

by an additional 90 percent or more over conventional "engine-out" control technologies alone.

NO<sub>x</sub> emissions from gasoline-powered vehicles are controlled to extremely low levels through the use of the three-way catalyst technology first introduced in the 1970s. Three-way-catalyst technology is very efficient in the stoichiometric conditions found in the exhaust of properly controlled gasoline-powered vehicles. Today, an advancement upon this well-developed three-way catalyst technology, the NO<sub>x</sub> adsorber, has shown that it too can make possible extremely low NO<sub>x</sub> emissions from lean-burn engines such as diesel engines.<sup>154</sup> The potential of the NO<sub>x</sub> adsorber catalyst is limited only by its need for careful integration with the engine and engine control system (as was done for three-way catalyst equipped passenger cars in the 1980s and 1990s) and by poisoning of the catalyst from sulfur in the fuel. The Agency set stringent new NO<sub>x</sub> standards for highway diesel engines beginning in 2007 predicated upon the use of the NO<sub>x</sub> adsorber catalyst enabled by significant reductions in fuel sulfur levels (15 ppm sulfur or less). In today's action, we are proposing similarly stringent NO<sub>x</sub> emission standards for nonroad engines again using technology enabled by a reduction in fuel sulfur levels.

NO<sub>x</sub> adsorbers work to control NO<sub>x</sub> emissions by storing NO<sub>x</sub> on the surface of the catalyst during the lean engine operation typical of diesel engines. The adsorber then undergoes subsequent brief rich regeneration events where the NO<sub>x</sub> is released and reduced across precious metal catalysts. The NO<sub>x</sub> storage period can be as short as 15 seconds and as long as 10 minutes depending upon engine-out NO<sub>x</sub> emission rates and exhaust temperature. A number of methods have been developed to accomplish the necessary brief rich exhaust conditions necessary to regenerate the NO<sub>x</sub> adsorber technology including late-cycle fuel injection, also called post injection, in exhaust fuel injection, and dual bed technologies with off-line regeneration.<sup>155 156 157</sup> This method for

NO<sub>x</sub> control has been shown to be highly effective when applied to diesel engines but has a number of technical challenges associated with it. Primary among these is sulfur poisoning of the catalyst as described in section III.F below. In the HD2007 RIA we identified four issues related to NO<sub>x</sub> adsorber performance: performance of the catalyst across a broad range of exhaust temperatures, thermal durability of the catalyst when regenerated to remove sulfur (desulfated), management of sulfur poisoning, and system integration on a vehicle. In the HD 2007 RIA, we provided a description of the technology paths that we believed manufacturers would use to address these challenges. We are conducting an ongoing review of industry's progress to overcome these challenges and have updated our analysis of the progress to address these issues in the draft RIA associated with today's NPRM.

One of the areas that we have identified as needing improvement for the NO<sub>x</sub> adsorber catalyst is performance at low and high exhaust temperatures. NO<sub>x</sub> adsorber performance is limited at very high temperatures (due to thermal release of NO<sub>x</sub> under lean conditions) and very low temperatures (due to poor catalytic activity for NO oxidation under lean conditions and low activity for NO<sub>x</sub> reduction under rich conditions) as described extensively in the draft RIA. Our review of highway HD2007 technologies showed that significant progress has been made to broaden the temperature range of effective NO<sub>x</sub> control of the NO<sub>x</sub> adsorber catalysts (the temperature "window" of the catalyst). Every catalyst development company that we visited was able to show us new catalyst formulations with improved performance at both high and low temperatures. Similarly, many of the engine manufacturers we visited showed us data indicating that the improvements in catalyst formulations corresponded to improvements in emission reductions over the regulated test cycles. It is clear from the data presented to EPA that the progress with regard to NO<sub>x</sub> adsorber performance has been both substantial and broadly realized by most technology developers. The importance of this temperature window to nonroad engine manufacturers is discussed in more detail later in this section.

Long term durability has been the greatest concern for the NO<sub>x</sub> adsorber catalyst. We have concluded as described briefly in III.F below and in

some detail in the draft RIA, that in order for NO<sub>x</sub> adsorbers to effectively control NO<sub>x</sub> emission throughout the life of a nonroad diesel engine the fuel sulfur level will have to be maintained at or below 15 ppm, that the NO<sub>x</sub> adsorber catalyst thermal durability will need to improve in order to allow for sulfur regeneration events (since adsorber thermal degradation, "sintering," is associated with each desulfation event, the number of desulfation events should be minimized), and that system improvements will have to be made in order to allow for appropriate management of sulfur poisoning. It is in this area of durability that NO<sub>x</sub> adsorbers had the greatest need for improvement, and it is here where some of the most impressive ongoing strides in technology development have been made. During our ongoing review, we have learned that catalyst companies are making significant improvements in the thermal durability of the catalyst materials used in NO<sub>x</sub> adsorbers. Similarly, the substrate manufacturers are developing new materials that address the problem of NO<sub>x</sub> storage material migration into the substrate.<sup>158</sup> The net gain from these simultaneous improvements are NO<sub>x</sub> adsorber catalysts which can be desulfated (go through a sulfur regeneration process) with significantly lower levels of thermal damage to the catalyst function. In addition, engine manufacturers and emission control technology vendors are developing new strategies to accomplish desulfation that allow for improved sulfur management while minimizing the damage due to sulfur poisoning. It was clear in our review that the total system improvements being made when coupled with changes to catalytic materials and catalyst substrates are delivering significantly improved catalyst durability to the NO<sub>x</sub> adsorber technology.

Practical application of the NO<sub>x</sub> adsorber catalyst in a vehicle was an issue during the HD2007 rulemaking and similarly there are issues regarding the application of NO<sub>x</sub> adsorbers to nonroad equipment. Although there is considerable evidence that NO<sub>x</sub> adsorbers are highly effective and that durability issues can be addressed, some worry that the application of the NO<sub>x</sub> adsorber systems to vehicles and nonroad equipment will be impractical due to packaging constraints and the

<sup>154</sup> NO<sub>x</sub> adsorber catalysts are also called, NO<sub>x</sub> storage catalysts (NSCs), NO<sub>x</sub> storage and reduction catalysts (NSRs), and NO<sub>x</sub> traps.

<sup>155</sup> Johnson, T. "Diesel Emission Control in Review—the Last 12 Months," SAE 2003-01-0039.

<sup>156</sup> Koichiro Nakatani, Shinya Hirota, Shinichi Takeshima, Kazuhiro Itoh, Toshiaki Tanaka, and Kazuhiko Dohmae, "Simultaneous PM and NO<sub>x</sub> Reduction System for Diesel Engines," SAE 2002-01-0957, SAE Congress March 2002.

<sup>157</sup> Schenk, C., McDonald, J. and Olson, B. "High Efficiency NO<sub>x</sub> and PM Exhaust Emission Control

for Heavy-Duty On-Highway Diesel Engines," SAE 2001-01-1351.

<sup>158</sup> Some NO<sub>x</sub> storage materials can interact with the catalyst substrate especially at elevated temperatures making the storage material unavailable for NO<sub>x</sub> storage and weakening the substrate.