Diesel Particulate Filter Maintenance: Current Practices and Experience

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EXECUTIVE SUMMARY

Diesel engines are important power systems for on-road and off-road vehicles. These reliable, fuel-efficient, high torque engines power many of the world's heavy-duty trucks, buses, and non-road vehicles. While diesel engines have many advantages, they have the disadvantage of emitting significant amounts of particulate matter (PM) and oxides of nitrogen (NOx) into the atmosphere. Diesel engines also emit toxic air pollutants. Health experts have concluded that pollutants emitted by diesel engines adversely affect human health and contribute to acid rain, ground-level ozone and reduced visibility. Studies have shown that exposure to diesel exhaust causes lung damage and respiratory problems and there is increasing evidence that diesel emissions may cause cancer in humans.

In response to these health concerns, a number of countries worldwide (including the United States, the European Union, and Japan) have established emission limits for new diesel engines, with recent regulatory programs for new diesel engines requiring significant reductions in diesel particulate emissions in the 2005-2010 timeframe. Health concerns associated with diesel exhaust have also focused attention on emissions from the large population of existing diesel vehicles. As a result, local, regional, and national voluntary and mandatory diesel retrofit programs have been initiated in a variety of world markets. To date these retrofit efforts have focused on the application of diesel oxidation catalysts and diesel particulate filters for the reduction of diesel PM on in-use diesel engines operated in both on-road and off-road applications. These retrofit programs are expanding rapidly with more cost-effective technology solutions being verified for use on in-use diesel engines and a greater variety of technology options available for application on a wider range of in-use engines.

Diesel particulate filters (DPFs) remove particulate matter in diesel exhaust by filtering exhaust from the engine. They can be installed on diesel-powered vehicles, off-road equipment, or stationary diesel engines. Wall-flow type filters can reduce diesel PM by more than 85% compared to an unfiltered diesel exhaust. A growing experience base is available for the application of filters on diesel engines, including more than 200,000 retrofit applications of filters worldwide and more than 1 million applications of filters on new light-duty diesel passenger cars in Europe. Successful application of diesel particulate filters on new or existing diesel engines requires a robust filter regeneration scheme that periodically oxidizes the collected soot present on the filter to maintain engine backpressure characteristics within specified limits. These regeneration methods include both passive (e.g., methods that rely strictly on the available exhaust temperatures in a given application) and active (e.g., supplemental heat inputs to the exhaust required to initiate soot combustion) systems. The effectiveness and durability of catalyst-based DPFs is maximized with the use of ultra-low sulfur diesel fuel.

In addition to collecting soot, filters also collect inorganic-based exhaust constituents that are derived from several sources, including the combustion of engine lubricants, products of normal engine wear and/or corrosion, and materials associated with fuel-borne catalysts in DPF applications that use these catalysts to assist in the filter regeneration process. Over extended operation on the vehicle, these ash species slowly accumulate within the filter and gradually increase the pressure drop across the filter. Since excessively high backpressure on the engine will result in a degradation of engine performance, the accumulated ash material within the filter needs to be periodically removed. This ash removal or cleaning operation is a necessary filter maintenance operation. Engine oil consumption characteristics, the total ash content of engine lubricant formulations, vehicle duty cycles, filter designs, and fuel-borne catalyst dosing rates all impact ash accumulation profiles and required filter maintenance cleaning intervals.

Retrofit applications of wall-flow filters on heavy-duty diesel vehicles and original equipment applications of wall-flow filters on passenger cars in Europe provide information on current filter maintenance interval recommendations from manufacturers of filters or new light-duty vehicles equipped with filters. In retrofit applications on existing heavy-duty diesel highway vehicles, filter manufacturers recommend that filters be cleaned of ash after either 12 to 24 months of operation, or at mileage intervals that range from 60,000 to 100,000 miles. It should be noted that actual maintenance intervals are based on factors such as engine lubricant consumption rates, duty cycles, and actual engine/vehicle applications. Older vehicles with higher lubricant consumption rates, for example, may need maintenance intervals that are more frequent than the maintenance intervals stated above. Late-model heavy-duty diesel engines with low oil consumption characteristics operated in over-the-road applications with retrofit, catalyst-based DPFs have successfully operated for more than 200,000 miles before filter cleaning was initiated. In Europe, passenger car filter maintenance intervals with systems using fuel-borne catalysts were initially designed for 80,000 km (ca. 50,000 mi) of operation but now have been extended up to 200,000 km (ca. 120,000 mi) with lower engine-out PM levels, lower fuel-borne catalyst dosing rates, and new filter designs featuring higher ash storage capacities.

Manufacturers of filter technologies have developed safe, reliable, and effective procedures for removing the ash from particulate filters. These practices have been put in place in both retrofit wall-flow filter applications and wall-flow filter-equipped passenger cars in Europe. The ash cleaning practices include well-documented procedures for cleaning filters and the development of stand-alone filter cleaning stations or facilities that automate many of the necessary procedures. These procedures include combinations of pressurized dry air streams directed at the exit side of the filter with industrial vacuum devices used on the inlet side to safely collect ash removed from the filter. In some cases very controlled high temperature treatments of the filters are used before or after air cleaning procedures to remove organic materials and soot that may be contained in the filter. Ash collected from used filters should be disposed of according to local, state, and/or federal solid waste disposal regulations.

The first large-scale application of diesel particulate filters in the U.S. on new vehicles will occur starting in 2007 for heavy-duty diesel engines used in highway trucks and buses. All heavy-duty engine manufacturers have indicated their intent to use diesel particulate filters to comply with the U.S. EPA's 2007 PM emission regulation of 0.01 g PM/bhp-hr. In public forums to date, the engine manufacturers have indicated that complying with EPA's 150,000 mile minimum filter maintenance interval for heavy heavy-duty vehicles is part of their development plan for 2007 engines. The emissions control industry is committed to work with their customers in the engine manufacturing industry to make the 150,000 mile filter maintenance interval a reality for as wide an application base on new heavy-duty diesel engines as possible.

1.0 INTRODUCTION

Diesel engines provide important fuel economy and durability advantages for large heavy-duty trucks, buses, and non-road equipment. They are often the power plant of choice for heavy-duty applications. While they have many advantages, they also have the disadvantage of emitting significant amounts of particulate matter (PM), oxides of nitrogen (NOx), and lesser amounts of hydrocarbon (HC), carbon monoxide (CO), and toxic air pollutants.

Particles emitted from diesel engines are small – in most cases less than 2.5 microns in aerodynamic diameter. The particles are complex, consisting of an uncombusted carbon core, adsorbed hydrocarbons from engine oil and diesel fuel, adsorbed sulfates, water, and inorganic materials such as those produced by engine wear. Because of their extremely small size and composition, the particles emitted by diesel engines have raised many health concerns. Health experts have expressed concern that diesel PM may contribute to or aggravate chronic lung diseases such as asthma, bronchitis, and emphysema.

There is growing evidence that exposure to diesel PM may increase the risk of cancer in humans. A comprehensive assessment of available health information, carried out by the International Agency for Research on Cancer (IARC) in June 1988, concluded that diesel particulate is probably carcinogenic to humans. The term "carcinogen" is used by the IARC to denote an agent that is capable of increasing the incidence of malignant tumors. In August 1998, California's Air Resources Board identified PM emissions from diesel-fueled engines as a toxic air contaminant. In 2000, the U.S. EPA declared diesel PM to be a "likely human carcinogen." A recent report, "Diesel and Health in America: The Lingering Threat," issued in February 2005 by the Clean Air Task Force (see www.catf.us for a copy of this report), reviews the health impacts of diesel particulate emissions in the United States. This report states that fine particulate pollution from diesel engines shortens the lives of nearly 21,000 people in the U.S. every year, with health-related damage from diesel PM estimated to total $139 billion in 2010.

Despite health and environmental concerns, the diesel engine remains a popular means of powering trucks, buses, and other heavy equipment. Most buses and heavy-duty trucks are powered by diesel engines for good reasons. Diesel engines are reliable, fuel-efficient, easy to repair, inexpensive to operate, and have a relatively low initial purchase price. One of the most impressive attributes of the diesel engine is its durability. In heavy-duty trucks, some engines have achieved operating lives of 1,000,000 miles or more while some engines power city buses for up to 15-20 years.

A number of countries worldwide have established emission limits for new diesel engines, with recent regulatory programs for new diesel engines requiring significant reductions in diesel particulate emissions in the 2005-2010 timeframe. In the United States, the Environmental Protection Agency finalized in 2000 a comprehensive regulatory program to reduce emissions from on-road heavy-duty engines (diesel and gasoline) in the 2007-2010 horizon (see www.epa.gov/OMSWWW/diesel.htm#hd2007 for details on EPA's 2007 highway diesel program). Specifically, this EPA highway program requires new heavy-duty diesel engines to meet a 0.01 g/bhp-hr PM standard starting in 2007, a 90% reduction in PM emissions compared to the current 0.10 g/bhp-hr PM standard for new diesel engines that heavy-duty engine manufacturers began to meet in 1994. Japan also has put in place emission standards starting in 2005 that require new heavy-duty diesel engines to meet a 0.027 g/kW-hr (0.02 g/bhp-hr) PM standard. These ultra-low PM emission standards for new heavy-duty engines in both the U.S. in 2007 and Japan in 2005 are expected to be achieved through the application of diesel particulate filters (DPFs). In Europe, discussions are on-going concerning the next round of emission standards for light-duty (Euro 5) and heavy-duty (Euro 6) vehicles. These next sets of standards will likely include significantly tighter standards for PM emissions from all new diesel-powered vehicles sold in Europe starting perhaps as early as 2010.

Since some diesel engines have very long operating lives, older uncontrolled diesel vehicles will continue to make up a significant portion of the heavy-duty vehicle fleet in world markets for years to come. Given the health and environmental concerns associated with diesel engines, there is increasing interest to retrofit older, "dirtier" diesel engines while newer, "cleaner" diesel engines enter the marketplace. Diesel particulate filters for controlling PM emissions from existing diesel cars and trucks are seeing growing retrofit applications in many world markets, including the U.S., Europe, Japan, and Korea, with pilot programs targeted for Mexico, Thailand, China, and other developing countries. These retrofit applications of DPFs have provided the first experiences with respect to filter maintenance practices. Filter maintenance of high efficiency particulate filters (e.g., ceramic wall-flow filters) is necessary due to the accumulation of inorganic material (ash) within the filter media over time that stems primarily from the combustion of engine lubricants. Filter maintenance procedures and equipment have been developed to serve the growing retrofit application of DPFs. This report summarizes the present filter maintenance experience base and highlights development trends in filter design, engine design, and lubricant formulations that will impact filter maintenance practices on new heavy-duty diesel engine applications as they come on-stream during this decade in the United States and Japan. The maintenance experience detailed in this report is based exclusively on filter designs employing ceramic wall-flow filters. These wall-flow filters currently dominate both the retrofit and original equipment-based applications of diesel particulate filters in all world markets. A brief overview of diesel particulate filters provides a backdrop to filter maintenance practices and experience.

2.0 DIESEL PARTICULATE FILTERS

2.1 Operating Characteristics and Performance

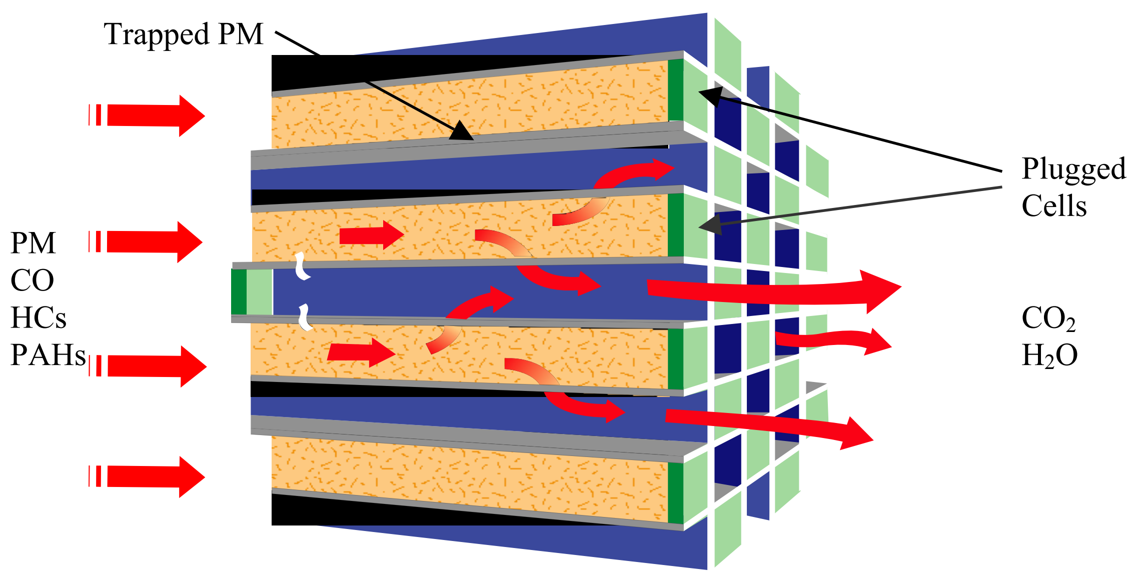
As the name implies, diesel particulate filters remove particulate matter in diesel exhaust by filtering exhaust from the engine. They can be installed on diesel-powered vehicles, off-road equipment, or stationary diesel engines. Since a filter will fill up over time, engineers that design filter systems must provide a means of burning off, or removing, accumulated particulate matter. A convenient means of removal of accumulated particulate matter is to burn or oxidize it on the filter when exhaust temperatures are adequate. By burning off trapped material, the filter is cleaned or "regenerated." Filters that regenerate in this fashion cannot be used in all situations, primarily due to insufficient exhaust gas temperatures associated with some types of diesel engines, the level of PM generated by a specific engine, and/or application operating experience. To ensure proper operation, filter systems are designed for the particular engine/vehicle application. In retrofit applications of filters, this application design process includes extensive data logging of the vehicle(s) under consideration to quantify the exhaust temperature history available during their normal operating conditions.

In some non-road applications, disposable filter systems have been used in retrofit applications. A disposable filter is sized to collect particulate for a working shift or some other predetermined period of time. After a prescribed amount of time, or when backpressure limits are approached, the filter is removed and discarded. Disposable filters target retrofit applications and would not meet original equipment requirements.

Filter Material A number of filter materials have been used in diesel particulate filters, including: ceramic (e.g., cordierite, aluminum titanate, or mullite formulations) and silicon carbide materials, fiber wound cartridges, knitted silica fiber coils, ceramic foam, wire mesh, sintered metal substrates, and temperature resistant paper in the case of disposable filters. Collection efficiencies of these filters range from 40 to over 90 percent. Filter materials capture particulate matter by interception, impaction, and diffusion. Filter efficiency has rarely been a problem with the filter materials listed above, but work has continued to: 1) optimize filter efficiency and minimize back pressure, 2) improve the radial flow of oxidation in the filter during regeneration, and 3) improve the mechanical strength of filter designs.

Figure 1 provides a diagram of a typical ceramic wall-flow filter system. These wall-flow filter designs are currently the design of choice for high efficiency (> 85%) diesel particulate matter reductions. In Figure 1, particulate-laden exhaust enters the filter from the left. Because

Figure 1.
Wall-Flow Diesel Particulate Filter



(Note: PM = particulate matter, HCs = hydrocarbons, PAHs = poly-aromatic hydrocarbons) the cells of the filter are capped at the downstream end, exhaust cannot exit the cell directly. Instead, exhaust gas passes through the porous walls of the filter cells. In the process, particulate matter is deposited, or trapped, on the upstream side of the cell wall. Cleaned exhaust gas exits the filter to the right.

Regeneration Many techniques can be used to regenerate a diesel particulate filter. Some of these techniques are used together in the same filter system to achieve efficient regeneration. Both on- and off-board regeneration systems exist. The major regeneration techniques are listed below.

- Catalyst-based regeneration using a catalyst applied to the surfaces of the filter. A base or precious metal coating applied to the surface of the filter reduces the ignition temperature necessary to oxidize accumulated particulate matter.

- Catalyst-based regeneration using an upstream oxidation catalyst with either a bare or catalytically-coated filter. In this technique, an oxidation catalyst is placed upstream of the filter to facilitate oxidation of nitric oxide (NO) to nitrogen dioxide (NO_2). The nitrogen dioxide oxidizes the collected particulate substantially reducing the temperature required to regenerate the filter.

- Fuel-borne catalysts. Fuel-borne catalysts reduce the temperature required for ignition of trapped particulate matter through direct contact between the catalyst and particulate that is collected together on the filter media. In the case of wall-flow filters, the catalyst remains in the filter media and adds to the inorganic ash that accumulates within the filter.

- Air-intake throttling. Throttling the air intake to one or more of the engine cylinders can increase the exhaust temperature and facilitate filter regeneration.

- Post top-dead-center (TDC) fuel injection. Injecting small amounts of fuel in the cylinders of a diesel engine after pistons have reached TDC introduces a small amount of unburned fuel in the engine’s exhaust gases. This unburned fuel can then be oxidized over an oxidation catalyst upstream of the filter or oxidized over a catalyzed particulate filter to combust accumulated particulate matter.

- Post injection of diesel fuel in the exhaust upstream of an oxidation catalyst and/or catalyzed particulate filter. This regeneration method serves to generate heat used to combust accumulated particulates by oxidizing fuel across a catalyst present on the filter or on an oxidation catalyst upstream of the filter.

- On-board fuel burners or electrical heaters. Fuel burners or electrical heaters upstream of the filter can provide sufficient exhaust temperatures to ignite accumulated particulate and regenerate the filter. In some cases regeneration can be accomplished while the vehicle is in operation, whereas in other cases the vehicle must be out of service for regeneration to proceed.

- Off-board fuel burners or electrical heaters. Off-board regeneration stations combust trapped particulate matter by blowing hot air through the filter system.

The experience with catalyzed filters indicates that there is a virtually complete reduction in odor and in the soluble organic fraction of the particulate, but some catalyst formulations may increase sulfate emissions. Companies utilizing these catalysts to provide regeneration for their filters have modified catalyst formulations to reduce sulfate emissions to acceptable levels. Low sulfur fuel (e.g., 0.0015 wt.% or 15 ppm S maximum) is becoming available in the U.S. and other world markets and has greatly facilitated these efforts.

In some situations, installation of a filter system on a vehicle may cause a slight fuel economy penalty (on the order of 1% or less). This fuel penalty is due to the increase in backpressure with the filter system. As noted above, some filter regeneration methods involve the use of fuel burners or fuel injection strategies and, to the extent those methods are used, there will be an additional fuel economy penalty. Many filter systems, however, have been optimized to minimize, or nearly eliminate, any noticeable fuel economy penalty. For example, in a demonstration program in Athens, Greece, no noticeable fuel penalty was recorded when the filter was regenerated with a cerium fuel-borne catalyst (29). More recently, experience in the New York City Transit program and in the San Diego school bus program has shown that fuel penalties for filters are zero or less than one percent. Little or no fuel economy impact was also reported as a part of DPF retrofit program in California involving late model tractor/trailer delivery trucks (13). During the required retrofit technology verification protocols established by either the U.S. EPA or the California Air Resources Board, fuel penalties have been documented at about 1% for high efficiency filter systems.

Filter systems do not appear to cause any additional engine wear or affect vehicle maintenance. Regarding maintenance of the filter system itself, manufacturers are designing systems to minimize maintenance requirements during the useful life of the vehicle. In applications that make use of high efficiency, wall-flow filters, accumulated lubricating oil ash will have to be periodically removed. Manufacturers provide the end-user with appropriate ash removal procedures. Current practices and experience with filter maintenance of wall-flow filters will be discussed in detail in the following sections of this report.

Filter systems have been designed so that vehicle drivability is not affected, or at least effects can be minimized, most notably by limiting exhaust backpressure. Diesel particulate filter systems, which replace mufflers in retrofit applications, have achieved sound attenuation equal to a standard muffler.

2.2 The Impact of Sulfur in Diesel Fuel on Diesel Particulate Filters

Sulfur in diesel fuel significantly affects the reliability, durability, and emissions performance of catalyst-based diesel particulate filters. Sulfur affects filter performance by inhibiting the performance of catalytic materials upstream of, or on the filter. Sulfur also competes with chemical reactions intended to reduce pollutant emissions (e.g., the oxidation of NO to NO_2) and creates particulate matter through catalytic sulfate formation. (Sulfate formation is sometimes referred to as “sulfate make.”) Catalyst-based diesel particulate filter technology works best when fuel sulfur levels are less than 0.0015 wt.% (15 ppm S). Meeting the most stringent emission standards requires both the use of catalysts and ultra-low sulfur diesel fuel.

Particulate filter technology can be successfully used in applications where the fuel sulfur level is greater than 15 ppm S, but only after filter application engineers make a careful assessment of the fuel sulfur level, the engine, the type of filter system, the operating conditions, and the emission reductions desired. PM emissions for catalyst-based filters operated with higher fuel sulfur levels will be higher than operation with ultra-low sulfur diesel fuel.

2.3 Operating Experience

Limited diesel particulate filter retrofit demonstration programs began in the 1980s and continued in the early 1990s. The number of vehicles retrofitted, the number of programs, and the interest in new programs has grown significantly over the past few years with approximately 200,000 DPFs installed as retrofits to date in a variety of world markets. Nearly all of these retrofit applications to date have utilized wall-flow filters like the design shown in Figure 1. Today, second and third generation retrofit filter systems can reduce PM emissions by 80 to more than 90 percent.

In Europe, new light-duty vehicles equipped with diesel particulate filters are being offered commercially. Filters were introduced on new diesel passenger cars in Europe in mid-2000, with more than 1,000,000 filter-equipped cars sold since that first introduction. These European light-duty vehicle applications have used ceramic wall-flow filters exclusively thus far. No performance or maintenance issues have been reported in Europe with passenger car DPFs. Peugeot (PSA) was the first manufacturer to introduce a DPF system for European diesel cars in 2000 (16, 17, 20, 23, 25). This system employs a fuel-borne catalyst combined with advanced engine controls available with a modern, high pressure, common rail fuel injection engine for filter regeneration. Other European automobile manufacturers (e.g., Audi, Fiat, Ford, VW, BMW, Mercedes) are now offering DPF systems based on the PSA system and the use of fuel-borne catalysts, or catalyzed filter systems that do not employ a fuel-borne catalyst.

Sweden’s Environmental Zones program resulted in the commercial introduction of diesel particulate filters on urban buses (14). More than 4,000 buses have been retrofit with passive wall-flow filter systems in Sweden. Some of these buses have accumulated more than 250,000 miles of service. Most recently in the summer of 2004 Volvo Bus launched a fleet of new diesel buses operating along the west coast of Sweden equipped with catalyst-based DPFs for controlling diesel PM combined with selective catalytic reduction (SCR) systems using urea as the reducing agent to control NOx emissions. This bus fleet is claimed to be the cleanest operating diesel bus fleet in the world. Transit fleets in other major European cities such as London and Paris have also been successfully retrofit with DPFs. Renault Trucks have introduced an active regeneration DPF system in combination with a thermal management strategy as an original equipment option on one of their Euro 3 certified engine families used in urban transit, refuse hauler, and other heavy-duty on-road applications (4). A particulate filter based on sintered metal foils is now available in Europe for retrofit on certain models of existing diesel passenger cars. A similar sintered metal foil-based particulate filter is being used on some new heavy-duty diesel engines offered by one heavy-duty engine manufacturer in Europe to comply with the Euro 4 heavy-duty PM standards that began in 2005 (1, 24).

Transit bus retrofits using DPFs have also occurred in many urban fleets across the U.S., including New York City (26), Boston, Philadelphia, Washington, D.C., Seattle, and many transit fleets in California. DPF retrofits are an important facet of the California Air Resources Board's (ARB) Diesel Risk Reduction Program (see ARB's report entitled "Risk Reduction Plan to Reduce Particulate Matter Emissions from Diesel-Fueled Engines and Vehicles" available at: www.arb.ca.gov/diesel/dieselrrp.htm). This broad based ARB regulatory effort is charged with reducing PM emissions by 75% from all existing diesel engines used in California by 2010 and by 85% by 2020. To date ARB has approved a series of hybrid PM reduction rules covering transit fleets, refuse haulers, transportation refrigeration units (TRUs), portable diesel engines, and stationary engines that include DPF retrofits on existing engines (where applicable and verified) along with engine repowers and replacements as options for reducing PM emissions from these existing engines. Future ARB regulatory measures will also require significant PM reductions from public and private on-road and off-road vehicle fleets.

School buses have also been a focus of both ARB and EPA retrofit programs in the U.S., with a significant number of DPFs equipped on school buses since 2000 in conjunction with the use of ultra-low sulfur diesel fuel (15 ppm S max.). Additionally, several U.S. engine manufacturers offer a "green" school bus engine fitted with a catalyzed DPF for use with ultra-low sulfur diesel fuel. Retrofits with DPFs on existing vehicles is also occurring in Japan as part of efforts by the Tokyo Metropolitan Government and other local government agencies to significantly reduce PM emissions from diesel trucks traveling through urban areas.

As noted in the introduction, all engine manufacturers will be equipping their new on-road heavy-duty diesel engines sold in the U.S. with DPFs beginning in 2007 in order to meet EPA's 2007 PM standards. These heavy-duty systems are expected to be integrated with advanced engine controls to ensure filter regeneration under all vehicle operating conditions and environments. An example of a heavy-duty engine equipped with a catalyst-based DPF system that includes active filter regeneration strategies using integrated engine controls was recently detailed by Hino Motors on a 12.9 liter engine targeting PM emission levels below Japan's 2005 heavy-duty diesel PM emission requirements (8). Additional presentations concerning the integration of DPFs on new heavy-duty diesel engines can be found in the recent proceedings for the U.S. Department of Energy's Diesel Engine Emission Reduction Conferences (see www.eere.energy.gov/vehiclesandfuels/resources/conferences/deer/index.shtml). Since 2001 some new heavy-duty diesel engines have already been certified with DPFs in the U.S. These original equipment DPF applications have been targeted at urban bus or school bus applications.

Diesel particulate filters have been installed on non-road equipment since 1986. Over 20,000 active and passive systems have been installed as either original equipment or as a retrofit worldwide. Some non-road filter systems have been operated for over 15,000 hours, or over 5 years, and are still in use. Examples of non-road equipment equipped with filters include: mining equipment, material-handling equipment such as cranes and forklift trucks, street sweepers, construction equipment, stationary power producing engines, and utility vehicles.

Germany, Austria, and Switzerland have established mandatory filter requirements for underground mining equipment (15). EPA finalized new emission standards for off-road diesel engines in mid-2004 that are expected to provide significant opportunities for DPFs over a wide range of new off-road diesel engines and applications sold in the U.S. in the 2011-2015 timeframe (see www.epa.gov/nonroad-diesel/2004fr.htm for details on EPA's off-road diesel program).

Diesel particulate filters can be combined with exhaust gas recirculation (EGR), NOx adsorber catalysts, or SCR (using hydrocarbons, urea/water, or ammonia as the reductant for NOx) to achieve significant NOx and PM reductions (9, 10, 22, 31). Engines retrofit with a low pressure EGR system and a DPF can achieve NOx reductions of over 40 percent and PM reductions of greater than 90 percent (22). Engines equipped with SCR and a filter or NOx adsorbers and a DPF can achieve NOx reductions of 60 to 90 percent and PM reductions greater than 90 percent (31). Combined NOx and PM reductions can also be achieved by recalibrating the engine to minimize NOx while using a filter to capture increased PM emissions. A lean NOx catalyst added to an exhaust system using a particulate filter (30) can reduce NOx emissions from 10 to 25 percent using diesel fuel as the reductant for NOx (NOx performance of such a lean NOx catalyst is generally strongly tied to the fuel reductant use and reductant dosing strategy.).

Toyota recently commercialized their DPNR (diesel particulate NOx reduction) system that directly applies a NOx adsorber catalyst formulation to a wall-flow ceramic filter for combined PM and NOx reduction. This system is available in limited production on a diesel passenger car sold in Europe (2.0 liter engine displacement, (12)) and a light-duty truck application sold in Japan (4.0 liter engine displacement, (11)).

3.0 FILTER MAINTENANCE PRACTICES

Typical wall-flow particulate filters like those shown in Figure 1 remove both particulate matter that is produced from the combustion of fuel in a diesel engine and assorted other inorganic materials that may be present in the engine exhaust. These assorted inorganic materials are generally referred to as "ash." Under normal filter operation, the filter collects particulate matter and periodically combusts the particulate matter during conditions that favor the oxidation of the largely carbon-based particulate (i.e., filter regeneration). The inorganic material that also collects on the filter does not completely combust into gaseous species that can exit through the filter but rather forms oxide and sulfate materials that remain in the filter. Over extended operation on the vehicle, these ash species slowly accumulate within the filter and gradually increase the pressure drop across the filter. Since excessively high backpressure on the engine will result in a degradation of engine performance, the accumulated ash material within the filter needs to be periodically removed. This ash removal or cleaning operation is a necessary filter maintenance operation. This section of the report will describe what makes up the ash species that collect in diesel particulate filters, what factors influence the rate of ash build-up in the filter, what the typical filter maintenance intervals are in current retrofit applications of wall-flow filters on heavy-duty diesel engines or wall-flow filters used on diesel passenger cars in Europe, and describe filter cleaning practices that are used today with wall-flow filters in either retrofit applications or in original equipment applications with European passenger cars.

3.1 Sources of Filter Ash

Inorganic material or ash that accumulates in a diesel particulate filter stems from three main sources. A primary source of ash is inorganic additives that are present in engine lubricants (3, 5, 18, 19). Engine oils are a complex mixture of a largely organic, refinery-derived "base stock" with an "additive package" that includes inorganic elements such as magnesium, calcium, zinc, phosphorus, and sulfur. These additives are used to impart important lubricating and stability properties to the oil. A lubricant used in heavy-duty diesel engines today in the U.S. can have a total inorganic ash content that ranges from 1.2 to 1.5 wt.%. Sulfur and calcium will generally make up the majority of the oil ash species with zinc, magnesium, and phosphorus generally found at lower levels in the oil ash. It is important to note, however, that there is a wide variation in lubricant compositions including ash constituents used in the marketplace today.

All four-stroke diesel engines consume oil as part of their normal lubrication requirements. (Note that in some applications two-stroke diesel engines are still in use. Two-stroke engines intentionally mix fuel with lubricating oils prior to combustion and generally have significantly higher oil consumption rates than four-stroke engines.) This consumed oil generally is combusted in the combustion chamber along with fuel. The products of the oil combustion process are contained in the engine exhaust gas and reach the particulate filter where the inorganic, ash constituents are collected and remain in the filter even after the organic particulate matter is removed in filter regeneration steps.

A second source of ash material comes from normal engine wear and exhaust component scale or corrosion. These ash species can contain iron, nickel, silicon, chromium, aluminum, copper, and/or tin. A third source of ash material is associated with the use of a fuel-borne catalyst. In some filter applications a fuel-borne catalyst is directly added to the fuel at relatively low levels (generally < 30 ppm in concentration) before combustion. After combustion, the inorganic catalyst species are carried by the exhaust to the filter where they collect along with the organic particulate and other inorganic ash materials. These catalytic species assist in the filter regeneration process by lowering the combustion temperature of the organic particulate below temperatures normally associated with the combustion of particulate by oxygen present in the exhaust. Like all other inorganic ash species, these inorganic fuel-borne catalysts remain on the filter and contribute to the total ash content of the filter. Fuel-borne catalyst inorganic species can include platinum, iron, and cerium (23, 25). Filter systems that do not make use of fuel-borne catalysts will not have this contributor to the ash content of the filter.

In some cases, soot and ash constituents that accumulate in a filter over time may interact and influence the combustion characteristics of the soot present in the filter. Fang and Lance (2), for example, have recently shown that phosphorus constituents of lubricants that make up some of the ash materials present in filters can form protective layers on some soot surfaces that in turn alters the combustion characteristics of soot. This ash-soot interaction can cause the soot to have a higher resistance towards oxidation and result in less complete regeneration of the filter under a given exhaust temperature history.

Recent SAE papers (27, 28) provide information on ash compositions collected from filters used without fuel-borne catalysts. Primary ash constituents included calcium oxide (CaO, 29-35 wt.%), sulfate (SO_3, 35-39 wt.%), magnesium oxide (MgO, 5-11 wt.%), phosphate (P_2O_5, 13-16 wt.%), and zinc oxide (ZnO, 5-10 wt.%), with a trace of iron oxide (Fe_2O_3, < 1%) reported in one of these references. Ash is reported to be comprised of 5-50 micron sized agglomerates of sub-micron primary particles. Particles from engine wear or corrosion of exhaust components, however, can be substantially larger than this.

In the case of applications that make use of fuel-borne catalysts, the portion of the ash stemming from the fuel-borne catalyst will depend on the composition and reactivity of the fuel-borne catalyst, the dosing rate of the fuel-borne catalyst, and the fuel and lubricant consumption characteristics of the engine (16, 20, 27, 28). For example, in the initial Peugeot passenger car DPF applications, the fuel-borne catalyst component of the ash was approximately 80% by weight of the total ash produced using a fuel-borne catalyst dosing rate of 25 ppm in the fuel (25). In the second generation Peugeot DPF system that utilized a fuel-borne catalyst dosing rate of only 10 ppm, the fuel-borne catalyst ash mass fraction was reduced to about 57% (23).

3.2 Factors that Influence Ash Accumulation

As stated above, inorganic constituents of engine lubricants are the primary source of ash material collected by wall-flow filters. Therefore, factors associated with lubricant consumption in the engine have a large impact on the rate of ash accumulation in a filter. Two primary parameters are the rate of oil consumption of a given engine and the ash content of the oil consumed by the engine. Higher rates (e.g., liters of oil per miles traveled or hours of engine operation) of oil consumption by an engine at a constant oil ash content or consumption of oil with a higher ash content will result in faster accumulation of ash in the filter and an associated faster rise in engine backpressure relative to some base case operation. Engine oil consumption rates are influenced by basic engine design, engine maintenance practices, engine duty cycles, and the service life of the engine. (Diesel engines are often "re-built" after a significant operating time. This re-build procedure can also influence engine oil consumption rates.) More recently manufacturers have introduced improved engine designs with lower engine oil consumption rates and continue to work on new engine designs with even lower oil consumption rates. Well-maintained engines can often consume less oil than engines that are poorly maintained. Engines operating over relatively low temperature, low speed duty cycles, such as some transit buses and refuse haulers, can have higher lubricant consumption rates than engines operating over duty cycles with higher operating temperatures such as highway vehicles.

Since diesel engines can have long operating lives, engines that have been in service over an extended time will generally consume more oil than low mileage or low hour usage engines due to normal engine wear. Oil consumption can also be intentionally influenced by the use of certain engine aftermarket products that deliberately add oil from an engine's oil sump to the combustion chamber while replenishing the oil reservoir with fresh lubricant, or by other procedures that mix used engine oil with fuel as part of a used oil disposal process. These procedures accelerate oil consumption by the engine and accelerate ash accumulation by the filter. Beginning in 2007, blending of oil into diesel fuel will not be allowed unless the oil sulfur content is no greater than 15 ppm (consistent with EPA's 15 ppm sulfur cap for on-road diesel fuel).

SAE paper no. 2003-01-1963 (19) reports that ash deposition profiles and filter pressure drop profiles can also be strongly influenced by the combustion of oil-doped diesel fuels, especially in the case when the oil doped into the fuel has a relatively high ash content. The use of engine lubricants with higher ash contents relative to other oil formulations will obviously result in a faster accumulation of ash material in the filter. In retrofit applications, filter manufacturers generally provide recommended maximum lubricant consumption rates as one parameter of whether an engine is an acceptable candidate for a filter retrofit – typical values can be in the range of one quart consumed per 500 to 1,000 miles of operation.

In the case of filter systems that work with the use of a fuel-borne catalyst, the dosing rate or concentration of the catalyst in the fuel will have a direct impact on the rate of ash accumulation within the filter. Since the introduction of filters using fuel-borne catalysts to assist with filter regeneration in European diesel passenger cars in mid-2000, the manufacturers of the fuel-borne catalysts used in these vehicles have been able to reduce dosage rates from 25 ppm to 8 ppm through compositional and particle size changes to the fuel-borne catalyst, as well as reduced engine-out PM emissions from continued improvements in diesel engine combustion characteristics (23). These lower fuel-borne catalyst dosage rates, in turn, reduce ash accumulation rates in the filter and help to extend the service interval of the filter without adversely impacting the regeneration characteristics of the filter. Continuing development efforts aimed at even more active fuel-borne catalysts have demonstrated the potential of further reducing dosage rates to 7 ppm (17).

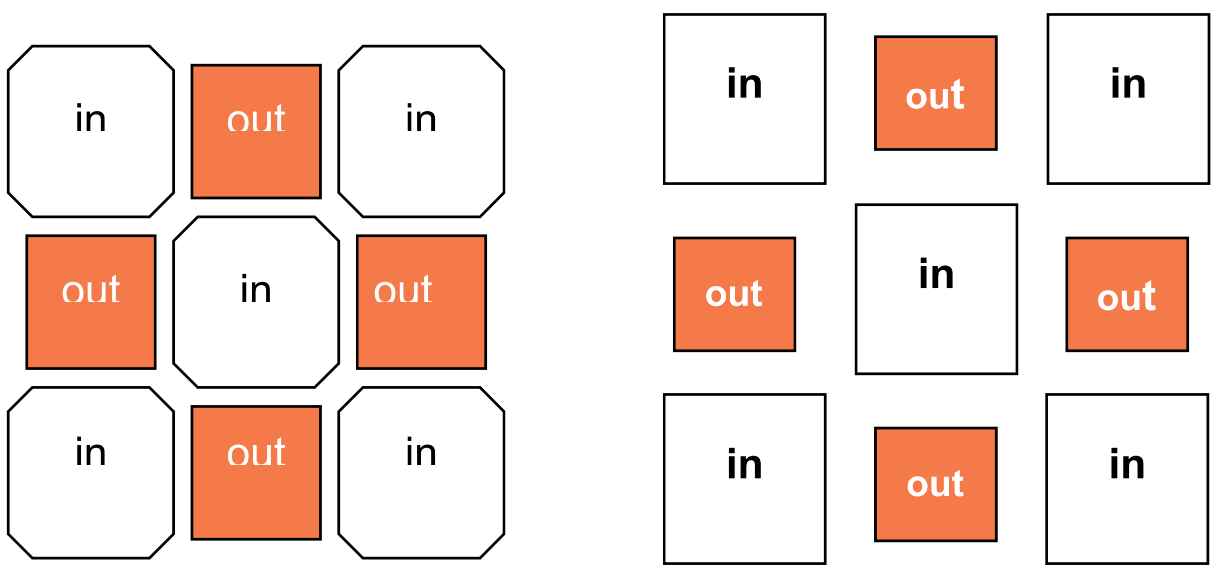
3.3 The Impact of Filter Properties on Ash Accumulation

The filter serves as a "storage tank" for ash during normal engine/vehicle operation. As this ash accumulates over time, the pressure drop through the filter increases and backpressure on the engine increases. Filter or engine manufacturers generally set a maximum backpressure limit on the engine that defines the service interval between ash removal maintenance events. These maximum backpressure criteria are based on engine performance versus backpressure characteristics. Particulate filter properties, including the total volume, length/diameter ratio of the filter, cell density, wall thickness, and the porosity of the wall that acts as the filter media on a given engine, are all important factors in defining the initial engine backpressure of the filter system. Filter substrate manufacturers have been engaged in a continuous development effort aimed at optimizing inherent filter physical properties such as wall porosity, cell density, and wall thickness to minimize filter pressure drop for applications with or without the presence of a catalytic coating on the filter (21, 32). In general, this substrate optimization process also includes other key filter properties such as mechanical strength, thermal conductivity, and thermal expansion properties. Catalyst manufacturers also have been actively involved in engineering the properties of catalyst coatings that can be applied to filter substrates to aid in backpressure reductions.

Ash storage capacity of a given filter with constant cell density and wall thickness is proportional to filter volume. Larger filter volumes will be able to accumulate more ash before reaching a set maximum engine backpressure criteria. However, the desire to maximize the filter cleaning interval is generally at odds with packaging limitations on-board the vehicle or maximum engine backpressure criteria. Filter volumes are designed to meet packaging constraints, with minimal engine backpressure, but with sufficient volume to allow for acceptable soot regeneration characteristics and an acceptable quantity of ash storage that defines the filter maintenance interval.

More recently substrate manufacturers have modified ceramic wall-flow filter designs to significantly increase ash storage capacity at a constant filter volume. This design alteration involves enlarging the inlet exhaust gas channel dimensions (6, 7). This provides additional geometric area for the ash to accumulate in the filter and expands the ash capacity of the filter by up to 50%. Figure 2 provides schematics of two alternative filter substrate designs that have been developed to increase ash storage capacity. One employs a large octagonal inlet channel

Figure 2.
Asymmetric Particulate Filter Substrate Designs with Larger Inlet Channel Cross-Sections Relative to Outlet Channel Cross-Sections



cross section and the second employs a large square inlet channel cross section relative to smaller outlet channel cross sections. Commercial application of these larger inlet channel substrate designs was initiated in 2004, with the first application (using the large octagonal inlet channel filter substrate design) launched on a new 2.7 liter V6 high pressure, common-rail diesel engine developed jointly by Peugeot and Ford for passenger car applications in Europe. The high ash capacity filter used in these applications allows the DPF to function without maintenance over the useful life of the vehicle (up to 200,000 km, or more than 120,000 miles). Additional applications of these large ash-capacity filter substrates are expected in 2005.

3.4 Filter Maintenance Intervals

Retrofit applications of wall-flow filters on heavy-duty diesel vehicles and original equipment applications of wall-flow filters on passenger cars in Europe provide information on current filter maintenance interval recommendations from manufacturers of filters or new light-duty vehicles equipped with filters. In retrofit applications on existing heavy-duty diesel highway vehicles, filter manufacturers recommend that filters be cleaned of ash after either 12 to 24 months of operation, or at mileage intervals that range from 60,000 to 100,000 miles. It should be noted that actual maintenance intervals are based on factors such as engine lubricant consumption rates, duty cycles, and actual engine/vehicle applications. Older vehicles with higher lubricant consumption rates, for example, may need maintenance intervals that are more frequent than the maintenance intervals stated above.

As a condition of filter retrofit verification requirements in the U.S., and to assist operators or fleet owners in determining when filters should be cleaned, retrofit filter manufacturers include some type of electronic diagnostic module that is installed on-board the vehicle at the time the filter is installed. This diagnostic module can provide several functions including monitoring and logging exhaust temperatures, engine backpressure, and/or filter pressure drop. Engine backpressure is typically monitored to determine when sufficient ash has accumulated in the filter to require a cleaning operation. These diagnostic modules generally include some type of display module that is mounted in the driver's compartment and alerts the operator when engine backpressure has reached a level that requires the filter to be cleaned. Backpressure threshold criteria are generally set with sufficient safety margins to ensure that excessive engine backpressure conditions are not reached under normal operations. These diagnostic modules can also alert operators to abnormal engine operating conditions that may impair normal filter operation. Backpressure monitoring capabilities for DPFs are required by both the EPA and CARB as a part of their retrofit programs.

The rather wide range of filter service intervals based on mileage or months of operation in retrofit applications are a reflection of the variety of engines, duty cycles of filter applications, and the age of existing vehicles. Retrofit filter manufacturers have established a large and growing experience base with filters in applications on buses, highway trucks, industrial vehicles, and off-road equipment that allows them to provide operators with guidelines for filter maintenance intervals along with diagnostic modules that monitor and alert operators when ash removal is required.

There are examples of recent retrofit filter applications on heavy-duty diesel highway engines that have demonstrated much longer filter maintenance intervals than the typical 60,000 – 100,000 mile recommended intervals mentioned above. In a multi-year demonstration program operating in Southern California, trucks and buses were retrofitted with catalyst-based diesel particulate filters and operated on ultra-low sulfur diesel fuel (< 15 ppm S) to assess the long-term durability of passively regenerating diesel particulate filters (13). This program included 10 Class 8 tractor-trailers used for delivery operations, a subset of which was evaluated for emission performance over a 3 ½ year period with mileage accumulations exceeding 340,000 miles for each of three test vehicles monitored by the program. Each of these tractors was powered by a 1998 model DDC Series 60 heavy-duty diesel engine (430 hp, 12.7 liters displacement). During the first 3 ½ years and 340,000+ miles of operation for each of these three test trucks, filters were cleaned of ash only once - after two years and approximately 220,000 miles of operation on each vehicle. Backpressure monitors on the test vehicles did not indicate that cleaning was required after two years of operation and the amount of ash collected from these filters was relatively small. An important contributor to the relatively low backpressure increase over time observed on these DPF-equipped vehicles is the low oil consumption characteristics observed on the engines equipped in these vehicles. Oil consumption rates on average of approximately 3 quarts per 10,000 miles of service were observed on these vehicles. These tractor-trailers equipped with retrofit filter systems continue in operation at the time this report was released. These results indicate that modern diesel engines equipped with filters and with low oil consumption characteristics are capable of extended operations between filter maintenance intervals.

In the case of new European passenger cars equipped with particulate filters, first generation systems employing fuel-borne catalysts are designed to operate for 80,000 km before filter maintenance is required. At 80,000 km, an owner is requested to bring his or her vehicle in for service at which time the filter is replaced with either an unused filter or a filter that has been cleaned of ash. Second generation systems employing lower dosage rates of fuel-borne catalysts have extended this maintenance interval to 120,000 km. Third generation systems introduced in 2004 include lower fuel-borne catalyst dosage rates with new asymmetric filter designs that employ large octagonal inlet channel cross sections, allowing service intervals to be extended up to 200,000 km (up to 120,000 miles). Recent reports of DPF designs based on the use of sintered metal sheets indicate that these designs are capable of running more than 260,000 km (more than 155,000 miles) on a 2.0 liter European diesel passenger car application employing a fuel-borne catalyst with a dosing rate of 10 ppm. First generation catalyzed DPFs available on some European diesel passenger cars (e.g., BMW, Mercedes, Renault) are currently sized to require maintenance at approximately 80,000 km intervals. The filter systems used in European passenger car applications include diagnostic capabilities to monitor exhaust temperatures, engine backpressure, and filter pressure drop with provisions to alert the driver if abnormal conditions are encountered.

Toyota and Hino recently reported on the ash accumulation characteristics of their DPNR technology that combines a NOx adsorber catalyst coating on a relatively high porosity, wall-flow ceramic filter (11). In a 4.0 liter engine used in a Japanese light-duty truck application, they found only a modest increase in pressure drop across the DPNR unit after 200,000 km (approximately 125,000 miles) of operation using available engine oil with 0.42 wt.% Ca. Analysis of the aged DPNR revealed that only about 20% of the theoretical ash amount consumed by the engine during this test deposited on the filter. The balance of the ash was assumed to be emitted in the exhaust of the vehicle. The authors speculate that the continuous PM oxidation characteristics of the DPNR system promote separation of the ash from the filter. The relatively high porosity of ceramic wall-flow filter used by Toyota in these DPNR applications may also contribute to the release of ash from the filter during normal vehicle operation.

3.5 Filter Cleaning Procedures and Equipment

Manufacturers of filter technologies have developed safe, reliable, and effective procedures for removing the ash from particulate filters. These practices have been put in place in both retrofit wall-flow filter applications and wall-flow filter-equipped passenger cars in Europe. The ash cleaning practices include well-documented procedures for cleaning filters and the development of stand-alone filter cleaning stations or facilities that automate many of the necessary procedures.

Ash cleaning procedures used in retrofit filter applications can involve the following steps:

(1) removal of the filter from the engine/vehicle; a filter weight before cleaning may be determined at this point
(2) removal of the ash with a combination of pressurized dry air gun (e.g., 50-100 psi; note that catalytically coated filters may require the use of air pressures on the lower end of this range to minimize damage to the catalytic coating. Suppliers of catalytically coated filters provide recommendations on air pressures that can be used with their coated filters.) on the exit side of the filter with an industrial vacuum device (equipped with a HEPA [high-efficiency particulate air] or ULPA [ultra-low penetration air] filter) on the filter's inlet side that includes provisions for collecting the ash. This pressurized air/vacuum treatment should direct the pressurized air flow across all channels on the filters to make sure each channel is cleaned of ash. Total time for air cleaning will depend on the size of the filter but is typically 30-50 minutes for a filter sized for a heavy-duty highway engine. In some cases specially designed pulsed-air equipment is used to do this air cleaning procedure.
(3) inspection of the cleaned filter by probing individual channels, and/or weight or flow characteristics (e.g., filter pressure drop measurements using ambient temperature airflows) to confirm that the cleaning has been successful
(4) re-installation of the filter on the engine/vehicle

Modifications to the procedure described above include the addition of a filter baking/heating step either before or after the air cleaning procedure described in (2) above. A typical filter baking/heating step includes placing the filter in an industrial oven or a stand-alone cleaning unit that includes a heating element to burn off any organic soot remaining on the filter. Baking temperatures may vary between 450 and 800^{o}C with total baking times (heat-up, hold, and cool-down) varying between 3 and 12 hours. These relatively long baking schedules include very controlled heat-up and cool-down schedules to minimize thermal stresses that may occur in the filter due to the release of heat associated with the oxidation of any remaining soot. If the baking step is done after an air cleaning procedure, an additional air cleaning procedure may be done on the filter following the baking procedure to remove ash still remaining in the filter. The heating strategy in some cases has been found to improve the ash collection process, but acceptable levels of ash removal have also been demonstrated by procedures that only use pressurized air or pressurized air in combinations with vacuum. In some cases a brief 5-10 minute treatment with pressurized air on the outlet side of the filter is recommended prior to the baking step. In all cases any pressurized air/vacuum treatments must be done using an acceptable dust collection strategy to prevent entry into the local environment and exposure of the maintenance technicians to the dust associated with the ash. Technicians employed to conduct ash cleaning procedures need to wear appropriate eye protection, dust masks, and appropriate gloves.

A number of filter system manufacturers offer automated or semi-automated machines or stand alone workstations for filter cleaning operations. These stations or machines include provisions for pressurized air streams, vacuum collection, and/or heating of filters. In some cases these cleaning devices are relatively portable to allow for filter cleaning at any convenient location with available utilities. A picture of a stand-alone filter cleaning system is shown in Figure 3.

Figure 3.
Diesel Particulate Filter Cleaning Unit

Additionally, a number of companies, including engine/vehicle original equipment dealers and distributors, are offering cleaning services to end-users who either do not have an interest in establishing their own cleaning capabilities or do not have the internal resources to establish a filter cleaning capability. These filter cleaning service providers offer a variety of service options including on-site cleaning and reinstallation of the filter at a customer's facility or “swap and clean” programs that substitute a clean filter element for an ash-containing filter, with subsequent cleaning of the ash-containing filter.

In Europe, where significant numbers of diesel passenger cars have been sold equipped with particulate filters, a complete centralized filter cleaning facility has been built by the exhaust component company that supplies uncatalyzed, filter-containing exhaust systems to the auto manufacturers (33). This facility allows for multiple filters to be cleaned in parallel for a relatively high throughput of filters per day (up to 1,000 DPFs per day). This operation features a filter cleaning procedure based on a washing protocol that utilizes warm water with detergent. This facility has been commissioned in stages based on wastewater recycling capacity with the first stage limited to 100 filters per day and the current second stage capacity limited to 250 filters per day. Through 2003 this facility had cleaned about 2000 filters.

In this European facility, operational cleaning steps include: (1) visual inspection and weighing of incoming filter elements, (2) regeneration of the filter with hot air to burn off any organic-based particulate matter retained on the filter, (3) weighing the regenerated filter, (4) a cleaning procedure that alternates flowing warm water (with detergent) and pulsed air flow through the filter walls to remove accumulated ash, (5) a drying step using warm, dry air, and (6) a final weight check and inspection steps including inspection of the filter using an endoscope. The regeneration step is monitored with backpressure measurements and on-line measurement of the exhaust gas that exits the filter. This filter cleaning facility also includes provisions for the treatment and recycling of the wash water used to clean filters before the wash water is returned to the local sewer system. Recovered ash materials are treated as a special industrial waste and disposed of in specific dedicated landfill sites. This cleaning process is ISO 14001 certified.

To date water-based filter cleaning procedures have only been used on uncatalyzed filter systems that make use of filter canning systems that have mounting materials compatible with the water cleaning operation. Some ceramic filter substrate mounting materials, such as intumescent-based mats (mats that contain vermiculite components that expand when heated), deteriorate when exposed to water and should not be cleaned using water. Deterioration of the mat mounting material can lead to permanent damage and failure of the filter in service. Similarly, catalyzed filter elements should not be water cleaned due to the potential for degradation or damage to the catalyst coating present on the filter element.

The use of excessive air pressures (above 100 psi) to clean catalyzed filters of ash should also be avoided since high cleaning pressures may damage or remove the catalyst coating from the filter substrate. Recommendations from suppliers of catalyzed filters regarding maximum air pressures used in filter cleaning procedures should be followed in all cases.

Filter baking/regeneration temperatures associated with ash cleaning above 850^{o}C are generally not recommended due to high temperature sintering reactions that occur within the stored ash or the potential for high temperature reactions between the stored ash and the ceramic filter substrate or catalyst coating. These high temperature solid-state reactions can result in an ash structure that is difficult to remove or the potential for damage to the substrate or catalyst coating.

Available filter cleaning machines are generally based on pressurized air/vacuum cleaning procedures described above since this procedure is compatible with both intumescent and non-intumescent filter mounting materials. Steam cleaning is not practical for ash removal on any filter systems due to the potential for forming cement-like species from unremoved ash. In all situations associated with filter maintenance procedures, filter elements need to be handled with care to avoid damage to the filters. In the case of filters used on heavy-duty engines, these filters can be large in size and weight and technicians must use appropriate safety procedures to minimize personal risks and damage to the filters.

Published studies of recommended ash cleaning procedures generally report that filter pressure drop is returned to acceptable levels but generally not equivalent to an unused filter (14). In the retrofit application of filters, filter manufacturers provide end users with training courses and complete documentation describing recommended filter cleaning practices and/or operation of specified filter cleaning equipment.

As detailed in Section 3.1, the ash collected from filter cleaning procedures consists primarily of oxides and sulfates of inorganic materials associated with lubricant additives and exhaust system corrosion. Disposal practices for ash collected from filters are determined by local and/or state environmental regulations. A compositional analysis of representative collected ash may be necessary to determine legal disposal practices. In some jurisdictions ash may be classified as a hazardous waste and can only be placed in landfill sites designated for hazardous waste. In general, states and/or local jurisdictions have landfills available that will accept collected filter ash, but end users need to consult with state and/or local environmental agencies to determine acceptable disposal methods.

Currently, laws are inconsistent regarding how to classify ash from particulate filters. In the State of New York, the New York State Department of Environmental Conservation (NYSDEC) provided information to NESCAUM (Northeast States for Coordinated Air Use Management, an organization representing state air quality officials in the Northeast U.S.) in a letter dated October 11, 2001 concerning the classification of ash waste associated with particulate filters. In this letter, NYSDEC indicated that both New York state law [NYCRR 371.1(e)(2)(iv)] and federal law [40 CFR 261.4(b)(4)] exclude residues from the burning of fossil fuels from being classified as a hazardous waste. Without this hazardous waste designation, NYSDEC indicated to NESCAUM that ash should be treated as a solid waste.

In California, laws may vary depending on location. For that reason, a statement is included in owners manuals of California-verified filters that ash disposal must be in accordance with all applicable Federal, state, and local laws governing waste disposal. In California, if zinc is present in the ash collected from a filter in high concentrations, it can make this material a hazardous waste. The California Code of Regulations (Title 22, section 66261.4) establishes two limits for zinc in waste: 250 milligrams per liter for the soluble threshold limit concentration, and 5,000 milligrams per kilogram for the total threshold limit concentration. The presence of zinc at or above these levels would cause an ash material to be characterized as a hazardous waste in California. Under California law, the generator of the waste has the responsibility to determine whether their waste is hazardous or not. This, in general, would require a chemical analysis of the collected ash sample to determine the zinc content. There are facilities in California that accept hazardous waste from conditionally exempt small quantity generators. Additional guidance concerning acceptable disposable methods of ash collected from filters in California is available from the California Department of Toxic Substances Control.

Diesel fuel ash is not listed as a hazardous waste by EPA in the Code of Federal Regulations (40 CFR Part 261). Federal regulations also conditionally exempt small quantity generators that generate less than 220 lbs. per month of solid waste from federal hazardous waste regulations. Additional information concerning federal hazardous waste requirements are available from the EPA Office of Solid Waste (OSW) by either calling their Resource Conservation and Recovery Act (RCRA) hotline at 703-412-9810 or 800-424-9346, or by visiting the following website: www.epa.gov/epaoswer/general/orientat/. The EPA also provides information about state contacts regarding solid and hazardous waste disposal issues at: www.epa.gov/epaoswer/osw/stateweb.htm.

It is also important to note that the amount of ash collected from a filter during a typical cleaning procedure is relatively small. For example, ARB reports that the amount of material collected from a single filter in a single cleaning procedure is in the range of 10-20 grams of ash. ARB extrapolated this ash collection amount to 10-20 kg of ash collected per year for a fleet of 1000 transit buses. Actual amounts of ash collected from a filter during a cleaning procedure will vary depending on variables including the oil consumption rate of the engine. Ash disposal costs will depend on the quantity of ash disposed of at any given time as well as local/state regulations covering ash disposal.

MECA believes that uniform ash disposal regulations are needed nationwide before 2007 to avoid confusion in the marketplace concerning ash disposal practices. MECA encourages federal, state, and local agencies to communicate on this topic and reach a common position on accepted safe disposal practices for ash collected from filters. EPA is expected to issue their own fact sheet concerning filter maintenance procedures sometime in 2005. This fact sheet will be posted on the EPA Office of Transportation and Air Quality (OTAQ) website (www.epa.gov/otaq).

4.0 U.S. 2007 HEAVY-DUTY DIESEL FILTER MAINTENANCE

The first large-scale application of diesel particulate filters in the U.S. on new vehicles will occur starting in 2007 for heavy-duty diesel engines used in highway trucks and buses. All heavy-duty engine manufacturers have indicated their intent to use diesel particulate filters to comply with the U.S. EPA's 2007 PM emission regulation of 0.01 g PM/bhp-hr. This 2007 introduction of filters on new highway heavy-duty diesel vehicles will encompass close to one million vehicles annually for vehicle weight classes above 8500 lb. GVW. EPA stipulates a 150,000 mile minimum maintenance interval for any emission control device, including particulate filters, used in the heaviest weight class of heavy-duty vehicles. This means that manufacturers will need to design filter systems that are capable of operating a minimum of 150,000 miles between ash removal procedures for these so-called heavy, heavy-duty vehicles.

In public forums to date, the engine manufacturers have indicated that complying with this minimum filter maintenance interval is part of their development plan for 2007 engines.

Several factors will contribute to the success in meeting this requirement. These include engine designs with inherently low and stable oil consumption characteristics, sufficient filter ash capacity to allow for long maintenance intervals, and reformulated lubricants that have lower ash content than lubricants currently in use today. Filter ash capacity may include the use of asymmetric filter designs like those shown in Figure 2, with larger inlet channel cross sections for increased ash storage capacity.

The lubricant industry is currently finalizing the specifications for the next generation lubricants that will be used by 2007 and later heavy-duty diesel engines. This 2007 PC-10 lubricant category will likely limit lubricant ash content to 1.0 wt.% relative to the current 1.5 wt.% ash limit for current heavy-duty lubricants to help extend filter maintenance intervals. SAE paper no. 2003-01-3109 describes some of the on-going efforts to develop new lubricant formulations designed for use in diesel engines using DPFs or other advanced diesel engine emission control technologies.

As demonstrated by the extended filter maintenance intervals reported by long haul tractor trailers evaluated in the BP-ARCO program (13), the 150,000 mile maintenance interval should be met by 2007 engines used in similar applications. Other applications such as transit buses or refuse haulers, where vehicles operate for many hours but accumulate miles at a relatively low rate, may present a challenge in complying with EPA's 150,000 mile minimum maintenance interval. The emissions control industry is committed to work with their customers in the engine manufacturing industry to make the 150,000 mile filter maintenance interval a reality for as wide an application base on new heavy-duty diesel engines as possible.

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