Der Autor des folgenden Beitrages ist einer der eminentesten Experten der Abgastechnologie, Mit-Erfinder des Dreiweg-Kats im Rahmen seiner langjährigen Tätigkeit bei Engelhard, dem damals bedeutendsten Katalysatorhersteller der Welt. Nach dem altersbedingten Ausscheiden von Engelhard gründete er das Environmental and Energy Technology Policy Institute, dessen Präsident er ist: In dieser Eigenschaft ist er Berater höchster amerikanischer Regierungsstellen.
Dr. Mooney ist Träger höchster Auszeichnungen, darunter der National Medal of Technology, die vom Präsidenten der USA unmittelbar überreicht wird.
Die ÖIAZ konnte Präsident Mooney gewinnen, eine ursprünglich für die Staaten New York und New Jersey vorgenommene Vergleichsexpertise von drei Zertifizierungsverfahren für Diesel-Abgasfilter so zu verkürzen, dass sie für den Abdruck in unserer Zeitschrift gerade noch geeignet ist, wofür wir zu Dank verpflichtet sind. Grundsätzlich sind Regeln für die technische Akzeptanz, für die Abnahme immer – nicht nur bei Filtern – erforderlich. Für Österreich besonders schmeichelhaft ist, dass das VERT-Verfahren, bei weitem am besten abschneidet. Diese Zertifizierung ist im Rahmen eines gemeinsamen Programms der österreichischen AUVA, der Schweizerischen SUVA und der deutschen Tiefbauberufsgenossenschaft sowie der zusätzlichen Projektträgerschaft des Schweizer Umweltministeriums, damals BUWAL, entwickelt worden.

Die Redaktion

Toxic solid nanoparticles, the importance of retrofitting diesel engine particle emission control systems to older in-use diesel engines, and available methods

Von John J. Mooney

Mit 4 Abbildungen und 1 Tabelle (Eingelangt am 25. November 2006)

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Abstract

Excluding diesel passenger cars, there are 200 million operating diesel engines in the world. Diesel exhaust emissions contain carcinogenic and toxic particles and chemical species. Of these, the very small solid nanometer size particles (10 to 500 nanometers in diameter) are considered an order of magnitude more serious health hazard than all other diesel emissions. They damage the health of millions, in working environments, in urban areas, near roadways, and while driving in traffic, as in school buses, which continue to run as the door is opened and children get on and off.
Correction of in-use diesel engine emissions is a societal obligation. The main culprit is the invisible soot – inhaled solid insoluble particles that penetrate deep into the lung, and in a relatively short time interval cross into the blood and are carried to internal organs. Recent attempts to produce new cleaner diesel engines have not eliminated the solid nanometer particle fraction (10 to 500 nm in size). New diesel engines do not emit the billowing black soot of former times and give the false impression that they are clean – but they are not clean of this most serious component.
Fortunately, retrofitting diesel engines with highly efficient diesel particle filters (DPF) astonishingly remove 99⁺ percent of the solid nanoparticles. Societal pressure has encouraged DPF retrofit programs. Some retrofit programs have not achieved the desired goal because the most efficient technology was not employed. As a result, sanctioning agencies are using technology verification programs that assess the filtration function of the various DPF technologies and systems as a requirement before retrofit can take place. There are three main verification programs: 1) California Air Resources Board (CA ARB); 2) Switzerland VERT; 3) US EPA Voluntary Retrofit (US EPA). The details of each of these programs were analyzed and compared – Table 1 is constructed to provide a comparative summary of each of the above verification processes.
This investigation is to provide officials and planners with information and understanding to help in selection of a verification process for a diesel engine retrofit program.
The VERT program is a fully comprehensive engineering specification and is recommended for consideration. VERT separates filtration from regeneration unit operations in its approach and utilizes ISO 8178 test cycles, which provide DPF design and scale-up inputs. Only Level 3 (not less than 85% PM mass removal) of the California air Resources Board should be considered. The US EPA program is a voluntary program and, although testing is equal to California, verification approval for non-filter technologies as low as 25% PM mass removal are allowed.

1. Introduction

Only US post 2007 and some European post 2005 new diesel engines, equipped with high efficiency diesel particle filters (DPF), are designed to address the most serious health hazard in diesel exhaust – solid nanometer particle emissions. We are all exposed – in urban areas, along roadways, in major air sheds, and especially in many working environments. The 40 year lifetime of diesel engines is often extended by engine rebuild. Replacement of existing in-use diesel engines with new cleaner engines will take decades.
Fortunately, older engines can now be retrofitted with a diesel particle filter that traps the exhaust solid nanoparticles. Based on the understanding that diesel exhaust is toxic and carcinogenic, coupled with the high level of human exposure, we are obliged to use best available technology (BAT) to remove this health hazard. The diesel oxidation catalysts that have been applied to older diesel engines since the late 1960s do little good, and there is a growing interest in retrofitting diesel particle filters (DPF) to in-use diesel engines.
Several diesel particle filter (DPF) designs are fully developed and have proved to be an effective, reliable and durable method

to filter and collect solid particles from diesel exhaust. The DPF is the main element of the total system designated as PFS (particle filter system) by VERT; Level 3 DECS (diesel emission control system) by CA ARB and DPFS (diesel particulate matter filter systems) by US EPA OTAQ.

Each PFS requires a highly efficient DPF to collect all solid particles and a filter cleaning process (regeneration) where collected particles are removed. The regeneration process can be accomplished by one of several combustion techniques that convert the collected soot by oxidation (combustion) to gaseous CO_2 which exits the tailpipe, returning the DPF to its original clean state. Many types of commercially available PFS have been developed and proven effective, reliable and durable. A PFS incorporating a high efficiency DPF will also filter inorganic solids originating from engine wear, toxic lubrication oil ash compounds, and certain PFS types remove gaseous toxic hydrocarbons and carbon monoxide. The most efficient DPF designs have been found to be 99.9% efficient for filtration of nanometer sized lung alveoli penetrating particles in the size range of 10 to 500 nanometers in diameter. Qualified VERT PFS systems are regarded best available technology (BAT) for this purpose.

PFS are successfully deployed in many cities and countries of the world, cleaning up diesel exhaust from existing buses and trucks, i.e. London, Paris, Berlin, Scandinavia, Netherlands, Tokyo, New York, and soon for the Olympic Games in Beijing and in Santiago, Chile.

A VERT coordinated project in Switzerland was organized to retrofit all existing diesel construction machines, vehicles, and equipment for use in tunnel construction. Because PFS are required, without any exceptions, on all Swiss tunnel vehicles and equipment, tunnel air is now cleaner than ambient air. In 2000, PFS were required on all construction-site diesel engines, without any exceptions, and over 25,000 have been completed. Within a few years all on-road and off-road vehicles operating in Switzerland will have diesel particle filter systems.

In the United States, under the US EPA OTAQ Voluntary Retrofit Program (with over 170,000 vehicles currently committed) some DPFS (Diesel Particle Filter Systems) are being retrofitted. California Air Resources Board (CA ARB), under the Diesel Risk Reduction Plan (DRRP), is enacting rules for diesel emission control retrofit of up to l.25 million existing diesel engine vehicles and equipment operating in the state. California desires equal or greater than 85% reduction of particulate matter (PM) mass for all in-use diesel engine vehicles and equipment. California compromised, however, and created DECS (Diesel Emission Control System [or Strategies]) Level 1, 2 and 3 PM control groups (Level 1, 25% to 50% PM removal; Level 2, 50% to 85%, and Level 3 => 85%). Level 1 and 2 can be met with partial filter technology and other non-filter technology. Level 3 currently can only be met with DPF BAT filter technology and would be required for all California diesel engine retrofits if it is available. The OTAQ and CA ARB test methods measure total PM mass (g/bhp-hr or g/kWhr and currently do not differentiate the solid nanoparticle fraction.

Diesel retrofit programs have proven to be, overall, quite reliable. By one count, over 182,000 verified PFS retrofitted vehicles and equipment have been made by a handful of manufacturers. Initially not all PFS retrofits were without problems and many did not live up to BAT performance and durability expectations. This gave rise to the establishment of a DPF technology screening program.

In Switzerland the VERT (VERT – Curtailing emissions of engines in tunnel sites. A collaborative of Swiss, Austrian and German agencies) group set up PFS suitability tests and PFS performance criteria that candidate diesel retrofit technology must pass before permitting retrofit to existing diesel engine vehicles and equipment. The process is called verification. Almost in the same time frame CA ARB set up a verification program in connection with the California DRRP. Like Switzerland, it is a mandatory program. The US Environmental Protection Agency, Office of Transportation Air Quality (OTAQ), constructed a Voluntary Diesel Retrofit program to encourage diesel engine retrofit in cities and states and set up another verification procedure to support the voluntary program concept.

Each of the above verification programs is designed to screen candidate retrofit technology for function and durability. The sanctioning agency (CA ARB, VERT, OTAQ) requires PFS to pass initial emissions test criteria and maintain performance in actual deployed use. CA ARB and VERT assures that BAT PFS is practical and can achieve ambient air quality goals. It provides vehicle and equipment owners with a degree of comfort before purchasing PFS technology, that the complete system has been given scrutiny with respect to performance, durability, robust design, and is rooted in science and engineering principles. It is not, however, a guaranty.

Cities, countries and regions considering diesel engine retrofit look to each of the above three verification procedures for guidance and potential adoption.

The paper compares and analyzes the PFS verification processes of the three sanctioning agencies – CA ARB DRRP, the VERT Filter List, and US EPA OTAQ Voluntary Diesel Retrofit Program. The comparative positive aspects and shortcomings, if any, of each program are scrutinized. Of particular importance will be the engineering approach taken to construct an effective basic system of suitability tests and pass/ fail criteria that define BAT particle filtration and regeneration. The objective is to help engineers and scientists understand the various factors of diesel emission control, and to help cities, regions and countries choose one or more of the established verification programs as a prerequisite for its planned diesel engine retrofit programs.

2. Diesel Engine Emissions Control Basic Information – Retrofit engine test cycle

PM mass-based emission standards in the European Union and the United States are in terms of grams/ kilometer or mile; grams/ kilowatt-hour or brake horse power-hour. Retrofit of existing engines targets additional exhaust emissions cleansing from in-use engines not provided by the original engine design. The efficiency measure of a retrofit technology is in terms of percent reduction (100% x engine baseline level – control level/ baseline) rather than g/km or g/kWh. One EU committee, after careful study under PMP, is considering including percent solid nanoparticle number count (PN) reduction to the proposed EURO diesel engine retrofit standards. Analytical instruments and techniques have been developed that give accurate and reproducible PN measurements.

A proper engine test cycle that provides the conditions needed to measure solid nanoparticle filtration efficiency has to be selected. The VERT program chose the ISO-8178 engine test cycle where only four points of the test cycle are needed to accurately measure all PN filtration mechanisms (diffusion, interception and impaction). It is very important to understand the physical and engineering principles that went into selection of ISO 8178 (Figure 1) used in the VERT suitability tests for defining BAT nanoparticle filtration at the engine and filter limit conditions as explained in Sections 4.2 and 5.iii. The ISO 8178 engine test cycle is able to test filtration efficiency at extreme conditions of filtration – high and low temperature and high and low exhaust flow rates and one test point producing the highest PFS space velocity – this is all that is needed and this is a critical point.

The established EURO and US EPA engine test cycles try to replicate actual engine use conditions, but these fail to differentiate BAT from non-BAT filtration.

3. Diesel Engine Emissions Control Basic Information – Diesel Particle Filter – Filtration and Regeneration

Diesel Particle Filters have two distinct functions: 1) filtration of solid particles produced by combustion [Fig 2], engine wear, and lubrication ash; and 2) regeneration to original clean filter state via combustion of collected carbon particles to CO_2 gas or other means. The functions of filtration and regeneration unit operations need separate consideration.

Filtration:
Filtration of solid diesel particles is a physical process (full description of the process is given in reference 1, Chapters 1, 12, 20, 30 and 35). Under the Swiss VERT tunnel program, some existing DPF designs were remarkable, consistently filtering 95^{+}% of elemental carbon particles and 99.9^{+}% of lung alveoli penetrating solid particles from hot diesel exhaust. This is confirmed by correlation of particle count with particle surface area. The filtration mechanism is independent of particle source. A BAT DPF design acts as a filter for the full range of solid particles from coarse to nanoparticle size and is independent of engine make, model, year, size or application. To assure BAT DPF filtration the filter must be tested at extreme engine conditions and thus extreme filtration conditions – when the filter is new, fully loaded with soot, and during and after filter regeneration. The DPF has to be sized for the test engine. Several DPF designs exist. Some have ceramic cell channels, similar to automobile catalysts, but with half of the inlet channels and adjacent outlet channels blocked in checkerboard fashion. The diesel exhaust must pass into the open inlet channels through the porous filter wall and out the adjacent open channels. Solid particles are cleansed from the exhaust gas as it flows through the porous wall and collected within the wall or on the wall surface [Fig 3]. Other designs include: 1) fabricated porous metal sheets formed into a filter much like the inlet air filter; 2) several types of ceramic fiber or yarn filters; and 3) ceramic or metal sponge-like structures [Fig 4].
Some DPF designs were found to provide inefficient solid nanoparticle filtration under extreme engine or filter condition. BAT DPF technology remove up to 99.9^{+}% of solid nanoparticles.

Regeneration:
A PFS regeneration process is needed to periodically remove collected soot particles and return the filter to the original clean state. It is possible to continuously or semi-continuously remove collected soot particles by combustion depending on engine temperature and flow conditions.
Several types of soot combustion options exist. These include: 1) thermal assist with fuel/ air burner that can be used as a full flow burner, standstill burner, or part of an off-board regeneration system; 2) thermal assist with electrical heaters that can be used under standstill conditions or off-board; 3) catalyst-based DPF (CB-DPF) assisted by incorporation of NO_2 catalysts within the filter or with a separate catalyst promoting catalytic oxidation of NO⇓ NO_2, a strong acid gas that oxidizes soot to CO_2. Some CB-DPF contain reducible metal oxides that via oxidation/reduction also oxidize soot; 4) non-NO_2 catalysts; 5) catalytic combustion; 6) thermal assist via fuel injection with catalytic combustion; 7) inlet/ outlet valve throttling; and 8) non-NO_2 fuel borne catalysts. Selection of the regeneration process is the responsibility of the PFS manufacturer. PFS manufacturers or installers examine and assess PM baseline emissions coupled with exhaust temperatures produced by a vehicle or equipment operating in normal daily use and decide which type of regeneration systems to install.

4. Diesel Particle Filter Verification Programs

Diesel engine risk reduction plans are being considered by European member states, the United States, and throughout the world with a focus on retrofit of on- and off-road vehicles and equipment. Construction-site vehicles and equipment have much higher emission factors than on-road trucks and are operated more intensely. PFS containing DPF have been successfully retrofitted to on- and off-road engines and they continue to be further developed. DPF technology is proven effective in removing up to 99% of solid nanoparticles and 90% of toxic hydrocarbons from existing engines in the full array of engine applications.
Studies have found certain DPF technology to be BAT. Not all DPFs are the same and some fail (non-BAT) to achieve a sustained level of performance under all diesel engine operating conditions, or are not robust. A procedure to verify the various diesel particle systems was needed. Diesel retrofit verification processes have been established.
The three major processes are: 1) the California Diesel Risk Reduction Plan; 2) the Switzerland VERT Filter List; and 3) the U.S. EPA Voluntary Retrofit Program.
Each of the above validation programs are described below, and compared in Table 1.

4.1 California: Verification Procedure, Warranty and In-Use Compliance Requirements for In-Use Strategies to Control Emissions from Diesel Engines

The CA ARB Verification Procedures for the California Diesel Engine Retrofit Plan (DRRP) target PM and NOx reductions from existing diesel fueled engines. Strategies that may be used include diesel particle filters (DPF), diesel oxidation catalysts (DOC), fuel additives, selective catalyst reduction of NOx with ammonia (SCR), exhaust gas recirculation (EGR), alternate diesel fuels, or other. The program defines any system that can achieve the above as a diesel emission control system or strategy (DECS). Particulate matter (PM) reduction DECS are categorized into three levels: Level 1 demonstrates (via verification procedures) PM mass reduction by at least 25% from baseline level; Level 2 – at least 50%; and Level 3 – at least 85% or to achieve 0.01 g/bhp-hr PM or less (the actual new engine standard for 2007 Heavy-duty engine on-road and 2010 Heavy-duty engine off-road). Of special note is that CA ARB is most interested in PM Level 3 > 85%. PM Level 3 devices must be used if verified and available for any diesel engine category. http://www.arb.ca.gov/diesel/verdev/proceduredec04.pdf.htm
The CA DRRP established specific retrofit rules for on-road diesel vehicle categories such as urban bus fleets; refuse trucks, stationary engines, transportation refrigeration units, portable equipment and non-urban buses. Other on-road vehicle categories are being considered.
Off-road engine rules are scheduled to be issued in 2007. Off-road emissions are calculated to be 71% of total diesel engine emissions in California. CA ARB considers off-road engines to be a greater retrofit challenge than on-road. For this reason CA ARB has not permitted verified on-road DECS for off-road applications
The CA ARB retrofit program is well defined and detailed. The program prefers highly efficient elimination of diesel particles under the PM Level 3 > 85% category as first priority but has recognized other lower efficiency levels for PM mass for older engines not thought amenable to PM Level 3 DPFS technology.

This compromise may change as CA ARB evaluates the VERT Filter List technology in 2007-8. California publishes and updates a PM Level 1, 2 and 3 Verified Technology List – http://www.arb.ca.gov/diesel/verdev/level3/level3.htm

Manufacturers are assigned responsibility for conducting emission tests, durability tests, field demonstration for compatibility and in-use compliance testing, and submitting data to the Executive Officer. It sets limits on primary or secondary pollutants. It requires exhaust back pressure monitoring, labeling, specific warranty text and limits of coverage (years or mileage). It allows only prescribed normal maintenance during durability tests. It requires that emissions tests during regeneration be scrutinized. It defines fuel and lubrication oil specifications and emission reduction calculations.

An international advisory committee assisted CA ARB with the verification procedure.

It is noted that CA ARB accepts individual DECS of the VERT Filter List provided certain test and in-use emissions data be submitted for review and approval. The VERT Filter List technologies will bring a rich variety of regeneration types, including: 1) catalyst assist; 2) thermal assist (fuel burner and electrical heater) on-board regeneration systems for standstill mode or off-board thermal assist regeneration; 3) fuel borne catalyst systems; 4) inlet and exhaust throttle valves; and 5) fuel injection. VERT verified thermal regeneration assist systems are being accepted by CA ARB provided that Section 2705 requirement for field compatibility is satisfied.

4.2 Switzerland BUWAL Program. VERT Filter List. Tested and Approved Particle-Filter Systems for Retrofitting Diesel Engines. Latest version: December 2005 to be updated December 2006. http://www.suva.ch.htm

The VERT program was started in the early 1990´s in conjunction with construction of a major tunnel under the Alps designed to carry freight and goods now carried over the roadways and surface railways of Switzerland. Plans were made to preserve tunnel air quality for workers during construction as well as for the completed tunnel. VERT found that diesel particles could not be removed by practical ventilation. VERT formed a Swiss, Austrian and German agency team with huge support from Swiss Technical Universities that set up test protocol for diesel engine particle emission control. The team developed analytical methods to measure diesel particles 10 to 500 nanometers in diameter and gave consideration to total particulate mass, solid particles, elemental carbon particles, and organic particles. They came to the conclusion that lung alveoli penetrating solid particles in the size range of 20 to 300 nanometers were the particles of greatest health concern, and developed analytic instruments to measure the number of particles and particle surface of this fraction. The team found ten to hundreds of millions of insoluble solid particles per cubic centimeter (10^7 – 10^8 /cm^3) of diesel exhaust in the 20 to 300 nm size range. This large number of particles had almost no mass but constituted the largest fraction of total particle surface. Particle surface is additionally important because toxic diesel exhaust hydrocarbons adhere to particle surface. The team concluded that particle mass (grams/kWh) was an incorrect metric for diesel emission control – in fact, in-use tests of diesel particulate filters found PM mass measurements to be confusing. VERT tests found that certain ceramic particle filters were highly efficient in removing the nanometer sized solid particles in this size range as well as the entire range of diesel engine emission particles. Therefore DPF technology was designated best available technology (BAT). However, VERT test work discovered that all diesel particle filters were not the same and some were inefficient under certain modes of operation.

A series of suitability tests were developed to determine acceptable particle-filter system (PFS) filtration levels suitable for use in tunnels. The PFS is tested under extreme modes of highest space velocity and temperature and under average use conditions by using portions of the ISO 8148 test cycle. One dedicated Euro II engine is installed on an engine dynamometer. The PFS is tested when new, when fully loaded with soot, during and after regeneration, with one test point at maximum filter space velocity, before and after 2,000 hours actual in-use deployment. It must exceed removal of 90% elemental carbon mass and 95% PN solid particle count performance. No filtration deterioration is permitted after 2,000 hours deployed use. Backpressure at limit engine RPM must be < 50 mbar for new PFS, regeneration initation threshold < 150 mbar and maximum burdened condition < 200 mbar. With this information and by using the space velocity reactor sizing model the tested PFS family can be accurately sized for any diesel engine. These tests only assure that efficient filtration will be achieved. Regeneration of the collected soot is a separate function. Each candidate regeneration technique must also undergo the 2,000 hour actual deployed use test. Each filter/ regeneration unit PFS must be verified together.

The end product is the VERT Filter List – a list of diesel particle-filter systems that pass the rigorous VERT suitability test protocol. The suitability tests are specific for the solid particle fraction under all conditions of engine operation. The suitability tests verify that PFS meet the established BAT criteria for filtration and durability. VERT verified PFS can be scaled and applied to any engine regardless of make, model, age, or application. However, as noted above the collected soot particles have to be combusted to regenerate the filter to original clean condition. The suitability tests cannot predict the in-use spectrum of engine exhaust conditions related to regeneration initiation and duration. The PFS manufacturer, retrofitter or installer has to select reliable regeneration for each engine application. Many types of regeneration techniques exist and one or more regeneration assist method is verified for each PFS during the VERT suitability tests. Selection of the regeneration type is made through experience and assessment of baseline PM emission and exhaust temperature duration profiles to assure that regeneration of collected soot takes place reliably every time it is needed. The regeneration can be self regeneration types (i.e. catalyst-based DPFs) or a variety of thermal assist components such as fuel burners, electrical heaters or other types. Regeneration components can be installed on-board the vehicle and operated when the engine is in actual use or alternately when the vehicle or equipment is out of service and at standstill. The PFS can also be removed and regenerated in an off-board thermal regeneration system. The VERT Filter List specifies the regeneration method/s permitted for each listed PFS. It is the PFS manufacturers or installer's responsibility to assure that the proper regeneration is selected for the vehicle or equipment applications. The PFS must be installed properly and safely.

Other features of the VERT Filter List and verification test process:

The VERT Filter List and filter suitability tests and performance criteria for particle filter system (PFS) focuses on filtration of solid 20 to 300 nanometer particles elemental carbon mass concentration emitted from diesel engines. It allows no increase in established PM mass emission standards and scrutinizes for secondary emissions that might exceed workplace standards. The selection of suitability tests and pass/fail criteria is based on physical science and engineering principles and practices – in fact it is an engineering specification. The VERT system is a relatively simple, basic, and cost effective method for determining effectiveness and reliability of PFS. Only one PFS family is tested on a standard Euro II engine. Results derived from this single engine test become engineering design information to size for any diesel engine. The VERT Filter List is open to all BAT technologies, for instance, it recognizes snap-on filters that can be used for brief deployment indoors, and disposed of safely. The VERT program requires bi-annual (every 2 years) opacity field test of each retrofitted engine during a prescribed free engine acceleration test while measurement of opacity is performed. This well-known test is simple, brief and easy to perform on in-use engines. The test is proven to be reliable in detecting failed PFS although a similar test using other analytical methods may replace it in the future. An opacity failure rate between 3 and 5% will require additional VERT filter testing and problem correction, and a failure rate above 5% will result in delisting from the VERT Filter List. PFS manufacturers are obliged to use verified technology without change, to conduct annual in-use filter failure tests, and to report on failures annually. VERT requires manufacturers to maintain an acceptable Quality Assurance program. http://www.umwelt-schweiz.ch/buwal/eng/fachgebiete/fg_luft/vorschriften/industrie_gewerbe/filter/index.html

All filters require a monitor that measures and records filter backpressure with alarm actuation if high level is reached. The recorded data has to be retrievable for at least 3 months. There are special additional monitor requirements for fuel borne catalysts systems. Durability is confirmed after a 2,000 hour field endurance test under all conditions mentioned above. No deterioration of filtration performance is permitted nor test averaging (only one test result below limit within < = standard deviation). PFS that pass the test series can be applied to any diesel engine, properly sized for that specific engine, and will perform filtration almost identically as found in the suitability test.

4.3 EPA Voluntary Diesel Retrofit Program (VDRP), Retrofit Technology Verification Process: OTAQ Verification Process and VDRP Verified Technology List

www.epa.gov/otaq/retrofit/documents/overview.txt; www.epa.gov/otaq/retrofit/retroverifiedlist.htm

The U.S. Environmental Protection Agency (EPA) established a national Voluntary Diesel Retrofit Program (VDRP). The program is being utilized by States and large cities throughout the country – over 170,000 vehicles have been committed by city and regional authorities. The EPA Office of Transportation Air Quality (OTAQ) established the verification process by which DPFS can be verified as applicable to existing diesel engines and to the objectives of the VDRP. OTAQ established the Environmental Technology Verification Program (ETV) and outlined the verification process which can be obtained from the above US EPA / OTAQ website. Total PM mass emission reductions of 25% and above, in percentile increments achieved under the OTAG ETV process, are verified. Two DPFS are verified for 60% and one DPF system for 90% PM mass reduction. The program does not test for the solid nanoparticle fraction. There is no official OTAQ indication that solid nanoparticle emissions is being considered for the future.

It is again noted that the program is voluntary, not mandated, and formulated to attract the greatest number of volunteer cities and fleets. Under the program diesel engine powered vehicles and equipment previously regulated and certified to earlier emission control standards can be upgraded (retrofitted) for PM emission control.

The Retrofit Technology Verification Process has the following objectives: 1) introduce innovative diesel engine emission reduction technology quickly and cost effectively by providing confidence in durability; 2) allow manufacturers of diesel engine emission reduction technology to demonstrate product effectiveness for multi-engine family applications; 3) provide streamlined steps for upgrading previously verified technology; 4) test candidate manufacturers' technology and product under standard test protocol (US Federal Test Procedures or other) to demonstrate emissions reduction. Once verified the product is placed on a Verification List; 5) a very important requirement is to test the technology in actual use to demonstrate that performance is maintained in actual field applications. If the technology fails in-use testing criteria then the product is removed from the list, noting its removal; and 6) provide for product upgrade of technologies already on the Verified Product List.

The US EPA Voluntary Retrofit Program / OTAQ Verification Process is less stringent than the CA ARB. OTAQ and ETV are willing to work with diesel emissions control technology manufacturers rather than establishing hard criteria or specifications. Following are differences between OTAQ and CA ARB: 1) PM verification is for the full range from 25% to 100% in percent increments. OTAQ does not have PM % conversion category levels. Thus an OTAQ technology just below a CA Level 3 category, say at 75% PM mass-based reduction, might be considerably less expensive. The danger is that the 75% technology may not collect and destroy solid lung alveoli penetrating particles; 2) CA ARB and OTAQ emissions testing are equal; 3) in-use testing is significantly less strict than the California program; and 4) an annual or biannual in-field test of all deployed filter systems (DPFS) is missing.

5. Highlights of Table 1 – Comparison of Verification Programs

A comparison of the essentials of each verification program is presented in Table 1. The text is in short cryptic form. For full details of specific interest see the respective full documents listed in References. The sequence of Table 1 is structured to follow the section order of the California Diesel Risk Reduction Plan – Verification Procedure. Text for the VERT Filter List and the US EPA Voluntary Retrofit Program – OTAQ Retrofit Technology Verification Process are aligned with the California sections to assist in the comparison. Table 1 provides the basis for the foregoing Section IV discussion. Acronyms and symbols used in Table 1 are listed in Table 2.

Below are important highlights of Table 1 – Sections i through xi:

i. *Applications Process:* Each procedure has a formal application process used for formal agency review prior to embarking on the verification test procedure. Each application is judged for sound science and engineering before proceeding.

ii. *Published Verification List:* Each verification program publishes and updates a list of verified technologies. California publishes separate verified technology lists for each of its three PM mass technology categories: Level 1 > 25% PM reductions, Level 2 > 50% to 85%, and Level 3 not less than 85%. The VERT publishes a VERT Filter List for PFS that have passed a strict set of solid particle filtration suitability tests that focus on 95% removal of nanometer sized particles (20 to 300 nm diameter) and 90% removal of elemental carbon mass reduction. OTAQ publishes a verified PM technology list that covers a range from 25% to 100% PM mass reduction in percentile increments, i.e. 46%, 49%.

***Table 1** – reduced version with minor items deleted Comparison of the Verification Procedures* of –*

California Air Resources Board – Warranty and In-Use
Compliance Requirements for In-Use Strategies in Control of Emission from Diesel Engines

VERT Filter List. Tested and approved Particle-Filter Systems for retrofitting Diesel Engines

US EPA Voluntary Diesel Retrofit Program (VDRP,
Retrofit Technology Verification Process: OTAQ Verification Process and VDRP Verified Technology List

** reduced version with minor items deleted*

Verification Items	***California Diesel Risk Reduction – Verification Procedure***	***VERT Filter List – Suitability Tests***	***EPA Voluntary Retrofit Verification***
i. Application Process for Verification: Application Details	Details given in Section 2702 of CA Reg. Title 13. ECG engine name, make, model, model-year and PM / NOx cert. Examples of in-use vehicles or equipment, typical duty cycles, etc. EO review practical / scientific basis.	Application to. http://:www.suva.ch Coordination by: TTM Technik Thermische Maschinen, Dipl.Ing A. Mayer –TTM.A.Mayer@bluewin.ch [Note 1]	QTAQ application – 3 paths. OTAQ/ETV Path = ETV manages. OTAQ Path = manufacturer manages. Path 3 = product update
ii. Published Verification List: [Note 2]	Website Note [3]. DECS Level 3 Verified Technology List regularly updated (check on regular basis)	Website Note [4]. Updated annually. Includes PFS ty4es, filter medium, regeneration method, and electronic filter monitoring for deployment. A separate filter class for brief deployment is listed	Website Note [5]. Verified Technology List updated periodically
iii. Emission Test Requirements:	**Section 2703**	**VERT Suitability Tests**	**RTI 5.0**
Baseline and Control Test Test Cycle:			
On-road: Engine cycle	FTP HD Transient, Title40,Part86,SubPartN (1 cold start; 3 hot start) NOx emission control technology may require additional testing	VERT qualifies PFS with VFT 1 – 4 modes of ISO 8178 100 / 60% engine speed; and 100 – 50% engine load tested in new condition, fully loaded with soot, during and after regeneration and at highest filter space velocity. All modes must pass	FTP 40 Part 86, Subpart N, 1 cold and 3 hot
Chassis cycle	FTP HD Transient,Title40, Part86,SubParttN as pertain to chassis + 3 hot-starts of UDDS CFR Title40, Part86, App I (d) plus 3 hot starts of low speed chassis cycle	Not used – engine test is sufficient	[Note 6]
Off-road: Engine cycle	CA C of Reg Title 13, Sect 2423 = CA Exhaust Emission Stds & Test Procedures for >2000 MY CI engines, Part 1 (B) (3 hot starts)	Same as On-road. All tests occur in VERT approved labs. VFT1 = new PFS test. Use ISO 8178 – average of 4 operating points including 1 at max permissible space velocity of the filter system and max T; VFT2 = PFS monitored prolonged deployment >2K op.hrs; VFT3 = PFS tests after VFT2, VFKT = test of electronic filter controls; VAST = test of additive system; VSET = VERT secondary emission test.	FTP 40 CFR Part 89, Subpart E. ETV Path 1 also Subpart D with 3 or more steady-modes to obtain 95% confidence. Allows for all-modes or selected modes of test
Monitor	Pressure + temperature and provide record	Mandated for all tests and deployed PFS. Minimum electronic log (3 months) backpressure and alarm signal functions are given. P max 200 mbar. Alarm 150 mbar. Max new 50 mbar. T found useful.	Not mentioned [Note 6]. Backpressure must be measured / reported during FTP at full load and rated speed
HC, CO and NOx analyses	Required. Additional analyses can be required depending on the technology	Required and compared to baseline – no emission increase permissible. Emissions also measured at high idle, low idle and converter stall for diagnostic purposes	Required

Verification Items	***California Diesel Risk Reduction – Verification Procedure***	***VERT Filter List – Suitability Tests***	***EPA Voluntary Retrofit Verification***
NO_2 analysis	Required	Required. No relevant increase (see 'relevant' in vi. Other Requirements)	[Note 6]
PM $_{(mass)}$ analysis	Required	Required – Elemental carbon mass per VDI 2465	Required
PM $_{(number)}$ analysis	Not Required	Required for particle count and elemental carbon mass concentration	Not required
Unregulated/Secondary Emission	EO can require if believed necessary	VSET (full ISO 8178 modes x 2) after VFT1 completed. Required for all catalytic systems. No relevant increase NO_2, dioxins, furans, PAH, nitro-PAH, sulfuric acid, additive ash particles or mineral fiber	Required as part of entire test data submission
Regeneration Tests	Emissions must be measured during regeneration event and taken into account for PM % reduction	VERT does not accept averaging. PFS must meet particle and elemental carbon criteria during each regeneration event	Repetitive cycles until regeneration = time weight average. Regeneration method described on issued ETV Verification Statement
iv. Durability Test Requirements:	**Section 2704**	**VFT2 Endurance**	**Durability RTI5.2.9**
Actual Field Tests	Extended service accumulation Option 1 is Actual Field Demo. 50K miles or 1K hours	Requires VFT2 prolonged 2000 hour endurance in monitored deployed application	Real-world operation for 33% of expected full-life. Table 3: 5y or 100K h, etc. MEDS BL and in-use tests. No MEDS specification given
Laboratory	Option 2 is Laboratory- based. 1K hours	VFT3 tests of PFS on laboratory engine after VFT2 2000 hour endurance	Accelerated bench testing simulating 33% of Table 2: 5y or 4200h. Filters or other can be removed from actual in-use vehicle and tested on lab engine
Fuel same for BL, control tests	Same fuel for all tests	All same fuel	[Note 6]
On-Road – x miles or x h service accumulation	50K miles, or 1K hours extended service or simulated lab aging	2000 hours in actual monitored deployment	Real world operation to 33% of 5 y or 150K miles HD, or 100K MD, or 60K MD or respective h
Off-Road – x h service accumulation	1K hours simulated lab aging (in-field or simulated lab aging is an option)	Same as on-road above	Engine aging to 33% of 5y or 4200 h for a > 50 hp
P, T data log – x miles or x h	Measured for 1000 hr or test duration. Also for 1 BL and each CNL test runs	Monitor and data log mandated for all tests and deployment of all PFS	T must be measured, RTI5.2.14
Electronic data log	Submit to EO	Mandated for all PFS tests and deployment	Not mentioned [Note 6]
3rd Party report	Required by EO approved 3rd party. Overall performance, maintenance, problems, visual and physical intact, secure mounting, leaks, observations	Not mentioned	Not mentioned
Test cycle type	Same as listed in Emission Test Requirements above for on-road and off-road	VFT3 is like VFT1 but modified	40 CFR Part 89, Subpart E for non-road. One or more full steady-state multimode FTP baseline and aged. Test method depends on retrofit product. BL and aged in-use tests have to be identical, rigorous, repeatable for tests to be directly comparable
Baseline/Control test emissions	B/L needed before start or at end – both recommended. Same set of control tests required before service accumulation, during and after completion – average result of each test series	Required	Required.
Before Start	Required	Required	Required
After	Required after 100% finished	Required after 2,000 hour durability test	After at least 33% of accumulated mileage or hours of minimum durability table for engine size
Maintenance	List of Scheduled Maintenance required – specify ash removal and disposal for DPF	Required - include maintenance interval/s and specify cleaning and disposal of ash residues. See also brief deployment PFS disposal	Required to be submitted with submission of test data

Verification Items	***California Diesel Risk Reduction – Verification Procedure***	***VERT Filter List – Suitability Tests***	***EPA Voluntary Retrofit Verification***
% Reduction Criteria	When aged to 100% of durability miles or hours must meet or exceed the verified % emission reduction level	PFS after 2 K op hrs must meet >95% reduction of 20-300 nm particle count and >90% EC mass. No change from new condition	New device aged to at least 33% of minimum durability miles or hours must meet verified % reduction level
Absolute Emission Criteria	Must be below 0.01 g/bhp-hr (applicable for Level 3 only)	No increase in legislated CO, HC, NOx and PM mass emission including during filter regeneration	Only % reduction
Physical Damage Criteria	Maintain physical integrity. Not cause engine damage, exceed backpressure, no maintenance beyond owner's manual	Safety – no additional risks. Assembly must comply to Swiss safety regulations	Not mentioned [Note 6]
Conditional Verification	EO can issue for off-road / stationary only. But! All durability requirements must be fulfilled 1 year	Verification only after passing all suitability tests	Not mentioned
Failure Criteria	EO may downgrade or deny verification	Must pass all suitability tests to be VERT listed. If >5% field failure = removal from list	Fail = removal from Verified Technology List
<u>v. Field Demonstration of Compatibility:</u>	Section 2705. Applicable when laboratory durability is chosen. In-field durability can satisfy this requirement		
Duration – x h or x miles	200 hours or 10,000 miles	California only	California only
3rd Party testament	Same as durability test		
Criteria: engine damage/malfunction	None		
Criteria: backpressure	Not exceed mfr limits **or cause damage to engine**		
Criteria: hindrance to engine, vehicle or equipment	None		
Criteria: physicals mounting, leakage, observable detectable damage	Robust		
Pressure and temperature data-logging requirements	Entire test period. Submit record to EO		
<u>vi. Other Requirements:</u>	Section 2706		
NO_2 level after catalyst technology. [Note 3]	NO_2 < than 30% over baseline engine NO_2 as of 1/1/07 and <than 20% over engine NOx as of 1/1/09 [CA ARB revision 3/23/06]	VSET - no relevant increase means less than permissible ambient air limits for workplaces; or OAPC limits; or shall not exceed thrice the without-filter at that operating point	Secondary emissions are mentioned - NO_2 limit not specified
HC, CO, NOx, PM emissions	Required – not exceed limits for each and also NH_3	Required – not exceed limits. VSET required.	Required. Must include secondary emissions. SOF of PM must be measured.
Fuel Borne Catalyst – require a DPF technology <u>[CA ARB term is Fuel Additive]</u>	Require DPF technology unless proven OK alone. _On-board monitor alarm for low and empty FBC level. Also must shut off FBC feed if monitor detect DPF failure. Requires additional testing [2706 (c)]. Requires multimedia evaluation and EPA registration	Require a DPF. Monitor must detect DPF rupture with automatic interrupt of FBC dosing. Special specification listed in VERT Filter List	Not mentioned
Monitor and alarm for backpressure and temperature	Monitor P and T. Alarm required.	Mandated for all PFS tests and field deployments – found useful for warranty claims. Measure and record P (keep for 3 months). Alarm for high pressure [cleaning] and low pressure [filter rupture]	DPF inlet/outlet T and P during tests must be reported. Monitor not mentioned
Fuel and Lube Oil spec	Applicant specifies if different than Durability – see comment above.	Fuel EU500K <10-ppm S; Lube oil w/o S and low metal ash, TBN <30	Same as durability spec – see above
Schedule Maintenance List	Required	Required - emphasizes cleaning / disposal of ash residues	Required with submission of test data

Verification Items	*California Diesel Risk Reduction – Verification Procedure*	*VERT Filter List – Suitability Tests*	*EPA Voluntary Retrofit Verification*
Label	Required to have defined information and number assigned by EO	Label – durable, legible and unambiguous – identify filter family, serial no. and mfr data for QC, legible even after long deployment	Not mentioned [Note 6]
Owner's Manual	Specifies 10 types of information to be included	Not mentioned [Note 1]. Mentions education and information programs for users	Not mentioned [Note 6]
vii. Warranty Requirements:	Section 2707		Not mentioned
Noise Level Control	Same or lower as the original muffler	Equivalent of muffler replaced – close up measurement. Flow direction and diagnostic access (inlet and outlet exhaust sample tap)	Not mentioned [Note 6]
Warranty	Product warranty is required for full DECS repair or replacement and re-pair of engine damage, if any, caused by DECS; Installation warranty is covered in (a) (1); Owners warranty responsibility is defined separately. Applicant must submit a warranty report Feb 1 each year and within 30 days if claims exceed 4%	Required for product performance and installation where exhaust pressure <200 mbar. If exceeded can incur engine damage. Owner/operator responsible for maintenance and action upon monitor alarm indication. Retrofitter must submit an annual warranty report and immediately if failure exceeds 5%	[Note 6]
Warranty Periods: On-Road	See below:	PFS Life Expectancy >5K op.hrs; Usable hours to cleaning >2K op.hrs; Maintenance Interval >500 op.hrs; Guarantee for materials and function >2 y or 1K op.hrs for all PFS deployed	RTI report assumes same as Table 3 – California Minimum Du-rability Requirements for On-road and Off-road However, states that OTAQ will issue new Table (TBD)
Lt HD, 70-170hp, <19.5 K lbs	5 y or 60K miles		CA same or TBD
Med HD, 170-250hp, 19.5- 33K lbs	5 y or 100K miles		CA same or TBD
Hvy HD, >250hp, >33K lbs	5 y or 150K miles		CA same or TBD
Hvy HD, >250hp, >33K lbs and Driven over 100K m/y with less than 300K miles odometer at time of installation	2 y, unlimited miles		CA same or TBD
Warranty Periods: Off-Road		Same note as on-road	Same as on-road above
<25 hp and for constant speed engine under 50 hp with engine speeds > or equal to 3K rpm	3 y, or 1.600 hours		CA same or TBD
At or >25 hp <50 hp	4 y or 2,600 hours		Same as above
At or >50 hp	5 y or 4,200 hours		Same as above
viii. Determination of Emissions Reduction:	Section 2708		
Calculation Equations for % and Absolute reduction	Calculations and equations given	Particle count and EC mass are cited. Tests by SMPS, ELPI (13 stage type), NanoMet and other. Determined by VERT using approved engine labs	Calculated from BL and control technology test results
Emission Reduction Categories, if any	PM Level 3 => 85% PM reduction from BL or achieve absolute mass PM of <0.01 g/bhp-hr; Level 2 => 50%; Level 1 => 25% [Board may approve adding 'plus' levels at March 06 meeting]	One PFS category: > 95% Particle count and >90% EC mass concentration	No categories. PM levels calcu-lated as PM mass % reduction. Example: 60% and 90%
ix. In-Use Compliance Testing:			
On-Road	Section 2709. Required	Manufacturer tests all deployed PFS biannually with smoke puff tests during engine free acceleration: pass equals less than 10% smoke (opacity <$0.24 m^{-1}$; failure <3% = stay on list; >3%<5% = tests and correction; >5% = delist	Required

Verification Items	*California Diesel Risk Reduction – Verification Procedure*	*VERT Filter List – Suitability Tests*	*EPA Voluntary Retrofit Verification*
Off-Road	CA ARB will set off-road rules in 2006	Same	Required – none yet on Verified List as of 6/30/05
Minimum number units sold for start in-use Compliance Tests	50 (sold or leased)	N/A	500
Number of units to be tested	Min. 4, max 10 (for each phase)	Manufacturer field test all deployed PFS biannually and report results	Initially 4, maximum 10
Age criteria – to conduct Phase 1 testing	Conduct within 3 months after 1 year or lst maintenance is reached	No Phases. Age or hours not specified	Phase 1: 25% of mileage or hours is reached
Age criteria – to conduct Phase 2 testing	Reach 60 to 80% min. warranty period	Same as above	Phase 2: reach 75% of mileage or hours
Pass / Fail criteria	+90% of verification level or <0.011 g/bhp-hr. If fail EO may lower verification level or delete from List	>5% failure of opacity K >0.24 m^{-1} value = remove from list. Manufacturer obliged to correct. <3% retained on list. >3% testing required	+ 75% of verification level – if fail remove from Verification List
4 of 4 pass	Pass	N/A	Pass
If one fails – new tests	+ 2 engines for each engine failed	N/A	Same as California
Final test criteria	70% of all engines tested meet >90% of verification level or <0.011 g/bhp-hr	>5% failure in one year = delete from list and manufacturer correction	70% of all engines tested must meet 75% of verification level
Report – timing, data	3 months after each phase – seven items covered	Must be reported annually to VERT – time not specified. Immediately if failures >5%	Test results in 3 months
Warranty claims	Claims report each year or when warranty claims exceed 4% (within 30 days)	VERT Listed Manufacturer must report to VERT each year	Not mentioned
Remedial report	If DECS family does not comply – remedial report with corrective measures in 90 days.	Not mentioned	Not mentioned
x. Manufacturers responsibility after verification:	a) Conducts in-use compliance test and provides results to EO. b) Submit annual warranty claims report to EO and when claims exceed 4% and submit in 30 days. c) If fails compliance tests submit remedial report to EO in 90 days	Obliged supply only technologies complying with VERT specifications that exactly fulfill the suitability tests. Promise advanced notice of intended changes; monitor the quality of their trap systems, and annual report to VERT on failure statistics of all PTS families on list.	a) Path 1 with ETV assistance. b) Path 2 Qualified manufacturers have complete application and test responsibility. c) Manufacturers use Path 3 for product upgrade or coverage revisions. d) Conduct and report in-use testing.
xi. Acceptance of other Verification Programs	ARB will review data from other programs and other preexisting data but will not blindly accept other programs' verifications. The ARB will work in conjunction with EPA to verify a technology. This applies to "hardware" only - fuel additives are not included. Accepts VERT Filter List but requires supplementary proof of filter compatibility with retrofitted engine types	None	Accepts CA Verified Process

[Note 1] All testing is conducted in approved laboratories with VERT coordination. It is assumed that test details not included in the VERT Filter List English Version are included in the German version in more detail or are covered in the VERT coordination activity

[Note 2] MSHA produces a DPM Technology List not reviewed here, http://www.msha.gov/01-995/Dieselpartmnm.htm. MSHA does not allow DOC for certain mines as it only removes organic soot and increases NO_2 and also limits DPF that produce NO_2

[Note 3] website for California Verification List, http://www.arb.ca.gov/diesel/verdev/level3/level3.htm

[Note 4] website for VERT Filter List; http://www.suva.ch, or http://www.umwelt-schweiz.ch/buwal/eng/fachgebiete/fg_luft/vorschriften/industrie_gewerbe/filter/index.html

[Note 5] website for US EPA OTAQ Verification List, http://www.epa.gov/otaq/retrofit/retroverifiedlist.htm

[Note 6] Each applicant has to submit a QA test plan RTI10.2. It is assumed that the test plan will include specifics on this other items will be included in the OTAQ approved test plan

iii. *Emission Test Requirements:* California and OTAQ use the same US Federal engine dynamometer test cycles and PM mass analytical test procedures, similar to certification of new on-road and off-road diesel engines. These cycles do not provide the extreme conditions necessary to evaluate retrofit BAT filtration function performance. VERT conducts a unique set of ´suitability tests´. VERT solid particle filtration emissions tests are conducted using four key modes of the ISO 8178 engine test cycle chosen to expose the PFS to extreme exhaust conditions Two modes expose the PFS to the highest diesel engine exhaust temperature and highest exhaust flow rate. The other two selected modes expose the PFS to lower exhaust flows and temperature. VERT specifies that one test cycle point be at the highest filter space velocity. Emission tests are made with a new DPF, when fully loaded with soot, during and after regeneration. Test results are not averaged and only one can exceed slightly within one standard deviation. VERT criteria are specific to the particle number (particle count) of lung alveoli penetrating particles in the 20 to 300 nanometer size range and total elemental carbon mass concentration. PM mass measurements are also taken in accordance with standard procedures. VERT studies have found particulate matter (PM) mass to be confusing and view it to be an incorrect metric. For this reason PM mass is always measured for each PFS but not reported. VERT tests and scrutinizes PFS for secondary filter emissions, especially required for catalyst-based PFS, utilizing the complete ISO 8178 8-mode test cycle. CA ARB Executive Officer can require unregulated secondary emission tests whereas OTAQ requires such data be part of test data submission. CA ARB, OTAQ, and VERT use ultra-low sulfur diesel fuel. VERT uses low ash lube oil and recommends its use in retrofit programs.

Comment: Two significant differences between VERT and the CA ARB, OTAQ emission test requirements are:

a) Selection of the engine test cycle. VERT determines DPF solid nanoparticle filtration function by exposing the PFS to the extreme modes of ISO 8178 to gain a thorough evaluation of DPF solid nanoparticle filtration performance at extreme engine and filtration conditions. CA ARB and OTAQ use FTP 40, Part 86, Subpart N, 1 cold and 3 hot starts, test cycle. The latter test cycles do not provide the extreme exhaust flow conditions where solid particles could pass through and not be filtered (cleaned filters) or filtered particles can be dislodged and re-entrained (high flow velocity) as has been found for some DPF types. The CA ARB and OTAQ engine and vehicle test cycles cannot differentiate best available filter technology from less efficient filters that are not BAT. The proper test condition is extremely important for off-road engines (studies show off-road are normally operated at higher intensity) as well as many on-road applications; and

b) VERT has developed analytical procedures and pass/fail criteria for the number of solid particles emitted (termed particle number (PN) expressed as particles per cubic centimeter in a size range of 20 to 300 nm). PN is of greatest importance because this particle fraction is of greatest health concern. PM mass measurements group all particles (large and small, solid and liquid) together and provide questionable ability to distinguish between good BAT diesel filters and poor filters. Elemental carbon mass concentration test focuses on solid insoluble particles, which is more reproducible and a better measure than PM mass of filtration efficiency. If particle number and elemental carbon mass limits were adopted and added to the CA ARB and OTAQ verification programs each would be significantly strengthened without adding much complexity. The current opinion is that Europe, CA, and other countries will adopt and add particle count to test procedures sometime in the near future.

iv. *Durability Test Requirements:*

a) Differences exist in accumulation of durability hours in actual deployed use. CA ARB is for 50K miles or 1K hours; VERT is for 2000 operating hours; OTAQ is for 33% of expected life (about 2 years or 1400 hours). These differences are not strongly significant since all require no deterioration in filtering efficiency over the respective durability test period. Of significance is that VERT does not allow test averaging and only permits one exceeds if within one standard deviation – in this case VERT is superior.

b) CA ARB requires a monitor be installed to record a log of backpressure and filter inlet exhaust temperature during the durability period; VERT mandates an active monitor that measures and records a downloadable data log of exhaust backpressure and activated alarm functions on all tests and deployment of all particle filter systems; OTAQ requires exhaust gas temperature measurement.

c) CA ARB, OTAQ and VERT require that regulated HC, CO, NOx and PM mass not deteriorate.

d) 3rd Party evaluation of DECS is unique to California but not required by OTAQ or VERT.

Comment: The VERT process mandates a monitor that measures and records backpressure limits and alarm events has proven to be an effective means to lessen field failures – the data record will show whether proper engine maintenance has been routinely provided, whether alarms have been responded to or ignored, and whether the engine was operated above or below redline backpressure of 200 mbar limit.

v. *Field Demonstration of Compatibility:* Unique to CA ARB only. **Comment:** CA ARB has recognized individual PFS technologies on the VERT Filter List but requires submission of complete VERT emissions test information for review and analysis prior to acceptance. Engine compatibility is inherently provided by the required VERT VFT2 2,000 hour operating hour deployed PFS durability and VFT3 test evaluation thereafter. Given some of the mild procedures included in CA ARB and OTAQ verification it is wise for them to scrutinize DECS compatibility in deployed diesel engines.

vi. *Other Requirements:*

a) <u>NO_2 emissions.</u> CA ARB requires < 30% NO_2 generated by DECS over NO_2 engine out baseline starting 2007 – this changes to <20% in 2009; VERT cites no relevant increase when deployed and PFS emissions must meet permissible ambient air limits for workplaces or OAPC limits; not specified by OTAQ; [Note: MSHA issued a bulletin to mine operators advising caution for NO_2 generated by platinum catalyzed diesel particulate filters];

b) <u>Fuel Borne Catalysts.</u> CA ARB requires a DPF as part of any FBC system unless the FBC has been proven acceptable for discharge into the atmosphere; VERT requires a BAT DPF and a monitor which shuts off FBC feed if filter ruptures and sounds an alarm if FBC feed tank level is low; OTAQ does not mention.

c) <u>Regeneration.</u> CA ARB and OTAQ require a description of regeneration process in the application form. A description is included on the verification certificate, but active regeneration with on and off-board thermal assist heaters or burners has not been taken up by CA ARB or OTAQ. There are no regeneration specifics provided in CA ARB or OTAQ verification procedures or process. VERT lists the main and alternate regeneration types for each verified PFS. For instance, regeneration types include one or several types: catalytic self regeneration; on- and off-board thermal burners; fuel borne catalysts; fuel injection promoting catalytic combustion; and inlet throttle or exhaust valve systems. Each VERT PFS regeneration type is tested for durability.

Comment: NO_2 limits defined by CA ARB and VERT are good examples for any future program – the lower NO_2 produced the better and lowering NO_2 below engine out is highly desirable. FBC have to comply with other constraints as defined by CA ARB and VERT. Approval of alternate active regeneration methods for each verified DECS or DPFS is important especially for off-road construction-site programs.

vii. *Warranty Requirements:*

CA ARB has specific warranty text that manufacturers have to use in warranty statements and minimum warranty periods; VERT lists engine life expectancy, useable hours to maintenance intervals, and guarantee for materials and function; OTAQ mentions it will provide a warranty section but currently accepts CA ARB minimum durability requirements.

Comment: CA ARB and VERT warranty requirements are acceptable. The CA ARB required warranty text has been thoroughly scrutinized by the CA legal department.

viii. *Determination of Emission Reduction:*

All verification programs describe common formulas for calculation of PM percent reduction.

Comment: There are no issues with these calculations.

ix. *In-Use Compliance Testing.*

There are significant differences between CA ARB, VERT, and OTAQ in-use tests. CA ARB specifies that in-use testing start after 50 DECS units are sold or leased. Then a minimum of 4 and maximum of 10 DECS engines are selected for PM emissions tests using the same tests used for original verification. In-use tests are run in two aged phases – Phase 1 after 1 year of first DECS installation and Phase 2 testing phase after 60% to 80% of expected life. OTAQ requires starting after 500 are sold and the two test phases are at 25% and 75% of life. However, CA ARB and OTAQ differ considerably for in-use pass/fail. CA ARB pass/fail is defined as 70% of DECS engines tested have to reach above 90% of PM verification level. OTAQ is 70% of retrofit control technology engines meet 75% of PM verification level. Failure in CA ARB in-use tests can result in downgrade to a lower level or removal from the list. Failure in OTAQ test will result in removal from the list Both CA ARB and OTAQ are completely different than the VERT in-use testing. VERT has determined and proven that a simple field test can discriminate in-field filtration function. VERT requires a simple biannual engine snap acceleration test while measuring smoke opacity be performed on all deployed PFS to detect good or failed filter function. Exceeding a failure rate of 5% will result in delisting and >3% <5% requires investigation and problem solution.

Comment: The CA ARB in-use tests are done once with a fairly high level of testing for all DECS groups. OTAQ in-use tests occur one time for each engine group. VERT in-use tests are ongoing for each deployed PFS and is essentially an Inspection and Maintenance (I&M) test. The VERT in-use test is performed by the supplier thus avoiding the expensive engine dynamometer testing required by CA ARB and OTAQ and, in addition the supplier tests are not onerous to the owner or operator.

x. *Manufacturers responsibility after verification.*

CA ARB and OTAQ place similar responsibilities on the manufacturers. VERT extracts promises for continued responsibilities – this will change to Swiss regulated responsibility soon.

Comment: Manufacturers have to agree to supply continued technical service for deployed DECS. Manufacturers have to agree to deploy only the actual verified technology without exception. Any contemplated product changes have to be reported and approved or require confirmation tests.

xi. *Acceptance of other Verification Programs.*

Comment: On Oct 3, 2006 CA ARB released preliminary modifications to the verification program for potential adoption in late 2007 – [see References].

6. Cost Effectiveness/ Stimulation of Invention and Development

Retrofit programs have costs but are effective. One estimate is a benefit/ cost ratio of 5/1 (Ref. 3, 4). There are over 200 million older diesel engines operating in actual use in the world that need to be retrofitted with DPF PFS.

When viewing the overall cost picture, the example of the SI engine 3-way catalyst (TWC) emission control system provides a valuable cost correlative to new and existing diesel engine emissions control. TWC required a major shift in fuel metering from carburetion to fuel injection, and additional components including an oxygen sensor, mass air meter, computer, electronic high energy ignition, and durable waterproof ignition wiring. The costs were substantial and affected many industries. Since 1977, TWC system brought about enormous benefits to society through ultra-low emissions of hydrocarbons (including toxic species), carbon monoxide and oxides of nitrogen. There were other related benefits. TWC is one of the main reasons for world elimination of leaded gasoline that removed the main source of airborne lead nanoparticles found to impair mental development of children and cause serious health effects of adults. There also were consequent improvements in engine life and durability. It postponed low-sulfur gasoline for 30 years as TWC did not emit sulfuric acid mist that oxidation catalysts did and did not create NO_2 acid gases. It engaged many manufacturers in continued development that improved performance and brought prices to mass production levels.

Similar benefits will unfold from a world focus on PFS DPF diesel engine retrofit to eliminate solid nanometer particles. A very large number of world diesel engines need to be retrofitted. PFS DPF and regeneration systems will continue to be developed and price will decline. We cannot use an inferior system. Society does not have to endure diesel engine solid nanoparticle emissions for the next 40 years.

The Swiss VERT program, by sticking to BAT principles and retrofit of all diesel engines without exception, has stimulated invention and development that led to a rich variety of filters and regeneration systems. A universal self regeneration PFS that could be applied to any engine or application that minimizes user/ owner attention and maintenance is still a highly desirable target. By comparison, the invention/ development driving force has been compromised in the CA ARB program and absent in the OTAQ program.

7. Conclusions

The established VERT suitability tests and diesel engine retrofit filtration criteria for Particle Filter Systems (PFS) is found to be comprehensive, elegant, thoroughly thought out, and can be regarded as an integrated engineering specification for diesel engine emissions retrofit programs. VERT is significantly stronger than CA ARB or OTAQ, yet the most simple. VERT suitability tests are least costly to perform. In-use testing is made periodically for all deployed PFS that employs an already established smoke opacity test. The principle outstanding features, which by comparison, make the VERT the recommended system for cities, countries and regions that are considering is-use diesel engine retrofit projects are as follows:

1. In conjunction with universities, industry and toxic air-borne health authorities, VERT established that the portion of inhaled diesel exhaust solid particles in the size range of 20 to 300 nm that penetrate to lung alveolus are an extreme health hazard.
2. VERT is the only sanctioning authority focused on solid nanoparticle particle removal and has designed filter suitability tests for removal efficiency measurements. VERT Filter List technologies have a proven record for deployment in underground workplaces, construction sites and road vehicles. The VERT system is now proven and being accepted throughout the world.
3. VERT rules are dynamic in character and can be upgraded for new BAT technologies
4. The VERT suitability tests include thorough scrutiny for secondary emissions. Certain candidate PFS technologies have been rejected for creating toxic emissions. Candidate PFS that increase NO_2 are limited to applications where NO_2 workplace limits are not exceeded.
5. VERT regards filtration and regeneration of collected soot particles as separate unit operations
6. Filtration unit operation:
   - VERT determines filtration performance under engine and filter extreme limits that can differentiate BAT filters. This avoids failings of established engine test cycles.
   - PFS DPF filter candidates are designed for a specific Euro II engine so that when operating at highest filter space velocity it demonstrates that it meets all solid nanoparticle 20-300 nm filtration performance criteria. Larger solid particles are also filtered. Tests are made when the filter is clean, fully loaded, and during and after filter regeneration, and at least one test point at the high filter space velocity. This assures almost zero solid nanoparticle penetration or particle exfoliation and re-entrainment under any filter operating condition.
7. Regeneration unit operation:
   - One or more regeneration techniques are scrutinized for each approved PFS.
   - A rich variety of regeneration techniques and variations have been invented and/or developed during the program. These include: thermal devices such as electrical heaters and fuel burners; catalytic devices such as precious metal or base metal catalyst-based DPFs and fuel borne catalysts; fuel injection with catalytic combustion; inlet and outlet throttling; and replaceable or throw-a-way glass fiber or paper filters.
   - Verified PFS can be applied to all engine applications. To achieve this requires the PFS manufacturer or supplier to choose one or more of the verified regeneration techniques needed to assure regeneration will occur reliably without exception.
8. A repeatable engine test cycle is critical and essential to achieving the above:
   - Existing OE engine certification test cycles designed for criteria pollutant mass emissions are useless for measuring filter performance at extreme filter exposure conditions. Such cycles lack ability to differentiate BAT.
   - VERT chose the recognized ISO 8178 engine test cycle and selected only four of the extreme steady state test modes. This decision has been proven to be the correct and reproducible approach.
   - Selection of four extreme test points of the ISO 8178 test cycle provides three vital and practical inputs for sizing the filter:

     One. The new filter design should have sufficient soot collection capacity for at least an 8 hour period of engine operation. When operating at the highest space velocity the filter pressure drop should be: a) less that 50 mbar when new; b) regeneration initiated at <150 mbar providing a 100 mbar operating window; c) maximum aged filter not to exceed 200 mbar.

     Two. The filter is designed to have a practical filtration/ regeneration cycle window of 100 mbar. With time (exceeding 500 operating hours) collected solid ash particles will likely raise the window toward the 200 mbar limit indicating that ash cleaning procedures should be initiated [low ash lubricating oil is encouraged].

     Three. The highest filter space velocity value to achieve all of the above allows the VERT approved filter supplier to design and scale for other engines by utilizing the space velocity reactor scale model that has been used by catalyst manufacturers and is now proven for PFS DPFs.

Where diesel retrofit programs already exist based on PM mass-based emission standards it is recommended that the VERT system be adopted while maintaining the existing mass-based emission standards. If PM mass based standards are not in place the VERT system is perfectly designed to provide for complete verification assurance.

The most important conclusions derived from this analysis of three verification programs are as follows:

- VERT targets solid insoluble nanoparticles (20 to 300 nm size) is the most serious toxic component of diesel exhaust affecting health. As the pioneer in this respect, VERT has developed a comprehensive series of filter suitability tests, pass/fail criteria, and measurement techniques. Criteria pollutants cannot be increased, and unregulated secondary emissions, if any, have to comply with workplace standards
- VERT did not choose commonly used existing engine test cycles because they were found useless as a means to define filtration BAT.
- In-use performance is conducted on all deployed retrofitted vehicles and equipment. This biannual in-field test is simple, easy to perform and not onerous to the owner.
- CA ARB has reviewed and scrutinized VERT suitability test data and, if satisfied, will grant full or conditional verification to an applicant

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9. Appendices

Appendix A.

Table 2. ACRONYMS

ASTM	American Society of Testing Material
BL	Baseline emissions level of an engine
BUWAL/SAEFL	Swiss Agency for the Environment, Forests and Landscape
CA	California
CA ARB	California Air Resources Board
CA C	California Code of Regulations
CB-DPF	Catalyst-based DPF
CFR	Code of Federal Regulations
CNL	Control technology
BAT	Best available technology
DECS	Diesel Emission Control System (CA ARB name)
DOC	Diesel oxidation catalyst
DPF	Diesel Particulate Filter
DPFS	Diesel Particulate Filter System (OTAQ name)
DPM	Diesel Particulate Matter
DRRP	Diesel Risk Reduction Plan (CA ARB)
EC	Elemental carbon
ECG	Emission Control Group (CA ARB)
EGR	Exhaust gas recirculation
ELPI	Electric low pressure impactor to measure particle surface
EO	Executive Officer
ETV	Environmental Technology Verification Program (OTAQ)
FBC	Fuel borne catalyst
FR	Federal Register
FTP	Federal Test Procedure
HD	Heavy Duty [vehicles or equipment]
HC	Hydrocarbons
ISO	International Standards Organization
I&M	Inspection and maintenance
MEDS	Mobile Emissions Detection System
MMA	Multi-Media Agency
MSHA	Department of Labor, Mine Safety and Health Administration
N/A	Not applicable
NanoMet	Nanoparticle measuring instrument using PAS and DC
Op.hrs	operating hours
OAPC	Swiss Ordinance on Air Pollution Control, 1 March 1998
OTAQ	US EPA Office of Transportation and Air Quality
PAH	Poly-aromatic Hydrocarbons
PEMS	Portable Emissions Monitor System
PFS	Particle Filter System (VERT name)
PM	Particulate Matter
QC/QA	Quality Control / Quality Audit
RTI	Research Triangle Institute International - a US EPA Contractor
RTVP	Retrofit Technology Verification Process (OTAQ)
SMPS	Scanning mobility particle sizer
TBD	To be determined
TWC	3-way catalyst for spark ignited engines - HC, CO and NOx control
UDDS	Urban Dynamometer Driving Cycle
ULSD	Ultra-low Sulfur Diesel fuel (usually < 15-ppm or 10-ppm
US EPA	United States Environmental Protection Agency
VDRP	Voluntary Diesel Retrofit Program (US EPA / OTAQ)
VERT	Swiss project of Swiss and German organizations to curtail emissions at tunnel sites, 1994-99
VFKT	Test of electronic filter controls [monitor test]
VFT	VERT Particle filter tests
VFT1	Test new filter systems - basic function
VFT2	Test of filter systems during monitored prolonged deployment >2000 operating hrs
VFT3	Test filter systems after VFT2
VSET	VERT secondary emissions test

SYMBOLS

%	percent
CO	Carbon Monoxide
CO_2	Carbon Dioxide
g/cm^3	grams per cubic centimeter
g/bhp-hr	grams per brake horse power hour
g/kWh	grams per kiloWatt hour
HC	Hydrocarbons
K	1000
lbs	pounds
m	meter
mbar	millibar
nm	nanometer (10^{-9} meters)
NH_3	ammonia

NO	Nitrous Oxide
NO_2	Nitrogen Dioxide - a strong oxidizing gas
NOx	Oxides of Nitrogen (N_2O, NO, NO_2)
P	Pressure or backpressure
ppm	parts per million
Pt	Platinum
S	Sulfur
T	Temperature [exhaust]
y	year

Appendix B – Additional Background Information

A. Diesel Engine Emissions.

Diesel fuel is injected directly into the engine cylinder where compression ignition and fuel/air burning starts almost instantly as the injected fuel penetrates cylinder compressed hot air. Burning continues until the exhaust valve is opened. Air is always in excess, but intimate air and fuel mixing via gas diffusion with the assistance of physical swirl and tumble mixing of the air/ fuel mixture within the combustion chamber is a developing process and, typical of closed combustion systems, is never fully completed by the time the exhaust valve is opened. All fuel/ air components are in an ionized state at the highest flame temperature [Fig 2]. Falling temperature during the expansion stroke gives rise to formation of entirely new solid carbon particles and hydrocarbon molecular structuring takes place. Primary nanometer sized solid carbon particles are formed along with basic chemical structures of typical diesel engine hydrocarbon species as peak temperatures continue to fall. The primary solid soot particles grow in diameter and then agglomerate into long chains and branches of particles. There are an enormous number (ten to hundreds of millions of solid particles per cubic centimeter) of agglomerated solid particles in the size range of 10 to 500 nanometers in diameter.

The number of diesel exhaust particles in the nanometer sized solid particle range is very large compared to the number of larger particles. Nanometer sized particles are invisible while the smaller number of larger particles is seen as typical diesel black smoke. Almost the entire total solid surface area is due to the surface area of nanometer sized particles, but this fraction contributes almost none of the total particle mass in terms of (grams/cm^3 or grams/bhp-hr) of diesel exhaust. The larger particles formed in the range of 1 micrometer (1,000 nanometers) to 10 micrometers constitute almost all of the total particle mass of diesel exhaust but comparatively few of the total particle number and less than 1 to 2% of particle surface area.

In the past decade, diesel engine technology has stepwise greatly reduced total particle mass emissions from about 1 g/kW-hr to 0.02 grams/kW-hr. Analysis shows that the main fraction reduced is the large particles. Only slight reductions of nanometer sized particles are achieved by improved engine design technology including high pressure fuel injection and common rail fuel feed systems. Particles in the 1 to 10 micrometer range are visible as black soot whereas particles in the 20 to 1,000 nanometers range are not visible. This gives an impression that recent new engines are quite clean when actually they are not clean with respect to lung alveoli penetrating solid particles – the fraction of greatest health concern.

Newly formed gaseous hydrocarbon species, among which are several toxic and carcinogenic compounds, adsorb and strongly adhere to active particle surfaces. The high surface area of nanometer sized solid particle fraction is available for toxic hydrocarbon adsorption. The inhaled solid particle fraction between 10 and 500 nanometers penetrate lung alveolus where a percent are captured, and represent the solid particle fraction of greatest health concern. The larger particles l.0 to >10 micrometers in diameter are deposited in the upper respiratory system and expelled by natural processes – for instance, upper respiratory mucous capture and bronchial cilia action.

B. Diesel oxidation catalyst; Diesel particle separators:

Two types of diesel emission control technology are not recommended:

Diesel Oxidation Catalyst (DOC). DOC are sometimes used because of lower cost, and the view point that retrofitting DOC is better than doing nothing. DOC has serious drawbacks as a stand alone technology. The largest concerns are: 1) DOC removes very little solid lung alveoli penetrating particles and DOC Pt types create NO_2; 2) It should never be used for school buses. DOC Pt types are banned by authorities for use in certain mines. On the other hand, DOC technology may be important when combined with certain types of DPF systems, NOx adsorber technology; and SCR NOx reduction systems.

Diesel particle separation or partial filter devices. Traditional diesel exhaust particulate matter standards are defined in terms of particle mass, grams per unit of distance (g/km) or grams per unit of engine power (g/kWhr). For this reason, removal of the larger particles constituting the overwhelming largest fraction of particle mass by particle separation techniques has become the focus of some manufacturers. Typically, the diesel particle separation is achieved by particle impaction and capture of the larger solid particle within the collection media. Some manufacturers claim that diesel exhaust impact filters remove a fraction of solid nanoparticles. However, this has proven to be inconsistent at all conditions of filter solids load and exhaust flow conditions. In a partial flow filter, the uncaptured fraction of solid nanoparticle ash and soot flies through with the exhaust gas flow into the surrounding environment. This type of technology is not BAT DPF filtration. Though it may be slightly less expensive, it allows the passage of solid nanometer lung alveoli penetrating particles and for this reason it is not the BAT that can eliminate the health consequences the public demands.

C. Combined PM and NOx Reduction Systems:

Of special note when studying PM reduction is the subject of NOx reduction. Diesel engines NOx emissions are regulated and NO_2 is the criteria pollutant. NOx emission control systems include EGR, lean NOx catalysts (LNC), NOx adsorber catalysts, and selective catalyst reduction of NOx with NH_3. All can be used alone for NOx reduction or combined with DPF particle filter systems to achieve exhaust emissions reduction of both NOx and solid nanoparticles. Issues related to each individually and in combination with DPF PFS are not covered in this report.

Appendix C – Acceptance of VERT Filter List and Suitability Tests

The established VERT Filter List and VERT suitability tests are being considered throughout the world. It is already accepted by:

BUWAL / SAEFL	– Swiss Agency for the Environment, Forests and Landscape*
Suva	– Swiss National Accident Insurance Organization, Luzerne
TBG	– German Association of Construction Professionals, Munich
AUVA	– Austrian Accident Insurance Agency
TRGS	– Technische Richtinien fur Gefahrstoffe (Technical guidelines for toxic substances)

UBA – German Federal Environmental Protection Agency, Berlin
MSHA – US Mine Safety and Health Administration, Department of Labor
DEEP – Diesel Emission Evaluation Program (Canadian mines)
Chile – country of
Denmark – country of
Netherlands – country of
Tyrol – region of northern Italy and western Austria
Alto Adige – region of northern Italy
CA ARB – California Air Resources Board - recognizes the VERT test results but requires supplementary proof of filter compatibility with retrofitted engine types

VERT is under consideration by the EURO PMP committee for potential diesel retrofit programs in EU member countries.

* Only Particle filter systems (PFS) in this filter List are approved for deployment in Switzerland for the following:
- Underground workplaces: Suva filter imperative promulgated 1 Mar 2000
- Construction sites: SAEFL Ordinance „Air Pollution Control at Construction Sites“ promulgated 1 Sept 2002
- Road vehicles: Art. 34 VTS, EJPD (Swiss Federal Police) Clarified EJPD 29 Sept 1995, Directive EJPD 7 Aug 1990

8. Figures

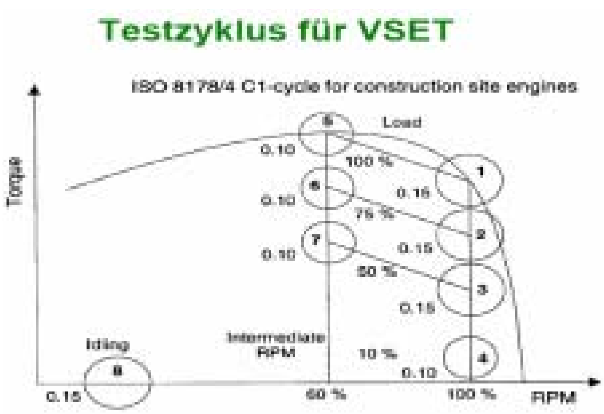

Fig.1. Test Cycle for Secondary Emissions Test. Only test modes 1, 3, 5 and 7 and engine mode for high filter space velocity is needed for PFS filtration evaluation

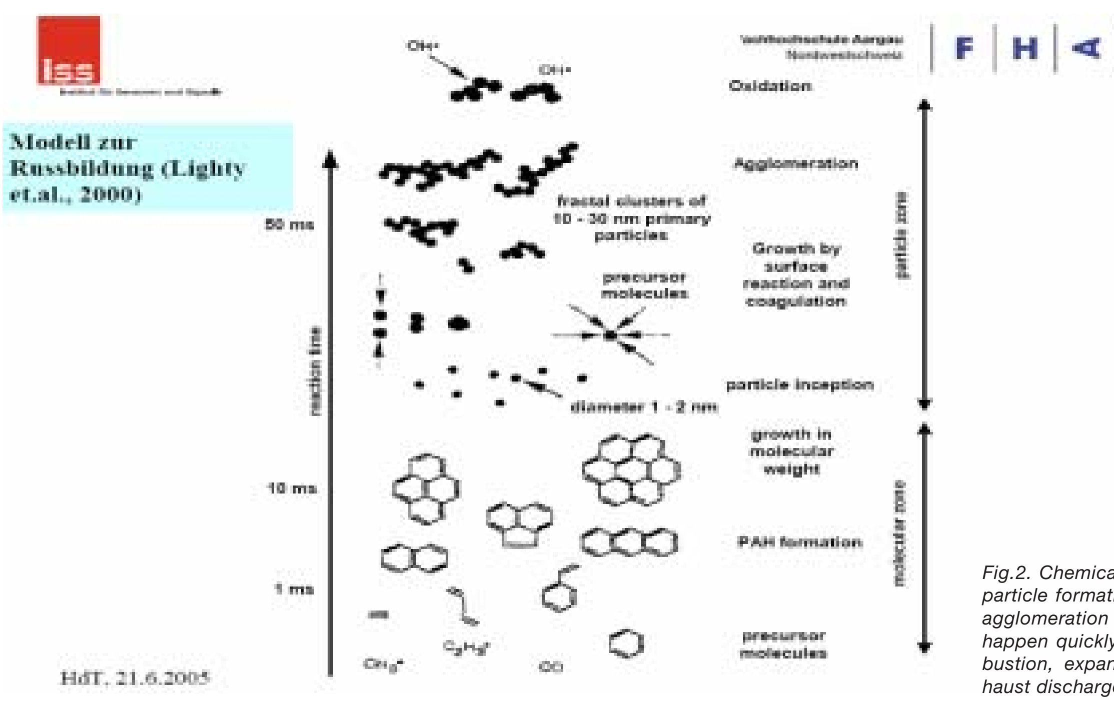

Fig.2. Chemical species and particle formation as well as agglomeration mechanisms happen quickly during combustion, expansion and exhaust discharge

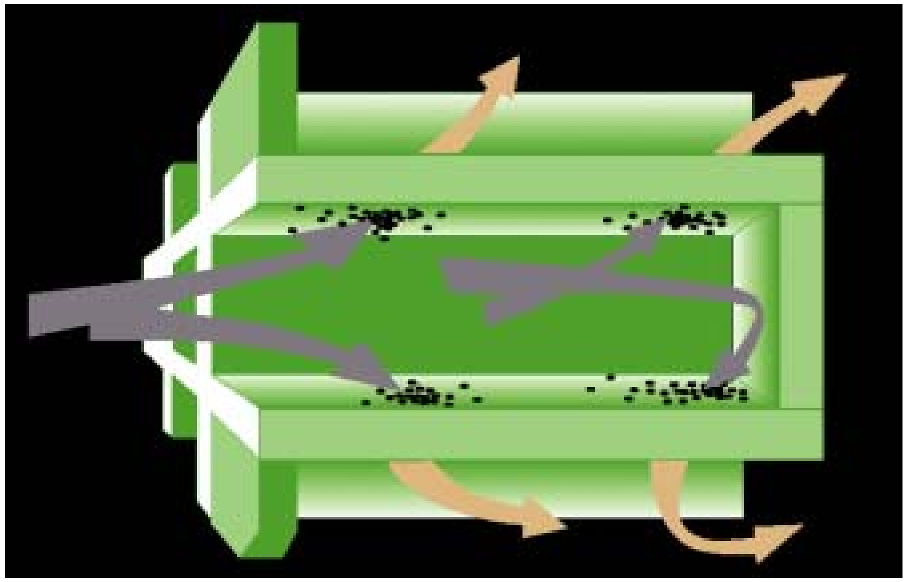

Fig.3. Open wall-flow diesel particle filter. 99% + removal of solid diesel particles – Diesel Particulate Filter

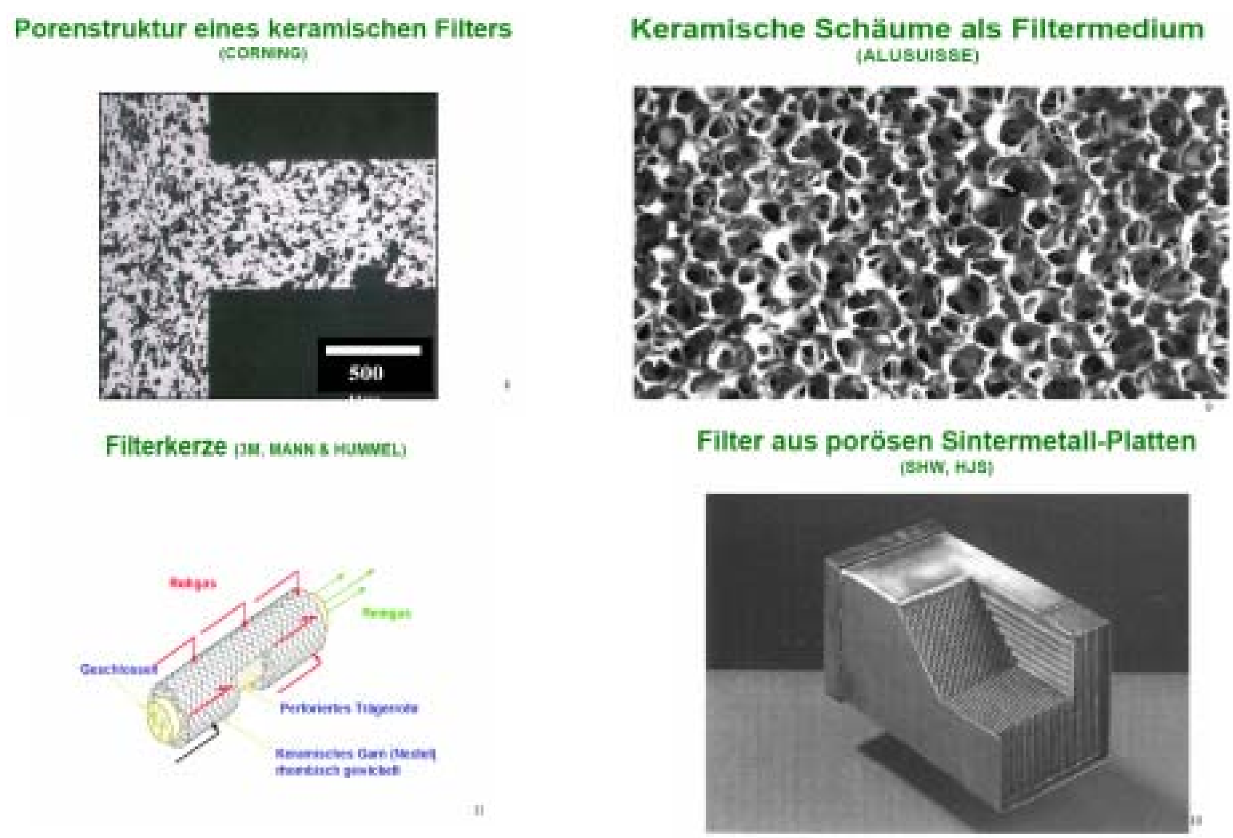

Fig.4. Many types of filtration materials are proven effective – ceramic honeycomb, ceramic open pore, fiber, and sintered metals

CALIFORNIA VERIFICATION

CALIFORNIA VERIFICATION – ADVANTAGES

- Thorough organized process covering all essential factors. CA Executive Officer carefully scrutinizes test data and in-use testing submitted by manufacturers
- Requires PM Level 3 technology (if available). Requires emissions tests during PM Level 3 filter regeneration
- Limits NO_2 generation in 2007 with lower limit 2009
- Fuel borne catalysts (FBC) must incorporate DPF and monitor that: 1) alarms when the FBC feed tank level nears empty; 2) automatic switch-off of the FBC dosing system if the DPF is ruptured. [Note: FBC, regarded a fuel additive, must undergo multimedia (MMA) test requirements]
- Requires DECS Monitor to detect and record filter backpressure and actuate an alarm when upper limit value is approached
- In-use emissions tests after 50 DECS units are installed: Phase 1 tests after 1 year or 1st maintenance; Phase 2 tests when DECS reaches 60 to 80% of warranty mileage or hours window
- Minimum of four in-use aged DECS up to 10 DECS are tested if failures occur in the first four. In the final analysis, 70% of DECS tested must reach 90% of PM Level-3 >85% reduction or equal to >76.5% PM removal [Note: However, permits unnecessary test averaging and filtration performance decline]
- Owner's Manual – defined areas of specific text coverage (see Section 2707) – i.e., required to have an explanation of backpressure alarm functions including the underlying meaning of monitor alarm signals so owner/ operator know actions to be taken
- Ash cleaning procedures are required in operator's manual for safe handling during the toxic ash removal and disposal
- Warranty limits for mileage or hours are described – warranty text examples are provided

CALIFORNIA VERIFICATION – DISADVANTAGES

- Uses existing Federal engine cycles and procedures that cannot provide extreme conditions needed to evaluate BAT filtration of all solid particles
- Nanometer solid particle count measurement not addressed. Therefore this excellent BAT property of DPF system is not assured
- Exhaust particle emissions not tested at DECS highest and lowest space velocity – known causes for particle breakthrough
- DPF design information would be valuable, i.e. maximum backpressure when DPF is new and fully burdened DPF at highest engine speed; design volume sufficient for 8 hour use before active regeneration
- Unnecessary PM test averaging and in-use filtration performance decline is permitted – encourages non-BAT filtration methods
- Secondary emissions tests are not mandated. Executive Officer has to request
- No on-going in-use test plan or I&M plan where in-use failures can be detected and corrected.
- Changing verification details to strengthen their program is a high level CA state process. The necessity of DRRP and verfication process improvements such as: engine test cycle selection, deletion of Level 1 and 2, addition of solid nanoparticle reduction criteria, and modification of unnecessary ageing filtration DF and test averaging will be a difficult and time consuming task.

VERT VERIFICATION

VERT VERIFICATION – ADVANTAGES

- VERT Filter List technologies have proven record for deployment in underground workplaces, construction sites and road vehicles
- VERT rules are dynamic in character and can be upgraded for new BAT technologies
- Selection of the proper retrofit engine test cycle that provides for extreme filtration conditions is a ***major VERT advantage***
- The extreme test points of the ISO 8178 test cycle that include highest exhaust flow and operating temperature is vital. This overcomes all the disadvantages of all other engine test cycles – that is, attempts to replicate actual engine use but miss testing at the extremes necessary to evaluate BAT filtration function
- VFT1 filter tests. Tests new state, burdened with soot, during and after regeneration, and one point at the highest space velocity. Filtration must exceed 95+% removal of solid 20 to 300 nanometer particles and 90+% elemental carbon mass concentration. Note: space velocity is standard exhaust gas hourly volume flow through the filter divided by filter volume. An approved PFS can use the space velocity model to design filters for any engine size – a catalyst industry model for reactor design calculations
- Extreme condition solid particle filtration testing combined with specification of backpressure limits for new and fully soot burdened PFS provides proven engineering design information and assurance that filtration efficiency measured in the VERT suitability tests will be replicated when applied to any diesel engine make, model, year, size or application
- VSET tests are required for secondary toxic emissions where individual toxic emissions must not exceed existing workplace levels, or if not established, then thrice the level without the PFS
- VFT2 2,000 hour in-field deployed endurance must be completed before being listed. A monitor measures and records exhaust gas temperature and back pressure data. Regeneration has to occur each time without exceeding 200 mbar backpressure
- VFT3 test, similar to VFT1 but shortened, is used after VFT2 2,000 hr. endurance is complete. No deterioration in filtration is permitted from original
- Mandatory bi-annual opacity smoke test (1 per 2y) for each deployed PFS. Free engine acceleration opacity turbidity <0.24 m1 turbidity coefficient K. This proven low-cost I&M test detects filter failures and is not onerous to user. When deployed PFS reach an opacity failure rate >5% = delisting; 3-5% require investigation and redesign; <2% is currently achieved; and <1% expected in the future. Rugged portable nanoparticle number count measurement technology instruments will likely improve and replace opacity test.
- VERT verification granted to several FBC types. Requires an approved $95\%^{+}$ DPF be used for all FBC PFS systems to assure collection of FBC solid nanoparticles. Backpressure monitor must include alarm functions when FBC tank is approaching empty and alarm and shut-off of FBC feed when filter rupture is detected. A distinct advantage is no excess NO_2
- Approval granted for prolonged deployment of: disposable paper filter cartridges with an exhaust gas cooler; and to non-catalyzed filter equipped with full flow burner
- Approval granted for brief employment of glass fiber wool disposable cartridges and ceramic/wire knit filters that can be regenerated

VERT VERIFICATION - DISADVANTAGES

- Particle count analysis of nanoparticles is not used in any US programs – only now under consideration by the EU and CA ARB
- Full understanding and acceptance of particle count analyzers is needed. VERT Filter List acceptance by CA ARB is a good step.

EPA OTAQ VERIFICATION

EPA OTAQ VERIFICATION – ADVANTAGES

- New technology applications submitted by new technology manufacturers are scrutinized by OTAQ and ETV authorities
- Authorities provide new applicants with considerable help during initial phases of verification
- Initial tests required to be conducted in OTAQ approved laboratory until manufacturer develops sufficient test experience to accept the full test responsibility
- Currently one DPFS approved at 90% PM and two at 60% PM mass reduction
- EPA recognizes diesel retrofit % reduction values achieved in OTAQ verification process as applicable for use in state air quality plans

EPA OTAQ VERIFICATION – DISADVANTAGES

- Encounters the same negative consequences as described for the CA ARB verification procedure
  - Test cycles not appropriate for PM testing [should be ISO 8178]
  - Allows for filtration decline in-use
  - Allows test averaging
- Allows for product upgrade without testing. Impact: inferior undetected changes. Solution: a) 500 hours of ISO 8178; b) Filtration evaluation at fully soot burdened condition under highest engine space velocity
- Durability testing is at zero and 33% of the specified durability period. Based on two points a projection is made to the full durability period reduction efficiency resulting in less testing but unsound outcome
- No PM performance pass/fail target. All levels accepted in increments 25 to 100%. A 75% PM mass technology could be considerable less expensive but the danger is that it may filter and destroy little, if any, solid lung alveoli penetrating nanoparticles
- In-use testing starts after 500 DPFS sold appears too long
- Notification period after in-use failures are found, and corrective actions to-be-taken, appears too long
- Testing for secondary toxic emissions is not specified. Though some data is expected in the DPFS application to OTAQ
- No on-going annual test plan or specific I&M plan to assure continued in-use performance and durability. When in-use test failure occurs a long time is allowed for corrections to be made without users being informed of this situation
- In-use testing with mobile emission detection systems (MEDS) or portable emission monitor system (PEMS). MEDS and PEMS are in the development stage and need test and approval for accuracy and repeatability by some authority before appearing in a verification program
- Urban buses up to 12 years old are grandfathered without testing. Not justified for buses in actual use

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