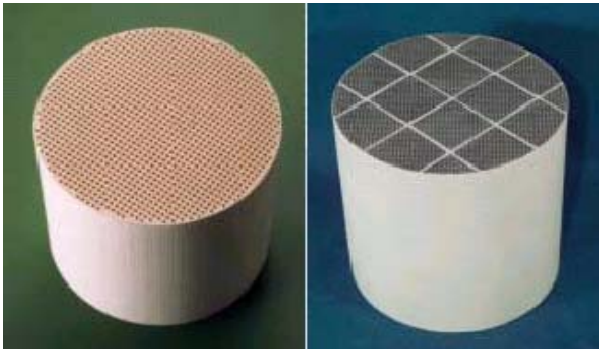
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left: new right: after 2000 op.hrs



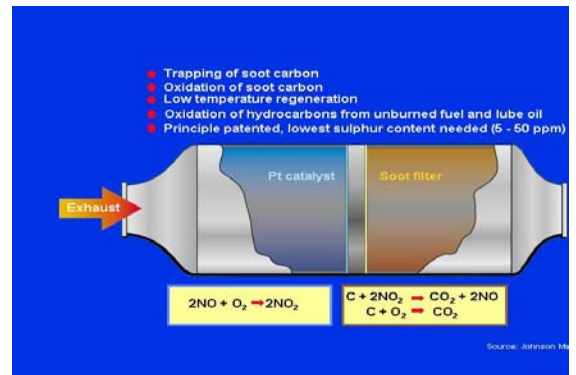
## Cordierite and Silicon Carbide typical Ceramics for Particle Filters

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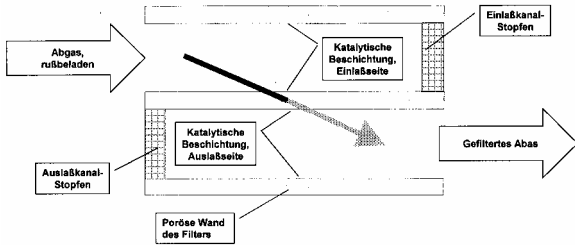


## CRT-Filter

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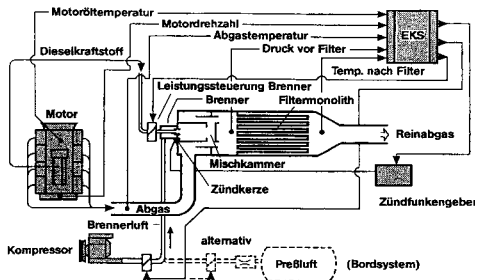
### Catalyst Coated Cell Filter (CSF = Catalytic Soot Filter (ENGELHARD))



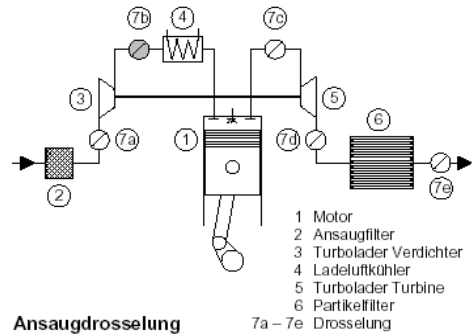
### Fuel-Additives to support Regeneration by Catalysis

- Cerium-Oxide – Product EOLYS / RHODIA
- Ce/Fe - RHODIA
- Fe as Ferrocen – Product satacen / OCTEL
- Fe/Sr - OCTEL
- Ce/Fe - RHODIA
- Fe - INFINEUM
- Ce/Pt - CDT

### PFS with Full-Flow-Diesel-Burner (DEUTZ)



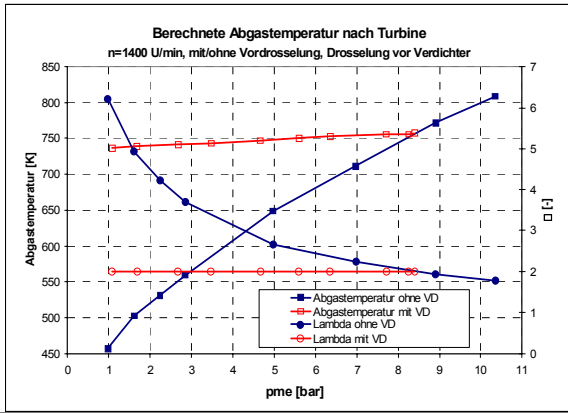
### Throttling of Intake Air or Exhaust Gas increase Temperature by 200-300 °C spontaneously



Ansaugdrosselung

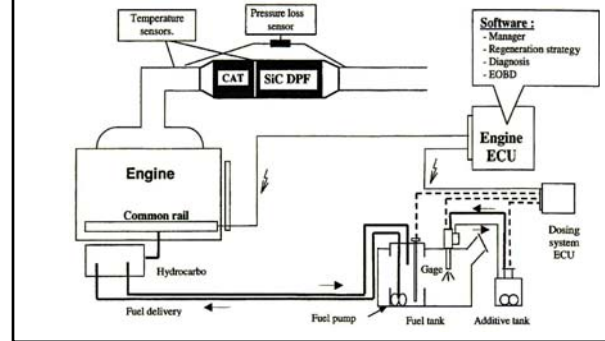
## Effect of Throttling

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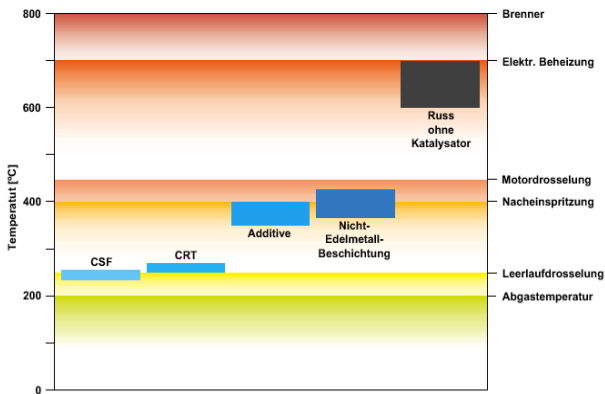
## PSA Filter System for Passenger Car

30



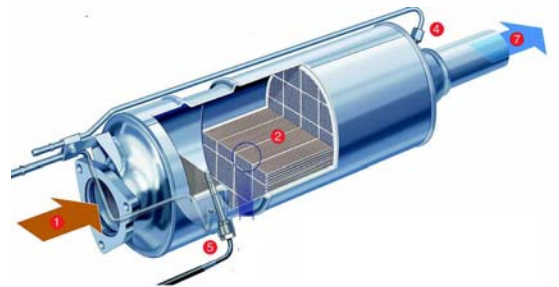
## Passive and active Regeneration

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## Filter-System for a Passenger Car

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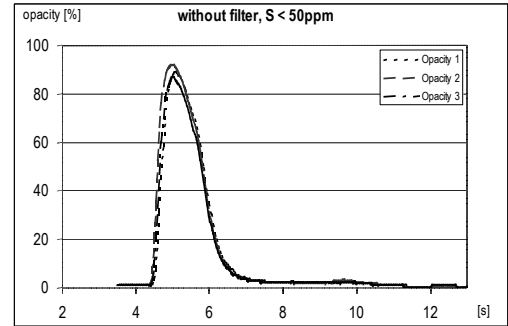


## Truck-Installation in place of Muffler



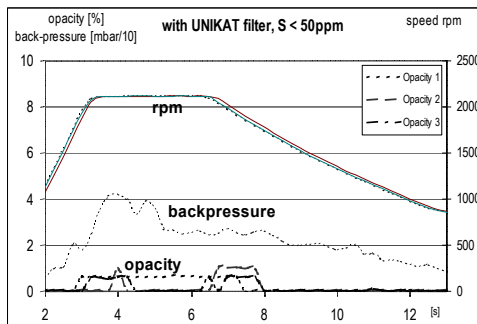
## Opacity during free acceleration without particle trap

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## Opacity during free acceleration with particle trap

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## Type Approval and Field Control

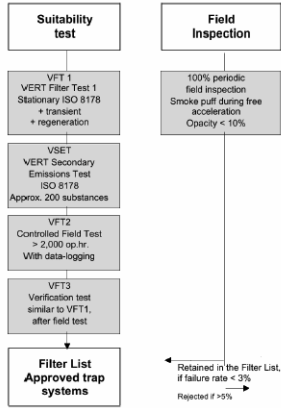
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Product Quality can not be left to Market Dynamics – the following instruments had to be developed

- **VERT-Suitability Test:**  
4-Stage Type Approval including 2000 Operation Hours Field Test
- **Filter List:**  
listing all VERT-tested-PFS – update every 3-4 Month
- **Engine Maintenance and Emissions Control by the Operator:**  
with and without Particle Filter every 24 Month
- **VERT-Filter Label (AKPF):**  
for PFS outstanding Quality only ( $k < 0,12 \text{ 1/m}$ )
- **Quality control by the Manufacturers and yearly Report to BUWAL**  
Immediate Measures if Failures exceed 3%
- **Official Vehicle Controls MFK – Period 2 Years**
- **Statistic Controls by the Local Clean Air Authorities**

## Overview of VERT suitability test

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## Spectacular Filter Damage Ring-off-Cracks and Melting of the Cordierite Material source Johnson Matthey

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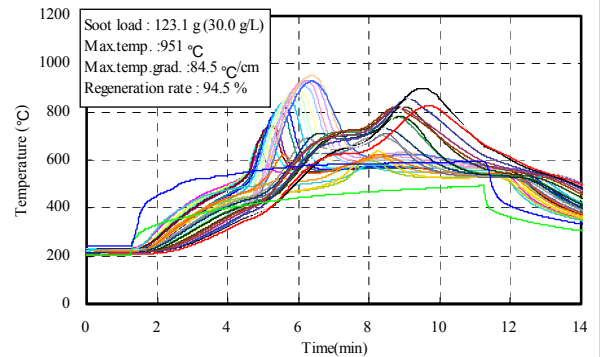


## and this is how it starts

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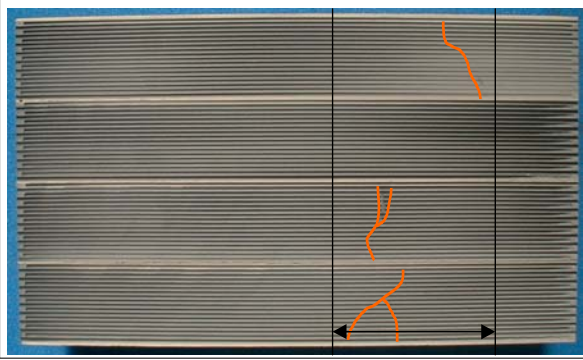


## Reasons for Failures: Local Temperature Peaks during Regeneration <sup>40</sup> (source IBIDEN)



### Typical Failure due to excessive Exothermics in a segmented Filter (source IBIDEN)

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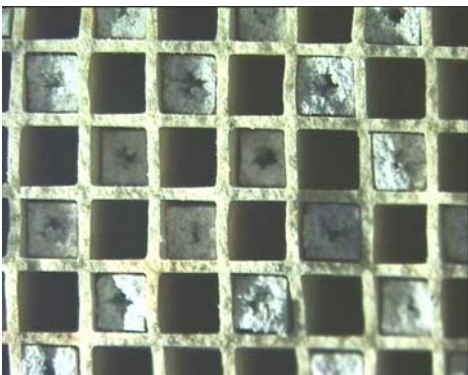
### Filter-Damage due to excessive Temperatures and Vibrations (source EMA)

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### Ash Plugging of Filter Cells (source SHELL)

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### Reliability of PFS in Switzerland

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- 1990: 230 Filters installed in Buses (DB/M&H-System)  
1998: still 200 in Operation
- 2000: 2400 PFS in Operation, > 6% Failures  
→ too many Failures → Measures
- 2003: > 6500 PFS in Operation
  - Failures < 2 % per year
  - PFS > 750'000 km with Trucks and Buses
  - PFS > 10'000 op.h on Construction Machines
  - PFS > 28'000 op.h on a Ferry Boat
- 2005: Construction Directive > 15'000 PFS expected  
Failure Target: < 1% pa

## Measures to improve Quality introduced Y 2000

- One Filter Family lost VERT-Approval (disappears immediately after from Swiss Market)
- Introduction of the 2000-hrs Operation Test (VFT2)
- Introduction of electronic On-board-Control and further mid-term measures
- Increase Use of active Filter-Systems
- Obligation for Engine Maintenance and Emission Control
- Access upstream of PFS for Emission Diagnosis
- Systematic PFS-Selection (CD available)

## Failure Statistics 10/2003

Manufacturer	Numbers of Retrofits			Reported Failures	
	2001	2002	2003	2001-2003	
A		280		5	1.8%
B		420		10	2.4%
C		225		5	2.2%
D	400	600	320	20	1.5%
E	200	250	370	12	1.5%
F	134	195	340	18	2.6%
G	-		18	1	5.5%
H	< 10	< 10	< 10		?
I	< 10	< 10	< 10		?
K	?	?	?		?
L	-	< 10	< 25		?
	Retrofits 01-03 3848			Number weighed Failures 2001-03	
	Total Retrofits 10/2003: 6231			1.8% (< 1 % pro year)	

## Character of Failures (1)

### Most Failures immediately after Retrofit

- Canning Failures of the Ceramic Monolith
- Material Failures of the Filter Media
- Cementing Failures with segmented Filters
- Mechanical Shock: during Transport or Installation
- Installation: often insufficient Vibration Decoupling
- Operation: wrong Fuel – Sulfur Content too high
- Application: wrong System selected
- High Lubrication Oil Consumption

## Character of Failures (2)

### Failures rarely happen after long Operation:

- Backpressure-Alarms not respected
- Ash-Cleaning unprofessional
- Engine Maintenance careless

Experience proves that VERT-Filters show no aging effects – loose no Filtration Quality

## Cost

- **Retrofit Cost at low Volume today**
  - Engine Range 100 kW: 100 Fr/kW
  - Engine Range 500 kW: 80 Fr/kW
  - Engine Range 25 kW: 125 Fr/kW
- **Cost Reduction expected**
  - Manufacturing Cost by 1/3 within 2 Years
  - Installation Cost will stay high

## Planning for Switzerland

### Retrofits

- Construction 25'000 (total 55'000) **today: 5'300**
- Agriculture 30'000 (total 110'000)
- Trucks 20'000 (total 65'000)
- Buses 3'500 (total 5'500) **today: 1'200**

### Incentives for new Vehicles

- LD-Vehicles Reduction of Import Tax (4%)
- HD-Vehicles Reduction of Road Tax LSWA

### Quality Criterion

- Ultrafine Particle Number Concentration

## Summary and Conclusions (1)

- Filtration Efficiency > 99.9%
- Filtered Exhaust Gas cleaner than Ambient Air
- Diesel Particle Filters show no Aging
- Reduction of CO, HC and PAH by > 95%
- Backpressure limited to < 200 mbar
- Impact on Fuel Consumption < 3%

## Summary and Conclusions (2)

- Mileage Trucks and Buses > 750'000 km
- Operation Construction Machines > 10'000 op.h.
- Best Reference Case Ferry Boat 28'000 hrs
- > 7'000 Retrofits in Switzerland
- Reported Failures < 2% pa
- Cost for individual Retrofits 100 Fr./kW,
- Cost Reduction by 1/3 over next 2 Years
- Cost Effectiveness „PFS Cost/Health Cost“ 1 : 3

### Summary and Conclusions (3)

- PFS are BAT to minimize high Health Risks of Machine Operators and Population
- PFS can be applied on Diesel Engines of any Age, Design and Application
- PFS will become a Standard Component of Diesel Engines (like 3-way Cats for SI-Engine)

**Thank You for your kind Attention**

**We are ready for Questions  
now or later**

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