

improvements in fuel efficiency concurrent with reductions in PM emissions. Improvements in combustion technologies and refinements of these systems is an ongoing effort for highway engines and for some nonroad engines where emission standards or high fuel use encourage their introduction. The application of better combustion system technologies across the broad range of nonroad engines in order to meet the new emission standards proposed here offers an opportunity for significant reductions in engine-out PM emissions and possibly for reductions in fuel consumption. The soot portion of PM can be reduced further with aftertreatment technologies as discussed later in this section.

The volatile and semi-volatile organic material in diesel PM is often simply referred to as the soluble organic fraction (SOF) in reference to a test method used to measure its level. SOF is primarily composed of engine oil which passes through the engine with no or only partial oxidation and which condenses in the atmosphere to form PM. The SOF portion of diesel PM can be reduced through reductions in engine oil consumption and through oxidation of the SOF catalytically in the exhaust.

The sulfate portion of diesel PM is formed from sulfur present in diesel fuel and engine lubricating oil that oxidizes to form sulfuric acid (H_2SO_4) and then condenses in the atmosphere to form sulfate PM. Approximately two percent of the sulfur that enters a diesel engine from the fuel is emitted directly from the engine as sulfate PM.¹³¹ The balance of the sulfur content is emitted from the engine as SO_2 . Oxidation catalyst technologies applied to control the SOF and soot portions of diesel PM can inadvertently oxidize SO_2 in the exhaust to form sulfate PM. The oxidation of SO_2 by oxidation catalysts to form sulfate PM is often called sulfate make. Without low sulfur diesel fuel, oxidation catalyst technology to control diesel PM is limited by the formation of sulfate PM in the exhaust as discussed in more detail in Section III.F below.

There are two common forms of exhaust aftertreatment designed to reduce diesel PM, the diesel oxidation catalyst (DOC) and the diesel particulate filter (DPF). DOCs reduce diesel PM by oxidizing a small fraction of the soot emissions and a significant portion of the SOF emissions. Total DOC effectiveness to reduce PM emissions is normally limited to approximately 30

percent because the SOF portion of diesel PM for modern diesel engines is typically less than 30 percent and because the DOC increases sulfate emissions reducing the overall effectiveness of the catalyst. Limiting fuel sulfur levels to 15 ppm, as we have proposed today, allows DOCs to be designed for maximum effectiveness (nearly 100% control of SOF with highly active catalyst technologies) since their control effectiveness is not reduced by sulfate make (*i.e.*, there sulfate make rate is high but because the sulfur level in the fuel is low the resulting PM emissions are well controlled). A reduction in diesel fuel sulfur to 500 ppm as we are proposing today, is also directionally helpful for the application of DOCs. While 500 ppm sulfur fuel will not make the full range of highly active catalyst technologies available to manufacturers, it will decrease the amount of sulfate make and may allow for slightly more active (*i.e.*, effective) catalysts to be used. We believe that this is an additional benefit of the proposed 500 ppm sulfur fuel program. DOCs are also very effective at reducing the air toxic emissions from diesel engines. Test data shows that emissions of toxics such as polycyclic aromatic hydrocarbons (PAHs) can be reduced by more than 80 percent with a DOC.¹³² DOCs also significantly reduce (by more than 80 percent) the already low HC and CO emissions of diesel engines.¹³³ DOCs are ineffective at controlling the solid carbon soot portion of PM. Therefore, even with 15 ppm sulfur fuel DOCs would not be able to achieve the level of PM control needed to meet the standard proposed today.

DPFs control diesel PM by capturing the soot portion of PM in a filter media, typically a ceramic wall flow substrate, and then by oxidizing (burning) it in the oxygen-rich atmosphere of diesel exhaust. The SOF portion of diesel PM can be controlled through the addition of catalytic materials to the DPF to form a catalyzed diesel particulate filter (CDPF).¹³⁴ The catalytic material is also very effective to promote soot burning.

This burning off of collected PM is referred to as "regeneration." In aggregate over an extended period of operation, the PM must be regenerated at a rate equal to or greater than its accumulation rate, or the DPF will clog. For a non-catalyzed DPF the soot can regenerate only at very high temperatures, in excess of 600°C, a temperature range which is infrequently realized in normal diesel engine operation (for many engines exhaust temperatures may never reach 600°C). With the addition of a catalytic coating to make a CDPF, the temperature necessary to ensure regeneration is decreased significantly to approximately 250°C, a temperature within the normal operating range for most diesel engines.¹³⁵

However, the catalytic materials that most effectively promote soot and SOF oxidation are significantly impacted by sulfur in diesel fuel. Sulfur both degrades catalyst oxidation efficiency (*i.e.* poisons the catalyst) and forms sulfate PM. Both catalyst poisoning by sulfur and increases in PM emissions due to sulfate make influence our decision to limit the sulfur level of diesel fuel to 15 ppm as discussed in greater detail in section III.F.

Filter regeneration is affected by catalytic materials used to promote oxidation, sulfur in diesel fuel, engine-out soot rates, and exhaust temperatures. At higher exhaust temperatures soot oxidation occurs at a higher rate. Catalytic materials accelerate soot oxidation at a single exhaust temperature compared to non-catalyst DPFs, but even with catalytic materials increasing the exhaust temperature further accelerates soot oxidation.

Having applied 15 ppm sulfur diesel fuel and the best catalyst technology to promote low temperature oxidation (regeneration), the regeneration balance of soot oxidation equal to or greater than soot accumulation over aggregate operation simplifies to: are the exhaust temperatures high enough on aggregate to oxidize the engine-out PM rate?¹³⁶ The answer is yes, for most highway applications and many nonroad applications, as demonstrated by the widespread success of retrofit CDPF systems for nonroad equipment and the

¹³² "Demonstration of Advanced Emission Control Technologies Enabling Diesel-Powered Heavy-Duty Engines to Achieve Low Emission Levels", Manufacturers of Emission Controls Association, June 1999. Air Docket A-2001-28.

¹³³ "Demonstration of Advanced Emission Control Technologies Enabling Diesel-Powered Heavy-Duty Engines to Achieve Low Emission Levels", Manufacturers of Emission Controls Association, June 1999. Air Docket A-2001-28.

¹³⁴ With regard to gaseous emissions such as NMHCs and CO, the CDPF works in the same manner with similar effectiveness as the DOC (*i.e.*, NMHC and CO emissions are reduced by more than 80 percent).

¹³⁵ Engelhard DPX catalyzed diesel particulate filter retrofit verification, www.epa.gov/otaq/retrofit/techlist-engelhard.htm, a copy of this information is available in Air Docket A-2001-28.

¹³⁶ If the question was asked, "without 15 ppm sulfur fuel and the best catalyst technology, are the exhaust temperatures high enough on aggregate to oxidize the engine-out PM rate?" the answer would be no, for all but a very few nonroad or highway diesel engines.

¹³¹ Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling—Compression-Ignition, EPA420-P-02-016, NR-009B. Copy available in EPA Air Docket A-2001-28.