Chapter III: Emissions Standards Feasibility

For the past 30 or more years, emission control development for gasoline vehicles and engines has concentrated most aggressively on exhaust emission control devices. These devices currently provide as much as or more than 95 percent of the emission control on a gasoline vehicle. In contrast, the emission control development work for diesels has concentrated on improvements to the engine itself to limit the emissions leaving the combustion chamber.[a]

However, during the past 15 years, more development effort has been put into diesel exhaust emission control devices, particularly in the area of particulate matter (PM) control. Those developments, and recent developments in diesel NOx exhaust emission control devices, make the widespread commercial use of diesel exhaust emission controls feasible. Through use of these devices, we believe emissions control similar to that attained by gasoline applications will be possible with diesel applications. However, without low sulfur diesel fuel, these technologies cannot be implemented on heavy-duty diesel applications. Low sulfur diesel fuel will at the same time also allow these technologies to be implemented on light-duty diesel applications.

Several exhaust emission control devices have been developed to control harmful diesel PM constituents–the diesel oxidation catalyst (DOC), and the many forms of diesel particulate filters, or traps. DOCs have been shown to be durable in-use, but they control only a relatively small fraction of the total PM and, consequently, do not address our PM concerns sufficiently. Uncatalyzed diesel particulate filters demonstrated high efficiencies many years ago, but the level of the PM standard was such that it could be met through less costly "in-cylinder" control techniques. Catalyzed diesel particulate filters (CDPF, also referred to as catalyzed filters or catalyzed traps, along with the very similar continuously regenerating DPF or CR-DPF) have the potential to provide major reductions in diesel PM emissions and provide the durability and dependability required for diesel applications. Throughout this document we will use the acronym CDPF to refer to both catalyzed diesel particulate filters and the similar continuously regenerating diesel particulate filter. Because of the significant PM reductions that they enable and their proven durability on low sulfur diesel fuel, we believe the CDPF will be the control

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[a] Note that throughout this document we refer to diesel and gasoline vehicles and engines. We tend to use those terms given the preponderance of vehicles using diesel fuel or gasoline fuel in the U.S. heavy-duty highway market. However, when we refer to a diesel engine, we mean any engine using the diesel cycle. When we refer to a gasoline engine or vehicle, we mean any Otto-cycle vehicle or engine. Therefore, the emission standards discussed throughout this preamble apply equally to engines and vehicles fueled by alternative fuels, unless otherwise specified in the regulatory text accompanying today's rule.

technology of choice for the future control of diesel PM emissions. However, CDPFs cannot be brought to market on diesel applications without low sulfur diesel fuel.

In addition to the diesel PM control devices, several exhaust emission control devices also have been developed to control diesel NOx. For reasons discussed in this chapter, we believe that the NOx adsorber is the most likely candidate to be used to meet future low diesel exhaust emission standards on the variety of applications in the heavy-duty diesel market. While other technologies exist that have the potential to provide significant emission reductions, such as selective catalytic reduction systems for NOx control, we believe that the NOx adsorber will likely be the only broadly applicable technology choice by the makers of engines and vehicles for the national fleet in the 2007-2010 time frame. Neither of the technologies for NOx control discussed here, the NOx adsorber or the compact SCR, can meet the Phase 2 standards without low sulfur diesel fuel.[b]

As for gasoline engines and vehicles, improvement continues to be made to gasoline emissions control technology. This includes improvement to catalyst designs in the form of improved washcoats and improved precious metal dispersion. Much effort has also been put into improved cold start strategies that allow for more rapid catalyst light-off. This can be done by retarding the spark timing to increase the temperature of the exhaust gases, and by using air-gap manifolds, exhaust pipes, and catalytic converter shells to decrease heat loss from the system.

These improvements to gasoline emission controls will be made in response to the California LEV-II standards and the federal Tier 2 standards. These improvements should transfer well to the heavy-duty gasoline segment of the fleet. With such migration of light-duty technology to heavy-duty vehicles and engines, we believe that considerable improvements to heavy-duty gasoline emissions can be realized, thus allowing vehicles to meet much more stringent standards than currently required.

The following discussion provides more detail on the technologies which are capable of achieving the emission standards contained in this final rule. The purpose of this Chapter is to discuss the emission reduction capability of these emission control technologies, as well as discuss their sensitivity to sulfur in diesel fuel. We start with diesel applications, the technology expected and its need for low sulfur diesel fuel, and finish with gasoline applications.

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[b] The Phase 1 heavy-duty diesel standards are those required in 65 FR 59896, October 6, 2000, and are often referred to as the "2004 standards." The standards required for 2007 and later model year engines, promulgated in this rule represent Phase 2.

A. Feasibility of the Heavy-Duty Diesel Standards

1. Engine Out Improvements

Diesel engines have made great progress in lowering engine out emissions from 6.0 g/bhp-hr NOx and 0.6 g/bhp-hr PM in 1990 to 4.0 g/bhp-hr NOx and 0.1 g/bhp-hr PM in 1998. These reductions came initially with improvements to combustion and fuel systems. Introduction of electronic fuel systems in the early 1990s allowed lower NOx and PM levels without sacrificing fuel economy. This, combined with increasing fuel injection pressures, have been the primary technologies that have allowed emission levels to be reduced to current levels.

Further engine out NOx reductions to the levels necessary to comply with the Phase 1 standard of 2.5 g/bhp-hr NOx+NMHC will come primarily from the addition of cooled exhaust gas recirculation (EGR). EGR recirculates a portion of the exhaust back to the intake manifold where it is drawn into the combustion chamber. The earliest EGR systems were uncooled. The recirculation of the hot exhaust gases to the intake manifold had the undesirable result of increasing the intake manifold temperature. This temperature rise reduces the NOx reduction potential of uncooled EGR since the NOx formation rate is proportional to temperature.[1] The intake manifold temperature rise also reduces the density of the fresh intake air, thus reducing the mass of fresh air drawn into the combustion chamber which lowers the air-fuel ratio. Lower air-fuel ratios generally increase PM emissions because there is less available oxygen to fully combust the carbon.

To overcome the lower air-fuel ratio and intake air density, the EGR gas can be cooled and/or the turbocharger can be adjusted to a higher pressure ratio. Both of these will almost certainly be done, but the latter tends to increase the work required of the turbocharger which increases fuel consumption. The former, cooling the recirculated exhaust gases, is limited by condensation concerns since a significant portion of the exhaust gases is water vapor.[2] The water vapor generally contains sulfuric acid as a result of the combustion of fuel-borne sulfur. This combustion results in SO_2 in the exhaust gas which can react with excess oxygen and water to form sulfuric acid (H_2SO_4). The level of EGR cooling is thus limited by the desire to prevent condensation of this corrosive water and sulfuric acid mixture. Therefore, the intake manifold temperature in an EGR equipped engine, even a cooled EGR engine, is usually higher than that found in a non-EGR engine.

More sophisticated electronic control systems will be necessary to control the EGR system and turbo machinery. EGR control algorithms will require additional engine condition information, possibly including mass air flow, oxygen, NOx, or EGR valve position sensors. These inputs will be necessary to control the EGR rate via an EGR valve or possibly a variable geometry turbocharger (VGT). These turbo chargers will also require a sophisticated control algorithm to take advantage of their transient response, EGR pumping, and air flow control

characteristics. In addition, the turbo machinery used with EGR will likely be pushed near the limits of its capability, and the engine's electronic control module (ECM–the engine's control computer) will need to ensure the limits of the hardware are not exceeded. Consequently, the Phase 1 heavy-duty diesel standards are expected to dramatically increase the capabilities of future ECMs compared to current non-EGR equipped ECMs.

We believe that reductions in engine out emissions beyond the Phase 1 levels may be attainable with low sulfur diesel fuel and more experience with cooled EGR systems. Low sulfur fuel will allow more EGR to be used at lower temperatures because of the reduced threat of sulfuric acid formation. In addition, recirculating the exhaust gases from downstream of a CDPF may allow different EGR pumping configurations to be feasible. Current EGR systems draw exhaust gases from the exhaust manifold upstream of the turbocharger turbine and recirculate them through the EGR cooler and into the intake manifold downstream of the turbo compressor and aftercooler. Such a system is called a high pressure loop EGR system because the gases are drawn from high pressure upstream of the turbo turbine and recirculated to high pressure downstream of the turbo compressor and aftercooler.

By contrast, a low pressure loop EGR system could draw some exhaust gases from the exhaust downstream of the turbo turbine and any exhaust emission control devices and recirculate those gases through the aftercooler and into the air intake system upstream of the compressor. The low pressure loop approach increases the effectiveness of the EGR system because it eliminates the high pressure loop EGR system's dependency on the pressure variations that exist between the intake and exhaust manifolds. To date, low pressure loop EGR has not been considered viable for HD applications because of the potential durability concerns associated with recirculating exhaust gas containing particles and sulfuric acid through the turbocharger compressor and aftercooler. The particles and acid accumulate in the aftercooler (typically made of aluminum) plugging and corroding it. The turbocharger compressor is also subject to particulate buildup and corrosion. But, by adding a CDPF and low sulfur fuel, the particles and acid would be reduced significantly and these durability concerns would be minimized.

Low pressure loop EGR systems provide many advantages over high pressure loop EGR systems. For example, low pressure loop EGR allows more EGR to be pumped across a wider engine operating range than with some other EGR configurations. As already pointed out, the EGR does not have to be pumped against changing turbocharger pressure differentials found in high pressure loop EGR systems that pump exhaust from the exhaust manifold upstream of the turbocharger turbine through an EGR cooler to the intake manifold. For promoting EGR, the pressure differential between the exhaust and intake manifolds can vary from very favorable at rated speed to very unfavorable near torque peak. The unfavorable pressure differential near torque peak requires work (i.e., pumping work) to be done to provide EGR during such engine operation, thereby causing a fuel economy penalty. However, the low pressure loop EGR system

is not dependent on the pressure differential characteristics of the turbocharger, meaning that it does not require this additional EGR pumping work. Therefore, we believe low pressure loop systems may allow increased EGR rates, improved fuel economy, and perhaps even further reductions of engine out emissions. However, these potential engine out emission reductions are expected to be modest and are not expected to be sufficient to meet the emission standards required by this final rule.

2.   Meeting the PM Standard

Diesel PM consists of three primary constituents: elemental carbon particles from incomplete combustion, which make up the largest portion of the total PM; the soluble organic fraction (SOF), which consists of unburned hydrocarbons that have condensed into liquid droplets or have adsorbed onto the surfaces of the elemental carbon particles; and sulfates with associated water, which result from oxidation of fuel-borne sulfur in the engine's exhaust.

Several exhaust emission control devices have been developed to control diesel PM constituents -- the diesel oxidation catalyst (DOC), and the many forms of PM filters, CDPFs, or PM traps. DOCs have been shown to be durable in use, but they effectively control only the SOF portion of the total PM which, especially on today's engines, constitutes only around 10 to 30 percent of the total PM. Therefore, the DOC alone is not capable of meeting the FTP 0.01 g/bhp-hr PM standard set in this final rule.

Only the catalyzed diesel particulate filter (CDPF) is capable of providing the level of control required to meet the Phase 2 standards. In the past, the CDPF has demonstrated high trapping efficiency, but regeneration of the collected PM has been a serious challenge, when operating on anything other than low sulfur diesel fuel. The CDPF works by passing the exhaust through a ceramic or metallic filter to collect the PM. The collected PM, mostly elemental carbon particles but also a fraction of the SOF portion of PM at some low temperature conditions, must then be burned off the CDPF before the filter becomes plugged. This burning off of collected PM is referred to as "regeneration." The CDPF demonstrated high PM trapping efficiencies many years ago, but the level of the applicable PM standard was such that it could be met through less costly "in-cylinder" control techniques. As a result, the CDPF found little use in the diesel market. The un-catalyzed diesel particulate filter is unlikely to be able to meet the 0.01 g/bhp-hr PM standard as they are only moderately effective at controlling the SOF fraction of the PM. In addition, they require active regeneration technology which must be engaged frequently making the systems expensive to operate (i.e., increasing fuel consumption) and less reliable.

a.   Catalyzed Diesel Particulate Filters

We believe the kind of diesel particulate filter that will be able to meet the PM standard in a reliable, durable, cost effective manner, and the type of diesel particulate filter that will prove to the be the industry's technology of choice, is one capable of regenerating on an essentially continuous basis such as the catalyzed diesel particulate filter or CDPF. These CDPFs will be able to achieve very low PM emissions because:

- they are highly efficient at trapping all forms of diesel PM;
- they employ precious metals to reduce the temperature at which regeneration occurs, thereby allowing for passive regeneration under normal operating conditions typical of a diesel engine;[c]
- they have lower average back-pressure thereby reducing potential fuel economy impacts, because they regenerate on a continuous basis; and,
- they need no extra burners or heaters as would be required by an active regeneration system, thereby reducing potential fuel economy impacts.

These CDPFs are able to provide in excess of 90 percent control of diesel PM, provided they are operated on diesel fuel with sulfur levels at or below 15 ppm. High sulfur level diesel fuel creates two problems for CDPFs. First, the CDPF cannot regenerate properly with current fuel sulfur levels as such sulfur levels poison the catalyst inhibiting the NO to NO_2 reaction severely limiting regeneration of the trapped PM.[3] Second, because SO_2 is readily oxidized to SO_3 across the precious metals catalysts used in CDPFs, the Supplemental Emission Test (SET) 0.01 g/bhp-hr PM standard contained in today's final rule cannot be achieved with diesel fuel sulfur levels greater than 15 ppm because of the resultant increase in sulfate PM emissions ("sulfate make"). Table III.A-1 shows that at a 15 ppm sulfur level, a CDPF can achieve 0.009 g/bhp-hr over the Supplemental Emission Test (SET), but at 30 ppm sulfur, the SET results are 0.017 g/bhp-hr, which would exceed the standard. See the discussion later in this chapter for further information on CDPFs and sulfur, in particular section III.A.7.a.ii, "Loss of PM Control Effectiveness."

More than one emission control manufacturer is developing these precious metal catalyzed, passively regenerating CDPFs. In field trials, they have demonstrated highly efficient PM control and promising durability. A recent publication documents results from a sample of these field test engines after years of use in real world applications.[4] The sampled CDPFs had on

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[c] For CDPF regeneration without precious metals, temperatures in excess of 650°C must be obtained. At such high temperatures, elemental carbon will burn provided sufficient oxygen is present. However, diesel engines rarely if ever operate with such high exhaust temperatures. For example, exhaust temperatures on the HDE Federal Test Procedure cycle typically range from 100°C to 450°C. Precious metal CDPFs use platinum to oxidize NO in the exhaust to NO_2, which is capable of oxidizing carbon at temperatures as low as 250°C to 300°C.

average four years of use covering more than 225,000 miles in applications ranging from city buses to garbage trucks to intercity trains, with some units accumulating more than 360,000 miles. When tested on the US Heavy-Duty Federal Test Procedure (HD FTP), they continued to demonstrate PM reductions in excess of 90 percent.

The experience gained in these field tests also helps to clarify the need for very 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 CDPFs have been introduced into retrofit applications without a single failure. This success on 10 ppm sulfur fuel is all the more impressive as some of these units have been in operation for more than six years. 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 sulfur fuel have been positive, with no reported durability issues. Of course, it should be mentioned that an HDDE equipped with a CDPF operating on 50 ppm sulfur would not meet the PM emission standards contained in this final rule, as discussed below. These good results in the UK are contrasted with field tests in Finland where colder winter conditions are sometimes encountered (similar to many northern regions of the United States). The testing in Finland revealed a failure rate of 10 percent (14 failures in the test program) when operated on fuel with a sulfur cap of 50 ppm. This 10 percent failure rate has been attributed to insufficient CDPF regeneration due to fuel sulfur in combination with low ambient temperatures.[5] 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.[6] 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.[d] 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 plugging of the CDPFs.[7] We believe that this real world testing clearly indicates that increasing diesel fuel sulfur levels limit CDPF regeneration, leading to plugging of the CDPF even at fuel sulfur levels as low as 50 ppm.

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[d] 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 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).

Another program evaluating CDPFs in the field is the ARCO Emission Control Diesel (EC-D) program.[e] In that program, a one-year technology validation is being run to evaluate EC-D and CDPFs using diesel vehicles operating in southern California. The fuel's performance, impact on engine durabiltiy and vehicle performance, and emission characteristics are being evaluated in several fleets in various applications. The program is still ongoing, but interim results have been made available.[8] These interim results have shown that vehicles retrofitted with CDPFs and fueled with EC-D (7.4 ppm sulfur) emitted 91 percent to 99 percent less PM compared to the vehicles fueled with California diesel fuel (121 ppm sulfur) having no exhaust filter equipment. Further, the test vehicles equipped with the CDPFs and fueled with EC-D have operated reliably during the program start-up period and no significant maintenance issues have been reported for the school bus, tanker truck and grocery truck fleets that have been operating for over six months (approximately 50,000 miles).[9]

From these results, we can further conclude that lighter applications (such as large pick-up trucks and other light- and medium-heavy-duty applications), having lower exhaust temperatures than heavier applications, may experience similar failure rates even in more temperate climates and would, therefore, need lower sulfur fuel even in the United Kingdom. These results are understood to be due to the effect of sulfur on the CDPF's ability to create sufficient NO_2 to carry out proper filter regeneration. Without the NO_2, the CDPF continues to trap PM at high efficiency, but it is unable to oxidize, or regenerate, the trapped PM. The possible result is a plugged CDPF.

Much development effort is underway worldwide to bring PM exhaust emission control devices to market. One of the drivers is the Euro IV PM standard set to become effective in 2005.[f] This standard sets a PM emission target that forces CDPF usage. In anticipation of the 2005 introduction date, field testing is already underway in several countries with CDPFs. We believe the experience gained in Europe with these technologies will coincide well with the 2007 standards contained in this final rule. The timing of the new standards harmonizes the heavy-duty highway PM technologies with those expected to be used to meet the light-duty highway Tier 2 standards. With this level of development already under way, we are confident that the PM standard will be met provided low sulfur fuel is made available.

The data currently available show that CDPFs can provide significant reductions in PM, and are capable of meeting a standard of 0.01 g/bhp-hr PM. CDPFs with precious metal catalysts, in conjunction with low sulfur fuel, have been shown to be more than 90 percent

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[e] EC-D is a diesel fuel developed recently by ARCO (Atlantic Richfield Company) from typical crude oil using a conventional refining process and having a fuel sulfur content less than 15 ppm.

[f] The Euro IV standards are 2.6 g/hp-hr NOx and 0.015 g/hp-hr PM over the European Stationary Cycle and European Transient Cycle.

efficient over the FTP and across the NTE zone.[10] Figure III.A-1[g] shows representative HD FTP CDPF efficiencies with fuel sulfur levels near 15 ppm.[11] [12] [13] [14] Since the total PM removal efficiency of the CDPF is roughly linear with fuel sulfur (as shown in the DECSE program results[15]), it can be seen from Figure III.A-1 that even at the 15 ppm sulfur cap, current CDPFs can produce greater than 90 percent trapping efficiency over the HD FTP. Based on the current FTP standard of 0.10 g/bhp-hr, these CDPFs will easily achieve the FTP 0.01 g/bhp-hr PM standard contained in today's final rule.
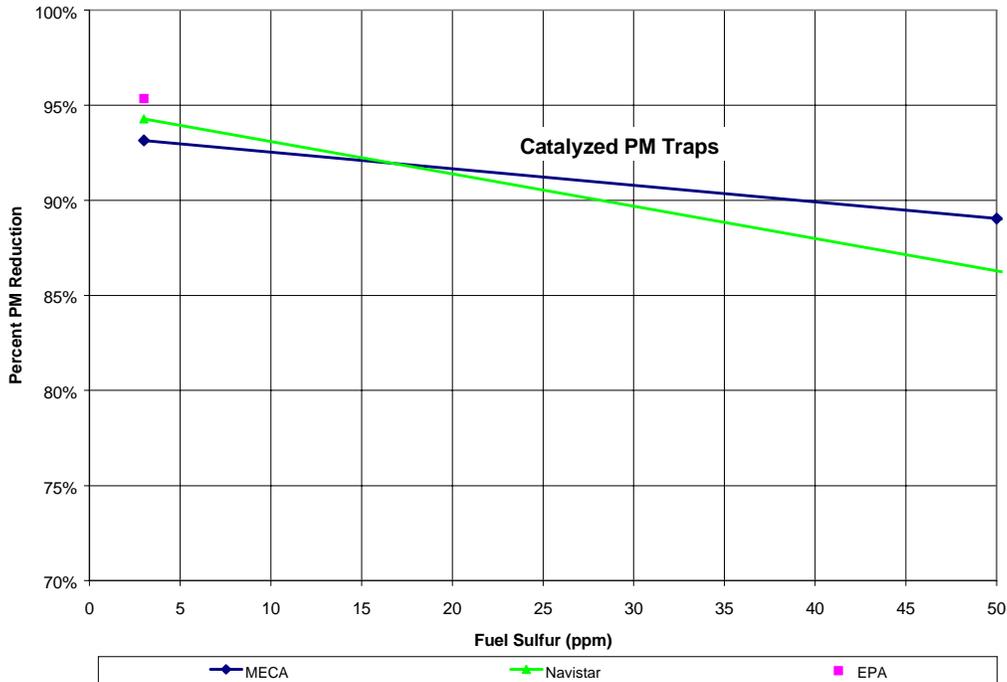

Figure III.A-1. HD CDPF PM Removal Efficiency Over the Federal Test Procedure

As part of the EPA National Vehicle and Fuel Emissions Laboratory (NVFEL) test program to evaluate CDPFs and NOx adsorbers, we performed CDPF testing over the hot-start HDDE FTP. This testing included CDPF evaluation with three ppm sulfur fuel, which produced greater than a 95 percent reduction in PM, with a post-CDPF emission rate of 0.004 g/bhp-hr PM.[16] In addition, we performed testing of a complete system which included CDPFs, NOx adsorbers, and a clean-up diesel oxidation catalyst, which also produced on average greater than a 95 percent reduction during triplicate hot-start HDDE FTP testing, with an average post-CDPF

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[g] Figure III.A-1 includes a Navistar data point at 200 ppm sulfur and 61 percent PM reduction; this data point does not appear in the figure so that the data from 0 ppm sulfur to 50 ppm sulfur can be more easily viewed.

emission rate of 0.002 g/bhp-hr PM (with a 95 percent confidence interval of ± 0.001 g/bhp-hr), using six ppm sulfur fuel (additional discussion of this NVFEL test program can be found in section III.A.3.b of this RIA, as well as in the docket for this final rule).[h] As indicated by Figure III.A-1, when typical particulate sulfate conversion rates for the HDDE FTP are considered, the EPA NVFEL test program would be projected to produce greater than a 90 percent PM reduction at a fuel sulfur level of 15 ppm.

The engine operating conditions have little impact on the particulate trapping efficiency of carbon particles by CDPFs, so the greater than 90 percent efficiency for elemental carbon particulate matter will apply to engine operation within the NTE zone, as well as the test modes which comprise the SET. This is supported by a study by Johnson Matthey which showed greater than 95 percent reduction in elemental carbon PM over a broad range of operating modes.[17] This same paper also shows large reductions in the soluble organic fraction of the PM across the engine operating map. However, engine operation will affect the CDPF regeneration and oxidation of SO_2 to sulfate PM (i.e., "sulfate-make"). Sulfate-make will reduce the measured PM removal efficiency at some NTE operating conditions and supplemental steady-state modes, even at the 15 ppm fuel sulfur cap. Figure III.A-2 shows PM removal efficiency as a function of fuel sulfur for a CDPF when tested over the SET.[18] From the graph, it can be seen that fuel sulfur level has a stronger effect on PM removal efficiency over the SET than over the HD FTP. This increased sensitivity to fuel sulfur is caused by the higher temperatures that are found at some of the steady-state modes. High exhaust temperatures promote the oxidation of SO_2 to SO_3 (which then combines with water in the exhaust, forming a hydrated sulfate) across the precious metals found in CDPFs. The sulfate emissions condense in the atmosphere (as well as in the CFR mandated dilution tunnel used for PM testing) forming PM. Figure III-A-2 shows PM reductions of 85 percent or greater are achievable with 15 ppm sulfur fuel. Engine-out PM emission rates over the SET test are typically 50 percent or less of the FTP PM emission rates, primarily because carbonaceous PM formation is greater under transient engine operation as compared to steady-state operation. For example, model year 2000 certification data for a number of HDDE families shows SET PM emission rates between 0.02 and 0.05 g/bhp-hr.[19] Therefore, an 85 percent reduction in PM over the SET test is sufficient to comply with the 2007 SET PM standard contained in this final rule.

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[h] The NVFEL emission measurement test equipment used to evaluate the performance of a HDDE equipped only with a CDPF (no NOx adsorbers) utilized PM sample equipment and procedures consistent with the existing 40 CFR part 86, subpart N provisions (including dual 70 mm filters). The NVFEL test equipment used to evaluate the performance of a complete system (CDPFs, NOx adsorbers, clean-up DOC) utilized PM sample equipment and techniques consistent with the new PM measurement regulations contained in this rule, including a single, high efficiency 47 mm filter.
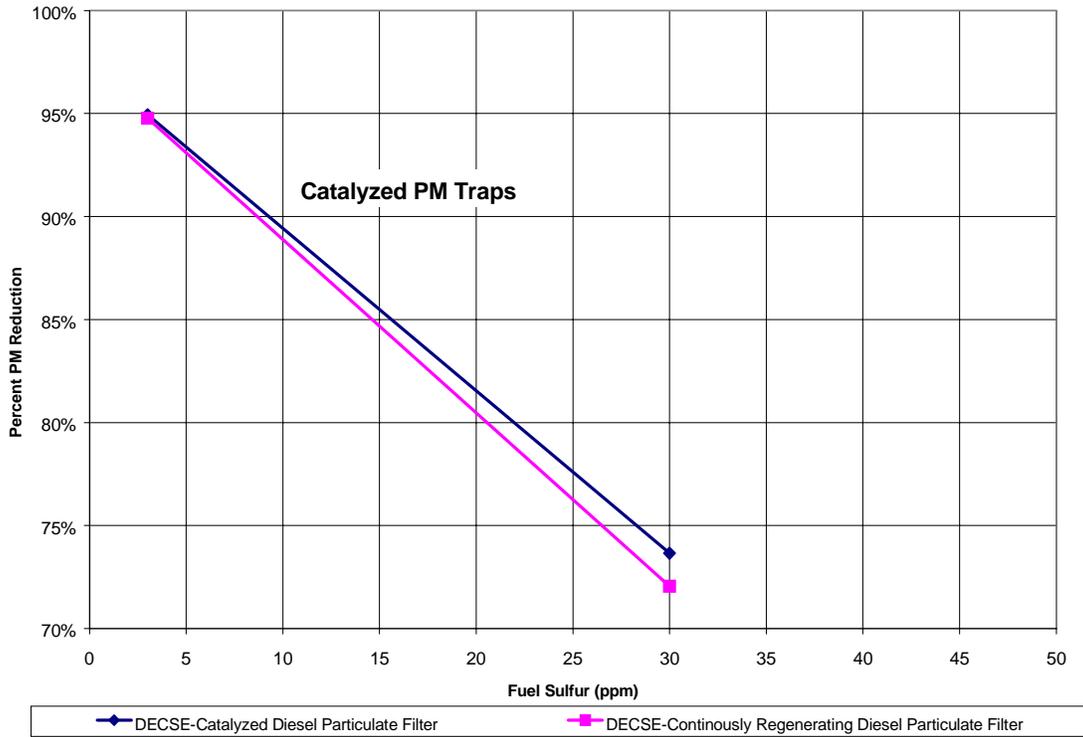
Figure III.A-2. HD PM Removal Efficiency for a CDPF Over the Supplemental Emission Test (SET)

Nonetheless, as shown in Table III.A-1, a HDDE equipped with CDPFs available today is capable of meeting the SET standard (equal to 1.0 x FTP standard, or 0.01 g/bhp-hr) with 15 ppm fuel.   Table III.A-1 shows data from the Diesel Emission Control Sulfur Effects (DECSE) test program, a program conducted by the US Department of Energy in cooperation with industry 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 PM emissions from a heavy-duty diesel engine operated with a CDPF on several different fuel sulfur levels. Table III.A-1 also shows interpolated points representing a straight line fit through the DECSE data illustrating the expected total PM emissions from a heavy-duty diesel engine on the SET at various fuel sulfur levels. As shown, the PM emissions at a 15 ppm sulfur level would be 0.009 g/bhp-hr, ten percent below the 0.01 g/bhp-hr standard set in this final rule, which demonstrates the feasibility of the standard at 15 ppm sulfur.

Table III.A-1. PM Emissions from a Heavy-Duty Diesel Engine at the Indicated Fuel Sulfur Levels

Fuel Sulfur Level	Supplemental Steady State	
	Tailpipe PM [g/bhp-hr]	Relative to the Standard (%)
3	0.003	-70
7*	0.006	-40
15*	0.009	-10
30	0.017	70
150	0.071	610

* The PM emissions at these sulfur levels are based on a straight-line fit to the DECSE program data;[20] PM emissions at other sulfur levels are actual DECSE data.

The NTE requirement, unlike the HD FTP or SET standard, is not a composite test (i.e., the 20 minute transient HD FTP cycle or the 13-steady-state SET modes). In fact, a number of the individual modes within the SET test fall within the NTE engine control zone. As discussed above, CDPFs are very efficient at capturing elemental carbon PM (>95 percent), but sulfate-make under certain operating conditions may exceed the FTP or SET standard, which is part of the reason the PM NTE standard is greater than the FTP and SET PM standards. In addition to the composite SET results, the DECSE test program also reported PM performance results at two individual steady-state modes, the peak-torque condition and a "road-load" condition. The peak-torque test mode produces very high exhaust gas temperature (and would therefore be representative of the highest sulfate particulate generating conditions) and the road-load condition is intended to be representative of a typical HD diesel engine line-haul cruise operation (75 percent load, Euro B speed). A linear fit of the DECSE PM emission results for the road-load and peak-torque conditions between the three ppm sulfur test fuel and the 30 ppm sulfur test fuel point shows that the two CDPFs which were tested produced an 88-94 percent or greater reduction at a linear interpolated sulfur level of seven ppm (near the expected in-use average) and an 83-90 percent reduction at a linear interpolated sulfur level of 15 ppm (capped level), for both test operating points. For both CDPFs, the road-load condition resulted in lower sulfate make and higher overall PM reduction than the peak-torque condition. Based on this information, under very high particulate sulfate formation conditions, at 15 ppm sulfur a CDPF can produce at least an 83 percent reduction, and at the expected refinery average sulfur level of seven ppm, when operated at very high sulfate conversion engine conditions a CDPF can produce at least an 88 percent reduction. It should be noted that a prolonged steady-state test condition at the peak-torque mode for a HDDE is representative of the highest exhaust gas temperature producing engine operating conditions. The DECSE testing conditions for these two steady-state points

prescribed a five minute warm-up and a 20 minute sample collection, for a total of 25 minutes of operation at peak-torque. The peak-torque test data described above could be considered representative of the worst case particulate sulfate generating conditions. The data show that even under these test conditions, an 83 percent reduction would be sufficient to comply with the NTE provisions, even considering PM sulfate make, when tested on 15 ppm sulfur fuel. Under the Phase 1 rule, a HDDE could emit PM emissions subject to the NTE requirements as high as 0.13 g/bhp-hr (1.25 x 0.10 g/bhp-hr). An 83 percent reduction from this engine would result in a PM emission rate of 0.022 g/bhp-hr, which would comply with the 2007 NTE PM standards contained in this final rule.[i]

Under the Phase 1 HDDE provisions (which includes the Phase 1 FTP standards and the 2007 NTE provisions as they apply to the Phase 1 FTP standards), emission "carve-out" zones of the NTE control zone were defined. These carve-out zones are areas within the defined NTE control zone which are excluded from meeting the NTE standards for specific emissions. The Phase 1 rule defined two types of carve-out zones, one which applied to all regulated emissions (gaseous emissions and PM), and one carve-out zone which only applied to PM. The PM only carve-out zone was specified to exclude low load, high speed engine operation from the NTE requirements. During these conditions, HDDEs not equipped with CDPFs can produce higher PM emission rates, and it was decided within the Phase 1 rule to exclude HDDEs from complying with the PM NTE requirements when operated within the defined PM carve-out zones. With the application of CDPFs to HDDEs, these PM only carve-out zones are not needed. As discussed previously, CDPFs are very effective at reducing engine-out PM. During the recent NVFEL test program which evaluated the effectiveness of diesel CDPFs on low sulfur diesel fuel, we included one steady-state test point which was within the Phase 1 rule's PM carve-out zone. Specifically, the test point was 228 ft-lbs torque and 2,415 rpm (listed as Mode 6 in Figure III.A-6 of this Chapter), which places the test condition near the center of the Phase 1 rule's PM carve-out zone for this engine. At this operating condition, one of the CDPFs reduced engine-out PM by more than 95 percent, from 0.068 g/bhp-hr to 0.003 g/bhp-hr, the second CDPF produced similar results. Based on the high PM reduction capability of CDPFs when operated on low sulfur diesel fuel, and their demonstrated ability to achieve >90 percent reductions when operated inside the Phase 1 PM carve-out zones, we have eliminated the PM-only carve-out zones from the NTE requirements.

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[i] The PM NTE standard contained in this final rule is 1.5 x FTP standard, or 1.5 x 0.01 g/bhp-hr. 40 CFR 86.007-11(a)(4)(v) specifies that the rounding procedures in ASTM E29-90 should be applied to the NTE emission standard, therefore, the NTE standard is rounded to the same number of significant digits as the FTP standard, i.e., 1.5 x 0.01g/bhp-hr is rounded to 0.02 g/bhp-hr. An engine with a measured NTE PM emission rate of 0.022 g/bhp-hr would also be rounded using ASTM rounding provisions, and would be rounded to the same number of significant digits as the standard, so 0.022 g/bhp-hr would round to 0.02 g/bhp-hr, and would meet the NTE PM standard.

The NTE requirements apply not only during standard laboratory conditions, but also during the expanded ambient temperature, humidity, and altitude limits defined in the regulations. We believe the NTE PM standard is technologically feasible across this range of ambient conditions. As discussed above, CDPFs are mechanical filtration devices, and ambient temperature changes will have minimal effect on CDPF performance. Ambient altitude will also have minimal, if any, effects on CDPF filtration efficiencies, and ambient humidity should have no effect on CDPF performance. As discussed above, particulate sulfate make is sensitive to high exhaust gas temperatures, however, at sea-level conditions, the NTE requirements apply up to ambient temperatures which are only 14°F greater than standard test cell conditions (100°F under the NTE, versus 86°F for HD FTP laboratory conditions). At an altitude of 5,500 feet above sea-level, the NTE applies only up to an ambient temperature within the range of standard laboratory conditions (i.e., 86°F). These small or non-existent differences in ambient temperature should have little effect on the sulfate make of CDPFs, and as discussed above, even when tested under at an engine operating test mode representative of the highest particulate sulfate generating conditions (25 minutes at peak-torque operation) with 15 ppm sulfur diesel fuel, we predict the engine would comply with the PM NTE standard. Based on the available test data and the expected impact of the expanded, but constrained, ambient conditions under which engines must comply with the NTE, we conclude that the PM NTE standard is technologically feasible by 2007, provided low sulfur diesel fuel (<15 ppm) is available.

There may be a need to remove, clean, and reverse these CDPFs at regular intervals to remove ash build-up resulting from engine oil. Small amounts of oil can enter the exhaust via the combustion chamber (past the pistons rings and valve seals), and via the crankcase ventilation system. This can lead to ash build-up, primarily as a result of the metallic oil additives used to provide pH control. This pH control is necessary, in part, to neutralize sulfuric acid produced as a byproduct of burning fuel containing sulfur. However, with reduced fuel sulfur, these oil additives could be reduced, thereby reducing the rate of ash build-up and lengthening any potential cleaning intervals. It may also be possible to use oil additives that are less prone to ash formation to reduce the need for periodic maintenance to at least those specified in CFR 86.004-25 (100,000 miles or 3,000 hours for light heavy-duty vehicles, and 150,000 miles or 4,500 hours for medium- and heavy-duty engines). Periodic maintenance would consist of reversing the CDPF and/or washing it out with compressed air or water. Consequently, we conclude that CDPFs will be able to meet the required emission life with minimal maintenance.

b.   Control of Ultra-Fine PM

CDPFs reduce PM by capturing and burning particles. Ninety percent of the PM mass resides in particle sizes that are less than 1000 nanometers (nm) in diameter, and half of these particles are less than 200 nm.[21][22][23][24][25] Fortunately, CDPFs have very high particle capture efficiencies. PM less than 200 nm is captured efficiently by diffusion onto surfaces within the CDPF walls. Larger particles are captured primarily by inertial impaction onto surfaces due to the

tortuous path that exhaust gas must take to pass through the porous CDPF walls. Capture efficiency for elemental carbon (soot) and metallic ash is nearly 100 percent; therefore, significant PM can only form downstream of the CDPF. Volatile PM forms from sulfate or organic vapors via nucleation, condensation, and/or adsorption during initial dilution of raw exhaust into the atmosphere. Kleeman, et al., and Kittelson, et al., independently demonstrated that these volatile particles reside in the ultra-fine PM range (i.e., <100 nm range).[26] [27] Thus ultra-fine PM is comprised primarily of semi-volatile PM. The organic portion of semi-volatile, ultra-fine PM can be controlled via oxidation over a PGM catalyst. The sulfate portion of semi-volatile, ultra-fine PM can be reduced by eliminating sulfur from the fuel. Furthermore, the work of Kittelson et al. suggests that reducing sulfate PM in this manner will reduce the number of nucleation sites available for the nucleation of ultra-fine organic PM, forcing more of the organic material to adsorb onto the much larger soot agglomerates and thus reducing the number of ultra-fine organic particles.

Modern CDPFs have been shown to be very effective at reducing PM mass. In addition, recent data shows 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 modern 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.[28] Kittelson, et al., confirmed that ultra-fine 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. CDPFs efficiently oxidize nearly all of the volatile organic PM precursors, and elimination of as much fuel sulfur as possible will substantially reduce the number of ultra-fine 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 ultra-fine particles.

3.   Meeting the NOx Standard

NOx 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. Historically, reduction of NOx emissions in the oxygen-rich environment typical of diesel exhaust has been significantly more difficult because known catalytic NOx reduction mechanisms like the gasoline three-way catalyst work only when the oxygen content of the exhaust is very low. Nevertheless, significant progress has been made in developing catalytic emission control technologies that reduce the NOx to form harmless oxygen and nitrogen in the oxygen rich (lean burn) exhaust environment typical of diesel engines. These devices are the lean NOx catalyst, the NOx adsorber, selective catalytic reduction (SCR), and non-thermal plasma.

a.   Lean NOx Catalysts

Lean NOx catalysts have been under development for some time, and two methods have been developed for using a lean NOx catalyst depending on the level of NOx reduction desired though neither method can produce more than a 30 percent NOx reduction. The "active" lean NOx catalyst injects a reductant that serves to reduce NOx to N_2 and O_2 (typically diesel fuel is used as the reductant). The reductant is introduced upstream of, or into, the catalyst. The presence of the reductant provides locally oxygen poor conditions which allows the NOx emissions to be reduced by the catalyst.

The lean NOx catalyst washcoat incorporates a zeolite catalyst that acts to adsorb hydrocarbons from the exhaust stream. Once adsorbed on the zeolite, the hydrocarbons will oxidize and create a locally oxygen poor region that is more conducive to reducing NOx. To promote hydrocarbon oxidation at lower temperatures, the washcoat can incorporate platinum or other precious metals. The platinum also helps to eliminate the emission of unburned hydrocarbons that can occur if too much reductant is injected, referred to as "hydrocarbon slip." With platinum, the NOx conversion can take place at the low exhaust temperatures that are typical of diesel engines. However, the presence of the precious metals can lead to production of sulfate PM, as already discussed for PM control technologies.

Active lean NOx catalysts have been shown to provide up to 30 percent NOx reduction under limited steady-state conditions. However, this NOx control is achieved with a fuel economy penalty upwards of 7 percent due to the need to inject fuel into the exhaust stream.[29] NOx reductions over the HD transient FTP are only on the order of 12 percent due to excursions outside the optimum NOx reduction efficiency temperature range for these devices.[30] Consequently, the active lean NOx catalyst does not appear to be capable of enabling the significantly lower NOx emissions required by the NOx standard.

The "passive" lean NOx catalyst uses no reductant injection. Therefore, the passive lean NOx catalyst is even more limited in its ability to reduce NOx because the exhaust gases normally contain very few hydrocarbons. For that reason, today's passive lean NOx catalyst is capable of best steady state NOx reductions of less than 10 percent. Neither approach to lean NOx catalysis listed here can provide the significant NOx reductions required to satisfy the air quality needs discussed in chapter II.

b.   NOx Adsorbers

NOx 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. Today, an advancement upon this well developed three-way catalyst technology, the NOx adsorber, has shown that it too can make possible extremely low NOx emissions from lean burn engines such

as diesel engines. The potential of the NOx adsorber catalyst is limited only by its need for careful integration with the total vehicle 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 following subsections describe the function, design and technical challenges remaining for application of the NOx adsorber catalyst to heavy-duty diesel vehicles.

i.   *How do NOx Adsorbers Work?*

The NOx adsorber catalyst is a further development of the three-way catalyst technology developed for gasoline powered vehicles more than twenty years ago. The NOx adsorber enhances the three-way catalyst function through the addition of storage materials on the catalyst surface which can adsorb NOx under oxygen rich conditions. This enhancement means that a NOx adsorber can allow for control of NOx emissions under lean burn (oxygen rich) operating conditions typical of diesel engines.

Three-way catalysts reduce NOx emissions as well as HC and CO emissions (hence the name three-way) by promoting oxidation of HC and CO to water and CO_2 using the oxidation potential of the NOx pollutant and in the process reducing the NOx emissions to atomic nitrogen, N_2. Said another way, three-way catalysts work with exhaust conditions where the net oxidizing and reducing chemistry of the exhaust is approximately equal, allowing the catalyst to promote complete oxidation/reduction reactions to the desired exhaust components, carbon dioxide (CO_2), water (H_2O) and nitrogen (N_2). The oxidizing potential in the exhaust comes from NOx emissions and some oxygen (O_2) which is not consumed during combustion. The reducing potential in the exhaust comes from HC and CO emissions, which represent products of incomplete combustion. Operation of the engine to ensure that the oxidizing and reducing potential of the combustion and exhaust conditions is precisely balanced is referred to as stoichiometric engine operation.

If the exhaust chemistry varies from stoichiometric conditions emission control is decreased. If the exhaust chemistry is net "fuel rich," meaning there is an excess of HC and CO emissions in comparison to the oxidation potential of the NOx and O_2 present in the exhaust, the excess HC and CO pollutants are emitted from the vehicle. Conversely, if the exhaust chemistry is net "oxygen rich" (lean burn), meaning there is an excess of NOx and O_2 in comparison to the reducing potential of the HC and CO present in the exhaust, the excess NOx pollutants are emitted from the vehicle. It is this oxygen rich operating condition that typifies diesel engine operation. Because of this, diesel engines equipped with three-way catalysts (or simpler oxidation catalysts) have very low HC and CO emissions while NOx (and O_2) emissions remain almost unchanged from the high engine out levels. For this reason, when diesel engines are equipped with catalysts (diesel oxidation catalysts, or DOCs) they have HC and CO emissions that are typically lower, but have NOx emissions that are an order of magnitude higher, than for gasoline engines equipped with three-way catalysts.

The NOx adsorber catalyst works to overcome this situation by storing NOx emissions when the exhaust conditions are oxygen rich. Unfortunately the storage capacity of the NOx adsorber is limited, requiring that the stored NOx be periodically purged from the storage component. If the exhaust chemistry is controlled such that when the stored NOx emissions are released the net exhaust chemistry is at stoichiometric or net fuel rich conditions, then the three-way catalyst portion of the catalyst can reduce the NOx emissions in the same way as for a gasoline three-way catalyst equipped engine. Simply put, the NOx adsorber works to control NOx emissions by storing NOx on the catalyst surface under lean burn conditions typical of diesel engines and then by reducing the NOx emissions with a three-way catalyst function by periodically operating under stoichiometric or fuel rich conditions.

The NOx storage process can be further broken down into two steps. First the NO in the exhaust is oxidized to NO_2 across an oxidation promoting catalyst, typically platinum. Then the NO_2 is further oxidized and stored on the surface of the catalyst as a metallic nitrate (MNO_3). The storage components are typically alkali or alkaline earth metals that can form stable metallic nitrates. The most common storage component is barium carbonate ($BaCO_3$) which can store NO_2 as barium nitrate ($Ba(NO_3)_2$) while releasing CO_2. In order for the NOx storage function to work, the NOx must be oxidized to NO_2 prior to storage and a storage site must be available (the device cannot be "full"). During this oxygen rich portion of operation, NOx is stored while HC and CO emissions are oxidized across the three-way catalyst components by oxygen in the exhaust. This can result in near zero emissions of NOx, HCs, and CO under the net oxygen rich operating conditions typical of diesel engines.

The NOx adsorber releases and reduces NOx emissions under fuel rich operating conditions through a similar two step process, referred to here as NOx adsorber regeneration. The metallic nitrate becomes unstable under net fuel rich operating conditions, decomposing and releasing the stored NOx. Then the NOx is reduced by reducing agents in the exhaust (CO and HCs) across a three-way catalyst system, typically containing platinum and rhodium. Typically this NOx regeneration step occurs at a significantly faster rate than the period of lean NOx storage such that the fuel rich operation constitutes only a small fraction of the total operating time. Since this release and reduction step, NOx adsorber regeneration, occurs under net fuel rich operating conditions, NOx emissions can be almost completely eliminated. But for some of the HC and CO emissions, "slip"(failure to remove all of the HC and CO) may occur during this process. The HC and CO slip can be controlled with a downstream "clean-up" catalyst that promotes their oxidation or potentially by controlling the exhaust constituents such that the excess amount of the HC and CO pollutants at the fuel rich operating condition is as low as possible, that is, as close to stoichiometric conditions as possible.

The difference between stoichiometric three-way catalyst function and the newly developed NOx adsorber technology can be summarized as follows. Stoichiometric three-way catalysts work to reduce NOx, HCs and CO by maintaining a careful balance between oxidizing

(NOx and O_2) and reducing (HCs and CO) constituents and then promoting their mutual destruction across the catalyst on a continuous basis. The newly developed NOx adsorber technology works to reduce the pollutants by balancing the oxidation and reduction chemistry on a discontinuous basis, alternating between net oxygen rich and net fuel rich operation in order to control the pollutants. This approach allows lean-burn engines (oxygen rich operating), like diesel engines, to operate under their normal operating mode most of the time, provided that they can periodically switch and operate such that the exhaust conditions are net fuel rich for brief periods. If the engine/emission control system can be made to operate in this manner, NOx adsorbers offer the potential to employ the highly effective three-way catalyst chemistry to lean burn engines.

ii. Where are NOx Adsorbers used Today?

NOx adsorber catalysts were first introduced in the power generation market less than five years ago. Since then, NOx adsorber systems in stationary source applications have enjoyed considerable success. In 1997, the South Coast Air Quality Management District of California determined that a NOx adsorber system provided the "Best Available Control Technology" NOx limit for gas turbine power systems.[31] Average NOx control for these power generation facilities is in excess of 92 percent.[32] A NOx adsorber catalyst applied to a natural gas fired powerplant has demonstrated better than 99 percent reliability for more than 21,000 hours of operation while controlling NOx by more than 90 percent.[33] The experience with NOx adsorbers in these stationary power applications shows that NOx adsorbers can be highly effective for controlling NOx emissions for extended periods of operation with high reliability.

The NOx adsorber's ability to control NOx under oxygen rich (fuel lean) operating conditions has lead industry to begin applying NOx adsorber technology to lean burn engines in mobile source applications. NOx adsorber catalysts have been developed and are now in production for lean burn gasoline vehicles in Japan, including several vehicle models sold by Toyota Motor Corporation.[j] The 2000 model year saw the first U.S. application of this technology with the introduction of the Honda Insight, certified to the California LEV-I ULEV category standard. These lean burn gasoline applications are of particular interest because they are similar to diesel vehicle applications in terms of lean NOx storage and the need for periodic NOx regeneration under transient driving conditions. The fact that they have been successfully applied to these mobile source applications shows clearly that NOx adsorbers can work under transient conditions provided that engineering solutions can be found to periodically cause normally lean-burn exhaust conditions to operate in a rich regeneration mode.

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[j] Toyota requires that their lean burn gasoline engines equipped with NOx adsorbers are fueled on premium gasoline in Japan, which has an average sulfur content of six ppm.

       iii.   *Can NOx Adsorbers be applied to Diesel Engines?*

NOx adsorbers work to control NOx emissions by storing the NOx pollutants on the catalyst surface during oxygen rich engine operation (lean burn engine operation) and then by periodically releasing and reducing the NOx emissions under fuel rich exhaust conditions. This approach to controlling NOx emissions can work for a diesel engine provided that the engine and emission control system can be designed to work in concert, with relatively long periods of oxygen rich operation (typical diesel engine operation) followed by brief periods of fuel rich exhaust operation. The ability to control the NOx emissions in this manner is the production basis for lean burn NOx emission control in stationary power systems and for lean burn gasoline engines. As outlined below we believe that there are several approaches to accomplish the required periodic operation on a diesel engine.

       (a)   With In-Cylinder Control Systems

The most frequently mentioned approach for controlling the exhaust chemistry of a diesel engine is through in-cylinder changes to the combustion process. This approach roughly mimics the way in which lean-burn gasoline engines function with NOx adsorbers. That is the engine itself changes in operation periodically between "normal" lean burn (oxygen rich) combustion and stoichiometric or even fuel rich combustion in order to promote NOx control with the NOx adsorber catalyst. For diesel engines this approach typically requires the use of common rail fuel systems which allow for multiple fuel injection events along with an air handling system which includes exhaust gas recirculation (EGR).

The normal lean burn engine operation can last from as little time as 15 seconds to more than three minutes as the exhaust NOx emissions are stored on the surface of the NOx adsorber catalyst. The period of fuel lean, oxygen rich, operation is determined by the NOx emission rate from the engine and the storage capacity of the NOx adsorber. Once the NOx adsorber catalyst is full (once an unacceptable amount of NOx is slipping through the catalyst without storage) the engine must switch to fuel rich operation in order to regenerate the NOx adsorber.

The engine typically changes to fuel rich operation by increasing the EGR rate, by throttling the fresh air intake, and by introducing an additional fuel injection event late in the combustion cycle. The increased EGR rate works to decrease the oxygen content of the intake air by displacing fresh air that has a high oxygen content with exhaust gases that have a much lower oxygen content. Intake air throttling further decreases the amount of fresh air in the intake gases again lowering the amount of oxygen entering the combustion chamber. The combination of these first two steps serves to lower the oxygen concentration in the combustion chamber, decreasing the amount of fuel required in order to reach a fuel rich condition. The fuel is metered then into the combustion chamber in two steps under this mode of operation. The first, or primary, injection event meters a precise amount of fuel in order to deliver the amount of

torque (energy) required by the operator demand (accelerator pedal input). The second injection event is designed to meter the amount of fuel necessary in order to achieve a net fuel rich operating condition. That is, the primary plus secondary injection events introduce an excess of fuel when compared to the amount of oxygen in the combustion chamber. The secondary injection event occurs very late in the combustion cycle so that no torque is derived from its introduction. This is necessary so that the switching between the normal lean burn operation and this periodic fuel rich operation is transparent to the user.

Additional ECM capability will be necessary to monitor the NOx adsorber and determine when the NOx regeneration events are necessary. This could be done in a variety of ways, though they fall into two general categories: predictive and reactive. The predictive method would estimate or measure the NOx flow into the adsorber in conjunction with the predicted adsorber performance to determine when the adsorber is near capacity. Then, upon entering optimal engine operating conditions, a NOx regeneration would be performed. This particular step is similar to an on-board diagnostic (OBD) algorithm waiting for proper conditions to perform a functionality check. During the NOx regeneration, sensors would determine how accurately the predictive algorithm performed, and adjust it accordingly. The reactive method is envisioned to monitor NOx downstream of the NOx adsorber and, if NOx slippage is detected, a regeneration event would be triggered. This method is dependent on good NOx sensor technology. This method would also depend on the ability to regenerate under any given engine operating condition, since the algorithm would be reacting to indications that the adsorber had reached its NOx storage capacity. In either case, we believe these algorithms are not far removed from those used today for other purposes. When used in combination with the sophisticated control systems that will be available, we expect that NOx regeneration events can be seamlessly integrated into engine operation such that the driver may not be aware that the events are taking place.

Using this approach of periodic switching between normal lean burn operation and brief periods of fuel rich operation all accomplished within the combustion chamber of a diesel engine is one way in which an emission control system for a diesel engine can be optimized to work with the NOx adsorber catalyst. This approach requires no new engine hardware beyond the air handling and advanced common rail fuel systems that many advanced diesel engines will have already applied in order to meet the Phase 1 EGR based NOx standard. For this reason an in-cylinder approach is likely to appeal to engine manufacturers for product lines where initial purchase cost is the most important factor in determining engine purchases. A Department of Energy (DOE) research program has already demonstrated that this approach can work.[34]

This in-cylinder approach is not without some drawbacks. The high EGR rates and very low oxygen content of the intake air supply during rich operation can lead to poor combustion quality, increased fuel consumption and increased PM formation. Since the all of the exhaust gases must be made rich under this approach, the amount of fuel added from the secondary

injection event can be substantial leading to an even greater increase in fuel consumption. Further the secondary injection event which occurs very late in the combustion cycle has the potential to lead to dilution of the engine lubricating oil with diesel fuel. This can occur when the fuel injection spray "over-penetrates" and impinges on the cylinder walls. The fuel on the cylinder walls is "scraped" into the engine crankcase by the same piston ring technology that is designed to control oil consumption. Dilution of the lubricating oil can lead to increased engine wear rates. Fortunately the period of fuel rich operation is typically very brief in relation to the period of normal lean burn operation. As an example lean burn operation may have a one minute duration while the fuel rich operation can be as brief as two seconds. The fact that the fuel rich operation occurs for only brief periods helps to alleviate concerns about this operating mode. Further, the complete emission control system can be designed to address concerns about the very brief increase in PM emissions through the use of a CDPF.

(b)   With External Control Systems

The in-cylinder approach to optimizing a diesel engine NOx emission control system to work with a NOx adsorber has several drawbacks which may make it a less desirable solution for heavy heavy-duty diesel engines which can have an extremely long engine life and for which fuel economy is a greater concern than initial purchase price. For these applications it would be desirable to develop a system which could function outside of the engine's combustion system independent of engine operating mode. This would allow the diesel engine itself to continue to be designed for maximum durability and minimum fuel consumption while always operating in an oxygen rich environment as is typical of today's diesel engines. This is precisely what is done today for NOx adsorber systems applied to stationary power sources.

One approach to accomplish this goal is through the use of a so called "dual-bed" or "multiple-bed" NOx adsorber catalyst system. Such a system is designed so that the exhaust flow can be partitioned and routed through two or more catalyst "beds" which operate in parallel. Multiple-bed NOx adsorber catalysts restrict exhaust flow to part of the catalyst during its regeneration. By doing so, only a portion of the exhaust flow need be made rich, reducing dramatically the amount of oxygen needing to be depleted and thus the fuel required to be injected in order to generate a rich exhaust stream. One simple example of a multiple bed NOx adsorber is the dual-bed system in Figure III.A-3. In this example, the top half of the adsorption catalyst system is regenerating under a low exhaust flow condition (exhaust control valve nearly closed), while the remainder of the exhaust flow is bypassed to a lower half of the system. A system of this type would have the following characteristics:

- Half of the system would operate with a major flow in an "adsorption mode", where most of the exhaust is well lean of stoichiometric ($\lambda > 1$ or $\gg 1$, typical

diesel exhaust), NO is converted to NO_2 over a Pt-catalyst, and stored as a metallic nitrate within the NOx adsorbent material.[k]

- The other half of the system would have its exhaust flow restricted to just a small fraction (~5 percent) of the total flow and would operate in a regeneration mode.
    - While the flow is restricted for regeneration, a small quantity of fuel is sprayed into the regenerating exhaust flow at the beginning of the regeneration event.
    - The fuel is oxidized by the oxygen in the exhaust until sufficient oxygen is depleted for the stored NOx to be released. This occurs at exhaust conditions of $\lambda \leq 1$.
    - At these conditions, NOx can also be very efficiently reduced to N_2 and O_2 over a precious metal catalyst.

- At the completion of regeneration, the majority of the flow can then be reintroduced into the regenerated half of the system by opening the flow control valve.

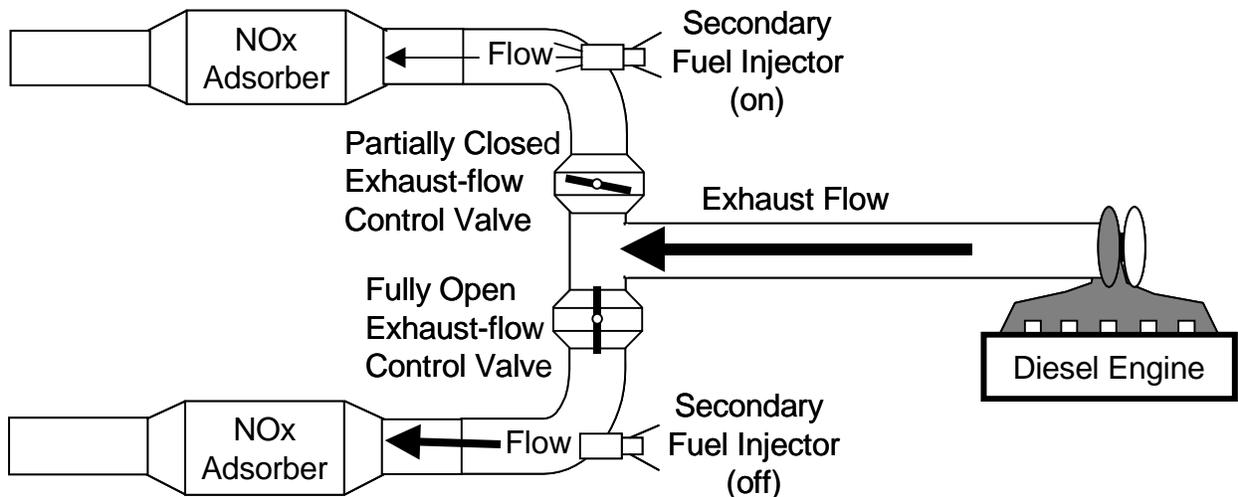- Simultaneously, flow is restricted to the other half of the system to allow it to regenerate.

Figure III.A-3. Schematic Representation of the Operation of a Dual-Bed NOx Adsorption Catalyst

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[k] A condition of $\lambda = 1$ means that there are precisely the needed quantity of reactants for complete reaction at equilibrium. $\lambda < 1$ means that there is insufficient oxygen, $\lambda > 1$ means that there is exess oxygen.

The primary advantage of such a system is to significantly reduce fuel consumption compared to single-bed approaches to NOx adsorber catalysts. Since oxygen must be depleted from the exhaust during regeneration of the NOx adsorber, depleting oxygen from a minor flow requires much less fuel than depleting oxygen from the entire exhaust as would be required with a single-bed NOx adsorber approach. Control of the system is also somewhat less complicated due to the segregation of the exhaust control external to the engine. This avoids some of the issues highlighted above with a secondary injection event used for an in-cylinder approach. The disadvantage is the need for additional hardware and a somewhat more complicated exhaust system.

Although the schematic shows two separate systems, the diversion of exhaust flow can occur within a single catalyst housing, and with a single catalyst monolith. Toyota has already demonstrated flow-switching within a single device with their new combination CDPF/NOx adsorber.[35] There may also be advantages to using more than one partition for the NOx adsorber system, for example:

- Multiple bed NOx adsorbers increase adsorption capacity by allowing more complete regeneration than is typically possible with a single bed.

- Use of multiple beds allows desulfation of one bed while normal NOx adsorption and regeneration events occur in other beds.

The NOx adsorber performance can be enhanced by incorporating a catalyzed diesel particulate filter (CDPF) into the system. A number of synergies exist between NOx adsorber systems and CDPFs. Both systems rely on conversion of NO to NO_2 over a Pt catalyst for part of their functioning. Partial oxidation reforming of diesel fuel to hydrogen and CO over a Pt-catalyst has been demonstrated for fuel-cell applications. A similar reaction to reform the fuel upstream of the NOx adsorber during regeneration would provide a more reactive reductant for desorption and reduction of NOx. Heavier fuel hydrocarbons are known to inhibit NOx reduction on the NOx adsorption catalyst since competitive adsorption by hydrocarbons on the precious metal sites inhibits NOx reduction during adsorber regeneration.[36] Partial oxidation of the secondary fuel injected into the exhaust during regeneration could lead to sooting of the fuel. Using a CDPF upstream of the NOx adsorber, but downstream of the secondary fuel injection, allows partial oxidation of the fuel hydrocarbons to occur over the Pt catalyst on the surface of the CDPF. The wall-flow design of the CDPF efficiently captures any soot formed during partial oxidation of the fuel injected into the exhaust, preventing any increase in soot emissions. The partial oxidation reaction over the CDPF is exothermic, which could be used increase the rate of temperature rise for the NOx adsorber catalyst after cold starts, similar to the use of light-off catalysts with cascade three-way catalyst systems.[37] The schematic in Figure III.A-4 shows the integrated dual-bed NOx adsorber and CDPF system developed for testing at EPA-NVFEL, along with a potential second generation of this type of emission control system having an

additional partition for NOx adsorption/regeneration and further integration of the components. The use of a DOC for HC and H2S control may be necessary downstream of the NOx adsorbers partitions.   The system tested at NVFEL is described in more detail in a memo to the docket for this final rule.[38]
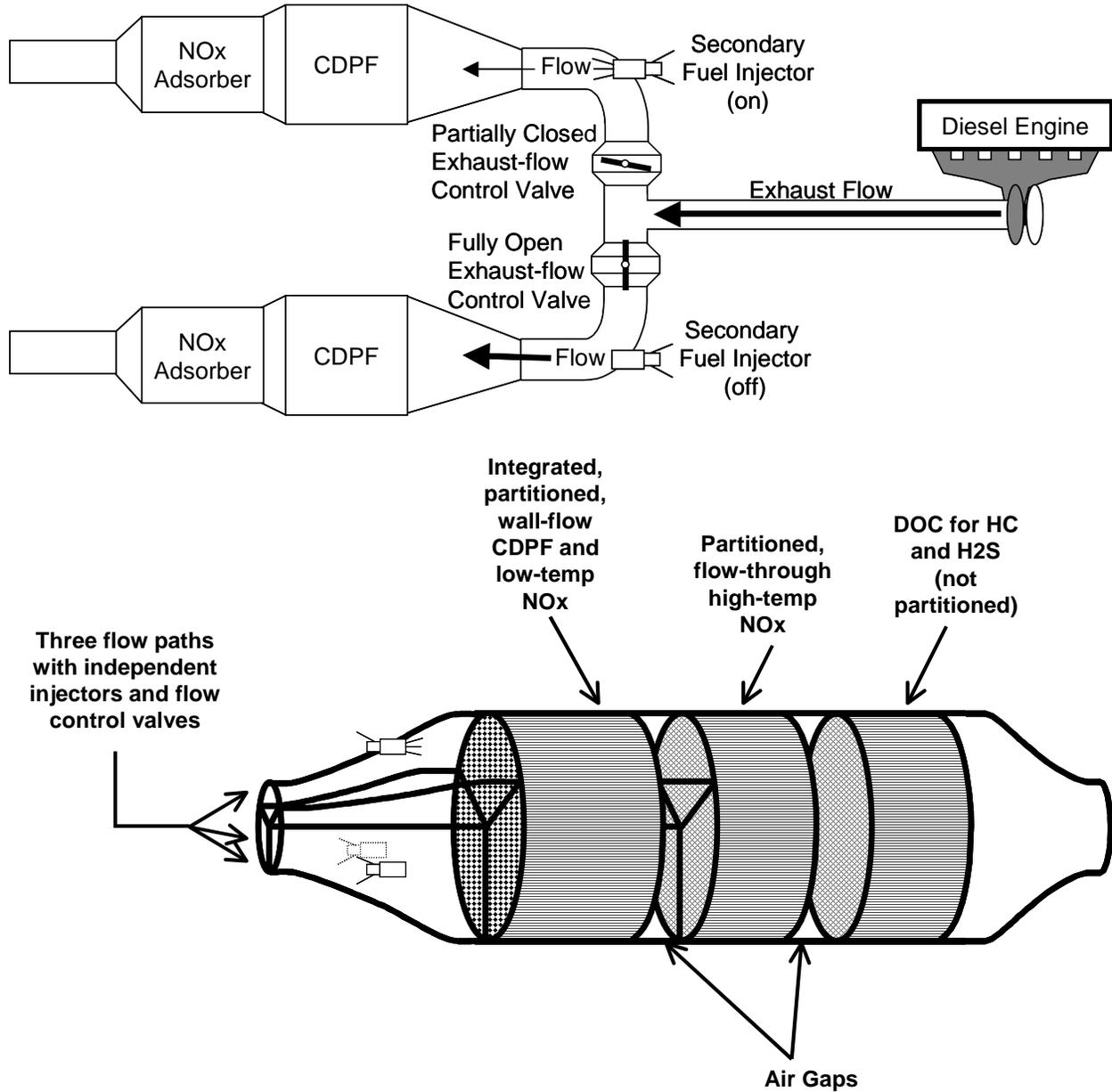
Figure III.A-4. A functional schematic representation of the PM and NOx exhaust emission control system tested at NVFEL shown together with one possible approach having the same functionality, but with further integration of components

A multiple-bed device of this type could be manufactured using a single, wall-flow monolith within a single housing with an internal valve for flow diversion. One possible configuration of such a system is shown in Figure III.A-4 above. Toyota has already demonstrated a similar concept, catalyst can with internal valving that uses a single wall-flow monolith. Components washcoated onto the surfaces of the wall-flow monolith of the Toyota system are used to provide oxidation catalysis for efficient PM regeneration, and also provide alkaline-metal adsorption sites for NOx storage during lean operation. The internal valving is currently used by Toyota for flow reversal, and the device was originally configured for the NOx adsorber function to regenerate as a single bed during full rich operation. A similar device could be reconfigured to allow diversion of the exhaust gases through alternating portions of the wall-flow monolith for a dual-bed approach. Integration of NOx and PM control components into this sort of dual-bed system would:

- allow the low-fuel consumption benefits of a multiple-bed NOx adsorber approach,
- provide a wall-flow CDPF for partial oxidation of the secondary fuel needed for regeneration
- reduce the mass of the entire system for improved performance
- reduce the size of the system for better integration of the system into applications with tight packaging constraints (as with some light- and medium-heavy-duty diesel engine applications)
- reduce the price of the system by allowing the use of a single monolith and housing instead of four or more separate devices.

iv.   *How Efficient are Diesel NOx Adsorbers?*

Research into applying the NOx adsorber catalyst to diesel exhaust is only a few years old but benefits from the larger body of experience with stationary power sources and with lean burn gasoline systems. In simplest terms the question is how well does the NOx adsorber store NOx under normal lean burn diesel engine operation, and then how well does the control system perform the NOx regeneration function. Both of these functions are affected by the temperature of the exhaust and of the catalyst surface. For this reason efficiency is often discussed as a function of exhaust temperature under steady-state conditions. This is the approach used in this section. The potential for both NOx storage and reduction to operate at very high efficiencies can be seen through careful emission control system design as described below.

(a)   At Storing NOx Under Oxygen Rich (fuel lean) Conditions?

The NOx storage function as described in section III.A.3.b.i., above, consists of oxidation of NO to NO_2 and then storage of the NOx as a metallic nitrate on the catalyst surface. The effectiveness of the catalyst at accomplishing these tasks is dependent upon exhaust temperature,

catalyst temperature, precious metal dispersion, NO storage volume, and transport time (mass flow rates through the catalyst). Taken as a whole these factors determine how effective a NOx adsorber based control system can store NOx under lean burn diesel engine operation.

Catalyst and exhaust temperature are important because the rate at which the desirable chemical reactions occur is a function of the local temperature where the reaction occurs. The reaction rate for NO to NO_2 oxidation and for NOx storage increases with increasing temperature. Beginning at temperatures as low as 100°C NO oxidation to NO_2 can be promoted across a platinum catalyst at a rate high enough to allow for NOx storage to occur. Below 100°C the reaction can still occur (as it does in the atmosphere) however the reaction rate is so slow as to make NOx storage ineffective below this temperature in a mobile source application. At higher exhaust temperatures, above 400°C, two additional mechanisms affect the ability of the NOx adsorber to store NOx. First the NO to NO_2 reaction products are determined by an equilibrium reaction which favors NO rather than NO_2. That is across the oxidation catalyst, NO is oxidizing to form NO_2 and NO_2 is decaying to form NO at a rate which favors a larger fraction of the gas being NO rather than NO_2. As this is an equilibrium reaction when the NO_2 is removed from the gas stream by storage on the catalyst surface, the NOx gases quickly "re-equilibrate" forming more NO_2. This removal of NO_2 from the gas stream and the rapid oxidation of NO to NO_2 means that in spite of the NO_2 fraction of the NOx gases in the catalyst being low at elevated conditions (30 percent at 400°C) the storage of NOx can continue to occur with high efficiencies, near 100 percent.

Unfortunately the other limitation of high temperature operation is not so easily overcome. The metallic nitrates that are formed on the catalyst surface and that serve to store the NOx emissions under fuel lean operating conditions can become unstable at elevated temperatures. That is, the metallic nitrates thermally decompose releasing the stored NOx under lean operating conditions allowing the NOx to exit the exhaust system "untreated." The temperature at which the storage metals begin to thermally release the stored NOx emissions varies dependent upon the storage metal or metals used, the relative ratio of the storage metals, and the washcoat design. Changes to catalyst formulations can change the upper temperature threshold for thermal NOx desorption by as much as 100°C.[39] Thermal stability is the primary factor determining the NOx control efficiency of the NOx adsorber at temperatures higher than 400-500°C.

> (b)   At Reducing NOx Under Fuel Rich Conditions?

The NOx adsorber catalyst releases stored NOx emissions under fuel rich operating conditions and then reduces the NOx over a three-way catalyst function. While the NOx storage function determines the NOx control efficiency during lean operation it is the NOx release and reduction function that determines the NOx control efficiency during NOx regeneration. Since NOx storage can approach near 100 percent effectiveness for much of the temperature range of

the diesel engine, the NOx reduction function often determines the overall NOx control efficiency.

NOx release can occur under relatively cool exhaust temperatures even below 200°C for current NOx adsorber formulations. Unfortunately the three-way NOx reduction function is not operative at such cool exhaust temperatures. The lowest temperature at which a chemical reaction is promoted at a defined efficiency (often 50 percent) is referred to as the "light-off" temperature. The 80 percent light-off temperature for the three-way catalytic NOx reduction function of current NOx adsorbers is between 200°C and 250°C. Therefore, even though NOx storage and release can occur at cooler temperatures, NOx control is limited under steady-state conditions to temperatures greater than this light-off temperature.

Under transient operation however, NOx control can be accomplished at temperatures below this NOx reduction light-off temperature provided that the period of operation at the lower temperature is preceded by operation at higher temperatures and provided that the low temperature operation does not continue for an extended period. This NOx control is possible due to two characteristics of the system specific to transient operation. First, NOx control can be continued below the light-off temperature because storage can continue below that temperature. If the exhaust temperature again rises above the NOx reduction light-off temperature before the NOx adsorber storage function is full the NOx reduction can then precede at high efficiency. Said another way, if the excursions to very low temperatures are brief enough, NOx storage can procede under this mode of operation followed by NOx reduction when the exhaust temperatures are above the light-off temperature. Although this sounds like a limited benefit because NOx storage volume is limited, in fact it can be significant, because the NOx emission rate from the engine is low at low temperatures. While the NOx storage rate may be limited such that at high load conditions the lean NOx storage period would be as short as 30 seconds, at the very low NOx rates typical of low temperature operation (operation below the NOx reduction light-off temperature) this storage period can increase dramatically. This is due to the NOx mass flow rate from the engine changing by several orders of magnitude between idle conditions and full load conditions. The period of lean NOx storage would be expected to increase in inverse proportion to the NOx emission rate from the engine. Therefore the period of NOx storage under light load conditions could likewise be expected to increase by orders of magnitude as well.

Transient operation can further allow for NOx control below the NOx reduction light-off temperature due to the thermal inertia of the emission control system itself. The thermal inertia of the emission control system can work to warm the exhaust gases to a local temperature high enough to promote the NOx reduction reaction even though the inlet exhaust temperatures are below the light-off temperature for the catalyst. In testing at NVFEL (discussed below in section III.A.3.b.v.c) exhaust temperatures were above the NOx reduction light-off temperature for testing at engine loads as low as 25 percent of full load. In as much as heavy-duty diesel engines are expected to operate under some load for most operating conditions, the exhaust temperature

will be expected to be above this threshold on average. Therefore the NOx emission control system temperature is expected to be above the light-off temperature for almost all operation, even when the engine exhaust temperature drops below this level due to the thermal inertia of the exhaust control system.

The combination of these two effects was observed during testing of NOx adsorbers at NVFEL especially with regards to NOx control under idle conditions. It was observed that when idle conditions followed loaded operation, for example when cooling the engine down after a completing an emission test, that the NOx emissions were effectively zero (below background levels) for extended periods of idle operation (for more than 10 minutes). Additionally it was discovered that the stored NOx could be released and reduced in this operating mode even though the exhaust temperatures were well below 250°C provided that the regeneration event was triggered within the first 10 minutes of idle operation (before the catalyst temperature decreased significantly). However, if the idle mode was continued for extended periods (longer than 15 minutes) NOx control eventually diminished. The loss of NOx control at extended idle conditions appeared to be due to the inability to reduce the stored NOx leading to high NOx emissions during NOx regeneration cycles.

NOx control efficiency with the NOx adsorber technology under steady-state operating conditions can be seen to be limited by the light-off temperature threshold of the three-way catalyst NOx reduction function. Further a mechanism for extending control below this temperature is described for transient operation and is observed in testing of NOx adsorber based catalyst systems.

(c)   For Overall Diesel NOx Control?

Overall NOx adsorber efficiency reflects the composite effectiveness of the NOx adsorber in storing, releasing and reducing NOx over repeated lean/rich cycles. As detailed above, exhaust temperatures play a critical role in determining the relative effectiveness of each of these catalyst functions. These limits on the individual catalyst functions can explain the observed overall NOx control efficiency of the NOx adsorber, and can be used to guide future research to improve overall NOx adsorber efficiency and the design of an integrated NOx emission control system.

At low exhaust temperatures overall NOx control is limited by the light-off temperature threshold of the three-way NOx reduction function in the range from 200°C to 250°C. At high temperatures (above 400° to 500°C) overall NOx control is limited by the thermal stability of the NOx storage function. For exhaust temperatures between these two extremes NOx control can occur at virtually 100 percent effectiveness.

The ability of the complete system including the engine and the emission control system to control NOx emissions consistently well in excess of 90 percent is therefore dependent upon the careful management of temperatures within the system. Figure III.A-5 provides a pictural representation of these constraints and indicates how well a diesel engine can match the capabilities of a NOx adsorber based NOx control system. The figure shows accumulated NOx emission (grams) over the heavy-duty FTP test for both a light heavy-duty (LHD) and a heavy heavy-duty (HHD) engine. The engine-out NOx emissions are shown as the dark bars on the graphs. The accumulated NOx emissions shown here, divided by the integrated work over the test cycle gives a NOx emission rate of 4 g/bhp-hr (the 1998 HD emission standard) for each of these engines. Also shown on the graph as a solid line is the steady-state NOx conversion efficiency for a NOx adsorber, MECA "B", used in testing at NVFEL (see section A.v.c below for more details on testing at NVFEL). The line has been annotated to show the constraint under low temperature operation (three-way catalyst light-off). The white bars on the graph represent an estimate of the tailpipe NOx emissions that could be realized from the application of the NOx adsorber based upon the steady-state efficiency curve for adsorber MECA "B". These estimated tailpipe emissions are highest in the temperature range below 250°C even though the engine out NOx emissions are the lowest in this region. This is due to the light-off temperature threshold for the NOx three-way reduction function.
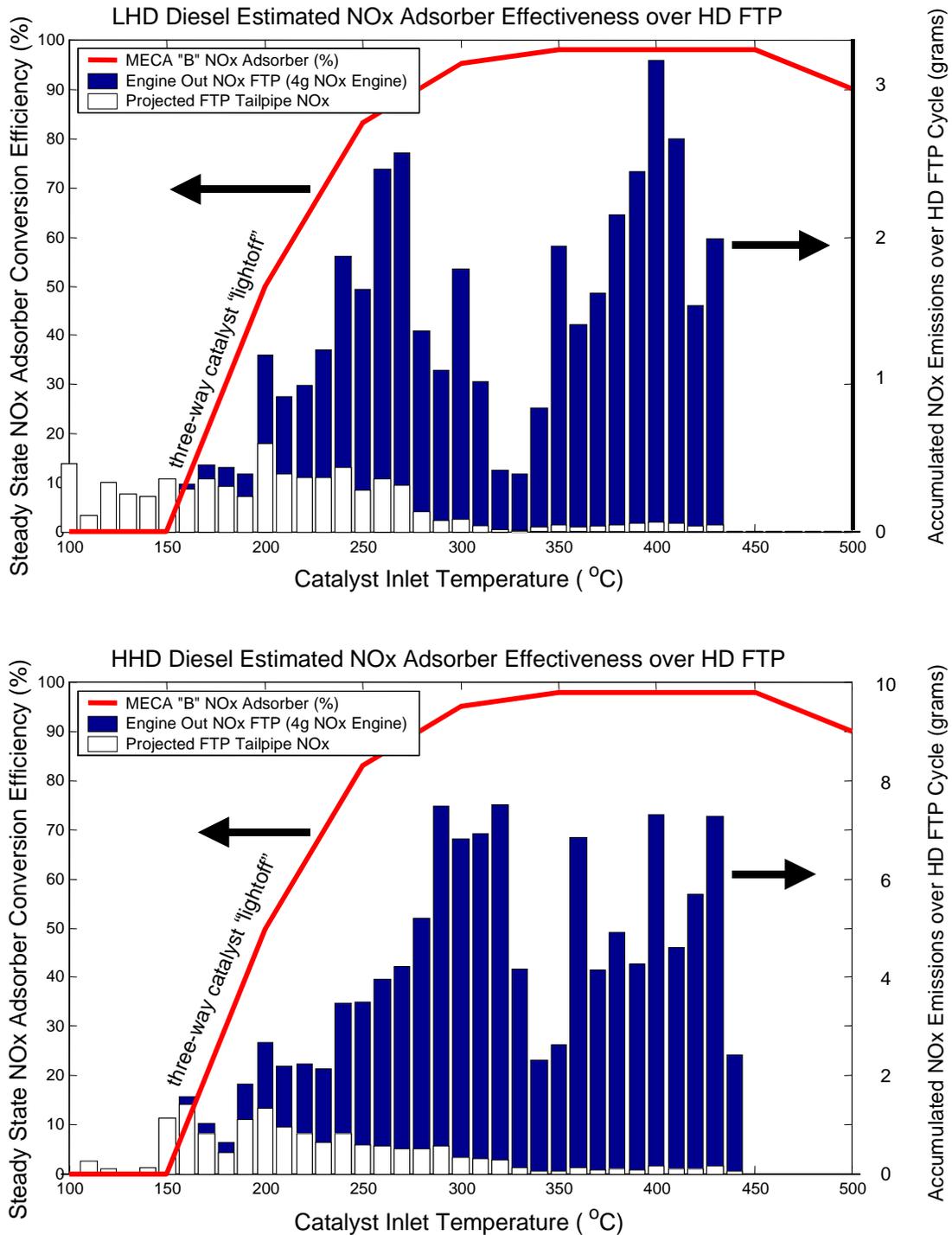
Figure III.A-5. NOx Adsorber Efficiency Characteristics versus Exhaust Temperature

Since the conversion efficiencies are based upon steady-state operation it is likely that the low temperature performance could be better than estimated here due to catalyst's ability to store the NOx emissions at these low temperatures and then to reduce them when transient operation raises the exhaust temperatures above the three-way light-off temperature. This assertion provides one explanation for differences noted between this approximation to the FTP NOx efficiency for the LHD engine shown in Figure III.A-5 above and actual NOx adsorber efficiency demonstrated with this engine in the NVFEL test program. Based upon the figure above (using the steady-state conversion estimate) the NOx adsorber catalyst should have provided less than an 84 percent reduction in NOx emissions over the FTP. However testing at NVFEL (detailed in section III.A.v.c) has already demonstrated a 90 percent reduction in NOx emissions with this same engine and catalyst pair without significant optimization of the system. Clearly then steady-state NOx adsorber performance estimates can underestimate the real NOx reductions realized in transient vehicle operation as typified by the HD FTP.

The tailpipe NOx emissions are the lowest in the range from 250°C to 450°C, even though this is where the majority of the engine out NOx emissions are created, because of the high overall NOx reduction efficiency of the NOx adsorber system under these conditions. At temperatures above 500°C the NOx conversion efficiency of the NOx adsorber can be seen to decrease. However since exhaust temperatures over the FTP for both of these engines remained below 450°C this loss of NOx control at high temperatures did not affect the overall NOx conversion efficiency. As detailed in section III.A.v.c below, this loss in NOx efficiency at high temperatures is a more important consideration for the SET test where higher exhaust temperatures at some test points are possible.

Figure III.A-5 shows that the temperature window of a current technology NOx adsorber catalyst is well matched to the exhaust temperature profiles of a light heavy-duty and a heavy heavy-duty diesel engine operated over the heavy-duty FTP driving cycle. Testing at NVFEL on the same light heavy-duty engine operated over the SET, shows that even for extended high load operation, as typified by the 100 percent load test points in the procedure, NOx conversion efficiencies remained near or above 90 percent (See discussion of the NVFEL test program in section III.A.3.b.v.c, below).

The discussion above makes it clear that when the engine and NOx adsorber based emission control system are well matched that NOx reductions can be far in excess of 90 percent. Conversely it can be inferred that if exhaust temperatures are well in excess of 500°C or well below 200°C for significant periods of engine operation then NOx control efficiency may be reduced. Fortunately the temperature window for NOx adsorber and diesel engines are inherently well matched as shown in Figure III.A-5. Researchers are known to be developing and testing new NOx adsorber formulations designed to increase the high temperature stability of the NOx adsorber.[40] The unique characteristics of the NOx adsorber will mean that integrated total

systems approaches will be needed in order to ensure compliance with the NOx standards under a wide range of conditions.

     v.   Progress in NOx Adsorber Development for Diesel Engines

          (a)   Industry Progress

The rapid development of the NOx adsorber technology is not limited to stationary power and gasoline applications, but includes markets where low sulfur diesel fuel is already available or has been mandated to coincide with future emission standards. In Japan, Toyota Motor Corporation has recently announced that it will begin introducing vehicles using its Diesel Particulate - NOx Reduction (DPNR) system in 2003. This system uses a NOx adsorber catalyst applied on the surface of a CDPF, providing greater than 80 percent reductions in both PM and NOx. This system is being designed to operate with fuel in Japan that will have a 50 ppm sulfur cap but only with a regulated useful life of 50,000 miles (for heavy heavy-duty diesel engines in the US, the regulated useful life is 435,000 miles). Toyota notes, however, that the DPNR system requires fuel with low sulfur content in order to maintain high efficiency and good fuel economy for a long duration.[41] In Europe, both Daimler Chrysler and Volkswagen, driven by a need to meet stringent Euro IV emission standards, have published results showing how they would apply the NOx adsorber technology to their diesel-powered passenger cars. Volkswagen reports that it has already demonstrated NOx emissions of 0.137 g/km (0.22 g/mi), a 71 percent reduction, on a diesel powered Passat passenger car equipped with a NOx adsorber catalyst.[42]

Likewise, in the United States, heavy-duty engine manufacturers have begun investigating the use of NOx adsorber technologies as a more cost effective means to control NOx emissions when compared to more traditional in-cylinder approaches. For example, Cummins Engine Company reported at DOE's 1999 Diesel Engine Emissions Reduction workshop, that they had demonstrated an 80 percent reduction in NOx emissions over the Supplemental Steady State test using a NOx adsorber catalyst.[43] In a separate presentation to members of the oil and engine industries, Cummins reported using a NOx adsorber catalyst to demonstrate 98 percent NOx control over the heavy-duty FTP, resulting in NOx emissions of 0.055 g/bhp-hr from an engine out level of approximately 3 g/bhp-hr.[44]

          (b)   DOE's DECSE Programs

The U.S. Department of Energy (DOE) has funded several test programs at national laboratories and in partnership with industry to investigate the NOx adsorber technology. Most of these test programs are part of the Advanced Petroleum Based Fuel (APBF) program of DOE's Office of Transportation Technology (OTT). These programs are often referred to as the Diesel Emission Control Sulfur Effects (DECSE) program which is itself one of the APBF

programs. Five reports documenting the DECSE program are available from the DOE OTT website (www.ott.doe.gov/decse) and were used extensively throughout our analysis.[45] [46] [47] [48] [49]

At Oak Ridge National Laboratory DOE researchers have been working to demonstrate the application of a NOx adsorber catalyst to a light-duty diesel passenger car. For this testing a Mercedes A170 diesel vehicle was evaluated on the light-duty chassis dynamometer driving cycle tests. The original equipment manufacturer (OEM) supplied catalysts were removed from the car and were replaced with a light-off catalyst, a NOx adsorber catalyst and a synthesis gas reductant system (bottled gases). The synthesis gas reductant system was designed to simulate exhaust constituents that could be produced by in-cylinder late cycle injection. Overall, NOx emissions were reduced by more than 90 percent when operating on three ppm sulfur diesel fuel. NOx reductions of 89 percent were realized over the USO6 test cycle while 96 percent reductions were realized over the SC03 test cycle. Subsequent testing of the vehicle revealed that poisoning of the catalyst with sulfur had substantially reduced the NOx adsorber performance of the car in a little as 600 miles of driving on 150 ppm sulfur fuel.[50]

The researchers concluded that NOx adsorbers show promise for enabling significant reductions in diesel NOx emissions based upon their demonstrated FTP and US06 emission results using a synthesis gas injection system to simulate late cycle, in-cylinder injection of diesel fuel. They further concluded that sulfur loading equivalent to 3,000 miles of operation on 30 ppm sulfur fuel caused a marked decrease in NOx conversion and that commercial use of the NOx adsorber will require effective desulfation, sulfur traps, or another solution to the sulfur poisoning problem.[51]

In the DECSE program, an advanced diesel engine equipped with common rail fuel injection and exhaust gas recirculation (EGR) was combined with a NOx adsorber catalyst to control NOx emissions. The system used an approach similar to the in-cylinder control approach described in section III.A.3.b.iii.a, above. Rich regeneration conditions are created for the NOx adsorber catalyst regeneration through increased EGR rates and a secondary injection event designed to occur late enough in the engine cycle so as not to change engine torque output. Using this approach, the DECSE program has shown NOx conversion efficiencies exceeding 90 percent over a catalyst inlet operating temperature window of 300°C to 450°C. This performance level was achieved while staying within the four percent fuel economy penalty target defined for regeneration calibration.[52]

(c)   NVFEL's NOx Adsorber Evaluation Program

As part of an effort to evaluate the rapidly developing state of this technology, the Manufacturers of Emission Control Association (MECA) provided four different NOx adsorber catalyst formulations to EPA for evaluation. Testing of these catalysts at the National Vehicle and Fuel Emission Laboratory (NVFEL) revealed that all four formulations were capable of

reducing NOx emissions by more than 90 percent over the broad range of operation in the SET procedure (sometimes called the EURO III test). At operating conditions representative of "road-load" operation for a heavy duty on-highway truck, the catalysts showed NOx reductions as high as 99 percent resulting in NOx emissions well below 0.1 g/bhp-hr from an engine out level of nearly 5 g/bhp-hr. Testing on the FTP has shown similarly good results, with hot start FTP NOx emissions reduced by more than 90 percent. These results demonstrate that significant NOx reductions are possible over a broad range of operating conditions with current NOx adsorber technology, as typified by the FTP and the SET procedures.

The test program at NVFEL can be divided into phases. The first phase began with an adsorber screening process using a single leg of the planned dual leg system. The goals of this screening process, a description of the test approach, and the results are described below. The next phase of the test program consisted of testing the dual leg system using a NOx adsorber chosen during the first phase in each of two legs.

Testing Goals -- Single Leg NOx Adsorber System

The goal of the NOx adsorber screening process was to evaluate available NOx adsorber formulations from different manufacturers with the objective of choosing an adsorber with 90 percent or better NOx reduction for continued evaluation. To this end, four different adsorber formulations were provided from three different suppliers. Since this was a screening process and since a large number of each adsorber formulation would be required for a full dual leg system, it was decided to run half of a dual leg system (a single leg system) and mathematically correct the emissions and fuel economy impact to reflect a full dual leg system. The trade-off was that the single leg system would only be able to run steady state modes, as the emissions could not be corrected over a transient cycle. The configuration used for this test was similar to that shown in Figure III.A-4, but with a catalyst installed on only one side of the system.

Test Approach -- Single Leg NOx Adsorber System

The single leg system consisted of an exhaust brake, a fuel injector, CDPF, and a NOx adsorber in one test leg. The other leg, the "bypass leg," consisted of an exhaust brake that opened when the test leg brake was closed; this vented the remainder of the exhaust out of the test cell. Under this set up, the test leg, i.e., the leg with the adsorber, was directed into the dilution tunnel where the emissions were measured and then compensated to account for emissions from the bypass leg. The restriction in the bypass leg was set to duplicate the backpressure of the test leg so that, while bypassing the test leg to conduct a NOx regeneration, the backpressure of the bypass leg simulated the presence of a NOx adsorber system. A clean-up diesel oxidation catalyst (DOC) downstream of the NOx adsorber was not used for this testing.

The measured emissions had to be adjusted to account for the lack of any NOx adsorber in the bypass leg. For this correction, it was assumed that the bypass leg's missing (virtual) adsorber would adsorb only while the actual leg was regenerating.   It was also assumed the virtual adsorber would have regeneration fuel requirements in proportion to its adsorbing time. The emissions performance of the virtual adsorber was assumed to be the same as the performance of the actual adsorber. With these assumptions, the gaseous emissions could be adjusted as detailed in a memo to the docket describing this test program further.[53]

Test Results -- Single Leg NOx Adsorber System

Two sets of steady-state modes were run with each adsorber formulation. These modes consisted of the SET modes and the AVL 8 mode composite FTP prediction.[1] The modes are illustrated in Figure III.A-6 and are numbered sequentially one through 20 to include both the eight AVL modes and the 13 SET modes (the idle mode is repeated in both tests). The mode numbers shown in the figure are denoted as "EPA" modes in the subsequent tables to differentiate between the AVL and SET modes which have duplicate mode numbers. The NTE zones are also shown in Figure III.A-6 to show that these two sets of modes give comprehensive coverage of the NTE zone. The modes were run with varying levels of automation, with the general strategy being to inject sufficient fuel during regeneration to obtain a lambda at or slightly fuel rich of stoichiometric ($\lambda \leq 1$). The NOx regenerations were then timed to achieve the desired NOx reduction performance. The adsorber formulations were identified as A, B, D, and E. Prior to testing, each set of adsorbers were aged at 2500 rpm, 150 lb-ft for 40 minutes, then 2500 rpm full load for 20 minutes, repeated for a total of 10 hours.

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[1] The AVL 8 mode test procedure is a steady-state test procedure developed by Anstalt für Verbrennungskraftmaschinen, Prof. Dr. Hans List (or Institute for Internal Combustion Engines) to approximate the transient FTP.
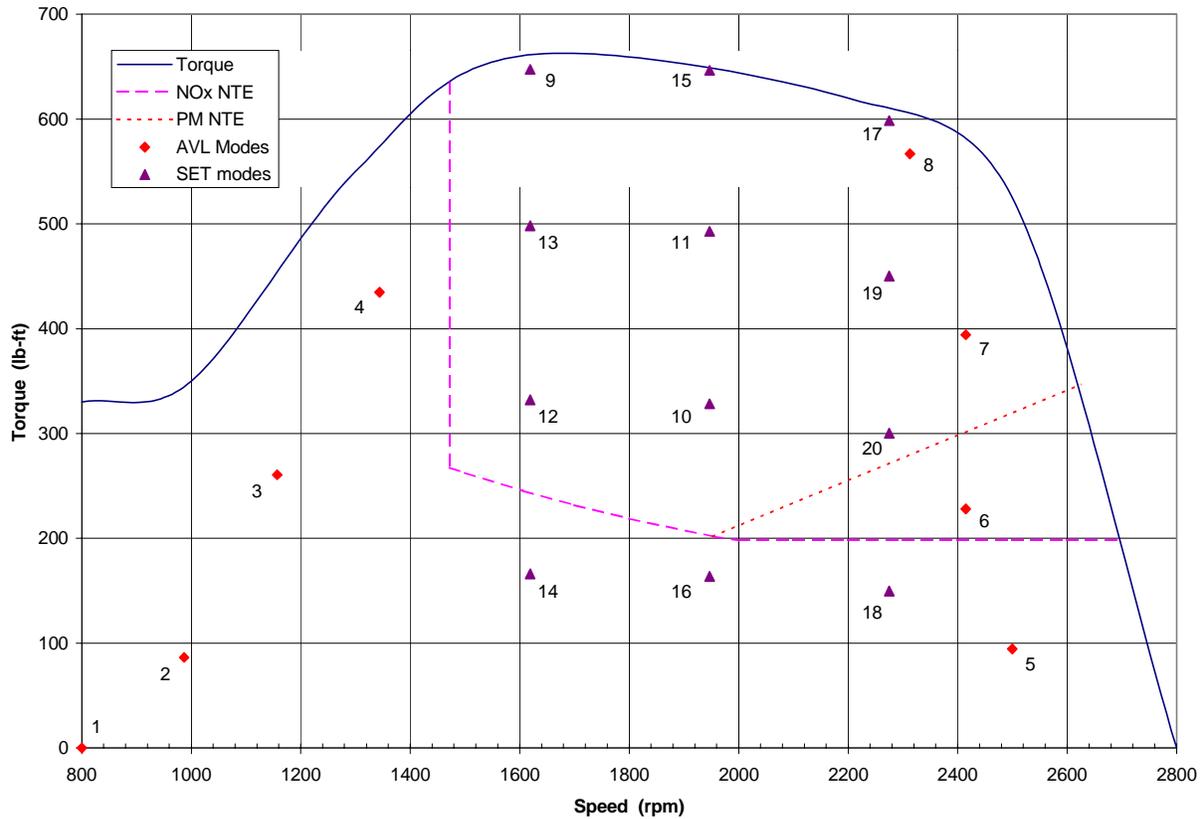
Figure III.A-6. Modal Definitions
(the mode numbers here correspond to the "EPA" modes given in the subsequent tables)

The SET and AVL Composite emission results, along with the NOx reduction performance vs. adsorber inlet temperature, are shown in Figures III.A-7 through III.A-10 for each of the tested NOx adsorber formulations. The SET composites for all four adsorber formulations had NOx reductions in excess of 90 percent with under a three percent FE impact. The HC emissions varied most widely, most likely due to differences in regeneration strategies, and to some extent, adsorber formulation. The HC emissions with the exception of adsorber "A" were very good, less than 0.1 g/hp-hr over the SET and less than 0.2 g/hp-hr over the AVL composite. It should be noted that no DOC was used to clean up the HC emissions.

Another point to note is that the EPA mode 1 data for each composite is the same. This is because EPA mode 1, low idle, is too cold for effective steady-state regeneration, but efficient NOx adsorption can occur for extended periods of time. For either of these composite tests, a regeneration would not be needed under such conditions and, therefore, the idle mode was

considered to have no FE impact (See discussion in section III.A.3.b.iv of this chapter). EPA mode 1 has very little impact on either composite in any case because of the low power and emission rate. EPA mode 2 also had very low steady-state temperatures, and the difficulty regenerating at this mode can be seen in the HC and FE impacts. But, like EPA mode 1, EPA mode 2 would adsorb for extended periods of time without need for regeneration.

The AVL composite showed greater differences between the adsorber formulations than the SET. Three of the adsorbers achieved greater than 90 percent NOx reduction over the AVL composites with the other adsorber at 84 percent NOx reduction. The greater spread in NOx reduction performance was, in part, due to this composite's emphasis on EPA mode 8, which was at the upper end of the NOx reduction efficiency temperature window. Adsorber E had an EPA mode 8 NOx reduction of 66 percent, and the NOx reduction efficiency vs. inlet temperature graph clearly shows that this formulation's performance falls off quickly above 450°C. In contrast, the other formulations do not show such an early, steep loss in performance. The FE impacts vary more widely also, partly due to the test engineers' regeneration strategies, particularly with the low temperature modes, and to the general inability to regenerate at very low temperature modes at steady-state. It should be noted that none of the regeneration strategies here can be considered fully optimized, as they reflect the product of trial and error experimentation by the test engineers. With further testing and understanding of the technology a more systematic means for optimization should be possible. In spite of the trial and error approach the results shown here are quite promising.

The AVL composite was developed as a steady state engine-out emission prediction of the HDDE transient cycle. With exhaust emission control devices, it loses some of its accuracy because of the inability of the emission control devices to be regenerated at the low temperature modes (EPA modes 1, 2, 5). In real world conditions, the HDDE does not come to steady-state temperatures at any of these modes, and the adsorber temperatures will be higher at EPA modes 1, 2, and 5 than the stabilized steady-state values used for this modal testing. Consequently, the actual HDDE transient cycle performance is expected to be much better than the composites would suggest (See discussion of transient testing below).

Based on the composite data and the temperature performance charts, amongst other factors, adsorber formulation B was chosen for further dual leg performance work. Both composites for this formulation were well above 90 percent. The NOx vs. temperature graph, Figure III.A-8, also shows that this formulation was a very good match for this engine.

					Base		Adsorber			
EPA	SET	SET	Speed	Torque	BSNOx	Inlet T	BSNOx	NOx Red	HC *	FE Impact
Mode	Mode	Weighting	(rpm)	(lb-ft)	(g/hp-hr)	(C)	(g/hp-hr)		(g/hp-hr)	*
1	1	15%	Idle	0	13.0	144	0.16	100%	0.00	0.0%
9	2	8%	1619	630	4.6	461	0.11	98%	0.92	2.4%
10	3	10%	1947	328	4.7	357	0.07	98%	1.02	2.0%
11	4	10%	1947	493	5.0	411	0.06	99%	1.35	2.6%
12	5	5%	1619	332	5.0	384	0.13	97%	0.11	1.3%
13	6	5%	1619	498	5.0	427	0.24	95%	0.81	1.6%
14	7	5%	1619	166	5.5	287	0.25	95%	1.39	3.3%
15	8	9%	1947	630	4.0	498	0.89	78%	0.36	1.9%
16	9	10%	1947	164	5.0	293	0.14	97%	1.88	4.1%
17	10	8%	2275	599	4.0	515	0.48	88%	1.12	3.8%
18	11	5%	2275	150	4.8	282	0.42	91%	0.68	3.5%
19	12	5%	2275	450	5.0	404	0.08	98%	0.62	3.0%
20	13	5%	2275	300	4.8	357	0.14	97%	0.70	2.8%
Composite Results					4.6		0.31	93%	0.91 *	2.6% *

					Base		Adsorber			
EPA	AVL	AVL	Speed	Torque	BSNOx	Inlet T	BSNOx	NOx Red	HC *	FE Impact
Mode	Mode	Weighting	(rpm)	(lb-ft)	(g/hp-hr)	(C)	(g/hp-hr)		(g/hp-hr)	*
1	1	42%	Idle	0	13.00	144	0.16	100%	0.00	0.0%
2	2	8%	987	86	8.80	172	0.83	91%	0.75	7.7%
3	3	3%	1157	261	8.40	346	0.36	96%	1.10	3.1%
4	4	4%	1344	435	5.90	430	0.20	97%	2.16	3.0%
5	5	10%	2500	94	5.50	286	0.37	93%	4.93	3.6%
6	6	12%	2415	228	4.60	325	0.08	98%	2.30	3.6%
7	7	12%	2415	394	4.90	386	0.10	98%	2.38	3.1%
8	8	9%	2313	567	4.10	505	1.06	74%	0.03	1.9%
Composite Results					4.9		0.44	91%	1.69 *	2.9% *

* HC results & FE Impacts do not reflect future potential as they are derived using a 5 g NOx engine which requires more frequent NOx regens than would result using a 2.5 g engine and the tested system was not a fully optimized engine & emission control system.
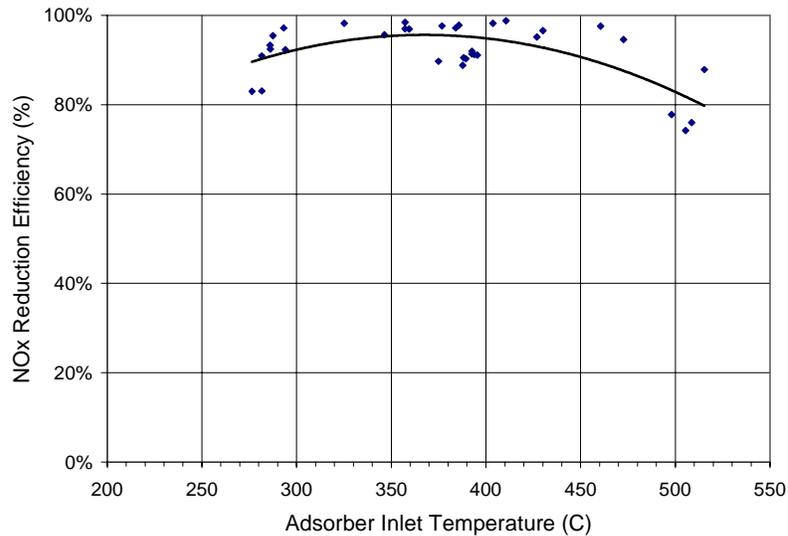

Figure III.A-7. SET & AVL Composites, and Temperature vs. NOx Chart for Adsorber A

					Base	Adsorber				
EPA	SET	SET	Speed	Torque	BSNOx	Inlet T	BSNOx	NOx Red	HC *	FE Impact
Mode	Mode	Weighting	(rpm)	(lb-ft)	(g/hp-hr)	(C)	(g/hp-hr)		(g/hp-hr)	*
1	1	15%	Idle	0	13.0	144	0.16	100%	0.00	0.0%
9	2	8%	1619	630	4.6	498	0.18	96%	0.01	1.2%
10	3	10%	1947	328	4.7	366	0.07	98%	0.04	0.5%
11	4	10%	1947	493	5.0	446	0.14	97%	0.01	1.5%
12	5	5%	1619	332	5.0	375	0.06	99%	0.08	0.7%
13	6	5%	1619	498	5.0	420	0.07	98%	0.10	2.3%
14	7	5%	1619	166	5.5	296	0.18	97%	0.10	0.3%
15	8	9%	1947	630	4.0	524	0.46	89%	0.01	3.2%
16	9	10%	1947	164	5.0	293	0.36	93%	0.05	0.4%
17	10	8%	2275	599	4.0	537	0.56	86%	0.04	4.3%
18	11	5%	2275	150	4.8	280	0.29	94%	0.03	0.4%
19	12	5%	2275	450	5.0	426	0.24	95%	0.04	4.3%
20	13	5%	2275	300	4.8	357	0.11	98%	0.02	0.9%
Composite Results					4.6		0.27	94%	0.03 *	2.2% *

					Base	Adsorber				
EPA	AVL	AVL	Speed	Torque	BSNOx	Inlet T	BSNOx	NOx Red	HC *	FE Impact
Mode	Mode	Weighting	(rpm)	(lb-ft)	(g/hp-hr)	(C)	(g/hp-hr)		(g/hp-hr)	*
1	1	42%	Idle	0	13.00	144	0.16	100%	0.00	0.0%
2	2	8%	987	86	8.80	162	0.56	94%	2.11	1.8%
3	3	3%	1157	261	8.40	355	0.30	96%	0.16	0.3%
4	4	4%	1344	435	5.90	446	0.09	98%	0.23	0.9%
5	5	10%	2500	94	5.50	263	0.66	88%	0.25	1.6%
6	6	12%	2415	228	4.60	346	0.11	98%	0.03	0.4%
7	7	12%	2415	394	4.90	403	0.05	99%	0.02	1.4%
8	8	9%	2313	567	4.10	544	0.73	82%	0.35	4.0%
Composite Results					4.9		0.33	93%	0.19 *	2% *

* HC results & FE Impacts do not reflect future potential as they are derived using a 5 g NOx engine which requires more frequent NOx regens than would result using a 2.5 g engine and the tested system was not a fully optimized engine & emission control system.
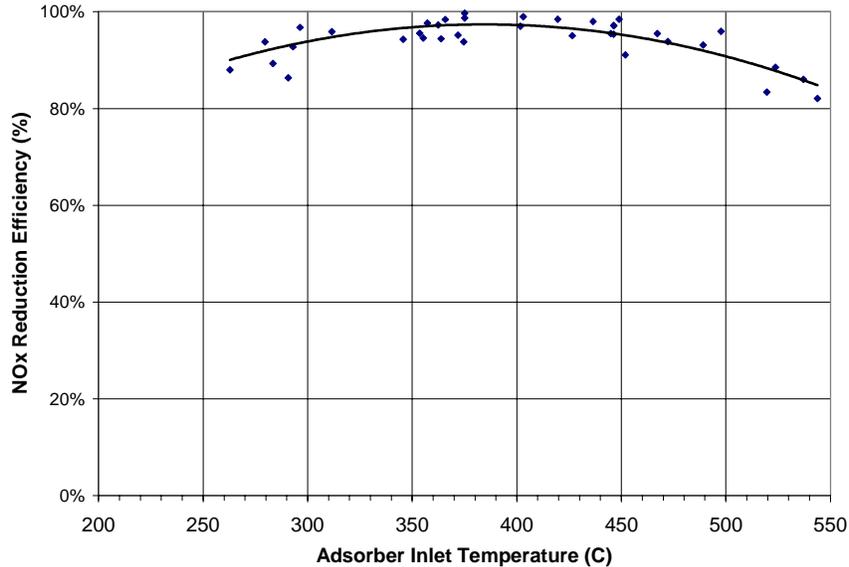

Figure III.A-8. SET & AVL Composites, and Temperature vs. NOx Chart for Adsorber B

EPA	SET	SET	Speed	Torque	Base BSNOx	Inlet T	BSNOx	NOx Red	HC *	FE Impact
Mode	Mode	Weighting	(rpm)	(lb-ft)	(g/hp-hr)	(C)	(g/hp-hr)		(g/hp-hr)	*
1	1	15%	Idle	0	13.00	144	0.16	100%	0.00	0.0%
9	2	8%	1619	630	4.60	451	0.18	96%	0.07	1.3%
10	3	10%	1947	328	4.70	356	0.14	97%	0.15	1.7%
11	4	10%	1947	493	5.00	400	0.09	98%	0.05	1.6%
12	5	5%	1619	332	5.00	377	0.07	99%	0.01	1.2%
13	6	5%	1619	498	5.00	431	0.11	98%	0.02	1.6%
14	7	5%	1619	166	5.50	305	0.23	96%	0.14	2.3%
15	8	9%	1947	630	4.00	501	0.16	96%	0.04	2.1%
16	9	10%	1947	164	5.00	303	0.15	97%	0.14	3.1%
17	10	8%	2275	599	4.00	489	0.93	93%	0.09	1.7%
18	11	5%	2275	150	4.80	278	0.57	88%	0.18	3.5%
19	12	5%	2275	450	5.00	391	0.12	98%	0.10	1.8%
20	13	5%	2275	300	4.80	330	0.21	96%	0.09	2.9%
Composite Results					4.6		0.28	94%	0.08 *	1.9% *

EPA	AVL	AVL	Speed	Torque	Base BSNOx	Inlet T	BSNOx	NOx Red	HC *	FE Impact
Mode	Mode	Weighting	(rpm)	(lb-ft)	(g/hp-hr)	(C)	(g/hp-hr)		(g/hp-hr)	*
1	1	42%	Idle	0	13.00	144	0.16	100%	0.00	0.0%
2	2	8%	987	86	8.80	162	0.56	94%	2.11	1.8%
3	3	3%	1157	261	8.40	359	0.08	99%	0.30	3.1%
4	4	4%	1344	435	5.90	427	0.14	98%	0.19	1.7%
5	5	10%	2500	94	5.50	273	1.25	77%	0.26	6.4%
6	6	12%	2415	228	4.60	301	0.52	89%	0.13	1.9%
7	7	12%	2415	394	4.90	363	0.66	87%	0.04	1.4%
8	8	9%	2313	567	4.10	493	0.31	92%	0.08	1.6%
Composite Results					4.9		0.51	90%	0.14 *	1.9% *

* HC results & FE Impacts do not reflect future potential as they are derived using a 5 g NOx engine which requires more frequent NOx regens than would result using a 2.5 g engine and the tested system was not a fully optimized engine & emission control system.
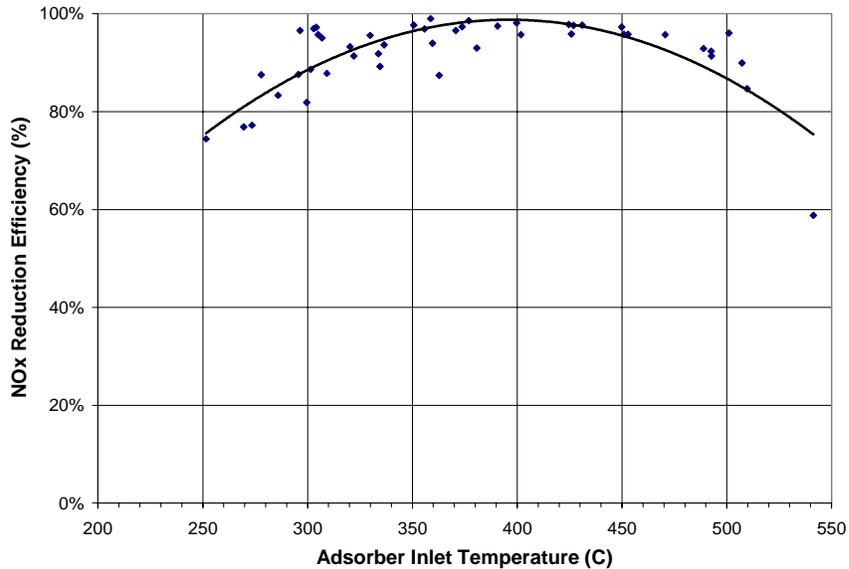

Figure III.A-9. SET & AVL Composites, and Temperature vs. NOx Chart for Adsorber D

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EPA Mode	SET Mode	SET Weighting	Speed (rpm)	Torque (lb-ft)	Base BSNOx (g/hp-hr)	Adsorber Inlet T (C)	BSNOx (g/hp-hr)	NOx Red	HC * (g/hp-hr)	FE Impact *
1	1	15%	Idle	0	13.00	144	0.16	100%	0.00	0.0%
9	2	8%	1619	630	4.60	455	0.47	89%	0.02	2.1%
10	3	10%	1947	328	4.70	343	0.07	98%	0.05	0.9%
11	4	10%	1947	493	5.00	442	0.36	93%	0.07	9.0%
12	5	5%	1619	332	5.00	377	0.08	98%	0.01	1.5%
13	6	5%	1619	498	5.00	419	0.29	94%	0.03	1.6%
14	7	5%	1619	166	5.50	412	0.14	98%	0.05	1.7%
15	8	9%	1947	630	4.00	392	0.05	99%	0.02	2.1%
16	9	10%	1947	164	5.00	294	0.09	98%	0.26	4.4%
17	10	8%	2275	599	4.00	492	0.95	76%	0.03	2.0%
18	11	5%	2275	150	4.80	388	0.11	98%	0.03	2.4%
19	12	5%	2275	450	5.00	391	0.12	98%	0.10	1.8%**
20	13	5%	2275	300	4.80	327	0.22	95%	0.02	1.4%
Composite Results					4.6	** Md 19 data from Adsorber D 0.33	0.33	93%	0.05 *	2.9% *

EPA Mode	AVL Mode	AVL Weighting	Speed (rpm)	Torque (lb-ft)	Base BSNOx (g/hp-hr)	Adsorber Inlet T (C)	BSNOx (g/hp-hr)	NOx Red	HC * (g/hp-hr)	FE Impact *
1	1	42%	Idle	0	13.00	144	0.16	100%	0.00	0.0%
2	2	8%	987	86	8.80	166	7.39	16%	1.02	71.9%
3	3	3%	1157	261	8.40	339	0.09	99%	0.05	2.3%
4	4	4%	1344	435	5.90	449	0.65	89%	0.01	2.1%
5	5	10%	2500	94	5.50	256	1.36	75%	0.91	15.8%
6	6	12%	2415	228	4.60	313	0.35	92%	0.21	5.6%
7	7	12%	2415	394	4.90	372	0.12	97%	0.10	2.6%
8	8	9%	2313	567	4.10	508	1.39	66%	0.04	3.3%
Composite Results					4.9		0.80	84%	0.16 *	5.4% *

* HC results & FE Impacts do not reflect future potential as they are derived using a 5 g NOx engine which requires more frequent NOx regens than would result using a 2.5 g engine and the tested system was not a fully optimized engine & emission control system.
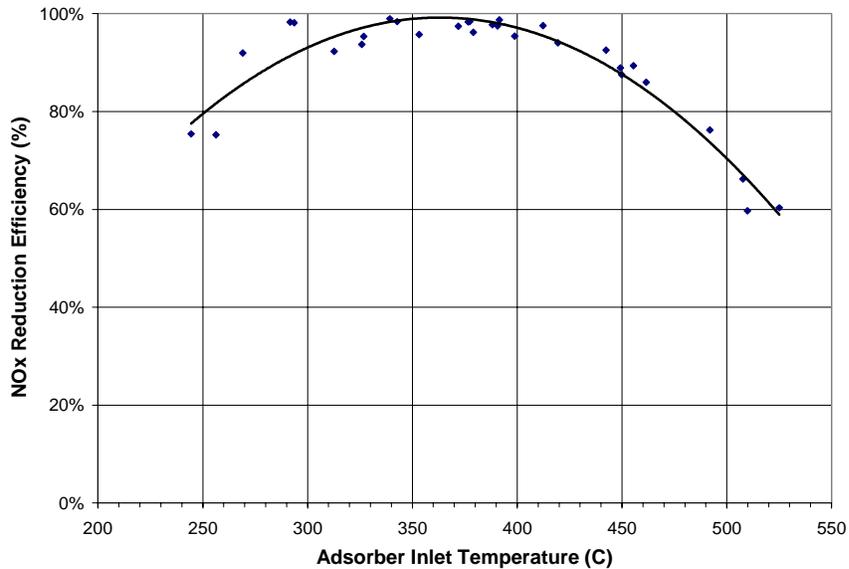

Figure III.A-10. SET & AVL Composites, and Temperature vs. NOx Chart for Adsorber E

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Testing Goals -- Dual Leg NOx Adsorber System

After completing the screening process and selecting NOx adsorber "B," the dual leg system was developed. The testing goal for the dual leg system was to demonstrate that NOx adsorbers are capable of 90 percent NOx reductions over the HD FTP and SET tests with a current production engine. Once the capability of the devices to achieve the NOx reductions is established, testing will be done to evaluate the impact of higher fuel sulfur levels (15 ppm) and aging effects on adsorber performance.

Testing Approach -- Dual Leg NOx Adsorber System

The steady state SET testing was conducted in a manner similar to that used in the screening process described above. The modes were run with varying levels of automation, with the general strategy being to inject sufficient fuel during regeneration to obtain a lambda at or slightly fuel rich of stoichiometric ($\lambda \leq 1$). The NOx regenerations were then timed to achieve the targeted 90 percent NOx reduction. Each mode was run twice by different calibrators to investigate the adsorber's emission and fuel usage sensitivity to different combinations of regeneration frequency and fuel injection rates. The regeneration control and optimization strategies are described in more detail in a memo to the docket for this rule.[54] The engine and the integrated dual-bed NOx adsorber/CDPF system are also described in more detail in section III.A.3.b.iii.

The transient HDDE FTP regeneration control was accomplished using a time-based regeneration schedule. This control regenerated on a prescribed schedule of time and fuel quantities so that regenerations occurred at predetermined engine conditions during the transient cycle. This control represents a simplified control strategy that was used due to the lack of time to develop a true, non-time based control algorithm.

The transient HDDE FTP results presented here are for hot-start cycles only. The adsorber system was not optimized for cold start performance and would not provide a meaningful assessment of adsorber warmup performance. In order to better simulate the "cold-soak-hot" procedure called for in the HDDE FTP, a preconditioning mode was chosen to provide adsorber temperatures at the start of the "hot" cycle that would be similar to those found following the "cold-soak" portion of the test. The mode chosen was EPA mode 10 (1947 rpm, 328 lb-ft) which resulted in adsorber inlet temperatures (i.e., at the outlet of the CDPF) at the start of the hot cycle of about 280°C. Another purpose for the preconditioning was to ensure the adsorbers were in the same condition at the start of each test. Given that our regeneration control system did not automatically take into account the starting condition of the NOx adsorbers, this preconditioning was necessary to provide repeatable transient test results. We expect more realistic control systems would not need such preconditioning. For this preconditioning, the

adsorbers were regenerated frequently in order to ensure a consistent, relatively clean adsorber state at the start of the transient cycle. The preconditioning consisted of 30 seconds of regeneration followed by 30 seconds of adsorption as shown below in Figure III.A-11.
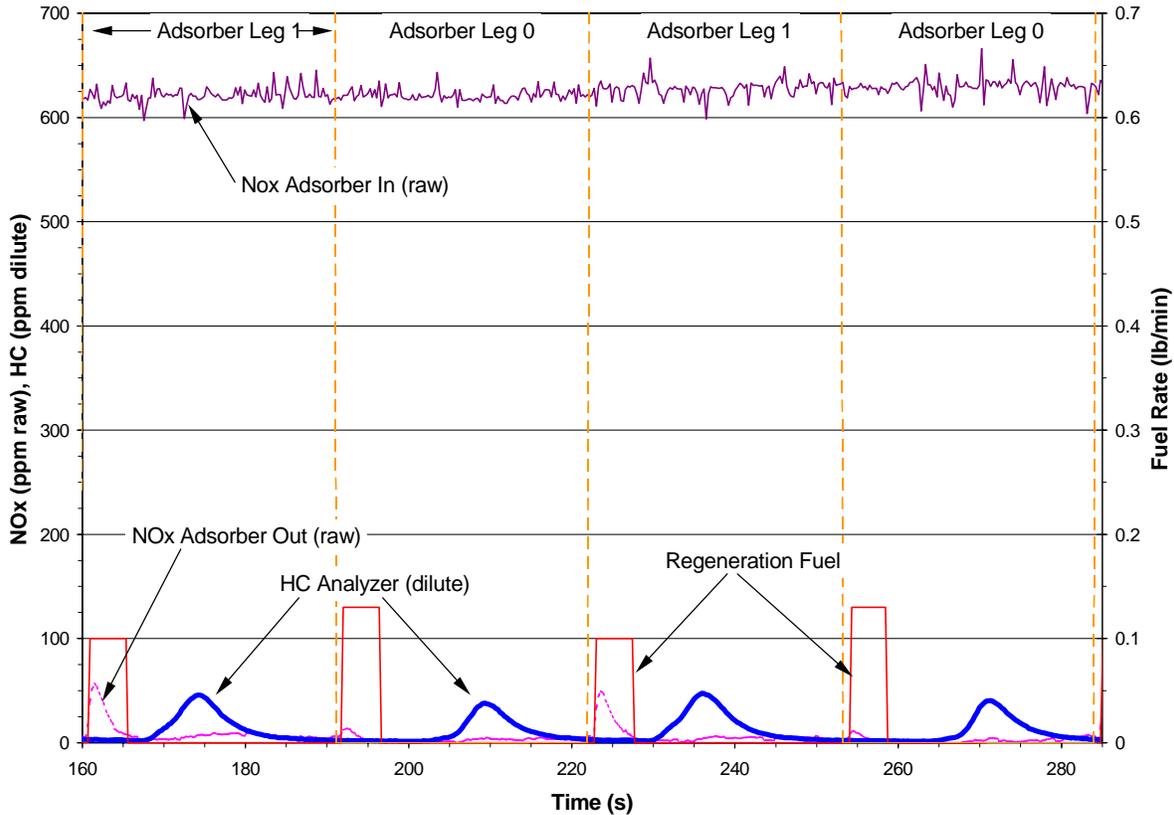

Figure III.A-11. NOx Adsorber FTP Preconditioning Cycle used in NVFEL Testing

Test Results -- Dual Leg NOx Adsorber System

Supplemental Emission Test (SET) Results

The SET is made up of the 13 Euro III modes. Several modes were run twice by different engineers, and the best calibration was chosen for the SET composite. Table III.A-2 shows the SET composite test results. These data show that 90 percent NOx reductions were possible over the SET composite, with a modal NOx reduction range from 77 percent to 98 percent. The adsorber NOx and HC reduction performance varied primarily as a function of exhaust temperature. Modes with high temperatures (>500°C) tended to have lower NOx reduction performance with this adsorber formulation. High temperature EPA modes 9, 15 and 17 had

lower performance due to the conflict between the high NOx mass flow rate from the engine, the reduced storage capacity of the NOx adsorber due to ongoing sulfur poisoning and the reduction in storage capacity near 500°C observed for this adsorber. The combination of these three factors resulted in higher NOx slippage during adsorption.

Table III.A-2. SET Composite Test Results with the Dual Leg NOx Adsorber System

EPA Mode	SET Mode	SET Weighting	Speed (rpm)	Torque (lb-ft)	Base BSNOx (g/hp-hr)	Inlet T (C)	Adsorber BSNOx (g/hp-hr)	NOx Red	HC (g/hp-hr)	FE Impact
1	1	15%	Idle	0	13.0	144	0.16	100%	0.00	0.0%
9	2	8%	1619	630	4.6	493	0.71	84%	0.16	1.8%
10	3	10%	1947	328	4.7	373	0.09	98%	0.28	2.3%
11	4	10%	1947	493	5.0	444	0.17	96%	0.24	2.8%
12	5	5%	1619	332	5.0	404	0.07	98%	0.14	2.6%
13	6	5%	1619	498	5.0	456	0.51	90%	0.11	1.9%
14	7	5%	1619	166	5.5	304	0.28	95%	0.11	2.5%
15	8	9%	1947	630	4.0	521	0.56	86%	0.31	2.2%
16	9	10%	1947	164	5.0	343	0.34	93%	0.09	1.9%
17	10	8%	2275	599	4.0	510	0.91	77%	0.54	1.8%
18	11	5%	2275	150	4.8	283	0.22	95%	0.56	3.0%
19	12	5%	2275	450	5.0	409	0.41	92%	0.13	1.8%
20	13	5%	2275	300	4.8	361	0.12	98%	0.10	2.0%
Composite Results					4.6		0.45	90%	0.27	2.1%

Conversely, low exhaust temperatures did not seem to impact the NOx storage capability of the adsorber. The ability to store at low temperatures is reflected in the low idle, EPA mode 1 performance. Nearly 100 percent NOx reduction could be realized for several minutes until the adsorber's storage sites filled up with NOx, particularly when coming down to low idle from higher temperature modes. NOx regeneration at low idle after the adsorber had cooled to a low steady-state temperature was not possible with this adsorber in our testing.

The FE impact was defined as the percent increase in fuel consumption caused by the adsorber regeneration fuel, or the mass of fuel used for regeneration, divided by the mass of fuel consumed by the engine during one regeneration and adsorption cycle. The FE impact varied from 1.8 to 3.0 percent depending on the mode. The low temperature modes (EPA modes 14, and 18) tended to have higher FE impacts. This was caused by the combination of low engine fuel consumption and low HC utilization efficiency seen with this catalyst at these temperatures. Given the short time spent calibrating the regeneration events, and the relatively early stage of catalyst development, we anticipate significant improvements in regeneration strategies will be possible.

Finally, at the time these SET emission tests were conducted, the NOx adsorber system had accumulated 172 hours of operation. During that time, 530 gallons of five ppm equivalent

(some three ppm and some six ppm) sulfur fuel was consumed by the engine and the NOx adsorber regenerations. For a light heavy-duty diesel truck averaging 20 miles per gallon of fuel, the 530 gallons of fuel consumed here would be equivalent to more than 10,000 miles of driving. No desulfations were performed during any of the testing, though it is expected that a NOx adsorber system in-use would have been desulfated at least twice, and more likely three times, during this amount of driving. Consequently, the adsorbers' performance would likely have been even better had they been desulfated as anticipated.

HDDE Transient FTP Test Results

The transient cycle data were taken with a DOC downstream of the NOx adsorbers and insulation on the exhaust from the engine to the CDPF. Table III.A-3 shows a timed regeneration schedule that was developed to switch between adsorbers, and to control when and how much fuel was injected for NOx regeneration. The first column in the table, "Time," represents the time from the start of the FTP and is used as a trigger to switch which leg is adsorbing. That is, at 30 seconds, and 60 seconds, etc., the adsorbing leg is bypassed and the previously bypassed leg starts adsorbing. The second column, "Fuel Rate," is the rate that fuel is injected into the bypassed (regenerating) adsorber. The final column is the time for which the fuel is injected at the rate specified in the previous column.

Figure III.A-3. Timed Regeneration Schedule for Switching between NOx Adsorber Legs

Time (s)	Fuel Rate (lb/min)	Injection Time (s)		Time (s)	Fuel Rate (lb/min)	Injection Time (s)
20	0	0		705	0.25	1.0
40	0	0		725	0.25	1.0
60	0	0		750	0.25	1.0
80	0	0		775	0.25	1.5
120	0.25	2.0		800	0.25	1.0
180	0.25	2.0		825	0.25	1.0
240	0.25	1.4		850	0.25	1.3
260	0.25	2.0		875	0.25	1.2
320	0.25	2.0		900	0.25	1.3
410	0.25	1.0		945	0	0
430	0.25	1.5		975	0	0
470	0.25	1.5		995	0.25	2.0
500	0.25	1.2		1070	0.25	2.0
530	0.25	1.5		1145	0	0
580	0.25	1.8		1165	0	0
630	0.25	1.0		1185	0	0
655	0.25	1.0		1200	0	0
680	0.25	1.0				

This regeneration strategy resulted in an average, over three HDDE FTPs, of 0.25 g/hp-hr NOx, 0.002 g/hp-hr PM and virtually no CO (See Table III.A-4). These represent greater than 90 percent reductions from the engine out emission levels. HC emissions decreased slightly compared to the baseline results. The relatively small HC emission increase was the result of HC slippage during NOx regeneration. Two factors contributed to the HC slippage. One factor was the relatively low HC oxidation efficiency of the DOC used downstream of the adsorbers. Back-to-back testing with a raw gas analyzer at several steady state modes revealed that the lightly catalyzed DOC (~10 g/ft^3 Pt) had an oxidation efficiency of less then 60 percent, where more effective DOCs are capable of 90 percent HC reductions. The second factor was that more fuel was injected than was absolutely necessary to release and reduce the stored NOx. The excess HC then contributed to HC emissions and FE Impact. Determining the best strategy for injecting the fuel so that it is most efficiently utilized will be important future work.

Table III.A-4. HDDE FTP Emissions from NVFEL Test Program

Emission	Run # 1	Run # 2	Run # 3	**Average**	Engine Out
NOx (g/hp-hr)	0.26	0.25	0.40	**0.25**	**3.66**
HC (g/hp-hr)	0.28	0.30	0.19	**0.28**	**0.29**
CO (g/hp-hr)	0.00	0.00	0.04	**0.00**	**1.46**
PM (g/hp-hr)	0.003	0.002	0.002	**0.002**	**0.089**
FE Impact (%)	2.4	2.3	2.3	**2.3**	**-**

At the time these FTP emission tests were conducted, the NOx adsorber system had accumulated 190 hours of operation. During that time, 653 gallons of five ppm equivalent (some three ppm and some six ppm) sulfur fuel was consumed by the engine and the NOx adsorber regenerations. For a light heavy-duty diesel truck averaging 20 miles per gallon of fuel, the 653 gallons of fuel consumed here would be equivalent to more than 13,000 miles of driving. No desulfations were performed during any of the testing, though it is expected that a NOx adsorber system in-use would have been desulfated at least twice, and more likely three or four times, during this amount of driving. Consequently, the adsorbers' performance would likely have been even better had they been desulfated as anticipated.

vi.   *Can a NOx Adsorber Equipped Diesel Engine Meet the NOx Standards?*

(a)   The FTP Standard

As discussed in section III.A.3.b.v.c, above, we have demonstrated in our laboratory that a NOx adsorber can produce greater than 90 percent reduction in NOx emissions over the hot-start HDDE transient FTP. The results of this test program lead us to believe NOx adsorbers will be capable of meeting the Phase 2 FTP NOx emission standard of 0.20 g/bhp-hr. The test program discussed under section III.A.3.b.v.c utilized a non-EGR equipped engine certified to the 1999 HD standards (i.e., the 4.0 g/bhp-hr NOx standard). As discussed in more detail in the test report in the docket which documents that test program, the regeneration strategy we used to produce the greater than 90 percent reduction had significant room for improvement.[55] For example, the raw data collected during the FTP runs indicated numerous regeneration events which were either unnecessary (because the adsorber bed was not slipping NOx) or regeneration events which released NOx but did not reduce the released NOx because the adsorber did not achieve a locally rich condition. We conclude from this initial test program that NOx reductions greater than 90 percent are achievable.

As mentioned, the data presented in Table III.A-4 is from an HDDE certified to the 4.0 g/bhp-hr NOx FTP standard. If the engine-out levels are reduced to achieve the 2004 FTP standards through the use of cooled EGR, our understanding of how the NOx adsorber technology works leads us to believe NOx adsorbers would also be capable of achieving 90 percent or greater emission reduction on a 2004 technology engine. Therefore, a NOx adsorber used on an HDDE certified to the Phase 1 FTP standard of 2.5 g/bhp-hr NMHC+NOx would enable a HDDE to achieve the Phase 2 FTP NOx standard. In addition, as discussed in section III.A.3.b.v.a of this chapter, one HDDE manufacturer has also demonstrated greater than a 98 percent NOx reduction over the HD FTP using a NOx adsorber.[56]

The results discussed above have all been demonstrated over the hot-start portion of the HDDE FTP, but the HD FTP also includes a cold-start test. A complete HDDE FTP involves three test sequences. First, the 20 minute duty-cycle test is run with the engine at the same ambient temperature as the test cell (between 68°F and 86°F). This can be achieved with a long soak period, or a forced engine cool-down. Second, following the cold-start run the engine undergoes a hot-soak which lasts 10 minutes. Finally, the 20 minute duty-cycle test is run a second time. The HDDE FTP emission level for the engine is determined by weighting the cold-start emissions by 1/7 (~14 percent), and weighting the hot-start emission results by 6/7 (~86 percent). Historically, for a HDDE not equipped with an exhaust emission control device, the cold-start and hot-start emissions from a HDDE have been nearly identical. However, with the application of exhaust emission control devices, such as a NOx adsorber, the cold-start test will become a design challenge for diesel manufacturers, just as it has been a design challenge for light-duty gasoline vehicle manufacturers for more than 20 years. As discussed above, NOx

adsorbers do have optimal temperature operating windows, and thus will represent a design challenge.

Manufacturers have a number of tools available to them to overcome this challenge:

- The volume, shape, and substrate material have a significant effect on the warm-up time of a NOx adsorber (just as they do for a light-duty three-way catalysts). Manufactures will optimize the make-up of the adsorber for best light-off characteristics, such as the thin-walled ceramic monolith catalysts typical of modern low emission light-duty gasoline applications.

- The packaging of the exhaust emission control devices, including the use of insulating material and air-gap exhaust systems, will also decrease light-off time, and we expect manufacturers to explore those opportunities.

- The location of the adsorber, with respect to it's proximity to the exhaust manifold, will have a significant impact on the light-off characteristics.

- As discussed in more detail in section III.A.3.b.iv.a, NOx adsorbers have the ability to store NOx at temperatures much less than the three-way catalyst function temperature operating window, on the order of 100°C. This is unlike the performance of light-duty gasoline catalysts, and it would allow the NOx adsorber to store NOx for some period of time prior to the light-off time of the three-way function of its catalyst, resulting in an overall lower effective temperature for the device.

These first four tools available to manufacturers all deal with system design opportunities to improve the cold-start performance of the NOx adsorber system. In addition, manufactures have a number of active tools which can be used to enhance the cold-start performance of the system. These include the use of engine start-up routines which have a primary purpose of adding heat to the exhaust to enhance NOx adsorber light-off. For example:

- retarded injection timing;

- intake air throttling;

- post-injection addition of fuel; or

- or increasing back-pressure with an exhaust brake or a VGT system.

We anticipate manufacturers will explore all of these tools in order to choose the best combination necessary to minimize light-off time and improve the cold-start FTP performance. Considering that the cold-start test is weighted approximately 14 percent, a manufacturer could achieve the composite FTP standard with considerably less than 90 percent reduction over the cold-start test, provided the hot-start test achieves greater than 90 percent reduction. Considering the tools available to manufacturers, and the several years of lead time, we conclude the cold-start FTP challenges will not be a barrier to the achievement of the FTP NOx standard established in this rule.

Based on the data and discussion provided in this section, we conclude that the Phase 2 FTP NOx standard is technologically feasible.

(b)   The Supplemental Emission Test (SET) NOx Standard

The SET NOx requirements established in the Phase 1 rule for 2007 sets an NMHC+NOx standard equal to 1.0 x the Phase 1 FTP standard of 2.5 g/bhp-hr NMHC+NOx. Based on current certification data for HDDE's which indicate HC values on the order of 0.2 to 0.3 g/bhp-hr, we anticipate that Phase 1 technology engines will achieve the SET standard with NOx emissions on the order of 2.2 to 2.3 g/bhp-hr. The SET standard promulgated with this Phase 2 rule sets a NOx standard of 1.0 x the Phase 2 FTP NOx standard of 0.20 g/bhp-hr. This requires a NOx reduction on the order of 90 percent or more from Phase 1 technology engines, which we have demonstrated is achievable with NOx adsorber technology, as discussed below.

Section III.A.3.b.iv.c discusses the NOx adsorber NOx reduction efficiencies as a function of exhaust gas temperature. The majority of these data show emission reductions of greater than 90 percent are achievable across the range of exhaust gas temperatures typical of a HDDE during the SET test procedure.

Section III.A.3.b.v.c contains SET emissions data from four different NOx adsorbers using a single-bed exhaust configuration tested at NVFEL. This test data shows NOx reductions for the SET between 93 and 94 percent. Section III.A.3.b.v.c also contains SET test data collected using a dual-bed exhaust configuration which achieved a 90 percent NOx reduction.

Based on the information presented in this Chapter, and summarized above, we conclude that the SET NOx standard will be technologically feasible by model year 2007.

(c)   The Not-to-Exceed NOx Standard

Under the Phase 1HDDE rule, NTE emission requirements for NMHC+NOx specify the NTE standard as 1.25 x FTP standard. The Phase 1 FTP standard for NMHC+NOx is 2.5 g/bhp-hr, therefore the Phase 1 NMHC+NOx NTE standard is 3.1 g/bhp-hr. As discussed in the Phase

1 final rule, we would expect the break-down between NMHC and NOx emissions for the Phase 1 NTE standard to mostly NOx emissions, on the order of 3.0 g/bhp-hr NOx, with the remainder being NMHC. In this rule, we have promulgated the Phase 2 engine NOx NTE standard as 1.5 x FTP standard, i.e., 1.5 x 0.20 g/bhp-hr, which is 0.30 g/bhp-hr NOx. Therefore, a 90 percent reduction in NOx emissions is necessary from Phase 1 engines in order to achieve the Phase 2 NTE NOx standard in this final rule. As discussed below, this 90 percent reduction is technologically feasible by model year 2007 across the range of engine operating conditions and ambient conditions subject to the NTE standards specified in this rule. Also as discussed below, some modifications to the NTE provisions to address technical issues which arise from the application of advanced NOx catalyst systems have been included in this final rule.

Section III.A.3.b.v.c ("NVFEL's NOx Adsorber Evaluation Program"), contains a description of the NOx adsorber evaluation test program run by our EPA laboratory. Included in that section is test data on four different NOx adsorbers for which extensive steady-state mapping was performed in order to calculate the SET and AVL composites (See Figures III.A-7 through III.A-10). Several of the test modes presented in these figure are not within the NTE NOx control zone, and would not be subject to the NTE standard. The following modes listed in these four figures are within the NTE NOx control zone, EPA modes 6 - 13, 15, 17, 19, 20. For all of the adsorbers, efficiencies of 90 percent or greater were achieved across the majority of the NTE zone. The region of the NTE zone for which efficiencies less than 90 percent were achieved were concentrated on or near the torque curve (EPA modes 8, 9, 15 and 17) with the exception of Adsorber D, for which EPA modes 6 and 7 achieved 87 percent and 89 percent NOx reduction respectively. However, Adsorber D was able to achieve NOx reductions greater than 90 percent along the torque curve. The test modes along the torque curve represent the highest exhaust gas temperature conditions for this test engine, on the order of 500°C. As discussed in Section III.A.3.b.iv.c, 500°C is near the current upper temperature limit of the peak NOx reduction efficiency range for NOx adsorbers, therefore it is not unexpected that the NOx reductions along the torque curve for the test engine are not as high as in other regions of the NTE zone. We would expect manufacturers to choose a NOx adsorber formulation which matches the exhaust gas temperature operating range of the engine. In addition, the steady-state mode data in section III.A.3.b.v.c were collected under stabilized conditions. In reality, actual in-use operation of a heavy-duty diesel vehicle would likely not see periods of sustained operation along the torque curve, and therefore the likelihood the NOx adsorber bed itself would achieve temperatures in excess of 500°C would be diminished. Regardless, as discussed in Section III.A.3.b.iv.a & c, we expect incremental improvements in the high temperature NOx reduction capabilities of NOx adsorbers between now and model year 2007 will be achieved through improvements in NOx adsorber formulations.[57, 58] As discussed above, only small improvements in the current characteristics are necessary in order to achieve 90 percent NOx reductions or greater across the NTE control zone.

As discussed in section III.A.3.b.vi.a, the use of advanced NOx reduction catalyst systems on HDDEs will present cold-start challenges for HDDEs similar to what light-duty gasoline manufacturers have faced in the past, due to the light-off characteristics of the NOx adsorber. We have previously discussed the tools available to HDDE manufacturers to overcome these challenges in order to achieve the Phase 2 FTP NOx standard. The majority of engine operation which occurs within the NTE control zone will occur at exhaust gas temperatures well above the light-off requirement of the NOx adsorbers. Figures III.A-7 through III.A-10 in section III.A.3.b.v.c ("NVFEL's NOx Adsorber Evaluation Program") show that all test modes which are within the NTE control zone have exhaust gas temperatures greater than 300°C which, as discussed in section III.A.3.b.iv, is well within the peak NOx reduction efficiency range of current generation NOx adsorbers. However, though the NTE does not include engine start-up conditions, it is conceivable that a HDDE vehicle which has not been warmed up could be started and very quickly be operated under conditions which are subject to the NTE standard; for example, within a minute or less of vehicle operation after the vehicle has left an idle state. The NTE regulations specify a minimum emissions sampling period of 30 seconds. Conceivably the vehicle emissions could be measured against the NTE provisions during that first minute of operation, and in all likelihood it would not meet the NTE NOx standard set in this final rule. Given that the FTP standards will require control of cold-start emissions, manufacturers will be required to pay close attention to cold start to comply with the FTP. As discussed above, operation with the NTE will be at exhaust gas temperatures within the optimum NOx reduction operating window of the NOx adsorbers. In addition, the NOx adsorber is capable of adsorbing NOx at temperatures on the order of 100°C. Figures III.A-7 through II.A.-10 all show NOx emission reductions on the order of 70 - 80 percent are achieved at temperatures as low as 250°C. Therefore, we have established a low temperature exhaust gas threshold of 250°C, below which specified NTE requirements do not apply.

The minimum emissions sample time established under the Phase 1 rule for NTE testing is 30 seconds. This testing requirement was premised on the use of Phase 1 HDDE emission control technology such as EGR and fuel injection timing. These emission control devices tend to produce brake-specific mass emission rates of exhaust pollutants which do not have periodic, orders of magnitude changes in brake-specific emission rates within the NTE control zone when averaged over a 30 second sample time. However, this is not the case for the NOx adsorber catalysts. As discussed throughout this Chapter, NOx adsorbers require active regeneration events, which can produce near zero mass emission rates during the adsorption phase, followed by relatively large spikes in NOx and HC emissions during the regeneration phase. This is illustrated in Figure III.A-11, above, which shows that engine out NOx under steady-state conditions on the order of 640 ±15 ppm, which is fairly continuous. However, the NOx emissions downstream of the NOx adsorber are both much lower and are characterized by periodic, orders of magnitude changes in emissions. The NOx concentration downstream of the adsorber shows periods of near zero ppm NOx lasting approximately 10 seconds, followed by a NOx peak with a maximum concentration of approximately 40 ppm, with the spike lasting

approximately four seconds. A similar phenomenon can be seen in Figure III.A-11 for hydrocarbon emissions. Because of this unique periodic nature of the NOx adsorber system, we have modified the NTE sample time provisions in the regulations, to assure that the emission spikes described above are not measured in isolation during NTE testing. The regulations specify that for any emission control system which requires discreet regeneration events, if a regeneration event occurs within the emissions sample, the emissions averaging time must be at least as long at the time between regenerations events (i.e., a regeneration period), multiplied by the number of full regeneration events within the sample period. This provision to account for regeneration events ensures that the unique operation of the NOx adsorber system will not cause an inappropriate exceedance of the NTE limits.

The NTE requirements apply not only during laboratory conditions applicable to the transient FTP and the SET tests, but also under the wider range of ambient conditions for altitude, temperature and humidity specified in the regulations. These expanded conditions will have minimal impact on the emission control systems expected to be used to meet the NTE NOx standard contained in this final rule. Under the Phase 1 rule, NTE emissions under the expanded NTE testing conditions can be as high as 3.1 g/bhp-hr NMHC+NOx (1.25 x 2004 FTP standard). Therefore, we assume here that engines in the 2007 time frame are capable of achieving 3.1 g/bhp-hr NMHC+NOx over the NTE without the use of the NOx control devices needed to achieve the standards contained in this rule. Thus, we analyze the impact of the NTE expanded testing conditions on the NOx adsorber, not on the base engine which is capable of achieving the Phase 1 NTE requirements. In general, it can be said that the performance of the NOx adsorbers are only effected by the exhaust gas stream to which the adsorbers are exposed. Therefore, the impact of ambient humidity, temperature, and altitude will only effect the performance of the adsorber to the extent these ambient conditions change the exhaust gas conditions (i.e., exhaust gas temperature and gas constituents). The ambient humidity conditions subject to the NTE requirement will have minimal, if any, impact on the performance of the NOx adsorbers. The exhaust gas itself, independent of the ambient humidity, contains a very high concentration of water vapor, and the impact of the ambient humidity on top of the products of dry air and fuel combustion are minimal. The effect of altitude on NOx adsorber performance should also be minimal, if any. The NTE test procedure regulations specify an upper bound on NTE testing for altitude at 5,500 feet above sea-level. The Phase 1 regulations require compliance with an NTE NMHC+NOx limit of 1.25 x the Phase 1 FTP standard up to this altitude. As discussed above, a 90 percent reduction in NOx emissions from the Phase 1 technology engines is, therefore, necessary to comply with the NTE standard established in this rule. The decrease in atmospheric pressure at 5,500 feet should have minimal impact on the NOx adsorber performance. Increasing altitude can decrease the air-fuel ratio for HDDEs which can in turn increase exhaust gas temperatures; however, as discussed in the Phase 1 final rule, Phase 1 technology HDDEs can be designed to target air-fuel ratios at altitude which will maintain appropriate exhaust gas temperatures, as well as maintain engine-out PM levels near the 0.1 g/bhp-hr level, within the ambient conditions specified by the NTE test procedure. Finally, the NTE regulations specify

ambient temperatures which are broader than the FTP temperature range of 68-86°F. The NTE test procedure specifies no lower ambient temperature bounds. However, as discussed above, we have limited NTE requirements on NOx (and HC) for engines equipped with NOx (and/or HC) catalysts to include only engine operation with exhaust gas temperatures greater than 250°C. Therefore, low ambient temperatures will not present any difficulties for NTE NOx compliance. The NTE also applies under ambient temperatures which are higher than the FTP laboratory conditions. The NTE applies up to a temperature of 100°F at sea-level, and up to 86°F at 5,500 feet above sea-level. At altitudes in between, the upper NTE ambient temperature requirement is a linear fit between these two conditions. At 5,500 feet, the NTE ambient temperature requirement is the same as the upper end of the FTP temperature range (86°F), and therefore will have no impact on the performance of the NOx adsorbers, considering that majority of the test data described throughout this chapter was collected under laboratory conditions. The NTE upper temperature limits at sea-level is 100°F, which is 14°F. (7.7°C) greater than the FTP range. This increase is relatively minor, and while it will increase the exhaust gas temperature, in practice the increase should be passed through the engine to the exhaust gas, and the exhaust gas would be on the order of 8°C higher. Within the exhaust gas temperature range for a HDDE during NTE operation, an 8°C increase is very small. As discussed above, we expect manufacturer to choose an adsorber formulation which is matched to a particular engine design, and we would expect the small increase in exhaust gas temperature which can occur from the expanded ambient temperature requirements for the NTE will be taken into account by the manufacturer when designing the complete emission control system.

To summarize, based on the information presented in this Chapter, and the analysis and discussion presented in this section, we conclude the NTE NOx requirement (1.5 x FTP standard) contained in this final rule will be feasible by model year 2007.

vii.   Are Diesel NOx Adsorbers Durable?

The considerable success in demonstrating NOx adsorbers, as outlined above, makes us confident that the technology is capable of providing the level of conversion efficiency needed to meet the NOx standard. However, there are several engineering challenges that will need to be addressed in going from this level of demonstration to implementation of durable and effective emission control systems on production vehicles. In addition to the generic need to optimize engine operation to match the NOx adsorber performance, industry will further need to address issues of system and catalyst durability. The nature of these issues are understood well today. The hurdles that must be overcome have direct analogues in technology issues that have been addressed previously in other automotive applications and are expected to be overcome with many of the same solutions. In this section we will describe the major technical hurdles to address in order to ensure that the significant emission reductions enabled through the application of NOx adsorbers is realized throughout the life of heavy-duty diesel vehicles. The

section is organized into separate durability discussions for the system components (hardware) and various near and long term durability issues for the NOx adsorber catalyst itself.

(a)   NOx Adsorber Regeneration Hardware Durability

The system we have described in Figure III.A-4 represents but one possible approach for generating the necessary exhaust conditions to allow for NOx adsorber regeneration and desulfation. The system consists of three catalyst substrates (for a CDPF/Low Temperature NOx Adsorber, a High Temperature NOx Adsorber and an Oxidation Catalyst), a support can that partitions the exhaust flow through the first two catalyst elements, three fuel injectors, and a means to divert exhaust flow through one or more of the catalyst partitions. Although not shown in the figure, a NOx /O_2 sensor is also likely to be needed for control feedback and on-board diagnostics(OBD). All of these elements have already been applied in one form or another to either diesel or gasoline engines in high volume long life applications.

The environment in an automotive exhaust system is extremely harsh with high temperatures, high humidity and high levels of mechanical vibration. For all of these reasons care is taken to design components to function over the life of a vehicle. Despite these challenging conditions, technologies have been developed over the last 30 or more years that are well suited to exhaust conditions. One of the most ubiquitous components on a modern passenger car is the three-way catalyst. Its design has evolved over the years so that today it is highly efficient, reliable and durable.

The NOx adsorber system we described earlier borrows several components from the gasoline three-way catalyst systems and benefits from the years of development on three way catalysts. The catalyst substrates (the ceramic support elements on which a catalyst coating is applied) have developed through the years to address concerns with cracking due to thermal cycling and abrasive damage from vehicle vibration. The substrates applied for diesel NOx adsorbers will be virtually identical to the ones used for today's passenger cars in every way but size. They are expected to be equally durable when applied to diesel applications as has already been shown in the successful application of diesel oxidation catalysts (DOCs) on some diesel engines over the last 10 years.

The NOx/O_2 sensor needed for regeneration control and OBD is another component originally designed and developed for gasoline powered vehicles (in this case lean-burn gasoline vehicles) that are already well developed and can be applied with confidence in long life for NOx adsorber based diesel emission control. The NOx/O_2 sensor is an evolutionary technology based largely on the current Oxygen (O_2) sensor technology developed for gasoline three-way catalyst based systems. Oxygen sensors have proven to be extremely reliable and long lived in passenger car applications, which see significantly higher temperatures than would normally be encountered on a diesel engine. Diesel engines do have one characteristic that makes the

application of NOx/O$_2$ sensors more difficult. Soot in diesel exhaust can cause fouling of the NOx/O$_2$ sensor damaging its performance. However this issue can be addressed through the application of a catalyzed diesel particulate filter (CDPF) in front of the sensor. The CDPF then provides a protection for the sensor from PM while not hindering its operation. Since the NOx adsorber is expected to be located downstream of a CDPF in each of the potential technology scenarios we have considered this solution to the issue of PM sooting is readily addressed.

The catalyst can, the metal frame that holds the catalyst substrates in place and in the exhaust system, is a well developed technology in its own right. The catalyst can must be able to secure the catalyst substrates while not chipping or cracking the substrates ceramic material. Further, in the system described in Figure III.A-4, the can must also partition the catalysts into two or more regions. While this is a departure from the way today's three-way catalysts are made, it is not a significant technical challenge when compared to the complex internal geometries of some muffler designs. Corrosion and weld durability are two other important considerations in can design. Advances in material science and manufacturing processes being made for gasoline catalysts designs to meet the stringent Tier 2 standards are expected address these issues.

Fuel is metered into a modern gasoline engine with relatively low pressure pulse-width-modulated fuel injection valves. These valves are designed to cycle well over a million times over the life of a vehicle while continuing to accurately meter fuel. Applying this technology to provide diesel fuel as a reductant for a NOx adsorber system is a relatively straightforward extension of the technology. A NOx adsorber system would expect to cycle far fewer times over its life when compared to the current long life of gasoline injectors. However, these gasoline fuel injectors designed to meter fuel into the relatively cool intake of a car can not be directly applied to the exhaust of a diesel engine. In the testing done at NVFEL, a similar valve design was used that had been modified in material properties to allow application in the exhaust of an engine. Thus while benefitting from the extensive experience with gasoline based injectors a designer can, in a relatively straightforward manner, improve the characteristics of the injector to allow application for exhaust reductant regeneration.

The NOx adsorber system we describe in Figure III.A-4 requires a means to partition the exhaust during regeneration and to control the relative amounts of exhaust flow between two or more regions of the exhaust system. Modern diesel engines already employ a valve designed to carry out this very task. Most modern turbochargers employ a wastegate valve that allows some amount of the exhaust flow to bypass the exhaust turbine in order to control maximum engine boost and limit turbocharger speed. These valves can be designed to be proportional, bypassing a specific fraction of the exhaust flow in order to track a specified boost pressure for the system. Turbocharger wastegate valves applied to heavy-duty diesel engines typically last the life of the engine in spite of the extremely harsh environment within the turbocharger. This same valve approach could be applied in order to accomplish the flow diversion required for diesel NOx

adsorber regeneration and desulfation. Since temperatures will be typically cooler at the NOx adsorber compared to the inlet to the exhaust turbine on a turbocharger, the control valve would be expected to be equally reliable when applied in this application.

Toyota has announced its intention to manufacture a CDPF/NOx adsorber based catalyst system (called Diesel Particulate NOx Reduction (DPNR)) for application to diesel trucks for the 2003 model year. Schematics of Toyota's prototype suggest that they are applying a wastegate type valve to accomplish flow diversion.[59] Also the catalyst can has been designed so that the exhaust flow-path can be redirected during the NOx regeneration step.[60] Toyota's intent to introduce this type of system in such a short time frame indicates that the technologies needed to apply the NOx adsorber catalyst are likely to be extensions of existing technologies with which Toyota is already well familiar.

Therefore, the system components needed to implement a NOx adsorber catalyst system reflect relatively straight-forward extensions of existing automotive hardware which has already demonstrated long life and high levels of reliability.

(b)   NOx Adsorber Catalyst Durability

In many ways a NOx adsorber like other motor vehicle catalysts, acts like a small chemical process plant. It has specific chemical processes that it promotes under specific conditions with different elements of the catalyst materials. There is often an important sequence to the needed reactions and a need to match process rates in order to keep this sequence of reactions going. Because of this need to promote specific reactions under the right conditions early catalysts were often easily damaged. This damage prevents or slows one or more the reactions causing a loss in emission control.

For example, contaminants from engine oil, like phosphorous or zinc, could attach to catalysts sites partially blocking the site from the exhaust constituents and slowing reactions. Similarly, lead added to gasoline in order to increase octane levels bonds to the catalyst sites causing poisoning as well. Likewise, sulfur which occurs naturally in petroleum products like gasoline and diesel fuel can poison many catalyst functions preventing or slowing the desired reactions. High exhaust temperatures experienced under some driving conditions can cause the catalyst materials to sinter (thermally degrade) decreasing the surface area available for reactions to decrease.

All of these problems have been addressed over time for the gasoline three-way catalysts, resulting in the high efficiency and long life durability now typical of modern vehicles. In order to accomplish this changes were made to fuels and oils used in vehicles (e.g., lead additives banned from gasoline, sulfur levels reduced in gasoline distillates, specific oil formulations for

aftertreatment equipped cars), and advances in catalysts designs were needed to promote sintering resistant catalyst formulations with high precious metal dispersion.

The wealth of experience gained and technological advancements made over the last 30 years of gasoline catalyst development can now be applied to the development of the NOx adsorber catalyst. The NOx adsorber is itself an incremental advancement from current three-way catalyst technology. It adds one important additional component not currently used on three-way catalysts, NOx storage catalyst sites. The NOx storage sites (normally alkali or alkaline earth metals) allow the catalyst to store NOx emissions with extremely high efficiency under the lean burn conditions typical of the diesel exhaust. It also adds a new durability concern due to sulfur storage on the catalyst.

This section will explore the durability issues of the NOx adsorber catalyst applied to diesel vehicles. It describes the effect of sulfur in diesel fuel on catalyst performance, the methods to remove the sulfur from the catalyst through active control processes, and the implications for durability of these methods. It then discusses these durability issues relative to similar issues for existing gasoline three-way catalysts and the engineering paths to solve these issues. This discussion shows that the NOx adsorber is an incremental improvement upon the existing three-way catalyst, with many of the same solutions for the expected durability issues.

(b.1)   Sulfur Poisoning of the NOx Storage Sites

The NOx adsorber technology is extremely efficient at storing NOx as a nitrate on the surface of the catalyst, or adsorber (storage) bed, during lean operation. Because of the similarities in chemical properties of SOx and NOx, the SO_2 present in the exhaust is also stored on the catalyst surface as a sulfate. The sulfate compound that is formed is significantly more stable than the nitrate compound and is typically not released during the NOx release and reduction step (NOx regeneration step). Since the NOx adsorber is virtually 100 percent effective at capturing SO_2 in the adsorber bed, sulfate compounds quickly occupy the NOx storage sites on the catalyst thereby reducing and eventually rendering the catalyst ineffective for NOx reduction (poisoning the catalyst).

Figure III.A-12 shows the effect of sulfur poisoning of a NOx adsorber catalyst as reported by the DOE DECSE program. The graph shows the NOx adsorber efficiency versus exhaust inlet temperature under steady-state conditions for a diesel engine based system. The three dashed lines that overlap each other show the NOx conversion efficiency of the catalyst when sulfur has been removed from the catalyst. The three solid lines show the effect of sulfur poisoning on the catalyst at three different fuel sulfur levels over different periods of extended aging (up to 250 hours). From the figure, it can be seen that even with three ppm sulfur fuel a significant loss in NOx efficiency can occur in as little as 250 hours. Further, it can be seen that quite severe sulfur poisoning can occur with elevated fuel sulfur levels. Catalyst performance

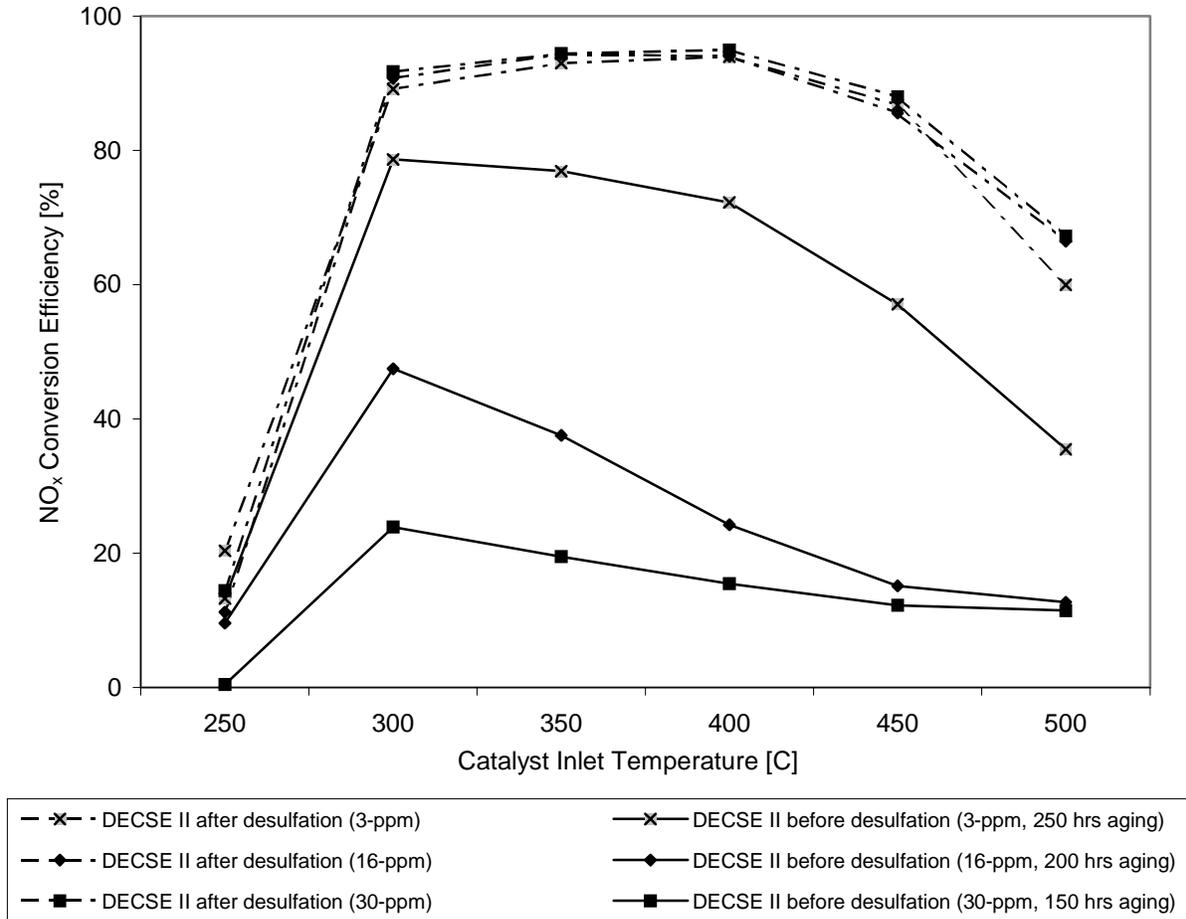was degraded by more than 70 percent over only 150 hours of operation when 30 ppm sulfur fuel was used.[61]

Figure III.A-12. Comparison of NOx Conversion Efficiency before and after Desulfation

The DECSE researchers drew three important conclusions from Figure III.A-12:

• Fuel sulfur, even at very low levels like three ppm, can limit the performance of the NOx adsorber catalyst significantly.

• Higher fuel sulfur levels, like 30 ppm, dramatically increase the poisoning rate, further limiting NOx adsorber performance.

• Most importantly though, the figure shows that if the sulfur can be removed from the catalyst through a desulfation (or desulfurization) event, the NOx adsorber can provide high NOx control even after exposure to sulfur in diesel fuel. This is

evidenced by the sequence of the data presented in the figure. The three high conversion efficiency lines show the NOx conversion efficiencies after a desulfation event which was preceded by the sulfur poisoning and degradation shown in the solid lines.

The increase in sulfur poisoning rate is important to understand in order to look at the means to overcome the dramatic sulfur poisoning shown here. Sulfur accumulates in the NOx storage sites preventing their use for NOx storage. In other words, they decrease the storage volume of the catalyst. The rate at which sulfur fills NOx storage sites is expected to be directly proportional to the amount of sulfur that enters the catalyst. Therefore, for a doubling in fuel sulfur levels a corresponding doubling in the SOx poisoning rate would be predicted. In the case of the two most commonly discussed fuel sulfur levels, our proposed 15 ppm sulfur cap with an expected in use average less than 10 ppm and a 50 ppm sulfur cap with a regulated average of 30 ppm, the difference in average sulfur levels would indicate at least a three-fold increase in sulfur poisoning rate (<10 versus 30).

The design of a NOx adsorber will need to address accommodating an expected volume of sulfur before experiencing unacceptable penalties in either lost NOx control efficiency or increased fuel consumption due to more frequent NOx regenerations. The amount of operation allowed before that limit is realized for a specific adsorber design will be inversely proportional to fuel sulfur quantity. In the theoretical case of zero sulfur, the period of time before the sulfur poisoning degraded performance excessively would be infinite. For a more practical fuel sulfur level like the <10 ppm average expected with a 15 ppm fuel sulfur cap the period of operation before unacceptable poisoning levels have been reached is expected to be less than 40 hours (with today's NOx adsorber formulations).[62] In the case of a 30 ppm average fuel sulfur level, this period would be reduced by a factor of three or more.

Future improvements in the NOx adsorber technology are expected due to its relatively early state of development. Some of these improvements are likely to include improvements in the kinds of materials used in NOx adsorbers to increase the means and ease of removing stored sulfur from the catalyst bed. However, because the stored sulfate species are inherently more stable than the stored nitrate compounds (from stored NOx emissions), we expect that future NOx adsorbers will continue to be poisoned by sulfur in the exhaust. Therefore a separate sulfur release and reduction cycle (desulfation cycle) will always be needed in order to remove the stored sulfur.

(b.2)   NOx Adsorber Desulfation

Numerous test programs have shown that sulfur can be removed from the catalyst surface through a sulfur regeneration step (desulfation step) not dissimilar from the NOx regeneration function.[63,64,65,66,67,68] The stored sulfur compounds are removed by exposing the catalyst to hot

and rich (air-fuel ratio below the stoichiometric ratio of 14.5 to 1) conditions for a brief period. Under these conditions, the stored sulfate is released and reduced in the catalyst. This sulfur removal process, called desulfation or desulfurization in this document, can restore the performance of the NOx adsorber to near new operation.

Most of the information in the public domain on NOx adsorber desulfation is based upon research done either in controlled bench reactors using synthetic gas compositions or on advanced lean burn gasoline engine vehicles. As outlined above these programs have shown that desulfation of NOx adsorber catalysts can be accomplished under certain conditions but the work does not directly answer whether NOx adsorber desulfation is practical for diesel engine exhaust conditions. The DECSE Phase II program answers that question.

Phase II of the DECSE program developed and demonstrated a desulfurization (desulfation) process to restore NOx conversion efficiency lost to sulfur contamination. The engine used in the testing was a high speed direct injection diesel selected to provide a representative source of diesel exhaust and various exhaust temperature profiles to challenge the emission control devices. The desulfation process developed in the DECSE Phase II program controlled the air to fuel ratio and catalyst inlet temperatures to achieve the high temperatures required to release the sulfur from the device. Air to fuel ratio control was accomplished in the program with exhaust gas recirculation (EGR) and a post injection of fuel to provide additional reductants. (See discussion in section III.A.3.b.iii.a, which describes this approach for NOx regeneration.) Using this approach the researchers showed that a desulfation procedure could be developed for a diesel engine with the potential to meet in-service engine operating conditions and acceptable driveability conditions. The NOx efficiency recovery accomplished in DECSE Phase II using this approach is shown in Figure III.A-12, above.

The effectiveness of NOx adsorber desulfation appears to be closely related to the temperature of the exhaust gases during desulfation, the exhaust chemistry (relative air to fuel ratio), and to the NOx adsorber catalyst formulation.[69, 70] Lower air to fuel ratios (more available reductant) works to promote the release of sulfur from the surface, promoting faster and more effective desulfation. Figure III.A-13 shows results from Ford testing on NOx adsorber conversion efficiency with periodic aging and desulfation events in a control flow reactor test.[71] The control flow reactor test uses controlled gas constituents that are meant to represent the potential exhaust gas constituents from a lean burn engine. The solid line with the open triangles labeled "w/o regen" shows the loss of NOx control over thirteen hours of testing without a desulfation event and with eight ppm sulfur in the test gas (this is roughly equivalent to 240 ppm fuel sulfur, assuming an air to fuel ratio for diesels of 30:1).[72] From the figure it can be seen that without a desulfation event, sulfur rapidly degrades the performance of the NOx adsorber catalyst. The remaining two lines show the NOx adsorber performance with periodic sulfur regeneration events timed at one hour intervals and lasting for 10 minutes (a one hour increment on 240 ppm fuel sulfur would be approximately equivalent to 34 hours of operation on seven

ppm fuel). The desulfation events were identical to the NOx regeneration events, except that the desulfation events occurred at elevated temperatures. The base NOx regeneration temperature for the testing was 350°C. The sulfur regeneration, or desulfation, event was conducted at two different gas temperatures of 550°C and 600°C to show the effect of exhaust gas temperature on desulfation effectiveness, and thus NOx adsorber efficiency. From Figure III.A-13 it can be seen that, for this NOx adsorber formulation, the NOx recovery after desulfation is higher for the desulfation event at 600°C than at 550°C.
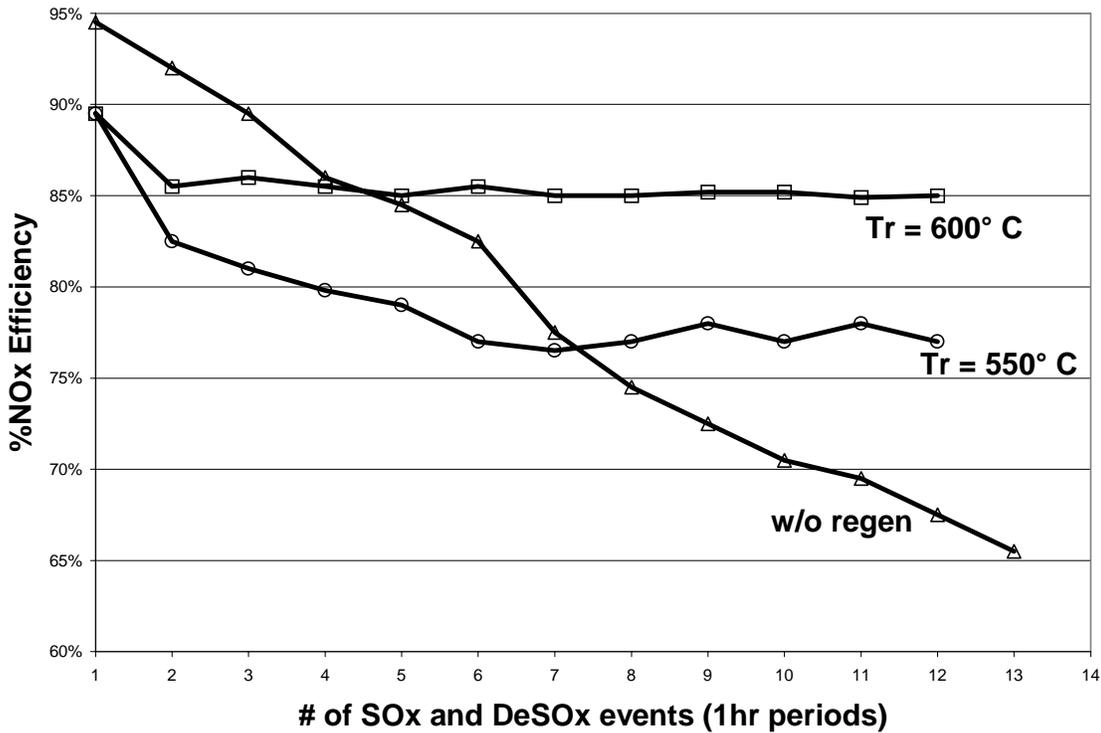
Figure III.A-13. Flow Reactor Testing of a NOx Adsorber with Periodic Desulfations

As suggested by Figure III.A-13, it is well known that the rate of sulfur release (also called sulfur decomposition) in a NOx adsorber increases with temperature.[73][74] However, while elevated temperatures directionally promote more rapid sulfur release, they also can directionally promote sintering of the precious metals in the NOx adsorber washcoat. The loss of conversion efficiency due to exposure of the catalyst to elevated temperatures is referred to as thermal degradation in this document.

(b.3)   Thermal Degradation

The catalytic metals that make up most exhaust emission control technologies, including NOx adsorbers, are designed to be dispersed throughout the catalyst into as many small catalyst "sites" as possible. By spreading the catalytic metals into many small catalyst sites, rather than into a fewer number large sites, catalyst efficiency is improved. This is because smaller catalyst sites have more surface area per mass, or volume, of catalyst when compared to larger catalyst sites. Since most of the reactions being promoted by the catalyst occur on the surface, increasing surface area increases catalyst availability and thus conversion efficiency. While high dispersion (many small catalyst sites) is in general good for most catalysts, it is even more beneficial to the NOx adsorber catalyst because of the need for the catalytic metal sites to perform multiple tasks. NOx adsorber catalysts typically rely on platinum to oxidize NO to NO_2 prior to adsorption of the NO_2 on an adjacent NOx storage site. Under rich operating conditions, the NOx is released from the adsorption site, and the adjacent platinum (or platinum + rhodium) catalyst site can serve to reduce the NOx emissions into N_2 and O_2. High dispersion, combined with NO oxidation, NOx storage and NOx reduction catalyst sites being located in close proximity, provide the ideal catalyst design for a NOx adsorber catalyst. High temperatures, especially under oxidizing conditions, can promote sintering of the platinum and other PGM catalyst sites, permanently decreasing NOx adsorber performance.

Catalyst sintering is a process by which adjacent catalyst sites can "melt" and regrow into a single larger catalyst site (crystal growth). The single larger catalyst site has less surface area available to promote catalytic activity than the original two or more catalyst sites that were sintered to form it. This loss in surface area decreases the efficiency of the catalyst.[75] High temperatures promote sintering of platinum catalysts especially under oxidizing conditions.[76] Therefore, it is important to limit the exposure of platinum based catalysts to high exhaust temperatures especially during periods of lean operation. Consequently, the desire to promote rapid desulfation of the NOx adsorber catalyst technology by maximizing the desulfation temperature and the need to limit the exposure of the catalyst to the high temperatures that promote catalyst sintering must be carefully balanced. An example of this tradeoff can be seen in Figure III.A-14 below, which shows the NOx conversion efficiency of three NOx adsorber catalysts evaluated after extended periods of sulfur poisoning followed by sulfur regeneration periods.[77] The three catalysts (labeled A, B, and C) are identical in formulation and size but were located at three different positions in the exhaust system of the gasoline direct injection engine used for this testing. Catalyst A was located 1.2 meters from the exhaust manifold, catalyst B 1.8 meters from the exhaust manifold and catalyst C was located 2.5 meters from the exhaust manifold. Locating the catalysts further from the engine lowered the maximum exhaust temperature and thus catalyst bed temperature experienced during the programmed sulfur regeneration cycle. Catalyst A experienced the highest catalyst bed temperature of 800°C, while catalyst C experienced the lowest catalyst bed temperature of 650°C. Catalyst B experienced a maximum catalyst bed temperature of 730°C. Figure III.A-14 shows that an optimum desulfation temperature exists which balances the tradeoffs between rapid sulfur regeneration and thermal degradation (thermal sintering) at high temperatures.
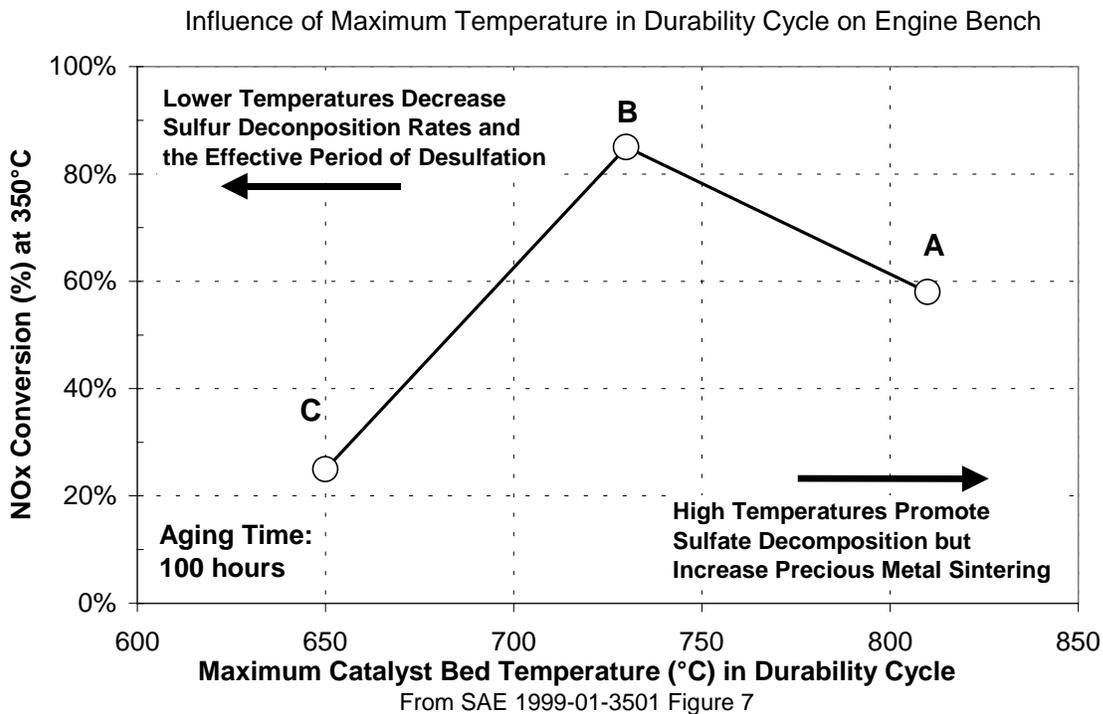
Influence of Maximum Temperature in Durability Cycle on Engine Bench

From SAE 1999-01-3501 Figure 7

Figure III.A-14. Influence of Maximum Catalyst Bed Temperature During Desulfation

The DECSE Phase II program, in addition to investigating the ability of a diesel engine / NOx adsorber based emission control system to desulfate, provides a preliminary assessment of catalyst durability when exposed to repeated aging and desulfurization cycles. Two sets of tests were completed using two different fuel sulfur levels (three ppm and 78 ppm) to investigate these durability aspects. The first involved a series of aging, performance mapping, desulfurization and performance mapping cycles. An example of this testing is shown below in Figure III.A-15. The graph shows a characteristic "sawtooth" pattern of gradual sulfur poisoning followed by an abrupt improvement in performance after desulfation. The results shown in Figure III.A-15 are for two identical catalysts one operated on 3 ppm sulfur fuel (catalyst S5) and the other operated on 78 ppm sulfur fuel (catalyst S7). For the catalyst operated on 3 ppm sulfur fuel the loss in performance over the ten hours of poisoning is noted to be very gradual. There appears to be little need to desulfate that catalyst at the ten hour interval set in the experiment. In fact it can be seen that in several cases the performance after desulfation is worse than prior to desulfation. This would suggest as discussed above, that the desulfation cycle can itself be damaging to the catalyst. In actual use we would expect that an engine operating on 3 ppm sulfur fuel would not desulfate until well beyond a ten hour interval and would be engineered to better withstand the damage caused by desulfation, as discussed later in this section. For the catalyst operated on 78

ppm sulfur fuel the loss in performance over the ten hour poisoning period is dramatic. In order to ensure continued high performance when operating on 78 ppm sulfur fuel the catalyst would require frequent desulfations. From the figure it can be inferred that the desulfation events would need to be spaced at intervals as short as one to two hours in order to maintain acceptable performance.
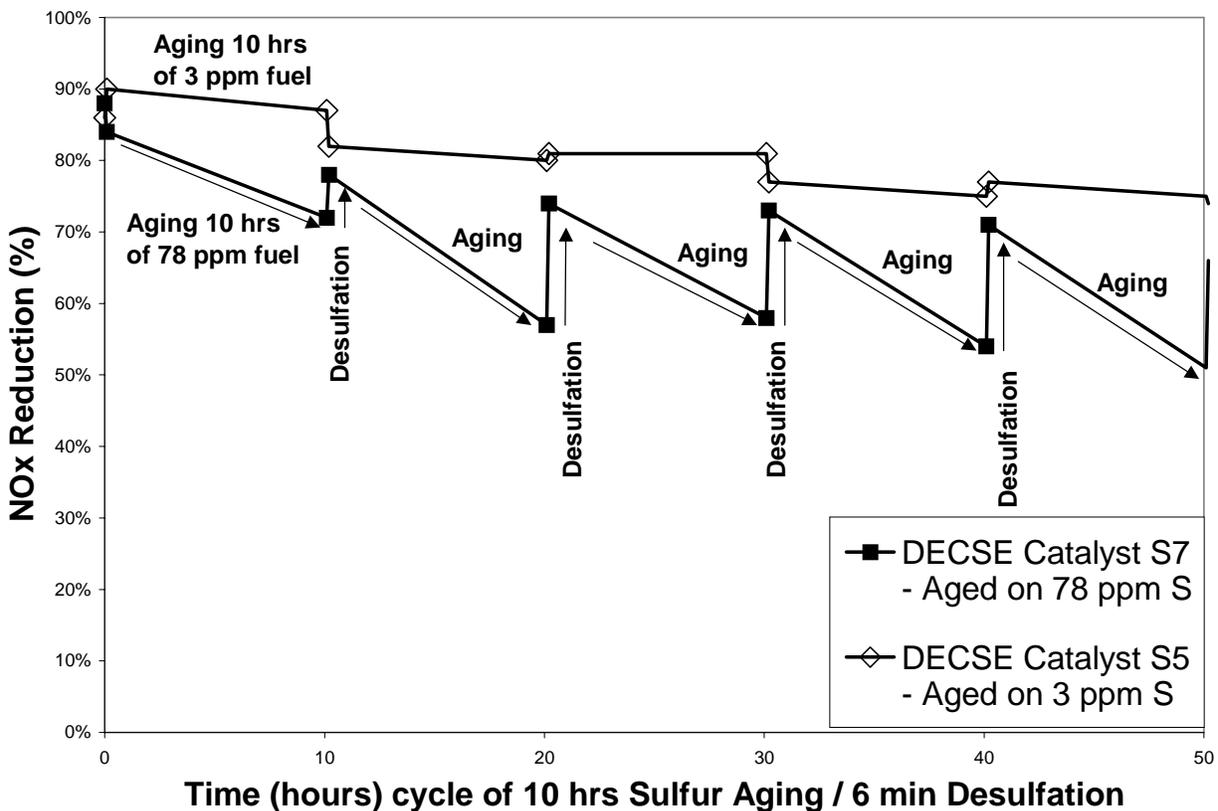

Figure III.A-15. Integrated NOx Conversion Efficiency following Aging and Desulfation

As a follow on to the work shown in Figure III.A-15, the desulfation events were repeated an additional 60 times without sulfur aging between desulfation events. This was done to investigate the possibility of deleterious affects from the desulfation event itself even without additional sulfur poisoning. As can be seen in Figure III.A-16, the investigation did reveal that repeated desulfation events even without additional sulfur aging can cause catalyst deterioration. As described previously, high temperatures can lead to a loss in catalyst efficiency due to thermal degradation (sintering of the catalytic metals). This appears to be the most likely explanation for the loss in catalyst efficiency shown here. For this testing, the catalyst inlet temperature was controlled to approximately 700°C, however the catalyst bed temperatures could have been higher.[78]

Based on the work in DECSE Phase II, the researchers concluded that

• The desulfurization procedure developed has the potential to meet in-service engine operating conditions and to provide acceptable driveability conditions.

• Although aging with 78 ppm sulfur fuel reduced NOx conversion efficiency more than aging with three ppm sulfur fuel as a result of sulfur contamination, the desulfurization events restored the conversion efficiency to nearly the same level of performance. However, repeatedly exposing the catalyst to the desulfurization procedure developed in the program caused a continued decline in the catalyst's desulfated performance.

• The rate of sulfur contamination during aging with 78 ppm sulfur fuel increased with repeated aging / desulfurization cycles (from 10 percent per ten hours to 18 percent per ten hours). This was not observed with the three ppm sulfur fuel, where the rate of decline during aging was fairly constant at approximately two percent per ten hours.
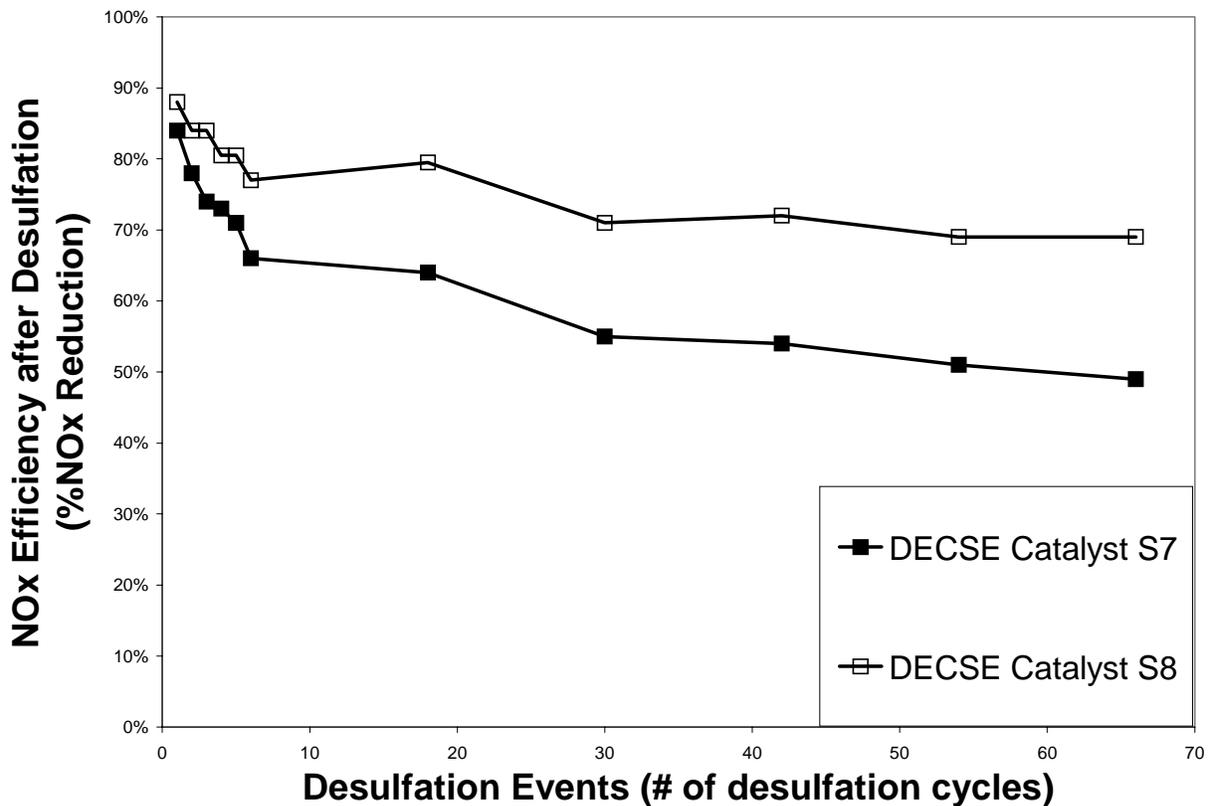

Figure III.A-16. Integrated NOx Conversion Efficiency after Repeated Desulfation

The data available today on current NOx adsorber formulations shows clearly that sulfur can be removed from the surface of the NOx adsorber catalyst. The initial high performance

after a desulfation event is then degraded over time by the presence of sulfur until the next desulfation event. The resulting characteristic NOx adsorber performance level over time exhibits a saw-tooth pattern with declining performance followed by rapid recovery of performance following desulfation. The rate of this decline increases substantially with higher fuel sulfur levels. In order to ensure a gradual and controllable decline in performance fuel sulfur levels must be minimized. However, even given very low fuel sulfur levels, gradual decline in performance must be periodically overcome. The development experience so far shows that diesel engines can accomplish the required desulfation event. The circumstances that effectively promote rapid desulfation also promote thermal degradation. It will therefore be important to limit thermal degradation.

(b.4)   Limiting Thermal Degradation

The issue of thermal degradation of NOx adsorber catalyst components is similar to the thermal sintering issues faced by light-duty three-way catalysts for vehicles developed to meet current California LEV and future Federal Tier 2 standards using platinum+rhodium (Pt+Rh) catalysts. Initial designs were marked by unacceptable levels of platinum sintering which limited the effectiveness of Pt+Rh catalysts. This problem has been overcome through modifications to the catalyst supports and surface structures that stabilize the precious metals at high temperatures (>900 °C). Stabilization of ceria components using Zirconium (Zr) has pushed the upper temperature limits of ceria migration to well over 1000 °C.[79, 80] Stabilization components can function in a number of ways. Some are used to "fill" structural vacancies, for example "open" locations within a crystalline lattice, thus strengthening the lattice structure. Such strengthening of crystalline lattice structures is particularly important at high temperatures. Other types of stabilizing components can act as obstructions within a matrix to prevent migration of components, or can enhance the mobility of other molecules or atoms, such as oxygen. An approach to the stabilization of NOx adsorber catalyst components that is similar to the approaches taken with LEV three-way catalyst designs should help to minimize thermal sintering of components during desulfation.

In many ways, limiting the thermal degradation of the NOx adsorber catalyst should be easier than for the gasoline three-way catalyst. Typical exhaust gas temperatures for a heavy light-duty gasoline truck (e.g., a Ford Expedition) commonly range from 450°C to more than 800°C during normal operation.[81] A heavy-duty diesel engine in contrast rarely has exhaust gas temperatures in excess of 500°C. Further, even during the desulfation event, exhaust temperatures are expected to be controlled well below 800°C. Therefore the NOx adsorber when applied to diesel engines is expected to see both lower average temperatures and lower peak temperatures when compared to an equivalent gasoline engine. Once thermal degradation improvements are made to NOx adsorber catalysts, thermal degradation will reasonably be expected to be less than the level predicted for future Tier 2 gasoline applications.

In addition to the means to improve the thermal stability of the NOx adsorber by applying many of the same techniques being perfected for the Tier 2 gasoline three-way catalyst applications, an additional possibility exists that the desulfation process itself can be improved to give both high sulfur removal and to limit thermal degradation. The means to do this might include careful control of the maximum temperature during desulfation in order to limit the exposure to high temperatures. Also, improvements in how the regeneration process occurs may provide avenues for improvement. Low air to fuel ratios (high levels of reductant) are known to improve the desulfation process. The high level of reductant may also help to suppress oxygen content in the exhaust to further limit thermal degradation.

Researchers at Ford Scientific Research Labs have investigated NOx adsorber catalyst desulfation (called DeSOx in their work) to answer the question: "if a regeneration process (sulfur regeneration) is required periodically, will the high temperatures required for the regeneration have deleterious, irreversible effects on NOx efficiency?" To explore the issue of NOx adsorber durability after repeated desulfation events, Ford conducted repeated sequential sulfur poisoning and desulfation cycles with a NOx adsorber catalyst. The results of their experiment are shown in Figure III.A-17.[82] As shown in Figure III.A-17, the NOx adsorber sample underwent more than 90 poisoning and desulfation cycles with 12 hours occurring between the end of one desulfation to the end of the next desulfation without a measurable loss in post-desulfation performance. This testing was done using a laboratory tool called a pulsator, used to study ceramic monolith catalyst samples. The ceramic test samples were heated to between 700°C and 750°C. These results indicate that for some combinations of temperatures and reductant chemistries the NOx adsorber can be repeatedly desulfated without a significant loss in NOx reduction efficiency. This work indicates that it is possible to optimize the desulfation process to allow for adequate sulfur removal without a significant decrease in NOx reduction efficiency.
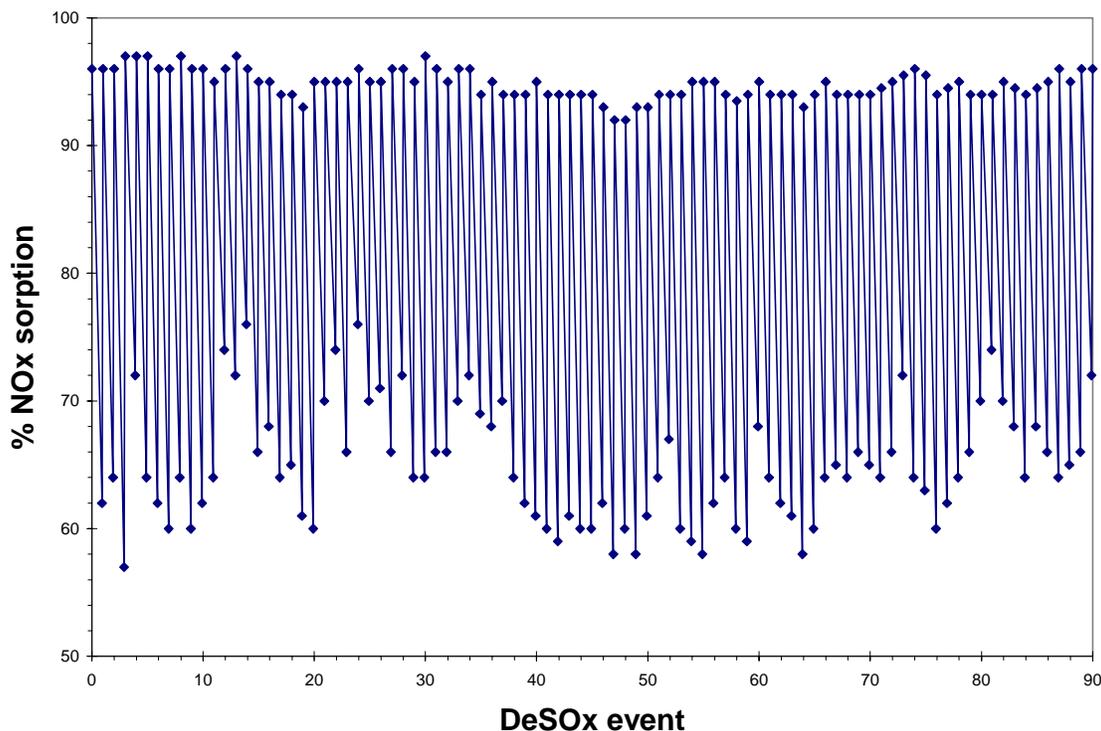
Figure III.A-17. Repeated Sulfur Poisoning and Desulfation on a Bench Pulsator

       These results indicate that, with further improvements to the NOx adsorber catalyst design incorporating the experience gained on gasoline three-way catalysts and continuing improvements in the control of the desulfation, degradation of the NOx adsorber catalyst with each desulfation event can be limited. However, the expectation remains that there will be some level of deterioration with desulfation that must be managed to ensure long term high efficiency of the NOx adsorber. This means that the number and frequency of desulfation events must be kept to a minimum. The key to this is to limit the amount of sulfur to which the catalyst is exposed over its life. In this way, the deterioration in performance between desulfation events is controlled at a gradual rate and the period between desulfations can be maximized to limit thermal degradation. There appears to be a general consensus among the technology developers in the emission control industry that, when sulfur levels are controlled with an average level below 10 ppm, the frequency and number of desulfation events will be at a level such that long term durability can be assured. This is evidenced by comments provided on our NPRM. Some examples of those comments are:

       1. *The Department* (the U.S. Department of Energy) *is confident that, assuming a reasonable rate of technology development before 2006, diesel fuel sulfur levels averaging 10 ppm or less will enable emission control devices* (NOx adsorbers and

CDPFs) *to operate effectively over the full useful vehicle life and, therefore, allow the vehicles/engines to meet the future standards* (the Phase 2 standards)." - letter from DOE to Bob Perciascepe 6 September 2000, EPA Docket A-99-06 Item IV-G-28.

2. *... the technological challenges posed by the proposed 2007 HDD standards are achievable. .. with the surety of specific standards at a known date, along with a concerted effort by the engine manufacturers and the emission control technology industry, once again we will "make it happen" with technology and integrated systems that meet the standards and are durable.* letter from Martin Lassen - Johnson Matthey Catalytic Systems division 19 October 2000, EPA Docket A-99-06 Item IV-G-55.

3. *We believe all NOx adsorber development issues have been identified and the technology is proceeding according to schedule.* Letter from John Mooney Director, Technology Development and Business Systems Engelhard Corporation to Margo Oge, U.S. EPA 3 October 2000, EPA Docket A-99-06 Item IV-G-38.

EPA agrees and expects this progress is likely to occur along the developmental paths discussed above.

(d)   Overall System Durability

NOx emission control with a NOx adsorber catalyst based systems is an extension of the very successful three-way catalyst technology. NOx adsorber technology is most accurately described as incremental and evolutionary with system components that are straightforward extensions of existing technologies. Therefore, the technology benefits substantially from the considerable experience gained over the past 30 years with the highly reliable and durable three-way catalyst systems of today.

The following observations can be made from the data provided in the preceding sections on NOx adsorber durability:

•   NOx adsorber catalysts are poisoned by sulfur in diesel fuel, even at fuel sulfur levels as low as three ppm.

•   A sulfur regeneration event (desulfation) can restore NOx adsorber performance.

•   A diesel engine can produce exhaust conditions that are conducive to desulfation.

•   Desulfation events which require high catalyst temperatures can cause sintering of the catalytic metals in the NOx adsorber thereby reducing NOx control efficiency.

- The means exist from the development of gasoline three-way catalysts to improve the NOx adsorber's thermal durability.

- In carefully controlled experiments, NOx adsorbers can be desulfated repeatedly without an unacceptable loss in performance.

- The number and frequency of desulfation events must be limited in order to ensure any gradual thermal degradation over time does not excessively deteriorate the catalyst.

Based on these observations, we are confident that NOx adsorber technology for MY2007 and later engines will be durable over the life of heavy-duty diesel vehicles, provided fuel with a 15 ppm sulfur cap is used. Without the use of this low sulfur fuel, we can no longer be confident that the increased number of desulfation cycles that will be required to address the impact of sulfur on efficiency can be accomplished without unrecoverable thermal degradation and thus loss of NOx adsorber efficiency. Limiting the number and frequency of these deleterious desulfation events through the use of diesel fuel with sulfur content less than 15 ppm allows us to conclude with confidence that NOx adsorber catalysts will be developed that are durable throughout a vehicle's life.

viii.   Will NOx Adsorber Desulfation Lead to Undesirable H_2S Emissions?

The desulfation process for a NOx adsorber catalyst is directly analogous to the NOx regeneration process. The stored sulfur emissions are released and reduced over the catalyst before exiting the tailpipe. The final reduction state for the sulfur emissions can be any one of several sulfur products including hydrogen sulfide (H_2S) and sulfur dioxide (SO_2). Hydrogen sulfide has a strong unpleasant odor which is often described as smelling like a rotten egg. For this reason it is preferable to emit the stored sulfur as SO_2 rather than H_2S.

There are several possible ways to control H_2S emissions from an automotive catalyst. For gasoline three-way catalysts which initially had problems with H_2S emissions, the solution has been the inclusion of nickel oxide to the catalyst formulation. Nickel oxide will store sulfur under reducing conditions as nickel sulfide and will release sulfur under oxidizing conditions as SO_2. This storage and release of sulfur emissions in the three-way catalyst has proved effective in controlling H_2S emissions. This approach to controlling sulfur emissions may be possible for NOx adsorber catalysts as well, although because NOx adsorbers store sulfur under lean conditions it may prove to be more difficult to use this approach. A catalyst formulated to store sulfur under both rich and lean conditions would presumably be hindered in its ability to completely remove sulfur under either condition.

Another solution to address H_2S emissions would be the inclusion of a downstream "clean-up" catalyst which could oxidize H_2S emissions, released under rich conditions, to a more desirable sulfur product, namely SO_2. The oxidizing potential for this reaction could come from either oxygen storage elements in the clean-up catalyst or from a second oxygen rich exhaust stream which would join the reducing stream from the desulfating NOx adsorber prior to entering the clean-up catalyst. The use of a clean-up catalyst is identified as a means to control NMHC emissions during NOx regeneration as described in sections III.A.3.b.iii and III.A.5. The same approach described in those sections will work well to control H_2S emissions. In our cost analysis described in Chapter V, we have included the cost of a diesel oxidation catalyst in the total system cost in order to address both NMHC emission concerns under NOx regeneration conditions and H_2S concerns under desulfation conditions.

ix.   Can SOx Traps Protect NOx Adsorbers from High Sulfur Diesel Fuel?

The preceding discussion of NOx adsorbers assumes that SOx (SO_2 and SO_3) emissions will be "trapped" on the surface of the catalyst, effectively poisoning the adsorber and requiring a "desulfation" (sulfur removal event) to recover catalyst efficiency. We believe that, at the 15 ppm cap fuel sulfur level, this strategy will allow effective NOx control over the life of heavy-duty vehicles. As an alternative to desulfation of the NOx adsorber itself, some researchers are investigating the use of an adsorber catalyst (SOx adsorber) designed to preferentially store sulfur emissions in order to serve as a protective catalyst for sulfur sensitive technologies such as NOx adsorbers. The device would then either require replacement or its own desulfation event in order allow the SOx adsorber to last for the life of a heavy-duty diesel vehicle.

Replacement of the SOx adsorber on a periodic basis appears to be a workable solution to the problem of sulfur in diesel fuel only for fuel sulfur levels well below 15 ppm. Analysis provided by Cummins Engine Company estimates that a sulfur trap could store approximately one pound of SO_2 per cubic foot of catalyst volume.[83] Based on this assumption an estimate was made of the package volume needed to store one year's worth of sulfur from diesel fuel for a heavy heavy-duty application that traveled 250,000 miles in one year while averaging seven miles per gallon:

- For five ppm sulfur fuel, the "disposable" SOx adsorber volume would be 2.5 ft^3.

- For 15 ppm sulfur fuel, the "disposable SOx adsorber volume would be 7.5 ft^3.

- For 50 ppm sulfur fuel, the "disposable" SOx adsorber volume would be 25 ft^3.

While it may be possible to imagine packaging a removable SOx adsorber with a volume of approximately 2.5 cubic feet (~71 liters) for a heavy heavy-duty vehicle, packaging a 25 cubic
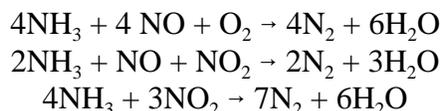
foot (710 liter) catalyst is probably impossible. For comparison typical heavy heavy-duty diesel engine displacements range from 10 to 15 liters in volume.

An alternative approach is to use a SOx adsorber in series with the NOx adsorber and then to either divert the effluent around the NOx adsorber during the SOx adsorber desulfation event or allow the effluent to go through the NOx adsorber under rich conditions which are less conducive to sulfur storage on the catalyst. The first approach of diverting the effluent around the NOx adsorber is theoretically possible, but has several practical limitations. Although SOx adsorbers are highly efficient at capturing sulfur in the exhaust they are not 100 percent effective.[84] This means that some fugitive sulfur will invariably be deposited on the NOx adsorber catalyst. In other words this approach only defers the needed desulfation event to a later time, although it would allow for less frequent desulfation events which is helpful in controlling thermal degradation. Additionally, diverting the sulfur laden gas around the NOx adsorber adds complexity to the system which is not necessary, since the NOx adsorber itself must also be able to be desulfated. If the sulfur emissions are allowed to travel through the NOx adsorber catalyst (rather than being diverted around) under rich conditions some significant fraction of the sulfur will still be trapped on the NOx adsorber catalyst.[85] Again, this approach may allow for somewhat less frequent NOx adsorber desulfations but will not eliminate the need for periodic desulfation of the NOx adsorber catalyst.

Based on the eventual need for NOx adsorber desulfation under any of the scenarios described here and the impractical package size of a replacement SOx trap, we believe the only viable approach is to have 15 ppm sulfur diesel fuel.

c.   Selective Catalytic Reduction (SCR)

Diesel Selective Catalytic Reduction (SCR) is an adaptation of stationary technology that has been in use for some time. Ammonia (NH_3) is injected into the exhaust upstream of a vanadium/titanium (V_2O_5/TiO_2) catalyst to reduce NOx. The following reactions occur:

$$4NH_3 + 4\,NO + O_2 \rightarrow 4N_2 + 6H_2O$$
$$2NH_3 + NO + NO_2 \rightarrow 2N_2 + 3H_2O$$
$$4NH_3 + 3NO_2 \rightarrow 7N_2 + 6H_2O$$

The ammonia is typically stored onboard the vehicle as a urea solution ($(NH_2)_2CO$) since ammonia is hazardous in its raw form. The urea solution is then injected upstream of the catalyst which breaks down the urea into ammonia and carbon dioxide. The ammonia must be injected in proportion to the NOx produced by the engine. If too much ammonia is injected for the amount of NOx present, the excess ammonia can pass unreacted through the SCR catalyst; this is referred to as "ammonia slip." In a mobile transient application, controlling the urea injection to prevent ammonia slippage is key. A diesel oxidation catalyst (DOC) containing platinum can be used

downstream of the SCR system to control ammonia slippage by oxidizing any slipped ammonia to N_2 and H_2O. A DOC can also be used upstream of the SCR system to improve NOx reduction performance by converting NO to NO_2. Optimum NOx reduction occurs when the NOx has a significant NO_2 fraction (note that diesel engine out NOx typically has only a small fraction of NO_2). Systems that use a DOC to improve cold temperature performance are called "compact SCR" systems due to their relatively small size when compared to conventional SCR systems.

The urea SCR has been developed for stationary applications and is currently being refined for the transient operation found in mobile applications. The reduction efficiency window for this device is similar to the NOx adsorber, with greater than 80 percent efficiency at exhaust temperatures as low as 250 C.[86] Testing has shown HD FTP cycle NOx reductions of 77 percent.[87] Such efficiencies would allow NOx levels of 0.5 g/hp-hr to be possible with today's technology starting with a 2.0 g/hp-hr cooled EGR engine. Lower levels would be possible with engine out emission reductions. Over the NTE zone the SCR has been shown to have 65-99 percent efficiency.[88]

Implementation of SCR poses unique difficulties due to the need to create a new supply chain for the urea. A SCR system consumes urea at a rate proportional to the NOx emission rate. SCR testing today has shown urea consumption rates ranging from three to six percent of the amount of fuel burned. Therefore, a line haul truck with a 300 gallon fuel tank would need 9 to 18 gallons of urea for every fill-up. Likewise, a large sport utility vehicle (SUV) with a 50 gallon fuel tank would need 1.5 to 3 gallons of urea for every fill-up. If the urea were distributed in liquid form, this would mean an additional on-board tank for urea that would probably have to be replenished at each refueling. Further, without an adequate urea supply onboard, whether by accident or by user intent, the SCR system would become useless, converting none of the NOx. Since the urea is expected to cost approximately 80 cents per gallon, there would be some incentive for the user not to refill the urea tank.[89] Since driving performance of the engine is not normally affected by the absence of urea, manufacturers would have to provide incentive for the users to continue refilling the urea tank so that the in-use benefit of the SCR system would be fully realized. What form such a refilling incentive would take is not known. A standardized ammonia distribution format (liquid, solid, etc.), delivery infrastructure, and anti-tampering measures are all issues that would need to be addressed to make this technology viable.

Urea SCR catalysts, like NOx adsorbers, need low sulfur diesel fuel to achieve high NOx conversion efficiencies and to control sulfate PM emissions. If low sulfur fuel is required, SCR NOx control may be possible in some applications by 2007. For a further discussion of SCR system sensitivity to sulfur in diesel fuel, and of its need for low sulfur diesel fuel, refer to section III.A.7. However we believe there are significant barriers to its general use for meeting the 2007 standards.

There would need to be adequate safeguards in place to ensure the urea is used throughout the life of the vehicle since, given the added cost of urea and the fact that urea depletion would not normally affect driveability, there would be an incentive not to refill the urea tank. This could lead to considerable uncertainties regarding the effectiveness of SCR, even if EPA were to promulgate the regulations that likely would be needed to require the regular replenishment of urea. Some would argue that this is the key issue with regard to urea SCR systems, but that this issue could be addressed by designing engines with on-board diagnostic systems utilizing a NOx sensor that would observe a loss of NOx control. When observed, the engine would be designed to reduce power gradually until a 50 percent loss of power was realized. This power loss would serve to encourage the user to replenish the urea tank.[90] While such an approach may be possible, it raises concerns for public safety as poor engine performance could lead to inadequate power for safe merging onto highways and other related driving situations. We remain hesitant to base a national program on such technology when important issues such as driver training on the need to refill the urea tank and the consequences of failure to do so cannot be appropriately controlled. This approach would seem to suggest a need for EPA mandated spot checks of individual vehicles to ensure compliance with the NOx standard. How such a program would work and the burden that it might place on small business entities was not addressed in the comments. The California Trucking Association has raised concerns about the appropriateness of putting this regulatory burden on truckers when a simpler technology such as a diesel NOx adsorber was available instead.[91] Without measures similar to these we doubt that users would consistently remember to fill their urea tanks. Since failure to provide urea would lead to a total loss of NOx control, we would need to model the loss of NOx control to be expected from an SCR based program.

While SCR systems are capable of limited operation on current sulfur level fuels, their efficiency is reduced at the low temperatures typical of much of diesel engine operation and they run the risk of ammonia slip. Consequently, to achieve the NOx standard, a SCR system would likely need platinum-containing oxidation catalysts upstream and downstream. The presence of any platinum in the system, whether for conversion of ammonia slip or for conversion of NO to NO_2, would lead to the production of sulfate PM and loss of NOx reduction efficiency. Therefore, like every exhaust emission control technology discussed so far, the elimination of fuel sulfur is imperative for this technology to be effective.

d.   Non-Thermal Plasma Assisted Catalysts

Another approach to NOx reduction is the non-thermal plasma assisted catalyst. This system works by applying a high voltage across two metal plates in the exhaust stream to form ions that serve as oxidizers. Essentially, the plasma would displace a conventional platinum based oxidation catalyst in function. Once oxidized to NO_2, NOx can be more readily reduced over a precious metal catalyst or used as an oxidizer, as in CDPFs. A potential drawback of this technology is the high voltage and power requirement. Generation of this power is expected to

entail a two to three percent fuel economy penalty.[92] We expect that, if and when the non-thermal plasma approach to NOx control becomes viable, it will also require the use of low sulfur diesel fuel due to its reliance on a precious metal catalyst to reduce the NO_2.[93]

4. Meeting the NMHC Standard

Meeting the NMHC standards under the lean operating conditions typical of the biggest portion of NOx adsorber operation should not present any special challenges to diesel manufacturers. Since all of the devices discussed above -- CDPFs, NOx adsorbers, and SCR -- contain platinum and other precious metals to oxidize NO to NO_2, they are also very efficient oxidizers of hydrocarbons. NMHC reductions of greater than 95 percent have been shown over transient FTP and the SET modes.[94] Given that typical engine out HC is expected to be in the 0.20 g/bhp-hr range for engines meeting the Phase 1 standards, this level of NMHC reduction will mean that under lean conditions emission levels will be well below the standard.

The NOx regeneration strategies for the NOx adsorber technology may prove difficult to control precisely, leading to a possible increase in HC emissions under the rich operating conditions required for NOx regeneration. Even with precise control of the regeneration cycle, HC slip may prove to be a difficult problem due to the need to regenerate the NOx adsorber under net rich conditions (excess fuel) rather than the stoichiometric (fuel and air precisely balanced) operating conditions typical of a gasoline three-way catalyst. It seems likely therefore, that in order to meet the HC standards we have set, an additional clean up catalyst may be required. A diesel oxidation catalyst, like those applied historically for HC and partial PM control, can reduce HC emissions (including Toxic HCs) by more than 90 percent.[95] This amount of additional control along with optimized NOx regeneration strategies will ensure very low HC emissions.

During the NVFEL NOx adsorber test evaluation program, we performed extensive testing of a system which included CDPFs, NOx adsorbers, and a clean-up diesel oxidation catalyst with low platinum loading. As discussed in section III.A.3.b of this RIA, and in more detail in the technical memorandum to the docket detailing this test program, without the use of a clean-up DOC we encountered test conditions which resulted in high HC emissions from the NOx adsorber regeneration events. As discussed in section III.A.3.b, this complete system, when tested over the hot-start HDDE FTP, resulted in HC emissions of 0.25 g/bp-hr, a 13 percent reduction from the baseline values for the test engine. However, the clean-up DOC we used for this evaluation program had a relatively light precious metal loading (~10 g/ft^3) and a relatively low cell density (300 cpsi). Emissions sampling upstream and downstream of this DOC indicated it's oxidation efficiency was less than 60 percent. More effective DOC formulations have been shown to produce greater than an 90 percent reduction in hydrocarbons.[96] In addition, as discussed in section III.A.3.b, the NVFEL evaluation program did not optimize the hydrocarbon reductant injection strategy in the short time available to the test program. During

the testing we saw opportunities for optimizing the use of the injected diesel fuel to achieve the desired NOx reduction which we were not able to pursue. With additional time, we would expect to both decrease the HC slip from the emission control system, as well as employ a much more effective DOC, capable of HC reductions on the order of 80 percent. When combined, we expect the NMHC standard will be achieved over the FTP and SET tests, as well as during NTE testing. With a more effective downstream clean-up DOC to control HC slip during the periodic NOx regeneration event, the HC standard we have set here can be met.

As discussed in section III.A.3.b of this RIA regarding NOx emissions, the minimum emission sample time provisions for the NTE test have been changed to reflect the potential for short-duration high HC emissions which can occur following a regeneration event.   This change to the NTE minimum sample time approach will address any feasibility concerns which could arise because of the short-term increase in HC emissions immediately following a regeneration event, by increasing the sample time to include the time period until the next regeneration. In addition, the NMHC NTE provisions do not apply until the hydrocarbon emission control device (e.g., DOC) has achieved a warmed up exhaust gas temperature of at least 250°C on the outlet of the device. This same provision applies to the NOx NTE standard. With these additional constraints placed on NTE testing, we conclude the NTE provisions can be achieved.

5.   Meeting the Crankcase Emissions Requirements

The most common way to eliminate crankcase emissions has been to vent the blow-by gases into the engine air intake system, so that the gases can be re-combusted. Until today's rulemaking, we have required that crankcase emissions be controlled only on naturally aspirated diesel engines. We have made an exception for turbocharged heavy-duty diesel engines in the past because of concerns regarding fouling that could occur from diesel PM and engine oil, which are included in the crankcase emissions, when routing the crankcase blow-by into the turbocharger and aftercooler. However, this is an environmentally significant exception since most heavy-duty diesel trucks use turbocharged engines, and a single engine can emit over 100 pounds of NOx, NMHC, and PM from the crankcase over its lifetime. Over the past several years technology has become available which allows us to eliminate the exception for turbocharged diesel engines, as discussed below.

We anticipate that the heavy-duty diesel engine manufacturers will be able to close the crankcase using one of two methods. First, by using closed crankcase filtration systems. We are aware of at least two companies which produce closed crankcase filtration systems for the heavy-duty diesel market today, as described in more detail below.[97, 98] Second, the blow-by gases could be routed directly into the exhaust system upstream of the emission control equipment. Finally, if the manufacturer chooses not to close the crankcase, the manufacturer must add the emission from the open crankcase ventilation system to the emissions from the engine downstream of any emission control equipment, e.g., the open-crankcase emissions would be added into the FTP

emission results. Thus, the regulatory provision has been written such that if adequate control can be had without "closing" the crankcase then the crankcase can remain "open."

We expect that in order to meet the stringent tailpipe emission standards set in this rule manufacturers will have to utilize closed crankcase approaches as described here. Closed crankcase filtration systems work by separating oil and particulate matter from the blow-by gases through single or dual stage filtration approaches, routing the blow-by gases into the engine's intake manifold and returning the filtered oil to the oil sump. Closed crankcases are required for new heavy-duty diesel vehicles in Europe starting in 2000. Oil separation efficiencies in excess of 80 percent have been demonstrated with production ready prototypes of two stage filtration systems after more than 500 hours of testing.[99] [100] By eliminating 80 percent or more of the oil that would normally be vented to the atmosphere, the system works to reduce oil consumption and to eliminate concerns over fouling of the intake system when the gases are routed through the turbocharger. Mercedes-Benz currently utilizes this type of system on virtually all of its heavy-duty diesel engines sold in Europe, and Mercedes-Benz has certified at least one on-highway HDDE in the U.S. equipped with such a system since at least 1999.[101]

An alternative approach could be to route the blow-by gases into the exhaust system upstream of the CDPF which would be expected to effectively trap and oxidize the engine oil and diesel PM. This approach may require the use of low sulfur engine oil to ensure that oil carried in the blow-by gases does not compromise the performance of the sulfur-sensitive emission control equipment. Further this approach would likely require some means to generate a favorable pressure differential in order to allow the blow-by gases to flow into the exhaust.

Given the available means to control crankcase emissions, we have eliminated this exception.

6.   The Complete System

We expect that the technologies described above would be integrated into a complete emission control system optimized for cost, reliability and package size. The engine-out emissions will be balanced with the exhaust emission control package in such a way that the result is the most beneficial from a cost, fuel economy and emissions standpoint. The engine-out exhaust characteristics will also have a role in assisting the exhaust emission control devices used. The NOx adsorber, for instance, will require periods of oxygen-depleted exhaust flow in order to accomplish NOx regeneration and to allow for sulfur control using desulfation events. This may be most efficiently done by reducing the air-fuel ratio that the engine is operating under during the regeneration to reduce the oxygen content of the exhaust, or alternatively by partitioning the exhaust flow such that only a small portion of the exhaust flow is used for NOx regeneration, thereby reducing the amount of oxygen needing to be depleted through fuel addition. Further, it is envisioned that the PM device will be integrated into the exhaust system

upstream of the NOx reduction device. This placement would allow the PM trap to take advantage of the engine-out NOx as an oxidant for the particulate, while removing the particulate so that the NOx exhaust emission control device will not have to deal with large PM deposits which may cause a deterioration in performance. Further it allows the NOx adsorber to make use of the upstream PM filter as a pre-catalyst to oxidize some NO to NO_2 and to partially oxidize the reductant (diesel fuel or exhaust hydrocarbons) to a more desirable reductant form such as CO before entering the NOx adsorber. Of course, there is also the possibility of integrating the PM and NOx exhaust emission control devices into a single unit to replace a muffler and save space (Toyota's DNPR system being an example of this approach).[102] The final component in any of these system configurations is likely to be some form of clean up catalyst which can provide control of HC slip during NOx regeneration as well as H_2S slip during SOx regeneration. Particulate free exhaust may also allow for new options in EGR system design to optimize its efficiency.

We expect that the emission reduction efficiency of the exhaust emission control system will vary across the NTE zone as a function of exhaust temperature and space velocity.[m] Consequently, to maintain the NTE emission cap, the engine-out emissions would have to be calibrated with exhaust emission control system performance characteristics in mind. This would be accomplished by lowering engine-out emissions where the exhaust emission control system was less efficient, for example by retarding fuel injection timing or increasing the EGR rate. Conversely, where the exhaust emission control system is very efficient at reducing emissions, the engine-out emissions could be tuned for higher emissions and better fuel economy. These trade-offs between engine-out emissions and exhaust emission control system performance characteristics are similar to those of gasoline engines with three-way catalysts in today's light-duty vehicles and can be overcome through similar system based engineering solutions. Managing and optimizing these trade-offs will be crucial to effective implementation of exhaust emission control devices on diesel applications.

In considering how these technologies might be integrated into a complete system, we have carefully considered the safety aspects of the above system. Based on our understanding of these technologies and the fact that we received no substantive comments on safety, we are confident that there are no undue safety concerns associated with the system. Given the proper diesel fuel sulfur level, actual field data have shown that PM traps function properly in-use without plugging. As for the NOx adsorber system, there is nothing about the expected system that causes concern for safety. Injection of diesel fuel upstream of the NOx adsorber for the purpose of NOx regeneration or desulfation presents no safety concern given the low volatility of diesel fuel.

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[m] The term, "space velocity," is a measure of the volume of exhaust gas that flows through a device.

7.   The Need for Low Sulfur Diesel Fuel

In discussing in the preceding sections the technologies that we expect to be needed in order to meet the stringent emissions standards set in this rulemaking, we have described in some detail the impact that sulfur has on these technologies. Because of the importance of the fuel sulfur control portion of this rulemaking, this section will provide a comprehensive overview of the need for low sulfur diesel fuel to enable the technologies capable of achieving the heavy-duty vehicle emission standards.

In order to evaluate the effect of sulfur on diesel exhaust control technologies we identified three key factors which we used to categorize the impact of sulfur in fuel on emission control function. These factors were efficiency, reliability, and fuel economy. Taken together these three factors lead us to believe that diesel fuel sulfur levels of 15 ppm will be required in order to make feasible the heavy-duty vehicle emission standards. Brief summaries of our analyses for each of these factors are provided below.

Efficiency: The efficiency of emission control technologies to reduce harmful pollutants is directly affected by sulfur in diesel fuel. Initial and long term conversion efficiencies for NOx, HC, CO and diesel PM emissions are significantly reduced by sulfur poisoning of the catalyst. NOx conversion efficiencies with the NOx adsorber technology in particular are dramatically reduced in a very short time due to sulfur poisoning of the NOx storage bed. In addition, total PM control efficiency is adversely impacted by the formation of sulfate PM. As explained in detail in the following sections, all of the advanced NOx and PM technologies described here have the potential to make significant amounts of sulfate PM under operating conditions typical of heavy-duty vehicles. The formation of sulfate PM is likely to be in excess of the total PM standard for diesel fuel sulfur levels above 15 ppm. Based on the strong negative impact of sulfur on emission control efficiencies for all of the technologies evaluated, we believe that 15 ppm represents an upper threshold for diesel fuel sulfur.

Reliability: Reliability refers to the expectation that emission control technologies must continue to function as required under all operating conditions for the life of the vehicle. As discussed in the following sections, sulfur in diesel fuel can prevent proper operation of both NOx and PM control technologies. This can lead to permanent loss in emission control effectiveness and even catastrophic failure of the systems. Sulfur in diesel fuel impacts reliability by decreasing catalyst efficiency (poisoning of the catalyst), increasing diesel PM loading on CDPFs, and by negatively impacting system regeneration functions. Among the most serious reliability concerns with sulfur levels greater than 15 ppm are those associated with failure to properly regenerate. In the case of the NOx adsorber, failure to regenerate will lead to rapid loss of NOx emission control as a result of sulfur poisoning of the NOx adsorber bed. In the case of the CDPF, sulfur in the fuel reduces the reliability of the regeneration function. If regeneration does not occur, catastrophic failure of the CDPF could occur . It is only by the availability of very low sulfur diesel fuels that

these technologies become feasible. The analysis given in the following section indicates that diesel fuel sulfur levels of 15 ppm are needed in order to ensure robust operation of the technologies we believe will be needed to meet the standards under the variety of operating conditions anticipated to be experienced in the field.

Fuel Economy: Fuel economy impacts due to sulfur in diesel fuel are associated with both NOx and PM control technologies. The NOx adsorber sulfur regeneration cycle (desulfurization or desulfation cycle) can consume significant amounts of fuel unless fuel sulfur levels are very low. The larger the amount of sulfur in diesel fuel, the greater this impact on fuel economy. As sulfur levels increase above 15 ppm, our projected fuel economy impact quickly transitions above one percent and doubles with each doubling of fuel sulfur level. Likewise, CDPF regeneration is inhibited by sulfur in diesel fuel. This leads to increased PM loading in the CDPF and increased work to pump exhaust across this restriction. With very low sulfur diesel fuel, CDPF regeneration can be optimized to give a lower (on average) exhaust backpressure and thus better fuel economy. Thus, for both NOx and PM technologies the lower the fuel sulfur level the better.

a.   Catalyzed Diesel Particulate Filters and the Need for Low Sulfur Fuel

As discussed earlier in this section, un-catalyzed diesel particulate filters require exhaust temperatures in excess of 650°C in order for the collected PM to be oxidized by the oxygen available in diesel exhaust. That temperature threshold for oxidation of PM by exhaust oxygen can be decreased to 450°C through the use of base metal catalytic technologies. Unfortunately, for a broad range of operating conditions diesel exhaust is significantly cooler than 400°C. If oxidation of the trapped PM could be assured to occur at exhaust temperatures lower than 300°C, then diesel particulate filters will be expected to be robust for most applications and operating regimes. The only means that we are aware of to ensure oxidation of PM (regeneration of the CDPF) at such low exhaust temperatures is by using oxidants which are more readily reduced than oxygen. One such oxidant is NO_2.

NO_2 can be produced in diesel exhaust through the oxidation of the nitrogen monoxide (NO), created in the engine combustion process, across a catalyst. The resulting NO_2-rich exhaust is highly oxidizing in nature and can oxidize trapped diesel PM at temperatures as cool as 250°C.[103] Platinum is the primary catalyst used to promote the oxidation of NO to NO_2. Therefore in order to ensure passive regeneration of the diesel particulate filters, significant amounts of platinum are being used in the wash-coat formulations of advanced catalyzed diesel particulate filters (CDPFs). The use of platinum to promote the oxidation of NO to NO_2 introduces several system vulnerabilities affecting both the durability and the effectiveness of the CDPF when sulfur is present in diesel exhaust. The two primary mechanisms by which sulfur in diesel fuel limits the robustness and effectiveness of CDPFs are inhibition of regeneration (as a result of inhibition of the oxidation of NO to NO_2) and a dramatic loss in total PM control

effectiveness due to the formation of sulfate PM. Unfortunately these two mechanisms tradeoff against one another in the design of CDPFs. Changes to improve the reliability of regeneration by increasing catalyst loadings lead to increased sulfate emissions and thus loss of PM control effectiveness. Conversely, changes to improve PM control by reducing the use of platinum group metals and, therefore, limiting sulfate make leads to less reliable regeneration. In our view, the only means of achieving good PM emission control and reliable operation is to reduce sulfur in diesel fuel to 15 ppm , as shown in the following subsections.

i.   Inhibition of CDPF Regeneration Due to Sulfur

The passively regenerating CDPF technologies rely on the generation of a very strong oxidant, NO_2, to ensure that the elemental carbon captured by the CDPF's filtering media is oxidized under normal operating conditions. NO_2 is produced through the oxidation of NO in the exhaust across a platinum catalyst. This oxidation is inhibited by sulfur poisoning of the catalytic metals.[104] This inhibition limits the total amount of NO_2 available for oxidation of the trapped diesel PM, thereby raising the minimum exhaust temperature required to ensure CDPF regeneration. The balance point temperature is the temperature at which PM accumulation matches the PM oxidation rate in a CDPF. In other words, the lowest temperature at which the CDPF would never plug due to PM buildup. Figure III.A-18 shows that going from three ppm sulfur fuel to 30 ppm sulfur fuel significantly increases the balance point of these CDPFs[n] through inhibition of the NO_2 conversion process.[105] This seemingly small change in balance point temperature (approximately 10 percent) is significant because temperatures in the range shown here are representative of likely exhaust temperatures for many diesel vehicles under normal driving cycles. Were typical exhaust temperatures in excess of 400°C for most engine operating conditions, this change would be less important. Without sufficient NO_2, the amount of PM trapped in the CDPF will continue to increase and can lead to excessive exhaust back pressure, low engine power, and even catastrophic failure of the CDPF itself.

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[n] CR-DPF in the figure refers to a continuously regenerating diesel particulate filter, CDPF refers to a catalyzed diesel particulate filter. Both devices are nearly functionally identical, and the term CDPF is used for either device in the text.
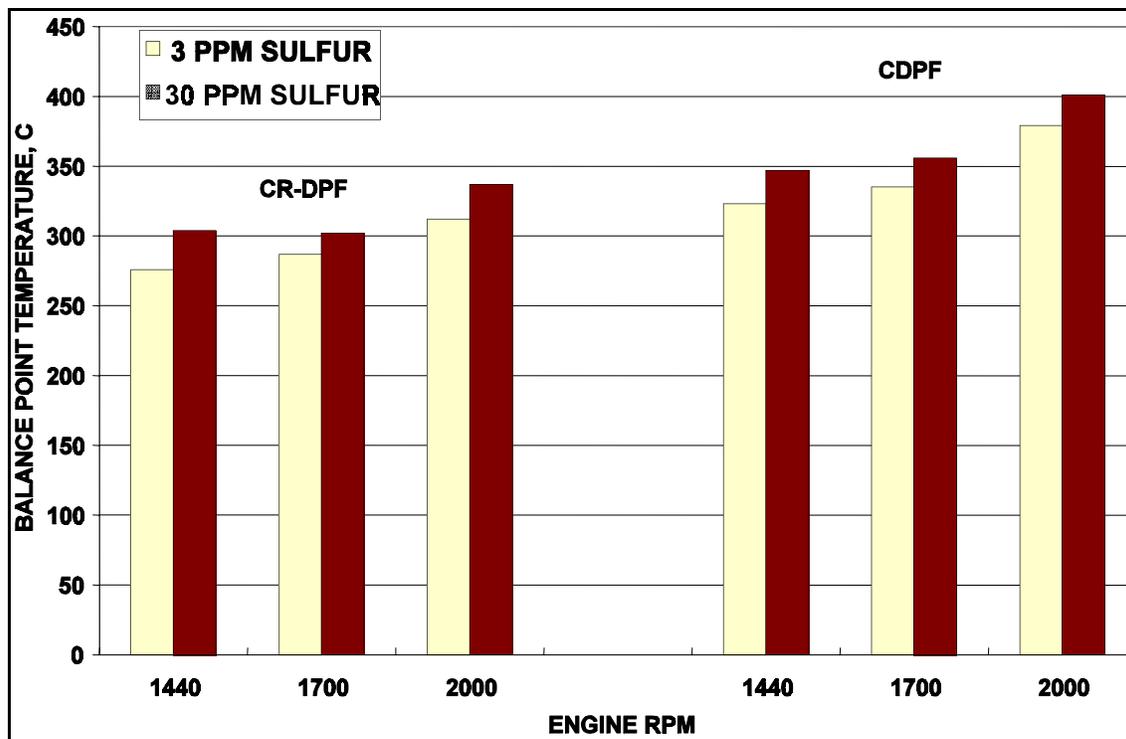
Figure III.A-18. Effect of Fuel Sulfur on Regeneration Temperature

Full field test evaluations and retrofit applications of these catalytic trap technologies are occurring in parts of Europe where low sulfur diesel fuel is already available.[o] The experience gained in these field 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), there is a strong indication of the robustness of this technology on 10 ppm low sulfur diesel fuel.[106] 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

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[o] Through tax incentives 50 ppm cap sulfur fuel is widely available in the United Kingdom and 10 ppm sulfur fuel is available in Sweden and in certain European city centers.

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.[107] 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.[108] 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.[p] 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.[109] 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_2 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_2 formation when higher sulfur level diesel fuel is used.

The failure mechanisms experienced by CDPFs due to low NO_2 availability vary significantly in severity and long term consequences. In the most fundamental sense, the failure is defined as an inability to oxidize the stored PM at a rate fast enough to prevent net accumulation of the PM over time. The excessive accumulation of PM over time blocks the passages through the filtering media, making it more restrictive to exhaust flow. The exhaust pressure upstream of the CDPF must increase in order to continue to force the exhaust through the now more restrictive filter. This increase in exhaust pressure is commonly referred to as increasing "exhaust backpressure" on the engine.

The increased exhaust backpressure represents increased work being done by the engine to force the exhaust gas through the increasingly restrictive CDPF. Unless the CDPF is frequently cleansed of the trapped PM, this increased work can lead to reductions in engine performance and increases in fuel consumption. This loss in performance may be noted by the vehicle operator in terms of poor acceleration and generally poor driveability of the vehicle. This

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[p] 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 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).

progressive deterioration of engine performance as more and more PM is accumulated in the filter media is often referred to as "trap plugging." Whether trap plugging occurs, and the speed at which it occurs, will be a function of many variables in addition to the fuel sulfur level; these variables include the vehicle application, its duty cycle, and ambient conditions. However, if the fuel sulfur level is sufficient to prevent CDPF regeneration in some real world conditions experienced, trap plugging could theoretically occur with just one fill-up.[q] This is not to imply that any time a vehicle is refueled once with high sulfur fuel trap plugging will occur. In fact, we believe the likelihood of a single misfueling event causing failure of the CDPF to be small, because adverse driving conditions (low duty cycle and very cold ambient conditions) would also have to occur while the fuel is in the vehicle.   Rather it is important to know that the use of fuel with sulfur levels higher than 15 ppm significantly increases the chances of CDPF failure.

Catastrophic failure of the CDPF can occur when excessive amounts of PM are trapped in the CDPF due to a lack of NO_2 for oxidation. This failure occurs when excessive amounts of trapped PM begin to oxidize at high temperatures (i.e., CDPF regeneration temperatures of >1000°C) leading to a "run-away" combustion of the PM. This can cause temperatures in the filter media to increase in excess of that which can be tolerated by the CDPF itself. For the cordierite material commonly used as the trapping media for CDPFs, the high thermal stresses caused by the high temperatures can cause the material to crack or melt. This can allow significant amounts of the diesel PM to pass through the CDPF without being captured during the remainder of the vehicle's life. That is, the CDPF is destroyed and PM emission control is lost.

As shown above, sulfur in diesel fuel inhibits NO oxidation leading to increased exhaust backpressure, reduced fuel economy, and compromised reliability. We, therefore, believe that in order to ensure reliable and economical operation over a wide range of expected operating conditions a diesel fuel sulfur level of 15 ppm will be needed. With these very low sulfur levels we believe, as demonstrated by experience in Europe, that CDPFs will prove to be both durable and effective at controlling diesel PM emissions to the very low levels required by this standard.

ii.   Loss of PM Control Effectiveness

In addition to inhibiting the oxidation of NO to NO_2, the sulfur dioxide (SO_2) in the exhaust stream is itself oxidized to sulfur trioxide (SO_3) at very high conversion efficiencies, by

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[q] Assuming a 10 liter engine, that a CDPF is plugged when it accumulates 7 g/l of CDPF volume, the CDPF is two times the volume of the engine, the engine emits 0.1 g/hp-hr PM, the CDPF does not regenerate, and a HD engine produces 3.013 hp-hr/mi (from MOBILE6). Then PM is emitted at a rate of 0.1 g/hp-hr times 3.013 hp-hr/mi, or 0.3 g/mi. Given that the CDPF can contain 7g/l times 10 l times 2, or 140 g of PM, then the CDPF will plug in 140 g PM divided by 0.3 g/mi, or 462 miles. HD trucks typically have a cruising range of more than 500 miles, so it is conceivable that the CDPF could plug in as little as one tank of fuel.

the precious metals in the CDPFs. The SO_3 serves as a precursor to the formation of hydrated sulfuric acid ($H_2SO_4+H_2O$), or sulfate PM, as the exhaust leaves the vehicle tailpipe. Virtually all of the SO_3 is converted to sulfate under dilute exhaust conditions in the atmosphere as well in the dilution tunnel used in heavy-duty engine testing. The sulfate formed in the dilution tunnel is then collected and measured as part of the total PM. Since virtually all sulfur present in diesel fuel is converted to SO_2, the precursor to SO_3, 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 CDPFs are very effective at trapping and/or oxidizing the elemental carbon and the SOF portions of the total PM, the overall PM reduction efficiency of CDPFs drops off rapidly with increasing sulfur levels due to the production of sulfate PM (i.e., "sulfate make," see Figures III.A-1 and III.A-2).

SO_2 oxidation is promoted across a catalyst in a manner very similar to the oxidation of NO, except it is converted at higher rates (Figure III.A-19[r]), with peak conversion rates in excess of 50 percent (Table III.A-5).[110] The SO_2 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 typical of some urban driving and the heavy-duty federal test procedure (HD-FTP), the oxidation rate is relatively low, perhaps no higher than ten percent. However at the higher temperatures that might be more typical of non-urban highway driving conditions and the supplemental emission test (SET, 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_2 oxidation rate typical of diesel engines (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.

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[r] In Figure III.A-19, the legend shows values of 42,000 hr^{-1} and 373,000 hr^{-1}. These values refer to "space velocity," which is a measure of the volume of exhaust gas that flows through a device; these can be taken to mean "low flow rate" at 42,000 hr^{-1} and "high flow rate" at 373,000 hr^{-1}.
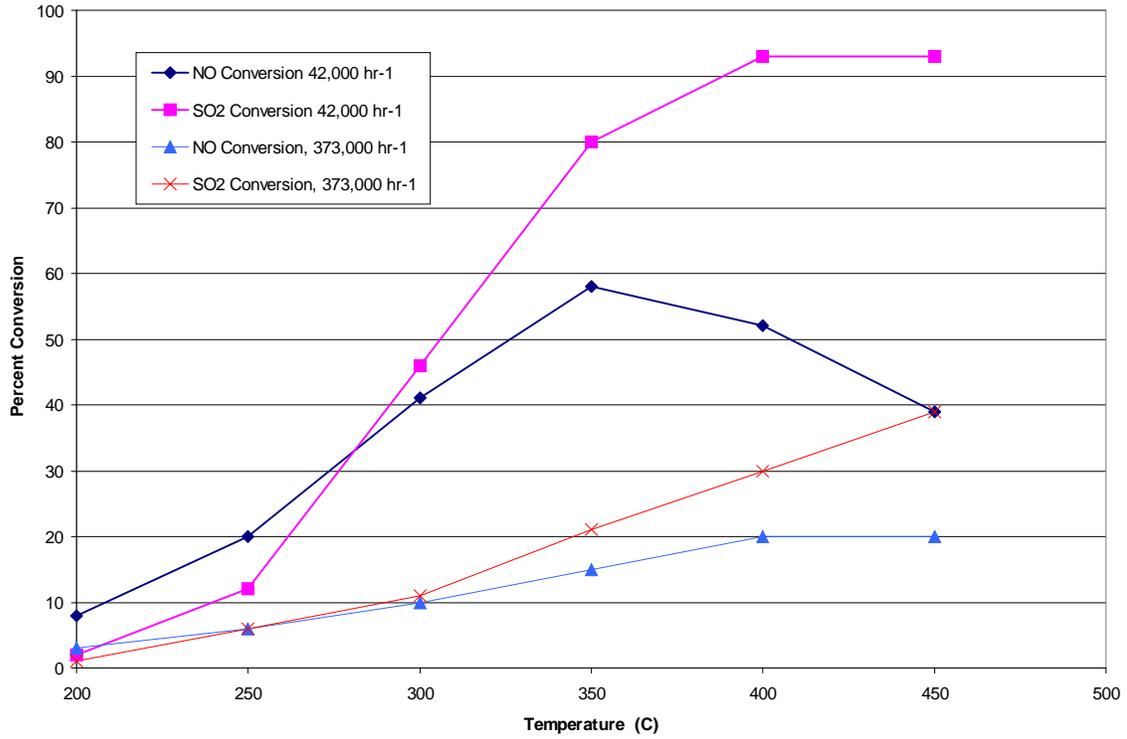
Figure III.A-19. NO and SO$_2$ Conversion Rates Over Platinum

**Table III.A-5. SO₂ Oxidation Rates for a Platinum Oxidation Catalyst
at the Indicated Catalyst Inlet Temperatures**

Catalyst Temperature	SO₂ Oxidation* Rate	Operation Represented
200°C	1-3%	Idle, very low load
250°C	4-11%	HD-FTP some Urban Driving
300°C	10-45%	EURO III some Rural Driving
350°C	20-80%	EURO III some Rural Driving
400°C	30-90%	EURO III some Rural Driving
450°C	40-90%	Peak Torque and Rated Conditions

* Range in oxidation rates accounts for variations in exhaust flow through the CDPF, at very
high flow rates SO₂ oxidation is minimized and at low flow rates SO₂ oxidation is maximized.

The US Department of Energy in cooperation with industry conducted a study entitled
Diesel Emission Control Sulfur Effects (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 PM emissions from a heavy-duty diesel engine operated with a
CDPF on several different fuel sulfur levels. A straight line fit through this data is presented in
Table III.A-6 below showing the expected total direct PM emissions from a heavy-duty diesel
engine on the supplemental steady state test cycle.[s]

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[s] 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 the combination of direct emissions and atmospheric constituents.

**Table III.A-6. Estimated PM Emissions from a Heavy-Duty Diesel Engine
at the Indicated Average Fuel Sulfur Levels**

Fuel Sulfur [ppm]	*Supplemental Steady State**	
	Tailpipe PM [g/bhp-hr]	*Total PM Increase Relative to 3 ppm Sulfur Test Point*
3	0.003	--
7*	0.006	100 %
15*	0.009	200 %
30	0.017	470 %
150	0.071	2300 %

* The PM emissions at these sulfur levels are estimated based on a straight-line fit to the
   DECSE program data; PM emissions at other sulfur levels are actual DECSE data. [111]

Table III.A-6 makes it clear that there are significant PM emission reductions possible
with the application of CDPFs and low sulfur diesel fuel.   At the observed sulfate PM
conversion rates, the DECSE program results show that the PM standard is feasible for CDPF-
equipped engines operated on fuel with a sulfur level at or below 15 ppm. The results also show
that CDPF control effectiveness is rapidly degraded at higher diesel fuel sulfur levels due to the
high sulfate PM make observed with this technology.   It is clear that PM reduction efficiencies
are limited by sulfur in diesel fuel and that, in order to realize the PM emissions benefits sought
in this rule, diesel fuel sulfur levels must be very low.

> iii.   *Increased Maintenance Cost for Catalyzed Diesel Particulate Filters Due to
>   Sulfur*

In addition to the direct performance and durability concerns caused by sulfur in diesel
fuel, it is also known that sulfur can lead to increased maintenance costs, shortened maintenance
intervals, and poorer fuel economy for CDPFs. CDPFs are highly effective at capturing the
inorganic ash produced from metallic additives in engine oil. This ash is accumulated in the
CDPF and is not removed through oxidation, unlike the trapped carbonaceous PM. Periodically
the ash must be removed by mechanical cleaning of the CDPF with compressed air or water.
This maintenance step is anticipated to occur on intervals of well over one hundred thousand
miles. However, sulfur in diesel fuel increases this ash accumulation rate through the formation
of metallic sulfates in the CDPF, which increases both the size and mass of the trapped ash. By
increasing the ash accumulation rate the sulfur shortens the time interval between the required
maintenance of the CDPF and negatively impacts fuel economy.

b. Diesel NOx Catalysts and the Need for Low Sulfur Fuel

All of the NOx aftertreatment technologies discussed previously in chapter III are expected to utilize platinum to oxidize NO to NO_2 to improve the NOx reduction efficiency of the catalysts at low temperatures or as in the case of the NOx adsorber, as an essential part of the process of NOx storage. This reliance on NO_2 as an integral part of the reduction process means that the NOx aftertreatment technologies, like the PM aftertreatment technologies, will have problems with sulfur in diesel fuel. In addition NOx adsorbers have the added constraint that the adsorption function itself is blocked by the presence of sulfur. These limitations due to sulfur in the fuel affect both overall performance of the technologies and, in fact, the very feasibility of the NOx adsorber technology.

i. Sulfur Poisoning (Sulfate Storage) on NOx Adsorbers

The NOx adsorber technology relies on the ability of the catalyst to store NOx as a nitrate on the surface of the catalyst, or adsorber (storage) bed, during lean operation. Because of the similarities in chemical properties of SOx and NOx, the SO_2 present in the exhaust is also stored by the catalyst surface as a sulfate. The sulfate compound that is formed is significantly more stable than the nitrate compound and is typically not released and reduced during the NOx release and reduction step. Since the NOx adsorber is highly effective at capturing SO_2 in the adsorber bed, the poisoning of the catalyst occurs rapidly. As a result, sulfate compounds quickly occupy all of the NOx storage sites on the catalyst thereby rendering the catalyst ineffective for NOx reduction (poisoning the catalyst). Figure III.A-20 clearly illustrates this effect at 3, 16, and 30 ppm fuel sulfur levels.[112]
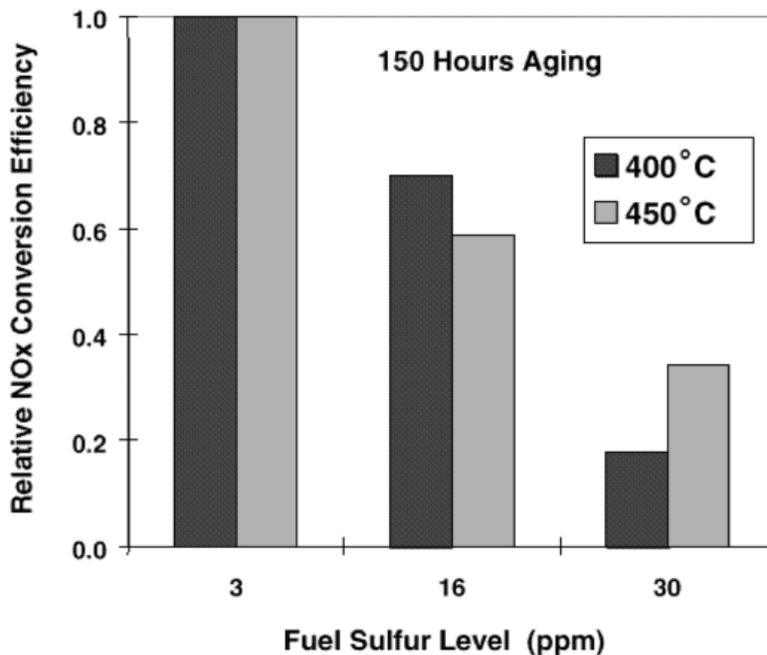
**Figure III.A-20. Diesel Fuel Sulfur Effect on NOx Adsorber
Performance after 150 hours**

    The stored sulfur compounds can be removed by exposing the catalyst to hot (>650°C) and rich (air-fuel ratio below the stoichiometric ratio of 14.5 to one) conditions for a brief period.[113] Under these conditions, the stored sulfate is released and reduced in the catalyst.[114] [115] While research to date on this procedure has been very favorable with regards to sulfur removal from the catalyst, it has revealed a related vulnerability of the NOx adsorber catalyst. Under the high temperatures used for desulfation, the metals that make up the storage bed can change in physical structure. This leads to lower precious metal dispersion, or "metal sintering," (a less even distribution of the catalyst sites) reducing the effectiveness of the catalyst.[116] This degradation of catalyst efficiency due to high temperatures is often referred to as thermal degradation. Thermal degradation is known to be a cumulative effect. That is, with each excursion to high temperature operation, some additional degradation of the catalyst occurs.

    One of the best ways to limit thermal degradation is by limiting the accumulated number of desulfation events over the life of the vehicle. Since the period of time between desulfation events is expected to be determined by the amount of sulfur accumulated on the catalyst (the higher the sulfur accumulation rate, the shorter the period between desulfation events) the desulfation frequency is expected to be proportional to the fuel sulfur level. In other words for each doubling in the average fuel sulfur level, the frequency and accumulated number of desulfation events are expected to double. We believe, therefore, that the diesel fuel sulfur level

must be set as low as possible in order to limit the frequency and duration of desulfation events. Without control of fuel sulfur levels below 15 ppm, we can no longer conclude with sufficient confidence that sulfur poisoning can be controlled without unrecoverable thermal degradation. Some would argue that the NOx adsorber technology could meet the NOx standard using diesel fuel with a 30 ppm average sulfur level. This would imply that the NOx adsorber could tolerate more than a three to four fold increase in desulfation frequency (when compared to an expected fuel sulfur level of 7 to 10 ppm with a 15 ppm cap) without any increase in thermal degradation. This conclusion is inconsistent with our understanding of the technology that, with each desulfation event, some thermal degradation occurs. Therefore, we believe that diesel fuel sulfur levels must be at or below 15 ppm in order to limit the number and frequency of desulfation events. Limiting the number and frequency of desulfation events will limit thermal degradation and, thus, enable the NOx adsorber technology to meet the NOx standard. For additional discussion of thermal degradation refer to the previous discussion in section III.A.3.b.vii on NOx adsorber durability.

Sulfur in diesel fuel for NOx adsorber equipped engines will also have an adverse effect on fuel economy. The desulfation event requires controlled operation under hot and net fuel rich exhaust conditions. These conditions, which are not part of a normal diesel engine operating cycle, can be created through the addition of excess fuel to the exhaust. This addition of excess fuel causes an increase in fuel consumption. We have developed a spreadsheet model that estimates the frequency of desulfation cycles from published data and then estimates the fuel economy impact from this event.[117] Table III.A-7 shows the estimated fuel economy impact for desulfation of a NOx adsorber at different fuel sulfur levels assuming a desired 90 percent NOx conversion efficiency. The estimates in the table are based on assumed average fuel sulfur levels associated with different sulfur level caps. Note that, although we can estimate the fuel consumption penalty of operation on diesel fuel sulfur levels higher than 15 ppm, this analysis does not consider the higher degree of thermal degradation due to the more frequent desulfation events which are required for operation on these higher sulfur levels.

**Table III.A-7. Estimated Fuel Economy Impact from
Desulfation of a 90 Percent Efficient NOx Adsorber**

Fuel Sulfur Cap [ppm]	Average Fuel Sulfur [ppm]	Fuel Economy Penalty [%]
500	350	27
50	30	2
25	15	1
15	7	< 1
5	2	<<< 1

The table shows that the fuel economy penalty associated with sulfur in diesel fuel is noticeable even at average sulfur levels as low as 15 ppm and increases rapidly with higher sulfur levels. It also shows that the 15 ppm sulfur cap will be expected to result in a fuel economy impact of less than one percent absent other changes in engine design.

As a consequence of requiring desulfation to occur before the NOx adsorber catalyst degrades to a level below 90 percent, the fuel economy impacts at higher sulfur levels described here are substantial. Therefore it would be logical to consider the possibility of allowing further degradations in NOx performance (below 90 percent) before desulfation in order to reduce this fuel economy impact. Recent results from industry contradict that position, however, indicating that when deep poisoning of the catalyst occurs due to higher fuel sulfur levels (or presumably extend periods of poisoning without desulfation) the ability of the catalyst to recover from the sulfur poisoning is compromised.[118] This data from a gasoline direct injection application indicates that desulfation events sequenced on a fixed interval with only minimal poisoning allowed for full recovery of NOx performance (eight ppm sulfur fuel, regenerated on a fixed driving cycle with 32,000 km of vehicle operation). These good results are contrasted with performance on 30 ppm sulfur fuel in which NOx adsorber desulfation occurred on the same fixed interval (thus allowing greater levels of poisoning before desulfation). For this case NOx control performance was never fully recovered at each desulfation step and, therefore, continued to gradually decrease over time from an initial efficiency of 95 percent to 80 percent over the same 32,000 km of vehicle operation.

Future improvements in the NOx adsorber technology are expected and needed if the technology is to provide the environmental benefits we have projected today. Some of these improvements are likely to include improvements in the means and ease to remove stored sulfur from the catalyst bed. However, because the stored sulfate species are inherently more stable

than the stored nitrate compounds (from stored NOx emissions), we expect that a separate release and reduction cycle (desulfurization cycle) will always be needed in order to remove the stored sulfur. Therefore, we believe that fuel with a sulfur level at or below 15 ppm sulfur will be necessary in order to control thermal degradation of the NOx adsorber catalyst and to limit the fuel economy impact of sulfur in diesel fuel.

ii.   *Particulate Sulfate Production for NOx Control Technologies*

The NOx adsorber technology relies on a platinum based oxidation function in order to ensure high NOx control efficiencies. As discussed more fully in section III.A.7.a, platinum based oxidation catalysts form sulfate PM from sulfur in the exhaust gases significantly increasing PM emissions when sulfur is present in the exhaust stream. The NOx adsorber technology relies on the oxidation function to convert NO to NO_2 over the catalyst bed. For the NOx adsorber this is a fundamental step prior to the storage of NO_2 in the catalyst bed as a nitrate. Without this oxidation function the catalyst will only trap that small portion of NOx emissions from a diesel engine which is NO_2. This would reduce the NOx adsorber effectiveness for NOx reduction from in excess of 90 percent to something well below 20 percent. The NOx adsorber relies on platinum to provide this oxidation function due to the need for high NO oxidation rates under the relatively cool exhaust temperatures typical of diesel engines. Because of this fundamental need for a catalytic oxidation function, the NOx adsorber inherently forms sulfate PM when sulfur is present in diesel fuel, since sulfur in fuel invariably leads to sulfur in the exhaust stream.

The Compact-SCR technology, like the NOx adsorber technology, uses an oxidation catalyst to promote the oxidation of NO to NO_2 at the low temperatures typical of much of diesel engine operation. As discussed above, there are substantial questions regarding the ability of SCR systems to be implemented successfully to meet the requirements finalized today. By converting a portion of the NOx emissions to NO_2 upstream of the ammonia SCR reduction catalyst, the overall NOx reductions are improved significantly at low temperatures. Without this oxidation function, low temperature SCR NOx effectiveness is dramatically reduced making compliance with the NOx standard impossible. As discussed previously in section III.A.7, platinum is known to be a good catalyst to promote NO oxidation, even at low temperatures.[t] Therefore, future Compact-SCR systems would need to rely on a platinum oxidation catalyst in order to provide the required NOx emission control. This use of an oxidation catalyst in order to enable good NOx control means that Compact SCR systems will produce significant amounts of sulfate PM when operated on anything but the lowest fuel sulfur levels due to the oxidation of SO_2 to sulfate PM promoted by the oxidation catalyst.

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[t] Platinum group metals include platinum, palladium, rhodium, and other precious metals.

Without the oxidation catalyst promoted conversion of NO to NO_2, neither of these NOx control technologies can meet the NOx standard set here. Therefore each of these technologies will require low sulfur diesel fuel to control the sulfate PM emissions inherent in the use of oxidation catalysts. The NOx adsorber technology may be able to limit its impact on sulfate PM emissions by releasing stored sulfur as SO_2 under rich operating conditions. The Compact-SCR technology, on the other hand, has no means to limit sulfate emissions other than through lower catalytic function or lowering sulfur in diesel fuel. The degree to which the NOx emission control technologies increase the production of sulfate PM through oxidation of SO_2 to SO_3 varies somewhat from technology to technology, but it is expected to be similar in magnitude and environmental impact to that for the PM control technologies discussed previously in section III.A.7.a.ii, since both the NOx and the PM control catalysts rely on precious metals to achieve the required NO to NO_2 oxidation reaction.

At fuel sulfur levels below 15 ppm this sulfate PM concern is greatly diminished. Without this low sulfur fuel, the NOx control technologies are expected to create PM emissions well in excess of the PM standard regardless of the engine-out PM levels.

c.   **Contribution of Sulfur from Engine Lubricating Oils**

Current engine lubricating oils have sulfur contents which can range from 2,500 ppm to as high as 8,000 ppm by weight. Since engine oil is consumed by heavy-duty diesel engines in normal operation, it is important that we account for the contribution of oil derived sulfur in our analysis of the need for low sulfur diesel fuel. One way to give a straightforward comparison of this effect is to express the sulfur consumed by the engine as an equivalent fuel sulfur level. This approach requires that we assume specific fuel and oil consumption rates for the engine. Assuming that a heavy-duty diesel engine consumes one quart of engine oil in 2,000 miles of operation, that engine oil sulfur levels range from 2,000 to 8,000 ppm, and that the engine consumes fuel at a rate of one gallon per six miles of operation, the range of equivalent fuel sulfur levels can be estimated. Using these assumptions, the estimated range is from two to seven ppm diesel fuel sulfur equivalence.[119] If values at the upper end of this range accurately reflect the contribution of sulfur from engine oil to the exhaust this would be a concern as it would represent as much as half of the total sulfur in the exhaust under a 15 ppm diesel fuel sulfur cap (with an average sulfur level assumed to be approximately seven to 10 ppm). However, we believe that this simplified analysis, while valuable in demonstrating the need to investigate this issue further, overstates the likely sulfur contribution from engine oil by a significant amount. Current heavy-duty diesel engines operate with open crankcase ventilation systems which "consume" oil by carrying oil from the engine crankcase into the environment. This consumed oil is correctly included in the total oil consumption estimates, but should not be included in estimates of oil entering the exhaust system for this analysis, since as currently applied this oil is not introduced into the exhaust. Thus the assumption of one quart of oil in 2,000 miles of operation being consumed and thus entering the exhaust system overstates the oil

contribution by the fraction of oil that exits from today's open crankcase systems. In the future we expect diesel engine manufacturers to rely on closed crankcase filtration systems to filter this oil from the blow-by gases and return the oil to the engine's crankcase, thus lowering engine oil consumption.

As an alternate approach to estimate the amount of oil and thus oil borne sulfur present in the exhaust, projected emission rates for Phase 1 technology engines can be made. The Phase 1 HD emission standards set a 0.1 g/bhp-hr PM emission rate for all classes of heavy-duty diesel vehicles. If we assume that virtually all oil consumed by the engine is emitted as diesel PM and that this soluble organic fraction (SOF) makes up 30 percent of diesel PM we can estimate how much oil is consumed. This estimate is made assuming that the engine oil has a sulfur content of 5,000 ppm, that 30 percent of PM emissions are from engine oil, and that the engine brake specific fuel consumption rate is 0.300 lbm/bhp-hr. The equivalent fuel sulfur level from engine oil is then calculated as

$$\text{sulfur level [ppm]} = \frac{(\ 5{,}000\ [\text{ppm}]\ \text{x}\ 0.1\ [\text{g/bhp-hr}]\ \text{x}\ 30\ [\%]\ )}{(\ 454\ [\text{g/lbm}]\ \text{x}\ 0.300\ [\text{lbm/bhp-hr}]\ )}$$

A higher fuel consumption rate decreases the relative amount of sulfur from engine oil in this estimate. Using this approach we have estimated that the equivalent fuel sulfur level from engine oil is approximately one ppm.

As a further attempt to better understand the amount of sulfur contributed from engine oil in the exhaust we have looked at the results from the DECSE test program. The DECSE program reports sulfate emissions from a heavy-duty diesel engine equipped with highly catalyzed CDPFs and operated on diesel fuel at several fuel sulfur levels. A commonly used motor oil with sulfur content of approximately 3,500 ppm was chosen for this testing. Since the PM emission control technologies used in this testing are very sensitive to sulfur (converting sulfur to sulfate PM emissions at a rate of approximately 40 percent) they should reveal sensitivities to sulfur from lube oil. By taking the sulfate emission results reported by DECSE at fuel sulfur levels of 3 and 30 ppm sulfur we can estimate the amount of sulfate emissions (and thus sulfur contribution) from the engine oil. The intercept (the predicted sulfate emissions at 0 ppm sulfur fuel) of a straight-line fit through the two test points should reveal the amount of sulfate produced from oil derived sulfur. Figure III.A-21 shows the results of this analysis.[120] The intercept value shown in the figure is slightly below zero indicating that in spite of the high sulfur conversion rate typical of these emission control devices the amount of lube oil derived sulfate emissions is unmeasurable. Although some amounts of sulfur from lubricating oils are almost certainly present in the exhaust, this analysis seems to indicate that it will not be a significant fraction of the total sulfur even for fuel sulfur levels as low as 15 ppm.
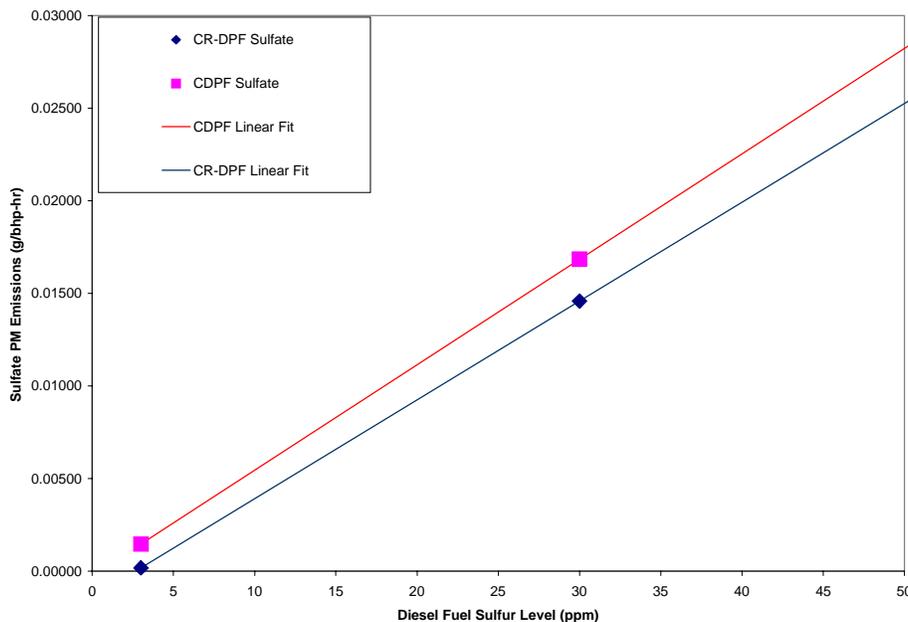
Figure III.A-21. Sulfate PM Emissions versus Diesel Fuel Sulfur Level with 3,500 ppm Sulfur Engine Oil

B.   Feasibility of the 2008 Standards for Heavy-Duty Gasoline Vehicles & Engines

Gasoline emission control technology has evolved rapidly in recent years. Emission standards applicable to 1990 model year vehicles required roughly 90 percent reductions in exhaust HC and CO emissions and a 75 percent reduction in NOx emissions compared to uncontrolled emissions. Since then, light-duty gasoline emission standards have undergone two major reductions, our Tier 1 and Tier 2 standards, and heavy-duty gasoline emission standards have undergone three changes toward ever lower levels. Despite that, some of today's heavy-duty vehicle emissions are well below levels necessary to meet the current federal heavy-duty gasoline standards, the Phase 1 heavy-duty gasoline standards to be implemented in the 2005 model year,[121] and the California Low Emission Vehicle (LEV) standards for medium-duty vehicles.[u] The continuing emissions reductions have been brought about by ongoing improvements in engine air-fuel management hardware and software plus improvements in exhaust system and catalyst designs.

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[u] The Phase 1 heavy-duty program is a reference to the 2004 heavy-duty final rule which set the 2004 model year HD diesel standards and the 2005 model year HD gasoline standards. (See 65 FR 59896, October 6, 2000) The 2007 final rule represents Phase 2 of this heavy-duty standard setting effort.

These improvements to gasoline emission controls have been made in response to the California LEV-II standards and the new federal Tier 2 standards.[122] [123] Some of this development work was contributed by EPA in a very short timeframe and with very limited resources in support of our Tier 2 rulemaking effort.[124] These improvements should transfer well to the heavy-duty gasoline segment of the fleet. Given the dramatic improvements in gasoline emission control technology in recent years, it is clear that there is no need to invent new technologies to meet emission levels below the 2005 heavy-duty gasoline standards. Instead, existing technologies can be applied to heavy-duty gasoline engines more effectively and more broadly; the focus being on the application and optimization of these existing technologies. With the migration of light-duty technology to heavy-duty vehicles and engines, we believe that considerable improvements to heavy-duty gasoline emissions can be realized, thus enabling the stringent 2008 standards.

The most significant improvement facilitating the low emission levels of today's gasoline vehicles has been to the traditional three-way catalyst, which now warms up and lights off very rapidly and is substantially more durable than in the past. Dramatic improvements have been realized also in fuel metering, which is now far more precise and accurate than previous systems. Improvements have been made also to base engine designs, which have resulted in lower engine-out emissions. Reduction of combustion chamber crevice volumes and oil consumption are examples of improvements to base engine designs. Equally important, if not more so, is that emission control calibrations continue to become more refined and sophisticated as calibrators become more skilled and computing power increases.

Fuel quality also plays an important role in improving vehicle emissions. In our Tier 2 rule for light-duty vehicles and trucks, we required that gasoline sulfur levels be reduced to a 30 ppm average with an 80 ppm cap. This sulfur level reduction is the primary enabler for the Tier 2 standards. Likewise for the 2008 heavy-duty gasoline standards. The Tier 2 gasoline sulfur reduction that enables the technology needed to meet the Tier 2 standards (0.07 g/mi NOx, on average) will enable that same technology on heavy-duty gasoline vehicles, thus enabling the 2008 heavy-duty gasoline standards.

1. Gasoline Exhaust Emission Control Technology Descriptions

Table III.B-1 below lists specific types of exhaust emission controls that we project may be used on heavy-duty gasoline vehicles to meet the 2008 heavy-duty gasoline standards. We do not believe that all of these technologies would be needed to meet the 2008 standards on every vehicle. The choices manufacturers make and the combinations of technologies will depend on several factors, such as current engine-out emission levels, effectiveness of existing emission control systems, and individual manufacturer preferences. In some cases, such as the need for increases in catalyst volume and precious metal loading, we believe that most, if not all, vehicles will use the technology.

**Table III.B-1. Exhaust Emission Control Hardware and
Technologies That May be Used to Meet the 2008 Heavy-Duty
Gasoline Standards**

Fast Light-Off Exhaust Gas Oxygen Sensor	Secondary Air Injection Exhaust
Retarded Spark Timing at Start-Up	Heat Optimized Exhaust Pipe
More Precise Fuel Control	Leak-Free Exhaust System
32-bit Microprocessor	Close-Coupled Catalyst
Manifold with Low Thermal Capacity	Improved Catalyst Washcoats
Air-Assisted Fuel Injection	Increased Catalyst Volume and Precious Metal Loading
Engine Modifications	Full Electronic Exhaust Gas Recirculation

This section discusses in detail some of the technologies that may be used to meet the 2008 standards. The technology descriptions are divided into five categories:

- base engine improvements;
- improved fuel control;
- improved fuel atomization;
- improved exhaust and exhaust emission control systems; and
- improved engine calibrations.

a.   Base Engine Improvements

There are several design techniques that can be used for reducing engine-out emissions, especially for HC and NOx.   The main causes of excessive engine-out emissions are unburned HCs and high combustion temperatures for NOx. Methods for reducing engine-out HC emissions include the reduction of crevice volumes in the combustion chamber, reducing the combustion of lubricating oil in the combustion chamber and developing leak-free exhaust systems. Leak-free exhaust systems are considered to be base engine improvements because any modifications or changes made to the exhaust manifold can directly affect the design of the base engine. Base engine control strategies for reducing NOx include the use of "fast burn"

combustion chamber designs, multiple valves with variable-valve timing, and exhaust gas recirculation.

i.   *Combustion Chamber Design*

Unburned fuel can be trapped momentarily in crevice volumes (i.e., the space between the piston and cylinder wall) before being subsequently released. Since trapped and re-released fuel can increase engine-out HC, the reduction of crevice volumes is beneficial to emission performance. One way to reduce crevice volumes is to design pistons with reduced top "land heights."[v] The reduction of crevice volume is especially desirable for vehicles with larger displacement engines, since they typically produce greater levels of engine-out HC than smaller displacement engines.

Another cause of excess engine-out HC emissions is the combustion of lubricating oil that leaks into the combustion chamber, since heavier hydrocarbons in oil do not oxidize as readily as those in gasoline. Oil in the combustion chamber can also trap gaseous HC from the fuel and release it as an unburned HC. In addition, some components in lubricating oil can poison the catalyst and reduce its effectiveness. To reduce oil consumption, vehicle manufacturers are expected to tighten tolerances and improve the surface finishes of cylinders and pistons, improve piston ring design and material, and improve exhaust valve stem seals to prevent excessive leakage of lubricating oil into the combustion chamber.

As discussed above, engine-out NOx emissions result from high combustion temperatures. Therefore, the main control strategies for reducing engine-out NOx are designed to lower combustion temperature. The most promising techniques for reducing combustion temperatures, and thus engine-out NOx emissions, are the combination of increasing the rate of combustion, reducing spark advance, and adding a diluent to the air-fuel mixture, typically via exhaust gas recirculation (EGR). The rate of combustion can be increased by using "fast burn" combustion chamber designs. A fast burn combustion rate provides improved thermal efficiency and a greater tolerance for dilution from EGR resulting in better fuel economy and lower NOx emissions. There are numerous ways to design a fast burn combustion chamber.   However, the most common approach is to induce turbulence into the combustion chamber which increases the surface area of the flame front and thereby increases the rate of combustion. Many engine designs induce turbulence into the combustion chamber by increasing the velocity of the incoming air-fuel mixture and having it enter the chamber in a swirling motion (known as "swirl"). Further improvements can be realized by positioning the spark plug in the center of the combustion chamber. Locating the spark plug in the center of the combustion chamber promotes more thorough combustion and allows the ignition timing to be retarded, decreasing the dwell time of hot gases in the combustion chamber thereby reducing NOx formation.

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[v] "Land height" is the distance between the top of the piston and the first piston ring.

ii.   Improved EGR Design

One of the most effective means of reducing engine-out NOx emissions is exhaust gas recirculation. By recirculating exhaust gases into the combustion chamber, the overall air-fuel mixture is diluted, lowering peak combustion temperatures and reducing NOx. As discussed above, the use of high swirl, high turbulence combustion chambers can allow the amount of EGR to be increased from current levels of 15 to 17 percent to levels possibly as high as 20 to 25 percent,[w] resulting in a 15 to 20 percent reduction in engine-out NOx emissions.

Many EGR systems in today's vehicles utilize a control valve that requires vacuum from the intake manifold to regulate EGR flow. Under part-throttle operation where EGR is needed, engine vacuum is sufficient to open the valve. However, during throttle applications near or at wide-open throttle, engine vacuum is too low to open the EGR valve. While EGR operation only during part-throttle driving conditions has been sufficient to control NOx emissions for most vehicles in the past, more stringent NOx standards may require more precise EGR control to improve upon NOx emission control. Some manufacturers use a mechanical back-pressure system that measures EGR flow (via delta pressure across an orifice) rather than inferring flow from the EGR pintle position. This system uses electronic control of the vacuum actuation and has very precise control. Many manufacturers are now using electronic EGR in place of mechanical back-pressure designs. By using electronic solenoids to open and close the EGR valve, the flow of EGR can, in some cases, be more precisely controlled.

 While most manufacturers agree that electronic EGR gives more precise control of EGR flow rate, not all manufacturers are using it. Numerous heavy-duty gasoline applications certified for the 1998 model year still use mechanical EGR systems, and in some cases, no EGR at all. Nonetheless, the use of EGR remains a very important tool in reducing engine-out NOx emissions, whether mechanical or electronic.

iii.   Multiple Valves and Variable-Valve Timing

Conventional engines have two valves per cylinder, one for intake of the air-fuel mixture and the other for exhaust of the combustion products. The duration and lift (distance the valve head is pushed away from its seat) of valve openings is constant regardless of engine speed. As engine speed increases, the aerodynamic resistance to pumping air in and out of the cylinder for

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[w] Some manufacturers have stated that EGR impacts the ability to control net air-fuel ratios tightly due to dynamic changes in exhaust back pressure and temperature, and that the advantages of increasing EGR flow rates are lost partly in losses in air-fuel ratio control even with electronic control of EGR. Higher EGR flow rates can be tolerated by modern engines with more advanced combustion chambers, but EGR cooling may be necessary to achieve higher EGR flow rates within acceptable detonation limits without significant loss of air-fuel control.

intake and exhaust also increases. By doubling the number of intake and exhaust valves, pumping losses are reduced, improving the volumetric efficiency and useful power output.

In addition to gains in breathing, the multiple-valve (typically 4-valve) design allows the spark plug to be positioned closer to the center of the combustion chamber (as discussed above) which decreases the distance the flame must travel inside the chamber. In addition, the two streams of incoming gas can be used to achieve greater mixing of air and fuel, further increasing combustion efficiency thereby lowering engine-out HC emissions.

Even greater improvements to combustion efficiency can be realized by using valve timing and lift control to take advantage of the 4-valve configuration. Conventional engines utilize fixed-valve timing and lift across all engine speeds. Typically the valve timing is set at a level that is a compromise between low speed torque and high engine speed horsepower. At light engine loads it would be desirable to close the intake valve earlier to reduce pumping losses. Variable valve timing can enhance both low speed torque and high speed horsepower with no necessary compromise between the two. Variable valve timing can allow for increased swirl and intake charge velocity, especially during low load operating conditions where sufficient swirl and turbulence tend to be lacking. By providing a strong swirl formation in the combustion chamber, the air-fuel mixture can mix sufficiently, resulting in a faster, more complete combustion, even under lean air-fuel conditions, thereby reducing emissions. Variable valve technology by itself may have somewhat limited effect on reducing emissions. Several vehicle manufacturers estimated emission reductions of 3 percent-10 percent for both NMHC and NOx, but reductions could be increased when variable valve timing is combined with optimized spark plug location and additional EGR.

Multi-valve engines already exist in numerous federal and California certified vehicles and are projected by ARB to become even more common. ARB also projects that, in order to meet LEV-II LEV and ULEV standards, more vehicles will have to make improvements to the induction system, including the use of variable valve timing.

iv.   *Leak-Free Exhaust Systems*

Leaks in the exhaust system can result in increased emissions, but not necessarily from emissions escaping from the exhaust leak to the atmosphere. With an exhaust system leak, ambient air is typically sucked into the exhaust system by the pressure difference created by the flowing exhaust gases inside the exhaust pipe. The air that is sucked into the exhaust system is unmetered and, therefore, unaccounted for in the fuel system's closed-loop feedback control. The excess air in the exhaust causes the computer to increase fuel to the engine, resulting in erratic and/or overly rich fuel control. This results in increased emission levels and potentially poor driveability. In addition, an air leak can cause an oxidation environment to exist in a three-

way catalyst at low speeds that would hamper reduction of NOx and lead to increased NOx emissions.

Some vehicles currently use leak-free exhaust systems today. These systems consist of an improved exhaust manifold/exhaust pipe interface plus a corrosion-free flexible coupling inserted between the exhaust manifold flange and the catalyst to reduce stress and the tendency for leakage to occur at the joint. In addition, improvements to the welding process for catalytic converter canning could ensure less air leakage into the converter and further reduce emissions.

b.   Improvements in Air-Fuel Ratio Control

Modern three-way catalysts require the air-fuel ratio (A/F) to be as close to stoichiometry (the amount of air and fuel just sufficient for nearly complete combustion) as possible. This is because three-way catalysts simultaneously oxidize HC and CO, and reduce NOx. Since HC and CO are oxidized during A/F operation slightly lean of stoichiometry, while NOx is reduced during operation slightly rich of stoichiometry, there exists a very small A/F window of operation around stoichiometry where catalyst conversion efficiency is maximized for all three pollutants (i.e., less than one percent deviation in A/F or roughly ± 0.15). Contemporary vehicles have been able to maintain stoichiometry, or very close to it, by using closed-loop feedback fuel control systems. At the heart of these systems has been a single heated exhaust gas oxygen (HEGO) sensor. The HEGO sensor continuously switches between rich and lean readings. By maintaining an equal number of rich readings with lean readings over a given period, and by limiting the degree to which the exhaust is rich or lean at any point in time, the fuel control system is able to maintain stoichiometry. While this fuel control system is capable of maintaining the A/F with the required accuracy under steady-state operating conditions, the system accuracy is challenged during transient operation where rapidly changing throttle conditions occur. Also, as the sensor ages, its accuracy decreases.

i.   *Dual Oxygen Sensors*

Many vehicle manufacturers have placed a second HEGO sensor(s) downstream of one or more catalysts in the exhaust system as a method for monitoring the catalyst effectiveness of the federally and California mandated on-board diagnostic (OBD II) system. In addition to monitoring the effectiveness of the catalyst, the downstream sensors can also be used to monitor the primary control sensor and adjust for deterioration, thereby maintaining precise A/F control at higher mileages. Should the front primary HEGO sensor, which operates in a higher temperature environment, begin to exhibit slow response or drift from its calibration point, the secondary downstream sensor can be relied upon for modifying the fuel system controls to compensate for the aging effects. By placing the second sensor further downstream from the hot engine exhaust, where it is also less susceptible to poisoning, the rear sensor is less susceptible to aging over the life of the vehicle. Because of this placement and the decreased susceptibility to aging, we

expect the downstream sensor to survive the full life of the vehicle without replacement. As a result, the use of a dual oxygen sensor fuel control system can ensure more robust and precise fuel control, resulting in lower emissions.

By 2008, most vehicle manufacturers are expected to use a dual oxygen sensor system for monitoring the catalyst as part of the OBD system required by the Phase 1 heavy-duty rule. As discussed above, most manufacturers also will use the secondary HEGO sensor for fuel trim (i.e., minor adjustments) of the fuel control system. We anticipate that all manufacturers will use this secondary sensor for fuel trim.

ii.   *Universal Oxygen Sensors*

The universal exhaust gas oxygen (UEGO) sensor, also called a "linear oxygen sensor", could replace conventional HEGO sensors. Conventional HEGO sensors only determine if an engine's A/F is richer or leaner than stoichiometric, providing no indication of the exact level of the A/F. In contrast, UEGO's are capable of recognizing both the direction and magnitude of A/F transients since the voltage output of the UEGO is "proportional" with changing A/F (i.e., each voltage value corresponds to a certain A/F). Therefore, proportional A/F control is possible with the use of UEGO sensors, facilitating faster response of the fuel feedback control system and tighter control of A/F.

Although some gasoline applications currently use UEGO sensors, discussions with various manufacturers suggest mixed opinions as to the future applicability of UEGO sensors. Because of their high cost, manufacturers claim that it may be cheaper to improve HEGO technology rather than utilize UEGO sensors. An example of this is the use of a "planar" design for HEGO sensors. Planar HEGO sensors (also known as "fast light-off" HEGO sensors) have a thimble design that is considerably lighter than conventional designs. The main benefits are shorter heat-up time and faster sensor response.

iii.   *Individual Cylinder A/F Control*

Another method for tightening fuel control is to control the A/F in each individual cylinder. Current fuel control systems control the A/F for the entire engine or a bank of cylinders. By controlling A/F for the entire engine or a bank of cylinders, any necessary adjustments made to fuel delivery for the engine are applied to all cylinders simultaneously, regardless of whether all cylinders need the adjustment. For example, there is usually some deviation in A/F between cylinders. If a particular cylinder is rich, but the "bulk" A/F indication for the engine is lean, the fuel control system will simultaneously increase the amount of fuel delivered to all of the cylinders, including the rich cylinder. Thus, the rich cylinder becomes even richer having a potentially negative effect on the net A/F.

Individual cylinder A/F control helps diminish variation among individual cylinders. This is accomplished by modeling the behavior of the exhaust gases in the exhaust manifold and using sophisticated software algorithms to predict individual cylinder A/F. Individual cylinder A/F control requires use of an UEGO sensor in lieu of the traditional HEGO sensor, and requires a more powerful engine control computer.

iv.   Adaptive Fuel Control Systems

The fuel control systems of virtually all current vehicles incorporate a feature known as "adaptive memory" or "adaptive block learn." Adaptive fuel control systems automatically adjust the amount of fuel delivered to compensate for component tolerances, component wear, varying environmental conditions, varying fuel compositions, etc., to more closely maintain proper fuel control under various operating conditions.

For most fuel control systems in use today, the adaption process affects only steady-state operation conditions (i.e., constant or slowly changing throttle conditions). Because transient operating conditions have always provided a challenge to maintaining precise fuel control, the use of adaptive fuel control for transient operation would be extremely valuable. Accurate fuel control during transient driving conditions has traditionally been difficult because of inaccuracies in predicting the air and fuel flow under rapidly changing throttle conditions. Air and fuel dynamics within the intake manifold (fuel evaporation and air flow behavior), and the time delay between measurement of air flow and the injection of the calculated fuel mass, result in temporarily lean A/F during transient operation. Variation in fuel properties, particularly distillation characteristics, also increases the difficulty in predicting A/F during transients. These can all lead to poor driveability and an increase in NOx emissions.

v.   Electronic Throttle Control Systems

As mentioned above, the time delay between the air mass measurement and the calculated fuel delivery presents one of the primary difficulties in maintaining accurate fuel control and good driveability during transient driving conditions. With the conventional mechanical throttle system (a metal linkage connected from the accelerator pedal to the throttle blade in the throttle body), quick throttle openings can result in a lean A/F spike in the combustion chamber. Although algorithms can be developed to model air and fuel flow dynamics to compensate for these time delay effects, the use of an electronic throttle control system, known as "drive-by-wire" or "throttle-by-wire," may better synchronize the air and fuel flow to achieve proper fueling during transients (e.g., the driver moves the throttle, but the fuel delivery is momentarily delayed to match the inertial lag of the increased airflow).

While this technology is currently used on several gasoline applications, it is considered expensive and those vehicles equipped with the feature are expensive, higher end vehicles.

Because of its high cost, it is not anticipated that drive-by-wire technology will become commonplace in the near future.

c.   Improvements in Fuel Atomization

In addition to maintaining a stoichiometric A/F ratio, it is also important that a homogeneous air-fuel mixture be delivered at the proper time and that the mixture is finely atomized to provide the best combustion characteristics and lowest emissions. Poorly prepared air-fuel mixtures, especially after a cold start and during the warm-up phase of the engine, result in significantly higher emissions of unburned HC since combustion of the mixture is less complete. By providing better fuel atomization, more efficient combustion can be attained, which should aid in improving fuel economy and reducing emissions. Sequential multi-point fuel injection and air-assisted fuel injectors are examples of the most promising technologies available for improving fuel atomization.

i.   *Sequential Multi-Point*

Typically, conventional multi-point fuel injection systems inject fuel into the intake manifold by injector pairs. This means that rather than injecting fuel into each individual cylinder, a pair of injectors (or even a whole bank of injectors) fires simultaneously, sending fuel into several cylinders. Since only one of the cylinders is actually ready for fuel at the moment of injection, the other cylinder(s) gets too much or too little fuel. With this less than optimum fuel injection timing, fuel puddling and intake manifold wall wetting can occur, both of which can hinder complete combustion. Sequential injection, on the other hand, delivers a more precise amount of fuel that is required by each cylinder to each cylinder at the appropriate time. Because of the emission reductions and other performance benefits "timed" fuel injection offers, sequential fuel injection systems are very common on today's vehicles and are expected to be incorporated in all vehicles soon.

ii.   *Air-Assisted Fuel Injectors*

Another method used to further homogenize the air-fuel mixture is to use air-assisted fuel injection. By injecting high pressure air into the fuel injector, and subsequently, the fuel spray, greater atomization of the fuel droplets can occur. Since achieving good fuel atomization is difficult when the air flow into the engine is low, air-assisted fuel injection can be particularly beneficial in reducing emissions at low engine speeds. In addition, industry studies have shown that the short burst of additional fuel needed for responsive, smooth transient maneuvers can be reduced significantly with air-assisted fuel injection due to a decrease in wall wetting in the intake manifold.

d.   Improvements to Exhaust and Exhaust Emission Control Systems

Over the last five years or so, there have been tremendous advancements in exhaust emission control systems. Catalyst manufacturers have been progressively moving to palladium as the main precious metal in automotive catalyst applications. Improvements to catalyst thermal stability and washcoat technologies, the design of higher cell densities, and the use of two-layer washcoat applications are just some of the advancements made to catalyst technology. There has also been much development in HC and NOx adsorber technology. The advancements to exhaust emission control systems are probably the single most important area of emission control development.

i.   *Catalysts*

As previously mentioned, significant changes in catalyst formulation, size and design have been made in recent years and additional advances in these areas are still possible. Palladium (Pd) is likely to continue as the precious metal of choice for close-coupled applications and may start to see more use in underfloor applications. Some manufacturers, for example, have suggested that they will use Pd/Rh in lieu of tri-metal or conventional Pt/Rh catalysts for underfloor applications. Palladium catalysts, however, are less resistant to poisoning by oil-and fuel-based additives than conventional platinum/rhodium (Pt/Rh) catalysts. Based on current certification trends and information from vehicle manufacturers and catalyst suppliers, it is expected that Pd-only and Pd/Rh catalysts will be used in the close-coupled locations while conventional Pd/Rh, Pt/Rh or tri-metal (Pd/Pt/Rh) catalysts will continue to be used in underfloor applications. As palladium technology continues to improve, it may be possible for a single close-coupled catalyst to replace both catalysts. In fact, at least one vehicle manufacturer currently uses a single Pd-only catalyst for one of their gasoline applications. According to MECA, new Pd-based catalysts are now capable of withstanding exposure to temperatures as high as 1100°C and, as a result, can be moved very close to the exhaust manifold to enhance catalyst light-off performance.

In addition to an increased reliance on Pd, catalyst manufacturers have developed "multi-layered" washcoat technologies. Automotive catalysts consist of a cylindrical or oval shaped substrate, typically made of ceramic or metal. The substrate is made up of hundreds of very small, but long cells configured in a shape similar to a honey-comb.   The substrate is coated with a substance containing precious metals, rare earth metals, and base-metal oxides, that is known as the catalyst washcoat. Typical washcoat formulations consist of precious metals which either oxidize or reduce pollutants, base-metal oxides, such as alumina, that provide the surface area support to which the precious metals adhere, and base components (rare earth metals) such as lanthanum, ceria, and zirconia, that act as promoters and stabilizers while also encouraging storage and reduction of oxygen.

Conventional catalysts have a single layer of washcoat and precious metals applied to the catalyst substrate. More advanced catalysts use multi-layered washcoats with two or more layers of different combinations of washcoat and precious metals. The washcoat can be applied to the substrate such that one layer can be applied on top of another. The use of multi-layered washcoat technology allows precious metals that have adverse reactions together to be separated such that catalyst durability and emission reduction performance are significantly enhanced. For example, Pd and Rh can have adverse reactions when combined together in a single washcoat formulation. A multi-layer washcoat architecture that uses Pd and Rh could have the Pd on the bottom layer and the Rh on the top layer. Rhodium is primarily used for reducing NOx emissions. Generally, and preferably, NOx emissions are reduced in the top washcoat layer while CO and HC are still present. Then, the CO and HC can be oxidized in the bottom washcoat layer. Figure III.B-1 illustrates the impact coating architecture (multi-layered washcoat technology) can have on emission performance.[x]
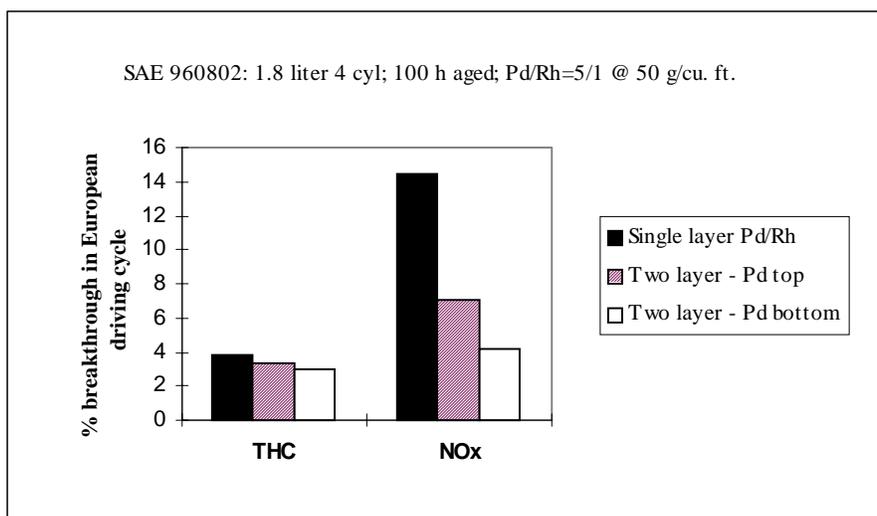

SAE 960802: 1.8 liter 4 cyl; 100 h aged; Pd/Rh=5/1 @ 50 g/cu. ft.

Legend: Single layer Pd/Rh; Two layer - Pd top; Two layer - Pd bottom

**Figure III.B-1. Impact of Coating Architecture on
HC and NOx Emissions**

Manufacturers also have been developing catalysts with thinner walled substrates that allow for a higher substrate cell density, and low thermal mass catalysts for close-coupled applications. These developments improve mass transfer at high engine loads, increase catalyst surface area, and speed up light-off time during cold starts. The greater the number of cells there are, the more surface area that exists to which washcoat components and precious metals can

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[x] Figure III.B-1 shows "% breakthrough in European driving cycle" on the y-axis; this can be defined as the percentage of emissions that pass through the catalyst without being converted to H_2O, CO_2, and N_2 during the European test cycle.

adhere. This results in more precious metal sites available for oxidizing and reducing pollutants. Cell densities of 600 cells per square inch (cpsi) have already been commercialized, and research on 900 and 1200 cpsi catalysts has been progressing. Typical cell densities for today's conventional catalysts are 400 cpsi.

We also have projected that, in order to meet the 2008 heavy-duty gasoline emission standards, catalyst volumes would have to increase. Current heavy-duty gasoline applications have catalyst volumes slightly lower than the corresponding engine displacement. We believe that most heavy-duty gasoline vehicles would likely need to increase catalyst volumes on the order of ten percent. As mentioned above, higher cell density substrates effectively provide more surface area for pollutant conversion. Therefore, catalyst volumes may not need to be increased as significantly if higher cell density substrates are used.

We also have projected that some level of increased precious metal loading (i.e., catalyst loading) would be necessary to meet the 2008 heavy-duty gasoline standards. Typical catalyst loadings for current heavy-duty gasoline applications are four grams/liter (g/L) of catalyst volume. We believe that, based on input from catalyst suppliers and vehicle manufacturers, catalysts meeting the 2008 standards would need loadings more on the order of five g/L. However, catalyst suppliers have also indicated to us that they and vehicle manufacturers are constantly working on ways to reduce the amount of precious metal loading (a process they refer to as "thrifting"). Thrifting is achieved in several ways. One of the most common is matching the catalyst to the attributes of the vehicle. By working in unison, vehicle manufacturers and catalyst suppliers are able to thrift or reduce the amount of precious metal used in a given application by attempting to optimize the vehicle fuel control strategy, exhaust mass flow rate, and exhaust temperature with various catalyst parameters, such as catalyst location, substrate design, cell density, oxygen storage capability, and precious metal and base metal dispersion, to name a few. Other methods of thrifting are the constant improvements being made to washcoat architecture - that is, constant improvement to the materials used in the washcoat formulation so that the precious metals and other components better adhere to the substrate surface. Finally, improvements to washcoat application processes also can improve significantly the catalyst performance while still allowing for thrifting of precious metals. Improvements to processes consist of advancements to the process used to coat the substrate with washcoat materials - allowing precious metals, base metals, and ceria to be better dispersed. Better precious metal dispersion means that, rather than having relatively large "clumps" of precious metals unevenly dispersed throughout the catalyst surface, many smaller precious metal sites are dispersed uniformly throughout the catalyst surface. This type of dispersion increases the chance for pollutants to come into contact with the precious metal and thus react into a harmless emission. Therefore, as thrifting continues, precious metal loading may actually decrease rather than increase, although this very likely outcome has not been incorporated into our cost estimates presented in Chapter V of this RIA.

The largest source of HC emissions continues to be cold start operation where the combination of rich A/F operation and the ineffectiveness of a still relatively cool catalyst results in excess HC emissions. One of the most effective strategies for controlling cold start HC emissions is to reduce the time it takes to increase the operating temperature of the catalyst immediately following engine start-up. The effectiveness, or efficiency, of the catalyst increases as the catalyst temperature increases. One common strategy is to move the catalyst closer to the exhaust manifold where the exhaust temperature is greater (e.g., a close-coupled catalyst). In addition to locating the catalyst closer to the engine, retarding the spark timing and increasing idle speed are other possible approaches. Retarding spark timing causes combustion to occur later in the power stroke. This results in more heat escaping into the exhaust manifold during the exhaust stroke while having a negligible impact on fuel economy.[125] Increased idle speed leads to a greater amount of combustion per unit time, providing a greater quantity of heat for heating the exhaust manifold, headpipe, and catalyst.

ii. Secondary Air Injection

Secondary injection of air into exhaust ports after cold start (e.g., the first 40-60 seconds) when the engine is operating rich, coupled with spark retard, can promote combustion of unburned HC and CO in the exhaust manifold and increase the warm-up rate of the catalyst. By means of an electrical pump, secondary air is injected into the exhaust system, preferably in close proximity of the exhaust valve. Together with the oxygen of the secondary air and the hot exhaust components of HC and CO, oxidation ahead of the catalyst can bring about an efficient increase in the exhaust temperature which helps the catalyst to heat up more quickly. The exothermic reaction that occurs is dependent on several parameters (secondary air mass, location of secondary air injection, engine A/F ratio, engine air mass, ignition timing, manifold and headpipe construction, etc.), and ensuring reproducibility demands a detailed individual application for each vehicle or engine design.

iii. Heat Managed Exhaust Systems

Insulating the exhaust system is another method of furnishing heat to the catalyst to decrease light-off time. Similar to close-coupled catalysts, the principle behind insulating the exhaust system is to conserve heat generated in the engine to aid the catalyst warm-up. Through the use of laminated thin-wall exhaust pipes, less heat will be lost in the exhaust system, enabling quicker catalyst light-off.

e. Improvements in Engine Calibration Techniques

Of all the technologies discussed above, one of the most important emission control strategies is not hardware-related. Rather, it is software related and, more specifically, involves the algorithms and calibrations contained within the software that are used in the power-train

control module (PCM) which control how the various engine and emission control components and systems operate. Advancements in software along with refinements to existing algorithms and calibrations can have a major impact in reducing emissions.

As computer technology and software continues to advance, so does the ability of the automotive engineer to use these advancements in ways to better optimize the emission control systems. For example, as processors become faster, it is possible to perform calculations more quickly, thus allowing for faster response times for controlling engine parameters, such as fuel rate and spark timing. As engine and powertrain control modules become more powerful with greater memory capability, algorithms can become more sophisticated. Manufacturers have found that as computer processors, engine control sensors and actuators, and computer software become more advanced, and, in conjunction with their growing experience with developing calibrations, as time passes, their calibration skills will continue to become more refined and robust, resulting in even lower emissions.

Manufacturers have suggested to us that perhaps the single most effective method for controlling NOx emissions will be tighter A/F control which could be accomplished with advancements in calibration techniques without necessarily having to use advanced technologies, such as UEGO sensors. Manufacturers have found ways to improve calibration strategies such that meeting federal cold CO requirements and complying with stringent light-duty LEV and NLEV standards has not required the use of advanced hardware, such as electrically heated catalysts or HC adsorbers as some had originally predicted they would need.

Since emission control calibrations are typically confidential, it is difficult to predict what advancements will occur in the future, but it is clear that improved calibration techniques and strategies are a very important and viable method for further reducing emissions.

2.   The 2008 Heavy-Duty Gasoline Exhaust Emission Standards

The 2008 heavy-duty gasoline complete vehicle standards are equivalent to the California LEV-II program LEV standards for vehicles in the same weight ranges, with the exception of the PM standards. The 2008 NOx level for 8,500 to 10,000 pound vehicles is 0.2 g/mi and the NOx level for 10,000 to 14,000 pound vehicles is 0.4 g/mile. The NMHC standards are 0.195 and 0.23 g/mile for the 8,500 to 10,000 pound and 10,000 to 14,000 pound vehicles, respectively. The California LEV-II LEV standards for PM emissions are 0.12 g/mi, while the new federal heavy-duty vehicle PM standard will be 0.02 g/mi. The California PM standards were originally set with consideration given to diesel vehicles not equipped with emission control devices, hence the much higher level than finalized for federal heavy-duty vehicles.

The 2008 heavy-duty gasoline incomplete vehicle standards, for which California has no standards as all gasoline vehicles are required by California to certify on the chassis

dynamometer, are 0.20 g/bhp-hr NOx, 0.14 g/bhp-hr NMHC, and 0.01 g/bhp-hr PM. Table III.B-2 shows the new 2008 heavy-duty gasoline exhaust emission standards along with the California emission standards for the equivalent vehicles. Also shown in Table III.B-2 are some of the federal Tier 2 bin levels for the purpose of comparison with the standards for light-duty trucks and medium-duty passenger vehicles (MDPVs).[y]

Table III.B-2. Emission Standards for Select Federal and California Gasoline Vehicles & Engines

Program	Weight Range or Tier 2 Bin	Useful Life (mi)	NOx	NMHC [A]	HCHO	PM
Phase 2 Heavy-Duty Gasoline Phase-in: 2008: 50% 2009: 100%	Vehicles 8,500-10,000 lbs (g/mi)	120,000	0.2	0.195	0.032	0.02
	Vehicles 10,000-14,000 lbs (g/mi)	120,000	0.4	0.230	0.040	0.02
	Engines > 8,500 lbs (g/bhp-hr)	110,000	0.20	0.14	N/A	0.01
Cal LEV-II MDV (LEV Only) Phase-in: 2004-2006 2007: 40% [B]	8,500-10,000 lbs (g/mi)	120,000	0.2	0.195	0.032	0.12
	10,000-14,000 lbs (g/mi)	120,000	0.4	0.230	0.040	0.12
Tier 2 Light-Duty Phase-in: 2004-2009 MDPV Bin available only thru 2008	MDPV Interim Bin (g/mi)	120,000	0.9	0.28	0.032	0.12
	Final High Bin (g/mi)	120,000	0.20	0.125	0.018	0.02
	Average Bin (g/mi)	120,000	0.07	0.09	0.018	0.01

[A] Non-methane hydrocarbon (NMHC) or, for LEV-II and Tier 2, non-methane organic gas (NMOG).
[B] In 2007, the remaining 60% of California MDVs must be certified to the more stringent ULEV levels.

[y] Medium-duty passenger vehicles are defined as any complete vehicle between 8,500 and 10,000 pounds GVWR designed primarily for the transportation of persons. The definition specifically excludes any vehicle that (1) has a capacity of more than 12 persons total or, (2) is designed to accommodate more than 9 persons in seating rearward of the driver's seat or, (3) has a cargo box (e.g., pick-up box or bed) of six feet or more in interior length. (See the Tier 2 final rulemaking, 65 FR 6698, February 10, 2000.)

The standards shown in Table III.B-2 for the 2008 heavy-duty gasoline vehicles and engines are phased-in on 50 percent of vehicles and engines in the 2008 model year, and 100 percent in the 2009 model year. Under the California LEV-II program, by the 2007 model year manufacturers are required to build at least 40 percent of their MDVs to the LEV category standards shown in Table III.B-2, and 60 percent of their MDVs to the tighter ULEV category standards. The LEV-II ULEV category standards for MDVs are, for NOx and NMOG respectively, 0.2 and 0.143 g/mi for 8,500 to 10,000 pounds, and 0.4 and 0.167 g/mi for 10,000 to 14,000 pounds.[126]

Under the federal Tier 2 program, the MDPVs are the vehicles most similar to the heavy-duty gasoline vehicles required to meet the 2008 HD gasoline standards. During the 2008 model year, half of the MDPVs can be certified in the MDPV interim bin shown in Table III.B-2, while the other half must be certified within the final Tier 2 bin structure and included in the manufacturer's corporate average NOx standard of 0.07 g/mi NOx.[127] The highest bin in the final Tier 2 structure is the final high bin shown in Table III.B-2. Then, in the 2009 model year, the MDPV interim bin is no longer available and all MPDVs must be certified in the final Tier 2 bin structure and included in the 0.07 g/mi NOx corporate average standard.

Therefore, the phase-in of the 2008 heavy-duty gasoline standards provides consistency with the Tier 2 program because the standards affecting similarly sized vehicles are phased-in on the same schedule. Further, those heavy-duty vehicles being phased-out (i.e., those 50 percent not meeting the new standard), would be certified to the Phase 1 heavy-duty gasoline standards which are equal to the MDPV interim bin for 8,500 to 10,000 pounds.[128] Again, the standard structure and implementation timing are consistent.

The engine standards shown in Table III.B-2 are equal to the engine standards set for diesel engines over 8,500 pound incomplete vehicles. For diesel engines, those standards are phased-in on a 50/50/50/100 percent schedule beginning in the 2007 model year. For gasoline engines, the phase-in schedule is consistent with the gasoline vehicle phase-in schedule of 50/100 percent beginning in the 2008 model year. This provides consistency and cost efficiency because the engines certified to the engine standards are the same engines being certified to the vehicle standards.

3.   Current Exhaust Emission Certification Levels for Heavy-Duty Gasoline Vehicles & Engines

Tables III.B-3 and III.B-4 provide certification results from the 2000 model year for heavy-duty gasoline vehicles and engines, respectively. The vehicle data is California medium-duty vehicle (MDV) certification data and the engine data is EPA certification data. The tables provide an indication of the emission levels that are being achieved through the application of current emission control technologies.

Table III.B-3 clearly shows that several vehicles have at least one emission constituent at or below the Phase 2 standards, and six vehicles have both NOx and NMHC levels at or below the future standards. We recognize that not all of these levels necessarily comply with the Phase 2 standards because they provide little or no compliance margin. Nonetheless such low levels eight years prior to implementation suggest that the future standards are clearly within reach. Table III.B-4 shows that current engines are being designed to be near the Phase 2 standards for 2008 despite being certified to the much higher current standards of 4.0 g/bhp-hr NOx and 0.9 g/bhp-hr NMHC. Based on industry input, we believe that manufacturers will continue the process of replacing their old engines with more advanced engines over the next several years. As new and more advanced engines are introduced, we anticipate that they will be capable of achieving the 2008 standards.

Table III.B-3. 2000 Model Year Vehicle Certification Data (gram/mile)[A]

Mfr	Same Eng Fam.	Model[B]	Engine Size (liters)	GVWR (lbs.)	NOx (g/mi)	HC[C] (g/mi)	Stds	Sales Area[D]
Daimler Chrysler	Y	Ram 3500 Cab Chassis 4WD	5.9	11000	0.48	0.16	Tier1	CA
	Y				0.4	0.097	LEV	CA
		Ram 2500 P/U 4WD	5.9	8800	0.2	0.084		
	Y	Ram 2500 P/U 2WD	8.0	8800	0.41	0.2	Tier1	CA
		Ram 3500 P/U 4WD	8.0	10500	0.34	0.19		
	Y			11000	0.56	0.22	Tier1	CA
		Ram 3500 P/U 2WD	8.0	11000	0.66 0.72	0.26 0.24		
					0.67	0.23		
	Y	B3500 Van 2WD	5.2	8700	0.29	0.14	Tier1	FA
		Ram 2500 Cab Chassis 4WD	5.9	8800	0.4	0.15		
Ford	Y	Excursion 4WD	5.4	8900	0.38	0.1675	LEV	CA
	Y	E350 2WD	5.3	9300	0.34	0.147	LEV	CA
					0.34	0.147	LEV	CF
	Y		6.8	9300	0.35	0.1615	LEV	CA
	Y	F350 4WD	6.8	11000	0.34	0.1421	LEV	CA
	Y	E250 Strip Chassis 2WD	4.2	8600	0.19	0.1003	LEV	CA
					0.19	0.1003	LEV	CF
	Y				0.22	0.12	Tier1	FA
		E250 Econoline 2WD			0.21	0.11		
General Motors	Y	K3500 P/U 4WD	5.7	10000	0.66	0.24	Tier1	CA
	Y		7.4		0.6	0.18	Tier1	CA
	Y	K2500 Silverado 4WD	6.0	8600	0.61	0.13	Tier1	CA
		K2500 Suburban 4WD	6.0	8600	0.67	0.17	Tier1	CA

[A] Shaded entries are those at or below the Phase 2 emission standards.
[B] Some of these models may be Tier 2 medium-duty passenger vehicles.

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Table III.B-4. 2000 Model Year Engine Certification Data (g/bhp-hr)[A]

Mfr	*Same Engine Family*	*Engine Size (liters)*	*Service Class*	*NOx (g/bhp-hr)*	*HC (g/bhp-hr)*	*NMHC (g/bhp-hr)*
DaimlerChrysler	Y	5.9	<14k	1.291	0.18	
	Y	8.0	<14k	1.14	0.13	
Ford	Y	5.4	CFF/ULEV	0.66	0.10	
	Y		<14k	0.66	0.10	
	Y	6.8	CFF/ULEV	0.48	0.13	
	Y		all	0.48	0.13	
	Y		<14k	0.48	0.12	
General Motors	Y	4.3	Fed <14k	0.9	0.2	
	Y	5.7	Fed CFF/LEV	2.7	0.3	0.2
	Y		50 State <14k	2.0	0.2	n/a
	Y	6.0	Fed CFF/LEV	1.7	0.3	0.2
	Y		50 State <14k	0.52	0.2	n/a
	Y	7.4	Fed CFF/LEV	1.7	0.6	0.5
	Y		50 State <14k	3.7	0.6	
	Y		50 State >14k	0.8	0.5	
	Y			3.7	0.6	

[A] Shaded entries are those at or below the Phase 2 emission standards.

4.   Technological Feasibility of the 2008 Heavy-Duty Gasoline Exhaust Emission Standards

We believe that the most promising overall emission control strategy for heavy-duty gasoline engines is the combination of improved three-way catalysts and improved electronic control of engine air-fuel ratio. Control of the air-fuel ratio is important because the three-way catalyst is only effective if the air-fuel ratio is at a narrow band near stoichiometry. For example, for an 80 percent conversion efficiency of HC, CO, and NOx with a typical three-way catalyst, the air-fuel ratio must be maintained within a fraction of one percent of stoichiometry. During transient operation, this minimal variation cannot be maintained with open-loop control. For

closed-loop control, the air-fuel ratio in the exhaust is measured by an oxygen sensor and used in a feedback loop. The throttle position, fuel injection, and spark timing can then be adjusted for given operating conditions to result in the proper air-fuel ratio in the exhaust. Most, if not all, engines have been equipped with closed loop controls. Some engines have been equipped with catalysts that are achieving catalyst efficiencies in excess of 95 percent. This is one key reason engine and vehicle certification levels are very low. In addition, electronic control can be used to adjust the air-fuel ratio and spark timing to adapt to lower engine temperatures, thereby controlling HC emissions during cold start operation.

All HD gasoline engines are equipped with three-way catalysts. Engines may be equipped with a variety of different catalyst sizes and configurations. Manufacturers choose catalysts to fit their needs for particular vehicles. Typically, current federal vehicle catalyst systems contain either a single converter, or two converters in series or in parallel.[z] A converter is constructed of a substrate, a washcoat, and a catalytic material (e.g., precious metals). The substrate may be metallic or ceramic with a flow-through design similar to a honeycomb. Improvements in substrate and washcoat materials and technology have improved catalyst performance significantly in recent years. A high surface area washcoat is used to provide a suitable surface for the catalytic material. Under high temperatures, the catalytic material will increase the rate of chemical reaction of the exhaust gas constituents. Current catalyst systems on HD vehicles tend to have fairly low precious metal loading and total catalyst volumes typically 80 to 90 percent of engine volumes. Current precious metal loadings tend to be in the range of one to four g/L, and we expect most precious metal loadings to be up to four g/L for the purpose of meeting the 2005 standards.

Significant changes in catalyst formulation have been made in recent years and additional advances in these areas are still possible. Platinum, palladium and rhodium (Pt, Pd, and Rh) are the precious metals typically used in catalysts.[aa] Historically, platinum has been widely used. Today, palladium is being used much more widely due to its ability to withstand very high exhaust temperatures. In fact, some HD vehicles currently are equipped with palladium-only catalysts. Other catalysts contain all three metals or contain no platinum but both palladium and rhodium. Some manufacturers have suggested that they will use Pd/Rh in lieu of tri-metal or conventional Pt/Rh catalysts for underfloor applications. The underlying driver of which metals are used, and in what proportion, is the price of those metals. As platinum prices rise, more palladium is used; as palladium prices rise, more platinum is used. The same can be said of rhodium.

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[z] In contrast to some California LEV program medium-duty vehicles which have close-coupled catalysts.

[aa] Platinum, palladium, and rhodium are platinum-group metals, or PGM, which also includes iridium, osmium, and ruthenium.

We project that the 2008 heavy-duty gasoline standards will require the application of advanced engine and catalyst systems similar to those projected for their light-duty counterparts to meet the Tier 2 standards. The technologies and emission control strategies that will be used for medium-duty passenger vehicles (MDPVs), which have a GVWR greater than 8,500 pounds, should also apply directly to heavy-duty gasoline vehicles. Historically, manufacturers have introduced technology on light-duty gasoline vehicles and then applied those technologies to their heavy-duty gasoline applications. We expect that manufacturers will take this same approach to meeting the 2008 heavy-duty gasoline standards, through the application of technology developed to meet light-duty Tier 2 standards beginning in the 2004 model year.

Improved calibration and systems management will be critical in optimizing the performance of the engine with the advanced catalyst system. Precise air/fuel control must be tailored for emissions performance and must be optimized. Calibration refinements may also be needed for EGR system optimization and to reduce cold start emissions through methods such as spark timing retard. We also project that electronic control modules with expanded capabilities will be needed on some vehicles and engines.

We also expect increased use of other technologies in conjunction with those described above. We expect some increased use of air injection to improve upon cold start emissions. We may also see air-gap manifolds, exhaust pipes, and catalytic converter shells as a means of improving upon catalyst light-off times, thereby reducing cold start emissions. Other, non-catalyst related improvements to gasoline emission control technology include higher speed computer processors which enable more sophisticated engine control algorithms and improved fuel injectors providing better fuel atomization and improved fuel combustion.

For engine certified systems, the biggest concern will be the thermal durability of the catalysts due to the heavier loads typical of the larger, more commonly engine certified, systems. However, there is less emphasis on cold start emissions on the engine certification test procedure than the chassis test procedure. As a result, there may be less use of close-coupled catalysts for engine certified systems, although we have assumed the same implementation of that technology for vehicles and engines.

Catalyst system durability is a key issue in the feasibility of the standards. Historically, catalysts have deteriorated when exposed to very high temperatures and this has long been a concern for heavy-duty work vehicles. Manufacturers have often taken steps to protect catalysts by ensuring exhaust temperatures remain in an acceptable range. Catalyst technologies in use currently are much improved over the catalysts used only a few years ago. The improvements have come with the increased use of palladium, which has superior thermal stability, and through much improved washcoat technology. The use of rhodium with palladium will also enhance performance of the catalyst. The catalysts have been shown to withstand temperatures typically experienced in heavy-duty applications. Nonetheless, as a worst-case assumption, we are

assuming that 2008 model year heavy-duty gasoline vehicles and engines will require up to a 25 percent increase in precious metal loadings over the estimated 2005 loadings (i.e., 5 g/L versus 2005 levels of 4 or 4.5 g/L) to ensure acceptable catalyst durability characteristics while meeting the standards. Further, we are assuming that catalyst volumes will increase to roughly coincide with engine displacement volume. As a result of the greater catalyst volume, and the greater PGM loading per unit volume, we are assuming considerably more precious metals for greater durability. These costs are reflected in the cost estimates in Chapter V.

We believe that manufacturers will be able to achieve the 2008 standards by optimizing all of these technologies. Current catalyst systems using some of these technologies have already shown potential to reduce emissions to close to the required levels. Some current California vehicles in the 8,500-10,000 pound range are certified to levels below 0.2 g/mile NOx. The California Air Resources Board tested an advanced catalyst system on a vehicle loaded to a test weight comparable to a heavy-duty vehicle test weight and achieved NOx and NMOG levels of 0.1 g/mile and 0.16 g/mile, respectively. Furthermore, the California vehicle with the advanced catalyst had not been optimized as a system to take full advantage of the catalyst's capabilities.

In a light-duty truck technology demonstration program performed for our Tier 2 rulemaking effort, we found that a combination of calibration changes and improvements to the catalyst system resulted in heavy light-duty truck (LDT4) NOx emission levels well below, and NMHC/NMOG emissions slightly below, the Tier 2 intermediate useful life standards (0.05 g/mi NOx and 0.075 g/mi NMOG).[129] The catalyst improvements consisted of increases in volume and precious metal loading, and higher cell-densities than those found in the original hardware. Figures III.B-2 and III.B-3 show the results of our testing on a Ford Expedition and a Chevrolet Silverado, respectively.[130] These figures demonstrate the dramatic improvements in emissions that are possible with even the fairly simple enhancements that were done in a very short time as part of this test program.
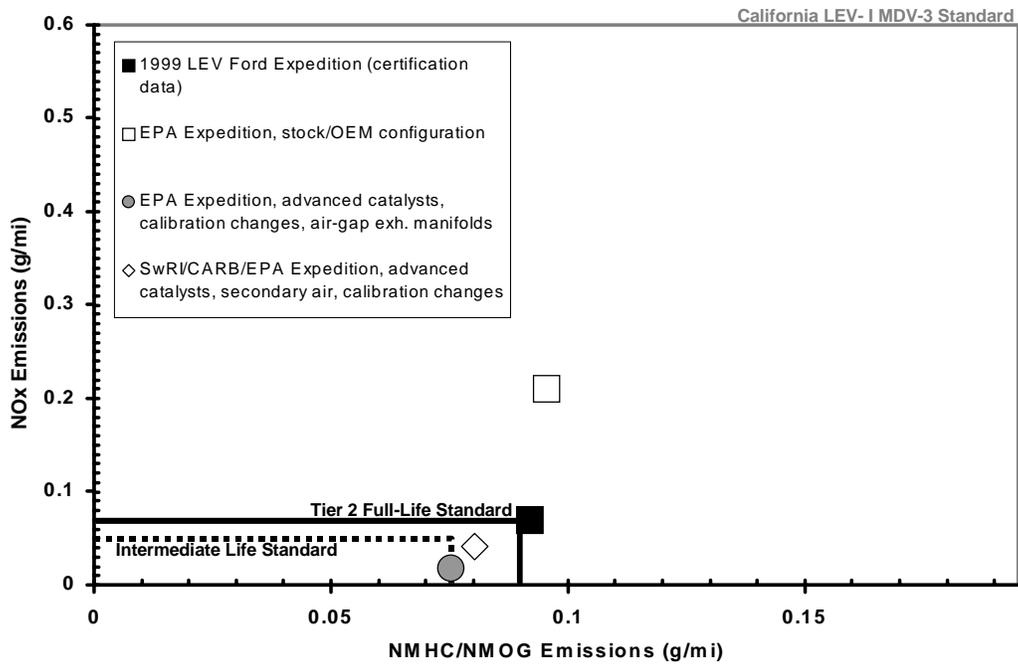
Figure III.B-2. Emissions after an equivalent of 50,000 miles for various tested configurations of Ford Expedition LDT4 SUVs with 5.4L V8 engines
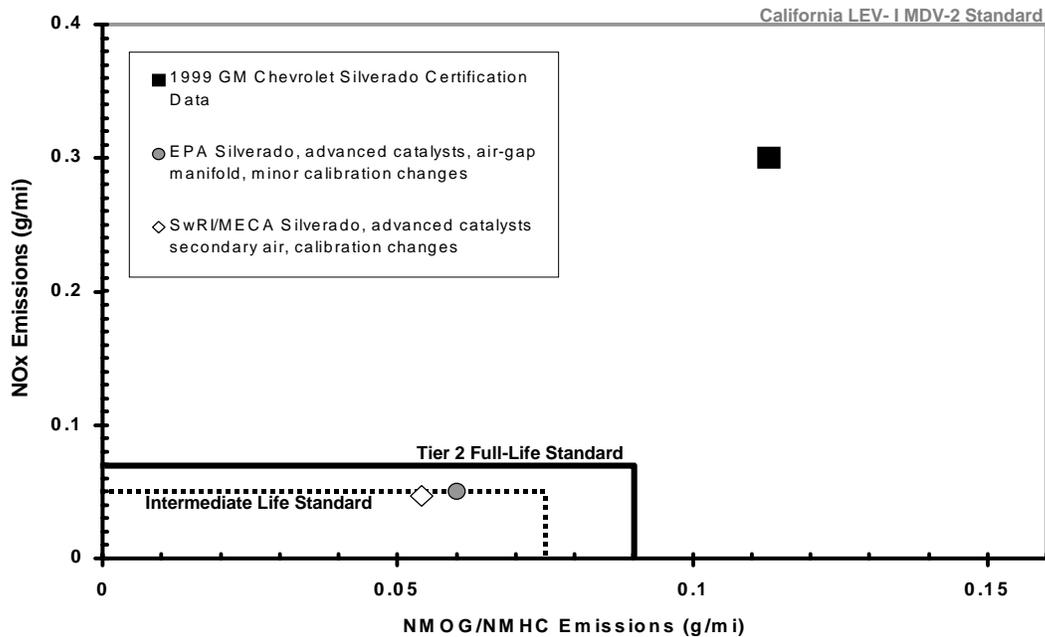
Figure III.B-3. Emissions after an equivalent of 50,000 miles for various tested configurations of 1999 GM Chevrolet Silverado LDT3 pickups with 5.3L V8 engines

The most significant difference between LDT4s (the heaviest of the light-duty classification) and medium-duty passenger vehicles (MDPV), which had been heavy-duty gasoline vehicles prior to our Tier 2 rule, is that MDPVs have a vehicle weight up to 800 pounds more than LDT4s. MDPVs will also be typically equipped with larger displacement engines. The potential impact of these differences is higher engine-out emissions than typical LDT4s. These higher engine out emissions may be expected due to both the larger engine displacement, and the greater load that the engine will be operated under due to the extra weight. However, neither of these preclude manufacturers from applying the same basic emission control technologies and strategies as used by light-duty vehicles and trucks. The only difference will likely be the need for larger catalysts with higher precious metal loadings than found in current systems.

We believe that the test weight difference should not have a significant impact on the emission levels to which these vehicles can be certified. We have tested a Ford Excursion and

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baseline results with a green (i.e., "new") catalyst indicate that emission levels are approximately at, or slightly above, the 2008 heavy-duty standards. We tested the Excursion at loaded vehicle test weight (curb weight + 300 lb, or ~7400 pounds) and again at adjusted loaded vehicle weight (curb + half payload, or ~8000 pounds) and found that the engine-out and tailpipe emission results for NMHC and NOx were within ten percent for the two test weights. In other words, the additional weight (approximately 600 lbs) had no impact on emission performance. This is borne out in the data shown in Table III.B-3, which shows that the DaimlerChrysler 8.0L engine used in the Ram 2500 Pickup (GVWR = 8,800 lbs) and the Ram 3500 Pickup (GVWR = 10,500 lbs) both have very similar emission levels despite having different payloads and, therefore, different test weights. In fact, the heavier vehicle actually had slightly lower emissions. This is also true with the Ford 6.8L engine used in the E350 (GVWR = 9300 lbs) and in the F350 (GVWR = 11,000 lbs); both of these vehicles have essentially the same emission levels. This is significant because the majority of the heavy-duty vehicles falling under the 2008 heavy-duty standards are large panel vans and pick-up trucks which typically weigh the same or less than MPDVs.

Additionally, we believe that the 2008 standards will require manufacturers to focus some effort on engine-out emissions control, and that engine-out NOx levels in the 6 to 8 g/bhp-hr are reasonably achievable.[bb] Since some engines are already in this range, we believe that future engines may even deliver lower engine out emissions. Current HD gasoline engines rely very little on EGR. Recalibration of engine systems, including the EGR system and perhaps some modest hardware changes to those systems, will be necessary. EGR plays a key role in reducing engine-out NOx and system redesign may allow more effective use of this technology.

Lastly, the proposed averaging, banking, and trading (ABT) program can be an important tool for manufacturers in implementing the new standards. The ABT program will allow manufacturers to comply with the more stringent standards by introducing emissions controls over a longer period of time, as opposed to doing so during one or two model years. Manufacturers plan their product introductions well in advance. With ABT, manufacturers can better manage their product lines so that the new standards do not interrupt their product introduction plans. Also, the program allows manufacturers to focus on higher sales volume vehicles first to earn credits and then use those credits for low sales volume vehicles. We believe manufacturers have significant opportunity to earn credits in the pre-2008 time frame by selling their California LEV II certified vehicles nationwide. Further, we are allowing manufacturers to apply credits earned on vehicle sales to their engine sales, and vice versa, although a 20 percent

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[bb] Note that the Phase 1 HD rule requires that diesel engines meet a standard of 2.5 g/bhp-hr NOx+NMHC, of which we believe 2.2 to 2.3 grams will be NOx emissions. That emission level will not require exhaust emission control technology (i.e., catalysts) and will instead be met through use of cooled EGR. In effect, the 2.2 gram NOx level is an engine-out NOx level that will be achieved by diesel engines complying with that standard.

discount will apply.[cc] This ability to use credits across the vehicle/engine categories provides even greater incentive to introduce LEV II vehicles earlier than 2008 to earn credits that can be applied to the lower sales volume engine certified systems. This should provide attractive cost efficiencies to manufacturers while having no negative effects on, and perhaps even improving, air quality.

This discussion highlights our belief that there are numerous proven and existing technologies available that will allow heavy-duty gasoline vehicles to meet our 2008 heavy-duty gasoline exhaust emission standards. Therefore, we believe that these technologies, combined with low sulfur gasoline, ABT, and considerable leadtime before the 2008 model year implementation, will make the 2008 standards technologically feasible for heavy-duty gasoline vehicles.

5.   The 2008 Heavy-Duty Gasoline Evaporative Emission Standards

The new evaporative emission standards for heavy-duty vehicles and engines are shown in Table III.B-5. These standards will apply to heavy-duty gasoline-fueled vehicles and engines, and methanol-fueled heavy-duty vehicles and engines. Consistent with existing standards, the standard for the two day diurnal plus hot soak test sequence would not apply to liquid petroleum gas (LPG) fueled and natural gas fueled HDVs.

Table III.B-5. New Heavy-Duty Evaporative Emission Standards[A]
(grams per test)

Category	3 Day Diurnal + Hot Soak	Supplemental 2 Day Diurnal + Hot Soak[B]
8,500 - 14,000 lbs	1.4	1.75
>14,000 lbs	1.9	2.3

[A] To be implemented on the same schedule as the gasoline engine and vehicle exhaust emission standards shown in Table III.B-2. These new standards do not apply to medium-duty passenger vehicles, and do not apply to diesel fueled vehicles and engines.
[B] Does not apply to LPG or natural gas fueled HDVs.

[cc] As explained in the preamble to this rule, we believe this 20 percent discount is necessary to account for the uncertainty in converting between g/mi standards and g/bhp-hr standards.

These new standards represent more than a 50 percent reduction in the numerical standards as they exist today. The Phase 1 heavy-duty rule made no changes to the numerical value of the standard, but it did put into place new evaporative emission test procedures for heavy-duty complete gasoline vehicles.[dd] For establishing evaporative emission levels from complete heavy-duty vehicles, the standards shown in Table III.B-5 presume the test procedures required in the Phase 1 heavy-duty rule.

The new standards for 8,500 to 14,000 pound vehicles are consistent with the Tier 2 standards for medium-duty passenger vehicles (MDPV). MDPVs are of consistent size and have essentially identical evaporative emission control systems as the remaining work-oriented HDVs in the 8,500 to 10,000 pound weight range. Therefore, the evaporative emission standards should be equivalent. We are requiring those same standards for the 10,000 to 14,000 pound HDVs because, historically, the evaporative emission standards have been consistent throughout the 8,500 to 14,000 pound weight range. The HDVs in the 10,000 to 14,000 pound range are essentially equivalent in evaporative emission control system design as the lighter HDVs; therefore, continuing this historical approach is appropriate.

The evaporative emission standards for the over 14,000 pound HDVs are slightly higher because of their slightly larger fuel tanks and for non-fuel emissions related to larger vehicle sizes. This is consistent with past evaporative emission standards. The levels for the over 14,000 pound HDVs maintains the same ratio relative to the 8,500 to 14,000 pound HDVs as exists with current evaporative standards. To clarify, the current standards for the 3 day diurnal test are 3 and 4 grams/test for the 8,500 to 14,000 and the over 14,000 pound categories, respectively. The ratio of 3:4 is maintained for the new 2008 standards, 1.4:1.9.

The new standard levels are slightly higher than the California LEV-II standard levels. The California standard levels are 1.0 and 1.25 for the 3-day and the 2-day tests, respectively. However, federal vehicles are certified using the higher-volatility federal test fuel.[ee] Arguably, the federal and California evaporative emission standards are equivalent in stringency despite the difference in standard levels.

[dd] The test procedure changes codify a commonly approved waiver allowing heavy-duty gasoline vehicles to use the light-duty driving cycle for demonstrating evaporative emission compliance. The urban dynamometer driving schedule (UDDS) used for heavy-duty vehicles is somewhat shorter than that used for light-duty vehicles, both in terms of mileage covered and minutes driven. This results in considerably less time for canister purge under the heavy-duty procedure than under the light-duty procedure. We recognize this discrepancy and have routinely provided waivers under the enhanced evaporative program that allow the use of the light-duty procedures for heavy-duty certification testing. This is consistent with CARB's treatment of equivalent vehicles. (See 65 FR 59896, October 6, 2000.)

[ee] The federal test fuel specification for fuel volatility, the Reid Vapor Pressure, is 8.7 to 9.2 psi. The California test fuel specification is 6.7 to 7.0 psi.

The new evaporative emission standards are to be implemented on the same schedule as the gasoline engine and vehicle exhaust standards shown in Table III.B-2. This will allow manufacturers to plan any needed changes to new vehicles at the same time, although it is not necessary that the exhaust and evaporative standards be phased-in on the same vehicles and engines. Also, the revised durability provisions finalized in the Tier 2 rule will apply. These provisions require a durability demonstration using fuel containing at least 10 percent alcohol. Alcohol can break down the materials used in evaporative emission control systems. This provision should not have an impact on the feasibility of the new standards.

6.   Technological Feasibility of the 2008 Heavy-Duty Gasoline Evaporative Emission Standards

The new evaporative emission standards appear to be feasible now. Many designs have been certified that already meet these standards. A review of 1998 through 2000 model year certification data indicates that nearly all evaporative system families in the 8,500 to 14,000 pound range comply with the proposed 1.4 g/test standard, while all evaporative system families in the over 14,000 pound range comply with the proposed 1.9 g/test standard. Table III.B-6 summarizes the 1998 through 2000 model year evaporative emission certification data.

**Table III.B-6. 1998-2000 Model Year Evaporative Emission
Certification Data
(grams/test)**

Manufacturer	Category (GVWR)	3 Day Diurnal Emissions (grams/test)
DaimlerChrysler	<14k	0.74 0.64 0.64 1.01 1.06
Ford	<14k	1.17 1.80
	>14k	1.17 1.80
General Motors	<14k	0.67 0.78 0.85 1.03 1.29 1.57 1.69 1.74
	>14k	0.67 0.73 0.85 1.03 1.29 1.57 1.69 1.74

There are two approaches to reducing evaporative emissions for a given fuel. One is to minimize the potential for permeation and leakage by reducing the number of hoses, fittings and connections. The second is to use less permeable hoses and lower loss fittings and connections. Manufacturers are already employing both approaches. Fluoropolymer materials can be added as liners to hose and component materials to yield large reductions in permeability over such conventional materials as monowall nylon. In addition, fluoropolymer materials can greatly reduce the adverse impact of alcohols in gasoline on permeability of evaporative components, hoses and seals. Alcohols, present in about 10 percent of gasoline sold in the U.S., cause swelling of conventional materials which leads to increases in permeability and can also lead to

tearing and leakage in situations where the materials are constrained in place, such as with gaskets and O-rings. Due to the common presence of alcohols such as ethanol in the gasoline pool, and its adverse affect on materials and emissions durability, we believe materials such as those discussed above are necessary to ensure that the benefits are captured in-use. Rather than requiring new application of these materials, our new evaporative standards will simply ensure their consistent and continued use on most engines by discouraging manufacturers from switching to cheaper materials or designs to take advantage of the large safety margins they have under current standards.

Additionally, most manufacturers are moving to "returnless" fuel injection systems. Through more precise fuel pumping and metering, these systems eliminate the return line in the fuel injection system. The return line carries unneeded fuel from the fuel injectors back to the fuel tank. Because the fuel injectors are in such close contact with the hot engine, the fuel returned from the injectors to the fuel tank has been heated. This returned fuel is a significant source of fuel tank heat and vapor generation. The elimination of the return line also reduces the total length of hose on the vehicle though which vapors can permeate, and it reduces the number of fittings and connections through which fuel can leak.

Steel fuel tanks and steel fuel lines have essentially zero losses due to permeation, but are vulnerable to leakage at joints and interfaces. Manufacturers are moving toward plastic fuel tanks for their lighter weight and greater ability to be molded to odd shapes. However, plastic tanks are permeable and are also susceptible to seepage and higher permeability at areas where connections and welds are made. Materials and manufacturing techniques exist to reduce these losses.

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