Verified particulate trap systems for Diesel engines

"Filter list"

suvaPro

BUWAL Bundesamt für Umwelt, Wald und Landschaft
OFEFP Office fédéral de l'environnement, des forêts et du paysage
UFAFP Ufficio federale dell'ambiente, delle foreste e del paesaggio
SAEFL Swiss Agency for the Environment, Forests and Landscape

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Prepared by: Dipl. Ing. A. Mayer
Technik Thermische Maschinen TTM
Fohrhölzlistrasse 14b
CH-5443 Niederrohrdorf
Switzerland

Tel:  ++41 (56) 496 64 14
Fax:  ++41 (56) 496 64 15
e-mail: ttm.a.mayer@bluewin.ch

To order: - SUVA Luzern
Customer Services
Postbox 4358
CH-6002 Luzern
Switzerland

Tel:  ++41 (41) 419 58 51

- BUWAL (Swiss Agency for the Environment, Forests and Landscape)
Documentation
CH-3003 Bern
Switzerland

Fax:  ++41 (31) 324 02 16
E-Mail: docu@buwal.admin.ch
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1. Introduction

Hot gas filters for diesel particulates have been the focus of intense activity during the last 20 years. Numerous filter media and regeneration methods were developed. Only a few of these reached maturity and were tested. Even the mature systems were not widely deployed because there was no legislation and the engine industry did not voluntarily implement this promising development.

Meanwhile a new situation has evolved. Legislation is now effective in Germany (TRGS 554 and the German TA Luft), Austria (Occupational Health) and Switzerland (the Ordinance on Air Pollution Control OAPC 98).

Accordingly, VERT\(^1\) initiated comprehensive investigations (1993 - 1998). These confirmed the particulate trap as the only efficient solution for sustained curtailment of the diesel particulates. The investigations particularly proved that such filters can intercept at least 99% of the sub-micron particulates in the range of heightened pulmonary intrusion. Thus, the imperatives to minimize carcinogenic substances in occupational health, and ensure air quality, are better fulfilled than with all other known measures. These results have been repeatedly published and discussed among specialists. The facts are now established.

Particulate filters are now imperative for many applications. They are a prerequisite for implementation of the VERT conclusions on occupational health (Suva, AUVA, TBG) and compliance with the Swiss Ordinance on Air Pollution Control 1998. The deployment of these traps is proven technically, operationally and economically feasible. The traps are state of the technology. The technology, in particular the availability of proven trap systems, was thoroughly investigated in the VERT project in collaboration with several industrial partners. Compliance with the resulting VERT specification must be individually assessed through the VERT suitability test.

This report does not cover the many filter media and regeneration systems that are yet undergoing development or are being researched. Recently, there have been many such R&D proposals. Besides simple filtration, these proposals combine filtration with oxidation catalysis, or filtration with deNOx catalysis, or even direct thermal conversion without filtration. The development efforts are expected to intensify. Soon, technical advances will be combined with significantly lower unit costs.

The items listed were coordinated with Suva, AUVA, TBG, BUWAL, UBA/Berlin, LFU/Munich and industry representatives. The list may be incomplete and will be enhanced through further inquiry and experience. Users are advised to contact the manufacturers (address list appended) directly and demand compliance with the specifications. The manufacturers must deliver proof of successful results from suitability tests.

BUWAL have appointed and financed TTM as consultants. The TTM mandate comprises advice on the selection, design and operation of particulate trap systems.

The working group "particulate trap system manufacturers" was established on 30 September 1998. Its task is to technically accompany the wide scale deployment of particulate trap systems. "Instructions for using particulate traps" were prepared for this purpose. The working group will evaluate experience and periodically inform both users and the authorities.

\(^1\) VERT: A project of SUVA+TBG+AUVA+BUWAL for curtailing construction engine emissions in tunnel sites
2. Objectives and criteria

The primary target is to minimize the pollutant emissions from diesel engines. In particular, the carcinogenic potential must be restricted to the minimum technically feasible. The carcinogens are mainly the particulate combustion aerosols, the so-called diesel soot. These particulates have a solid core mainly consisting of elementary carbon. They also have a very surface-rich morphology. This adsorbs many other toxic substances, which are transported with the particulates, and can penetrate deep into the lungs. Besides these combustion aerosols, the exhaust gas also contains further solid aerosols, e.g. ash particulates, metallic abrasion, sulfates and silicates. The vast majority of these particulates are in the invisible sub-micron range of 100nm. Trap systems must therefore efficiently diminish the particulate count as well as the particulate mass.

Trap systems for this duty must have a very high filtration rate in the entire range of pulmonary intruding particulate sizes. Modern systems can attain values above 99%. The value of these trap systems is enhanced when they also eliminate further pollutants, in particular the carcinogenic PAH, through the binding on the particulate surface. The deployment of filtering exhaust gas treatment systems must not generate any additional pollutants (secondary emissions). This is not a forgone conclusion, as experience with metallic fuel additives has shown.

Trap operation is characterized through long periods of soot collection alternating with short burn-off sequences. These should not result in emission peaks, i.e. caused by rapid regeneration with phases of incomplete combustion or trap rupture tendencies. An additional criterion is that these traps only cause a negligible back-pressure. Otherwise the engine process is impacted and, in turn, increases fuel consumption, increases pollutant emissions or shortens durability. There are many other practical criteria, e.g. trap size, weight, thermal inertia, muffling, and surface temperature. Of course, the investment and operating costs as well as the maintenance effort are decisive criteria in the success of such exhaust-gas after-treatment technology.

Compliance with the outlined criteria list cannot be left to chance. The risk of set-backs, in the introduction of this technology must be minimized. Hence, the VERT principals Suva, AUVA, TBG and BUWAL decided to develop pertinent mechanisms together with the industry. These include:

- **Specifications for trap systems**: Besides the demands on the filtration characteristic of the filter media, the specifications also define requirements on the regeneration procedure and the self-monitoring.

- **Suitability test**: The trap system must be tested under engine conditions. The suitability test also verifies the regeneration response and the aging during operation.

- **Field verification and field measurement**: Periodic control of the trap system during operation is imperative. The measurements must be suitable to dependably verify the essential performance criteria under field conditions.

The appended list of tested trap systems is an initial orientation. The Suva and BUWAL jointly publish this list and periodically update it.

Only those trap systems can be truly recommended for deployment that comply with the specifications and passed both stages of the suitability test.

An exception can be made for traps that have passed the first part of the suitability test but are yet undergoing field-testing. Such systems may be deployed, provided the manufacturer gives the pertinent guarantee and the second phase of the suitability test is definitely planned.
3. Available filter systems

A filter system consists of the following components:

- Filter medium
- Regeneration arrangement and procedure
- Control and monitoring

All three components must be integrated, maintained, and ecologically disposed off at the end of their life-cycle. Obviously, the operators prefer to single-source the entire system and thus ensure reliability.

Fully automatic systems are desirable; i.e. neither the driver nor the workshop need intervene during the life-cycle of the trap system. Such systems are commercially available. Systems that are not fully automatic, e.g. systems with standstill regeneration and exchangeable filters, must be justified in a cost/benefit analysis.

A special case is the use of fuel additives to lower the soot ignition temperature. To ensure effectiveness, the dosage and sufficient additive storage should be connected to the vehicle. Fuel supply from pre-mixed tanks is risky, because other vehicles could be fueled from such tanks and emit additive ash particulates when not equipped with appropriate traps.

Some trap systems already comply with all these specifications and thus represent the state of the technology. Surprisingly, many filter media fulfilled the minimum criteria of the specification. The VERT field tests, however, revealed that many traps require further refinement to dependably sustain the quality criteria during a long operational period.

There is a multitude of applications for diesel engines. Experience is not yet accumulated for all applications. In certain instances, it may therefore be necessary to specifically evaluate several trap systems.

Some properties of the trap systems are not addressed in these lists. Nevertheless, they are very significant for the comprehensive evaluation and recommendation for practical deployment.

These include:

- Combating ash accumulation: The traps retain the ash components due to the high filtration efficiency. The ash particulates are not combustible. Hence, they progressively clog the pores of the filter medium and thus increase the back pressure. The filter elements must therefore be periodically replaced or cleaned. The cleaning interval mainly depends on the fuel, lubricants, operations, filter properties and filter design. These aspects can only be satisfactorily resolved when the users collaborate with the filter manufacturers. It can be advantageous to use premium fuels (low sulfur), or better lubricants (lower TBN) or even more efficient inlet-air filters.

- Easy maintenance: The specification indeed defines the maximum maintenance interval. The maintenance effort can vary widely depending on the filter system.

- Ecological disposal: The filtration efficiency results in the trap retaining several toxic substances during deployment. Hence, simple disposal is not permissible. Many traps also contain precious metals that should be recovered. Filter disposal should therefore be contractually decided with the suppliers.

The following tables list the available filter systems with their many characteristics.
# Filter systems

Prerequisite for selection is the successful completion of the filter suitability tests (4.2) according to the criteria of the VERT specifications (4.1)

<table>
<thead>
<tr>
<th>Filter systems</th>
<th>Tests 1)</th>
<th>Deployment range</th>
<th>Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suitability test when new</td>
<td>Suitability test after deployment</td>
<td>Automobile</td>
</tr>
<tr>
<td>DEUTZ</td>
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<tr>
<td>Ceramic cell or wound fiber filter</td>
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<tr>
<td>• Full-flow diesel burner</td>
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<tr>
<td>• Replaceable filter (ext.regeneration)</td>
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<tr>
<td>• Snap-on filter</td>
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<td></td>
<td></td>
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<tr>
<td>ECS</td>
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<td></td>
<td></td>
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<tr>
<td>Ceramic cell filter</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>• Additive regeneration 2)</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>• Electr. standstill regen. on board</td>
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<tr>
<td>• Catalytic coating</td>
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<tr>
<td>HJS</td>
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<td></td>
<td></td>
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<tr>
<td>Ceramic cell filter</td>
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<td></td>
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<tr>
<td>• CRT-System:</td>
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<tr>
<td>reg. via NO₂ / produced by oxi-cat prerequisite: fuel Sulfur &lt; 50 ppm</td>
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<tr>
<td>Sintered metal filter (Type SHW)</td>
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<tr>
<td>• With additive regeneration and/or burner heating</td>
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<tr>
<td>HUG</td>
<td></td>
<td></td>
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<tr>
<td>Woven fiber filter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Catalytic coating and/or additive 2) and/or burner</td>
<td>•</td>
<td>•</td>
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</tr>
</tbody>
</table>

1) Tests
* | * Unconditional recommendation after successful completion of the suitability tests in both parts (new state and after deployment). There are conditions attached to all other cases.

2) Proviso: Copper is not permissible
Filter systems

Prerequisite for selection is the successful completion of the filter suitability tests (4.2) according to the criteria of the VERT specifications (4.1)

<table>
<thead>
<tr>
<th></th>
<th>Tests 1)</th>
<th>Deployment range</th>
<th>Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suitability test when new</td>
<td>Suitability test after deployment</td>
<td>Automobile</td>
</tr>
<tr>
<td><strong>HUSS</strong></td>
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<tr>
<td>Ceramic cell filter</td>
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<td></td>
<td></td>
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<tr>
<td>• Electr. standstill regen. on board</td>
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<tr>
<td><strong>Johnson Matthey</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Ceramic cell filter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• CRT System</td>
<td>•</td>
<td>•</td>
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<tr>
<td>• Diesel injection + catalytic ignition</td>
<td>•</td>
<td>•</td>
<td></td>
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<tr>
<td>• Electr. standstill regen. on board</td>
<td>•</td>
<td>•</td>
<td></td>
</tr>
<tr>
<td>• Additive 2) + diesel burner</td>
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<tr>
<td><strong>Oberland-Mangold</strong></td>
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<tr>
<td>Fiber knitted filter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Additive regeneration 2)</td>
<td>•</td>
<td>•</td>
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</tr>
<tr>
<td>and/or cat. coating</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>and/or electrical internal heating</td>
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<td></td>
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</tr>
<tr>
<td><strong>UNIKAT</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ceramic cell filter (Option: + cat)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Electr. standstill regen. on board</td>
<td>•</td>
<td>•</td>
<td></td>
</tr>
<tr>
<td>• Replaceable filter (ext.regeneration)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

1) Tests
   • | •  Unconditional recommendation after successful completion of the suitability tests in both parts (new state and after deployment). There are conditions attached to all other cases.

2) Proviso: Copper is not permissible
Filter elements

Prerequisite for selection is the successful completion of the filter suitability tests (4.2) according to the criteria of the VERT specifications (4.1).

<table>
<thead>
<tr>
<th>Filter elements</th>
<th>Tests</th>
<th>Deployment range</th>
<th>Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suitability test when new</td>
<td>Suitability test after deployment</td>
<td>Automobile</td>
</tr>
<tr>
<td>BUCK</td>
<td></td>
<td></td>
<td>● (●) 2)</td>
</tr>
<tr>
<td>Knitted fiber filter</td>
<td>Catalytic coating and/or additive 3) and / or electrical internal heating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IBIDEN</td>
<td></td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>Ceramic cell filter</td>
<td>Additive regeneration 3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electrical full-flow regeneration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3M</td>
<td></td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>Wound fiber filter</td>
<td>Additive regeneration 3) and electrical internal heating</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1) Tests
- ● ● Unconditional recommendation after successful completion of the suitability tests in both parts (new state and after deployment). There are conditions attached to all other cases.

2) Shortened deployment

3) Proviso: Copper is not permissible
4. Control measures

The intention is to prevent deployment of unsuitable trap systems. Hence, the following control measures were developed, during the VERT project, in collaboration with trap manufacturers, engine operators, engine manufacturers and the authorities:

- **Filter specification** (see 4.1)
  This specification does not reflect the best values obtained within the scope of the VERT program. Several traps demonstrated more than 99% filtration of the ultra-fine particulates. This represents the capability of the technology. The specifications only demand 95%.

  The appended list distinguishes between obligatory and desirable criteria, thus emphasizing the priorities. The specification does not claim technical completeness. It must be further refined in discussions between operators and manufacturers.

- **Filter suitability test** (see 4.2)
  Test in new state: It is often impossible to adequately verify the filtration characteristics in the field after retrofitting. This is because the necessary test conditions usually cannot be represented in the field, or because the required measurement techniques are unsuitable for the field. Hence, it was decided to perform the suitability test of the trap system in the laboratory instead. This suitability test is staged on a representative (construction site) diesel engine. The filtration characteristic is determined under steady-state and quasi-transient (free acceleration) conditions. The mass criteria and the particulate counts for nano-particulates are measured. The pressure loss, regeneration and secondary emissions are verified, too.

  Test after deployment: The suitability test is repeated after an appropriate operational deployment (minimum 30% of the manufacturer's declared life-cycle). This permits a statement on the aging tendency of the entire system. A filter system can only be recommended after positive completion of both parts of the suitability test.

- **Filter self monitoring** (see 4.3)
  It is essential that the trap system itself monitors the back-pressure. The measurements must be recorded and alarms promptly annunciated to prevent damage to the engine and the trap system.

- **Field measurements of emissions** (see 4.4)
  Extensive field measurements of the emissions were performed during the VERT project. The pertinent proposals were formulated in a sub-project and verified in field tests.

  Fleet operators in the United States are obliged to equip engines with appropriate instruments for systematic emission measurements. This is a good example for operators who deploy several diesel engines at construction sites, in enclosed spaces, or similar emission critical situations over a prolonged period. These measurements also assist diagnosis and are indicative of the engine state. Thus, preemptive maintenance can be done and damage prevented.
### 4.1 VERT specifications for particulate trap systems on construction engines

The VERT Project established the following criteria for construction machines. They can be practically employed fully for other machines, e.g. forklifts, trucks, buses and other utility vehicles.

<table>
<thead>
<tr>
<th>Filtration rate (on the reference engine Liebherr 914 T)</th>
<th>new</th>
<th>after 2000 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total particulates, gravimetric (ISO 8178 C1, 4 test points)</td>
<td>&gt; 80%</td>
<td>&gt; 75%</td>
</tr>
<tr>
<td>Elementary carbon EC, Coulometric (mass)</td>
<td>&gt; 90%</td>
<td>&gt; 85%</td>
</tr>
<tr>
<td>Soot puff during free acceleration: opacity measurement (turbidity)</td>
<td>&lt; 10%</td>
<td>&lt; 10%</td>
</tr>
<tr>
<td>Particulate penetration in the size range 10-500 nm (conc. Count)(^1)</td>
<td>&lt; 5%</td>
<td>&lt; 10%</td>
</tr>
</tbody>
</table>

The above values must be maintained both for the clean filter and also for the filter clogged with soot and/or ash. Compliance is required during the entire life cycle and the limits shall not be exceeded even during regeneration processes.

### Additional constraints for emissions

There shall be no clearly detectable and relevant increase of the following emissions compared to the initial engine conditions. Such increases are not permissible even during regeneration:

- Sulfuric acid and / or sulfate formation
- Secondary emissions due to fuel additives (e.g. dioxins/furanes)
- Secondary emissions due to dioxin formation
- Increase of basic emissions CO, HC, NO, NO\(_2\) (cycle total)
- Mineral fiber emissions

### Emission verification in the field

- Vehicles: Verification is according to the method of free acceleration. Maximum opacity of construction diesel engine with soot filter: < 10%
  (corresponds to \(K = 0.24 \text{ m}^{-1}\), or approx. 1 Bosch or approx. 0.03 g/m\(^3\) soot)
- Stationary engines: Blackening measurement at full load Maximum according to MIRA correlation < 5 mg/m\(^3\)

### Pressure loss at rated RPM / full load

- Fresh filter < 50 mbar
- Limit till regeneration < 150 mbar
- Maximum burden (warning) < 200 mbar

### Regeneration

- Preferably in situ and automatically during operation
- Additive dosage on board fully automatic with fill-gauge warning. The additive should not be pre-mixed in containers, if there is a risk of other vehicles being fueled from such tanks.

\(^1\) During the suitability testing, certain traps filtered 99% and more of the nano-particulates counted, i.e. particulate penetration <1% was measured.
<table>
<thead>
<tr>
<th>mandatory</th>
<th>desirable</th>
</tr>
</thead>
</table>

**Filter self monitoring**

* Back pressure monitored electronically with 2 warning set-points: Upper level for filter clogging / lower level for filter damage (rupture)
* Data storage
* Trap size $< 0.6 \text{l/kW}$
  - Approximately the size of the muffler replaced
  - Sight obstruction must comply with applicable regulations
* Muffling $> 25 \text{dBA}$
  - At least equivalent to the muffler replaced

**Costs of trap system**

* Rating $> 200 \text{kW}$ $< \text{CHF 75/kW}$
* Rating $100 - 200 \text{kW}$ $< \text{CHF 100/kW}$
* Rating $50 - 100 \text{kW}$ $< \text{CHF 125/kW}$
* Operating costs $< \text{CHF 0.02/kW}$
* Annual maintenance costs $< 10\%$ of filter cost

**Durability and maintenance**

<table>
<thead>
<tr>
<th>Vehicle:</th>
<th>Stationary engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life expectancy $&gt; 5'000 \text{op.h.}$ $&gt; 20'000 \text{op.h.}$</td>
<td></td>
</tr>
<tr>
<td>Usable hours until cleaning filter from residues $&gt; 2'000 \text{op.h.}$ $&gt; 2'000 \text{op.h.}$</td>
<td></td>
</tr>
<tr>
<td>Maintenance interval $&gt; 500 \text{op.h.}$ $&gt; 1'000 \text{op.h.}$</td>
<td></td>
</tr>
</tbody>
</table>

**Suitability for deployment underground**

* Availability in 3 shift operation
* Maintenance-free during operation
* On-site maintenance
* No additional risk of fire and ignition
* No toxicity risks
* Invulnerable to dusty air and extreme ambient temperatures
* Invulnerable to high air humidity and water spray

The quality-of-service requirements in the specification are verified according to the VERT suitability test on the reference engine Liebherr D 914 T. The measurements shall be performed in the new state and after field deployment corresponding, as a rule, to at least 30\% of the life expectancy (as declared by the manufacturer).
4.2 Filter suitability test

Objective is to measure:
- First measurement of particulate mass and particulate count filtration characteristic.
- Dependence of filtration response on the filter deposition state
- Back pressure response in operation
- Efficiency of the regeneration system
- Behavior under field conditions
- Second measurement of filtration characteristic after field deployment

Test arrangement and measurement technique:
- Test bed: LIEBHERR 914 T/105 kW construction site engine or customer’s choice
- Test scope: 4 operating point according to ISO 8178 C1 plus transient tests “free acceleration” as per 72/306/EWG Appendix 4
- Emission measurements: as per European Guideline No. 91/542/EWG including PM gravimetric and soot-puff opacimetric
- Particulate size distribution: using the SMPS procedure

The VERT reports contain a detailed description of the measurement methods.

Fuel: Diesel fuel as per SN EN 590 KO (sulfur content < 500 ppm) except when the manufacturer explicitly specifies another fuel for operating the filter system.

Lubricants: preferably synthetic lubricant with TBN < 5 (ISO 3771)

Suitability test part 1: New condition
- Conditioning the particulate trap
- Filtration characteristic in deposited state
- Filtration characteristic after regeneration
- Regeneration response including emissions during regeneration

Field testing
- Field deployment in a typical application that the trap manufacturer selects and monitors.
- Three filters during 30% of the declared life cycle, as a rule, at least 2’000 operating hours per filter.
- The filter systems should be sealed to detect tampering.
- Employ data-loggers that record the temperature and pressure during the tests.
- Record all problems, break-downs and repairs, fuel and oil consumption.
- The system may only be modified after consultation with the certifying institution.
- At least two of the three systems must survive field deployment without damage.
  One of the two systems can then be the object for the 2nd part of the suitability test.

Suitability test part 2: Verification after field deployment
- Repeat the pertinent part 1
- Criteria are slightly relaxed according to the specifications
4.3 Filter self monitoring

Traps must be equipped with modern electronic control systems. Two warning levels should be set. The controls ensure that the prescribed trap back-pressure is not exceeded (upper set-point). The controls also detect trap failure, e.g. due to rupture of the filter structure (lower set-point).

Desirable supplementary functions:

- Data storage
- Remote indication (driver cabin)
- Warning signals (driver cabin)
- Self monitoring
- Diagnostic access

Unfortunately, many trap systems are delivered without such controls. Often there is merely a recommendation to use a control manometer.

Modern automatic trap-systems are supplied with the above controls integrated.

Moreover, electronic systems are commercially available that can be combined with any filter. These are recommended as autonomous control systems.

Manufacturers:

- **Johnson Matthey GmbH**, Sulzbach/Germany

- **Nöthiger Elektronik AG**, Niederrohrdorf/Switzerland
  
  The logger system from Nöthiger Elektronik was verified within the scope of the VERT field test. The second generation is now available with substantially enhanced electronic features.

- **G. + M. Schurz**, Unterpremstätten/Austria
4.4 Field measurements of emissions

Within the scope of the VERT working group, the EAM/Wabern (Swiss Federal Office of Metrology) took the lead in preparing recommendations for emission measurement under field conditions (Status 16 April 98; can be obtained from TTM). The following field measurements should be periodically done to track performance.

- **Smoke puff during free acceleration (Opacimetry, 72/306/EWG Appendix 4)**
  This is a legislated method for the periodic inspection of diesel engines in many countries. The method is not without problems and the results can be manipulated. It is important to accurately maintain the RPM range, acceleration time and the number of measurements. Large errors can occur due to careless measurements. However, the method is very simple and can be used for all engines without exception. Particularly for super-charged engines, it is usually a very sensitive method to detect faulty settings and damage.
  Engines that are very clean under steady-state conditions, often have a noticeable smoke puff. Particulate traps that function well under steady-state conditions can, as a rule, also filter this smoke puff very efficiently; i.e. an opacimetric signal is not visible when such a trap is deployed. This method is therefore very suitable as a "black and white" indication to clearly detect filter damage.

- **Blackening measurements at full load:**
  If operationally feasible, the “full load” measurement is preferable to measurements under free acceleration. Full load measurements can be difficult because many engines under field conditions are not at stand-still and cannot be operated at full load for prolonged periods. This is however possible for most construction site engines thanks to hydraulic elements in the transmission. Torque converter engines can, for a short period, be operated at stall. Hydraulic systems, too, can be operated at full load for a short time. In both cases, the operating temperature must be carefully monitored. Usually, 2 - 3 minutes is permissible and sufficient for such measurement.
  Results are generally reproducible. They give valuable information about the emission state of the engine, and supplement the opacimetry. The measurement parameter is basically the black smoke as per the filter method. It is essentially interpreted as elementary carbon and can also be calculated in g/m$^3$ soot using the globally accepted so-called MIRA-correlation. This conversion is even built into many instruments. Increased sensitivity can be obtained with instruments having prolonged filtration collection times, e.g. AVL 407.

- **Measuring gaseous emissions under steady-state conditions**
  Measurements of the legislated pollutants NOx, HC and CO and in addition NO/NO$_2$, CO$_2$ and O$_2$ is possible. This is accomplished using computer-controlled instruments based on electrochemical reaction or infrared absorption sensors. The samples are extracted using modern sampling techniques adapted to diesel engine conditions.

- **Monitoring the filter back pressure, exhaust gas temperature and oil temperature.**

The following manufacturers participated in developing the field measurement techniques:

- **AVL LIST GmbH** Graz/Austria
- **MRU** Emissionsmesstechnik, Heilbronn-Obereisesheim/Germany
- **rbr-ecom** Iserlohn/Germany
- **Testo GmbH & Co.** Lenzkirch/Germany
- **VLT** Gümligen/Switzerland
5. Appendices

5.1 Filter media

There are stringent technical requirements for the diesel particulate trap. It must withstand high temperatures and rapid temperature fluctuations. It must have a high filtration rate for nano-particulates (10-500 nm), too. Further, it must have the lowest possible pressure-loss, long durability and be inexpensive. The only suitable filter media are surface-rich structures of temperature resistant materials such as ceramic substrate or fiber structures. The following filter types are reliable:

- **Ceramic monolith cell filter:**
  The construction is similar to the cell catalytic converter. However, the cells are closed at alternating ends and have a large surface area (1-3 m²/l). Hence, the back-pressure is low and the filtration rate is high, at low gas velocities (a few cm/s) through the cell wall. These filters are usually cordierite extrusions (NGK, CORNING). A new filter material is silicon carbide (NOTOX, IBIDEN). Further intensive development of these materials has resulted in structures largely resistant to thermal shock. Comprehensive global experience spans several decades for filter media of this type, particularly cordierite.

- **Sintered metal filter**
  SHW have developed a metallic filter that has a structure similar to the ceramic monolith. Compared to ceramic, the metal filters are relatively heavy but very robust. They have a naturally high thermal conductivity. A recent development is a lighter sintered metal filter having a bellows structure of filter sheets.

- **Wound fiber filters**
  Yarn from high temperature fiber (material mullite, product name NEXTEL from 3M) is wound on a perforated carrier tube using a special technique to create rhombic canal structures. Filter cartridges of this type were developed and widely tested by 3M and MANN & HUMMEL. Refinements in the winding technique have resulted in a dependable filter element.

- **Knitted fiber filter**
  Ceramic yarn is ring knitted and folded into deep structures. The fiber surface typically attains 200 m²/l. BUCK developed this filter type. It is offered with catalytic coating and internal electrical heating. The preferred flow direction is radially outwards.

- **Fiber weaves**
  High temperature fibers are also woven and can be fixed to metallic carrier structures for filtration. HUG and 3M developed such systems.

- **Filter paper /Filter felt**
  Paper filters, constructed like the inlet air filters, are only feasible when the exhaust gas temperatures are dependably held low. Papers are available (DONALDSON) for deployment temperatures up to about 300°C. In principle, these papers, too, are fiber filters. The short fibers are arranged in a random form and the structure fixed using binders. For higher temperatures, ceramic fiber felts can be deployed. This is a well-established method for industrial hot gas filtration (BWF).

Compared to the above high surface structures, flow dynamic procedures and electrostatic methods are not successful. Gas washing is totally unsuitable for trapping nano-particulates. Hence it is no longer employed, except in underground coal mining.
5.2 Regeneration systems

Particulate traps, fitted to normal diesel engines, become quickly clogged with soot. Within hours, the back-pressure increases to the maximum permissible limit. Hence, the traps must be frequently regenerated. The regeneration is performed through combustion of the retained soot. This combustion is almost without residue. However, the prevalent diesel exhaust gas temperature is usually insufficient. Hence, additional measures are needed to promote regeneration.

The main factors are:

- "Active" and "passive" regeneration: Passive denotes spontaneous regeneration on reaching a certain operating condition. Active denotes controlled triggering using the back-pressure as a feedback signal.
- "Vehicle connected systems" (on board systems) denotes that all regeneration functions can be performed without dismounting the filter.
- Exchangeable filter denotes that the filter must be dismounted for regeneration.
- Snap-on filter denotes that it is only used for a short specific duration, e.g. indoor loading of trucks, or garage operations.

Presently, the following are the most popular regeneration systems. They can be classified into three groups.

1. Regeneration during engine operation

- **Full-flow burner**
  A diesel fuel burner is installed in the inflow plenum of the particulate trap. The burner is designed to heat the exhaust gas, irrespective of the engine state, until the regeneration temperature (>700°C). The burner is activated when the back-pressure attains the limiting value. The burner is extinguished when the filter is relieved from soot. The process is completed within about 10 minutes. The burner rating must be very high. There are demanding requirements regarding temperature uniformity, ignition conditions, combustion rules, etc.
  The hardware and control systems are very complex. They can however master all possible situations occurring. Mature systems are commercially available and were successfully tested during the VERT project.

- **Partial-flow burner:**
  These are twin filter systems. One of the filters is operated at partial-flow and controlled conditions promoting regeneration. Meanwhile, the second filter is performing the exhaust gas after-treatment. These systems are less complex than full-flow burners. However, they are less competitive because they are bulky and cumbersome. Twin systems have not been commercially successful.

- **Electrical heating:**
  Both the filter element and the entire exhaust gas flow must be heated to the regeneration temperature. Hence, the power consumption is very high, and not feasible with the on-board electrical system. Sequential regeneration systems, i.e. heating individual filter-cartridges, are under development. Here too, excessive electrical power is required to attain regeneration temperature and sustain it for a sufficiently long regeneration period. This is usually prohibitive in vehicles, except when the through-flow is restricted.
• **Regeneration additives:**
Several substances have the property of depressing the soot ignition temperatures to below 400°C. Some examples are Cerium, Iron and Copper. This method is usually described as passive. Favorable results have been mainly obtained in buses, cars and fork-lifts. Good results were also obtained for construction-site engines during the VERT project. The prerequisite is an automated "on-board dosage" of the additive substance. Unfortunately, the oxides of the additive substance are also trapped in the filter and these worsen its back-pressure.
Filter systems are a prerequisite for using fuel additives. The additives generate fine oxide particulates (about 20 nm) in the exhaust gas stream. The filters must dependably trap these fine particulates. This cannot be automatically assumed just because the traps have good filtration rates for the soot particulates. Probably, the retained regeneration additives also promote undesirable catalytic reactions. These result in secondary emissions. In particular, sulfates, dioxins and furanes can form (see report EMPA Nr. 172847). This risk must be individually verified.

• **Catalytic combustion:**
An oxidation filter is placed before the particulate trap. The injected fuel is combusted flame-less and raises the exhaust gas to the regeneration temperature. A prerequisite for this method is well controlled operating conditions. Hence, this method is mainly used for stationary engines.

• **Catalytic coating**
Transition metals can depress the soot ignition temperature to about 400°C (some results even indicate conversion temperatures below 360°C). The temperature can be further depressed using precious metals (NO/NO₂ reaction with the soot, analogous to the CRT system). No further measures are required, if the pertinent engine attains this temperature frequently and for sufficient duration. This is called a completely passive regeneration method. Note that regeneration is slower on a catalytic coated wall. This is beneficial in the more complete conversion of the substances, requires however higher exhaust gas temperatures during a longer period.

• **CRT-System** (Continuous Regenerating Trap):
This method exploits the properties of an oxidation catalytic converter coated with precious metals. These catalytically promote the conversion of the NO in the engine exhaust gas to NO₂. The reverse process occurs in the subsequent particulate trap. The liberated oxygen atom burns the carbon already at very low exhaust-gas temperatures. This too, is a passive system. It assumes the usage of very low sulfur (< 50 ppm) fuel. Otherwise, unacceptably high sulfate emissions occur that can permanently damage the catalytic converter. The increased NO₂ content in the exhaust gas may be tolerable in many applications, assuming sufficiently high dilution. High NO₂ content is however unacceptable in closed spaces. The ratio of soot to NO₂ is an important criterion. Good results have been attained with modern engines in bus services. The system yielded good result during suitability testing with a construction site engine. Engines emitting much soot cannot provide the necessary NO₂ content at high exhaust-gas temperatures.

• **Counter-flow** (Pulse-Cleaning)
A periodic pressure pulse, from the trap exit, dislodge the filter cake, which is then evacuated via a sluice. This system is commonly used in power plants. It is being developed for vehicular applications, but is not yet mature enough for wide scale deployment.
• Combinations
Combinations of several different regeneration methods are also possible. Particularly interesting are the use of fuel additives with heating systems, or catalytic coating with heating. These combinations substantially reduce the power requirements to heat the exhaust gas.

2. Electrical standstill regeneration (on board)
If the vehicular and engine duty cycles permit, regeneration under well-controlled conditions can be performed during standstill. There are two possibilities: The engine can be idling and the meager flow of relatively cool exhaust gas heated electrically, from the power mains, to the required temperature. The second possibility is to use a supplementary air pump for the gas flow. The heating is a slow process because of the low flow rates, i.e. can take several hours. (Recent developments permit regeneration quicker than 1 hour).

3. Exchangeable filters (for external regeneration)
External regeneration is feasible if the filter can be frequently, e.g. daily, dismounted from the engine. The regeneration is then performed electrically or with burners in a controlled process. This method is popular for fork-lifts. Quick mechanical disconnection facilitates replacing the filter in the exhaust gas system. This method is particularly favored for so-called snap-on filters that are only deployed for short duration.

Besides the above variants, new systems are becoming available in which the clogged filter cartridge is disposed like an air filter (throw away). Such systems either must have a high capacity or can only be deployed where the soot load is low. Further, an uncontrolled fire or sparks must be prevented due to the filter attaining the flammability conditions.

Substantial emission peaks can occur during the combustion of the deposited soot. Particulate emissions shall be prevented. However, during rapid regeneration cycles, it is unavoidable that C is combusted to CO and not to CO₂. Further, some of the adsorbed hydrocarbons may escape the trap in the vapor phase, without being completely combusted to innocuous substances. Frequently, large quantities of water vapor (white plume) is observed.

In addition to the (combustible) soot, all particulate traps also intercept inert ash components. These gradually clog the filter element during operation. Hence, it is necessary to clean the filter elements, from these residues, after prolonged operation. This cleaning procedure is not defined as "regeneration". Periodical cleaning of the filter should preferably be done by returning it to the manufacturer or replacing it with an exchange element. This pre-supposes easy replacement of the filter medium.
5.3 Fuel additives for filter regeneration

Fuel additives can be employed to promote regeneration of the particulate traps. The catalytic effect of the additives lowers the light-off temperature of the diesel soot retained in the filter. Thus, regeneration can occur at normal operating temperatures (≤ 400°C).

The VERT project investigated the following additives:

- **satacen**: main ingredient is Ferrocen
  The filter catalytic effect emanates from the iron oxide formed during combustion.
  Manufacturer: OCTEL GERMANY GmbH (Sales agency Switzerland: DETEGO AG)
  Satacen is already deployed in Switzerland, since a long time, as an additive to heating oil.

- **EOLYS (DPX 9)**: main ingredient is Cerium
  The filter catalytic effect emanates from the cerium oxide formed during combustion.
  Manufacturer: RHODIA
  EOLYS DPX9 is notified in Switzerland as a new substance (and therefore its use is legally permissible).

- **OS 96401** from Lubrizol: main ingredient is Copper
  The catalytic effect emanates from the copper oxide formed during combustion. The regeneration capability of this substance, too, was proved during the VERT field test. The copper oxide retained in the filter, however, incites the formation of secondary emissions such as sulfates, dioxins and furanes. Caution OS 96401 is a new substance. It does not comply with the BUWAL criteria. Hence, this additive is not permitted.

- **Other additives** Further additives are being investigated. The VERT tests indicated the beneficial effects of combining Cerium and Platinum in low dosages (manufacturer CDT). Thus, the oxide load on the filter was substantially reduced.

**Prerequisites to using additives:**

1. New substances intended as additives must be submitted to and obtain BUWAL approval.
2. Additives form fine particulate-ash substances. These must be filtered with high efficiency. It must be proved that the combustion products of the pertinent additive are retained in the intended filter (system suitability test).
   The VERT suitability test proved several filters for satacen and Eolys.
   It is forbidden to use fuel additives without suitable particulate traps.
3. The dosage of the additives into the fuel shall be automatic. This ensures effectiveness and prevents over-dosage that would unnecessarily clog the filters. Fueling from pre-mixed containers should be avoided, if there is any risk of other vehicles (without traps) being fueled from the same tanks.

Additives can substantially curtail (up to 30%) of the raw soot emissions from engines. Together with the correct filter, according to the VERT results, additives can substantially improve the filtration efficiency (in some instances up to an order of magnitude).

See the opinion of UBA/Berlin, 1 April 1998.
5.4 Regulations (some examples)

Germany:

- Technical rules for toxic substances TRGS 554/30. April 1993
  The TRK limit of 0.2 mg/m$^3$ (EC + OC) is valid for workplaces. Exceptionally, a TRK value of 0.6 mg/m$^3$ is permissible for underground (not coal) mines and for construction sites.
  In 1997 the values were tightened from 0.2 to 0.1 mg/m$^3$ and redefined as elementary carbon EC.
  To comply with these limits, the TRGS 554 prescribes: Diesel engines must be equipped with particulate traps, when the engines are entirely or partially operated in enclosed spaces or underground sites. These filters must achieve at least 70% (total gravimetric) filtration rate, with respect to the UBA test and load cycle.
  To verify compliance, the blackening number (before and after the particulate trap) and the CO content must be measured in reproducible operating states, at the latest after 800 operating hours or 6 months.
  Specifications of the Bavarian state Environmental Ministry StMLU/26.Nov.1996 to implement the BImSchG using soot filter technology on stationary diesel engines.
  New equipment must not emit more than 20 mg/m$^3$ dust (at 5% oxygen in the exhaust gas).
  It has been established that the deployment of soot filters to contain emissions is state-of-the-art for installations requiring legal approval. Therefore, such filters must be employed to prevent the limiting values being exceeded.
  Compliance with the emission limits shall be proved using gravimetric measurement of the total dust concentration.
  Note: The Bavarian rules are less strict than the German federal TA-Luft clean air regulations. TA-Luft prescribes a general ceiling of 5 mg/m$^3$ for substances newly identified as carcinogenic. The IARC has long ago established that diesel engine exhaust gases are carcinogenic. Most countries have legislated limits for these carcinogens.

Austria:

- According to the Publication in the federal law gazette of 5 May 1994, § 98 of the occupational hygiene directive:
  Diesel powered vehicles and equipment shall only be deployed using low emission diesel engines together with catalytic converters and soot filters. Compliance with this prerequisite must be documented and proved.
  In 1997, the AUVA initiated discarding the clause "catalytic converters" from the pertinent paragraphs. Thus the directive remains, diesel engines (without restrictions) shall be equipped with soot filters.
Switzerland

Emissions:
- Suva list of carcinogenic substances: Diesel engine emissions < 0.2 mg/m$^3$
- Swiss Ordinance on Air Pollution Control (OAPC 98)
  The new version of the OAPC has 3 essential aspects pertaining to soot filters:
  - According to OAPC 98, diesel soot is categorized as carcinogenic: limit 5 mg/m$^3$.
  - The valid limit for dust emissions from stationary engines is 50 mg/m$^3$ without restrictions regarding rating, application duty and annual operation period. The more stringent value of 5 mg/m$^3$ is valid for diesel soot.
  - Article 88 now addresses construction site engines: It specifies that construction sites must restrict emissions from engines and machines to the extent that is technically, economically and operationally feasible. The federal environmental agency can ordain guidelines.

Immissions:
- OAPC legislated limits for suspended dust (PM10): 20 µg/m$^3$ annual average 50 µg/m$^3$ 24-hour average

Imperative to minimize carcinogens:

There is an imperative to generally minimize emissions of carcinogens such as diesel soot. Hence, it is mandatory to deploy the best available technology (BAT) irrespective of the economics.
5.5 Experience reports and market information

A comprehensive literature now exists pertaining to experience with particulate traps. These are compiled annually into the collective publications of the SAE conferences "Diesel Exhaust After-treatment". Herewith some additional references in German (titles partially translated):

- VERT-Bulletins 1-5 (available Suva/Lucerne, Switzerland)
- SAE 980539: VERT: Diesel Nano-Particulate Emissions: Properties and Reduction Strategies
- SAE 1999-01-0116: Particulate Traps for Retro-fitting Construction Site Engines
- VERT Final Measurements and Implementation
- Russfilter-Grossversuch des Bundesministeriums für Umwelt, Naturschutz und Reaktorsicherheit, (Extensive soot filter investigations; German ministry for environment and reactor safety, can be obtained from UBA Berlin)
- Hat der Dieselmotor im PKW eine Zukunft? (Does the automobile diesel engine have a future?), M. Dürnholz, M. Krüger, FEV Motorentechnik GmbH & Co. KG, Aachen
- 6. Aachener Kolloquium 97
- Abgasemissionen aus Dieselmotoren von Gabelstaplern (Exhaust gas emissions from forklift diesel engines)
  Bericht Nr. 90 01252, BIA
- Schwarz und ungesund. Eine Zusammenstellung von Erfahrungen mit Russfiltern an Gabelstaplern, (Black and unhealthy, Compilation of experience with forklift soot traps)
  H. Petschinka, NGK, Fördermitteljournal 4/94
- Einfluss von Partikelfilter-Systeme auf die Zusammensetzung der Abgasemissionen eines Dieselmotors, (Influence of particulate trap systems on the composition of exhaust gas emissions from a diesel engine)
  N. Heeb, Untersuchungsbericht 167985 / EMPA, March 1997
- Stellungnahmen des Umweltbundesamtes zum Einsatz von Additiven als Regenerationshilfe für Partikelfilter-Systeme, (Response of the environmental agency regarding the use of additives as regeneration aids in particulate trap systems), 16. March 1998
- The results of the VERT field test are not yet published.
  Information available from TTM.

Herewith some deployment statistics of particulate trap systems as evidence that this technology has attained wide market share.

- Over 4,500 CRT systems deployed in England, Scandinavia and Germany.
- Deutz has deployed 400 systems with full-flow burners rated 50 - 600 kW
- The company Oberland-Mangold has approx. 1,000 systems field deployed during 8,400 op.h. in forklifts, 10,600 op.h. in construction site engines, 19,200 op.h. in stationary engines, 187,000 km in automobiles and 225,000 km in trucks.
- The company Unikat has, in Switzerland alone, over 250 traps deployed since 1989. Worldwide there are 3,000 such traps. Some of these have operated more than 20,000 h without problems.
- Germany annually installs approx. 1,500 particulate-traps in forklifts.
- Since 1990, there are 150 city busses running in Zurich equipped with the so-called Daimler-Benz system (wound filter, copper coated with acetyl-acetonate regeneration). See TTM report of 25 January 1999.
- There are 400 city buses operational in Munich/Germany since 1990.

Further, the manufacturers DAIMLER-BENZ and MAN (buses), LIEBHERR (construction engines) and DEUTZ (for construction site engines) are accepting orders for soot filter systems as original equipment.
5.6 Glossary

- **Filter medium:**
  A passive structure that intercepts the solid particles through inertial forces (impaction), electrical forces, or diffusion onto the surfaces. The intercepted particulates are dependably retained through physical binding (van der Waals), electrical or even chemical forces. The filter media are roughly classified as either surface filters or deep bed filters. A soot cake ("soot filters soot") forms on the surface filters. The dust is "uniformly" (in reality logarithmically decreasing in the flow direction) distributed within deep bed filters. Both filter systems can attain high filtration rates. However, the back pressure and filtration rates are different under loading. Many commercially available filter media are hybrid types.

- **Regeneration:**
  The soot deposited in the trap must be periodically eliminated to prevent the filter clogging. There are two regeneration methods: The deposited soot can be combusted (hot regeneration), or the filter can be pulsed (counter-flow cleaning). Hot regeneration is the prevalent procedure. The required energy must be supplied through heating (electric or burner). The energy can be minimized through catalytic promotion (coating or fuel additives). Inorganic dusts, e.g. ash particulates, cannot be eliminated through hot regeneration. These particulates can only be removed through periodic cleaning, e.g. through back-blow or washing.

- **Filter system**
  Filter system describes the complete system ensuring functionality. Besides the filter medium, it includes all elements of the regeneration system and the monitoring system. The filter systems together with all elements should be obtained from a single supplier responsible for the complete system. This facilitates customer introduction of this technology.

- **Automatic system**
  A filter system that is operated fully automatic and monitors itself.

- **Particulates**
  Particulates are suspended substances created during combustion and normally emitted with the exhaust gas. A gas loaded with such particulates is described as an aerosol. The term particulates comprises solid and liquid (condensate) components. Particulates are partitioned into size categories for evaluating the alveolar penetration. The Swiss OAPC 98 defines PM10 for environmental aerosols, i.e. all particulates smaller than 10 µm (more precisely: a filtration characteristic with 50% filtration at 10 µm aerodynamic diameter).
  PM10 in exhaust gas is defined as the total mass of all particulates in the exhaust gas that fulfill this size definition and can be filtered under defined measurement conditions (dilution approx. 10 and temperature < 325°K).
  Further size definitions that are increasingly in use: PM2.5 / PM1 / PM0.1
  The conventional measurement methods do not distinguish the particulates according to their chemical composition and phase (solid/liquid). There are efforts to introduce such criteria. These will influence the selection and evaluation of particulate traps.
• **Nano-particulates:**
  This term begins to be popular. It describes the particulates in the size range of approx. 5 - 500 nm usually found in the exhaust gases of combustion engines. Sometimes these particulates are also referred to as ultra-fine particulates.
  The trend is to no longer evaluate ultra-fine particulates according to their mass. Instead, the concentration count is used in defined finely sub-divided size classes.

• **Diesel soot**
  The definitions are not uniform:
  According to the Swiss (Suva) MAK list: Diesel engine emissions (DME).
  The Swiss define diesel soot as the sum of elementary carbon (EC) and organic carbon (OC) in the exhaust gas of diesel engines (measurement method coulometry).
  The German definition, as per TRGS 554, is more stringent and based on EC alone.
  The worldwide valid standards, for vehicular diesel soot emissions, use the nomenclature "diesel soot", or "diesel particulates" or "particulate matter". These comprise all substances that are filtered under normal measurement conditions. In addition to the actual carbon content and the hydrocarbons, several other substances are filtered. These include ash particulates, sulfates, adsorbed acids, maybe water, and other solid and fluid components. This plethora hinders meaningful comparisons and comprehension.

• **Minimization imperative:**
  The Swiss Ordinance on Air Pollution Control OAPC demands limiting carcinogenic emissions to the extent reasonably feasible. The effective limits are individually determined by the best available technology. Economic factors are secondary.
5.7 Abbreviations

AFHB Abgasprüfstelle Fachhochschule Biel  
(Biel School of Engineering and Architecture, Biel/Switzerland)

AUVA Österreichische Allgemeine Unfallversicherungsanstalt  
(Austrian Accident Insurance Agency)

AVL AVL/List, Messtechnikfirma Graz/Austria

BIA Berufsgenossenschaftliches Institut für Arbeitssicherheit St. Augustin  
(Trade institute for occupational safety)

BlmSchG Bundes-ImmissionsSchutzGesetz  
(Federal immissions legislation)

BUWAL Bundesamt für Umwelt Wald und Landschaft  
(Swiss Agency for the Environment, Forests and Landscape, SAEFL  
"Swiss Environmental Protection Agency")

Cercl’Air Vereinigung der Schweizerischen Luftreinhaltefachstellen der Kantone  
(Association of Swiss cantonal authorities for air quality)

CHF Swiss Francs, monetary unit

CRT Continuously Regenerating Trap

DEEP Diesel Emissions Evaluation Programm (Canadian mines)

EAM Eidgenössische Amt für Messwesen  
(Swiss Federal Office of Metrology, Wabern/Switzerland)

EC Electrochemical sensor

EC Elementary carbon (in coulometric measurement)

EN European Norm

EMPA Eidgenössische Material Prüfungs Anstalt, Dübendorf/Switzerland  
(Swiss Federal Laboratories for Materials Testing and Research)

ETH Eidgenössische Technische Hochschule/Zürich  
(Swiss Federal Technical University, Zurich/Switzerland)

IARC International Agency for Research on Cancer, Lyon/France

IR Infra red sensors

LFU Bayrisches Landesamt für Umweltschutz/München  
(Bavarian state environmental agency, Munich/Germany)

ISO International Standards Organization

MECA Manufacturers of Emission Controls Association

MIRA Motor Industry Research Association/England

µm Micrometer $= 10^{-6}$ m

NIOSH National Institute for Occupational Safety and Health

nm Nanometer $= 10^{-9}$ m

OC Organic carbon

OAPC Luftreinhalte-Verordnung der Schweiz, novelliert 1.3.98  
(Swiss Ordinance on Air Pollution Control, revised 1 March 1998)

op.h. Operating hours

PAH Polycyclic aromatic hydrocarbons

SAE Society for Automotive Engineers

SiC Silicium Carbide

SMPS Scanning Mobility Particle Sizer (Instrument form TSI Inc., Minneapolis)

SN Swiss Norm
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>StMLU</td>
<td>Bayerisches Staatsministerium für Landesentwicklung und Umweltfragen (Bawarian ministry for development and environment)</td>
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<td>Suva</td>
<td>Schweizerische Unfallversicherungsanstalt/Luzern (Swiss National Accident Insurance Organization, Lucerne/Switzerland)</td>
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<td>TA Luft</td>
<td>Technische Anweisung zur Reinhaltung der Luft (Deutschland) (Technical directive on air quality, Germany)</td>
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<td>TBG</td>
<td>Deutsche Tiefbauberufsgenossenschaft/ München (German Association of Construction Professionals, Munich/Germany)</td>
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<td>TBN</td>
<td>Total Base Number (index for the Calcium content of lubricants)</td>
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<td>TTM</td>
<td>Technik Thermische Maschinen/Niederrohrdorf (Engineering Consultants, Niederrohrdorf/Switzerland)</td>
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<tr>
<td>UBA</td>
<td>Umweltbundesamt der Bundesrepublik Deutschland/Berlin (German Federal Environmental Protection Agency, Berlin/Germany)</td>
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<td>VERT</td>
<td>Verminderung der Emissionen von Realmaschinen im Tunnelbau (A joint project of Suva + TBG + AUVA + BUWAL to curtail the emissions from engines at tunnel sites.)</td>
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## 5.8 Address list

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<td>3M</td>
<td>Hammfelddamm 11 D-41453 Neuss</td>
<td>M. Schaschke</td>
<td>++49(2131) 143655</td>
<td>++49(2131)142626</td>
<td><a href="mailto:Mschaschke@MMM.com">Mschaschke@MMM.com</a></td>
</tr>
<tr>
<td>AVL LIST GmbH</td>
<td>Kleiststrasse 48 A-8020 Graz</td>
<td>Dr. E. Schiefer</td>
<td>++43(316)787-1137</td>
<td>++43(316)987-530</td>
<td></td>
</tr>
<tr>
<td>Swiss agent:</td>
<td>Fänrring 1 CH-6403 Küsnacht</td>
<td>J. Zurkirchen</td>
<td>++41(41)854 88 00</td>
<td>++41(41)854 88 77</td>
<td><a href="mailto:zuriag@bluewin.ch">zuriag@bluewin.ch</a></td>
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<tr>
<td>BUCK</td>
<td>Benzstrasse 1 D-71149 Bondorf</td>
<td>A. Buck</td>
<td>++49(7457)9457-0</td>
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<td><a href="mailto:Buck.TSP@T-online.de">Buck.TSP@T-online.de</a></td>
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<td>DEUTZ AG</td>
<td>Deutz-Mülheimer Str.147-149 Abt. VS-TN5 D-51057 Köln</td>
<td>K.H. Breuer</td>
<td>++49(221)822 36 67</td>
<td>++49(221)822 3663</td>
<td><a href="mailto:breuer.kh@deutz.de">breuer.kh@deutz.de</a></td>
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<td>Swiss agent:</td>
<td>Industriestr. 17 CH-8910 Affoltern</td>
<td>L. Hürlimann</td>
<td>++41(1)762 11 22</td>
<td>++41(1)761 82 03</td>
<td><a href="mailto:lhuerlimann@pop.agri.ch">lhuerlimann@pop.agri.ch</a></td>
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<td>Würgler AG</td>
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<td>ECS</td>
<td>Units 8/9 Berkshire Business Centre, Berkshire Dr. Thatcham Berkshire RG19 4EW England</td>
<td>B. Southgate</td>
<td>++44(1635)871776</td>
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<td>HJS</td>
<td>Dieselweg 12 D-58706 Menden</td>
<td>Dr. G. Hüthwohl</td>
<td>++49(2373)987-254</td>
<td>++49(2373)987-259</td>
<td><a href="mailto:Entwicklung@hjs.com">Entwicklung@hjs.com</a></td>
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<td>Swiss agent:</td>
<td>Augenweidstr. 34 CH-8966 Oberwil-Lieli</td>
<td>R. Blunier</td>
<td>++41(56)631 15 57</td>
<td>++41(56)631 6141</td>
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<td>René Blunier</td>
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<td>HUG Engineering AG</td>
<td>Gewerbezentrum Moos Postfach 31 CH-8484 Weisslingen</td>
<td>Chr. Hug</td>
<td>++41(52)384 22 55</td>
<td>++41(52)384 21 94</td>
<td><a href="mailto:christoph.hug@hug-eng.ch">christoph.hug@hug-eng.ch</a></td>
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<td>HUSS Maschinenfabrik GmbH &amp; Co.KG</td>
<td>Postfach 11 02 06, Stresemannstr. 56 D-28207 Bremen</td>
<td>Th. Stumpp</td>
<td>++49(421)49 90 00</td>
<td>++49(421)4990040</td>
<td><a href="mailto:sales@hussrides.com">sales@hussrides.com</a></td>
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<td>Swiss agent: René Blunier</td>
<td>Augenweidstr. 32/34, CH-8966 Oberwil-Lieli</td>
<td>R. Blunier</td>
<td>++41(56)631 15 57</td>
<td>++41(56)631 61 41</td>
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<td>IBIDEN EUROPE B.V.</td>
<td>P.O. Box 2011 NL-2130 Hoofddorp</td>
<td>T. Ninomiya</td>
<td>0031(23)568 50 55</td>
<td>0031(23)568 50 54</td>
<td><a href="mailto:tninomiya@ibieuro.nl">tninomiya@ibieuro.nl</a></td>
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<td>Johnson Matthey GmbH</td>
<td>Otto-Volger-Strasse 9B D-65843 Sulzbach/Ts.</td>
<td>P. Werth</td>
<td>++49(6196)703 832</td>
<td>++49(6196)724 50</td>
<td><a href="mailto:hansej@matthey.com">hansej@matthey.com</a></td>
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<td>Swiss agent: Hüga Import und Handel</td>
<td>Oberdorf CH-8558 Rapperswilien</td>
<td>J. Hansen</td>
<td>++49(6196)703 817</td>
<td>++49(6196)703 812</td>
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<td>MRU</td>
<td>Emissionsmesstechnik Postfach 2736 Fuchshalde 8 D-74017 Heilbronn-Obereisesheim</td>
<td>J. Schuhmacher</td>
<td>++49(7132)9962-59</td>
<td>++49(7132)9962-20</td>
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<td>Swiss agent: Wohlgroth</td>
<td>Schwerzenbacherhof Eschenstr. 8 CH-8603 Schwerzenbach</td>
<td>B. Merki</td>
<td>++41(1)825 50 60</td>
<td>++41(1)825 50 90</td>
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<td>Nöthiger</td>
<td>Nöthiger Elektronik Fohrhölzlistr. 10c CH-5443 Niederrohdorf</td>
<td>P. Nöthiger</td>
<td>++41(56)496 2839</td>
<td>++41(56)496 4663</td>
<td><a href="mailto:pne@pop.agri.ch">pne@pop.agri.ch</a></td>
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<td><strong>OBERLAND MANGOLD</strong></td>
<td>Amselstrasse 4 D-82467 Garmisch-Partenkirchen</td>
<td>B. Kahlert</td>
<td>++49(8821)9338-24</td>
<td>++49(8821)9338-33</td>
<td><a href="mailto:oberland_mangold@compuserve.com">oberland_mangold@compuserve.com</a></td>
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<td><strong>GmbH</strong></td>
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<td><a href="mailto:dani.honegger@sf-filter.ch">dani.honegger@sf-filter.ch</a></td>
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<td>Schupp AG Industriefilter</td>
<td>Weieracherstr. 3 CH-8184 Bachenbühlach</td>
<td>D. Honegger</td>
<td>++41(1)864 1065</td>
<td>++41(1)864 1458</td>
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<td><strong>OCTEL</strong></td>
<td>OCTEL Deutschland GmbH Thiesstr. 61 D-44649 Herne</td>
<td>W. Kalischewski</td>
<td>++49(2325)980-281</td>
<td>++49(2325)980-289</td>
<td><a href="mailto:Kalischewski@octel.de">Kalischewski@octel.de</a></td>
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<td>DETEGO AG</td>
<td>Eulerstr. 54 CH-4051 Basel</td>
<td>W. Hofmann</td>
<td>++41(61)271 62 22</td>
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<td><strong>RHODIA</strong></td>
<td>Rhodia Terres Rares 7, rue Ambroise Paré F-95520 Osny</td>
<td>J. Lemaire</td>
<td>++33(1)30 73 22 70</td>
<td>++33(1)30 73 22 70</td>
<td><a href="mailto:jacques.lemaire@fr.rhodia.com">jacques.lemaire@fr.rhodia.com</a></td>
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<td>Wolfgang Naschke Consulting</td>
<td>Chattenpfad 8 D-85232 Taunusstein</td>
<td>W. Naschke</td>
<td>++49(6128)71432</td>
<td>++49(6128)973933</td>
<td><a href="mailto:w.naschke@t-online.de">w.naschke@t-online.de</a></td>
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<td>TESTO GmbH &amp; Co.</td>
<td>Postfach 1140</td>
<td>K. Hoyer</td>
<td>++49(7653)681-192</td>
<td>++49(7653)681104</td>
<td><a href="mailto:khoyer@testo.de">khoyer@testo.de</a></td>
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<td>Chriesbaumstr. 4</td>
<td>D. Kiener</td>
<td>++41(1)908 40 50</td>
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<td>UNIKAT</td>
<td>Box 9015</td>
<td>L. Hergart</td>
<td>++46(40)212 035</td>
<td>++46(40)210 335</td>
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<td>S-20039 Malmö</td>
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<td>N+K Abgasreinigungs-</td>
<td>Gewerbestrasse 1</td>
<td>W. Nowak</td>
<td>++41(52)721 01 12</td>
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<td>technik GmbH</td>
<td>CH-8502 Frauenfeld</td>
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<td>VLT</td>
<td>Schulhausstr. 7</td>
<td>P. Sperisen</td>
<td>++41(31)950 66 66</td>
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<td><a href="mailto:info@protec-swiss.ch">info@protec-swiss.ch</a></td>
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