

ensuring robust regeneration and high SOF oxidation; however, it can also oxidize the sulfate in the exhaust with high efficiency. The result is that the predominant form of PM emissions from CDPF equipped diesel engines is sulfate PM. Even with 15ppm sulfur diesel fuel a CDPF equipped diesel engine can have total PM emissions including sulfate emissions as high as 0.009 g/bhp-hr over some representative operating cycles using conventional diesel engine oils.<sup>147</sup> Although this level of emissions will allow for compliance with our proposed PM emissions standard of 0.01 g/bhp-hr, we believe that there is room for reductions from this level in order to provide engine manufacturers with additional compliance margin. During our 2002 Highway Progress Review, we learned that a number of engine lubricating oil companies are working to reduce the sulfur content in engine lubricating oils. Any reduction in the sulfur level of engine lubricating oils will be beneficial. Similarly, as discussed above, we expect engine manufacturers to reduce engine oil consumption in order to reduce SOF emissions and secondarily to reduce sulfate PM emissions. While we believe that sulfate PM emissions will be the single largest source of the total PM from diesel engines, we believe with the combination of technology, and the appropriate control of engine-out PM, that sulfate and total PM emissions will be low enough to allow compliance with a 0.01 g/bhp-hr standard, except in the case of small engines with higher fuel consumption rates as described later in this section.

CDPFs have been shown to be very effective at reducing PM mass by reducing dramatically the soot and SOF portions of diesel PM. In addition, recent data show that they are also very effective at reducing the overall number of emitted particles when operated on low sulfur fuel. Hawker, *et al.*, found that a CDPF reduced particle count by over 95 percent, including some of the smallest measurable particles (< 50 nm), at most of the tested conditions. The lowest observed efficiency in reducing particle number was 86 percent. No generation of particles by the CDPF was observed under any tested conditions.<sup>148</sup> Kittelson, *et al.*, confirmed that ultrafine particles can be reduced by a factor of ten by oxidizing volatile organics, and by an additional factor of ten by reducing sulfur in the

fuel. Catalyzed PM traps efficiently oxidize nearly all of the volatile organic PM precursors (*i.e.* SOF), and the reduction of diesel fuel sulfur levels to 15ppm or less will substantially reduce the number of ultrafine PM emitted from diesel engines. The combination of CDPFs with low sulfur fuel is expected to result in very large reductions in both PM mass and the number of ultrafine particles.

As described here, the range of technologies available to reduce PM emissions is broad, extending from improvements to existing combustion system technologies to oxidation catalyst technologies to complete CDPF systems. The CDPF technology along with 15ppm or less sulfur diesel fuel is the system that we believe will allow engine manufacturers to comply with the 0.01 g/bhp-hr PM standard that we have proposed for a wide range of nonroad diesel engines. While it may be possible to apply CDPFs across the full range of nonroad diesel engine sizes, the complexity of full diesel particulate filter systems makes application to the smallest range of diesel engines difficult to accurately forecast at this time. As described in the following sections, the Agency has given consideration to the engineering complexity, cost and packaging of these systems in setting emission standards for various nonroad engine power categories.

#### b. NO<sub>x</sub> Control Technologies

Oxides of nitrogen (NO and NO<sub>2</sub>, collectively called NO<sub>x</sub>) are formed at high temperatures during the combustion process from nitrogen and oxygen present in the intake air. The NO<sub>x</sub> formation rate is exponentially related to peak cylinder temperatures and is also strongly related to nitrogen and oxygen content (partial pressures). NO<sub>x</sub> control technologies for diesel engines have focused on reducing emissions by lowering the peak cylinder temperatures and by decreasing the oxygen content of the intake air. A number of technologies have been developed to accomplish these objectives including fuel injection timing retard, fuel injection rate control, charge air cooling, exhaust gas recirculation (EGR) and cooled EGR. The use of these technologies can result in significant reductions in NO<sub>x</sub> emissions, but are limited due to practical and physical constraints of heterogeneous diesel combustion.<sup>149</sup> 150

EPA is investigating strategies to address these limitations of heterogeneous diesel combustion in a research program. This concept consists of higher intake charge boost levels using a low-pressure loop cooled EGR system, combined with a proprietary fuel injection and combustion system to control engine-out NO<sub>x</sub>.<sup>151</sup> The results from prototype laboratory research engines show NO<sub>x</sub> control consistent with the standards proposed today. The technology must still overcome the limitations of increased PM emissions at low NO<sub>x</sub> levels as well as other practical considerations of performance and durability. EPA intends to continue investigating this technology, but at this time cannot project that this technology would be generally available for use in compliance with the proposed standards.

A new form of diesel engine combustion, commonly referred to as homogeneous diesel combustion or premixed diesel combustion, can give very low NO<sub>x</sub> emissions over a limited range of diesel engine operation. In the regions of diesel engine operation over which this combustion technology is feasible (light load conditions), NO<sub>x</sub> emissions can be reduced enough to comply with the 0.3 g/bhp-hr NO<sub>x</sub> emission standard that we have proposed today.<sup>152</sup> Some engine manufacturers are today producing engines which utilize this technology over a narrow range of engine operation.<sup>153</sup> Unfortunately, it is not possible today to apply this technology over the full range of diesel engine operation. We do believe that more engine manufacturers will utilize this alternative combustion approach in the limited range over which it is effective, but will have to rely on conventional heterogeneous diesel combustion for the bulk of engine operation. Therefore, we believe that catalytic NO<sub>x</sub> emission control technologies will be required in order to realize the NO<sub>x</sub> emission standards proposed today. Catalytic emission control technologies can extend the reduction of NO<sub>x</sub> emissions

<sup>150</sup> Dickey, D. *et al.*, "NO<sub>x</sub> Control in Heavy-Duty Diesel Engines—What is the Limit?," SAE 980174, February 1998.

<sup>151</sup> Gray, Charles "Assessing New Diesel Technologies," November 2002, MIT Light Duty Diesel Workshop, available on MIT's website or in Air Docket A-2001-28. [http://web.mit.edu/chrisng/www/dieselworkshop\\_files/Charles%20Gray.PDF](http://web.mit.edu/chrisng/www/dieselworkshop_files/Charles%20Gray.PDF).

<sup>152</sup> Stanglmaier, Rudolf and Roberts, Charles "Homogenous Charge Compression Ignition (HCCI): Benefits, Compromises, and Future Engine Applications". SAE 1999-01-3682.

<sup>153</sup> Kimura, Shuji, *et al.*, "Ultra-Clean Combustion Technology Combining a Low-Temperature and Premixed Combustion Concept for Meeting Future Emission Standards", SAE 2001-01-0200.

<sup>147</sup> See Table III.F.1 below.

<sup>148</sup> Hawker, P., *et al.*, Effect of a Continuously Regenerating Diesel Particulate Filter on Non-Regulated Emissions and Particle Size Distribution, SAE 980189.

<sup>149</sup> Flynn, P. *et al.*, "Minimum Engine Flame Temperature Impacts on Diesel and Spark-Ignition Engine NO<sub>x</sub> Production," SAE 2000-01-1177, March 2000.