



# Highway Diesel Progress Review



## **Highway Diesel Progress Review**

Assessment and Standards Division  
Office of Transportation and Air Quality  
Office of Air and Radiation  
U.S. Environmental Protection Agency

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## Executive Summary

In December 2000, the U.S. Environmental Protection Agency (EPA or the Agency) finalized a comprehensive national emissions control program, the 2007 Highway Diesel (HD 2007) program, that regulates highway heavy-duty vehicles and diesel fuel as a single system. Under the HD 2007 program, the Agency established new emission standards that will significantly reduce particulate matter (PM) and oxides of nitrogen (NOx). The monetized benefits of this program exceed its costs by a factor of nearly 17 to one.

These PM and NOx engine standards reflect emission levels that are 90 percent and 95 percent below the standards in effect today, respectively. They will begin to phase-in in model year 2007 (full compliance is not required until 2010) and will apply to heavy-duty highway engines and vehicles. These standards are based on the use of high-efficiency catalytic exhaust emission control devices or comparably effective technologies. The use of these technologies is enabled by a reduction of sulfur in highway diesel fuel by 97 percent, to 15 parts per million (ppm), by June 2006.

While some industry stakeholders supported this program, other industry groups challenged specific provisions of the rulemaking in the United States Court of Appeals for the District of Columbia Circuit. After reviewing the arguments of the litigants and the substantial rulemaking record, on May 3, 2002, the District of Columbia Court of Appeals found for the Agency on all matters of substance. In particular, the Court found that the Agency's conclusions regarding the level of sulfur in diesel fuel and the feasibility of advanced NOx and PM control technologies were reasonably determined and supported by the rulemaking record.

Since December 2000, we have conducted a comprehensive progress review of the technologies needed to implement the program. This report documents the findings of our review. Specifically, this report provides our review of the progress of 1) manufacturers of diesel engines and emission control systems in developing technology to reduce engine exhaust pollutants, and 2) the petroleum refining industry in developing and demonstrating technologies to effectively lower the sulfur level of diesel fuel. Consistent with our stated intention in the HD 2007 rulemaking, we are planning to continue monitoring, on an annual basis, industry's progress in introducing technologies to meet the HD 2007 emission standards.

To characterize the progress by the heavy-duty diesel engine industry (the engine manufacturers and the emission control technology manufacturers), we undertook a comprehensive company-by-company review. As part of this review, we visited technical research centers and met with engineers from more than twenty companies and received comprehensive high level briefings on technical progress and business plans to comply with the 2007 emission standards. From these visits, we have been able to gauge industry progress to develop these technologies as well as industry plans and processes to meet the emission standards

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for 2007. Although it is still early in the process, every major engine manufacturer that we visited told us that they expect to have emission-compliant products in 2007.

We undertook a similar process to review diesel desulfurization technology progress. Specifically, this review involved company visits and conference calls, a review of information submitted through the program's registration and reporting requirements, and a literature review. From the company meetings and reported information, we assessed progress in implementing diesel desulfurization technology as well as plans to produce 15 ppm diesel fuel. Our progress review shows that the technology needed to desulfurize diesel fuel to 15 ppm sulfur is well understood and will produce compliant fuel. While it is still early in the process given the 2006-2010 window for compliance, the refining industry is where we anticipated it to be at this point in time. Moreover, some refining companies are ahead of schedule and will be capable of producing significant volumes of 15 ppm sulfur diesel fuel as early as next year. In fact, small amounts of 15 ppm sulfur diesel fuel are being produced today for use in retrofit and emission reduction programs in some metropolitan areas.

### *Engine Technology Progress*

Catalyzed diesel particulate filters (CDPFs) were already well developed when we set the emissions standards for heavy duty vehicles that begin in 2007. As we discussed extensively in Chapter III of the Regulatory Impact Analysis (RIA) associated with the HD 2007 standards, CDPFs have been introduced in retrofit applications with great success where low sulfur diesel fuel is available. The CDPFs available at the time of the rulemaking provided dramatic emission reductions and good robustness for soot regeneration for most applications. Yet further improvements in CDPFs have continued including even better soot regeneration characteristics, better methods for dealing with oil ash, and reduced exhaust restrictions (reduced exhaust back-pressure) while maintaining a high level of emission control effectiveness.

We were pleased to observe during our progress review that industry has made improvements in the CDPF technology. CDPF catalyst systems have improved soot oxidation characteristics for passive filter regeneration. Total vehicle systems are being introduced that provide an active regeneration backup to ensure that under all driving conditions PM filters can regenerate. Every engine manufacturer that we visited was working on engine and emission control systems to ensure robust PM regeneration characteristics under all driving conditions. One manufacturer has even shown that the periodic NOx regeneration function necessary for proper NOx control can provide a synergistic improvement in PM soot regeneration. Based on the information shared by industry, we are more convinced than ever that, given low sulfur diesel fuel, CDPFs can be implemented with good soot regeneration characteristics on all heavy-duty diesel vehicles. In fact, one engine and vehicle manufacturer, International Truck and Engine Company, has already certified an engine with a CDPF that meets the HD 2007 emission standards for PM and hydrocarbons (HCs) for use in fleets where 15 ppm sulfur diesel fuel is already available.

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Although some application-specific technical challenges remain for CDPFs, all of the engine manufacturers expect and are planning to apply this technology fleet-wide by 2007. Furthermore, it is clear to us, as evidenced by International Truck and Engine Corporation's Green Diesel Vehicles, that if low sulfur diesel fuel was broadly available prior to 2007, CDPFs could be introduced even sooner.

NOx adsorbers were a less mature technology compared to CDPFs when we set the NOx emission standards for 2007. While NOx adsorbers had been applied successfully to light-duty lean-burn gasoline vehicles, additional development was still necessary to apply them to diesel vehicles. We identified areas requiring further development in Chapter III of the RIA for the HD 2007 rulemaking and provided an analysis explaining how we expected the technology to improve to allow for its use for compliance with the HD 2007 NOx emission standard. Our review thoroughly investigated and examined what progress had occurred regarding the issues identified in the RIA. We were pleased to observe that significant progress has been made regarding each of the major issues confronting the NOx adsorber technology.

One of the areas that we identified in the HD 2007 RIA as needing improvement for the NOx adsorber catalyst was performance at low and high temperatures. NOx adsorber performance is limited at very high temperatures (due to thermal release of NOx under lean conditions) and very low temperatures (due to poor catalytic activity for NO oxidation under lean conditions and low activity for NOx reduction under rich conditions) as described extensively in Chapter III of the HD 2007 RIA. We were pleased to discover during our review that significant progress has been made to broaden the temperature "window" (temperature range of effective NOx control) of the NOx adsorber catalysts. The catalyst development companies that we visited showed us a number of new catalyst formulations with improved performance. Similarly, many of the engine manufacturers we visited shared data with us that show the improvements in catalyst formulations corresponded to improvements in emission reductions over the regulated test cycles. It was clear from the data presented to us that the progress with regard to NOx adsorber performance was both substantial and broadly realized by most technology developers.

Long term durability has been the greatest concern for the NOx adsorber catalyst as we explained in the HD 2007 RIA. We concluded in the RIA that, in order for NOx adsorbers to effectively control NOx emission throughout the life of a heavy-duty diesel engine, the fuel sulfur level would have to be maintained at or below 15 ppm, the NOx adsorber catalyst thermal durability needed to improve in order to allow for sulfur regeneration events, and system improvements would have to be made in order to allow for appropriate management of sulfur poisoning. It is in this area of durability that NOx adsorbers had the greatest need for improvement, and it is here where some of the most impressive strides in technology development have been made. During our review, we learned that catalyst companies are making significant improvements in the thermal durability of the catalyst materials used in NOx adsorbers. Similarly, the substrate manufacturers are developing new materials that do not react with the NOx storage materials (storage catalyst interaction with the catalyst substrate has been an important

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degradation mechanism). The net gain from these simultaneous improvements is NO<sub>x</sub> adsorber catalysts which can be desulfated (go through a sulfur regeneration process) with significantly lower levels of thermal damage to the catalyst function. In addition, engine manufacturers and emission control technology vendors are developing new strategies to accomplish desulfation that allow for improved sulfur management while minimizing the damage due to sulfur poisoning. It was clear in our review that the total system improvements being made when coupled with changes to catalytic materials and catalyst substrates are delivering significantly improved catalyst durability to the NO<sub>x</sub> adsorber technology.

Practical application of the NO<sub>x</sub> adsorber catalyst in a vehicle was a major concern of the industry during the HD 2007 rulemaking. Although there was considerable evidence that NO<sub>x</sub> adsorbers were highly effective and that durability issues could be addressed, some worried that the application of the NO<sub>x</sub> adsorber systems to vehicles would be impractical due to packaging constraints and the potential for high fuel consumption. Our review of progress has left us more certain than ever that practical system solutions can be applied to control emissions using NO<sub>x</sub> adsorbers. We have tested a diesel passenger car (one of the most difficult packaging situations) with a complete NO<sub>x</sub> adsorber and particulate filter system that demonstrated both exceptional emission control and good fuel economy. Heavy-duty engine manufacturers have shared with us their improvements in system design and means to regenerate NO<sub>x</sub> while minimizing fuel consumption. Similarly the various Department of Energy (DOE), Advanced Petroleum Based Fuel - Diesel Emission Control (APBF-DEC) program NO<sub>x</sub> adsorber projects are working to address the system integration challenges for a diesel passenger car, a large sport utility vehicle and a heavy heavy-duty truck. The challenge of full system design and implementation for the NO<sub>x</sub> adsorber catalyst remains but the number of entities working to resolve the issues and the substantial success to date suggests that these issues will be overcome.

Over the last year and a half we met with a number of engine and vehicle manufacturers along with emission control system and component manufacturers in order to review progress to develop the NO<sub>x</sub> adsorber catalyst for introduction in 2007. In addition, we tested a NO<sub>x</sub> adsorber system on a heavy-duty diesel engine in our laboratory and tested a complete light-duty vehicle with a NO<sub>x</sub> adsorber system over the regulated emission cycles. Our review shows that the NO<sub>x</sub> adsorber catalyst and the associated system changes required to enable it are continuing to develop at a rapid pace. Given the short time window since December 2000, the substantial progress realized in that short time, and the relatively long lead time between now and 2007, and especially 2010, we believe that continued development of the technology will lead to its successful implementation.

### *Diesel Desulfurization Technology Progress*

As discussed in the HD 2007 rule, conventional diesel desulfurization technologies have been available and in use for many years. We projected that all refiners would be technically capable of meeting the 15 ppm sulfur standard with extensions of the same conventional

hydrotreating technology that they are using today to meet the current highway diesel fuel standard of 500 ppm sulfur. We also projected that all refiners would use recently developed, high activity catalysts, which increase the amount of sulfur that can be removed relative to the catalysts which were available when the current desulfurization units were designed and built more than 10 years ago.

The information we have obtained to date from the discussions we had with technology vendors and refiners (since the final rule was promulgated) is consistent with the projections we made in the HD 2007 program – refiners are technically capable of producing 15 ppm sulfur diesel fuel using extensions of conventional technology and, in fact, they are moving forward with their plans to comply with the program.

### *Refiners' Plans for Producing 15 ppm Diesel Fuel*

We also reviewed the information submitted through the program's registration and reporting requirements and met with a number of diesel fuel refiners to learn about their plans to produce 15 ppm diesel fuel by the June 2006 program compliance date. Since the 15 ppm diesel fuel sulfur standard was established based on the use of extensions of conventional diesel desulfurization technologies, diesel fuel refineries are well positioned to make firm plans for implementation by 2006. Our review has found that this is exactly what refiners are doing. We are very encouraged by the actions some refiners have already taken in terms of announcing specific plans for low sulfur diesel fuel production. It may still be early in the process, but virtually all refiners are already in the stage of planning their approach for compliance. Thus, the refining industry is where we anticipated it to be at this point in time. Moreover, some refining companies are ahead of schedule and will be capable of producing significant quantities of 15 ppm sulfur diesel fuel as early as next year.





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## I. Introduction

### *Background on the Highway Diesel Program*

In December 2000, the U.S. Environmental Protection Agency (EPA or the Agency) finalized a comprehensive national emissions control program, the 2007 Highway Diesel (HD 2007) program, that regulates highway heavy-duty vehicles and diesel fuel as a single system.<sup>a</sup> Under the HD 2007 program, the Agency established new emission standards that will significantly reduce particulate matter (PM) and oxides of nitrogen (NOx). The monetized benefits of this program exceed its costs by a factor of nearly 17 to one.

These PM and NOx engine standards reflect emission levels that are 90 percent and 95 percent below the standards in effect today, respectively. They will begin to phase-in in model year 2007 (full compliance is not required until 2010) and will apply to heavy-duty highway engines and vehicles. These standards are based on the use of high-efficiency catalytic exhaust emission control devices or comparably effective technologies. The use of these technologies is enabled by a reduction of sulfur in highway diesel fuel by 97 percent, to 15 parts per million (ppm), by June 2006.

While some industry stakeholders supported this program, other industry groups challenged specific provisions of the rulemaking in the United States Court of Appeals for the District of Columbia Circuit. After reviewing the arguments of the litigants and the substantial rulemaking record, on May 3, 2002, the District of Columbia Court of Appeals found for the Agency on all matters of substance. In particular, the Court found that the Agency's conclusions regarding the level of sulfur in diesel fuel and the feasibility of advanced NOx and PM control technologies were reasonably determined and supported by the rulemaking record.

### *Final Rule Commitments and Implementation Activities*

This report summarizes several important steps that the Agency is taking in order to ensure a smooth implementation of the program. Specifically, the Agency is following through on actions to which it committed in the final rule and is pursuing additional activities (as it has done historically) to assist regulated entities with program implementation and compliance. These commitments and activities are described in more detail below.

In the preamble to the HD 2007 rule, the Agency committed to biennial assessments of the progress of NOx adsorber technology (66 FR 5063, January 18, 2001):

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<sup>a</sup> *Control of Air Pollution From New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel sulfur Control Requirements; Final Rule*; 66 FR 5002, January 18, 2001 (signed December 21, 2000).

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*As a mechanism for monitoring and evaluating this technological progress, we believe it will be important to publicly reassess the status of heavy-duty diesel NOx adsorber systems on an ongoing basis. To accomplish this, we will conduct regular biennial reviews of the status of heavy-duty NOx adsorber technology...At the end of each review cycle, we will release (and post on the Web) a report discussing the status of the technology and any implications for the heavy-duty engine emission control program. We will release the first report by December 31, 2002 and subsequent reports at the end of each second year through December 31, 2008.*

The HD 2007 rule also contains registration and reporting requirements for the petroleum industry which were designed to ensure a smooth transition to the program and to evaluate compliance once the program has begun. These reports will assist in educating the marketplace so that refiners can plan for compliance with more certainty regarding market conditions.

### *Independent Review on Industry Progress*

In addition to the activities described above, the Agency announced its intention to establish an independent review panel to report on industry progress toward compliance with the program's requirements. Administrator Whitman described this independent review panel in a letter to Senator James Jeffords, Chairman of the Senate Committee on Environment and Public Works:

*...EPA will convene an outside panel of experts to independently assess the progress of: (1) manufacturers of diesel engines and emission control systems in developing technology to reduce engine exhaust pollutants; and (2) the fuels industry in developing and demonstrating technologies to effectively lower sulfur levels. The panel will be comprised of representatives of the major stakeholder groups....<sup>b</sup>*

The Clean Diesel Independent Review Panel<sup>c</sup> will operate under the auspices of the Federal Advisory Committee Act (FACA) as a Subcommittee of the Clean Air Act Advisory Committee. The panel is a temporary subcommittee (similar to the MTBE Blue Ribbon Panel which reviewed the use of methyl tertiary-butyl ether (MTBE) and other oxygenates in gasoline) which began its work in May and will conclude its work in September. As Administrator Whitman announced, the panel's purpose is to review industry's progress in implementing the program. Since the highway diesel program was only recently promulgated and the affected industries will have six to nine years lead time to meet the standards, we do not expect the panel

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<sup>b</sup> Letter from Administrator Whitman to Senator James Jeffords, September 27, 2001.

<sup>c</sup> [http://www.epa.gov/air/caaac/clean\\_diesel.html](http://www.epa.gov/air/caaac/clean_diesel.html).

## I. Introduction

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to find widespread adoption of technologies that meet the 2007 program requirements. Instead, the panel will focus on the development progress of applicable technologies, looking at information and activities since January 2001.

The panel is composed of leading experts from the public health community, petroleum industry, engine manufacturing industry, exhaust emission control industry, and state governments. Daniel Greenbaum, President of the Health Effects Institute, will serve as the panel's chairperson. Administrator Whitman has asked the panel to report its findings to her by mid-September 2002.

As described above, EPA is also conducting a technical review, as part of the commitment it made in the final rule for an ongoing assessment of progress that industry is making toward the program's implementation. This report is our first biennial report and has been expanded to include the refinery industry technology progress. We will be providing this report to the Clean Diesel Independent Review Panel to bring all the participants up to date with our assessment of program implementation and to provide a starting point from which to conduct its review. Specifically, this report provides our review of the progress to date of 1) manufacturers of diesel engines and emission control systems in developing technology to reduce engine exhaust pollutants, and 2) the petroleum refining industry in developing and demonstrating technologies to effectively lower the sulfur level of diesel fuel to 15 ppm or less.





## **II. Progress Review of Engine Technologies**

This section is organized chronologically to allow the reader to develop an understanding of the HD 2007 emissions program, the status of technology in December 2000, the process the EPA has gone through since the rulemaking to follow industry progress and finally a description of the progress that we have observed in our review.

### **A. Heavy Duty 2007 Standards**

The highway diesel program contains a PM emissions standard for new heavy-duty engines of 0.01 grams per brake-horsepower-hour (g/bhp-hr), beginning with the 2007 model year. The program also establishes standards for NOx and non-methane hydrocarbons (NMHC) of 0.20 g/bhp-hr and 0.14g/bhp-hr, respectively. The NOx and NMHC standards will be phased-in together between 2007 and 2010, for diesel engines. The phase-in will be on a percent-of-sales basis: 50 percent from 2007 to 2009 and 100 percent in 2010. These standards are described in Table II.1, below.

**Table II.1 Emission Standards for Model Year 2007 and Beyond Heavy-Duty Engines.**

		Standard (g/bhp-hr)	Phase-In by Model Year			
			2007	2008	2009	2010
Diesel	NOx	0.20	50%	50%	50%	100%
	NMHC	0.14				
	PM	0.01	100%	100%	100%	100%

The program includes flexibility provisions to facilitate the transition to the new standards and to encourage the early introduction of clean technologies, and adjustments to various testing and compliance requirements to address differences between the new technologies and existing engine-based technologies.

EPA adopted a special provision for the Averaging, Banking, and Trading (ABT) program in the final rule that allows a manufacturer to create a single engine family meeting both the phase-out and phase-in standards during 2007-09 through averaging (see 40 CFR 86.007-11(m)(9)). The manufacturer would split this family, declaring half of the engines in it to be “phase-out” engines, generating credits against the 2.5 g/bhp-hr NMHC+NOx standard,

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and half to be “phase-in” engines, using these credits to demonstrate compliance with the 0.20 NOx standard. A single set of Family Emission Limits (FELs) would be declared for both subfamilies, and no banked credits or credits from other engine families could be used, or vice-versa. As a result, a manufacturer could, if desired, produce only engines meeting approximately a 1.2 g/hp-hr NOx FEL during the 2007-09 model years.<sup>d,e</sup> This corresponds to a roughly 50 percent NOx adsorber efficiency on a 2.5 g/hp-hr NOx+NMHC engine. None of these split family provisions affect the separate requirement to demonstrate compliance with the 0.01 g/bhp-hr PM standard.

This provision of the program means that for manufacturers choosing to do so, the program has a two-step NOx standard with an intermediate standard of 1.2 g/bhp-hr beginning in 2007 that requires approximately a 50 percent reduction in NOx emissions. Full compliance with the 0.2 g/bhp-hr standard is then not required until 2010. This gives manufacturers substantially more flexibility in developing new technologies.

### **B. Technology Status at the Time of the Rule**

In December 2000, we finalized a Regulatory Impact Analysis (RIA) that documented the technologies we expected would be used by industry to comply with NOx and Particulate Matter (PM) standards set in the associated HD 2007 rulemaking. The RIA detailed both the technologies we expected industry to use and particular challenges that industry would have to overcome in order to apply these technologies. In effect, the RIA laid out a path we thought it likely that the industry would follow in order to develop new technologies capable of meeting the HD 2007 emissions standards. While laying out a relatively well defined path for technology development, we also noted that technology developments are inherently difficult to predict and that, given the substantial lead time (six to nine years) available to develop technologies for compliance with the new emission standards, it would be appropriate for EPA to conduct biennial technology reviews. In particular, the preamble for the HD 2007 rule identified remaining technical issues with regard to the NOx adsorber technology that would need to be addressed. This report documents our findings in the first of these technology reviews.

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<sup>d</sup> The NOx FEL of the split family could vary somewhat depending on the NMHC emissions level, from 1.16 for an engine emitting at the 0.14 g/bhp-hr NMHC standard, to 1.22 for an engine emitting no NMHC. This range is sufficiently narrow that, for the purposes of this technology review, it is sufficient to assume a 1.2 g/bhp-hr NOx level for any split family.

<sup>e</sup> It should be noted too that this level is within the threshold values for application of the in-use add-on standards (1.3 g/bhp-hr NOx threshold-- see 40 CFR 86.007-11(h) ) and the 1.5x NTE NOx and NMHC multipliers (1.5 g/hp-hr NOx threshold-- see 40 CFR 86.007-11(a)(3) and (4)).

## **II. Progress Review of Engine Technologies**

The RIA identified some specific steps that we thought industry would take in order to commercialize the technology we thought most likely to be used to meet the NO<sub>x</sub> standard, the NO<sub>x</sub> adsorber catalyst. These steps, laid out in detail in Chapter III of the RIA, included:

- Improvements to broaden the temperature range over which the NO<sub>x</sub> adsorber is effective (temperature window)
- Improvements in thermal durability (resistance to thermal sintering)
- Improvements in methods and performance for desulfation (sulfur cleansing)
- Improvements in system integration (NO<sub>x</sub> regeneration, package, fuel economy)

We focused on the need to make progress on these issues in conducting our review of technology developments reported here. The review process reveals, as detailed in the following sections, that industry has in fact made substantial progress toward addressing each of these issues. Even though a short amount of time has transpired since we finalized the HD 2007 rule, the results chronicled in this report show that the industry is well on its way to producing a NO<sub>x</sub> adsorber technology capable of meeting the HD 2007 NO<sub>x</sub> standards.

While the PM filter technology was already well developed and in some cases commercially available at the time of the HD 2007 rulemaking, technology developers since that time have continued to improve the Catalyzed Diesel Particulate Filter (CDPF). Specific improvements in CDPFs include:

- Improvements in PM filter regeneration (oxidation and removal of stored soot)
- Improvements in ash handling (increase service interval before ash cleaning)
- Reductions in the pressure drop across the PM filter (improved fuel economy)

The CDPF technology has progressed such that where low sulfur diesel fuel is available (<15 ppm sulfur), one manufacturer is already selling vehicles with CDPFs that are in compliance with both the HC and PM standards set for 2007, a full five years before required.

The RIA provided a much shorter analysis of the potential for future improvements in engine-out emissions. It noted that further modest emission reductions beyond the levels required by the emission standards for 2004 may be possible, but that significant reductions in NO<sub>x</sub> and PM would not be possible. While we continue to believe that catalyst based emission control technologies represent the only viable path for reducing NO<sub>x</sub> and PM emissions to levels substantially below the 2004 standards, we now also believe based on this review, that there are a number of in-cylinder emission control technologies which can provide valuable synergistic benefits in conjunction with catalyst based emission control technologies for compliance with the HD 2007 emission standards. These system solutions are limited to a relatively narrow range of engine operation but offer the potential to enhance the performance of both the NO<sub>x</sub> adsorber and CDPF technologies in order to improve the overall emission control performance of diesel engines across the broad range of engine operation. These new developments in in-cylinder emission

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control and the synergies with NOx adsorbers and CDPFs further convinces us that a systems approach incorporating better engine management with the latest technologies and diesel fuel with a sulfur content below 15 ppm will allow engine manufacturers to meet these stringent new emission standards.

### **C. The Review Process**

Our review of progress to develop technologies to meet the HD 2007 emission standards is based upon a broad spectrum of information provided by a cross-section of industry as well as government sources. We have aggregated some of the publicly available data in this report, but the conclusions we are drawing in this report are based upon both the publicly available information and the Confidential Business Information (CBI) that was shared with us during our meetings with industry. The following sections will detail how we conducted our progress review, and what we learned from that process.

#### **1. Company Visits**

We have conducted this progress review over the last year-and-a-half tracking developments by industry and by government / industry consortiums to develop technologies for heavy-duty diesel vehicles to meet the HD 2007 emission standards. We visited technical research centers and met with engineers from more than twenty companies and received comprehensive high level briefings on technical progress and business plans to comply with the HD 2007 emission standards.<sup>f</sup> These visits included tours of research and development facilities, future manufacturing facilities for new diesel emission control equipment and detailed reviews of technology development and future planning. During each of these visits, we asked industry to estimate, based on each company's experience, the current state of the NOx adsorber and CDPF technologies. We also asked the companies to review their plans and expectations to improve the technologies in the coming years. Finally, we asked the companies to provide us with detailed descriptions of their current and future investments in R&D and in new manufacturing that would be needed in order to bring the technologies to market by 2007. In composite then, we could evaluate the current status of the technologies, the expected performance of the technologies given further planned development and the level of financial commitment by each company to deliver a product by 2007.

The information shared during these visits with the regulated industry provided the primary basis for our conclusions regarding progress by industry. Much of the information shared with EPA by industry was designated as Confidential Business Information (CBI) and as such can

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<sup>f</sup> Appendix B includes a list of the companies and organizations that we met with in conducting this review.

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## II. Progress Review of Engine Technologies

not be described in detail here. This report attempts to provide a contemporaneous view of progress by industry as a whole using representative data from industry that has been released from designation as CBI.

### **2. Testing at the National Vehicle and Fuel Emissions Laboratory (NVFEL)**

It is difficult to judge progress to develop new technologies without becoming first well familiar with the technologies and the challenges that must be overcome. EPA constituted a team of engineers and scientists at the National Vehicle and Fuel Emissions Laboratory (NVFEL) in 1999 to begin work to evaluate and develop advanced diesel emission control technologies in support of the HD 2007 rulemaking. This team working with technical support from a number of emission technology and engine companies showed that NO<sub>x</sub> adsorber catalysts and diesel particulate filters can dramatically reduce diesel emissions. The work from that team, documented in detail in the HD 2007 RIA, provided a primary basis for our understanding of the technologies as we developed the HD 2007 emission standards. That team continued its work even after the rulemaking was completed in order to advance the state-of-the-art in emission control technologies and to inform this progress review. The experience gained by EPA staff in working on that team and the novel data gathered by the team helped inform our view of the current state-of-the-art of the NO<sub>x</sub> adsorber catalyst and the CDPF. Results from that work are documented throughout this report.

### **3. Department of Energy (DOE) Research Programs**

The Department of Energy (DOE) along with a number of industry partners began a joint research program called the Diesel Emission Control Sulfur Effects (DECSE) program in 1998. The program evaluated the effect of sulfur in diesel fuel on the performance and durability of a number of diesel emission control technologies. The information from that program documented in five technical reports played an important role in informing the Agency during the HD 2007 rulemaking.<sup>1</sup> Based on the success of the DECSE program, DOE along with a number of other government agencies including EPA, and an even larger group of industry supporters has begun a new research program entitled the Advanced Petroleum Based Fuels - Diesel Emission Control (APBF-DEC) program. The APBF-DEC program has separate research efforts focused on developing a NO<sub>x</sub> adsorber and CDPF based emission control system for a diesel passenger car, a sport utility vehicle, and a heavy heavy-duty engine. Although it is too early in the APBF-DEC program to have emission results from the systems, the work that has gone into designing the emission control systems for each of the applications has provided insight into how these technologies may be applied in the future.

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The DOE has also sponsored a number of other research programs at National Laboratories and with industry to promote the development of advanced diesel engine systems. DOE has reviewed progress and results from these programs with EPA on an ongoing basis as the programs have developed new information. For this report, DOE provided a summary of the most significant research programs to EPA.<sup>2</sup> The DOE programs, similar to our own experience, show that NO<sub>x</sub> adsorbers offer the potential for large emission reductions and that significant progress is being made to improve their performance, but that technical issues remain to be addressed in the future.

Our review of progress to develop technologies to meet the HD 2007 emission standards is based upon a broad spectrum of information provided by a cross section of industry as well as government sources. We have aggregated some of the publicly available data in this report, but the conclusions that we are drawing in this report are based upon both the publicly available information and the Confidential Business Information that was shared with us during our meetings with industry.

### **D. Expectations for Progress and Industry Investment**

The regulations for heavy-duty diesel engines in 2007 were published less than 18 months ago and will not begin to go into effect for another five years and will not be fully phased-in until 2010. Defining success for progress to meet emission standards with significant lead time remaining can be difficult. In this case, we were looking for two important aspects with regard to progress by industry to prepare for 2007. First, we looked to see that improvements were being made on the most important technical issues identified in the Regulatory Impact Analysis (RIA) (see Chapter III). Significant improvements in performance and durability have been made with regard to all of the technical issues identified in the RIA as detailed in Sections II.E and II.F of this report.

The second important question that we looked to understand was whether financial investments and business plans were being made to deliver the technology by 2007. Absent significant investments by industry in research and development, in product planning and in manufacturing, a new technology can not be brought to market. As part of our progress review visits with industry we reviewed research plans, research spending levels, product plans and manufacturing investment in order to confirm that industry was making the appropriate commitments needed to deliver the clean diesel product for 2007. Our review found that industry is making substantial investments in research and development as well as for new manufacturing facilities in order to bring technologies to market for 2007. Although the manufacturers indicated that they are a number of years away from making their final technology selections for 2007, all had targeted plans showing how technology development and manufacturing would be integrated for 2007. No engine manufacturer indicated that they expected to be unable to develop a product

## **II. Progress Review of Engine Technologies**

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for 2007. Similarly, the engine manufacturers plans for compliance in 2010 were all designed to build upon their individual approaches for 2007.

In order to provide information to the Agency on the degree of investment by industry to develop technologies for HD 2007 without revealing the confidential business plans of its members, the Manufacturers of Emission Control Association (MECA) surveyed its members and aggregated their responses regarding spending on research, development and capital improvements in order to develop new technologies for diesel engines. That data show that the MECA member companies will spend in excess of \$1 billion cumulatively from 1999 to 2007 on diesel engine technologies (both for light and heavy duty diesel vehicles). This represents a substantial investment by the industry to develop new technologies and to put manufacturing systems in place to produce advanced emission control systems. A number of companies emphasized in their survey responses that these investments are being premised on the knowledge that these technologies will be needed and available for 2007. The fact that such significant investments are being made shows that this industry has high confidence that the technology will be ready for production by 2007.

Although, final technology decisions have not been made by any of the engine manufacturers, most indicated that they intend to make use of a flexibility in the HD 2007 rule allowing manufacturers to certify to an average NO<sub>x</sub> standard of approximately 1.2 g/bhp-hr in 2007. The manufacturers that are planning to follow this path indicated that they are expecting to use NO<sub>x</sub> aftertreatment technologies to comply with the effective average standard. None of the manufacturers felt that they would have an engine-out emission control technology capable of meeting the NO<sub>x</sub> and PM standards. Nor did any manufacturer believe that they could develop a sulfur insensitive technology to comply in 2007. Manufacturers gave a number of reasons for following this path:

- simpler to apply and market a single technology across all engines
- provides additional "headroom" below the standard for catalyst deterioration
- allows for orderly progress of technology toward full compliance in 2010.

In summary, then, based on our review of manufacturers plans and successes to date, we are left well convinced that industry is making the appropriate financial investments and prudent planning to deliver compliant technology for 2007 and for 2010. In fact, the investments that industry is making are so large that serious financial hardship could be incurred were changes to the program considered that would, in effect, delay the implementation of the new technologies. These significant investments are paying substantial dividends in technology advancements as detailed in the following sections.

## **E. PM Filter Progress**

We identified the Catalyzed Diesel Particulate Filter (CDPF) as the technology most likely to be adopted by industry in order to comply with the 0.01 g/bhp-hr particulate matter (PM) standard set for heavy-duty diesel vehicles beginning in 2007. The technology is highly effective at controlling PM when used with low sulfur diesel fuel as described in detail in Chapter III of the HD 2007 RIA. The technology has proven itself in tens of thousands of retrofit applications where low sulfur diesel fuel is already available. Yet, there are some aspects of the catalyzed diesel particulate filter which we believe will be improved before 2007.

This section details specific areas where we have observed further improvements in the CDPF technology.

### **1. Improvements in PM Filter Regeneration (Oxidation and Removal of Stored Soot)**

CDPFs control diesel PM by capturing the soot (solid carbon) portion of PM in a filter media, typically a ceramic wall flow substrate, and then by oxidizing (burning) it in the oxygen-rich atmosphere of diesel exhaust.<sup>§</sup> In aggregate over a driving cycle, the PM must be burned at a rate equal to or greater than its accumulation rate, or the CDPF will clog. Given low sulfur diesel fuel (diesel fuel with a sulfur content of 15 ppm or lower), highly active catalytic metals (e.g., platinum) can be used to promote soot oxidation. This is the primary means of soot oxidation that we projected industry would use in 2007.

During our review of technology developments for 2007, we learned that additional progress is being made both to improve catalytic-based soot regeneration technologies and to develop system solutions to ensure that even under the most extreme conditions soot regeneration can be assured. Improvements in catalytic soot oxidation are important because more active soot oxidation can help to improve fuel economy and to ensure robust soot regeneration. A PM filter with a more effective soot oxidation catalyst would be expected to have a lower average soot loading and therefore would be less restrictive to exhaust flow, thus decreasing the pressure drop across the PM filter and leading to better fuel economy. Additionally, improved soot oxidation effectiveness will provide additional assurance that excessive soot loading which could lead to PM filter failure will not occur.

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<sup>§</sup> The gas phase hydrocarbons that make up the soluble organic fraction (SOF) of PM are controlled with CDPFs through oxidation of the SOF on the catalyst. The CDPF does not control the sulfate fraction of PM, and in fact, can increase the sulfate fraction due to the oxidation of sulfur species on the catalyst. See Chapter III of the HD 2007 RIA for a more complete description of CDPFs.



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At a recent conference of the Society of Automotive Engineers (SAE) a paper was presented that documented improvements in catalyzed diesel particulate filter system design in order to improve soot oxidation effectiveness. The paper showed that changes in where catalytic materials were coated within a PM filter system (on an up-front flow through catalyst, on the surface of the PM filter or a combination of both) influenced the effectiveness of the catalyst material to promote soot oxidation.<sup>3</sup> This kind of system analysis suggests that there remains opportunities to further improve how diesel particulate filters are designed to promote soot oxidation and that different solutions may be chosen dependent upon expected vehicle operation (expected exhaust temperature history), packaging constraints and cost. The fact that there continues to be system enhancements of the relatively mature diesel particulate filter technology gives us great confidence that PM filters can be applied broadly in 2007.

Although highly effective catalytic soot oxidation, enabled by clean diesel fuel (15 ppm S), suggests that PM filters will regenerate passively for most vehicle applications, there remains the possibility that for some conditions active regeneration systems (backup systems) may be desirable. This is perhaps most likely for vehicles which are operated primarily as passenger vehicles (light duty cars and trucks, and some light heavy-duty trucks). For this reason a number of vehicle manufacturers have developed systems to help ensure that PM soot regeneration can occur under all conditions. One example of this is a current production product sold in Europe by PSA/Peugeot. On diesel powered Peugeot passenger cars a PM filter system is installed that includes mechanisms for engine-promoted soot oxidation.<sup>h</sup> The vehicle estimates soot loading from a number of parameters including exhaust backpressure and can periodically promote more rapid soot oxidation by injecting additional fuel late in the combustion cycle. This fuel is injected so late in the cycle that it does not contribute to engine power but instead is combusted (oxidized) across an oxidation catalyst in front of the PM filter. The combustion of the fuel across the catalyst increases the exhaust temperature substantially promoting rapid soot oxidation. By the end of 2002, Peugeot expects to have 270,000 passenger cars with this technology on the road.<sup>4</sup> Other vehicle manufacturers indicated to EPA during our progress review, that they intend to introduce similar technologies in the near future.<sup>i</sup> They noted that this was not driven by regulation but by customer demand for clean diesel technologies. The fact that manufacturers are introducing PM filter technologies in advance of mandatory regulations suggests that the technology is well developed and mature.

The potential for synergistic benefits to the application of both PM filters and NOx adsorbers was highlighted by EPA in the HD 2007 rulemaking but at that time little was known as

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<sup>h</sup> The PSA system also uses a cerium fuel additive to promote soot oxidation. However, the exhaust temperature is often still too low for adequate soot oxidation necessitating an active regeneration strategy.

<sup>i</sup> One important difference between these new systems and the PSA system is the use of a fuel additive to promote soot oxidation. While the current PSA system uses a cerium fuel additive, future systems from other manufacturers are not expected to use a fuel additive.

to the extent of these synergistic benefits. Toyota has developed a combined diesel particulate filter and NOx adsorber technology dubbed DPNR (Diesel Particulate NOx Reduction). The mechanism for synergistic PM soot regeneration with programmed NOx regeneration was recently documented by Toyota in a SAE publication. The paper showed that active oxygen molecules created both under lean conditions as part of the NOx storage function and under rich conditions created by the NOx regeneration function were effective at promoting soot oxidation at low temperatures.<sup>5</sup> This suggests that the combination of a NOx adsorber catalyst function with a diesel particulate filter can provide a more robust soot regeneration system than a PM filter-only technology. This benefit may be one consideration for engine manufacturers who choose to apply the NOx adsorber technology across all of their product lines in 2007 as allowed for in the ABT program. Most catalyst development companies that we visited with indicated that they are presently developing similar technologies and at least one has announced that they will have a product available by 2007.<sup>j</sup>

Soot regeneration under all possible vehicle operating conditions is the most important issue for the PM filter technology. Failure of the system to regenerate can lead to unacceptable vehicle operation and excessive fuel consumption. We believed, as explained in Chapter III of the HD 2007 RIA, that the PM filter systems had advanced to the point that regeneration under all conditions could be ensured. Given the further improvements in the technology, and the fact that PM filters are already being applied by vehicle manufacturers in what are perhaps the most difficult applications (passenger car driving cycles), makes us even more confident that this technology is appropriate for widespread vehicle application. Significantly, all engine manufacturers have indicated to us that they intend to use PM filters in order to comply with the HD 2007 emission standards. We believe that the only thing preventing the opportunity for widespread use of PM filters today is the limited availability of clean diesel fuel (15 ppm sulfur fuel). In areas of the country where low sulfur diesel fuel is available early introductions of the technology are in fact occurring today a full five years before the emission standards go into effect.

## **2. Improvements in Ash Handling (Increased Service Interval Before Ash Cleaning)**

Inorganic solid particles present in diesel exhaust can be captured by diesel particulate filters. Typically these inorganic materials are metals derived from engine oil, diesel fuel or even engine wear. Without a PM filter these materials are normally exhausted from the engine as diesel PM. While the PM filter is effective at capturing inorganic materials it is not typically effective at removing them, since they do not tend to be oxidized into a gaseous state (carbon soot is oxidized to CO<sub>2</sub> which can easily pass through the PM filter walls). Because these inorganic materials are

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<sup>j</sup> Johnson Matthey has recently announced that they will sell an integrated NOx adsorber PM filter technology dubbed Total Catalytic Reduction Technology or TCRT.

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not typically combusted and remain after the bulk of the PM is oxidized from the filter they are typically referred to as ash. While filtering metallic ash from the exhaust is an environmental benefit of the PM filter technology it also creates a maintenance need for the PM filter in order to remove the ash from the filter.

The maintenance function for the removal of ash is relatively straightforward, and itself does not present a significant technical challenge for the industry. However, both the industry and EPA would like to see ash related PM filter maintenance reduced as much as possible if not eliminated. EPA has specific guidelines for acceptable maintenance intervals intended to ensure robust emission control technologies (100,000 mile minimum intervals for light heavy-duty trucks and 150,000 miles for medium and heavy heavy-duty trucks). Engine manufacturers are similarly motivated to improve reliability and reduce maintenance to minimize end-user costs. The issue of ash accumulation was raised consistently during our progress review visits with the industry. The industry is investigating a number of ways to address this issue including means to improve ash tolerance and to reduce the amount of ash present in diesel exhaust.

For most current PM filter designs ash accumulates at the end of the inlet passages of the PM filter. As more ash is accumulated, the effective filter size is reduced because the ash fills the end of the passage shortening the effective filter length. One simple approach to address ash is to increase PM filter size in order to tolerate higher levels of ash accumulation. This approach, although effective, is undesirable due to the added cost and size of the resulting PM filter. A number of companies are investigating means to develop PM filter mechanisms which are more ash tolerant. These approaches include concepts to increase storage area within the filter itself and concepts which promote self-cleaning of the filter perhaps driven by engine and vehicle vibrations during normal vehicle operation. It was not clear during our review that these technologies would be able to fully address ash accumulation, but they were indicative of the potential to increase the interval between necessary ash removal maintenance activities.

In addition to concepts to improve ash handling, possibilities exist to decrease the amount of ash present in diesel exhaust. The predominant source of ash in diesel exhaust is inorganic materials contained in engine oil (oil ash). A significant fraction of the ash in engine oil is from additives necessary to control acidification of engine oil due in part to sulfuric acid derived from sulfur in diesel fuel. As the sulfur content of diesel fuel is decreased, the need for acid neutralizing additives in engine oil should also decrease. The concept of an engine oil with less ash content is often referred to as "low-ash oil." A number of technical programs are ongoing to determine the impact of changes in oil ash content and other characteristics of engine oil on exhaust emission control technologies and engine wear and performance. Historically, as engine technologies have changed (often due to changes in emission regulations) engine oil formulations have also changed. These changes have been accomplished through industry consensus on oil specifications based on defined test protocols. This process of consensus definition has begun for 2007, and we have every confidence that as in the past, this process will succeed in delivering new oil formulations

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appropriate for 2007 engine technologies. A more complete description of industry programs to define a new engine oil for 2007 is presented in Section II.G below.

It may also be possible to reduce the ash level in diesel exhaust by reducing oil consumption from diesel engines. Diesel engine manufacturers over the years have reduced engine oil consumption in order to reduce PM emissions and to reduce operating costs for vehicle owners. Further improvements in oil consumption may be possible in order to reduce ash accumulation rates in PM filters. If oil accumulation rates could be halved and engine oil ash content similarly decreased, the PM filter maintenance interval would be increased fourfold. Current retrofit PM filter ash maintenance intervals can range from 60k miles to more than 125k miles.<sup>6</sup> The HD 2007 RIA estimated that PM filter maintenance for ash accumulation would occur at 150k mile intervals. Progress by industry to decrease oil ash maintenance would suggest that this interval is conservatively short and actual maintenance intervals for 2007 will be longer.

### **3. Reductions in the Pressure Drop Across the PM Filter (Improved Fuel Economy)**

The most common type of PM filter is a wall flow ceramic filter made of either cordierite or silicon carbide. The filter consists of a honeycomb ceramic similar to the ubiquitous flow-through catalyst substrate used on almost all passenger cars today but with alternately plugged channels such that no flow-through channel exists. Instead, gases enter an open channel and must diffuse through the wall of the filter into an adjacent channel which is open to the exit of the filter. The wall between the adjacent inlet and outlet channels serves as the filtering media. The pressure drop (essentially the pumping work) across the PM filter is determined by flow losses in the inlet and exit channels and the flow loss through the filter wall. There are a number of filter design parameters that engineers can change in order to reduce the flow restriction of the PM filter. Recent work by several PM filter manufacturers shows that PM filter designs can be improved to reduce the pressure drop across the PM filter (improve fuel economy) without necessarily adversely impacting filtering efficiency.

In a paper entitled *SiC (silicon carbide) and Cordierite Diesel Particulate Filters Designed for Low Pressure Drop and Catalyzed, Uncatalyzed Systems* researchers at NGK Insulators documented their work to define the controlling characteristics of PM filter efficiency and pressure drop.<sup>7</sup> The researchers investigated the effects of changes to filter porosity, mean pore size, cell density, and wall thickness to determine differences in the observed pressure drop between various combinations of design changes. They used both modeling results and experimentation to identify the key parameters affecting flow restriction through the PM filter. The results showed that flow characteristics changed significantly between a clean PM filter (no soot loading) and one with a developed layer of soot. Once a filter has developed a layer of filtered soot, their research showed that flow losses through the filter wall dominated the observed

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pressure drop. The modeling and experimental results suggest that high cell density (more narrow channels in a given area) will lead to reduced pressure-drop due to the increase in filter area (total wall area) up to a point, when the channel flow losses begin to dominate. The researchers concluded that a cell density of 300 cells per square inch represents an optimal cell density. Similarly, they showed that high porosity and large pores reduce the pressure drop observed with soot loading. However, this reduction in flow losses comes with a reduction in PM filtering efficiency. The researchers concluded that an optimal uncoated filter design will have a porosity within a range from 10 micron to 70 micron. The research described primarily the performance of uncoated soot filters, future work by the researchers will investigate the performance and pressure drop for soot filters with a catalytic coating. The addition of a catalytic coating was shown to change the pressure drop characteristics dramatically. The mean pore diameter and the distribution of pore sizes are expected to be critical design elements relating to coated PM filter designs.

In our meetings with PM filter manufacturers, we learned that similar internal studies are being made by a number of researchers. The companies have made significant research investments to apply science to design PM filter materials. These investments have resulted in a dramatic improvement in the understanding of the various design parameters that are critical to PM filter design. Based on this improved science, future PM filter designs are expected to offer better tradeoffs between pressure drop (fuel economy) and filtering efficiency.<sup>k</sup>

### **F. NO<sub>x</sub> Adsorber Progress**

NO<sub>x</sub> adsorbers work to control NO<sub>x</sub> emissions by storing NO<sub>x</sub> on the surface of the catalyst during the lean engine operation typical of diesel engines and then by undergoing subsequent brief rich regeneration events where the NO<sub>x</sub> is released and reduced across precious metal catalysts. This method for NO<sub>x</sub> control has been shown to be highly effective when applied to diesel engines but has a number of technical challenges associated with it. In the HD 2007 RIA we identified four primary issues related to: performance of the catalyst across a broad range of exhaust temperatures, thermal durability of the catalyst when desulfated, management of sulfur poisoning and system integration on a vehicle. Over the last 18 months we have conducted a review of progress by industry and various government entities to address these technical challenges. This section describes what we have learned with regard to each of these issues.

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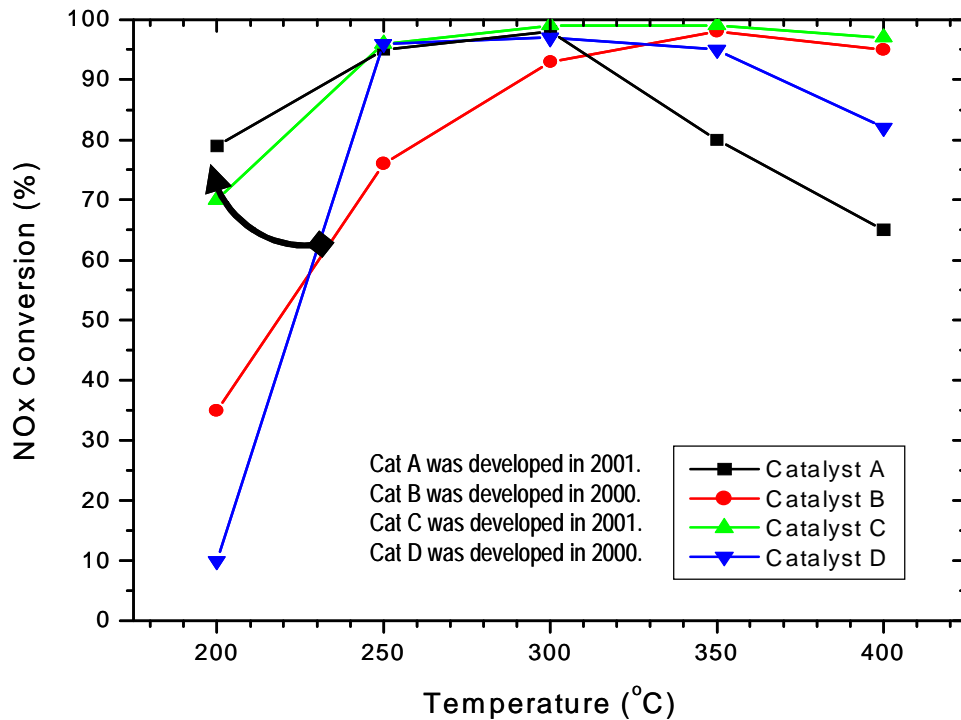
<sup>k</sup> It should be noted that the fuel economy impact of even today's PM filter technology is quite small if not negligible. Tests of PM filter equipped diesel vehicles are often unable to determine the impact of the PM filter on fuel consumption because the change in fuel consumption is smaller than the variation in the fuel consumption measurement accuracy.

## **1. Expanding the Temperature Window**

NO<sub>x</sub> adsorber performance is limited at low temperatures (due to poor catalytic activity for NO oxidation under lean conditions and low activity for NO<sub>x</sub> reduction under rich conditions) and at high temperatures (due to thermal release of NO<sub>x</sub> under lean conditions). There is an extensive discussion in Chapter III of the HD 2007 RIA describing these issues. This section of the report documents some of the progress to address these issues.

We visited a number of catalyst development companies during this progress review and asked them to describe and characterize progress in improving NO<sub>x</sub> adsorber performance since the HD 2007 rulemaking was completed. Figure II.1 below shows data provided by a major catalyst development and manufacturing company characterizing improvements that they have made in NO<sub>x</sub> adsorber performance since that time. The figure shows that substantial improvements have been made in low temperature NO<sub>x</sub> adsorber performance. NO<sub>x</sub> conversion efficiencies at 200° C have improved from approximately 10-30 percent to greater than 70 percent (compare curves B and D, representing catalyst formulations from 2000, with curves A and C representing catalyst formulations from 2001).

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**Figure II.1 Improvements in NOx Adsorber Conversion Efficiency versus Temperature**

Similar improvements in NOx adsorber efficiency across a broad temperature range were reported by almost all of the catalyst manufacturers that we visited during our progress review. Although the improvements as shown in Figure II.1 are significant, further enhancements in NOx adsorber efficiency may yet be possible. A recent publication by researchers from Toyota documents a newly developed NOx adsorber catalyst technology that shows a dramatic increase in NOx storage capacity (more than two-fold) at high temperatures while reducing slightly the amount of sulfur stored (reducing sulfur poisoning).<sup>8</sup> This technology enhancement may allow for improvements not only in storage capacity but also in high temperature NOx adsorber performance for diesel engines, since NOx storage capacity at temperatures above 500° C are related to the decrease in NOx adsorber efficiency observed there.

It was known at the time of the HD 2007 rulemaking that different NOx storage compounds could be selected in order to improve high temperature NOx storage function.<sup>9</sup> What was less well understood was how durable NOx adsorber technologies would be that relied on these high temperature storage elements. Since the rulemaking considerable work has been done to better understand this aspect of the NOx adsorber technology and to develop new catalyst formulations that take advantage of the high temperature storage function while maintaining

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acceptable durability. A recent publication by Danan Dou and Jean Balland of Delphi Automotive Systems documents some of this work.<sup>10</sup> Their research shows that the addition of alkali earth metals to barium based NOx adsorber catalysts dramatically improves high temperature NOx adsorber performance when compared to a barium only formulation. While this relationship to high temperature performance was known previously, the authors also showed that this improved performance (compared to the barium only case) held true even after high temperature aging and after repeated sulfur poisoning and desulfation events. These improvements when coupled with improvements in catalyst substrate materials (discussed in Section II.F.2 below) mean that NOx adsorber performance at high temperature can be improved without unacceptably harming long term durability. This improved understanding represents significant progress in the development of NOx adsorber catalysts for diesel engines operated under high load and for gasoline engines.

Further improvements in NOx adsorber reduction efficiency across the temperature range of a diesel engine may yet be possible. Also as discussed in Section II.H below, new combustion technologies may offer a means to raise diesel exhaust temperatures at low load conditions enhancing the performance of the NOx adsorber catalyst system. Our review of progress by industry to improve the match between the operating temperature window of the NOx adsorber catalyst and the operating range of diesel engines leads us to continue to believe that the NOx adsorbers systems that will be available in 2007 will be highly effective across the broad range of diesel engine operation.

### **2. Improvements in Thermal Durability**

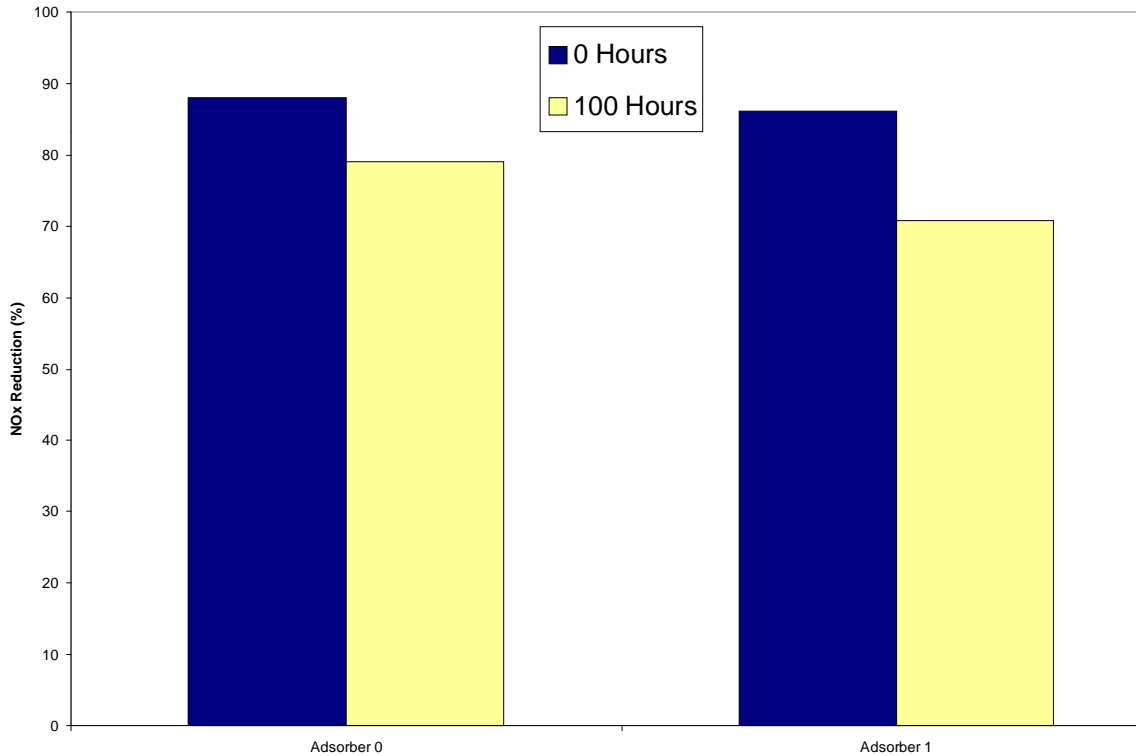
Long term durability for the NOx adsorber catalyst was another issue that we outlined in the HD 2007 RIA. Heavy-duty diesel vehicles are extremely durable, lasting for hundreds of thousands of miles. In order to realize significant emission reductions, emission control technologies must be similarly durable. NOx adsorbers are poisoned by sulfur in diesel fuel and the means to recover the performance loss from poisoning can damage the NOx adsorber thermally as explained in Chapter III of the HD 2007 RIA. Our concern regarding NOx adsorber durability was one of the primary reasons for controlling sulfur in diesel fuel to 15 ppm. However, even with 15 ppm sulfur fuel NOx adsorber catalysts must be periodically desulfated, a process which can itself damage the NOx adsorber catalyst due to the high temperatures (>650C) required for desulfation.<sup>11</sup> Our progress review has therefore focused on what progress has been made to improve the thermal durability of the NOx adsorber catalyst, especially with regard to the periodic high temperature excursions experienced during desulfation.

At the National Vehicle and Fuel Emissions Laboratory (NVFEL) in Ann Arbor, Michigan a team of EPA engineers and scientists has been working to characterize various aspects of NOx adsorber thermal aging. In order to do that the team first investigated the temperature mechanism by aging the adsorbers with zero sulfur fuel and low sulfur engine oil (750 ppm) at high engine operating temperatures (510 C). Figure II.2 below shows results from some of this testing on two different NOx adsorber formulations (from two different catalyst manufacturers). The graph



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shows that both NO<sub>x</sub> adsorber formulations deteriorated from their fresh condition. The degree of deterioration is exaggerated in the figure by showing the difference at the highest temperature mode (where the degradation is the largest) in order to highlight differences between catalyst technologies. The results have shown that changes in NO<sub>x</sub> adsorber formulation (presumably somewhat different technologies) give different performance with thermal aging. The results suggest that even at exhaust temperatures which are at the high end of normal operation, differences in NO<sub>x</sub> adsorber formulations can lead to improvements in aged performance.



**Figure II.2 Example NO<sub>x</sub> Adsorber Thermal Degradation**

These results have been shared with the catalyst manufacturers that are supporting the test programs. Based on information from these results, catalyst manufacturers are developing new catalysts to address the issues highlighted here. The team is continuing its investigations and will add periodic desulfation temperature excursions (600-700° C) to investigate what impact the higher temperatures will have on the adsorber aging. Finally, sulfur will be added to the fuel to investigate the combined temperature and sulfur impacts on adsorber aging.

One of the pieces of information that we considered in the HD 2007 RIA was the loss in NO<sub>x</sub> adsorber performance experienced in the DECSE program when the NO<sub>x</sub> adsorber catalyst in that program was subjected to repeated desulfation events.(DECSE)<sup>12</sup> The high rate of NO<sub>x</sub> aging observed in the DECSE study was contrasted with the very good NO<sub>x</sub> adsorber

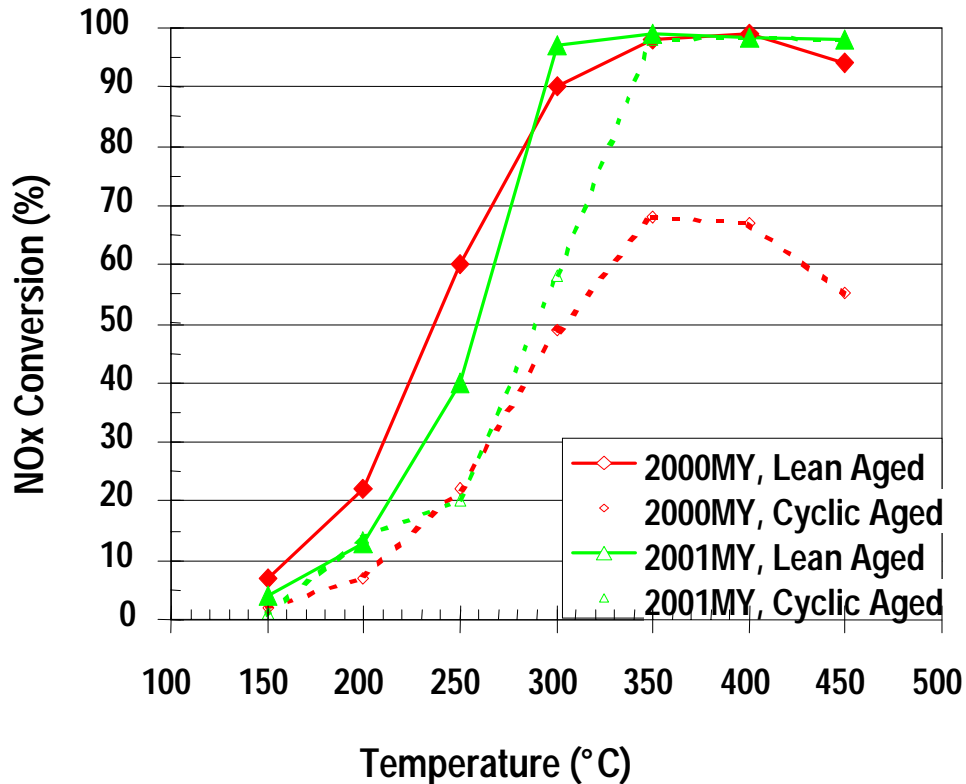
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performance noted in the work by Dearth, et al. at Ford's Scientific Research Laboratory also referenced in RIA.<sup>13</sup> Under what appear to have been similar test conditions of repeated lean/rich cycling at elevated temperatures (both near 700° C) one catalyst showed exceptionally good recovery of NOx adsorber performance (the Ford study), while the other catalyst exhibited a gradual but substantial loss in NOx adsorber performance, even when the lean / rich cycling was done in the absence of sulfur.<sup>14</sup> At the time, we believed that the observed differences in catalyst performance were related to differences in the catalyst formulation and the selection of the appropriate temperature for desulfation (i.e., we believed 700° C was too hot for the DECSE catalyst formulation). Data shared with us as part of this progress review by a major catalyst developer and manufacturer suggests that this assessment was accurate but incomplete. Their testing shows that the history of lean/rich cycling of the catalyst at elevated temperature is also an important factor in NOx adsorber deterioration. These results are explained below.

New test data from a major catalyst development company was shared with EPA as part of this technical review. The data shows thermal testing of a candidate 2000MY NOx adsorber catalyst carried out by subjecting the catalyst to 700° C temperature under lean conditions for 16 hours (the diamond solid line in Figure II.3 below). The results from that testing were very encouraging showing high NOx conversion efficiency even after the lean aging period. Subsequent testing of the catalyst however showed an unexpected decrease in performance over time. Because of this loss in performance, the catalyst manufacturer designed a new test to verify the thermal aging characteristics of the catalyst when aged at the same temperature but with periodic lean/rich transitions. The results of that testing for the 2000MY NOx adsorber catalyst formulation are shown as the open diamond dashed line in Figure II.3 below. It can be seen from the figure that the aged performance under lean/rich cycling conditions (similar to those experienced in the desulfation portion of the DECSE study) resulted in a significant loss in NOx adsorber performance. The loss in NOx performance shown here is roughly equivalent to the loss in performance observed in the DECSE program discussed in the HD 2007 RIA.

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**Figure II.3 Improvements in NOx Adsorber Thermal Durability with Cyclic Aging**

The catalyst manufacturer developed a number of theories for why lean/rich cycling could lead to more severe thermal aging when compared to lean aging alone. Based on these theories new catalyst formulations were developed for testing. The results for one of these 2001MY candidate technologies are shown as the pair of lines with solid and open triangles in Figure II.3. From the figure it can be seen that the lean aged catalyst performance was very similar between the 2000MY catalyst and the 2001MY catalyst with both technologies showing high NOx conversion efficiency even after extensive lean thermal aging (the two solid lines). When tested under conditions including both high temperatures (again 700° C) and repeated lean/rich cycling however, the new 2001MY catalyst formulation (the open triangle dashed line) gave substantially better performance when compared to the 2000MY catalyst showing almost no loss in performance at temperatures in excess of 300° C. Like the results from the Ford study described in the HD 2007 RIA, this data shows that repeated lean/rich cycling at high temperatures as required for NOx adsorber desulfation is not necessarily harmful to NOx adsorber durability. The results here indicate that progress is being made to develop NOx adsorber formulations that maintain high NOx conversion performance even after exposure to repeated desulfation events. The catalyst manufacturer in this case indicated that they still had a number of theories related to the observed thermal degradation under desulfation conditions and subsequent changes in NOx adsorber formulations to be tested. Therefore, they believed that opportunities remained to improve upon the results documented here.

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The addition of alkali earth metals (e.g., potassium) to barium based NO<sub>x</sub> adsorber can significantly improve high temperature NO<sub>x</sub> adsorber performance as we discussed in Section II.F.1 above. However, early testing of NO<sub>x</sub> adsorber catalysts using potassium showed that potassium was highly mobile under high temperatures and had a strong affinity for the cordierite catalyst substrate typically used for NO<sub>x</sub> adsorber catalysts. It was observed that eventually most of the potassium in the catalyst washcoat would migrate into the cordierite substrate making the potassium unavailable for NO<sub>x</sub> storage and also weakening the catalyst substrate. This effect is believed to have been related to the loss of NO<sub>x</sub> adsorber performance after thermal aging observed in a number of prior test programs. To address this problem Corning Incorporated has been working to develop a new catalyst substrate material which is not reactive with potassium. The new material called Celcor NX<sup>TM</sup> has been shown to have no reactivity with potassium even up to temperatures of 1,000° C. This new material, which catalyst developers are only now beginning to test, has the potential to significantly improve the thermal durability of NO<sub>x</sub> adsorber catalysts by eliminating potassium migration into the catalyst substrate. Very early testing of the catalyst formulations applied to the new substrate reveal just that. This is an example of a new technology wholly unanticipated in the HD 2007 RIA that it appears will dramatically improve the long term durability of NO<sub>x</sub> adsorber catalysts.

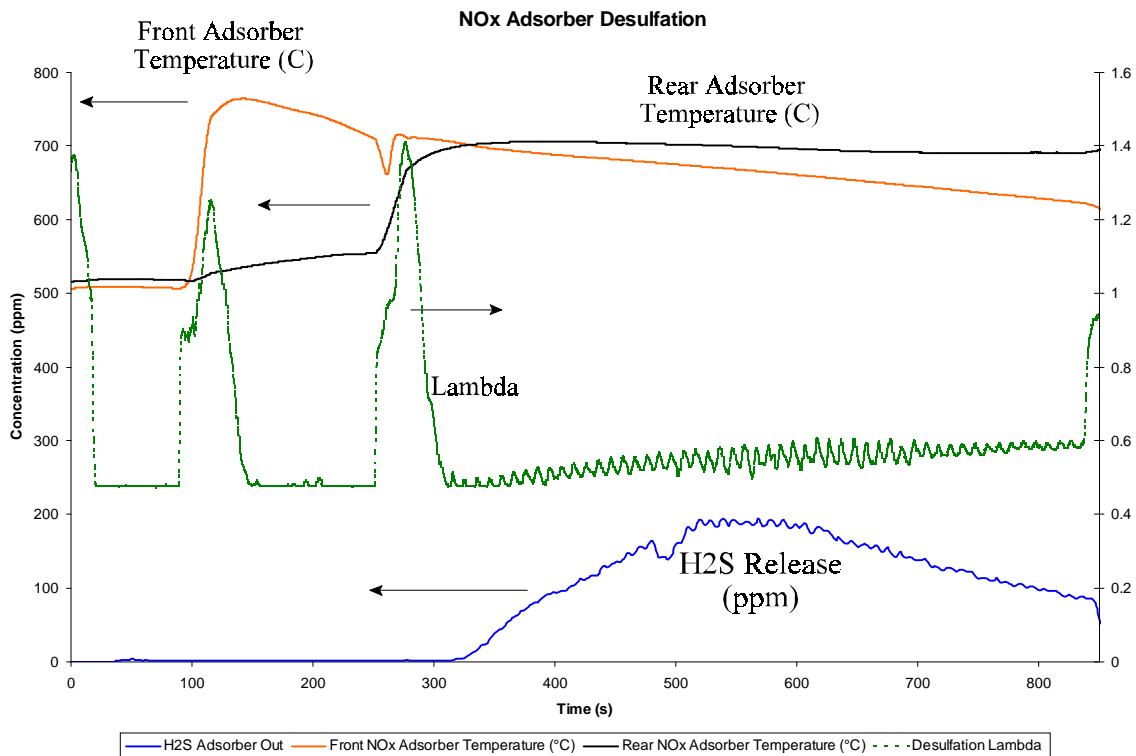
At the beginning of the progress review process long term thermal durability of NO<sub>x</sub> adsorbers subjected to repeated desulfation events was one of the key areas needing to be addressed as the technology was developed. While issues and opportunities for improvement remain, clearly substantial progress has been made with regard to the long term durability of the NO<sub>x</sub> adsorber catalyst. The progress to improve NO<sub>x</sub> adsorber durability observed in our review was clearly significant, and yet opportunities for further improvements seem to be possible.

### **3. Methods and Performance for Desulfation (Sulfur Cleansing)**

Sulfur poisoning remains a challenge for the NO<sub>x</sub> adsorber catalyst even with diesel fuel sulfur capped at 15 ppm. Over time even very low levels of sulfur will lead to a loss of NO<sub>x</sub> adsorber performance as explained in Chapter III of the HD 2007 RIA. Therefore a means to cleanse sulfur from the NO<sub>x</sub> adsorber catalyst is a necessary step in order to ensure long term NO<sub>x</sub> adsorber performance. It has been shown that sulfur can be removed from the catalyst through a sulfur regeneration step (desulfation step) where the catalyst is heated to a temperature in excess of 650° C and exposed to fuel rich exhaust conditions. This desulfation process while effective at removing sulfur can also lead to damage of the NO<sub>x</sub> adsorber catalyst. The previous section of this report discussed advancements in catalyst and substrate materials that reduce dramatically the amount of catalyst damage caused by the high temperature conditions of desulfation. This section of the report will document new developments in the methods and procedures for desulfation intended to limit sulfur poisoning and improve the long-term performance of the NO<sub>x</sub> adsorber catalyst.

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EPA scientists and engineers at the National Vehicle and Fuel Emissions Laboratory (NVFEL) have been working to develop a procedure to desulfate a NO<sub>x</sub> adsorber catalyst in a dual leg catalyst system (a discussion of the dual leg system can be found in Chapter III of the HD 2007 RIA). Figure II.4 below shows an example of a NO<sub>x</sub> adsorber desulfation event from this test program. The figure shows that high exhaust temperature (in excess of 650° C) can be created in an emission control system and that with the appropriate exhaust composition (fuel rich operation, lambda < 1) sulfur is released from the catalyst. The sulfur release shown here is primarily hydrogen sulfide (H<sub>2</sub>S) which is oxidized by a clean up catalyst in the EPA system. Sulfur removal from the adsorber catalysts has been measured in the exhaust stream and improvements in post-desulfation NO<sub>x</sub> reduction efficiency have been measured. The team is continuing its work to include the fine-tuning of the desulfation strategy and the determination of the effects of high desulfation temperature on NO<sub>x</sub> adsorber degradation for multiple desulfation events. The effects of engine speed, engine load, catalyst temperature, and exhaust lambda on desulfation will also be investigated.



**Figure II.4 Example of NO<sub>x</sub> Adsorber Desulfation**

Catalyst development companies are also working to develop improved methods for NO<sub>x</sub> adsorber desulfation. A number of important parameters are being investigated to learn of their effect on the resulting NO<sub>x</sub> adsorber performance. Changes in catalyst formulation to improve

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thermal durability are an important part of this optimization and are discussed in the previous section of this report. Another parameter being investigated is the relative frequency of desulfation events. Work by Toyota reported in 1999 suggested that the larger sulfate crystals formed when a vehicle is operated on higher sulfur fuel can be more difficult to remove in a desulfation event and can eventually lead to a significant loss in NO<sub>x</sub> adsorber performance even with periodic desulfations.<sup>15</sup> Figure II.5 below, documents recent work by a major catalyst manufacturer to evaluate the desulfation performance of a NO<sub>x</sub> adsorber catalyst that is desulfated on a fixed time interval approximately equivalent to once per tank full. This approach is different from the desulfation work mentioned previously in the Ford Study and the DECSE program where desulfation was not attempted until significant levels of catalyst deterioration had occurred.<sup>16,17,18</sup> The results in Figure II.5 show that NO<sub>x</sub> adsorber performance remains high even after more than 600 hours of catalyst aging with sulfur. The exceptionally good results shown here suggest that desulfation strategies which clean sulfur from the catalyst before high levels of sulfur have accumulated, can maintain long term NO<sub>x</sub> adsorber performance. In addition to providing better improved durability, this approach may also lead to improved fuel economy. Although, the desulfation event typically consumes fuel in order to raise temperatures (and as a reductant), it frees NO<sub>x</sub> storage sites increasing NO<sub>x</sub> storage capacity and allowing for a reduction in the frequency of NO<sub>x</sub> regeneration events. A decrease in the frequency of NO<sub>x</sub> regeneration lowers the fuel consumption associated with NO<sub>x</sub> regeneration. Therefore, a tradeoff exists between increasing fuel use for desulfation and decreasing fuel use of NO<sub>x</sub> regeneration.

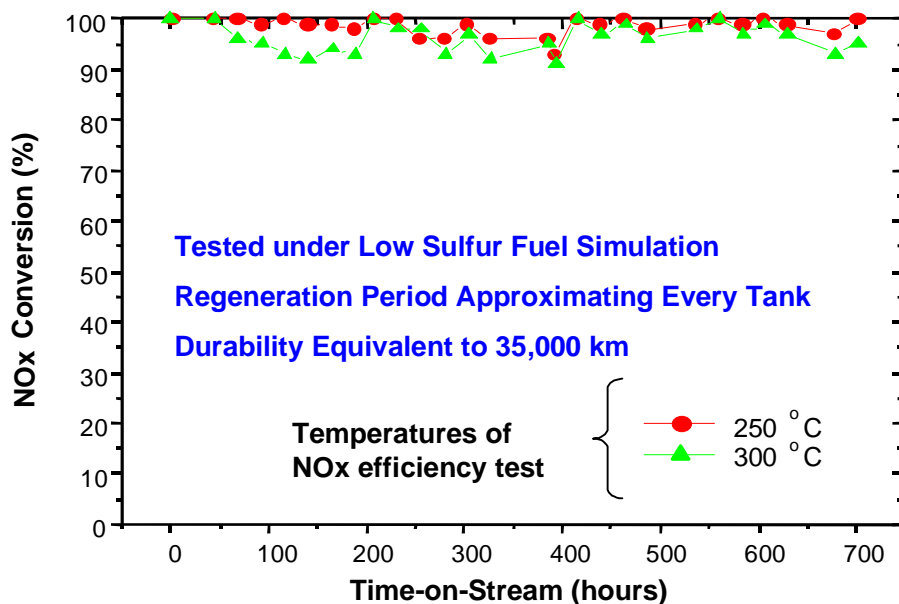
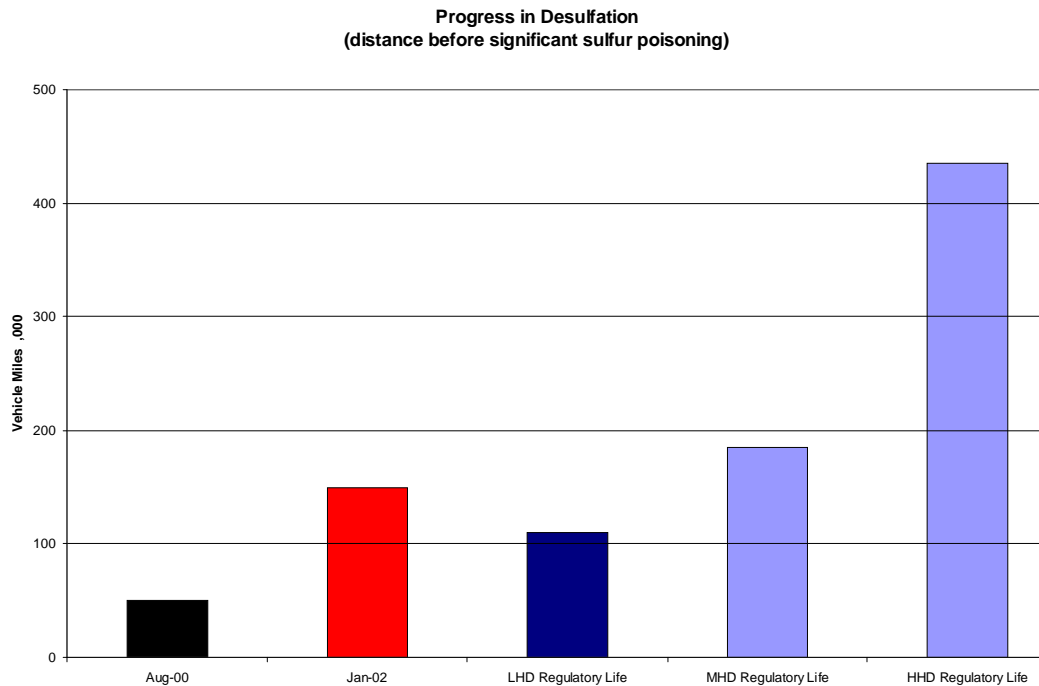


Figure II.5 NO<sub>x</sub> Adsorber Performance with Repeated Desulfation Events

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Engine manufacturers are also working to develop procedures and methods for NOx adsorber desulfation. Figure II.6 below shows progress by one of the largest diesel engine manufacturers in their evaluation of NOx adsorber desulfation over the long term. The figure shows the equivalent number of miles that a NOx adsorber catalyst could maintain an average efficiency in excess of 70 percent.<sup>1</sup> The figure shows that methods for improving sulfur management plus unspecified changes in NOx adsorber formulations have almost tripled the life of the NOx adsorber catalyst compared to the experience from less than two years ago. The improvements in NOx adsorber life noted in the figure do not include the thermal durability improvements due to substrate improvements noted in Section II.F.2 above as those new technologies have not yet been sampled to the engine manufacturers for evaluation.



**Figure II.6 Improvements in NOx Adsorber Durability with Repeated Desulfations**

It is our expectation based upon the evidence made available to us during our progress review that even though substantial improvements in NOx adsorber durability have been made there remains a significant room for progress in the future. Given the short time window of this

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<sup>1</sup> The manufacturer chose the 70 percent efficiency threshold based upon their plans to develop a single NOx control technology for use across their entire range of engines in 2007. The HD 2007 rule requires that 50 percent of a manufacturer's engine sales to meet a 0.2 g/bhp-hr standard, but averaging provisions give manufacturers a flexibility to have 100 percent of their engines meet an average NOx standard of approximately 1.2 g/bhp-hr. Most of the heavy-duty engine manufacturers that we met with during this progress review indicated that they will use the flexibilities allowed in the rule to produce a single NOx control technology for all of their engines in 2007.

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review and the substantial lead time remaining before 2007, we believe that this progress is encouraging.

### **4. Improvements in System Package Size and Integration**

During the HD 2007 rulemaking a number of diesel engine and vehicle manufacturers expressed concerns regarding the feasibility of applying the NOx adsorber catalyst to a diesel powered vehicle. Their concern was less focused on the functionality or durability of the catalyst technology itself but rather over the ability of the diesel engine system to be designed to operate in a manner that was compatible with the catalyst technology. As we started our review process this is the one area where we expected to find the smallest amount of progress. Given the long lead time remaining for 2007 and an expectation that system engineering would occur much closer to the production date, we had assumed that most manufacturers would still be at a very early stage in the process. What we discovered was that although manufacturers are indeed still in the pre-product development stage for heavy-duty NOx adsorbers, they have made considerable progress in developing systems that are compatible with the NOx adsorber technology.

In our meetings with heavy-duty diesel engine manufacturers they characterized a number of changes in the industry that are ongoing due to their development efforts on NOx adsorbers and diesel particulate filters. They discussed a paradigm shift in the way that they thought of catalyst technologies, no longer as aftertreatment, but rather as an integral part of the engine emission control system design from the very beginning of the process. This had led them to learn and develop a new vocabulary and new tools to talk and work as partners with the catalyst industry. This new language and new processes have accelerated their learning and is paying benefits in their technology development programs. One chief engineer at a major engine manufacturer characterized it this way, a year ago he said that he could only describe his technical expectations/specifications for the NOx adsorber catalyst in the most vague terms, and he could not accurately predict what changes could be made to his diesel engine to match the conditions required for a NOx adsorber to function. Over the last year he indicated that he has learned a great deal about the language and characteristics of catalyst technology and about the limits of his company's engine technology. In his view, the ability to now provide very specific and accurate feedback to his catalyst company partners and to in-turn be able understand their feedback was the most important first step for him and his company to make progress on developing emission compliant engine and catalyst technologies for 2007.

This characterization by a chief engineer and other similar discussions that we had with companies has left us with the impression that the industry is now undergoing a shift in how it works to develop emission control technologies. In many ways the companies appear to be changing to work as if they were a single vertically integrated manufacturer rather than as a series of steps in a supply chain. This change would appear to allow industry to take better advantage of the synergies between engine and catalyst technology. We were left with the impression, similar to that of the chief engineer described here, that this represents an important step in progress to



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develop technologies for 2007. This is supported by the fact that many of these companies were able to show us real improvements in their engine and catalyst system integration in the short time since the rulemaking was completed.

One of the largest U.S. based heavy-duty diesel engine manufacturers provided graphical representations of their progress to calibrate a heavy-duty diesel engine for NO<sub>x</sub> adsorber regeneration. In this case their strategy is to use a single NO<sub>x</sub> adsorber catalyst that is regenerated by periodic operation of the engine such that the total exhaust is made to be fuel rich. This is accomplished by a sequence of changes in the air-handling system of the engine (i.e., turbocharger, EGR valve, and an intake throttle) along with optimized injection timing. Their early work on this strategy documented in Figures II.7 and II.8 as Aug00 (August 2000) shows that they were only able to accomplish the strategy at very light loads (brake mean effective pressure, BMEP <5 bar)<sup>m</sup> and when they did accomplish regeneration the fuel consumption rate increased by 20 percent. Since August of 2000, the company has continued to work to improve this strategy demonstrating in January of 2002 (Jan 02 in the figures) that they could accomplish NO<sub>x</sub> regeneration at engine loads up to 15 bar (BMEP) with a fuel consumption increase of five percent. As the figures show, the company has made dramatic improvements in their engine technology in order to accomplish NO<sub>x</sub> regeneration and are approaching the internal targets that they have set for the technology in 2007.

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<sup>m</sup> Brake Mean Effective Pressure (BMEP) is a term used to describe normalized engine power. It is calculated as work per cycle divided by cylinder displacement per cycle. It allows the performance of engines of different sizes to be compared more easily. In Figure II.7 the value of 20 bar BMEP is indicated as the required BMEP for a heavy-duty diesel engine (the same power density as today's diesel engines). Early testing by this manufacturer showed that NO<sub>x</sub> regeneration could only be accomplished at low loads (BMEP levels < 5 bar). Subsequent technology developments have allowed the manufacturer to demonstrate NO<sub>x</sub> regeneration at engine loads up to 15 bar (75 percent of full load). The manufacturer is continuing to make system improvements in order to accomplish acceptable NO<sub>x</sub> adsorber regeneration across the full range of diesel engine operation.

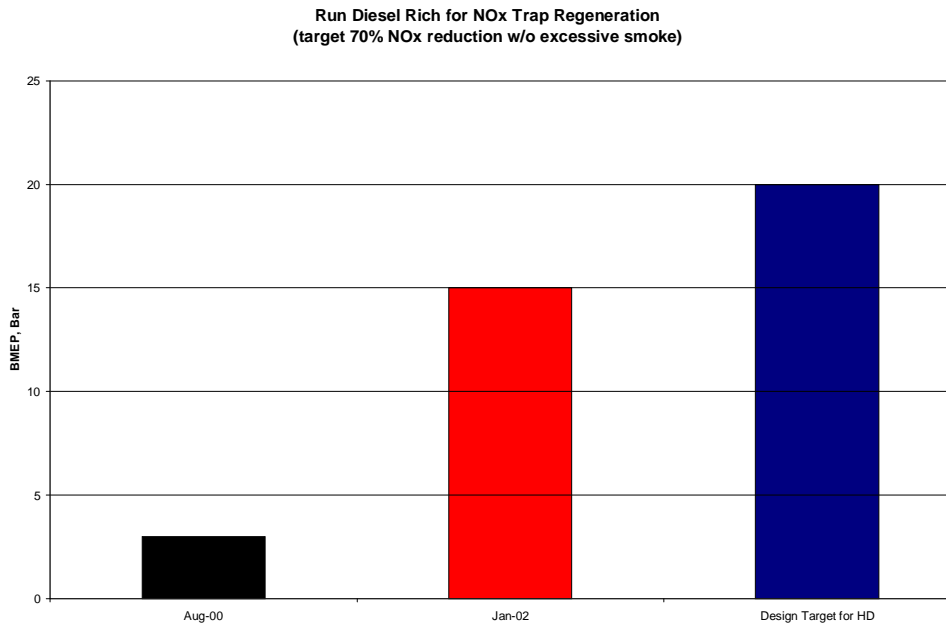


Figure II.7 Improvements in Ability to Create Regeneration Conditions Engine-Out

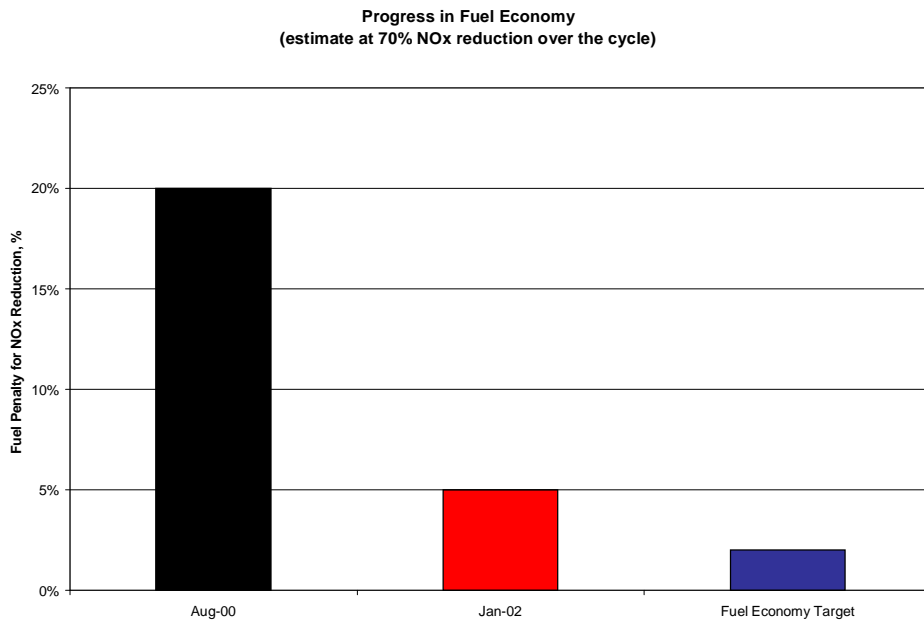


Figure II.8 Improvements in Fuel Consumption associated with NOx Regeneration

Although there were variations in demonstrated progress to develop these types of technologies among the different engine manufactures, the progress shown here in Figures II.7

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and II.8 is representative of the kinds of progress that the industry has made as a whole. Diesel engine combustion fundamentals have been an important part of diesel engine emission controls for many years. For this reason the industry has developed sophisticated models and measurement tools to better understand combustion and to predict the effect of changes in combustion parameters. These tools are now being utilized to develop new combustion strategies consistent with NO<sub>x</sub> adsorber operation. Rapid progress as documented here is possible because of the industry's fundamental understanding of diesel engine combustion.

Another strategy for NO<sub>x</sub> adsorber regeneration is to employ multiple NO<sub>x</sub> storage catalysts which can then be taken "off-line" one at a time for periodic regeneration. Since the NO<sub>x</sub> regeneration event is accomplished off-line it can be done under reduced flow conditions in order to improve the NO<sub>x</sub> regeneration efficiency and to reduce fuel consumption. A team of EPA engineers and scientists have been working to evaluate this type of approach at NVFEL. The work on a dual-leg NO<sub>x</sub> adsorber system by this team was documented in the HD 2007 RIA and in subsequent peer reviewed publications.<sup>19,20</sup> The team has shown that a combined catalyzed diesel particulate filter and NO<sub>x</sub> adsorber catalyst system can deliver greater than 90 percent reductions in NO<sub>x</sub> and PM over a wide range of heavy-duty diesel engine operation. The work to date by this team has been conducted on a 'proof of concept' two leg NO<sub>x</sub> adsorber/PM trap system. This system is large and consequently would have poorer cold start and vehicle packaging properties than a single pass system. Concept work is underway to improve these aspects of the system. With a two leg system, each leg as to handle the full engine exhaust flow. A system composed of more legs would have a smaller overall catalyst volume. For instance, a four leg system would only have to be about thirty percent larger than a single leg system because only one leg would be regenerating at a time leaving the other three flowing the full exhaust. Lower cost fuel injectors and leg switching mechanisms are also being investigated by the team. The team has made significant progress in concept development for such a system with reduced size and cost that may offer benefits for heavy-duty diesel engines in performance and fuel consumption.

Toyota Motor Corporation announced in 2000 that they were developing a new emission control technology that integrated a NO<sub>x</sub> adsorber catalyst on the surface of a particulate filter called Toyota's diesel particulate NO<sub>x</sub> reduction (DPNR) system. In their press release, Toyota cited NO<sub>x</sub> and PM reductions in excess of 80% on a 2-ton diesel truck.<sup>21</sup> On March 6 of 2002, Toyota announced that 60 diesel passenger cars equipped with the DPNR system would be introduced in monitor testing in Europe as a step toward Toyota's planned introduction of a DPNR-equipped vehicle.<sup>22</sup> Although a number of lean burn gasoline engines have previously been introduced with a NO<sub>x</sub> adsorber catalyst, we believe that this will be the first commercial application of the technology to a diesel powered vehicle.

As part of our progress review, we requested that Toyota provide a DPNR equipped vehicle to EPA for testing at NVFEL. Toyota agreed to provide a vehicle and testing was completed in March of 2002 on a Toyota Avensis passenger car equipped with a 2 liter

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turbocharged diesel engine and the DPNR system. The vehicle was representative of the fleet of 60 vehicles that Toyota is putting into the monitor test program in Europe. Table II.2 below summarizes the results of testing at NVFEL on this vehicle. The final Tier 2 Bin 5 (corporate average for NOx) emission standards are provided in the table for reference.

**Table II.2 Toyota DPNR Vehicle Test Results at NVFEL**

Test Cycle	NOx (g/mile)		PM (g/mile)		NMHC (g/mile)		Fuel <sup>†</sup>
	Test Results	Tier 2 Bin 5	Test Results	Tier 2 Bin 5 Std	Test Results	Tier 2 Bin 5 Std	Economy (mpg)
FTP75*	<b>0.05</b>	0.05	<b>0.006</b>	0.01	<b>0.07</b>	0.075	37
US06**	<b>0.14</b>		<b>0.005</b>	0.07	<b>0.19</b>		35
HWFET***	<b>0.001</b>	0.075	<b>0.002</b>	-	<b>0.12</b>	-	53
NYCC****	<b>0.003</b>	-	<b>0.007</b>	-	<b>0.04</b>	-	22

\* Final Tier 2 FTP Bin 5 Intermediate Life (50k) standards, NMHC reported for NMOG  
 \*\* Final Tier 2 SFTP 4k standards, US06 std is NOx + NMHC = 0.14, PM is a weighted Std  
 \*\*\* Highway Fuel Economy Test NOx limit is 1.5 times the FTP standard  
 \*\*\*\* New York City Cycle  
 † Fuel economy numbers are actual test results. For comparison to reported City and Highway fuel consumption numbers the values here should be adjusted to account for historically observed test to real world shortfalls. For comparative fuel economy estimates the highway fuel consumption should be reduced by 22% (41 mpg) and the city/FTP by 10% (33 mpg).

The Toyota system as applied in the Avensis passenger car demonstrates a number of things regarding overall system integration possibilities for NOx adsorber catalyst systems. The total integrated NOx adsorber and diesel particulate filter system as applied by Toyota is quite compact, fitting into the existing package volume of the Avensis passenger car. The required NOx regeneration events are also well integrated into the vehicles operation. Toyota performs the required periodic NOx regeneration events in a number of different ways depending upon the engine operating mode. Under some conditions Toyota operates the engine under a newly developed combustion mode called Low Temperature Combustion (LTC).<sup>23</sup> The Toyota system can also use a secondary in-cylinder injection event to accomplish NOx regeneration. At engine operating conditions where the secondary injection may be undesirable (e.g., where it could lead to unsatisfactory smoke or excessive temperatures) Toyota can accomplish NOx regeneration by supplemental fuel injection into the exhaust manifold. The combination of these three approaches allows the Toyota system to accomplish NOx regeneration across a broad range of diesel engine operation.<sup>24,25</sup> The DPNR vehicle shows that although the challenges of integrating a complete

## **II. Progress Review of Engine Technologies**

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NOx and PM emission control system into a diesel vehicle are difficult, they are not insurmountable.

Our review of system engineering progress to develop a complete system solution to meet the HD 2007 emission standards has revealed an industry that is changing in response to new technologies while benefitting from its existing competencies in combustion system development. We see the progress in system developments as substantial with at least one manufacturer able to produce production like prototypes for testing. Although a number of challenges remain, we are convinced that industry is well on its way to develop NOx adsorber technologies for 2007.

### **G. Changes to Engine Oil Formulations**

The possibility that changes to engine oil formulations would be needed in order to ensure long life and acceptable maintenance intervals for emission control systems was raised by various industry representatives during our progress review. This is a concern of EPA's as well, and we have therefore been working to facilitate progress to address this issue.

Engine oil components can affect emission control technologies in a number of ways. Sulfur in engine oil can contribute to catalyst poisoning in a manner similar to sulfur in diesel fuel. Therefore, it is desirable for engine oils to have low sulfur concentrations. Various metals in engine oils, including phosphorous and zinc, can also poison catalyst function over the long term. Therefore, it is desirable to reduce the metal content of engine oils. Metals in engine oil also are the major constituents of ash (in-organic, nonconsumable products of combustion) which are captured by the PM filter and which must be periodically removed. The frequency of the ash removal from the PM filter is proportional to the ash content of engine oil. Therefore, it is desirable to minimize the ash content of engine oils in order to reduce the frequency of PM filter maintenance. Unfortunately, sulfur, phosphorous, zinc, and other metals are present in engine oils primarily because they can provide some desirable characteristics to engine oils (e.g., base number control and anti-wear). Changes to engine oils will therefore likely require the development of new engine oil additives as well as engineering tradeoffs between desirable engine characteristics and catalyst characteristics.

Changing engine oils in order to accommodate changes in engine emission control technologies is not a new phenomenon. Engine oils for heavy-duty diesel engines have gone through a successive series of changes over the last 20 years as engine design and operating characteristics have changed. Many of these technology changes have been due to changes in emission standards. Since changes to engine oil formulations linked to new engine technologies have been a normal part of technology development in the past, we were initially surprised by the number of companies and individuals that raised concerns about oil formulations for 2007. We now believe that the reason for this concern is the increase in the number of stakeholders in this process.

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Historically heavy-duty engine manufacturers have been the primary determinants of future engine oil characteristics. Major diesel engine original equipment manufacturers (OEMs) such as Cummins and Mack would set their own engine oil standards in advance of the introduction of new engine technologies. Engine oil formulators would then develop new oil formulations that could meet all of the various individual OEM specifications and the oil would be marketed appropriately. Over time a new industry-wide oil specification would be agreed upon by representatives of the engine manufacturers, oil companies, and speciality chemical companies. The new specification would then become the industry standard for all heavy-duty diesel engines. This process has allowed industry to respond rapidly to changes in engine technologies while at the same time working towards a common engine oil product standard across the industry. What is changing in this field now is the need for another industry participant, the catalyst manufacturers, to become part of the engine oil specification cycle. The fact that this process will necessarily need to change to some extent may remove some control over the process from the heavy-duty engine manufacturers leading to increased concern over the process. However, it still appears likely that the engine manufacturers will serve as the final system integrators for the new technologies, and as such, will ultimately control much of this process. We are committed to working with industry to facilitate finding a consensus oil specification that respects engine and emission control system performance for 2007.

An important first step in that process has already taken place with the Diesel Engine Oil Advisory Panel's (DEOAP) designation of a new proposed category (PC-10) engine oil specification. This industry panel meets on a regular basis to develop a consensus specification for engine oil formulations. The newly designated PC-10 category will be for a low sulfur, low ash oil formulation for on-road heavy-duty diesel vehicles. EPA is represented on this panel and will work to promote information sharing and consensus building among industry members to help facilitate the definition of an appropriate engine oil specification for 2007. We believe that this is the appropriate avenue for changes to engine oil formulations to be decided by all stakeholders in a customer driven process.

Progress is already being made to characterize the tradeoffs between changes in oil formulations that will be desirable for catalyst systems but which may be less desirable for engine systems. Two industry-wide research efforts have been started to determine the effect of engine oil formulations on engine wear and emissions component degradation. One program is the Advanced Petroleum Based Fuels – Diesel Emissions Controls Project (APBF-DEC). This program is investigating the effect of different oil formulations on heavy-duty diesel engine component wear and emissions. Another program looking at the effect of oil formulation on engine wear and emissions is an industry consortium organized by Southwest Research Institute (SwRI) titled Diesel After Treatment Sensitivity to Lubricants (DASL), Non-Thermal Catalyst Deactivation (N-TCD). In DASL the effects of lubricating oil components, such as sulfur, phosphorus, zinc, calcium and others, will be determined by measuring the deactivation of the emissions control systems as a consequence of oil exposure. The N-TCD portion is a research/mechanistic study designed to explore the mechanisms of emissions control system

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deactivation as a result of oil exposure. The results from these and other test programs will serve to inform the process for engine oil specification.

### H. New Combustion Technologies

We have been aware for some time that various research groups have been investigating novel diesel combustion concepts. These new concepts break the traditional NO<sub>x</sub> versus PM tradeoff typical of heterogenous diffusion controlled diesel combustion. They therefore have the potential to offer both low NO<sub>x</sub> and low PM emissions.<sup>26</sup> Our understanding of the various approaches has in the past lead us to conclude that the technologies would not be viable for production engines within the next ten years. Our visits with a number of diesel engine companies during this review has lead us to revise our opinion of these technologies somewhat. While no company believed that these novel approaches could be applied across the full spectrum of diesel engine operation and therefore could themselves enable compliance with the HD 2007 emission standards, several companies suggested that for a relatively narrow range of engine operation, these new approaches could potentially be applied, perhaps even as early as 2007.

Nissan Motor Company has developed a diesel passenger car engine capable of operating under two distinct combustion modes. When engine torque demand is greater than approximately 40 percent the engine operates using conventional diesel combustion. However, for lower engine operating loads, as typified by much of passenger car operation and some portions of heavy-duty diesel operation, the engine is operated with a low-temperature premixed combustion approach called modulated kinetics (MK) combustion. NO<sub>x</sub> and PM emissions are reduced by more than 90 percent when the engine is operated in the MK combustion mode. When combined with a NO<sub>x</sub> adsorber catalyst Nissan has presented data that suggests that the technology may enable compliance with the light-duty Tier 2 corporate average NO<sub>x</sub> emission standard.<sup>27</sup> It is this synergistic application of novel combustion approaches under light load conditions with a NO<sub>x</sub> adsorber catalyst that can control NO<sub>x</sub> emissions at higher engine loads that potentially raises new opportunities for heavy-duty diesel engines.

One of the challenges for the NO<sub>x</sub> adsorber catalyst is controlling NO<sub>x</sub> emissions at low exhaust temperatures (<250° C). Although new catalyst formulations are improving the low temperature characteristics of the NO adsorber (as we discussed in Section II.F.1 ), there may be additional improvements afforded by changes in diesel engine operation at light-loads as well. The Nissan data suggests that a diesel engine combustion system can be designed to operate under two different combustion modes without unacceptable compromises in either mode of operation (i.e., low engine out emissions at cool temperatures / light load using MK combustion and low tailpipe out emissions at higher temperatures / higher load due to a NO<sub>x</sub> adsorber catalyst). Whether or not such an approach can be applied to heavy-duty diesel engines is yet unknown. Our impression from visits with a number of engine manufacturers is that they are aggressively investigating this possibility.

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In addition to the benefit of reduced engine out NOx and PM emissions at light-loads, novel combustion approaches may also be a means for NOx adsorber regeneration and possibly desulfation. The Toyota Low Temperature Combustion (LTC) technology like the Nissan MK combustion system gives very low engine out NOx and PM emissions. Additionally, the LTC technology produces fuel rich exhaust appropriate for NOx adsorber regeneration.<sup>28</sup> It would appear that approaches such as these may have the potential to improve the effectiveness of the NOx adsorber catalyst over a broader range of engine operation. The progress by several manufacturers for light-duty passenger cars in this area has been very impressive and causes us to consider that such approaches may be possible for heavy-duty diesel engines as well.

Diesel engine manufacturers are working very hard to develop new and novel combustion technologies in order to reduce NOx and PM emissions while maintaining the good fuel economy associated with diesel engine technology. Although, we remain convinced that these technologies can not deliver the needed emission controls over much of the engine operating cycle alone, we do believe that they have some potential to be applied synergistically with the NOx adsorber catalyst in order to improve the overall emission control system effectiveness.



### **III. Progress Review of Desulfurization Technology**

As described above, the HD 2007 program regulates the heavy-duty vehicle and its fuel as a system. In the previous chapter, we described progress on the emission control technologies that are developing to meet the program's emission standards. Specifically, our engine technology review involved company visits, a test program at the NVFEL, and DOE research programs. We concluded that substantial advancements in NO<sub>x</sub> adsorber and PM trap technologies have been made to date—only a year and a half since the HD 2007 rule was promulgated—and industry is on track to meet the program's 2007 compliance date.

This chapter describes our progress review on the technologies that will be used to remove sulfur from diesel fuel as well as specific refiner plans for producing the cleaner fuel. We followed a process very similar to our engine technology review. Specifically, our desulfurization technology review involved company visits and conference calls, a review of information submitted through the HD 2007 program's reporting requirements, and a literature review. However, unlike the emission control technologies described in Chapter II, above, conventional diesel desulfurization technologies have been available and in use for many years. In the HD 2007 rule, we projected that all refiners would be technically capable of meeting the 15 ppm sulfur standard with extensions of the same conventional hydrotreating technology that they are using today to meet the current highway diesel fuel sulfur standard of 500 ppm.

Since the final rule, industry progress to date confirms our projections that conventional diesel hydrotreating technology could, in fact, be extended for use in compliance with the 15 ppm sulfur standard for highway diesel fuel. Refiners themselves have recognized this fact as well. Many of them are basing their compliance plans on the use of this technology. Consequently, in addition to reporting on the advancements that have been made to this technology to extend it for application to 15 ppm, this review focuses on the plans that refiners have begun to make to incorporate this technology into their refineries.

New technologies are also being developed that offer promise for reduced costs. However, these technologies are not critical to the implementation of the HD 2007 program. Based on the conclusions we reached in the HD 2007 rule as well as new information that was made available to us during our progress review, we have concluded that the refining industry is making significant progress toward complying with the requirements of the HD 2007 program.



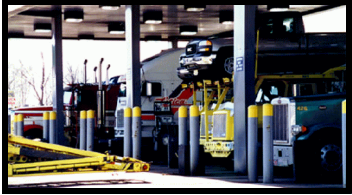
#### **A. Summary of the Highway Diesel Fuel Program Provisions**

The HD 2007 program establishes a sulfur limit of 15 ppm for highway diesel fuel. Refiners will be required to produce 15 ppm diesel fuel for use in highway vehicles beginning June 1, 2006. At the terminal level, highway diesel fuel will be required to meet the 15 ppm sulfur

## Highway Diesel Progress Review – June 2002

standard as of July 15, 2006. For retail stations and wholesale purchaser-consumers, highway diesel fuel sold as low sulfur fuel must meet the 15 ppm sulfur standard by September 1, 2006. These compliance dates are shown below in Table III.1.

**Table III.1 Industry Compliance Dates for the Highway Diesel Fuel Program.**

		
Refiners and Importers	Terminals	Retail Outlets and Wholesale Purchaser-Consumers
June 1, 2006	July 15, 2006	September 1, 2006

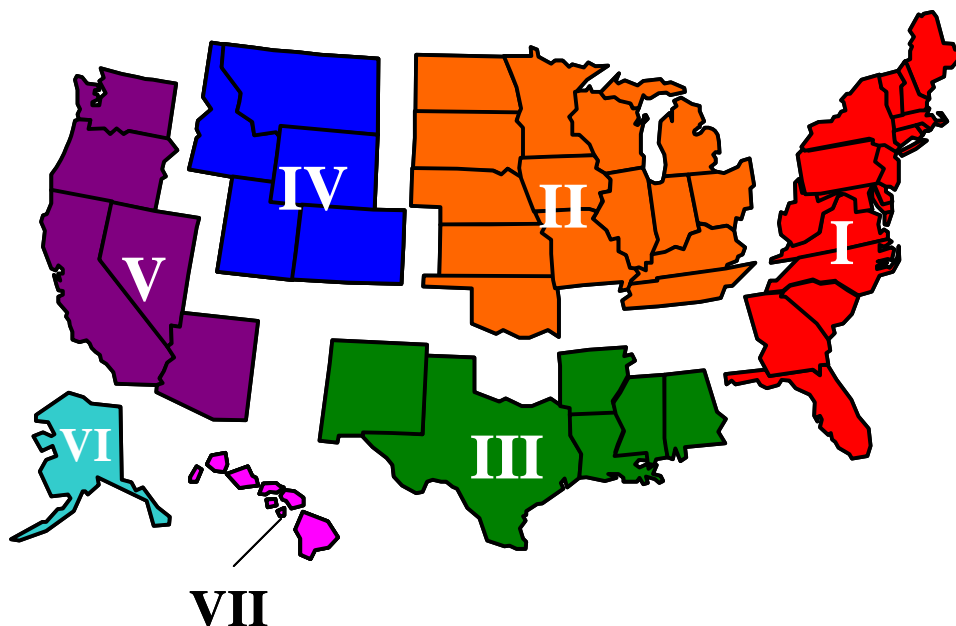
The program includes a combination of flexibilities available to refiners. First, refiners may take advantage of a voluntary transitional flexibility known as the Temporary Compliance Option (TCO), which includes an Averaging, Banking and Trading component (ABT). Second, the HD 2007 program includes hardship provisions for small refiners to minimize their economic burden in complying with the 15 ppm sulfur standard. Third, the program provides additional flexibility to refiners subject to the Geographic Phase-in Area (GPA) provisions of the Tier 2/Gasoline Sulfur program (65 FR 6698, February 10, 2000) which will allow them the option of staggering their gasoline and diesel fuel related investments. Finally, the program contains a general hardship provision for which any refiner may apply on a case-by-case basis under certain conditions.

### 1. Temporary Compliance Option

Under the HD 2007 program's TCO, a refinery may voluntarily produce up to 20 percent of its total highway diesel fuel at the existing highway diesel fuel sulfur standard of 500 ppm, determined on an annual basis. The remaining 80 percent of the highway diesel fuel produced at that refinery during the year must meet a sulfur standard of 15 ppm. The TCO also includes a regional ABT component. Figure III.1 presents the Credit Trading Regions (CTRs) into which

### III. Progress Review of Desulfurization Technology

the United States is divided for the HD 2007 program. These regions are largely based upon the Department of Energy's Petroleum Administrative Districts for Defense (PADD). However, Alaska and Hawaii, which are part of PADD V, are separate CTR's under the HD 2007 program.



**Figure III.1 Map of the Credit Trading Regions Under the HD 2007 Program.**

If a refiner opts to use the ABT component of the HD 2007 program, it may produce more than 80 percent of its highway diesel fuel as low sulfur diesel fuel and generate credits based on the volume of highway diesel fuel produced at 15 ppm that exceeds the 80 percent requirement. Within the same CTR<sup>n</sup>, these credits may be averaged with another refinery owned by that refiner, banked for use in future years, or sold to another refinery.

While the minimum low sulfur diesel fuel requirement under the TCO is 80 percent, we expect that most refineries will focus on production of either 15 ppm or 500 ppm sulfur diesel fuel. Certain refineries will find it more economically advantageous to install the necessary equipment to produce all of their highway diesel fuel at the 15 ppm sulfur level and generate credits. Conversely, other refineries may find it advantageous to continue producing all of their highway diesel fuel at the 500 ppm sulfur level during the TCO, by obtaining credits to demonstrate compliance. The benefits of this voluntary option, for those refiners that choose to take advantage of it, are described in detail in the final rule.

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<sup>n</sup> The ABT program has certain additional limitations for any state with an EPA-approved waiver from the federal program which is more stringent than the federal program. This is explained in more detail in the preamble to the HD 2007 rule.

### 2. Hardship Provisions

#### a. Small Refiner Hardship Provisions

In addition to the TCO, the HD 2007 program contains special provisions for qualifying small business refiners.<sup>o</sup> These flexibility provisions will provide small business refiners with additional time to meet the 15 ppm sulfur standard or balance investments needed to produce low sulfur gasoline. Approved small refiners under the highway diesel fuel program may choose from the following three compliance options:

*500 ppm Option.* A small refiner may continue to produce and sell diesel fuel meeting the current 500 ppm sulfur standard for four additional years, until May 31, 2010, provided that it reasonably ensures the existence of sufficient volumes of 15 ppm fuel in the marketing area(s) that it serves.

*Small Refiner Credit Option.* A small refiner that chooses to produce 15 ppm fuel prior to June 1, 2010 may generate and sell credits under the broader TCO. Since a small refiner has no requirement to produce 15 ppm fuel under this option, any fuel it produces at or below 15 ppm sulfur will qualify for generating credits.

*Diesel/Gasoline Compliance Date Option.* For small refiners that are also subject to the Tier 2/Gasoline sulfur program (40 CFR Part 80, Subpart H), the refiner may choose to extend by three years the duration of its applicable interim gasoline standards, provided that it also produces all of its highway diesel fuel at 15 ppm sulfur beginning June 1, 2006.

Twenty-one refineries owned by 16 refining companies have applied for and/or been approved for small refiner status under the HD 2007 program. Thirteen of these refineries were grand-fathered into the HD 2007 program because they have approved small refiner status under the low sulfur gasoline program.<sup>p</sup> The remaining eight refineries have applied for small refiner status under the HD 2007 program; their applications are pending.

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<sup>o</sup> The rationale behind these provisions as well as the eligibility requirements for them are described in detail in the preamble to the HD 2007 rule.

<sup>p</sup> The low sulfur gasoline program also contains provisions for small refiners which allow them more time at less stringent interim standards to comply with the national gasoline standards. Currently, 12 refineries owned by nine refining companies have approved small refiner status under the low sulfur gasoline program.

### III. Progress Review of Desulfurization Technology

#### b. GPA Refiner Provision

The HD 2007 program also includes flexibility for refiners who supply fuel to the West and Alaska. Specifically, the program allows refiners who supply fuel to the Geographic Phase-in Area (GPA), Figure III.2, below,<sup>9</sup> to stagger their gasoline and diesel desulfurization investments. Refiners that comply with the 15 ppm sulfur standard by June 1, 2006 for all of their highway diesel fuel production may receive a two-year extension of their interim GPA gasoline standards for 2006, that is through December 31, 2008.

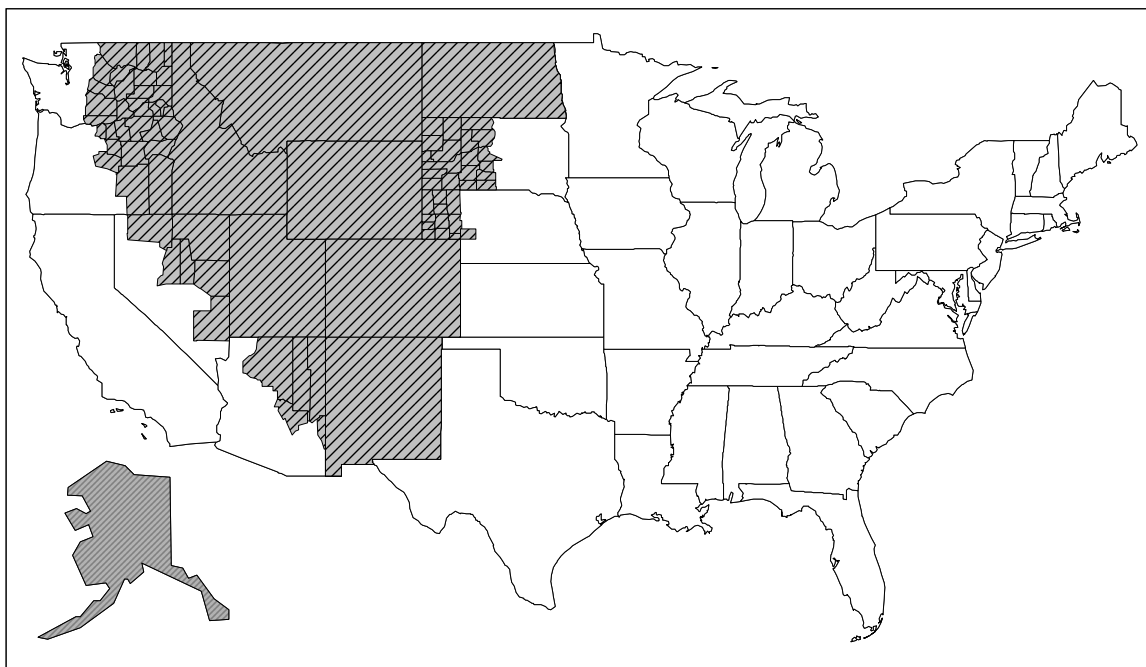


Figure III.2 Geographic Phase-in Area.

#### c. General Hardship Provision

In addition to the small refiner and GPA flexibility provisions described above, the HD 2007 program includes two general hardship provisions:

- Temporary waivers based on extreme unforeseen circumstances

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<sup>9</sup> The GPA program was established under the Tier 2 rule. It provides temporarily less stringent standards for gasoline sold in the West and Alaska thereby giving some refiners additional time to comply with the national low sulfur gasoline standards.

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- Temporary waivers based on extreme hardship circumstances

Under the first provision, EPA may, at its discretion, permit domestic or foreign refiners to seek a temporary waiver from the 15 ppm diesel fuel sulfur standard under certain rare, unanticipated circumstances, such as a refinery fire or a natural disaster.

The second general hardship provision provides a waiver for relief based on extreme hardship circumstances. This provision was designed for refiners that may face particular difficulty in complying with the 15 ppm sulfur standard in the lead time provided (for example, due to the inability to raise capital for desulfurization investments or relatively poor economies of scale).

### **B. The Review Process**

#### **1. Company Meetings and Visits**

We conducted this review over the last year and a half tracking industry's progress in improving and implementing desulfurization technologies to produce 15 ppm sulfur diesel fuel. We have spoken to, met with, or visited five major technology vendors and more than 30 refining companies since promulgation of the HD 2007 rule.

The purpose of these meetings was for us to affirm our final rule projections that extensions of existing diesel fuel desulfurization technology are feasible and will be used for compliance. During our meetings with technology vendors, we asked industry to estimate, based on each company's experience, the current state of desulfurization technology development and implementation. Specifically, we sought answers to the following questions:

- What is the capital cost of your technology?
- What are the operating costs associated with your technology?
- Will your technology require an increase in capacity?
- What is the hydrogen consumption requirement of your technology?
- When do you expect commercial introduction of your technology?
- Can your technology be used in the revamp of existing equipment?

In addition to discussions with technology vendors, we also held conversations with refining companies regarding the implementation of diesel desulfurization technologies to produce 15 ppm sulfur diesel fuel. During our meetings with refining companies, we polled them on their plans for complying with the requirements of the HD 2007 program. Specifically, we posed the following questions to each company for each of their refineries:

### **III. Progress Review of Desulfurization Technology**

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- Do you plan to construct a completely new hydrotreating unit? or
- Will you revamp an existing unit?
- Will you be able to comply by simply changing catalysts?
- Do your plans include using any of the “new” desulfurization technologies that have recently become available?
- Assuming compliance by June 1, 2006, will the volume of ultra low sulfur diesel you produce likely be greater than, less than, or the same as your current production?
- Do any synergies exist in complying with both the low sulfur gasoline and HD 2007 programs?

With this information, we evaluated the current status of diesel desulfurization technologies and refiners’ plans for implementing the technology (revamped versus new equipment) to produce 15 ppm sulfur diesel fuel. The information shared during these meetings and visits with the regulated industry provided the primary basis for our conclusions regarding industry’s progress. Some of the information shared by industry was designated as CBI and as such cannot be described in detail.

#### **2. Information Obtained Through Reporting Requirements**

As described above, the HD 2007 rule contains registration and reporting requirements for the petroleum industry. The information obtained through these requirements will 1) provide an essentially complete and current picture of the universe of highway diesel fuel suppliers that exist at the beginning of the program, 2) help us to track industry’s progress in implementing the program and 3) enable us to evaluate compliance with the program once it has begun.

##### **a. General Requirements**

- Registration Information

Refiners and importers that currently or in 2006 expect to produce or supply highway diesel fuel were required to register with us by December 31, 2001.

- Pre-Compliance Reports

Refiners or importers that are planning to produce or import highway diesel in 2006, are required to submit an annual pre-compliance report. These reports are required from 2003 through 2005 and must contain the following information:

- Volume estimates of 15 ppm sulfur fuel and 500 ppm sulfur diesel fuel that will be produced at each refinery,

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- A projection of how many credits will be generated or must be used by each refinery (for those refineries planning to participate in the credit trading program), and
- Information outlining each refinery's schedule for compliance including information regarding engineering plans (e.g., design and construction), the status of obtaining any necessary permits, and capital commitments for making the necessary modifications to produce 15 ppm sulfur highway diesel fuel.

We plan to issue an annual report that summarizes the information contained in the pre-compliance reports (without compromising the confidentiality of individual refiners and importers). Our annual report will provide information, summarized and aggregated on a regional basis, on the volumes of 15 ppm and 500 ppm sulfur highway diesel fuel planned to be produced, and estimates of the number of credits that refineries expect to generate or use. This will provide industry with informed projections of the highway diesel market and allow them to adjust their plans accordingly.

### **b. Small Refiners**

- Registration Information

In addition to the basic registration requirements above, a refiner seeking small refiner status under the HD 2007 program had to apply for this status as a part of its registration (including corporate employment and crude oil capacity information as specified in the regulations). The application had to include which small refiner option the refiner expects to use at each of its refineries.

- Pre-Compliance Reports

In addition to the information required for all refiners above, small refiners must provide additional information in their pre-compliance reports. The information required varies according to which small refiner option the refiner plans to use. The following paragraphs summarize the supplementary information required for each small refiner option.

- i. 500 ppm Option*

The pre-compliance report for a refiner planning use the 500 ppm Option must make a showing that sufficient sources of 15 ppm sulfur fuel will likely exist in the area. If after 2003 the sources of 15 ppm sulfur fuel decrease, the pre-compliance reports for 2004 and/or 2005 must identify this change and must include a supplementary showing that the sources of 15 ppm sulfur fuel are still sufficient.



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#### *ii. Small Refiner Credit Option*

Pre-compliance reporting for small refiners choosing the Small Refiner Credit option is identical to that for the 500 ppm sulfur option (that is, if the small refiner is also producing 500 ppm sulfur highway diesel fuel), with the additional requirement that the refiner also report on any credits it expects to generate and sell.

#### *iii. Diesel/Gasoline Compliance Date Option*

Pre-compliance reports from small refiners that expect to use the Diesel/Gasoline Compliance Date Option must provide information showing that diesel desulfurization plans are on track. In addition to the information described above for refiners in general, the pre-compliance reports from a small refiner that expects to use this option need to reasonably show that the refiner will be in a position by June 1, 2006, to produce 100 percent<sup>r</sup> of its highway diesel fuel at the 15 ppm sulfur level.

#### **c. GPA Refiners**

As with small refiners expecting to use the Diesel/Gasoline Compliance Option above, pre-compliance reports from any refiners or importers expecting to use the extension of the GPA gasoline sulfur standards must provide information showing that diesel desulfurization plans are on track. In addition, pre-compliance reports from a prospective GPA refiner need to reasonably show that the refiner will be in a position by June 1, 2006 to produce 100 percent of its highway diesel fuel at the 15 ppm sulfur level.<sup>s</sup>

### **3. Literature Review**

The final step of our progress review was a literature search. We conducted a search for information related to the production of 15 ppm sulfur diesel fuel, including conventional and emerging desulfurization technology developments as well as announcements of specific refiner plans for producing 15 ppm sulfur diesel fuel.

The results of this search are located in Appendix C of this report.

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<sup>r</sup> The total volume of 15 ppm sulfur diesel fuel must meet or exceed 85 percent of the small refiner's baseline volume (which is based on data for 1998 and 1999), except for 2006 where the total volume must meet or exceed 50 percent of the baseline volume.

<sup>s</sup> The 85 percent baseline volume requirement also applies to the GPA option.

## **C. Desulfurization Technology Progress**

### **1. Final Rule Estimates and Conclusions**

In Chapter IV (Fuel Standard Feasibility<sup>1</sup>) of the HD 2007 rule RIA, EPA concluded that it would be feasible for refiners to achieve the 15 ppm sulfur standard using extensions of conventional diesel desulfurization technology. This feasibility conclusion was based on conversations with the vendors of highway diesel fuel desulfurization technology, including Akzo Nobel, Criterion Catalysts, Haldor Topsoe, IFP and UOP. This view was further corroborated by refiners with whom EPA spoke as it developed the final rule.

In meeting the 15 ppm diesel fuel sulfur standard, which is expected to result in highway diesel fuel being desulfurized down to about seven ppm, refiners are expected to take a number of actions, including the following:

- Upgrade to a higher activity catalyst in the existing reactor of a revamped highway diesel hydrotreater,
- Add a second reactor vessel to increase catalyst volume with some or most of the reactor volume being comprised of a nickel-molybdenum (Ni-Mo) catalyst,
- Scrub the hydrogen sulfide (H<sub>2</sub>S) out of the recycle hydrogen gas,
- Use improved liquid distributors to improve the distribution of the liquid over the catalyst bed,
- Increase the hydrogen partial pressure by increasing the hydrogen purity available from the source, or increase the amount of recycle gas,
- Increase the reactor temperature of the current highway diesel hydrotreater, or operate the first reactor of a new hydrotreater at a higher temperature,
- Scrub the H<sub>2</sub>S from the liquid/gas mix between the first reactor (existing reactor in the case of revamps) and second reactor.

The Agency estimated that achieving a 15 ppm sulfur cap using a conventional Ni-Mo catalyst and applying a combination of the changes described above would require 480 standard

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<sup>1</sup> [http://www.epa.gov/otaq/regs/HD\\_2007/frm/ria-iv.pdf](http://www.epa.gov/otaq/regs/HD_2007/frm/ria-iv.pdf)

### **III. Progress Review of Desulfurization Technology**

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cubic feet of hydrogen per barrel (scf/bbl) of diesel feed. This hydrogen consumption value assumed a diesel fuel which would be composed of a typical mix of blendstocks.

The technology choice for achieving a 15 ppm sulfur level must also consider whether the existing hydrotreater will be revamped, or whether it will be replaced with a new highway diesel fuel desulfurization unit. After discussing this issue individually with vendors and refiners and at a refining industry technology sharing meeting, EPA estimated that 20 percent of highway diesel fuel, on average, would be produced by new highway diesel hydrotreaters, while the other 80 percent of the volume would be produced by revamped hydrotreaters. EPA also concluded that sufficient time and resources (engineering and construction, in particular) were available for implementation of the technology by the program's compliance date.

## **2. Progress Since the Final Rule**

This section describes the progress made in deep desulfurization technology for meeting the 15 ppm sulfur standard since the HD 2007 rule was promulgated. During late 2001 and early 2002, we held discussions with Akzo Nobel, Criterion Catalysts, Haldor Topsoe, IFP, and UOP about improvements in their conventional deep desulfurization technologies for diesel fuel.

### **a. Progress with Conventional Diesel Desulfurization Technology**

As stated above, we concluded in the HD 2007 rule RIA that meeting the 15 ppm sulfur standard would be feasible using extensions of known conventional, fixed bed desulfurization technology. This conclusion was based on conversations with diesel desulfurization technology companies and refiners that were drawing upon some limited data and expertise on the issue. In most cases, these firms did not have commercial data and had only limited data from their pilot plants upon which they made their conclusions. However, they did have some commercial experience with deep desulfurization units which serve as first stages for upgrading diesel fuel to meet cetane or density specifications, or to produce highway diesel fuel under the European tax incentives for meeting the 50 ppm sulfur standard which applies there.

Since the final rule, these vendors have been running desulfurization tests in their pilot plants using various feedstocks and at varying conditions for meeting the 15 ppm sulfur standard. In addition, the vendors have been working with several refiners who have been running tests using their existing highway diesel hydrotreaters operated under conditions where they could achieve 10 to 15 ppm sulfur diesel fuel. After collecting these additional data, the vendors are all concluding, with certainty, that the 15 ppm sulfur standard is achievable with conventional technology treating the diversity of diesel fuel blendstocks comprising diesel fuel today.

The feasibility of complying with the highway diesel fuel sulfur standard is enhanced even further through advances in conventional technologies. These advances are associated with

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improvements in existing catalyst technology or other developments associated with diesel desulfurization. The improvements in catalyst technology are summarized here and are organized into three primary areas: 1) incremental improvements in current catalyst technology, 2) significant improvements in the coatings used on catalysts, and 3) improvements on the substrate used with catalysts. The discussion about improvements in catalysts is followed by a discussion about several other important issues including reactor internals, the amount of hydrogen needed for desulfurizing highway diesel fuel and the projected fraction of new versus revamped units.

### *i. Incremental Improvements in Catalyst Technology*

Three vendors with whom we spoke regarding diesel desulfurization mentioned that their companies were planning to announce a new line of desulfurization catalysts<sup>u</sup> before the June 2006 compliance date for the HD 2007 program. IFP is one of these. Its previous catalysts were designed primarily for realizing improvements in density and cetane for the European and Asian markets. However, IFP announced that, by the end of 2002, it will be selling a new line of catalysts for the U.S. refining industry which will focus strictly on deep desulfurization of diesel fuel for meeting the 15 ppm sulfur standard. Haldor Topsoe also announced that it would make another line of catalysts available in 2002 or 2003. Finally, Criterion Catalysts stated that it would be making another line of catalysts available before the program's June 2006 compliance date. These vendors did not provide estimates of the desulfurization efficiency improvement that these catalysts would deliver. However, the past improved catalyst introduced by Haldor Topsoe (comparing TK-574 to TK-554) would allow an existing hydrotreater to desulfurize the same untreated feed at the same reactor conditions down to 280 ppm versus 400 ppm with the previous catalyst. Criterion's most recent catalyst introduction, Centinel, is 80 percent more active than conventional catalysts used in the mid 1990s. This increased activity is achieved by better dispersion of the active metal on the catalyst substrate. While these new or improved catalysts are not sufficient to enable an existing hydrotreater to meet the 15 ppm sulfur standard, they can help to reduce the size of the second reactor, and the amount of additional catalyst needed.

### *ii. Catalyst Coatings*

Last year, Akzo Nobel announced a new highly active catalyst named Nebula which offers a different way in which coatings are used for catalysts. A typical catalyst is composed of two parts: an active coating which contains metals and a generally inactive substrate. For Nebula, Akzo Nobel concentrated the metal coatings and omitted the substrate. Because of the very high metals content, Nebula costs several times more than conventional catalysts. The higher activity of the Nebula catalyst leads to an increased tendency for coking, which must be countered by using a high hydrogen partial pressure, resulting in a higher hydrogen consumption. (The

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<sup>u</sup> Desulfurization catalysts are manufactured by applying Cobalt-Molybdenum (Co-Mo) or Nickel-Molybdenum (Ni-Mo) metals to a substrate.

### **III. Progress Review of Desulfurization Technology**

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hydrogen consumption is higher because a higher percentage of the aromatics are saturated to nonaromatic compounds.) According to Akzo Nobel, a refiner may be able to meet the 15 ppm sulfur standard by simply replacing its existing catalyst with Nebula and providing significantly more hydrogen (which may possibly require the addition of a hydrogen plant). However, it is conceivable that a refinery located on the Gulf Coast which has an external supply of hydrogen could meet the 15 ppm sulfur standard with only a catalyst change, avoiding significant capital costs.

While Nebula is a new catalyst that could avoid some or much of the capital investment that would otherwise be required for meeting the 15 ppm sulfur standard, another company said that it is experimenting with using its previously developed catalyst technology for meeting the 15 ppm sulfur standard. Criterion catalysts indicated that it is working with some refiners to use its Synshift catalyst technology to meet the 15 ppm sulfur standard. The Synshift technology is a ring opening technology that would open at least one of the aromatic rings of polyaromatics. Like the Nebula catalyst, the Synshift catalyst would trade higher hydrogen consumption for capital costs as an existing large, higher pressure (1000 psia) highway diesel fuel reactor could be used to meet the 15 ppm sulfur standard with potentially only a change in catalyst. The result of this commercial testing is expected to be made available within a year. A more complete summary of Synshift is contained in Chapter IV of the HD 2007 RIA.

#### *iii. Catalyst Substrate*

Another catalyst vendor shared some information about its catalyst development program which involves advances in the geometry of its substrate. These advances have resulted in significant improvements in the contact of diesel fuel with the catalyst. The vendor also shared that it is combining its substrate technology with other reactor enhancements to further increase the contact between diesel fuel and the catalyst and hydrogen. Preliminary tests suggest that this combination could improve the catalyst activity by a factor of three. While this technology is still under development in the laboratory, the vendor is optimistic that it will be commercially available by 2006.

#### *iv. Reactor Internals*

Diesel desulfurization technology improvements extend beyond the desulfurization catalyst. As described above, a high quality distributor for distribution of the liquid feed over the catalyst bed is necessary to maximize the desulfurization capability of the reactor. Since the final rule, IFP announced an improved distributor called EquiFlow. IFP presented a paper on EquiFlow at the National Petrochemical and Refiners Association (NPR) Annual Meeting in March 2001. A comparison of its EquiFlow distributor to a conventional distributor shows an impressive improvement in temperature consistency both just below the top of the catalyst bed and at the exit at the bottom of the catalyst bed. The improved temperature gradients provide a sound basis for concluding that the new IFP distributor would 1) improve the distribution of the

## **Highway Diesel Progress Review – June 2002**

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liquid thus avoiding channeling around the catalyst bed, and 2) reduce hot spots in the reactor thus improving diesel fuel color and avoiding unnecessary coke build up in the catalyst bed. This distributor as well as other improved distributors that are already available provide refiners an important array of options for meeting the 15 ppm sulfur target.

### **b. Other Issues**

The hydrogen consumption of a diesel hydrotreater unit is, in most cases, the highest cost line item associated with deep diesel fuel desulfurization. We based our cost estimates for producing 15 ppm sulfur diesel fuel on the hydrogen consumption provided by the two vendors which provided information on the capital, utility, and other inputs required for diesel fuel desulfurization. During our conversations on diesel desulfurization technology, we questioned the vendors on their most recent estimates for hydrogen consumption. Specifically, we inquired whether our hydrogen consumption estimate of 480 (scf/bbl) for desulfurizing a typical undesulfurized diesel feed down to under 15 ppm sulfur was still reasonable. All of the vendors agreed that it was.

We also inquired about whether refiners would be revamping their existing diesel fuel desulfurization units, or removing those from service and installing new units. The vendors indicated that the refiners who were further along in the planning process were intending to revamp their existing desulfurization units. This information was corroborated, as described in Section E, below, by the conversations and meetings we held with refiners. Because most refiners have still not finalized their compliance plans for producing 15 ppm sulfur diesel fuel, the exact fraction of highway diesel fuel that will be produced by revamped units versus new units cannot be determined at this time. However, given this information and the absence of any other evidence to the contrary, we continue to believe that our previous 80 percent revamp / 20 percent new unit projection was reasonable.

### **3. Shared Desulfurization or Hydrogen Units**

Sharing desulfurization or hydrogen units between or among refineries can greatly reduce the per-gallon capital costs for complying with the 15 ppm sulfur standard. This is because larger desulfurization and hydrogen units benefit from the economies of scale that larger units offer,<sup>v</sup> with smaller refiners having more to gain than larger refiners. For example, a small refiner that makes highway diesel fuel would make an agreement with another refiner, either small or large, to share the cost of building and operating a common hydrotreater serving the desulfurization needs of two or more neighboring refineries. This same investment approach could be used to build common hydrogen generating plants. For example Praxair, a producer of hydrogen in the Gulf

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<sup>v</sup> As an example, smaller desulfurization units incur similar design and instrumentation costs as larger units, despite the smaller volumes treated.

### **III. Progress Review of Desulfurization Technology**

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Coast, announced its intention to build two 100 million cubic feet per day hydrogen-producing facilities there to satisfy the upcoming hydrogen demand by a number of refiners to desulfurize their gasoline and highway diesel fuel. Actions such as these will lower the cost of complying with the 15 ppm sulfur standard.

#### **4. Emerging Technologies**

The HD 2007 rule also contained brief descriptions of developmental diesel fuel desulfurization technologies which may serve as alternatives for meeting the 15 ppm sulfur standard if they are proven successful. One such diesel desulfurization technology was announced in early 2002 by Linde Process Plants Incorporated and Process Dynamics Incorporated. As explained by the engineers developing this process, the process is also a fixed bed desulfurization technology using conventional desulfurization catalysts, but it incorporates a significant amount of product recycled back to the reactor feed as the means to overcome the hydrogen mass transfer limitations which normally plague conventional fixed bed diesel desulfurization. Operating closer to the kinetic potential for desulfurization, this process is capable of space velocities an order of magnitude greater than those using conventional fixed bed desulfurization. Thus, capital costs are significantly reduced and cycle lengths are extended. The Linde and Process Dynamics engineers also explained that a current highway diesel fuel desulfurization unit revamped using this technology would recover the incremental operating costs of this added unit through improved reaction heat recovery, thus incurring a small payback. This process is being installed in a U.S. refinery with an expected start-up in the summer of 2002. If the commercial demonstration unit performs as well as the pilot plant data suggests, it could provide a much lower cost option for meeting the 15 ppm sulfur standard even in 2006.

Another technology is the Phillips S-Zorb process which has been demonstrated in a laboratory, and more recently in a pilot plant. The S-Zorb process works by adsorbing the sulfur molecules of the hydrocarbon onto a catalyst which then cleaves the sulfur molecule from the hydrocarbon molecule. To avoid saturating the catalyst with sulfur, the catalyst is constantly removed from the reactor and regenerated. Petrostar and UniPure have developed another type of technology which chemically oxidizes and extracts sulfur from diesel fuel. Both the Petrostar and UniPure processes have been demonstrated in the laboratory, and the Petrostar process has been demonstrated in a pilot plant.

Although the emerging technologies are unnecessary for refiners' compliance in 2006 since extensions of conventional technology can meet the 15 ppm sulfur standard, they may offer lower costs for some refiners, particularly those that are able to delay production of 15 ppm sulfur diesel fuel until 2010 by taking advantage of the program's flexibilities. Based on our conversations with these technology vendors, some of these technologies may require an upstream desulfurization unit for removing the bulk of the sulfur in diesel fuel, thus, they would likely be installed in series as a revamp to an existing conventional diesel fuel hydrotreater. An exception to relying on revamps is that Petrostar may be able to adapt its pre-extraction

technology to meet the 15 ppm sulfur standard from high sulfur untreated feedstocks, and UniPure is working on adapting its process for higher sulfur feeds. These technologies consume little or no hydrogen, which provide an operating cost advantage, especially to those refiners short on hydrogen. This quality also makes these processes excellent candidates for reprocessing off-specification distillate that is generated as a result of pipeline shipment and tank storage cross-contamination. Therefore, if installed at terminals, these alternative processes could play an important role in helping to maintain the integrity of highway diesel by reducing the volume of highway diesel fuel that is downgraded to other products.

### **D. Refiners' Plans for Producing 15 ppm Diesel Fuel**

As described above, the HD 2007 rule was published only last year and refiners have four to eight years to meet the 15 ppm diesel fuel standard. Given the timing of this progress review report relative to the June 2006 compliance date for the HD 2007 program, we focused our progress review efforts on information and activities since January 2001, related to the desulfurization technologies. However, it is important to note that some refiners will have the capability to produce 15 ppm sulfur diesel as early as next year, and small volumes are being produced today to enable retrofit programs in transit and school bus programs across the country.

The refining industry is very diverse and every refinery within the industry is unique. There are approximately 112 refineries that produce highway compliant diesel fuel in the U.S., ranging from very large refineries with crude capacities in excess of 450,000 barrels per day (bpd) to the relatively small that process as few as 5000 bpd. Some of these refineries are owned by small businesses and as such may qualify for the small refiner hardship provisions of the HD 2007 program. Likewise, refineries located in the West or Alaska that produce both gasoline and highway diesel fuel may benefit from the program's GPA refiner provision. Some refineries are already well positioned to comply with the program's requirements (and, in some cases, have announced their specific plans to do so) while other refineries are exploring technology options for producing 15 ppm diesel fuel.

While refineries are very diverse in terms of their corporate ownership, capacity, configuration, location, and product slate, they will, in general, follow a common pathway toward compliance with the requirements of the HD 2007 program. Progress toward compliance can be assessed by reviewing refiners' transitions from one stage to the next along the compliance pathway over time. That is, we can compare how many refiners are at a given stage from one year to the next until the program is fully implemented. Until the end of 2002, most refiners will be in the planning stage to determine how they will comply with the program's requirements. After refiners have made their technology selections (including detailed design and engineering), they will begin the permitting process to obtain the necessary approvals for revamping existing or installing new refinery equipment. Finally, after the plans have been established and the necessary permits have been obtained, refineries will begin the final stage of the pathway toward



### **III. Progress Review of Desulfurization Technology**

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compliance—engineering, construction, and ultimately start-up. These stages are described in more detail below.

#### **1. Steps in the Planning Process for Producing Low Sulfur Diesel**

##### **a. Strategic Planning – Deciding What to do and When**

Strategic planning occurs once upper management has determined that a regulation will affect a facility. As the word “strategic” implies, it is at this stage that upper management decides on a response to the regulation that will position the company most advantageously relative to its competitors. Input may include order-of-magnitude estimates of what compliance costs could be; or, how the bottom line may be affected if the decision is made not to comply and to instead shift product into other markets. Specific planning begins once management determines that, strategically, compliance will be necessary and will require the expenditure of significant capital. The decision to hire an outside engineering firm may be made at this time. Suggestions or directions as to how the project will be organized, who will be in charge, and how progress will be reported usually come out of this state. If a refiner has multiple refineries, representatives of each facility are usually involved in this stage in order to determine how the overall company should proceed and how each refinery will fit into the plan. By the time strategic planning is complete or nearly complete, each refinery will have a basic plan and direction in which to proceed.

The length of time required for this stage varies by facility or company, depending on size, complexity, and the number of refineries. It is nearly impossible to precisely project how much time a specific refinery may need to complete this stage. However, our best estimate is that a small, single-facility refiner may need as few as three to six months; a large, complex, multiple facility refiner may need up to two years. Given that the rule was promulgated in late 2000 and that it was anticipated well before that, we expected and found that the refineries which currently produce 500 ppm sulfur diesel fuel have completed their strategic planning and intend to produce 15 ppm sulfur diesel fuel. Additionally, as discussed below, several refiners have found it strategically wise to convert significant volumes of their high sulfur distillate production to 15 ppm sulfur diesel fuel.

##### **b. Planning & Front-end Engineering – Deciding How to Do it**

Accurate and complete information is gathered during this stage so that preliminary process engineering work can proceed. Accurate feedstock and product characteristics are produced and initial contacts made with technology vendors to find the best, least expensive technology whereby feedstocks can be treated to produce finished products. With the help of vendors, decisions can be made regarding whether revamps of existing equipment are possible or whether new units will be necessary. Temperatures, pressures, and flowrates must be determined

## **Highway Diesel Progress Review – June 2002**

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early on, from which heat and material balances and process flow diagrams can be produced. Detailed engineering cannot begin until this stage is mostly complete.

The length of time required for this stage varies by facility. We expect most refiners, regardless of size, to begin front-end engineering no later than early to mid 2003. Larger, more complex units will likely require detailed engineering before then. Indeed, we found that all but a few of the very small refiners have finished planning and are into front-end engineering, although perhaps 80 percent overall have yet to make final technology decisions.

### **c. Detailed Engineering and Permits – Making the Arrangements**

Detailed engineering usually overlaps with the preceding and the following stages, but cannot begin in earnest until a hydrotreating technology has been chosen. The technology sets the operating conditions around which the rest of the unit is designed. Once that decision is final, various pieces of equipment, especially reactors, separators, and compressors specific to that technology, can be designed and ordered. As these plans are completed, structures can be designed to support them and piping and pumps designed to connect them at the specified flowrates. Heat exchangers and furnaces are designed to provide the necessary heat balance and instrumentation is designed to control the whole process. Eventually, piping and instrument diagrams and electrical drawings can be completed for the entire process.

Once sufficient information is available, Notices of Intent to make changes to a refinery can be filed. This is critical and must be done in a timely manner, since actual construction cannot be started until construction permits are issued.

The time required for detailed engineering and permits varies widely depending on the size and complexity of the unit or process. Given that we expect that Front-End Engineering would take about six months and Detailed Engineering and Permits about 11 months, we expect most refineries to begin this stage by late 2003 to early 2004.

### **d. Procurement and Construction – Building It**

This stage necessarily overlaps with the preceding stage. Procurement includes purchasing long-lead items, as well as inventorying pipe, pumps, insulation, structural steel, a variety of valves, wire, and other consumables such as conduit, nuts, bolts, and gaskets. Long-lead items such as furnaces, compressors, high-pressure pumps, and thick-walled, high-pressure vessels must be ordered early in a project, sometimes well before other plans are complete.

Once permits are issued, construction can begin in earnest. Welding the stainless steel and alloy pipe used in most of the current hydrotreating technologies is time consuming. Once pipe arrives onsite, many contractors setup staging areas where long runs of pipe that do not require close length measurement can be fabricated for later use. Once concrete, vessels, furnaces, heat

### **III. Progress Review of Desulfurization Technology**

exchangers, and pumps have been set, the previously welded long runs of pipe can be trimmed, flanges, valves, and instrumentation installed, and final connections made. Pressure testing, x-raying, and other quality and workmanship inspections are carried out as construction proceeds. As runs and connections are completed, insulation can be installed and bare pipe painted. As heavy construction winds down, electrical and instrumentation connections are made and check-out is begun. Many instrumentation adjustments, such as loop-testing, cannot be made until liquid has been introduced and startup is progressing.

Large, single unit projects can take as long as two to two and one-half years to build. Even minor problems can extend construction by as much as six months or more. Revamps can take less time, although tie-ins, changes to existing equipment, and the need to work within an operating facility can lengthen the time by several weeks or months. With careful planning, refiners can make critical tie-ins during planned shutdowns and turnarounds. Some facilities are located in warm winter climates where year-round construction is possible, while others must deal with winter construction which usually takes longer. Accessibility to construction workers and the ease with which large vessels can be delivered can have a major effect on construction schedules. Construction workers, as a rule, tend to stay in areas where they can easily and in reasonable comfort work year-round. Also, since most large high-pressure vessels are currently manufactured overseas, it is easier for coastal refineries to receive them. While these types of issues do not prevent inland or less accessible refineries, typically located in colder regions of the country, from making necessary changes, they certainly must be planned for as delays almost always occur. We expect that even the smaller units should be under construction by no later than the end of October 2004.

#### **e. Commissioning and Startup – Making it Work**

Depending on the complexity of the project, commissioning and startup usually happen together. Some vendors have specific startup procedures for their technologies, whether for commissioning an entire process or for a catalyst alone. A critical part of commissioning and startup is the Occupational Safety and Health Administration's (OSHA) "Process Hazard Analysis", a very complicated and time consuming, multi-part procedure that must be completed and signed-off on before startup can proceed. For this, accurate, final construction and as-built drawings, including complete piping and instrument diagrams, must be completed. A competent team of process and design engineers, environmental engineers, safety experts, and operation and maintenance personnel, among others, conduct a thorough, item-by-item, flow-by-flow, hazard analysis to determine whether everything, including equipment, instrumentation, and safety devices, was designed to adequately protect plant personnel and the environment. If anything is found to be unsafe or otherwise inadequate, it must be changed according to a rigorous set of OSHA guidelines.

Depending on the size and complexity of the process, startup can take from three to six months. In spite of all the precautions and planning that will have gone into the project over the

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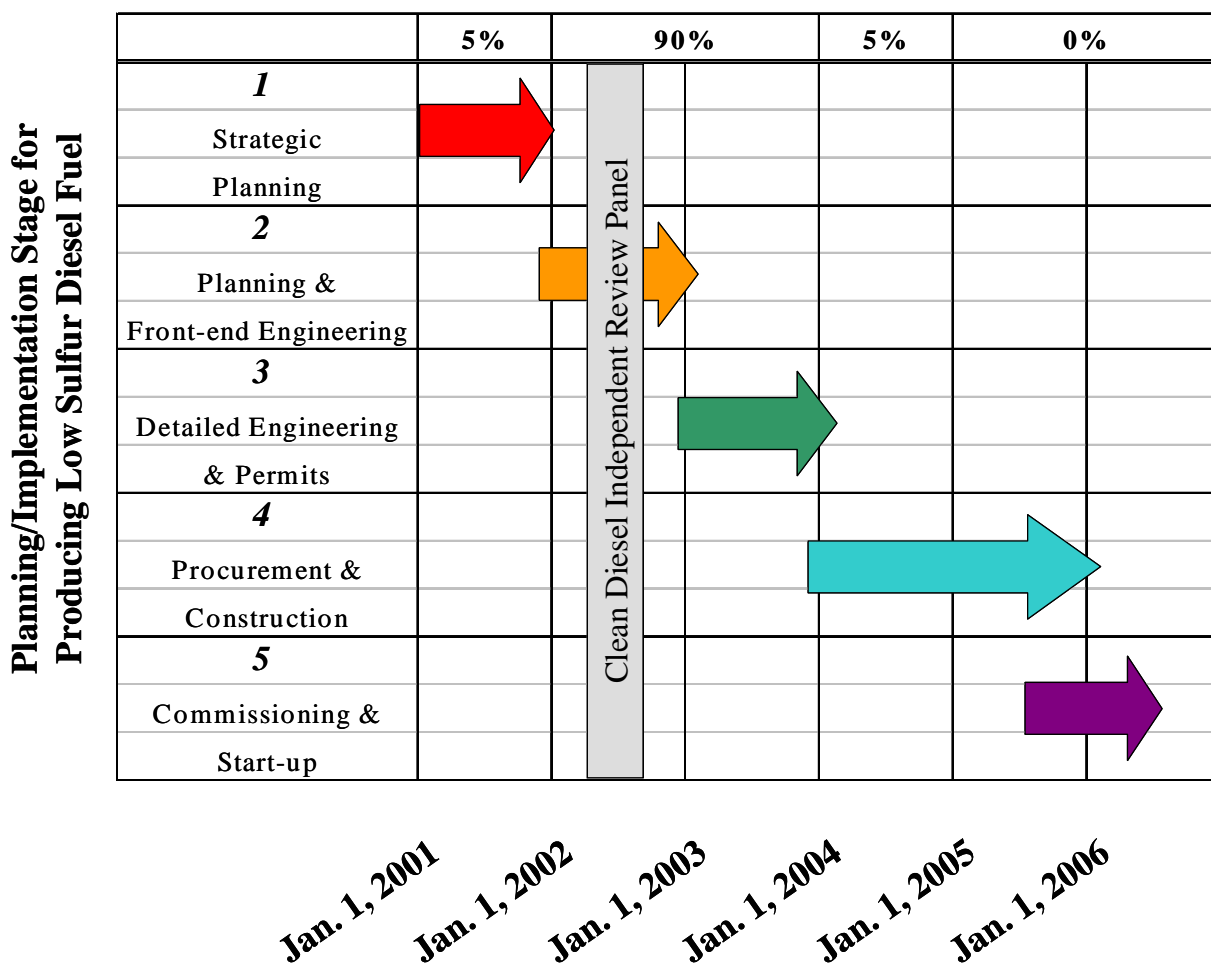
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preceding three or four years, most refiners judiciously plan for unforeseen events. Refiners in cold weather areas may delay a possible winter startup until perhaps early spring, but only if they fully expect the startup to go reasonably smoothly. If they delay too long, and run into startup problems, it is possible they may not startup on time. Additionally, some will need to provide for time to wash out tanks and old piping in preparation for 15 ppm sulfur product. Dealing with 15 ppm sulfur diesel will also require changes in operating procedures as well as testing procedures. However, final introduction of new methods and procedures must wait until the fuel is actually produced. Refiners will need to account for and settle these issues well before the 15 ppm fuel must be delivered.

Figure III.3, below, illustrates the estimated percentage of highway diesel fuel refiners that are at each of the stages described above.

### III. Progress Review of Desulfurization Technology

**Estimated Percent of Industry Currently at Given Stage**



**Figure III.3 Low Sulfur Diesel Fuel Progress Timeline**

## 2. Production Plans and Announcements

As described above, most refiners will follow a common pathway to comply with the requirements of a regulatory program. The purpose of this section is to characterize the refining industry and to determine where refiners and their refineries are on the pathway toward compliance with the HD 2007 program.

There are approximately 150 active refineries in the U.S. with a combined crude capacity of about 16.5 million bpd according to the Energy Information Administration (EIA) for 2001. Based on CBI data we obtained from EIA, approximately 110 refineries currently produce about 2.5 million barrels per day of highway-compliant diesel fuel (that is, diesel fuel with a sulfur

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content less than 500 ppm). Nearly one-half of these refineries are considered to produce only highway compliant diesel fuel. That is, 95 percent of their total distillate production has a sulfur content less than 500 ppm. The remaining refineries produce some highway and some off-highway distillate fuel. Approximately 30 refineries have no significant production of highway grade diesel fuel (less than 10 percent of their distillate production is highway-compliant diesel fuel) but some have indicated that they intend to enter the highway market by 2006.

### a. Public Announcements

Part of our progress review was to track public announcements of specific refiner plans for producing 15 ppm diesel fuel. These refiners are ahead of schedule with respect to the program's June 2006 implementation date.

- *Murphy Oil* confirmed that it will produce not only EPA-compliant low sulfur gasoline, but also approximately 25,000 bbl/day of 15 ppm sulfur diesel fuel when its Greener Fuel Project at its Meraux, Louisiana refinery is completed in mid-2003. The refinery's decision to produce 15 ppm on-highway diesel prior to 2006 will be based on customer demand and market economics.<sup>29</sup>
- *Holly* announced a new hydrotreater project at its Navajo refinery in New Mexico that will allow it to produce low sulfur gasoline and make it "easier" to produce 15 ppm diesel fuel in advance of 2006.<sup>30</sup>
- *Flint Hills* (formerly Koch) announced upgrades to its Corpus Christi, Texas refinery that are designed to meet upcoming low-sulfur gasoline standards. The upgrades will help create "synergies" for the eventual production of 15 ppm diesel fuel.<sup>31</sup>
- *Chevron Products Company* has confirmed that desulfurization capacity upgrades at its Pascagoula, Mississippi refinery will make the refinery capable of producing at least 25,000 bbl/day of 15 ppm on-highway diesel fuel by mid-to-late 2003. The refinery's decision to produce 15 ppm on-highway diesel prior to 2006 will be based on customer demand and market economics.<sup>32</sup>
- *Frontier Oil* (a small refiner) announced that it will delay 15 ppm diesel fuel compliance until 2010 at their Cheyenne, Wyoming refinery and comply with the low sulfur gasoline rule on time. The company will comply by June 2006 with the low sulfur diesel fuel program and delay low sulfur gasoline compliance until 2010 at its El Dorado, Kansas refinery.<sup>33</sup>

### III. Progress Review of Desulfurization Technology

#### b. Other Refiner Indications

##### i. Small Refiner Indications

Twenty-one refineries owned by 17 refining companies have applied for and/or been approved for small refiner status under the HD 2007 program. Of these 21 refineries, four have indicated their intent to use the 500 ppm Option, six have indicated their intent to use the Small Refiner Credit Option, eight have indicated their intent to use the Diesel/Gasoline Compliance Date Option, and just four refineries are undecided. This information is summarized in Table III.2, below. Note that some double-counting occurs as the categories are not mutually exclusive. Because some refineries have indicated their intent to use more than one option, the total number of refineries indicated in the table below is greater than 21.

**Table III.2 Intended Small Refiner Compliance Options by Number of Refineries**

Option	Description	Number of Refineries
A.	500 ppm Option	4
B.	Credit Option	6
C.	Diesel/Gasoline Compliance Date Option	8
	Undecided	4
	Total	22*

\* Some double-counting occurs as the categories are not mutually exclusive. Because some refineries have indicated their intent to use more than one option, the total number of refineries indicated in the table below is greater than 21.

##### ii. GPA Refiner Indications

Thirty-five refining facilities owned by 15 companies have indicated their intent to produce GPA gasoline under the low sulfur gasoline program. Nearly one-third of these refining facilities have indicated their intent to take advantage of the GPA refiner provision under the HD 2007 rule. As described above, this provision will provide them two additional years to comply with the national gasoline standards if they produce all of their highway diesel fuel<sup>w</sup> at the 15 ppm specification beginning June 1, 2006.

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<sup>w</sup> As described in the preamble to the final rule, a refinery must also maintain a production volume of 15 ppm highway diesel fuel that is at least 85 percent of the baseline highway diesel fuel volume that was produced at the refinery during 1998 and 1999.

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### *iii. Hardship Approvals*

Under the low sulfur gasoline program, four refineries pursued hardship waivers. Three of these applications were approved last year and the final one was approved this year. Hardship applications under the highway diesel program were due June 1, 2002. A few applications were received and we will be reviewing them over the next few months.

### **c. Conversion of Off-highway to Highway Diesel Fuel Production**

In addition to tracking the plans of current highway diesel producers to comply with the HD 2007 program, we are also tracking the plans of other refiners who currently produce no to very little highway fuel to enter the highway market. Several refineries have already indicated that they will convert most, if not all, of their current high sulfur off-highway diesel fuel (which averages about 3000 ppm) to 15 ppm sulfur diesel by 2006. At present, we expect at least nine refineries to convert an aggregate volume of about 66,000 bbl/day of high-sulfur diesel to 15 ppm sulfur diesel fuel. (Most of these nine refineries have indicated their intent to take advantage of the small refiner, GPA, or hardship provisions offered under the program.) This represents only those refineries that have completed their initial planning and preliminary engineering. Given that only a few refineries have progressed beyond initial planning, we expect an increase in the number of refineries that expect to expand their low sulfur diesel production volumes.

### **d. Summary of Indicated Production Plans and Announcements**

The following table describes projects, plans, and commitments already made by refiners to produce 15 ppm sulfur diesel fuel by the June 2006 program compliance date. Note that some double-counting in the “Number of Refineries” column occurs as the categories are not mutually exclusive. However, the “Highway Diesel Fuel Volume for 2000” and “Highway Diesel Fuel Volume %” columns exclude double-counting.



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**Table III.3 Summary of Refinery Production Plans and Announcements**

Number of Refineries	Category	Highway Diesel Fuel Volume for 2000 (000 bbls/day)	Highway Diesel Fuel Volume %
8	Small (Option C)	91	3.6 %
12	GPA	114	4.5 %
9	Other Hwy Diesel Refinery Indications and Public Announcements	118	4.7 %
9	Conversion of Off-hwy to 15 ppm Sulfur Hwy Diesel Fuel		
38	<i>Total of All Categories</i>	323	12.8 %

**e. U.S. Refinery Construction Projects**

As part of our progress review, we have also been tracking crude expansion projects as well as hydrotreating, hydrocracking, and hydrogen capacity projects. We included this information in our review to demonstrate that the production of distillate fuel, distillate feed stocks, and other finished products such as gasoline, is increasing as a result of refineries adding capacity. In addition to planning for low sulfur diesel fuel, refiners will likely continue to expand their capacity over time to meet ever increasing fuel demand. As we projected in the HD 2007 rule, this also appears to be occurring.

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**Table III.4 Crude Expansion Projects at U.S. Refineries.**

<b>CRUDE</b>					
<b>Refinery</b>	<b>Location</b>	<b>State</b>	<b>Present Capacity (bpcd)</b>	<b>Crude Expansion (bpcd)</b>	<b>Projected Completion</b>
Alon	Big Springs	TX	61,000	4,000	By 2002
Citgo	Lake Charles	LA	333,000	100,000	2002
Navajo Refining	Artesia	NM	60,000	20,000	1st phase by end-2003
Murphy Oil USA	Meraux	LA	100,000	25,000	Mid-2003
Phillips	Borger	TX	130,000	20,000	2002
Valero*	Texas City	TX		20,000	
Williams Energy	Memphis	TN	175,000	20,000	By March 2002

\*Announced it wants to spend additional profits from merger with UDS to expand refineries

**Table III.5 Hydrotreating and Hydrocracking Projects at U.S. Refineries.**

<b>HYDROTREATING &amp; HYDROCRACKING</b>					
<b>Company</b>	<b>Location</b>	<b>State</b>	<b>Hydrocracking</b>	<b>Hydrotreating</b>	<b>Projected Completion</b>
ExxonMobil	Baytown	TX		x	By 2002; revamp
Flint Hills	Corpus Christi	TX		x	May 2001
MAP LLC	Delaware City	DE		x	2001
NCRA	McPherson	KS		x	2006
Shell	Los Angeles	CA	x	x	By 2003; expansion
	Puget Sound	WA	x	x	By 2003; expansion
	Port Arthur	TX	x	x	By 2003
	Deer Park	TX	x	x	By 2003
	Norco	LA	x	x	By 2003
	Convent	LA	x	x	By 2003
Valero	Texas City	TX		x	2001; expansion

### III. Progress Review of Desulfurization Technology

Table III.6 Hydrogen Plant Projects at U.S. Refineries.

HYDROGEN				
Company	Location	State	Hydrogen MMSCF	Projected Completion
NCRA	McPherson	KS	25	2006
Valero	Texas City	TX		2001

Our progress review indicates that the vast majority of refiners are exactly where we would expect them to be relative to the June 2006 compliance date for the HD 2007 program. These refiners have decided that they will comply with the program and are now in the midst of figuring out how to best do so. We are very encouraged by the actions some refiners have already taken in terms of announcing specific plans for low sulfur diesel fuel production.

Thus, the refining industry is where we anticipated it to be at this point in time. Moreover, some refining companies are ahead of schedule and will be capable of producing significant quantities of 15 ppm sulfur diesel fuel as early as next year.



## IV. Conclusions

The Agency has completed a comprehensive technical review of progress by 1) the manufacturers of diesel engines and emission control systems in developing technology to reduce engine exhaust pollutants, and 2) the petroleum refining industry in developing and demonstrating technologies to effectively lower the sulfur level of diesel fuel. From this review, we can conclude the following:

### *Engine Emission Control Technologies*

- Every major engine manufacturer expects to be able to comply with effective standards in 2007.
- The CDPF technology is rapidly maturing and will be broadly applicable by 2007.
- Catalyzed diesel particulate filters (CDPFs) are already being applied where 15 ppm sulfur diesel fuel is available.
- NOx adsorbers are improving in effectiveness and durability at a rapid pace. We are confident that they will be available for use to comply with the 2007 emission standards.
- EPA intends to continue to monitor progress to develop the NOx adsorber catalyst technology and will report out again on its progress in a second biennial review by December 31 of 2004.

### *Diesel Fuel Desulfurization Technologies*

- The 15 ppm diesel fuel sulfur standard was established based on the use of conventional diesel desulfurization technologies. These technologies have been commercially proven and refineries are basing their refinery changes for producing 15 ppm diesel fuel on them.
- Diesel fuel refineries are well positioned to make firm plans for 2006 implementation.
- Virtually all refiners are already in the stage of planning their approach for compliance with the 2006 fuel sulfur standard.
- New lower cost desulfurization technologies are being developed.

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- These new technologies could prove to be valuable for small refineries that can delay implementation of the new fuel under flexibilities provided in the rulemaking.
- The refining industry appears to be where we would have anticipated it to be at this point in time relative to the June 2006 compliance date of the HD 2007 program.
- Some refiners are ahead of schedule and will be capable of producing significant volumes of 15 ppm sulfur diesel fuel as early as next year.

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## Appendix A: List of Acronyms

ABT	Averaging, Banking, and Trading
APBF – DEC	Advanced Petroleum Based Fuels – Diesel Emission Control
CAA or the Act	Clean Air Act
CDPF	Catalyzed Diesel Particulate Filter
CTR	Credit Trading Region
DASL	Diesel Aftertreatment Sensitivity to Lubricants
EIA	Energy Information Administration
EPA or the Agency	U.S. Environmental Protection Agency
DECSE	Diesel Emission Control Sulfur Effects
DEOAP	Diesel Engine Oil Advisory Panel
DOE	Department of Energy
DPNR	Diesel Particulate NO <sub>x</sub> Reduction
FACA	Federal Advisory Committee Act
FR	Federal Register
GPA	Geographic Phase-in Area
HDE	Heavy-duty Engine
HDV	Heavy-duty Vehicle
LTC	Low Temperature Combustion
MECA	Manufacturers of Emission Control Association
NAAQS	National Ambient Air Quality Standards
NMHC	Non-methane Hydrocarbons
NO <sub>x</sub>	Oxides of Nitrogen
NPRM	Notice of Proposed Rulemaking
NTE	Not-to-exceed
NVFEL	National Vehicle and Fuel Emissions Laboratory
OEM	Original Equipment Manufacturer
PADD	Petroleum Administrative Districts for Defense
PM	Particulate Matter
ppm	Parts per Million
RIA	Regulatory Impact Analysis
SET	Supplemental Emission Test

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SO <sub>2</sub>	Sulfur Dioxide
SO <sub>x</sub>	Oxides of Sulfur
SwRI	Southwest Research Institute
TCO	Temporary Compliance Option
VOC	Volatile Organic Compound



## **Appendix B: HD 2007 Progress Review Meetings**

### **Meetings Related to EPA's HD 2007 Progress Review (Engines and Vehicles)**

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Caterpillar Inc.	Isuzu Motors LTD.
Corning Incorporated	Japan Automobile Manufacturers Assoc.
Cummins Incorporated	Japan Ministry Land Infrastructure Transport
DaimlerChrysler	Johnson Matthey
Detroit Diesel Corporation (DDC)	Mack/Volvo/Renault
Delphi / ASEC	Manufacturers Emission Control Assoc.
Department of Energy (DOE)	Mitsubishi Motors Corporation
EmeraChem	NGK
Engelhard Corporation	Nissan Diesel Motor Company
Ethyl Corporation	Nissan Motor Company, LTD.
Ford Motor Company	OMG
General Motors Corporation	PSA/Peugeot
Hino Motors LTD.	Toyota Motor Corporation
International Truck and Engine Corp.	Volkswagen AG

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### Meetings and Conference Calls Related to EPA's HD 2007 Progress Review (Technology Vendors and Refiners)

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#### *Technology Vendors*

Akzo Nobel	IFP
Criterion Catalysts	UOP
Halder Topsoe	UniPure

#### *Refining Companies*

Alon USA LP	Marathon Ashland
Atofina Petrochemicals	Montana Refining
Big West Oil Company	Murphy Oil Corporation
BP Amoco PLC	Navajo Refining
Cenex Harvest States Coop	NCRA
Chevron	Phillips Tosco
Citgo	Placid Refining
Coastal Refining	Premcor Refining
Conoco	Silver Eagle
Countrymark Coop Incorporated	Sinclair Oil Corporation
ExxonMobile	Somerset Refinery Incorporated
Farmland Industries	Sunoco
Frontier Refining	Tesoro
Equilon/Shell	United Refining
Gary Williams Energy Corporation	Valero-UDS
Giant Refining	Western Refining
Koch	Williams
Hunt Refining	Wyoming Refining

## Appendix C: Literature Review

Mayo, S., Brevoord, E., Plantenga, F., Gudde, N., and Hoekstra, G.; *ULSD in Real Life: Commercial Performance of Stars and Nebula Technology*; AM-02-38; 2002 NPRA Annual Meeting; San Antonio, TX.

McIntosh, K., Petrinc, B., Hacker, S., DeBerry, K. Jr.; *Crystasulf : A Process That Removes Both H<sub>2</sub>S and Light Hydrocarbons From HDS Hydrogen Recycle Streams*; AM-02-13; 2002 NPRA Annual Meeting; San Antonio, TX.

Torrise, S., DiCamillo, D., Remans, T., Street, R., Svendsen, J., Criterion Catalyst & Technologies; *Proven Best Practices for ULSD Production*; AM-02-35; 2002 NPRA Annual Meeting; San Antonio, TX.

Lamourelle, A., McKnight, J., Nelson, D.; *Clean Fuels: Route To Low Sulfur Aromatic Diesel*; AM-01-28; 2001 NPRA Annual Meeting; New Orleans, LA.

Stynes, P., Shepard, T., Thompson, M., Kidd, D.; *Innovation Key To New Technology Project Success Phillips S Zorb Becomes Low Sulfur Gasoline Solution*; AM-01-43; 2001 NPRA Annual Meeting; New Orleans, LA.

Vaarkamp, M., Chung-Ming, C., Duijndam, B.; *Upgrading Light Cycle Oil to Diesel Using The Engelhard-Washington Redar Process*; AM-01-23; 2001 NPRA Annual Meeting; New Orleans, LA.

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