

tests helps to clarify the need for low sulfur diesel fuel. In Sweden and some European city centers where below 10 ppm diesel fuel sulfur is readily available, more than 3,000 catalyzed diesel particulate filters have been introduced into retrofit applications without a single failure. Given the large number of vehicles participating in these test programs, the diversity of the vehicle applications which included intercity trains, airport buses, mail trucks, city buses and garbage trucks, and the extended time periods of operation (some vehicles have been operating with traps for more than 5 years and in excess of 300,000 miles<sup>218</sup>, there is a strong indication of the robustness of this technology on 10 ppm low sulfur diesel fuel. The field experience in areas where sulfur is capped at 50 ppm has been less definitive. In regions without extended periods of cold ambient conditions, such as the United Kingdom, field tests on 50 ppm cap low sulfur fuel have also been positive, matching the durability at 10 ppm, although sulfate PM emissions are much higher. However, field tests on 50 ppm fuel in Finland, where colder winter conditions are sometimes encountered (similar to many parts of the United States), showed a significant number of failures (10 percent) due to trap plugging. This 10 percent failure rate has been attributed to insufficient trap regeneration due to fuel sulfur in combination with low ambient temperatures.<sup>219</sup> Other possible reasons for the high failure rate in Finland when contrasted with the Swedish experience appear to be unlikely. The Finnish and Swedish fleets were substantially similar, with both fleets consisting of transit buses powered by Volvo and Scania engines in the 10 to 11 liter range. Further, the buses were operated in city areas and none of the vehicles were operated in northern extremes such as north of the Arctic Circle.<sup>220</sup> Given that the fleets in Sweden and Finland were substantially similar, and given that ambient conditions in Sweden are expected to be similar to those in Finland, we believe that the increased failure rates noted here are due to the higher fuel sulfur level in a

50 ppm cap fuel versus a 10 ppm cap fuel.<sup>221</sup>

Testing on an even higher fuel sulfur level of 200 ppm was conducted in Denmark on a fleet of 9 vehicles. In less than six months all of the vehicles in the Danish fleet had failed due to trap plugging.<sup>222</sup> The failure of some fraction of the traps to regenerate when operated on fuel with sulfur caps of 50 ppm and 200 ppm is believed to be primarily due to inhibition of the NO to NO<sub>2</sub> conversion as described here. Similarly the increasing frequency of failure with higher fuel sulfur levels is believed to be due to the further suppression of NO<sub>2</sub> formation when higher sulfur level diesel fuel is used. Since this loss in regeneration effectiveness is due to sulfur poisoning of the catalyst this real world experience would be expected to apply equally well to nonroad engines (*i.e.*, operation on lower sulfur diesel fuel, 15 ppm versus 50 ppm, will increase regeneration robustness).

As shown above, sulfur in diesel fuel inhibits NO oxidation leading to increased exhaust backpressure and reduced fuel economy. Therefore, we believe that, in order to ensure reliable and economical operation over a wide range of expected operating conditions, nonroad diesel fuel sulfur levels should be at or below 15 ppm.

#### b. Loss of PM Control Effectiveness

In addition to inhibiting the oxidation of NO to NO<sub>2</sub>, the sulfur dioxide (SO<sub>2</sub>) in the exhaust stream is itself oxidized to sulfur trioxide (SO<sub>3</sub>) at very high conversion efficiencies by the precious metals in the catalyzed particulate filters. The SO<sub>3</sub> serves as a precursor to the formation of hydrated sulfuric acid (H<sub>2</sub>SO<sub>4</sub>+H<sub>2</sub>O), or sulfate PM, as the exhaust leaves the vehicle tailpipe. Virtually all of the SO<sub>3</sub> is converted to sulfate under dilute exhaust conditions in the atmosphere as well in the dilution tunnel used in heavy-duty engine testing. Since virtually all sulfur present in diesel fuel is converted to SO<sub>2</sub>, the precursor to SO<sub>3</sub>, as part of the combustion process, the total sulfate PM is directly proportional to the amount of sulfur present in diesel fuel. Therefore,

even though diesel particulate filters are very effective at trapping the carbon and the SOF portions of the total PM, the overall PM reduction efficiency of catalyzed diesel particulate filters drops off rapidly with increasing sulfur levels due to the formation of sulfate PM downstream of the CDPF.

SO<sub>2</sub> oxidation is promoted across a catalyst in a manner very similar to the oxidation of NO, except it is converted at higher rates, with peak conversion rates in excess of 50 percent. The SO<sub>2</sub> oxidation rate for a platinum based oxidation catalyst typical of the type which might be used in conjunction with, or as a washcoat on, a CDPF can vary significantly with exhaust temperature. At the low temperatures the oxidation rate is relatively low, perhaps no higher than ten percent. However at the higher temperatures that might be more typical of agricultural tractor use pulling a plow and the highway Supplemental Emission Test (also called the EURO III or 13 mode test), the oxidation rate may increase to 50 percent or more. These high levels of sulfate make across the catalyst are in contrast to the very low SO<sub>2</sub> oxidation rate typical of diesel exhaust (typically less than 2 percent). This variation in expected diesel exhaust temperatures means that there will be a corresponding range of sulfate production expected across a CDPF.

The U.S. Department of Energy in cooperation with industry conducted a study entitled DECSE to provide insight into the relationship between advanced emission control technologies and diesel fuel sulfur levels. Interim report number four of this program gives the total particulate matter emissions from a heavy-duty diesel engine operated with a diesel particulate filter on several different fuel sulfur levels. A straight line fit through this data is presented in Table III.F-1 below showing the expected total direct PM emissions from a diesel engine on the supplemental emission test cycle.<sup>223</sup> The SET test cycle, a 13 mode steady-state cycle, that this data was developed on is similar to the C1 eight mode steady-state nonroad test cycle. Both cycles include operation at full and intermediate load points at approximately rated speed conditions and torque peak speed conditions. As a

<sup>218</sup> Allansson, *et al.*, "European Experience of High Mileage Durability of Continuously Regenerating Filter Technology," SAE 2000-01-0480.

<sup>219</sup> Letter from Dr. Barry Cooper, Johnson Matthey, to Don Kopinski, U.S. EPA. Copy available in EPA Air Docket A-2001-28.

<sup>220</sup> Telephone conversation between Dr. Barry Cooper, Johnson Matthey, and Todd Sherwood, EPA, Air Docket A-99-06.

<sup>221</sup> The average temperature in Helsinki, Finland, for the month of January is 21°F. The average temperature in Stockholm, Sweden, for the month of January is 26°F. The average temperature at the University of Michigan in Ann Arbor, Michigan, for the month of January is 24°F. The temperatures reported here are from [www.worldclimate.com](http://www.worldclimate.com) based upon the Global Historical Climatology Network (GHCN) produced jointly by the National Climatic Data Center and Carbon Dioxide Information Analysis Center at Oak Ridge National Laboratory (ORNL).

<sup>222</sup> Letter from Dr. Barry Cooper to Don Kopinski U.S. EPA. Copy available in EPA Air Docket A-2001-28.

<sup>223</sup> Note that direct emissions are those pollutants emitted directly from the engine or from the tailpipe depending on the context in which the term is used, and indirect emissions are those pollutants formed in the atmosphere through chemical reactions between direct emissions and other atmospheric constituents.