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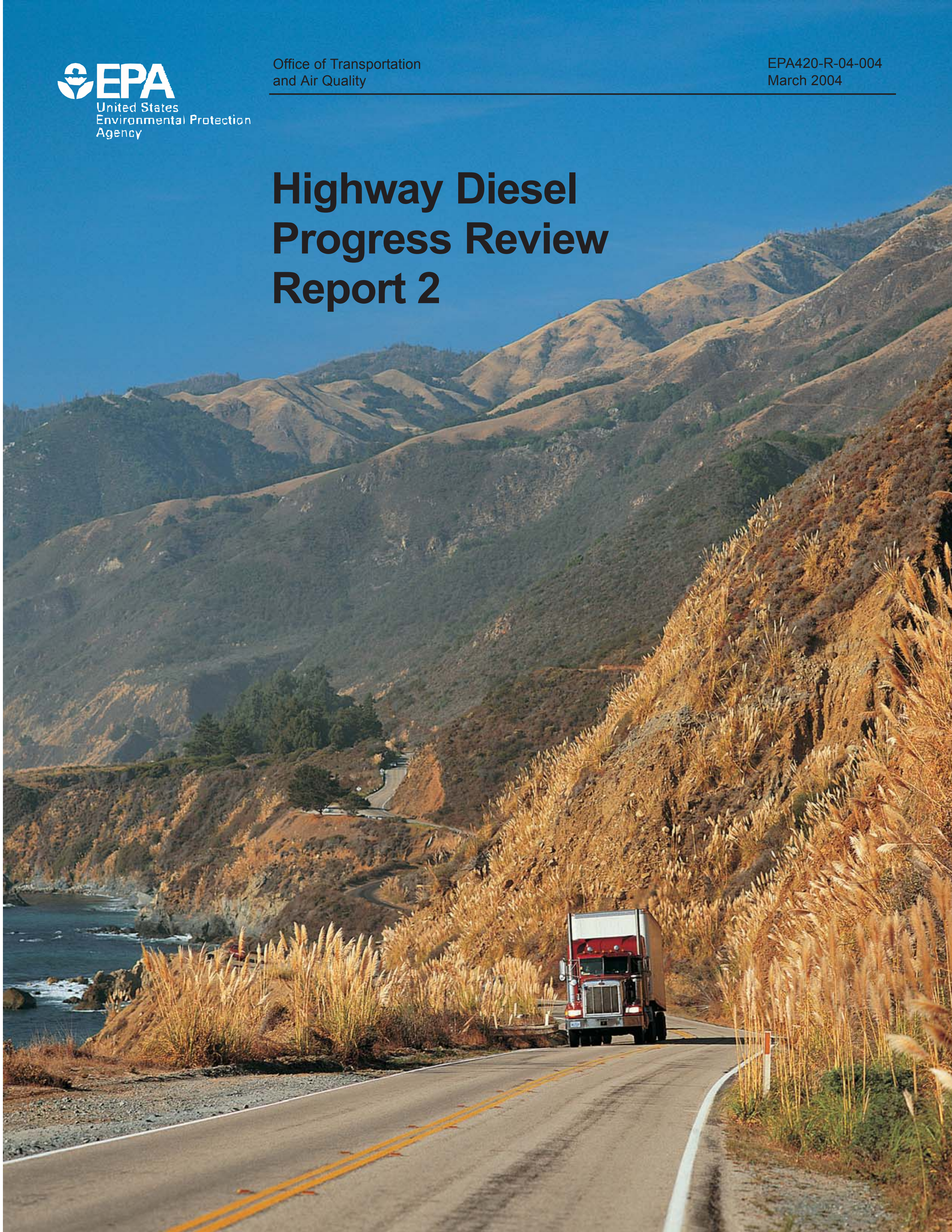
Highway Diesel Progress Review Report 2



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

Executive Summary

The Environmental Protection Agency (EPA or the Agency) established in 2000 new far reaching emission standards beginning in 2007 for heavy-duty diesel vehicles and the fuel used in them. These standards were premised on the introduction of new catalyst based emission controls for diesel engines and the removal of a catalyst poison, sulfur, from diesel fuel. The scale of the changes and the long-term benefit for society have only one parallel in the thirty plus year history of mobile source emission control: the introduction of unleaded gasoline and catalysts on cars in the 1970s. The monetized benefits of this program exceed its cost by more than 16 to one.

Given the scope of these new regulations and their importance for public health, it is only prudent that the Agency carefully follow the progress of industry in implementing this rule. This report is the second in a series of technical progress reviews by EPA to document the status of engine and vehicle technology development to meet the 2007 standards. The first report, published in June of 2002, concluded that progress to that time had been substantial and was in keeping with the expected progress necessary for successful implementation of the new standards in 2007. We concluded this based primarily on the extensive research efforts since the rule was finalized and the good results from that research.

This second report also considers the continuing progress in the research laboratory but, more importantly, the transition of these technologies from research into business plans, product development programs, engines and vehicles for field testing, and finally into real products for sale in the marketplace in 2007. Thus, while we continue to be impressed by the amount of technical progress shown in the laboratory, it is the concrete steps that manufacturers have taken in their new product development programs that gives us great confidence for 2007.

The data that we have used in reaching the conclusions summarized here come from a number of sources gathered over the last year and a half. The most compelling evidence, and that which we rely on most heavily, came from confidential one-on-one technical and business reviews conducted with engine manufacturers and with manufacturers of emission control technologies. EPA has met with almost 30 companies to gather this information and to understand fully the breadth of development for 2007. The companies we have met with are making substantial investments to bring products to the market for 2007 because of the confidence they have in those products.

As projected by the Agency in the 2007 rulemaking, all manufacturers are planning to use catalyzed diesel particulate filters (CDPFs) to comply with the 2007 particulate matter (PM) standard. In applications where 15 ppm sulfur diesel fuel is available, manufacturers have already introduced PM filter systems on engines for urban and school buses meeting the 2007 standards. This report documents the continued improvements in CDPF system technology to improve filter regeneration, lower fuel consumption, and reduce maintenance.

The report documents substantial progress to develop the NOx adsorber technology including improvements in catalyst formulation, durability, overall system performance and vehicle integration. In fact, late last year the first light heavy-duty diesel truck equipped with the NOx adsorber technology went into limited production in Japan. Although, we are not projecting that NOx adsorbers will be broadly used in 2007 to comply with these standards, we are continuing to conclude from the evidence shared during our review that manufacturers could comply using the NOx adsorber technology in 2007.

For 2007, all of the engine manufacturers have demonstrated the ability to further improve their current 2004 NOx emission control systems (either cooled EGR or ACERT™) to comply with the program. While the final NOx standard in 2010 is 0.20 g/bhp-hr, the 2007 program includes a number of implementation flexibilities that will allow manufacturers to comply with engines meeting an averaging level of approximately 1.2 g/bhp-hr in the years 2007-2009. All engine manufacturers have indicated they intend to adopt such a two-step compliance strategy. This strategy will allow engine manufacturers that choose to do so to make incremental changes to their current proven 2004 products for NOx control in 2007.

Engine manufacturers that sell similar products in Europe will have urea SCR based solutions for Euro IV that could be adopted to the US standards provided they can address issues related to urea infrastructure and end-user compliance. Two engine manufacturers are considering such an approach for 2007 in a limited way for centrally-fueled fleets. While it seems unlikely that such an approach could be broadly applied by 2007 given the significant urea infrastructure that would need to be put in place we believe such a solution could have a limited role in 2007 and potentially a broader role by 2010.

All of the engine manufacturers follow similar new product introduction programs built around a series of milestone reviews (i.e., gateway reviews to the next step in product development). The first of these gateway reviews defines the step from research to product development and requires that manufacturers have defined the product they intend to build, a target production cost, a business plan built around that target cost, and the resources necessary to bring the product to market. Prior to this step, engine manufacturers and technology suppliers have worked primarily to prove out potential technology solutions from which an engine manufacturer can then choose to define a new product. Completing this step means manufacturers are ready to begin the hard but well-defined work of successfully bringing a new product to market.

In earlier meetings with engine manufacturers, they indicated to us their confidence that they would be able to clear this first crucial step for 2007 products successfully and on time. The manufacturers have been working over the last year to complete all of the necessary analyses required to complete this first milestone review. The detailed confidential information shared with the Agency during our meetings reflected these analyses. In the time between our last detailed review meetings and the drafting of this report, four of the five major engine manufacturers have completed this crucial first step. The one company that has not completed this step has indicated to the Agency that it will in the coming weeks. The fact that the engine manufacturers have cleared this gateway says clearly that companies are on track to comply with the 2007 standards. This is not to say that no development tasks remain or that the remaining challenges are trivial. Substantial work to prove out these engines must be done over the next three years prior to their introduction in 2007, but completing this review step means manufacturers have concluded that the issues they have identified will be satisfactorily addressed in the hard work of their development programs.

To help allay concerns expressed by some in the trucking industry, engine manufacturers are planning to use their normal product development process as an avenue for their customers to learn more about the 2007 products. The manufacturers are indicating they will provide early prototype vehicles for selected customer testing in 2005.

This second progress report documents an extensive range of ongoing emission control technology development. Whether for PM or NOx control, the ingenuity shown by industry to develop better technologies or further enhance existing emission control solutions for diesel engines is impressive. Yet, it is not this impressive progress that provides us with continued confidence that 2007 products will be developed on time, but rather the fact that manufacturers can say with confidence that they have technological solutions that can be brought to market through their rigorous product development programs. Based on our careful review of both the detailed confidential information shared with the Agency during this review and the broader public information summarized in this report, we can conclude:

- Engine manufacturers are on track for 2007 implementation.
- CDPFs will be used by all manufacturers for PM control.
- Generally, manufacturers will treat the NOx standards as a two-step process.
- All manufacturers can comply in 2007 with existing proven technologies.
- NOx control should not adversely affect fuel consumption and improvement may be possible over today's engines.
- Engine manufacturers will provide prototype vehicles in 2005 for early customer fleet testing consistent with their product development plans.
- Engine manufacturers’ 2007 compliance plans are a building block for the technology package they plan to use to meet the 0.20 g/bhp-hr NOx standard in 2010.

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I. Introduction

A. 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.[1] 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 more than 16 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 for NOx 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 to 15 parts per million (ppm), by June 2006.

1. Heavy-Duty 2007 Engine 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 1, below.

		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%

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

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)). These provisions allow a manufacturer to split an engine 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, 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.[a,b] This corresponds to a roughly 50 percent NOx reduction 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 allows a two-step NOx standard with an intermediate standard of 1.2 g/bhp-hr

[a] 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.

[b] 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)).

beginning in 2007 that requires approximately a 50 percent reduction in NOx emissions. Full compliance with the 0.2 g/bhp-hr NOx standard is then not required until 2010. This gives manufacturers substantially more flexibility in developing new technologies.

2. Technology Status at the Time of the Rule

As part of the final rulemaking package we completed 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 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 address 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. EPA's first progress review report documented our findings regarding industry's progress regarding these issues. Similarly, this report follows the same issues and the continued developments by industry to overcome these challenges.

The RIA identified some specific steps that we thought industry would take in order to commercialize the technology we believed most likely to be used to meet the NOx standard, the NOx adsorber catalyst. These steps, laid out in detail in Chapter III of the RIA, included:

- Improvements to broaden the temperature range over which the NOx 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 (NOx regeneration, packaging, fuel economy)

We have focused on the need to make progress on these issues in conducting our reviews of NOx adsorber 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. However, as discussed in detail throughout the report, the NOx adsorber technology is only one of several possible solutions which may be applied by industry to comply with the 2007 program. In fact, most manufacturers have indicated that they will not use NOx adsorber catalysts prior to 2010.[2,3]

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).[c] Specific improvements in CDPFs include:

- Improvements in PM filter regeneration (oxidation and removal of stored soot)
- Improvements in ash handling (increased 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), a number of highway heavy-duty diesel engine manufacturers are already selling engines with CDPFs that are in compliance with both the HC and PM standards for 2007.

The RIA provided a shorter analysis of the potential for future improvements in engine-out emissions. It noted that further relatively modest emission reductions beyond the levels required by the emission standards for 2004 may be possible, but that the significant reductions in NOx and PM sought in the 2007 rulemaking would not be possible. While we continue to think that catalyst based emission control technologies represent the most likely path for reaching the final NOx and PM emission levels in 2010, we now also believe, 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. Specifically, it is now becoming clear that the NOx emission control technologies being applied to meet the 2.5 g/bhp-hr NOx+NMHC standard for 2004 can be further improved to allow compliance with the NOx averaging level of 1.2 g/bhp-hr in 2007. As discussed later, a number of manufacturers have publicly indicated that they intend to follow such an evolutionary approach to 2007 (i.e., to introduce an engine in 2007 whose NOx control technology is very similar to the product they will have sold in 2006).[4,5,6]

Although the RIA did not include a detailed analysis of the urea selective catalytic reduction (SCR) technology, it did detail the reasons why we chose not to base the emission standards for 2007 on the use of urea SCR. The two reasons described in the 2007 RIA were: 1) the lack of a national infrastructure to supply urea at diesel retail stations; and 2) the lack of a mechanism to ensure that urea is added in use. Those same reasons continue to be a concern for the Agency should a manufacturer choose to use the technology to comply with the 2007 standards. In spite of these concerns, the Agency has always viewed the emission standards as technology neutral and has been open to the use of urea SCR as part of a compliance strategy provided that the certifying entity (e.g., an engine manufacturer) could demonstrate that our concerns regarding infrastructure and end-user compliance can be resolved. In the last year, some engine manufacturers have indicated to the Agency an interest in possibly using urea SCR

[c] Generally, we have referred to diesel particulate filter systems that rely on catalysts to promote passive regeneration as catalyzed diesel particulate filters (CDPFs). Using the CDPF designation, we have not distinguished between systems with upfront oxidation catalysts, systems with the catalytic coating directly applied to the filter, or systems that combine both strategies.

to comply with the 2007 emission standards. We have met with manufacturers to understand how they would propose to solve our concerns and have encouraged any manufacturer interested in pursuing such an approach to provide the Agency with a plan that can be shared as part of a public process to allow all stakeholders an opportunity to judge the ability of the plan to address EPA's concerns.

As this section summarizes and the remainder of the report details, progress to meet the 2007 emission standards has not only been significant in the areas that EPA predicted in the 2007 RIA but also in a number of unanticipated areas including engine-out NOx control. We consider these developments to be a normal part of the process to meet new emission standards and are pleased that manufacturers have confidence in a number of technology paths to compliance in 2007.

B. 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 HD 2007 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.

1. Biennial Progress Reviews

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):

> *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.*

This report is the second in the series of progress reviews that the Agency has committed to undertake. The first progress review was released in June 2002 (EPA420-R-02-016) and is available our website at http://www.epa.gov/air/caaac/dieselreview.pdf. As with our first report, this report includes information regarding not only the NOx adsorber catalyst but more broadly, the progress by industry regarding a range of technologies which may be used to comply with the

HD 2007 emission regulations. Reflecting this wider scope, the rate of progress to develop technologies, and the implementation timelines of industry, the timing of this report is significantly earlier than the December, 31 2004 date set for the second report in the HD 2007 preamble. The timing of subsequent reports may similarly be adjusted to reflect the need to report out on progress by industry to develop technologies for compliance with the HD 2007 regulations.

2. Implementation Workshops

As with previous EPA regulations, we have organized, with interested stakeholders, implementation workshops designed to identify and address implementation issues related to the HD 2007 regulations. EPA workshops are not designed to revisit rulemaking decisions nor are they duplicative of the technical progress review process, but rather they are designed to address technical implementation issues. For example, an implementation workshop can serve as a forum to discuss best practices for PM filter maintenance and the role of EPA maintenance regulations in helping to define these best practices. By bringing a wide range of informed stakeholders including truck, engine and technology manufacturers together with end-users, the workshops serve to foster better understanding and a smooth implementation of the program.

The first of EPA's HD 2007 workshops, the Clean Diesel Fuel Implementation Workshop, was held on November 20-21, 2002 in Houston, Texas. The workshop was jointly sponsored by EPA and several diesel fuel industry associations. This workshop was focused on fuel-related implementation issues such as record keeping and reporting requirements as well as challenges associated with diesel fuel refining, distribution, storage, and marketing. Information regarding this workshop including the presentation materials from the various stakeholder presentations can be found at http://www.epa.gov/otaq/diesel.htm#fuelworkshops.

EPA, along with a number of co-sponsors including the Engine Manufacturers Association (EMA), the American Trucking Associations (ATA), the Truck Manufacturers Association (TMA), the Truck Renting and Leasing Association (TRALA), the Manufacturers of Emission Controls Association (MECA) and the California Air Resources Board (CARB), held a engine and truck focused implementation workshop on August 6-7, 2003 in Chicago, Illinois. As with the Clean Diesel Fuel Implementation Workshop, the purpose of the engine implementation workshop was to facilitate the exchange of information among EPA, the regulated industry (e.g., engine manufacturers) and other parties (e.g., truck manufacturers and truck users), and for EPA to provide clarification and additional guidance on implementation-related issues as appropriate. A significant portion of the time for the workshop was devoted to question and answer sessions between the attending audience and the expert panels assembled for the workshop. For those questions which went unanswered at the workshop for reasons of time or otherwise, EPA prepared a question and answer document which is posted on our website at www.epa.gov/otaq/diesel.htm#engineworkshops. Presentation materials from the Clean Diesel Engine Workshop can also be found on that same webpage.

We are committed to working with all stakeholders to ensure that the HD 2007 emission program is implemented as smoothly as possible, and we will continue to hold public workshops related to the implementation of the 2007 highway diesel program as appropriate.

3. Fuel Precompliance Reports

In the HD 2007 regulations, we developed a pre-compliance reporting program for the 15 ppm sulfur fuel program. Any refiner or importer planning to produce or import highway diesel fuel in 2006-10, is required to submit to EPA pre-compliance reports. These reports are due annually from June 2003 through 2005. They must contain estimates of the volumes of 15 parts-per-million (ppm) sulfur highway diesel fuel and 500 ppm sulfur diesel fuel that will be produced at each refinery or imported by each importer from June 2006 through May 2010. For those refineries planning to participate in the credit trading program, the reports must contain a projection of how many credits will be generated or used by each refinery. The pre-compliance reports must also contain information outlining each refinery's timeline for compliance with the 15 ppm sulfur standard and provide 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.

Last summer, we received pre-compliance reports and/or information for all refineries that produced highway diesel fuel in the year 2000. In addition to the reports that we received from current highway diesel fuel producers, we received reports from six refineries that did not produce highway diesel fuel in 2000 but indicated that they would shift into the highway diesel fuel market beginning in 2006.

We recognize that the 2003 highway diesel fuel pre-compliance reports reflect preliminary information as most refineries were still in the planning stage when the reports were submitted. Our conclusions from these reports are based on this preliminary information. Future reports that we release (i.e., our Summary and Analysis of the Pre-Compliance Reports for 2004 and 2005) will be based on the pre-compliance reports that are submitted in 2004 and 2005 and will therefore reflect new or updated information relative to the information that we received in 2003.

In general, the reports for 2003 indicate that 1) the industry is on target for complying with the 15 ppm sulfur standard on time, 2) highway diesel fuel production will be sufficient to meet demand, and 3) 15 ppm sulfur diesel fuel will be widely available nationwide.

Industry is On Target to Comply with the 15 ppm Sulfur Standard On Time

While the reported information is preliminary, the results provide the clearest snapshot of the highway diesel fuel market available at the present time. They represent the assessment of those who have first hand knowledge of the unique situation faced by each refinery. Furthermore, consistent with the expectations in the highway diesel fuel final rule[7] and EPA's 2002 Highway Diesel Progress Review,[8] most companies were in the planning stage at the time that the pre-compliance reports were submitted. The reports also indicate that the compliance flexibility provisions (small refiner options, GPA option, general hardship provision) in the final rule will be used.

Highway Diesel Fuel Production Will Be Sufficient to Meet Demand

According to the submitted pre-compliance reports, highway diesel fuel production will be sufficient in 2006 and beyond as refiners' plans are consistent with projected growth in highway diesel fuel consumption. The pre-compliance reports project 2.9 million bbls/day (bbls/day) of highway diesel fuel production for 2006. In comparison, the highway diesel final rule projected a highway diesel fuel consumption of 2.6 million bbls/day for 2006, based on the Energy Information Administrations (EIA) Annual Energy Outlook (AEO) 2000. Projected highway diesel fuel consumption using EIA's AEO 2003 is around three million bbls/day. Based on this information, we conclude that refiners appear to be planning for the increased growth projected for the future. On a Petroleum Administrative Defense District (PADD) basis, increased production is projected in PADDs 2, 3, and 5, while slight decreases are projected in PADDs 1 and 4. The decreases in PADDS 1 and 4 are dwarfed by the gains in PADDs 2, 3, and 5, and should be easy to offset through inter-PADD diesel fuel shipments.

15 ppm Sulfur Highway Diesel Fuel Will Be Available Nationwide

Finally, the industry submitted pre-compliance reports show that 15 ppm sulfur highway diesel fuel will be widely available. On a volume basis, 96 percent of highway diesel fuel produced in 2006 is projected to meet the 15 ppm sulfur standard. On a refinery basis, over 90 percent of refineries/importers have stated that they plan to produce at least some 15 ppm diesel fuel. Given that the majority of highway diesel fuel is expected to meet the 15 ppm sulfur standard, a large credit volume is also expected. This will help to accommodate off-spec material and will also provide a supply "safety valve" by allowing refiners to produce additional 500 ppm highway diesel fuel, should this be necessary, without violating the program requirements.

4. Clean Fuels Corridor

The Agency is working with a number of interested stakeholders including engine manufacturers, trucking companies, and refiners to facilitate the early introduction of 15 ppm sulfur highway diesel fuel for existing fleets who wish to use it (e.g., EPA's Smartway program partners or diesel retrofit technology users). In 2005, the availability of 15 ppm sulfur diesel fuel could also serve to facilitate customer fleet testing of prototype 2007 compliant heavy-duty engines. Under this project, participants will designate geographic areas of the country ("corridors") where 15 ppm sulfur diesel fuel will be available for participating fleets. To meet the needs of the 2007 prototype test fleets, the focus would be on long-haul trucks operating on interstate highways, where application extremes are represented (e.g., temperature, humidity, speed/load, altitude, etc.). Based on our early discussions with stakeholders, we are confident the early introduction of 15 ppm fuel will be achieved.

5. Other EPA Activities Related to Heavy-Duty Diesel Engines

The Agency is continuing to work with the regulated industry and other stakeholders on two issues targeted to help ensure that the emission benefits from the 2007 program are realized in-use for the life of the vehicle. These programs, one regarding manufacturer led in-use testing, and another addressing on-board diagnostic system requirements, will be implemented through the rulemaking process over the next year and a half. Together, these programs will provide a firm basis for assuring to the public and to the industry the 2007 program benefits. We are committed to working through these programs and the rulemaking process in a way that complements the 2007 implementation program. It is our goal that these programs augment and not detract from the 2007 program.

Heavy-Duty In-Use Test Program

The Agency has issued a number of rules regarding Not-To-Exceed (NTE) emission standards for diesel powered vehicles and equipment since 1999. The Engine Manufacturers Association (EMA) and some individual manufacturers challenged parts of these rules regarding legal authority and technical feasibility. In May 2003, EPA, the California Air Resources Board (CARB), and EMA, along with its member companies, reached an agreement that will end these lawsuits. The settlement agreement calls for the creation of a manufacturer-run, in-use emissions testing program for heavy-duty diesel trucks. The in-use testing program will measure exhaust emissions from these diesel engines using portable onboard emission measurement systems. A pilot program will be conducted in 2005 and 2006. A fully enforceable program will begin in 2007. The Agency will propose the detailed regulatory provisions for this program by May 2004. As part of the agreement, EPA will also issue guidance documents that will provide engine manufacturers additional certainties and details of the requirements they must meet in testing and certifying their engines. This cooperative effort represents a significant advance in helping to ensure that the benefits of more stringent emission standards are realized under real-world driving conditions.

On-Board Diagnostics

In October of 2000, we published a final rule requiring on-board diagnostic (OBD) systems on heavy-duty vehicles and engines up to 14,000 pounds GVWR. (65 FR 59896) In that rule, we expressed our intention to develop OBD requirements for >14,000 pound vehicles and engines in a future rule. We expressed this same intention in our 2007 heavy-duty highway final rule. (66 FR 5002)

EPA is in the process of following through on our previous commitments regarding the application of OBD requirements for the entire HD highway engine industry by developing a new proposal which would apply OBD requirements for >14,000 pound highway vehicles and engines. We intend to publish a proposal by the end of this year, and a final rule is targeted for the end of 2005. This effort will also propose new availability requirements for emission-related service information that will make this information more widely available to the industry servicing >14,000 pound vehicles. We will continue to work closely with California, the engine and truck manufacturers, as well as other stakeholders as we develop the federal OBD program for > 14,000 pound vehicles.

C. The Engine Technology 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 detail our ongoing progress review process, and what we have learned from that process.

1. Company Visits

We have continued the progress review process over the last year-and-a-half since our last report, 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 have again visited technical research centers and met with engineers and senior executives from almost thirty companies and received comprehensive high level briefings on technical progress and business plans to comply with the HD 2007 emission standards.[d] These visits included tours of research and development facilities and of 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 experts to describe, based on each company's experience, the current state of the NOx adsorber, CDPF, and other emission control technology development. We also asked the companies to review with us their plans and projections 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

[d] Appendix B includes a list of the companies and organizations that we met with in conducting this second progress review.

manufacturing that would be needed in order to bring the technologies to market by 2007. In composite then, we could evaluate with first-hand data 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 detailed first-hand information shared during these meetings provides the primary basis for our conclusions regarding progress by industry. Much of the information shared with EPA by industry has been designated as Confidential Business Information (CBI) and as such can 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 NOx 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.

The EPA team has continued its work since the completion of the rulemaking process and is advancing the state-of-the-art in emission control technologies. Since the rulemaking, the diesel team has published five technical papers documenting its work.[9,10,11,12,13] The experience gained by EPA staff engineers and scientists working on that team and the novel data gathered by the team help to inform our view of the current state-of-the-art of the NOx adsorber catalyst and the CDPF.

3. Department of Energy (DOE) Research Programs

The Department of Energy (DOE) along with a number of industry partners began a joint research study 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 results from that study, documented in five technical reports, played an important role in informing the Agency during the HD 2007 rulemaking.[14] 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, began a new research activity entitled the Advanced Petroleum Based Fuels - Diesel Emission Control (APBF-DEC) program.

Within APBF-DEC, five projects are being conducted to determine how systems of advanced fuels, lubricants, engines, and emission control systems can be integrated to significantly reduce vehicle emissions without compromise to fuel economy. Three of the projects are focused on NOx adsorber catalyst and CDPF based emission control systems integrated with a diesel passenger car, a sport utility vehicle/light-truck, and a heavy-duty engine. In addition to the NOx adsorber catalyst studies, a fourth project is evaluating the impact of fuel sulfur on performance of a urea selective catalytic reduction (SCR) and CDPF system on a heavy-duty engine including 6,000 hour aging studies on two different systems. A fifth project is examining how lubricants impact engine-out emissions as well as NOx adsorber catalyst performance. Since our last report, the APBF-DEC projects have advanced beyond preliminary system development, and performance and aging results are becoming available. The latest results from the APBF-DEC study including results from a heavy-duty diesel engine equipped with a NOx adsorber catalyst are summarized later in this report.

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. The DOE programs, similar to the industry solutions for 2007, cover a wide range of technology choices evolving to meet the 2007 emission standards. The results from the programs show that industry will not be constrained to the use of a single technology to comply with the 2007 NOx standard, but will have a number of viable technology paths.

4. Summary

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.

II. The Engine System Development Process

As we visited with each of the major engine manufacturers during this progress review, one significant difference from our previous review became clear. Manufacturers were moving from broad research efforts into detailed product development programs for the 2007 model year. During our previous review, engine and technology manufacturers shared with us the results of their varied research programs but in only limited cases (e.g. PM filters) did they discuss new product development programs. In essence, the previous report documented the work by industry to develop potential emissions solutions from which they could choose to develop a new product. During our more recent meetings, manufacturers discussed their detailed product development plans to bring specific solutions to market. The specificity and certainty of the plans they shared with the Agency during our meetings was a direct expression of this change.

This section will briefly describe the general process that heavy-duty diesel engine manufacturers use to design, build, and bring a new product to market, their new product introduction process. It will describe the steps in the process and the decisions that the manufacturers must make before proceeding to the next step. Finally, we will summarize the current status of manufacturers in this process for 2007 and what that means for 2007 product introductions.

A. The New Product Introduction Process

All of the diesel engine manufacturers follow similar new product introduction (i.e., product development) processes defined by a sequence of milestone gateways timed to pre-production prototype engine builds. The processes are designed to manage the product development process and to ensure that any number of potential issues, including cost, performance, or quality, are addressed during the development process prior to production. The milestone gateways consist of high level engineering and business reviews including measuring progress against specific metrics. Each manufacturer has its own nomenclature and specific guidelines for this process. For illustrative purposes, we will describe generically the steps in the process and will use the terms “A”, “B”, “C”, “D”, and “E” reviews to designate the steps in the process. Individual companies may have fewer or additional development gateways, but in general, the process we will describe here is representative of the industry as a whole.

The first step in the product development process, in our example the “A” review, occurs prior to the manufacture of product intent prototypes, although system prototypes may have been developed as part of product preceding research (i.e., in research programs designed to develop the data necessary to begin product development). As such, the first review is a paper study which includes a virtual engine build based on the data from research programs, the product development plan and business plan for the new product to be introduced. Although the new engine product may only exist on paper, it is quite real in the sense that it fully defines the product to be introduced. A complete build list of parts will have been created listing all of the parts which will go into producing the new engine. This parts list will include both carry-over parts from existing products and new parts which will be produced for the first time in this new product. The build list will be based on technologies which the company has determined from its research programs will deliver the emissions and other performance characteristics required of the new product.

For the "A" level review, a business plan will have been developed for the new product that includes a target manufacturing cost, a target sales price, an estimate of sales volumes for the product and from this information an analysis of the potential for the new product to return a profit for the company. An estimate of the new product cost is made from the engine part build list based on existing part costs and estimates of new part costs including estimates made based on firm price quotes from potential parts suppliers. In the end, all of the data and analysis developed in order to clear this gateway can be summarized into two lists. The first is a list defined in the business plan describing target characteristics (metrics) for the new engine intended to satisfy customer expectations. This list includes metrics for customer expectations on engine performance, acceptable costs, reliability, durability and emissions. Similarly the list includes metrics describing the company's expectations for return on an investment to bring a new product to market. Against these metrics, a second list of expected engine characteristics based on the virtual engine build, will be compared.

At the "A" level review, the virtual engine must satisfy the performance metrics defined in the business plan in order for the development process to proceed to the next step. Thus completing the "A" level review means that a company has defined completely the product it intends to produce, the expected performance for that product and the business case for producing the new product. At each subsequent step in the process the performance characteristics and data developed through that step will be compared against the same metrics developed to complete this first "A" level review.

Subsequent reviews occur approximately every six months to nine months based on schedules for prototype engine builds and tests. In the interval between the "A" level and "B" level review the first production prototype engines are built. These prototypes are built to the design approved in step "A" but using individually fabricated parts, not production processes or production suppliers. The engines built in this step are inherently very expensive as they are essentially unique assemblies requiring substantial labor and machining costs. Manufacturers only build a limited number of these engines and use them primarily to confirm performance, and to begin reliability and durability confirmatory testing. As these engines are not based on manufactured parts, the reliability and durability data are limited. Testing at this point reveals inherent design flaws or limitations. The "B" level review then consists of comparing the performance and design characteristics of these prototype engines against the metrics developed at the beginning of the process. Design flaws are uncovered and corrected. Changes in design or characteristics are continually tracked regarding their impact against the metrics for performance and cost.

Between the “B” and “C” level reviews, additional prototype engines are built. These engines differ from the previous prototypes incorporating design improvements and including parts from the selected production suppliers. Although the parts are supplied by the production intent supplier, in general they are not yet production parts and are not produced in production processes. Thus these prototype engines remain expensive to build. A somewhat larger volume of prototypes are built and for the first time a few samples are shared with truck manufacturers for chassis installation to confirm fit and design. As with the previous prototype step, these engines are tested thoroughly, some in laboratory test facilities and some in engine manufacturer owned vehicles. Design issues are identified and design changes are made. As you would expect, the number and significance of the design changes are less than in the previous step. The “C” level review then consists of confirming the characteristics of the prototypes against the original metrics.

Between the “C” and “D” level reviews, a significant number of prototype engines are built. These are the first prototypes built using the planned production processes and parts. They are not built using the actual production tooling, but are built using the planned manufacturing processes. Thus while these engines are very similar (virtually identical) to production parts in design and process, they remain expensive to build because of their low volumes and lack of production machine tooling. In addition to extensive in-house testing to confirm the reliability and durability of these engines, a limited number are for the first time provided to selected customer fleets for testing. The testing allows the engine manufacturers to confirm that the performance and reliability shown in the test cell is realized also in the real world. As with each previous step, design issues are identified and incorporated. The “D” level review confirms that the prototype engine characteristics match metrics required of the engine. After successfully clearing the metrics at the “D” level review, production tooling is confirmed and ordered.

Between the “D” and “E” level reviews, the last prototype engines are built. These engines will be essentially identical to the final production parts. They are built using production tooling and production processes. The only difference between these engines and the final production products will be the final assembly process. Although these engines are assembled using the same processes as the final assembly, they may not be actually assembled on the production assembly line. The largest number of prototypes so far are produced at this level. They are supplied in greater, although still limited, quantities to the truck manufacturers and a limited number of customer fleets for final confirmatory testing. If the production tooling or other aspect of the production process are going to cause a reliability problem, it can be found in these prototypes and still corrected prior to full production. The “E” level review then, based on what are in essence production engines, serves as the final gateway prior to limited and finally full production of the new products.

By going through this step-by-step process with rigid review schedules that require confirmation that the new product is meeting expectations, the companies assure that the product they bring to market will meet customer expectations and corporate business plans. Without such a process, it is possible for shortcomings in design or cost to remain unaddressed until after a product is brought into production. The product development process is specifically designed to ensure that this does not happen.

B. Status of New Product Introduction Plans

As was discussed in the introduction, our previous progress review focused almost entirely on the progress to develop new technologies but not new products. That is, the data shared with EPA by the companies was from research engines and test beds intended to test concepts. From this data, we could measure the progress to improve technologies and to understand industry's efforts learn how to best use these technologies. Significantly in this progress review, manufacturers, while continuing their important research efforts, have now begun their formal product development processes.

At the time of our formal detailed progress review meetings, the engine manufactures that we met with were all working to complete the analyses necessary to proceed through their "A" level reviews. The information they shared with the Agency was based on those analyses and their expectations for 2007. Our conclusions regarding details of technology development and engine manufacturer readiness are thus based on the same data that engine manufacturers have used to make their decisions for 2007. Subsequent to our meetings, most of the companies have completed their "A" level reviews and can say with some significant certainty to the Agency their expectations for product performance, cost and quality in 2007. Those that have not completed this step have indicated to the Agency that they will in the coming weeks. By definition and actual statements to the Agency, this means that the manufacturers have determined that these characteristics will be satisfactorily met with their 2007 products. This is not to say that manufacturers do not have concerns regarding cost or performance of technologies that they will implement. Nor does it mean that every technical issues has already been solved. Any change in cost or any application of new technology is always an appropriate concern for a manufacture in any industry. Completing the "A" level reviews says strongly though that manufacturers can conclude with confidence that the issues they have identified will be satisfactorily addressed in their development process. Moving forward from this point, complying in 2007 is no longer an abstract discussion of possible technology choices but real products following a specific process to reach production in 2007.

C. The Technology Choices for 2007

Section III of this report will describe in some detail the progress being made by industry to develop new technologies which may be applied as part of an emission solution. In this section here, we will summarize briefly what is known about the choices that industry is making with regard to these technologies as evidenced by their public statements. Additional detailed information regarding technology choices have been shared with the Agency in the course of this progress review and in the normal course of industry consultation with the Agency regarding compliance and certification plans. Such detailed information shared by companies with the Agency is inherently confidential, and having been designated so by the companies, can not be repeated here. Yet, we can say that the more public information made through press releases and in various industry settings gives an appropriately accurate representation of the situation and will be summarized here.

1. PM Filters Will Be Universally Used in 2007

Consistent with EPA's expectations for the HD 2007 program, all engine manufacturers have indicated that they will use catalyzed diesel particulate filter (CDPF) systems for compliance with the HD 2007 PM standard. Although each manufacturer may implement somewhat unique solutions for their own CDPF technology, common attributes will include a means to ensure CDPF regeneration under all driving conditions. This will include some form of active backup regeneration whereby a means for supplemental heat addition is realized to promote soot oxidation and guarantee filter regeneration. As discussed in section III, there continues to be significant development efforts to better optimize this technology to improve robustness and minimize operating costs.

2. Manufacturers Will Use ABT to Make a Two-Step NOx Program

In developing the HD 2007 emission program, we recognized that the NOx emission standard would be very challenging and that a compliance program with flexibilities to allow manufacturers to manage the introduction of new technologies would be desirable. Therefore, the program was constructed with a 50% NOx phase-in schedule and with provisions for averaging, banking and trading. We assumed that the resulting provisions could allow an engine manufacturer to either focus its development efforts on only a fraction of its product range, applying technology that was more than 90 percent effective, or alternatively to more broadly apply new technology that was initially only approximately 50 percent effective. Of course, the program is not limited to these two options, but in fact, a wide range of options are available to the manufacturer depending on the technology and product mix most desirable for the individual manufacturer.

Based on the decisions made for the "A" level reviews described previously, it is now clear that engine manufacturers will generally treat the HD 2007 NOx emission standard as a two-step emission standard with a first initial reduction in NOx to approximately 1.2 g/bhp-hr in 2007 and then a second step to 0.2 g/bhp-hr in 2010. While this is generally the case, we should be clear that manufacturers may choose any number of alternate compliance paths for specific portions of their product range in 2007. Further, although it appears clear this will not be the choice for the industry in general, we continue to believe that it would be possible for manufacturers to meet the 0.2 g/bhp-hr for a fraction of their total production in 2007 as projected in our HD 2007 RIA.

Figure 1 below summarizes the common understanding of many in the industry regarding the technology options to be used for the largest heavy-duty engines in 2007. The figure is from a presentation by a single manufacturer at a recent DOE conference, but is representative of a broader understanding for much of the industry. The figure shows three technology choices which could be used for compliance with the 0.2 g/bhp-hr emission standard. The three paths, all assume that the standard need not be fully met prior to 2010, and thus a progressive introduction of technology is assumed. For 2007, two possible solutions are shown both based on the evolution of NOx control technologies which are or will be in production prior to 2007. The first NOx technology path shown in blue assumes that the 1.2 g/bhp-hr average NOx standard could be met through the application of a urea SCR catalyst system along with a CDPF for compliance with the PM standard. This technology path for NOx is substantially similar to the commonly understood path for meeting the EURO IV standard for NOx in 2005.

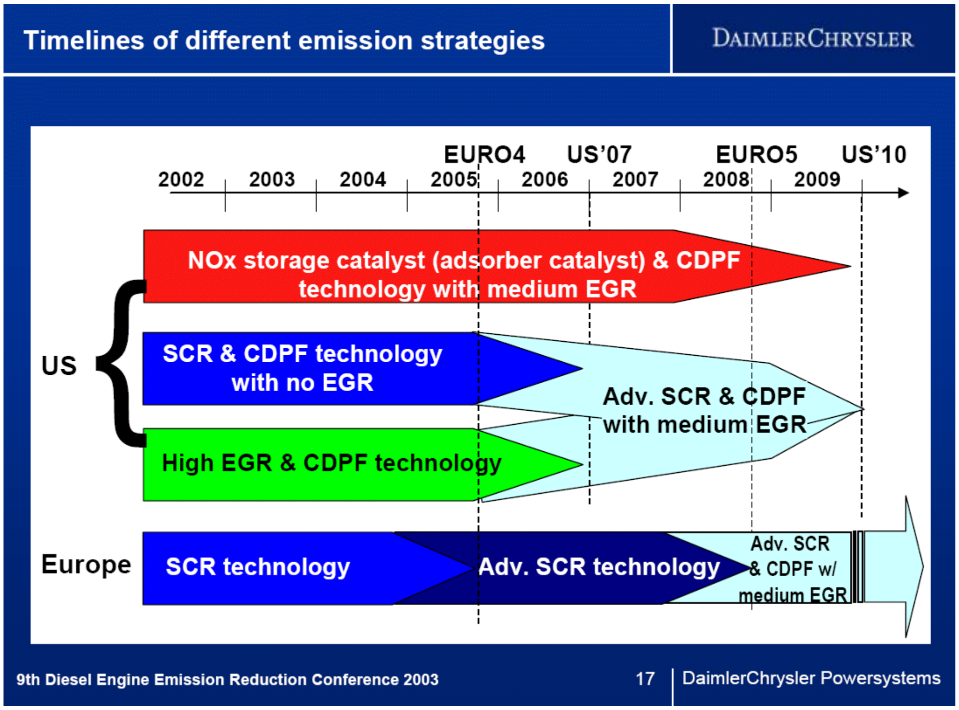

Figure 1. Technology Pathways for 2007 and 2010.

The second NOx technology path shown for 2007 in green is based on the use of high flow cooled exhaust gas recirculation (EGR), or more generically, engine-out NOx control to meet the 1.2 g/bhp-hr averaging standard. This approach is based on a further enhancement to the cooled EGR technology which has been used broadly for compliance with EPA's 2004 emission standards. According to one engine manufacturer, the changes to their current product to meet this lower NOx level amounts to fine-tuning their existing cooled EGR system. As a result, such an approach is considered to be a reliable and sure means to show compliance in 2007. Similarly, Caterpillar has stated that its ACERT™ technology will form the basis for a non-SCR based 2007 emission strategy. Like the SCR approach, the engine-out NOx approaches will also require the use of the CDPF technology to comply with the PM standard.

Significantly, the two approaches shown in the figure as possible for use in 2007 are based on further enhancements to existing technology solutions. The third path, that for the NOx adsorber technology, is assumed not be implemented prior to 2010 likely at least in part due to the lack of existing heavy heavy-duty systems using this technology prior to 2007. We continue to believe, based on the detailed information shared with Agency during this review, that the NOx adsorber technology could be applied successfully in 2007. As shown later in this report, Toyota has already introduced a light heavy-duty diesel truck in Japan using the NOx adsorber technology with NOx and PM emissions below the levels necessary to comply in 2007. We see no reason why such an approach could not be used in the U.S. in 2007. Given the time for further development between now and 2007, we remain convinced that such a system could even meet the final 0.20 g/bhp-hr NOx emission standard.

One engine manufacturer has indicated that on a limited basis it may consider introducing a 2010 compliant heavy-duty engine in 2007. This manufacturer has indicated that most of its products will comply with the 1.2 g/bhp-hr averaging level in 2007 using an enhanced version of its current 2004 cooled EGR technology. However for limited applications, the manufacturer has shown the potential to introduce an enhanced EGR technology with urea SCR to meet the 0.20 g/bhp-hr standard. The concept would be to sell the vehicle into limited captive fleet applications where the manufacturer believes the urea infrastructure issues could be addressed by 2007. The manufacturer suggests that such a fully compliant system could be especially desirable for fleets operating in specific geographic areas with particular air quality issues, perhaps with incentives from local governments for its purchase (not dissimilar from the current practice for some natural gas products).[15]

Figure 1 makes clear the manufacturers' intent to follow a smooth and gradual technology path for their 2007 products which can be further evolved for compliance in 2010. This approach provides manufacturers with several more years for research into enhanced NOx control technologies prior to the beginning of formal product development for 2010. The gradual introduction process with a first step in 2007 and a second step in 2010 has been embraced by manufacturers to allow for the continued development of existing technologies concurrent with research into new technologies. In this way manufacturers can have assurance that the products they will introduce have been well tested and proven prior to their market introduction.

3. Early Fleet Testing of New Engines and Trucks

Some in the trucking industry have made the case that they would like to test the new engines in real world conditions for more than one year prior to their formal product introductions in 2007. The engine and truck manufacturers would like to address the trucking industry's concerns, and therefore, have been working to align their normal developmental fleet testing, described in the product development section previously, as a mechanism for informing their customers regarding the new products. To that end, the engine manufacturers have made very public statements regarding their intent to have an early introduction of some trucks in 2005 to provide approximately one and a half years of real world test experience for some customer fleets. The fact that manufacturers are able to align their product development programs to engage in such early fleet testing is indicative of their growing confidence for 2007 and their commitment that the program be smoothly implemented.

D. Conclusions

Our previous HD 2007 progress review did not discuss the new product development and introduction process used by heavy-duty diesel engine manufacturers. The report focused almost entirely on the status of technology progress in pre-product development research laboratories reflecting the work being done at that time by engine manufacturers and technology companies. Significantly, this report discusses in some detail the new product development process used by manufacturers and the fact that manufacturers have now formally entered into their new product introduction processes. Having completed their "A" level gateway reviews we can conclude the following regarding the product introduction expectations for 2007:

- Engine manufacturers are on track for 2007 implementation.

- CDPFs will be used by all manufacturers for PM control.

- Generally, manufacturers will treat the NOx standard as a two-step process.

- In 2007, manufacturers will generally meet a 1.2 g/bhp-hr NOx emission level.

- NOx control for 2007 will be based on incremental changes to well proven existing NOx control technologies.

- The cost and expected performance for the new products is consistent with the business plans of the heavy-duty engine manufacturers.

- Engine manufacturers will provide prototype vehicles in 2005 for early customer fleet testing consistent with their product development plans.

- Engine manufacturers' 2007 compliance plans are a building block for the technology package they plan to use to meet the 0.2 g/bhp-hr NOx standard in 2010.

III. Diesel Engine Emission Technology Progress

This section is organized by emission control technology type. Each section will briefly discuss the emission control technology and the particular challenges remaining to be addressed. Particular emphasis is placed on the progress for diesel particulate matter (PM) filters and NOx adsorber catalysts as these are the technologies that we identified in the HD 2007 RIA as most likely to be used by industry to comply with the HD 2007 regulations. However, as discussed earlier in this report, significant progress has been made regarding a number of other emission control technologies, primarily for NOx, that are being considered for use for compliance with the HD 2007 regulations. Given these developments, we have included summaries of additional emission control technologies in this section.

We should note here that in general this section summarizes technology developments that have been made public in one forum or another over the last two years. While our overall impression of technology progress is influenced both by the technology developments shared with the Agency in confidence during our progress review and the more general information shared with the public in technical forums, as a practical matter we can only summarize information that is generally available. In some cases, companies or other organizations have allowed us to present information that has not been released previously and such information is noted where appropriate. We believe this section accurately summarizes the general trends in technology progress realized since our last progress review, but the reader should understand that the conclusions we are drawing regarding technology progress are not based solely on this information but are also based on the confidential information shared with the Agency during our progress review meetings.

A. 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. In section II of this report, we discussed the intent of all engine manufacturers to use this technology 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. More than 500,000 light-duty passenger cars in Europe now have diesel particulate filters. Yet, as we will summarize in the following section, the CDPF technology is continuing to improve in a number of important ways.

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.[e] 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 method of PM filter regeneration, called passive regeneration, is the primary means of soot oxidation that we projected industry would use in 2007.

Engine manufacturers and emission control developers have continued to improve both catalyst technologies used to promote PM filter regeneration and system designs to make the best use of these catalyst technologies. In addition, engine and emission control system designs are being developed which will provide the possibility for active PM filter regeneration. There are a number of approaches and technologies available to accomplish this, including microwave regeneration, fuel burners, electric heaters, exhaust restrictors and any number of other ways to episodically increase exhaust temperatures above a level for which rapid soot combustion can be assured. For 2007, a common method for active filter regeneration will be to inject supplemental (i.e., a quantity greater than needed for motive power) diesel fuel late in the combustion cycle or directly into the exhaust. This fuel will be oxidized across a diesel oxidation catalyst located in front of the PM filter. The oxidation process will increase the exhaust temperature entering the PM filter to a level sufficient to promote rapid soot oxidation within the PM filter. The duration of the supplemental fuel injection will in general last for several minutes. The regeneration event will be determined by the engine controller's estimate of the soot accumulation on the PM filter and could occur at intervals as frequently as every 5-10 hours or as infrequently as every 5-10 days. In some applications the active regeneration system may never engage because the filter will remain clean due to passive regeneration as described in the previous paragraph.

In this section we will briefly describe progress on two fronts, progress to improve passive regeneration systems and progress to develop and improve active regeneration systems. For 2007, we expect that all manufacturers will design systems intended to operate passively under most conditions but which include an active regeneration system to guarantee that PM filter regeneration will occur under all circumstances. We refer to such combined systems as

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[e] 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.

CDPFs with active backup regeneration. This description reflects the primary reliance of the catalyst in the CDPF to promote passive regeneration, but affords the availability of active regeneration as a backup to ensure regeneration.

It is desirable for passive filter regeneration to be the primary means for filter regeneration. Passively regenerated systems maintain a relatively low soot loading level which decreases exhaust flow restriction and thus improves fuel economy. Also, being passive, they have no moving parts and are highly reliable. Therefore, work has continued to improve CDPF technology to expand its effectiveness for passive filter regeneration. Figure 2 summarizes recent work by Mitsubishi to compare the effectiveness of various system configurations for passive filter regeneration as measured by PM oxidation rate.[16] The work compares PM oxidation rate for systems with an uncoated filter, an uncoated filter with an upfront oxidation catalyst, a catalytically coated filter, and a system that combines both an upfront oxidation catalyst and a catalytically coated filter.[f] The best performance as judged by the highest PM oxidation rate was demonstrated by the system combining an upfront oxidation catalyst with a CDPF. Comparing the other three systems, a number of things can be seen. Once exhaust temperatures reach 600˚C catalytic coatings only marginally increase PM oxidation rates whether applied on the filter or on an upfront oxidation catalyst. At the lower temperatures (200 and 300 ˚C) where NO to NO_2 oxidation can be very high, all of the catalytically coated systems showed similar performance. In the intermediate temperatures (300 to 500 ˚C) the systems containing a coated filter showed the best performance, presumably due to limited NO to NO_2 oxidation on the upfront catalysts (total NO_2 formation at these temperatures is limited by the chemical equilibrium between NO and NO_2).

[f] Generally, we have referred to diesel particulate filter systems that rely on catalysts to promote passive regeneration as catalyzed diesel particulate filters (CDPFs). Using the CDPF designation, we have not distinguished between systems with upfront oxidation catalysts, systems with the catalytic coating directly applied to the filter, or systems that combine both strategies.

Table 1 DPF System (Filter : Wall-Flow Type)

1	Filter Only	
2	Pre. Cat.+Filter	
3	Coated Filter	
4	Pre.Cat.+Coated Filter	

Table 2 Model Gas Components

NO	300ppm
O_2	10%
H_2O	6%
N_2 Balanced	

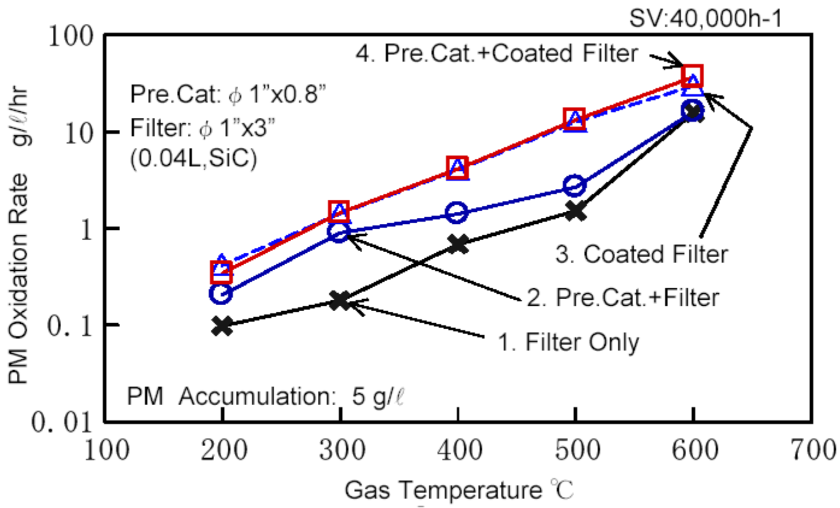

Figure 2. CDPF System Configuration Impact on Soot Regeneration.

Thus based on soot oxidation rates alone, one might assume that systems using coated diesel particulate filters will be the preferred solution for 2007. In practice however, a number of other considerations impact this choice. Since an upfront oxidation catalyst is an integral part of the most common solution for active backup systems, most manufacturers are likely to employ one, and thus an upfront oxidation catalyst will be part of the passive regeneration function as well. Also, ash cleaning may be somewhat easier for uncoated PM filters, although manufacturers are actively developing ash cleaning systems that can work well for both coated and uncoated filters. Having provided some level of catalytic activity with the upfront oxidation catalyst, the manufacturer must determine if the additional PM oxidation performance realized by also using a coated filter warrants the additional cost.

The decision to use a coated or uncoated filter for 2007 is one that can be made and changed throughout the design process as it does not necessarily change diesel particulate filter size or configuration. Catalyst manufacturers shared with us during our progress review that they are actively working to refine catalytic coatings to reflect the primary task for the coating in individual applications. For example, the coating for an upfront oxidation catalyst would first be optimized for its role in active PM filter regeneration to oxidize diesel fuel and thus to raise exhaust temperatures accepting some tradeoff in its effectiveness for NO oxidation. Conversely, catalytic coatings designed for application directly onto diesel particulate filters would be designed primarily to promote passive soot regeneration and thus be designed to promote NO and soot oxidation. Continuing progress to refine the catalyst coating technologies used in CDPF systems promises to improve overall system performance and reliability for 2007. Further, it is indicative of the clarity regarding system selections for 2007 (i.e., the intent to use CDPF systems with active backup technologies relying on an upfront oxidation catalyst).

Just as progress to improve passive PM filter regeneration has continued, there has been even greater activity to develop the best means for active PM filter regeneration to serve as a regeneration failsafe for 2007. Figure 3 below, shows results from one test program investigating the efficacy of air-to-fuel ratio control to raise exhaust temperatures and promote PM filter regeneration.[17] The figure shows two sets of histograms, one in blue summarizing exhaust temperatures for a typical diesel engine operated in stop and go traffic; and a second in red representing the exhaust temperatures for the same engine and driving cycle but after modifications to the engine to promote higher exhaust temperatures and soot regeneration.

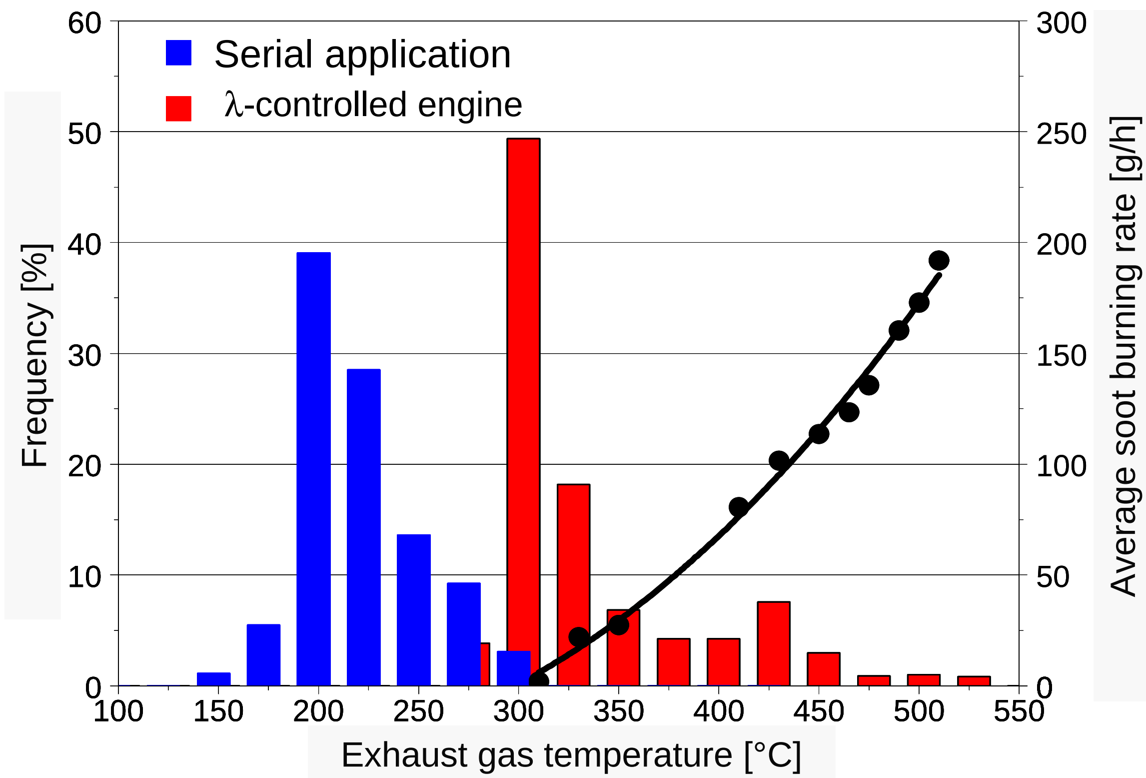

Figure 3. Modifying Engine Operation to Raise Exhaust Temperatures and Promote PM Filter Regeneration.

The histograms show the proportion of time (frequency) that exhaust temperatures were within the temperature band represented by the bars for each of the two engine configurations. Superimposed over the histograms is a graph showing soot oxidation rate as a function of exhaust temperature. From the graph it can be seen that in severe stop and go driving, exhaust temperatures may not exceed 300˚C and that soot regeneration rates will be very low. In fact, testing conducted as part of this test program showed that passive regeneration for this engine under these severe stop and go driving conditions was not sufficient to prevent soot accumulation over time.

From Figure 3, it can also be seen that increasing exhaust temperatures, in this case by throttling the intake to reduce the amount of air flowing through the engine, can raise exhaust temperatures even under stop and go driving conditions to a level consistent with rapid soot oxidation and safe filter regeneration. Test results from this program showed that by operating the engine for 30 minutes with reduced air flow, the soot loading level on the filter would be reduced by more than the amount accumulated over 4 hours of continuous stop and go driving under normal conditions. Comparing the fuel economy impact of throttling intake air (in this case approximately 7 percent) to the duty cycle necessary to maintain a clean filter (in this example 30 minutes in a period of more than 4 hours) results in an overall fuel economy penalty of less than one percent for active filter regeneration under difficult stop and go driving conditions.

The results summarized in Figure 3 represent but one example in a wide range of both publicly available and confidential work by manufacturers to develop systems for active PM filter regeneration to provide absolute assurance that PM filters will not plug under any operating condition.[18] These systems are expected for 2007 to be fully integrated into the engine's control system and to be totally unobtrusive to the vehicle operator. We believe the development of such failsafe systems represents significant progress for 2007 and ultimately an ideal robust solution for diesel PM control for both on-highway vehicles in 2007 and in the long term for nonroad diesel equipment as well.

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

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.

Inorganic solid particles present in diesel exhaust are 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_2 which can easily pass through the PM filter walls). Because these inorganic materials are 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.

EPA regulations for heavy-duty diesel engines set a minimum allowable maintenance interval for PM filter cleaning of 150,000 miles for diesel engines used in vehicles with gross vehicle weight greater than 14,000 pounds (for light heavy-duty engines the interval is 100,000 miles). This means that a manufacturer can not generally specify a PM filter maintenance interval shorter than EPA’s minimum of 150,000 (100,000) miles. Ultimately, engine manufacturers would like to design systems with much longer maintenance intervals in order to reduce the maintenance costs for PM filter systems. The simplest approach to extend the interval for PM filter regeneration is to increase the size of the PM filter. The resulting larger filter can hold more ash before requiring cleaning. Of course, such simplistic solutions come at the cost of higher weight and expense.

Diesel particulate filter developers have therefore been working to develop better filter designs capable of storing more ash (i.e., extending the ash service interval) without adversely impacting overall filter size and cost. Figure 4 below shows one such solution from Ibiden. The technology shown here, is a silicon carbide (extruded ceramic) diesel particulate filter designed with unique inlet and outlet channel geometry called, Oct-Square.

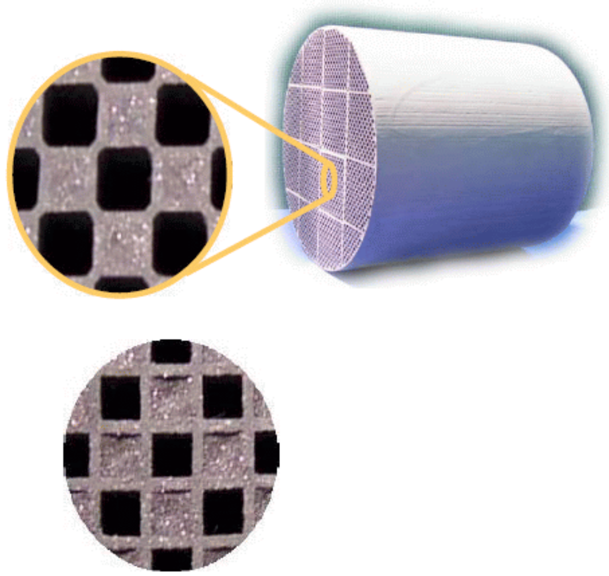

Figure 4. Ibiden Oct-Square PM Filter Technology.

The inlet channels, into which PM laden exhaust flows, are octagonal in shape and significantly larger in cross sectional area than the square outlet channels through which the clean exhaust exits the filter (the figure shows a blow-up of the Oct-Square geometry inlet with a conventional filter below for comparison). Since ash is deposited in the inlet channels, increasing the cross sectional area of the inlet channels increases the ash holding capacity of the PM filter. Thus the Oct-Square filter uses a clever geometric pattern that increases the inlet channel area and decreases the outlet channel area without changing the overall frontal area (size) of the PM filter. This approach increases ash storage capacity by approximately 50 percent and thus can extend ash service intervals by the same ratio. We are aware that other manufacturers of ceramic based wall-flow PM filters are working to develop similar solutions as well, although perhaps using different geometric relations from the Octagonal inlet / square outlet approach developed by Ibiden.

Just as clever geometric relations are being used to increase ash holding capacity, so too are new material options for PM filters. PM filter technologies based on sintered metal filters are being developed and marketed for both light-duty diesel vehicles (by Bosch) and heavy-duty diesel engines (by Purem). Sintered metal can be folded and welded into a number of different configurations in order to form a diesel particulate filter. Figure 5 below, shows an example of a sintered metal PM filter that Bosch is marketing for diesel engines.

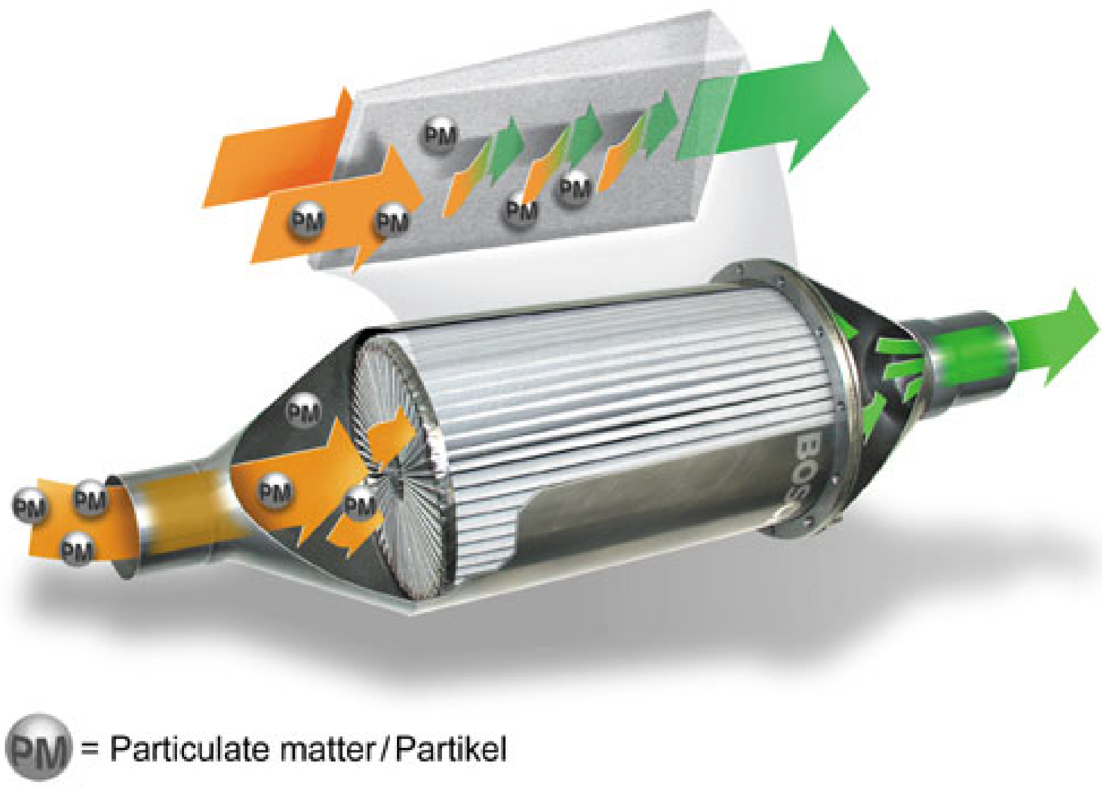

Figure 5. Bosch Sintered Metal PM Filter Technology.

In the configuration shown in Figure 5, the sintered metal is formed into pleats that are narrow at the entrance to the filter and wide at the exit. Bosch is projecting that for light-duty diesel vehicles the ash storage volume will be so large as to require no ash cleaning service for the life of the vehicle.

Although diesel particulate filter technology was relatively well-developed when we set the 2007 emission regulations, manufacturers are continuing to find new and novel ways to improve the technology and to reduce maintenance for PM filter systems. These advancements in technology reflect the substantial investments made by emission control companies, investments that would likely not have been made were it not for the certainty of broadly available 15 ppm sulfur diesel fuel and emission regulations requiring substantial PM reductions that the 2007 regulations provided. We continue to be pleased by the efforts industry has made to resolve issues big and small regarding technologies for 2007. Increasing ash storage volume within diesel particulate filters is but one example of a broad range of technology developments for 2007.

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

When diesel exhaust flows through a PM filter a pressure drop is created between the inlet and outlet to the filter. 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. Our previous progress review reported out on work being done by diesel particulate filter developers to optimize the porosity and pore size of diesel particulate filters to reduce pressure drop while maintaining filtering efficiency. That work has continued and been further refined to carefully consider the impact of catalytic coatings and soot loading on overall pressure drop.

A number of wall flow filter characteristics impact exhaust restriction (i.e., backpressure) and can thus impact fuel consumption. These include the porosity of the filter, the mean pore size, the distribution of pore sizes around the mean, and pore connectivity. Filter designers can tune each of these characteristics in order to reduce backpressure while maintaining high filtering efficiency, and physical properties. One example of the work being done to optimize these systems in summarized in Figure 6 below. The figure shows the backpressure characteristics of five sample filter designs reported in a recent SAE paper.[19] Interestingly, the results show not only that soot loading impacts the pressure drop across the catalyst, but also that systems with the best performance when clean may not have the best performance when loaded with soot. This is apparently due to the impact of how the soot is deposited on the filter and how tightly the soot is packed. Because changes in pore size and distribution can change the characteristics of soot deposition, tuning these parameters can have an overall positive or negative impact on the pressure drop of the soot-loaded filter. Based on these observations, engineers were able to develop a new PM filter substrate design that in the catalyzed form reduces the backpressure restriction by 50 percent when compared to other catalyzed commercial filters with the same cell geometry and filtering efficiency.

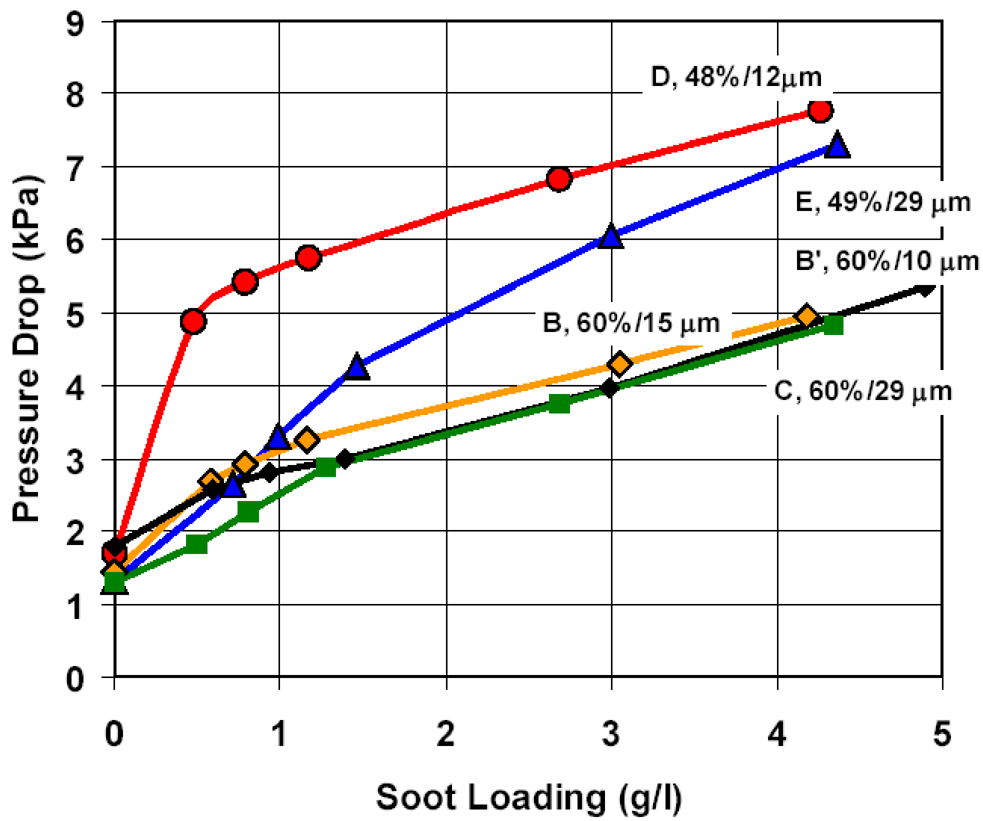

Figure 6. CDPF Design to Reduce Backpressure.[g]

Similar examples of research by other substrate manufacturers are available in the technical literature and were discussed with EPA during our progress review meetings. These include the use of new filter materials, such as sintered metal filters, which can also be optimized in a similar manner. While these changes and improvements to filter designs may not be fundamental to compliance with the 2007 standard (today's filters are already adequately effective), they are indicative of the broad range of technical progress being made to optimize systems for 2007.

[g] The notes on the figure (e.g., B, 60% / 15micron) refer to the percent porosity (%) and wall thickness (micron) of the PM filter tested.

B. NOx Adsorber Progress

NOx adsorbers work to control NOx emissions by storing NOx 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 NOx is released and reduced across precious metal catalysts. This method for NOx 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.

Our previous progress review report organized this section with subsections discussing each of the issues highlighted in the 2007 RIA. We have carried forward that approach here for consistency and to allow the reader to quickly find information regarding specific issues. However, because of the highly interrelated systems aspects of NOx adsorber catalysts and diesel engines, the resulting subsections in this new report have significant overlap. Since our last report, significant progress has been made to demonstrated improved NOx adsorber durability for diesel applications operated on diesel fuel with fuel sulfur content at or below 15 ppm. While the progress is obvious and dramatic, attributing the progress to improvements in catalyst design, or better system integration, or improvements in desulfation techniques can not be easily done. Here, we have not tried to determine with precision what fraction of the improvements to attribute to any one aspect, but instead we are simply reporting out on the overall dramatic progress. As such, information regarding each of these subsections is likely to be found within other related subsections as well.

1. Expanding the Temperature Window

NOx adsorber performance is limited at low temperatures (due to poor catalytic activity for NO oxidation under lean conditions and low activity for NOx reduction under rich conditions) and at high temperatures (due to thermal release of NOx under lean conditions). There is an extensive discussion in Chapter III of the HD 2007 RIA describing these issues. There we described both the characteristics and shape of the NOx adsorber performance curve as a function of exhaust temperature. We also discussed the possibility for future improvements in catalyst formulation in order to broaden the temperature range over which NOx adsorbers are effective. Finally, we considered the potential for engine and vehicle manufacturers to better tailor exhaust temperatures to the performance window of the catalyst (i.e., control exhaust temperatures so as to be well matched to the NOx adsorber performance characteristics).

In our previous progress review, we documented and discussed progress by catalyst manufacturers to broaden the temperature range over which NOx adsorbers were effective. Based on the evidence shared with us in meetings with catalyst manufacturers in preparing this progress review, we can clearly say that progress is continuing with regards to expanding the temperature range over which NOx adsorbers can be highly effective. However, judging and defining that progress is difficult due to the various tradeoffs in catalyst design that affect durability, sulfur tolerance and NOx storage capacity. For example, the addition of alkali metals to NOx adsorbers has been shown to be highly effective to improve NOx control at higher exhaust temperatures but with a corresponding tradeoff regarding sulfur release (storage materials that hold NOx well at high temperatures also bind sulfur tightly and can require more extreme desulfation conditions to ensure sulfur release and regeneration).[20] Thus, progress to broaden the performance window for NOx adsorbers should be made comparing similar catalyst designs (e.g., storage metal content and size) so that the progress documented reflects technical improvements over one concept or another and not simply the difference between various storage metals with conflicting tradeoffs in durability.

In meetings with catalyst manufacturers we have learned that the NOx adsorber catalyst designs have continued to improve through changes in washcoat designs and characteristics including the use of layered washcoats. The resulting catalysts can provide improved performance without compromising catalyst durability. Additionally, catalyst manufacturers are working to develop improved system configurations that can further improve NOx adsorber performance. One example is the development of specialized diesel oxidation catalysts specifically tuned to oxidize NOx emissions at low temperatures to enhance NOx storage and hence NOx efficiency when placed in front of a NOx adsorber catalyst. Such system approaches have been shown to be effective for broadening the temperature window for NOx adsorbers at low temperature.[21]

Figure 7 below, summarizes work by one catalyst company to broaden the effective temperature window for a NOx adsorber catalyst while maintaining other important attributes of the catalyst such as durability and relative ease of desulfation.[22] The figure shows a series of three NOx adsorber catalysts (NACs in the figure), denoted as A, B, and C. The designations correspond in ascending order to enhancements in catalyst design to broaden the temperature window without unduly compromising other characteristics of performance. As can be seen from the figure, improvements in both low temperature and high temperature performance are realized through further enhancements in catalyst design. Yet further improvements in low temperature performance may be possible by the application of an upfront diesel oxidation catalyst as discussed previously.

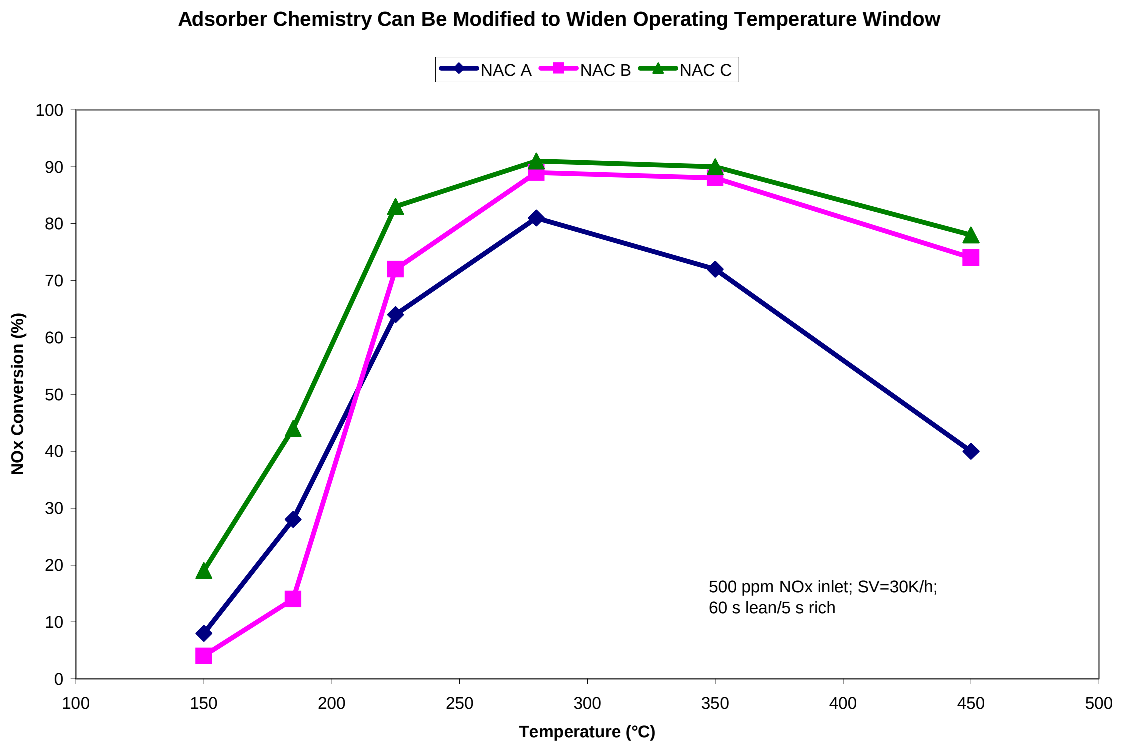

Figure 7. NOx Adsorber Catalyst Improvements to Broaden Temperature Window.

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 (> 650˚C) required for desulfation.[23] 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.

As discussed in section I.C.3 of this report, the Department of Energy (DOE) in cooperation with a number of other industry and government sponsors, including EPA, are working to demonstrate technology progress for 2007 in a study entitled Advanced Petroleum Based Fuels - Diesel Emission Control (APBF-DEC). Five projects are currently underway within APBF-DEC, including three that are studying fuel sulfur effects on NOx adsorber catalyst aging as measured against EPA regulations for light and heavy-duty diesel vehicles/engines. One of the APBF-DEC projects is being conducted at Ricardo, Inc (Burr Ridge, IL) and includes development of a system targeting NOx and PM emissions that meet the 2007 heavy-duty engine standards. The base engine, a Cummins ISX (15L, 475 hp), is representative of the technology currently being used to meet the 2004 emission standards and has been modified to enable NOx adsorber catalyst regeneration and desulfation. Researchers at the National Renewable Energy Laboratory and Ricardo are jointly publishing a paper describing the system, the regeneration and desulfation strategies, and the resulting emission performance at the 2004 SAE World Congress (March 2004).[24] Preliminary data from the catalyst aging study that accompanied this system development work is summarized below with permission from the APBF-DEC sponsors. Upon completion of testing, the research partners plan to publish a more complete report that goes beyond the brief summary provided here.

As detailed in the SAE paper, the system includes an upfront diesel oxidation catalyst (DOC) followed by the CDPF, the NOx adsorber catalyst and a downstream DOC for clean-up of hydrocarbons.[h] NOx adsorber regeneration and desulfation are accomplished through changes in EGR rates, throttling of the intake air, and supplemental fuel injection either in the combustion chamber or in the exhaust system. The appropriate combination of approaches is dictated by operating speed and load. The total NOx adsorber catalyst volume (44.4 L) is slightly less than three times the engine's swept volume. Using catalysts that were oven aged for 16-hours prior to installation, the system reduced NOx emissions over the combined hot and cold FTP test cycle to 0.18 g/bhp-hr. This 92% reduction from the base engine's NOx emissions was achieved with an 8.2% increase in fuel consumption. Performance over the 13-mode supplemental emission test (SET) was similar, with a NOx emission level of 0.14 g/bhp-hr (95% NOx reduction, 4.5% fuel consumption increase). The fuel consumption penalty associated with this strategy is higher than is desirable, and we believe more sophisticated strategies could be optimized with respect to fuel consumption impact. Nevertheless, the results from the project are indicative of the significant progress that has been made towards developing fully integrated and compliant systems.

A critical facet of the development work associated with this effort was to investigate desulfation strategies and to examine their impact on emission control system performance

[h] In this system, two NOx adsorber catalysts and two CDPFs have been installed in parallel in order to give a higher catalyst frontal area and shorter catalyst length for a given volume. This design limits the exhaust restriction attributable to the emission control system. Functionally, this is the same as a system consisting of single larger diameter exhaust components. For 2007, we expect diesel engines to be designed to tolerate higher levels of exhaust restrictions than the limit imposed by this research engine, and thus, such parallel systems will not necessarily be used in 2007. Of course, parallel systems may be desirable in some instances for aesthetic reasons (e.g., dual exhaust stacks on conventional cab trucks)..

during aging. To address this, a 2,000 hour aging test is being conducted with time-based (every 100-125 hours) desulfation events to restore the catalyst performance. Previous studies, including the earlier Diesel Emission Control Sulfur Effects (DECSE) program summarized in the HD 2007 RIA, reported substantial loss in NOx control in as few as 100 hours of operation. As a result, we remain interested in the development of sulfur control strategies that do not significantly impair catalyst performance.

Details of the desulfation strategy used in the APBF-DEC study are described in the SAE paper. In summary, it involves a combination of intake throttling, supplemental fuel injection and steady-state operation at 1,200 rpm and 1,000 N-m to achieve catalyst mid-bed temperatures greater than 675˚C and a net rich exhaust ($\lambda<0.9$) for an extended period of time. The strategy, including the duration of the event, was refined throughout the course of the study but generally required 30 to 60 minutes at that steady-state condition. Development of a more robust strategy that would be practical under actual driving conditions was outside the scope of this study. It is also important to note that a time-based regeneration strategy was employed during the aging test. The strategy was not developed to compensate for reduction in NOx storage capacity resulting from sulfur accumulation. As a result, the performance prior to the desulfation events is generally poorer than the performance measured after the desulfation events. A more sophisticated control system could be developed to compensate for changes in storage capacity, thereby tempering any large swings in performance.

Figures 8 and 9 below, present the preliminary results from the first 1,500 hours of the aging test being conducted on this system. For comparison purposes, Figure 8 documents the average hot start FTP emissions before and after each scheduled desulfation event (composite values are not available for the pre-desulfation tests). Figure 9 shows the composite FTP results post-desulfation and the corresponding NOx reduction realized by the system. A couple of observations are significant. First, after 1,500 hours of operation, the desulfation strategy is able to restore the performance of the device to levels achieved prior to aging (>90% NOx reduction). The variability associated with the post-desulfation performance is a function of the varying degree of desulfation and to some extent measurement uncertainty. Further analysis is required to quantify the relative contribution of the two effects to the overall variability. In any case, it is significant to note the degree to which performance can be recovered through desulfation. Had any significant thermal deactivation occurred, this would have been reflected in the pre- and post-desulfation performance. The performance of the emission control system over the course of this aging test is encouraging and we are looking forward to more thorough analysis of the results from this important study.

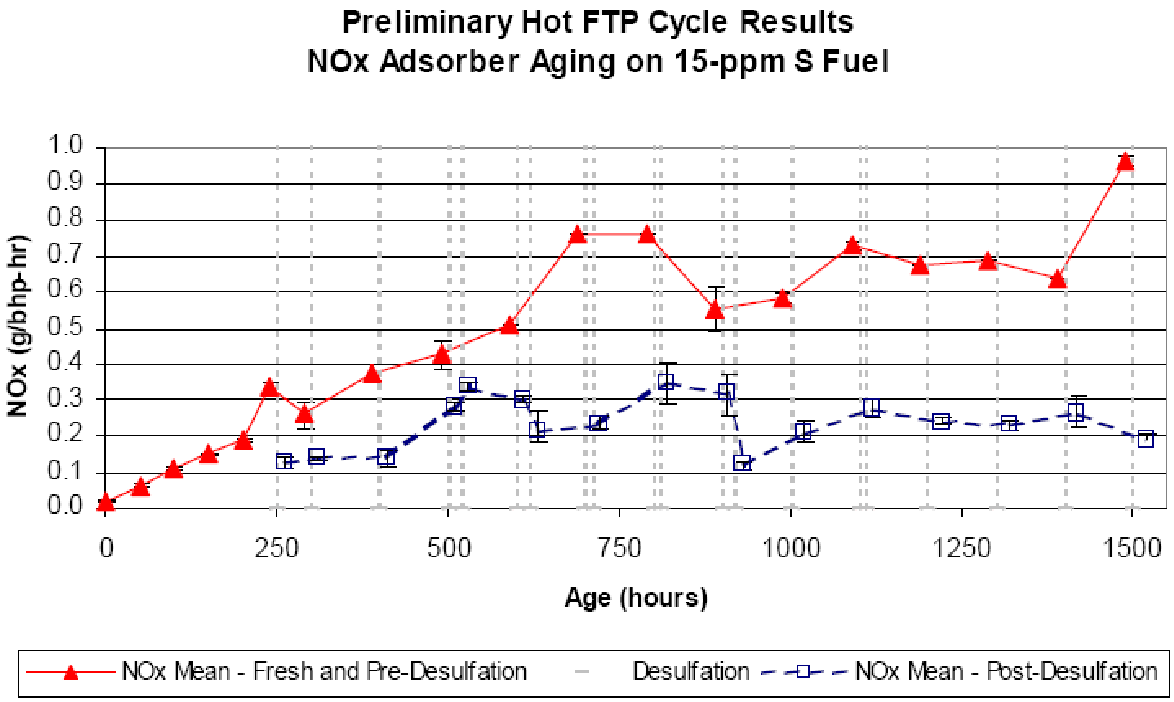

Figure 8. NOx Adsorber Catalyst Performance (before and after desulfation) over 1,500 hrs. of Catalyst Aging.

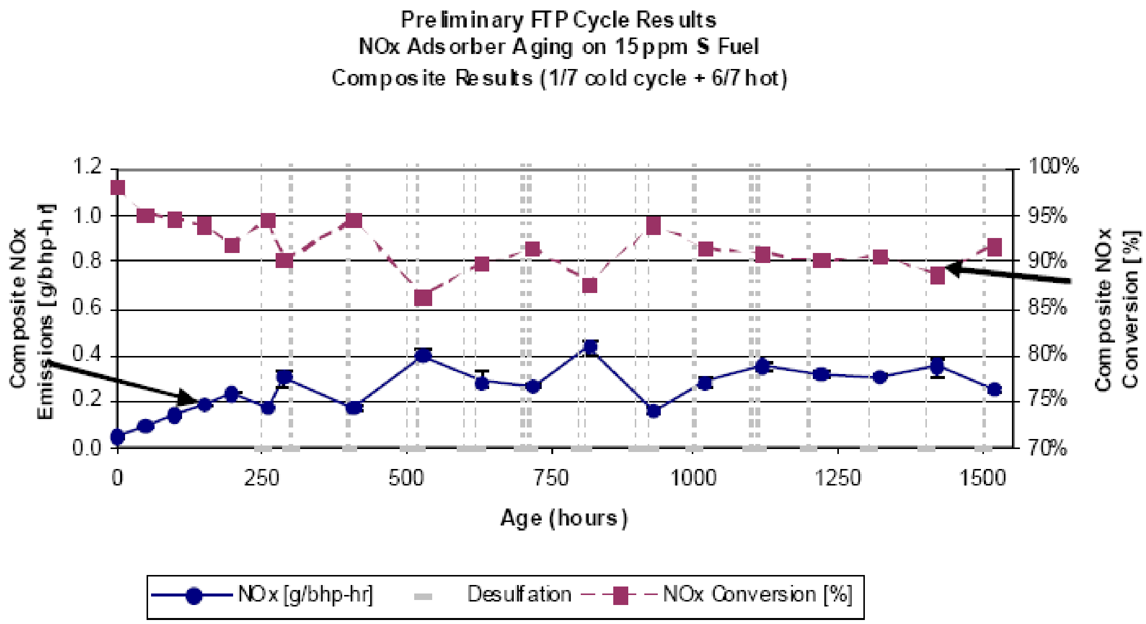

Figure 9. FTP Composite NOx Emissions (after desulfation) and Associated NOx Conversion Efficiency over 1,500 hrs of Catalyst Aging.

Two Japanese truck manufacturers, Toyota and Hino have recently introduced light heavy-duty diesel trucks in Japan using the Toyota developed Diesel Particulate NOx Reduction (DPNR) catalyst system. The DPNR system described in a light-duty application in our previous progress review, consists of a diesel particulate filter with NOx storage catalyst coated onto the PM filter substrate. In some applications, the system can be further enhanced with the addition of an oxidation catalyst and an additional NOx adsorber catalyst applied to a conventional flow through catalyst substrate. The new trucks introduced in Japan, the Toyota Dyna and the Hino Dutro are commonly used as urban delivery vehicles and as refuse hauling vehicles.

In July 2003, EPA engineers visited Toyota's Higashifuji Technical Center in Japan to participate in testing of the engine and DPNR catalyst system being introduced later in the year as the Toyota Dyna product. EPA participated in several days of testing and reviewed detailed technical information regarding the emission control system and its potential for further development. The information shared with EPA in that test program was designated as confidential business information by Toyota. However, Toyota has published a relatively detailed SAE paper in Japan describing the system and its performance.[25] We have reproduced several figures from that paper here to discuss the performance of this system.

Figure 10 below, shows the NOx and PM emissions of the system as tested periodically over a 250,000 km equivalent durability test. The results are expressed in g/kWhr and can be converted to g/bhp-hr by multiplying the emission results by approximately 3/4 (i.e., emissions of 1 g/kWhr are approximately equivalent to emissions of 0.75 g/bhp-hr). The graphs include two sets of data, one for durability tests conducted on 40 ppm sulfur fuel and a second set with testing on 7 ppm sulfur fuel.[i] As can be seen in the graph of NOx emissions, NOx adsorber performance is significantly and quickly degraded by fuel sulfur levels even as low as 40 ppm. Conversely testing on 7 ppm sulfur fuel, in the range of estimates for the average fuel sulfur level in 2007, shows significantly better performance well below the 1.2 g/bhp-hr (1.6 g/kWhr) NOx averaging standard as allowed under our 2007 regulations. It is not clear from these results whether the loss in NOx performance observed in this test work is related to thermal damage of the catalyst due to periodic desulfations or due to sulfur poisoning of the catalyst that is not entirely cleaned from the desulfation process. The gradual nature of the performance loss and the dramatic difference noted between operation at 40 ppm and 7 ppm sulfur, suggest to us that the performance loss can be largely attributed to sulfur poisoning. Thus, it appears that after the initial loss in performance seen during the first 10,000 km or so, the catalyst is showing good thermal durability.

[i] Currently, diesel fuel in Japan has a sulfur limit of 50 ppm. In 2007, the Central Environmental Council is recommending that the sulfur level be reduced to 10 ppm. Currently, Toyota and Hino are only selling vehicles into municipal vehicle fleets fueled on 10 ppm sulfur diesel fuel.

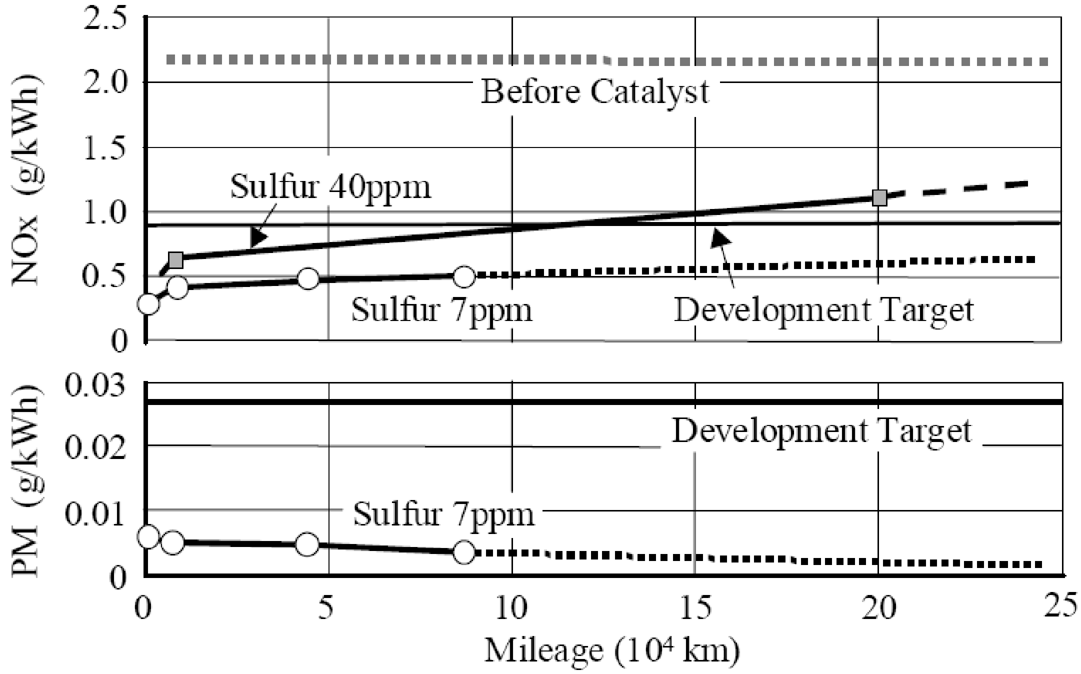

Figure 10. NOx and PM Emissions for a Light Heavy-Duty Truck w/ DPNR.

From Figure 10, it can also be seen that PM emissions continue to decrease during the lifetime of this truck. This counter-intuitive trend can be explained by the improved filtration efficiency of a PM filter as it continues to accumulate soot. A perfectly clean PM filter is less efficient than a partially soot-filled filter due to the formation of a soot cake layer in the filter that acts to filter the PM. In actual practice, we would expect some variation in PM emissions up and down during the life of the vehicle depending on the amount of soot stored on the PM filter and the potential for releases of stored sulfate emissions during regeneration events. In no case, would we expect emissions to exceed the NTE limits and in general, we would expect the emissions trend to track as shown in this durability test data from Toyota. The PM emissions shown here are well below the 0.01 g/bhp-hr 2007 emission standard.

Figure 11 below, summarizes the same results after 250,000 km equivalent expressing the results in terms of NOx versus, PM, HC and CO emissions (typically NOx and PM emissions tradeoff against one another). The figure shows that the emissions of four pollutants would be well below the level required to meet the 2007 emission standards (assuming the NOx averaging approach is used). The results also show good promise for improvement to meet the final 2010 NOx emission standard of 0.2 g/bhp-hr with further system and catalyst development. The excellent performance demonstrated by the DPNR system in this production application gives us high confidence that a similar system could be used as part of a compliance plan for model year 2007 in the United States when 15 ppm sulfur diesel fuel will be broadly available.

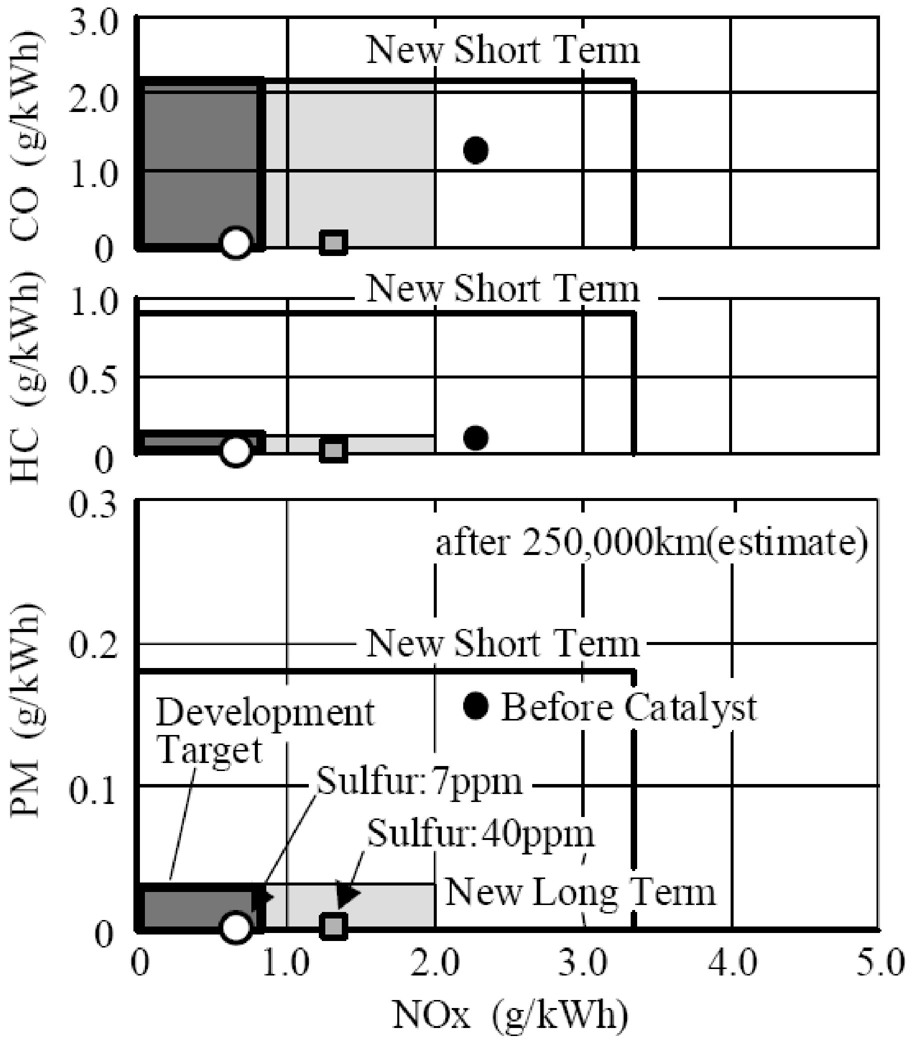

Figure 11. Emissions Performance for a DPNR Equipped Light Heavy-Duty Truck.

During our progress review we met with a number of catalyst companies to discuss both their internal NOx adsorber catalyst development work and their external work with engine manufacturers. Figure 12 below is but one example of the work that was shared with the Agency during these meetings. The figure shows NOx adsorber efficiency at four test modes corresponding to different engine speeds and load for a NOx adsorber catalyst that was purposefully undersized to make clear the impact of space velocity. The results are summarized for three catalyst systems (all with the same NOx adsorber formulations), one tested "fresh" and two tested after simulated aging to full useful life for a medium heavy-duty diesel engine (185,000 miles). The brake specific NOx emissions (BS NOx) shown in the table represent the NOx emissions entering the catalyst from the engine. The NOx emissions entering the catalyst at the A-100 test mode are nearly 5 g/bhp-hr and thus approximately double the baseline NOx emissions that we would project a 2007 compliant diesel engine would emit (4 times the level that a 1.2 g/bhp-hr engine would emit). Thus the results here are not to be taken as indicative of overall system performance, but rather are useful for looking at progress by catalyst manufacturers to improve the thermal durability of NOx adsorber catalysts.

NOx-Trap Performance on Medium-Duty Engine with Rich Control by Engine Management. (DOC + LNT)

- Catalyst System Undersized to Demonstrate SV Importance.
  - ➔ 1.3X Engine Displacement

Mode	SV (Khr $^{-1}$)	Temp (°C)	[NOx] (ppm)	BS NOx (g/kW.h)
A-25	42.7	288	169	2.6
A-50	70.5	355	311	3.9
A-75	96.7	397	523	5.6
A-100	118.4	426	652	6.5

- Catalyst Durable in End-of Life Simulation.
- Rich Quality During DeSOx Mode Impacts Aged Performance.
- Total Activity Can be Improved by Optimization of Catalyst Size.

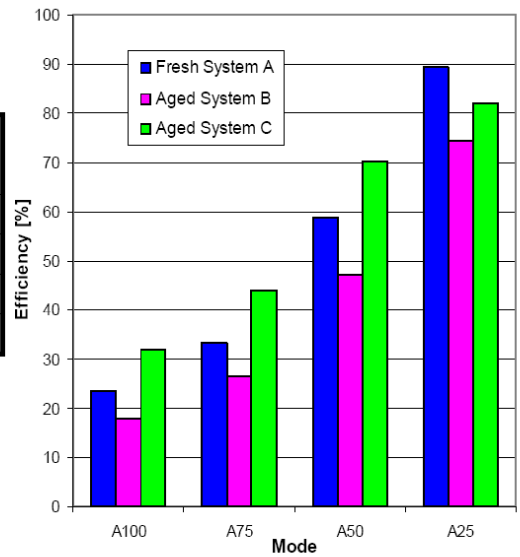

Figure 12. Catalyst Improvements for NOx Adsorber Durability.

The two aged systems shown in the figure were both aged to the full useful life of the engine and both contain catalysts with the same NOx adsorber formulation. During the aging process the catalyst systems were periodically desulfated to remove the sulfur that had been accumulated during the aging process. The results show that even at the full useful life of the engine, the loss in NOx adsorber performance is relatively small and for one of the systems no loss is seen at three of the four operating modes. These results are indicative of two trends that we observed during our progress review regarding NOx adsorber thermal durability. First, that careful control of the desulfation process to avoid excessively high temperatures and improving NOx adsorber catalyst formulations can give NOx adsorber catalyst performance that is maintained for the useful life of a heavy-duty diesel engine. Second, small variations in desulfation quality (presumable either in temperature control or in reductant properties) can over an extended period have a significant impact on NOx adsorber performance. Said another way, failure to remove sulfur during a desulfation event can lead to a gradual loss in NOx adsorber performance over time that is not demonstrated in another similar catalyst that experiences somewhat better desulfation characteristics. The catalyst manufacturer in this example has pointed to variations in the quality of rich pulses used for desulfation as an important factor in explaining the observed differences in the full useful life performance of the catalyst (i.e., improved performance was correlated the quality of the rich mixture formation in the desulfation event). However, we should note that even the poorer performing NOx adsorber system in this example only showed a relatively modest loss in catalyst performance over the useful life period for this engine.

Based on the results summarized here and other results shared with the Agency in confidence, we are concluding that there has been substantial progress to improve NOx adsorber catalyst thermal durability as measured over the full useful life of a diesel engine. We believe this improved performance is related not only to catalyst technology improvements but also to improvements in methods to accomplish desulfation without realizing excessively high catalyst temperatures. We believe the current state of the art NOx adsorber catalysts are now showing thermal durability which is consistent with the exceptionally long useful life period for heavy-duty diesel engines. The key to assuring full useful life compliance for diesel engines using NOx adsorber catalysts appears to be carefully controlled and highly effective desulfation cycles to ensure the removal of sulfur on the catalyst.

3. Methods and Performance for Desulfation (Sulfur Cleansing)

Sulfur poisoning remains a challenge for the NOx 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 NOx adsorber performance as explained in Chapter III of the HD 2007 RIA. Therefore, a means to cleanse sulfur from the NOx adsorber catalyst is a necessary step in order to ensure long term NOx 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 NOx adsorber catalyst.

Our previous progress review report separated the discussion of progress to improve NOx adsorber thermal durability and progress to develop better methods for desulfation. This reflected that status at that time and the fact that a number of narrowly focused efforts were ongoing to address each issue. Since that report, significant progress has been made to develop and commercialize NOx adsorber catalysts. As a result, the test and development programs for the catalyst have become more encompassing including improved catalyst formulations and methods in the same test program. Thus, although this section title has been repeated here to provide for easy reference to our previous progress review report, the results relevant for this section are included also in the preceding section on thermal durability and the following section on system integration.

NOx adsorber desulfation is critical to ensuring the long term durability of NOx adsorber catalysts even when operated on 15 ppm sulfur diesel fuel. The three durability test programs summarized in the previous section all included periodic desulfation cycles to clean the sulfur from the catalyst surface and restore NOx performance. The resulting good long term durability shown in each of the programs is indicative of the progress to develop effective means for NOx adsorber desulfation that can be accomplished not only on the catalyst test bench but on real diesel engines and in real diesel vehicles in operation. Thus we are pleased to see that substantial progress has been realized, but we note that more progress is needed and possible in the future. As discussed in the previous section, the desulfation results in some of these test programs has been somewhat uneven. That is, in some situations NOx performance after desulfation returned to near new conditions, showing that the desulfation process was highly effective. However, in other instances, using the same catalysts and nominally the same desulfation events, the recovery of NOx performance was less than full. This suggests to us that subtle differences in the desulfation process (or in the conditions leading up to the desulfation process) can play a relatively significant role in overall desulfation effectiveness. Further work by researchers to clearly define these differences and to develop simple mechanisms to evaluate the effectiveness for desulfation will be desirable as the technology progresses further.

In the following section on system integration there is a discussion of various methods for generating the reductant species most conducive to effective NOx regeneration and desulfation. It is quite possible that these system developments to tune reactant species in the exhaust will hold the key to further improving desulfation methods and realizing more complete NOx adsorber restoration. We are therefore looking with anticipation to further work in this area in the coming year.

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. In our previous progress review report, we described the progress to develop systems to integrate the NOx adsorber catalyst technology to work with diesel engines as significant, but preliminary, reflecting an early state of development and the long lead time remaining for 2007 and 2010. We discussed a significant paradigm shift in how catalyst technologies were viewed by diesel engine manufacturers. No longer would catalyst technologies be thought of solely as aftertreatment, but instead, as part of an integrated system solution for emission control. In this review, we note that this change in thinking is no longer considered as new or revolutionary, but has rapidly become the commonly understood norm for new technology. Whether for active PM filter regeneration, NOx adsorber regeneration and desulfation, or urea SCR based NOx control, the conventional process is now to consider new technology as part of a total system solution.

Progress to fully integrate the NOx adsorber technology as part of a total system solution for emission control has been substantial since our last progress review. A significant fraction of the new work regarding every aspect of NOx adsorber performance is now being conducted using diesel engine systems rather than the more typical gas reactor studies of a few years ago. The three programs discussed in the previous section on thermal durability all reflect work done on real engines showing the overall system ability to maintain NOx adsorber efficiency. Included in this section is a discussion of work done to better define important system characteristics for NOx regeneration and the introduction of the first production heavy-duty diesel vehicle using the NOx adsorber catalyst for NOx control, the Toyota Dyna truck. These programs represent only a small part of the overall substantial work to integrate NOx adsorber catalysts as part of a total diesel engine and vehicle emissions system.

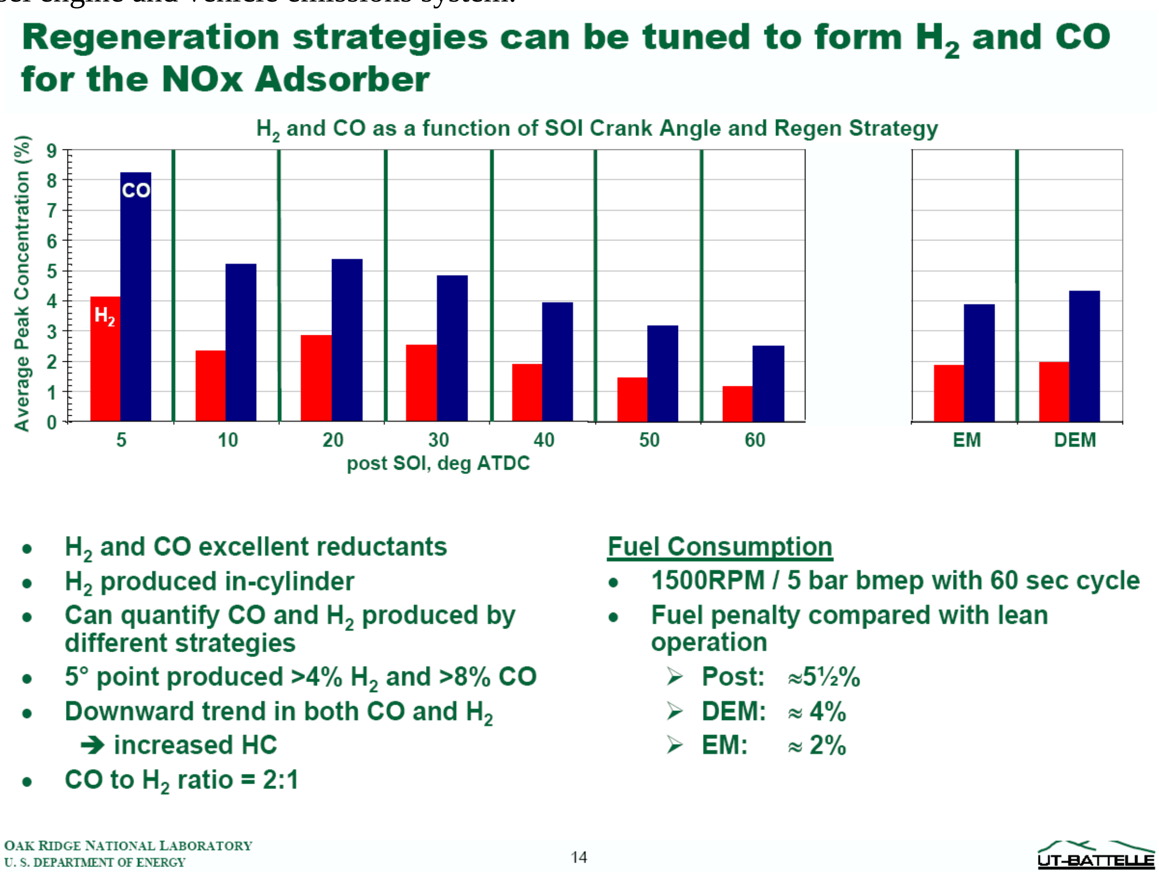

Figure 13. Strategies to Provide Better Reductants for NOx Adsorber Regeneration.

Researchers at Oak Ridge National Laboratory (ORNL) are investigating the interrelationship between reductant species that can be developed in the exhaust of a diesel engine and the effectiveness of those reductant species for NOx regeneration and desulfation. Early gas reactor studies on NOx adsorber catalysts have shown that changes in reductant species can have a substantial impact on NOx adsorber performance. It was found that hydrogen (H_2) and carbon monoxide (CO) were particularly effective reductants for NOx adsorber regeneration and desulfation. Raw diesel fuel was shown to be less effective. The work at ORNL summarized in Figure 13 above, looked to define the quantity and ratio of preferred reductant species (H_2 and CO, along with light and heavy hydrocarbons) generated by different methods within diesel engine exhaust. The engineers investigated different methods for generating reductant species including extended main (EM) injection, delayed extended main (DEM) injection, and post injection (Post). Their work shows that significant amounts of the preferred reductant species can be formed in a diesel engine and further that the ratio of the reductant species can be altered by changing the operating mode. Significantly too, they showed that the fuel economy impact of NOx adsorber regeneration can vary depending upon the method for reductant generation. The least fuel intensive method in their study was found to be the extended main method with a demonstrate fuel economy impact of approximately two percent. The most common method used for NOx adsorber regeneration today is post injection, yet the work by ORNL showed the potential for extended main injection to improve fuel economy over the post injection method by more than 60 percent.

As discussed previously in our review of progress for CDPFs, catalyst manufacturers have shared with the Agency significant progress in their work to tune DOCs to perform very specific tasks. These include tuning the DOC to serve for active CDPF regeneration, for hydrogen sulfide (H_2S) cleanup, for improved low temperature NOx storage and to create more effective reductant species for NOx adsorbers from diesel fuel (i.e., to serve as a fuel reformer). One example of this optimization of DOC technology and its benefits can be seen in related work done by ORNL. Figure 14 below summarizes results from work at ORNL investigating the benefits of a DOC for fuel reformation in front of a NOx adsorber catalyst. The resulting system shows significantly reduced fuel consumption at the same NOx conversion efficiency when the fuel is reformed by the DOC prior to the NOx adsorber catalyst. This coupled with the earlier observations that a DOC can be used to promote low temperature NOx adsorber performance suggests that a DOC may be part of the total NOx adsorber engine system solution for 2007.

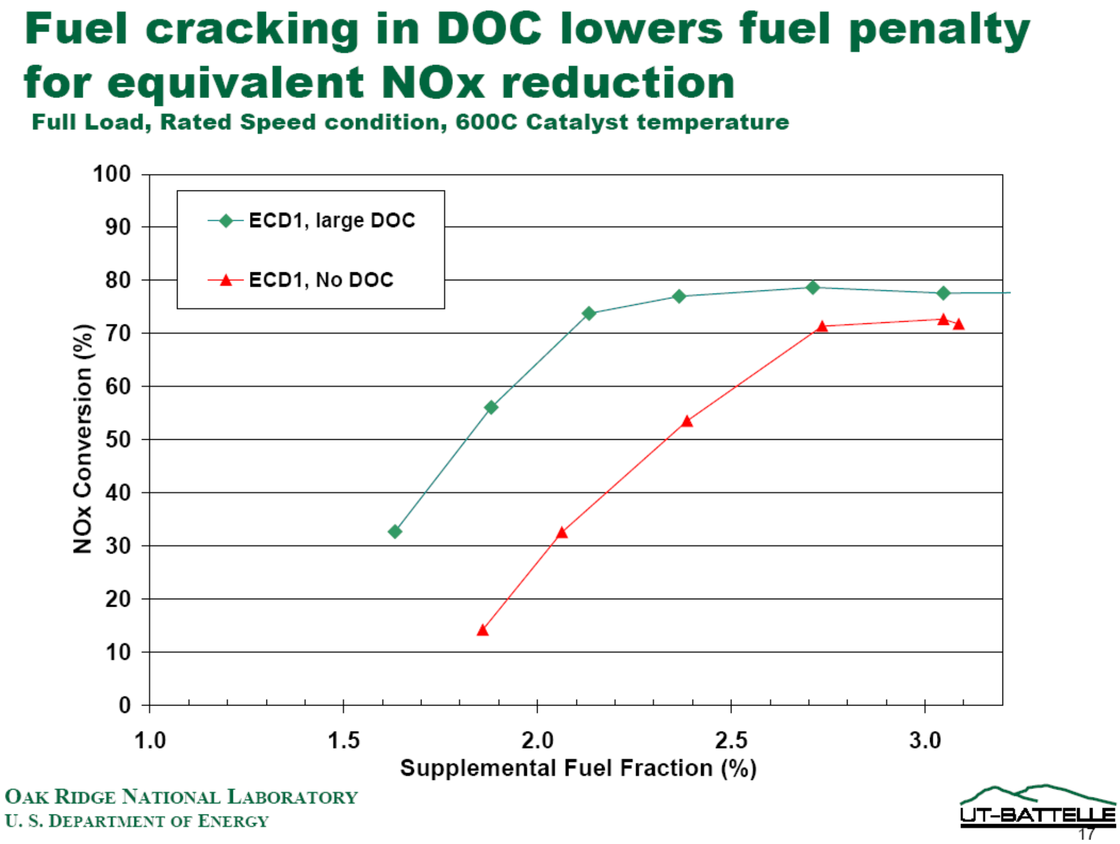

Figure 14. System Approaches to Lower Fuel Consumption with NOx Adsorbers.

As discussed briefly in section I.C.2 of this report, EPA is conducting advanced NOx adsorber and PM filter system development and durability research at the National Vehicle and Fuel Emissions Laboratory (NVFEL) in Ann Arbor, Michigan. The NVFEL program has pioneered work in dual-bed NOx adsorber regeneration systems and techniques. Dual-bed regeneration refers to a process whereby the exhaust flow is split between two or more catalysts such that some portion of the catalyst volume can be periodically isolated from the exhaust flow and regenerated off-line. In its simplest form, the system has two catalyst beds and switches between the beds on a 50 percent cycle (i.e., half the time exhaust is going through one catalyst and half the time the other). Because regeneration is conducted offline without high exhaust flow and without significant exhaust oxygen content, the fuel consumption required to regenerate the catalyst can be low. In 2000, this EPA team demonstrated emission levels below the final 2007 levels using such a system.[26]

Having demonstrated the potential for such a system to deliver very low NOx and PM emissions, the team began work to reduce the overall size and cost for the system. The initial proof of concept approach that EPA used in 2000 resulted in a catalyst system that was approximately twice as large as needed. This was because, each of the catalysts needed to be able to treat the entire exhaust flow while the other was regenerated thus, the resulting catalyst was designed to be full size. The EPA team reasoned that only a fraction of the total catalyst volume would need to be regenerated at a time (regeneration can be accomplished in a matter of seconds, while storage can last for a minute or more). Therefore, they devised a system with four catalyst beds such that at any given time, three of the catalysts would be storing NOx and one regenerating. The resulting system was half the volume of EPA's initial prototype system. EPA's system also incorporates CDPFs for PM control and a trailing DOC for HC and H_2S cleanup. Figure 15 below shows a picture of EPA's four-leg system next to a conventional muffler for the same size diesel engine. As can be seen from the picture, the resulting emission control system (including CDPF, NOx adsorbers and DOCs) is approximately the same size as the muffler system it might replace.

Figure 15. Comparing the Package Size of EPA's 4 Leg System to a Conventional Muffler

Although EPA substantially reduced the size of the overall NOx adsorber/CDPF system, the emissions performance remained very high. The EPA system has demonstrated hot FTP NOx emission reductions of 80 percent with an associated fuel penalty of 3.4 percent. The NOx control performance was also very impressive over the SET test cycle as summarized in Table 2 below.

Cummins ISB (baseline)						Cummins ISB w/post-combustion emission controls				
SET Mode	SET Weighting	Speed (rpm)	Torque (lb-ft)	$BSNO_x$ (g/hp-hr)	BSHC (g/hp-hr)	Outlet T (°C)	$BSNO_x$ (g/hp-hr)	NO_x (% Reduction)	BSHC (g/hp-hr)	Reductant FE Impact (%)*
1	15%	Idle	0	0.00	0.00	144	0.16	100%	0.00	0.0%
2	8%	1616	649	3.48	0.10	475	0.29	92%	0.06	1.4%
3	10%	1943	331	3.06	0.22	355	0.08	97%	0.11	1.4%
4	10%	1942	495	2.98	0.13	419	0.14	95%	0.07	1.3%
5	5%	1615	335	3.50	0.26	368	0.13	96%	0.11	2.1%
6	5%	1616	500	3.45	0.15	426	0.11	97%	0.08	1.6%
7	5%	1614	169	5.25	0.53	251	0.72	86%	0.27	1.5%
8	9%	1942	635	3.16	0.09	496	0.47	85%	0.06	1.5%
9	10%	1941	167	4.46	0.57	291	0.60	87%	0.44	4.3%
10	8%	2271	594	3.24	0.08	509	0.80	75%	0.07	1.6%
11	5%	2269	153	3.81	0.71	282	0.67	82%	0.36	2.5%
12	5%	2270	453	3.21	0.11	406	0.19	94%	0.06	1.3%
13	5%	2269	303	3.17	0.19	343	0.19	94%	0.17	1.4%
SET Weighted Composite Results:				3.33	0.17		0.36	89%	0.11	1.6%**

* Fuel economy impact of fuel-reductant addition for NO_x adsorber regeneration.
** Increased exhaust restriction from the wall-flow and flow through monoliths results in a further FE impact of approximately 1-2% over the SET composite.

Table 2. NOx and HC Performance for EPA's 4 Leg System over the HD SET Test Cycle

As can be seen from Table 2, the fuel economy impact over this test cycle is very modest (1.6% composite) over a wide range of engine operating modes. For test modes 3 and 4, which are representative of a significant fraction of typical in-use operation, the fuel economy impact is 1.5 percent and the NOx reductions are over 95 percent. In all testing with this system, the PM emissions were below the applicable standards for 2007. EPA has documented the work to develop the 4-leg system and the results from all of its development work for NOx adsorber catalysts in a series of SAE technical papers which are readily available.[27,28,29,30] The work of EPA's NOx adsorber development team, summarized here shows that substantial NOx and PM emission reductions are possible using a reasonably sized multi-leg emission control system. The continued work by the EPA team is an important part of our overall role to understand the progress by industry to develop these technologies and, through our own efforts, to help to advance new solutions for emission control in the future.

Previously in our description of progress regarding NOx adsorber thermal durability, we discussed the introduction of the DPNR equipped light heavy-duty diesel trucks by Toyota and Hino in Japan. These are the first examples of fully integrated and commercialized NOx adsorber equipped heavy-duty diesel vehicles in the world. As such, they provide strong evidence that the NOx adsorber technology could be used as part of a compliance program for 2007, and further, provide an excellent example of system integration on a real vehicle. Figure 16 below is reproduced from a Japanese SAE paper by Toyota describing the design of a diffuser plate installed in front of the DPNR catalyst. The figure shows that without the diffuser plate, the catalyst experienced significant temperature differentials across the face of the catalyst during desulfation events. This is undesirable as temperatures that are too cool can reduce the effectiveness for sulfur release and temperatures that are too hot can thermally damage the catalyst. Thus significant variations in catalyst inlet temperatures are undesirable as they increase the likelihood of experiencing exhaust temperatures that are either too hot or too cool. To address this issue Toyota developed a diffuser plate designed to ensure a more even distribution of exhaust flow into the DPNR catalyst. The resulting system showed a significant reduction in the spread between the coolest catalyst location and the hottest. At the same time, the NOx reduction efficiency demonstrated by the catalyst was also improved. As described in our previous discussion, the resulting system performance was consistent with one possible means for compliance in 2007.

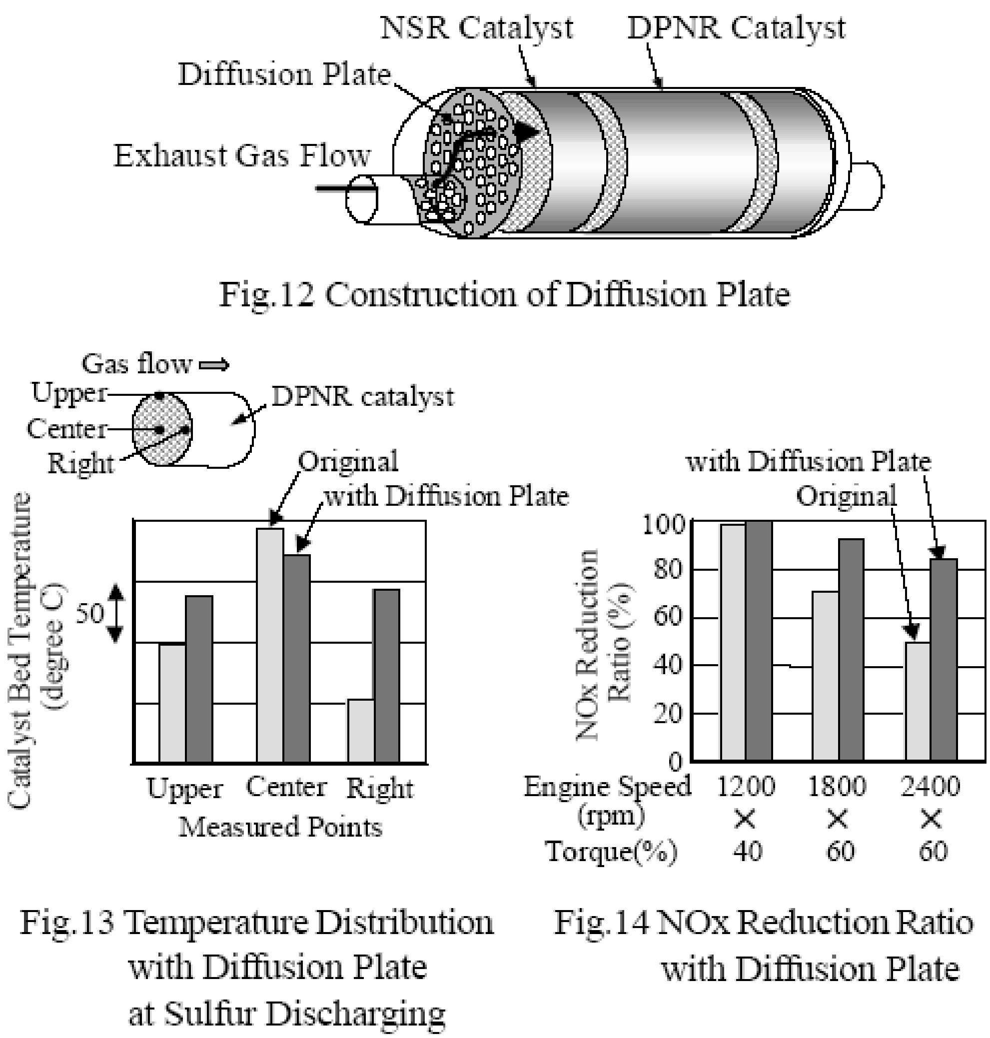

Figure 16. System Improvements (diffuser plate design) to Improve NOx Adsorbers

As the first commercial introduction of a heavy-duty diesel engine with a NOx adsorber and PM filter system, the Toyota truck serves as the first benchmark for the impact that such systems can have on overall vehicle fuel economy. Toyota has reported out the fuel economy for this system (summarized in Figure 17 below) in terms of the overall fuel economy of the vehicle and the portion of the fuel consumption associated with the DPNR system.[31] As the figure shows, the overall fuel consumption of the vehicle remains unchanged from the current model even through NOx and PM emissions are significantly reduced. The figure does show that approximately five percent of that fuel consumption is related to emission controls but that overall system performance due to engine optimization and other changes results in no net fuel economy impact. This is consistent with the analysis in the HD 2007 RIA which considered not only impact in fuel economy from the PM filter restriction, the NOx adsorber regeneration and desulfation events, but also the ability of manufacturers to recover that fuel economy impact through re-optimization of the engine. We think that the ability of Toyota to introduce a new clean diesel vehicle that reduces NOx and PM emissions dramatically without changing overall fuel consumption is an very strong sign of the dramatic progress being made in total system engineering of clean diesel technologies applicable to the 2007 standards.

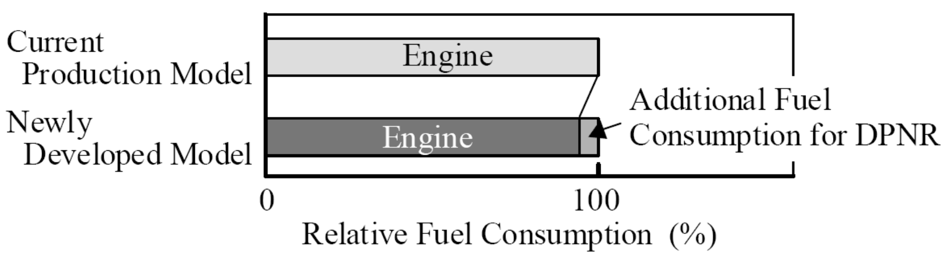

Figure 17. No Net Fuel Economy Difference for Clean Diesel Truck.

EPA has been conducting a test program to evaluate efforts to bring light-duty diesel vehicles into compliance with U.S. Federal Tier 2 light-duty emission standards. Between April 2002 and October 2003, five advanced prototype light-duty diesel vehicles equipped with NOx adsorption catalysts, PM filters, and diesel oxidation catalysts were tested at EPA's National Vehicle and Fuel Emission Laboratory (NVFEL). The vehicle testing was conducted using low sulfur (<15 ppm) diesel fuel. All of the tested vehicles demonstrated the considerable progress made by vehicle manufacturers and systems integrators in applying advanced NOx and PM emission control technology to light-duty diesel vehicles. PM emissions for all of the vehicles were well below the Tier 2 Bin-5 emission levels. The most recently tested vehicle demonstrated intermediate-useful life (50,000 miles) PM, NOx, and NMHC emissions at, or below, the Tier 2 Bin-5 standard. The results from this test program are documented in a recent SAE paper and are summarized below in Table 3 reproduced from that paper.[32]

Vehicle Tested	PM (mg/mi)	NOx (g/mi)	NMHC (g/mi)	CO (g/mi)	CO_2 (g/mi)	FE (mi/gal)
Vehicle A (<4k-miles)	5.7 (± 0.8)	0.05 (± 0.01)	0.07 (± 0.03)	0	273 (± 2)	37.2 (± 0.2)
Vehicle B (<4k-miles)	<2	0.04 (± 0.02)	<0.03	<0.1	277.4	36.6 (±0.4)
Vehicle C (<4k-miles)	3	<0.06	<0.02	<0.03	329 (±1.4)	30.9 (±0.1)
Vehicle C (@60k-miles)	3 (±1)	0.26 (±0.04)	0.018 (± 0.009)	0.07 (±0.01)	337 (±8)	30.2 (±0.7)
Vehicle D (<4k miles)	< 2	< 0.03	<0.02	0.018 (±0.007)	298 (±15)	34 (±2)
Vehicle E (@50k-miles)	1.0 (±0.1)	0.05 (±0.01)	0.07 (±0.01)	2.3 (±0.2)	317 (±2)	31.0 (±0.3)

Table 3. FTP Emission Results from Light-Duty Diesel Testing at EPA NVFEL.

The results in Table 3 show that all five of the vehicles tested have demonstrated very low NOx and PM emissions in complete vehicle chassis tests. While the vehicles were all prototypes, they demonstrated the substantial progress by vehicle manufacturers to integrate advanced NOx and PM emission control technologies into diesel passenger cars. All of the vehicles tested relied primarily on NOx adsorption catalyst technology for NOx control and PM filter technology for PM control. In all cases, PM emissions were very low ranging from 40% to 90% below the Tier 2 Bin-5 PM emission standard. Significantly the last vehicle tested, vehicle E, demonstrated Tier 2 Bin-5 NOx emissions levels following a significant degree of aging of the emission control system. The results from this program show not only the substantial progress to develop Tier 2 compliant diesel vehicles, but also the ability of manufacturers in general to develop well integrated NOx and PM emission technologies into full vehicle designs.

The evidence summarized in this subsection regarding system integration progress for 2007 represents only a small part of the total work by industry in this area. Yet it accurately summarizes what we observed during this progress review; that there has been and continues to be significant progress to integrate the NOx adsorber technology into the overall engine and vehicle design to realize substantial reductions in NOx emissions while maintaining the benefits of the diesel engine. In the case of the Toyota DPNR system, work has progressed well into the system optimization stage that characterizes late stage development. Based on the progress noted in a number of areas, we continue to believe that manufacturers could introduce products in 2007 compliant with our emissions program using the NOx adsorber catalyst technology.

C. Further Refining Engine-Out Technologies

At the time of the HD 2007 rulemaking, we projected that additional improvements would be made in controlling emissions from diesel engines but that these improvements would be limited in magnitude and not sufficient to allow compliance with the HD 2007 emission regulations without the addition of aftertreatment technologies. We are pleased to note in this review that we underestimated the potential for further engine-out NOx reductions from diesel engines. As summarized in the following sections and described also in Section II.C of this report, in-cylinder methods for controlling NOx emissions have continued to progress and will allow for compliance with the NOx averaging level of 1.2 g/bhp-hr in 2007.

At this time, we are not able to project that engine-out emission controls will be able to allow compliance with the final NOx standard of 0.2 g/bhp-hr under all conditions without the use of aftertreatment technologies, yet we include data in this report showing some promise that such an outcome may be possible in the future, perhaps even as early as 2010.

1. High Flow Exhaust Gas Recirculation (EGR)

A number of diesel engine manufacturers introduced cooled EGR systems on their heavy-duty diesel engines in 2002 compliant with the 2004 emission standards for NOx and NMHC of 2.5 g/bhp-hr. The engines circulate a portion of the exhaust gases through a heat exchanger cooling the exhaust before reintroducing the gases into the engine intake manifold. The systems control NOx emissions by providing a diluent (spent exhaust gases) reducing the oxygen content of the intake air and recirculated exhaust mixture. Engine manufacturers have now demonstrated that these systems can be further refined to allow NOx emissions compliant with the 2007 NOx averaging level of approximately 1.2 g/bhp-hr. To reduce NOx emissions below 1.2 g/bhp-hr engine manufacturers will likely need to increase EGR rates (use higher levels of EGR), thus here we are referring to such refinements for 2007 as high flow EGR.

During our progress review meetings, engineers from a number of engine manufacturers shared data with the Agency demonstrating that further refinement of existing cooled EGR systems would allow compliance with the 2007 NOx averaging standard. Further, the manufacturers shared information regarding the impact of these system refinements on PM emissions prior to a PM filter and impacts on fuel economy. The data shared in those settings was all classified as Confidential Business Information (CBI) and is not repeated here. However, in recent weeks manufacturers have made public statements regarding the performance and characteristics of cooled EGR products that are not inconsistent with the data shared with EPA during our progress review meetings. Thus, although we can not directly verify the claims made in the articles we can say that the claims are broadly consistent with the data and other evidence shared with the Agency during our review.

In a January 12, 2004 article in Transport Topics, senior Cummins executives made the following claims regarding their expectations for 2007 cooled EGR engine products.[33] The article emphasizes that the 2007 cooled EGR products will be very similar to the current 2004 engine products requiring fine-tuning of the cooled EGR system and the addition of a particulate trap (i.e., particulate filter). Further the article quotes Cummins' chief technical officer, John Wall, as saying the 2007 engines would have, "certainly no loss in fuel economy. In fact, for some applications we think we can actually improve fuel economy." Mack and Volvo have also made recent public statements regarding their intent to use cooled EGR to comply with the 2007 emission regulations.[34,35]

The dramatic progress to lower engine out NOx emissions through evolutionary refinement of the cooled EGR technology was not anticipated by EPA in setting the 2007 emission standards. Although we knew that complying in 2007 at an averaging standard of 1.2 g/bhp-hr was a possibility, we believed that the 1.2 g/bhp-hr averaging level would still require a NOx control catalyst technology of approximately 50 percent efficiency. While we continue to believe that NOx catalyst technologies will likely be needed to meet the final NOx standard of 0.2 g/bhp-hr and that NOx catalysts can be applied to diesel engines in a cost effective manner, we are pleased to see that, for 2007, manufacturers will be able to fine tune existing NOx control technologies to realize a significant fifty percent reduction in NOx emissions.

2. Caterpillar ACERT™

Caterpillar has introduced a package of emission control technologies which it calls ACERT™ (Advanced Combustion Emissions Reduction Technology). The package includes technologies to improve engine air management, advanced fuel systems, electronic controls and aftertreatment technologies. This suite of technologies forms the basis for Caterpillar's 2004 compliant heavy-duty engines. ACERT™ is somewhat difficult to discuss in terms of technology development and process because, unlike cooled EGR or other emission technologies, it is not so much a single emission solution as an overall design philosophy incorporating a number of engine technologies. As such, it is not a static technology to which a particular analysis can be done to find the limit of its application. Thus, we have not performed an independent analysis to try and define the limits of ACERT™ progress, but instead, here we will simply summarize some of the demonstrated progress that Caterpillar has made in furthering the ACERT™ technology package for 2007.

At the 2003 DOE DEER conference, Caterpillar presented a summary of their diesel engine combustion work and included in the presentation some results from a 2007 demonstration engine. The results summarized in Figure 18 below, show NOx emissions consistent with the 1.2 g/bhp-hr NOx average level for 2007, with fuel economy improved over today's ACERT™ product.[36] These results, coupled with the recent public statements regarding readiness of the ACERT™ technology for 2007, gives us confidence that the ACERT™

technology can be further refined for model year 2007 compliance.[37] It is our understanding from discussions with Caterpillar that for 2010 they currently believe additional catalytic NOx control will be necessary.

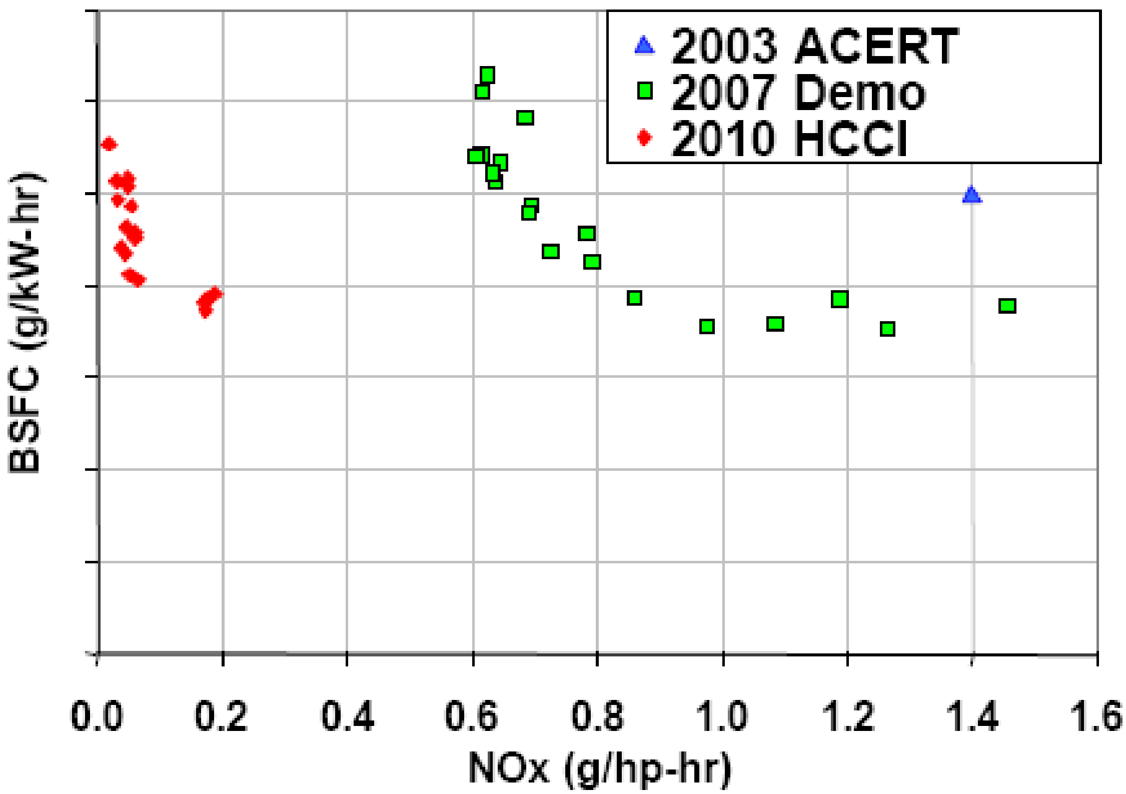

Figure 18. Emission and Fuel Economy Trade-Offs for Future Technology Engines.

3. Pre-mixed Diesel Combustion

Typical diesel combustion is characterized by the start of combustion being closely linked to the start of fuel injection and to fuel injection continuing during the combustion event. Such combustion processes are inherently heterogenous having regions within the combustion chamber which are made up almost entirely of diesel fuel, and other regions where diesel fuel and air are mixed in stoichiometric proportion, and yet other regions made up of the intake charge free of any fuel.[j] The resulting combustion process is largely determined by the

[j] It should be clarified that there are not simply three distinct regions within typical diesel combustion but a continuum of air and fuel mixtures ranging from regions comprising only diesel fuel and other regions made up of only the intake charge.

characteristics of the fuel and air mixing and is often called diffusion control combustion because the diffusion of the fuel into the charge air determines the combustion characteristics. Typical diesel combustion results in high PM emissions being formed in regions of the combustion chamber with excess diesel fuel and little intake air. Similarly, typical diesel combustion results in high NOx formation in regions where the air-to-fuel ratio approaches the stoichiometric ideal and thus the highest combustion temperatures are realized. Although, a number of technologies are available to reduce emissions in these conditions, including the use of EGR to reduce NOx emissions and high fuel injection pressures to promote mixing and reduce PM emissions, there appear to be real physical limitations for how much NOx and PM emissions can be reduced in this combustion process.[38]

Pre-mixed diesel combustion refers to a combustion process where the diesel fuel is mixed into the intake charge prior to the start of combustion. Various forms of pre-mixed diesel combustion have been tested in recent years and one technology, Nissan's MK combustion, has even been put into production (we discussed MK combustion in our previous progress review). A pre-mixed diesel combustion approach that has been the focus of a number of research programs in recent years is homogenous charge compression ignition (HCCI). This combustion process is distinguished by the fuel being well mixed with the intake charge (i.e., the resulting mixture is homogenous) prior to the beginning of combustion which is initiated by the high temperatures and pressures due to compression of the pre-mixed charge (compression ignition). Because the combustion mixture is homogenous there are no regions with excess fuel and little air to form PM. HCCI combustion therefore has virtually no soot emissions (carbon emissions) and very low total PM emissions. The air to fuel ratio of HCCI combustion typically has excess air to fuel resulting in very low NOx emissions because the temperature increase for combustion under excess air conditions is significantly reduced.[k]

[k] Typical diesel combustion also has an overall high air to fuel ratio with excess air, yet has high NOx emissions. This is because combustion occurs primarily in a region of the cylinder where the air to fuel ratio is near stoichiometry. This does a number of things to cause high peak temperatures and high NOx emissions.

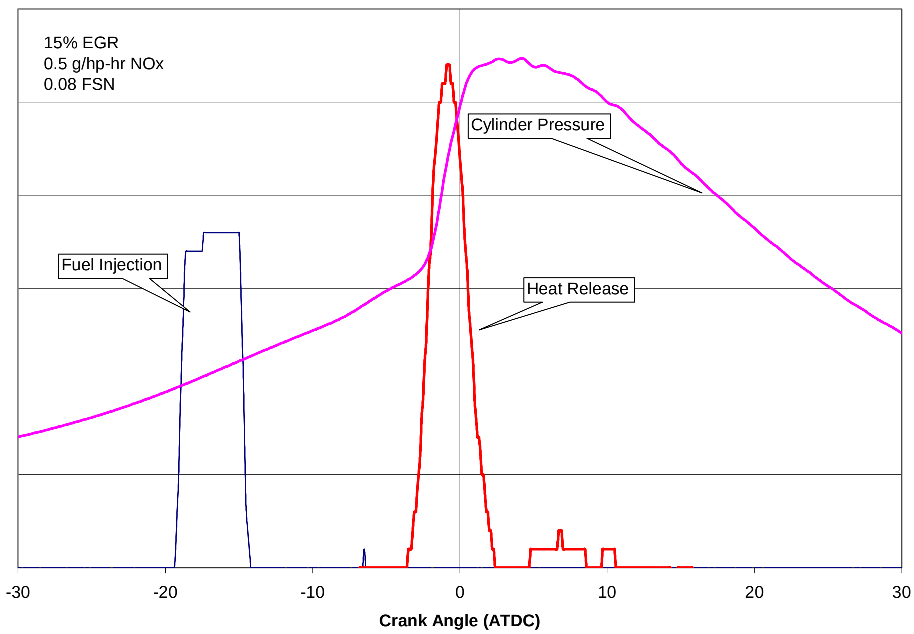

Figure 19. Example of Pre-Mixed Diesel Combustion from EPA Testing at NVFEL

Figure 19 above shows an example of pre-mixed combustion work being conducted by an EPA research team at the NVFEL. The results in the figure show some typical characteristics of this combustion approach. The heat release (the combustion event) is de-linked from the fuel injection event with the fuel injection event and subsequent mixing of the intake charge occurring well before the start of combustion. The combustion event occurs at or before the piston reaches top-dead-center resulting in relatively high cylinder pressure. The resulting NOx and PM emissions are quite low. In this example, NOx emissions are approximately 0.5 g/bhp-hr and the smoke number (a test surrogate for PM emissions here) is very low at 0.08 FSN. EPA, like a number of other government and industry research groups,is continuing to research various approaches to pre-mixed combustion because of its high potential for very low NOx and PM emissions.

We did not point to HCCI as a potential means to meet the 2007 emission standards in the 2007 RIA, nor do we believe today, that it will be part of an overall emissions solution in the 2007 timeframe. There are a number of difficult technical challenges which must be addressed with HCCI combustion before it can be commercialized.[39] Primary among these is the difficulty in controlling the start of combustion. Given a pre-mixed homogenous charge in the cylinder, the start of combustion occurs whenever the pressure and temperatures in the cylinder are high enough to initiate combustion. If those conditions are reached during the compression stroke well before the piston reaches the top of its motion, the resulting exceedingly high pressures can damage the engine. This is one reason that HCCI combustion has historically been limited to operation at relatively light load. Engine load is often expressed in terms of Brake Mean

Effective Pressure (BMEP) with larger BMEP numbers corresponding to higher engine loads (higher engine torque). Modern heavy-duty diesel engines can have BMEPs greater than 2,000 kPa at high load conditions such as peak torque. Most laboratory work reported to date shows HCCI combustion limited to regions of operation approximately half of that number (i.e., 1,000 kPa or 10 bar). Figure 20 below, summarizes work by Caterpillar presented at the 2003 Department of Energy Diesel Engine Emission Reduction (DEER) conference. The figure shows that Caterpillar has demonstrated HCCI combustion in the laboratory over better than three-fourths of the total engine operating range for this engine up to 1,600 kPa.

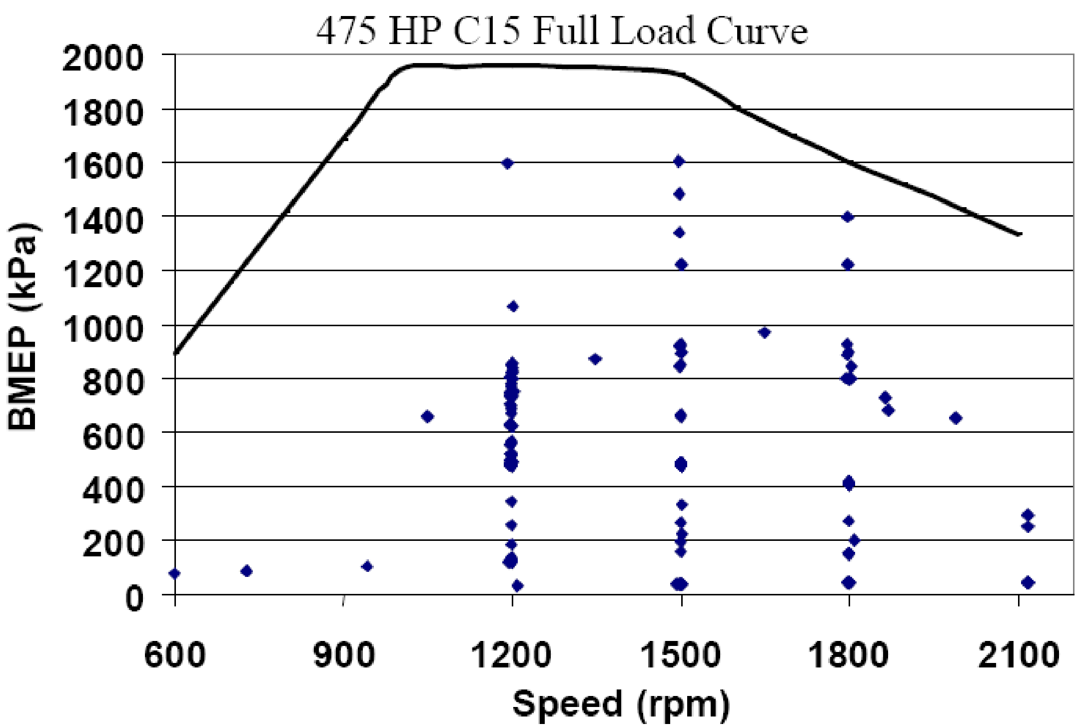

Figure 20. HCCI Combustion Demonstrated Across a Wide Operating Range.

Demonstrating HCCI combustion across such a broad operating range on a heavy-duty diesel engine represents considerable progress in the state of the art for HCCI combustion. Although these results are very promising and we are encouraged by the rapid rate of progress to develop this technology, we understand from engine manufacturers that its application by model year 2007 as the sole means of compliance with the NOx or PM standards is not possible. It may be possible for so-called mixed mode engines, engines that operate as HCCI engines under light load conditions and as conventional diesel engines at high load, to be introduced by 2007. However, such engines would still require a PM filter for PM control under high load and likely an additional NOx control technology (e.g., EGR) to control NOx under high load.

Manufacturers that we have met with indicate that although a number of difficult technical challenges remain for HCCI, they are still actively developing the technology with the hope that it might become part of an emission solution for 2010 and beyond. Reviewing the results summarized in Figure 21 below, NOx and PM emissions below the 2010 standards, one can readily see why engine researchers at all of the engine manufacturers remain interested in continuing to develop this technology.

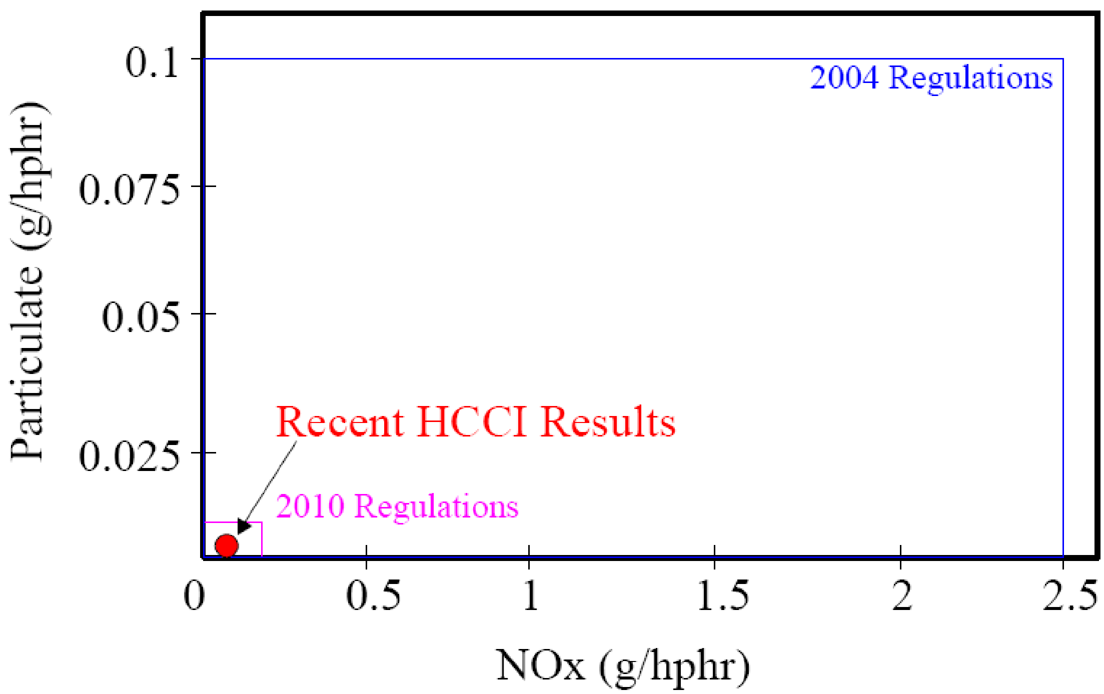

Figure 21. Demonstrated HCCI Performance for NOx and PM.

4. Clean Diesel Combustion

An EPA research team, with industry partners, is developing a low NOx diesel engine system called, Clean Diesel Combustion ("CDC"). CDC technology is based upon a design philosophy that utilizes management of the in-cylinder combustion process as the primary control for NOx reduction. Since the design philosophy relies upon several technology areas, it is difficult to quantify any single limit in its potential. In laboratory testing, the CDC system has demonstrated very low NOx emissions without the use of NOx after-treatment.

CDC technology relies upon in-cylinder NOx control, where NOx emissions are reduced in the engine combustion chamber. In-cylinder NOx control is achieved through advances in technology in the engine's fuel system, boost control, EGR and PM aftertreatment systems. CDC technology may be scaled to both light-duty and heavy-duty applications.

The key features of CDC technology include the following:

• A hydraulically intensified fuel system to lower PM and smoke emissions while improving engine efficiency

• A boost system which increases engine power and the efficiency of the combustion process, thus reducing emissions and increasing fuel economy

• Cooled Low Pressure Exhaust Gas Re-circulation which lowers peak combustion temperatures, reducing the formation of NOx

• PM aftertreatment to reduce remaining smoke, unburned hydrocarbons and carbon monoxide in the exhaust to levels required for future emissions standards.

Several engine and vehicle manufacturers are working to advance this technology with the EPA research team. These industry partners include both automotive manufacturers and heavy-duty diesel engine manufacturers. Detailed test results publicly disclosed have been limited to small-bore "automotive" sized engines.

D. Urea SCR

Selective Catalytic Reduction (SCR) catalysts that use ammonia as a NOx reductant have been used for stationary source NOx control for a number of years. Frequently, urea is used as the source of ammonia for SCR catalysts, and such systems are commonly referred to as Urea SCR systems. In recent years, considerable effort has been invested in developing urea SCR systems that could be applied to heavy-duty diesel vehicles with low sulfur diesel fuel. We now expect that urea SCR systems will be introduced in 2004 or 2005 in Europe to comply with the EURO IV heavy-duty diesel emission standards. The actual introduction dates in some countries will be earlier than the EURO IV implementation requirements due to tax incentives in those countries to promote early technology introduction.

EPA was aware that urea SCR systems were being developed for automotive applications at the time we set the 2007 emission standards, but we recognized two issues with the technology that precluded us from setting emission standards based on the urea SCR technology: 1) the lack of a national infrastructure to supply urea at diesel retail stations; and 2) the lack of a mechanism to ensure that urea is added in use. These two issues continue to be a concern of the Agency.

Over the last year, some engine and vehicle manufacturers have discussed with the EPA the possibility of using urea SCR as a means to meet the 2007 emission standard for NOx. Consistent with our statements in the 2007 rule, we have expressed our expectation that any manufacturer intending to certify a diesel engine using the urea SCR technology would need to first make a demonstration satisfactory to the Agency that the needed urea would be available to the end-user, and that the vehicle had appropriate systems designed to ensure the user appropriately filled the urea tank as necessary to guarantee emission control. The represented industry agreed with the Agency, that these were the appropriate metrics for ensuring emission control and that the burden should lie with the certifying manufacturer to show the metrics are being met.

As the Agency projected for 2007, it appears unlikely that urea will be generally available and therefore, we continue not to predicate our 2007 feasibility assessment on urea SCR use. However, we now believe it is possible that some engine manufacturers may introduce urea SCR systems in 2007 on a limited basis using a centrally-fueled fleet model. This means that the engine would not be certified for general use, but only for use by fleets that the certifying manufacturer can demonstrate to the Agency will have urea appropriately available to address our urea infrastructure concern. Just as for the general case, engine manufacturers would need further to demonstrate to the Agency that systems are in place to ensure urea use and to prevent system tampering (i.e., to ensure benefits are realized in use). We believe that it will be appropriate for the Agency to publish the provisions proposed by such manufacturers to address these issues and for the Agency to seek public comment from all interested stakeholders before making our own determination regarding the acceptance or denial of a plan. Presuming that manufacturers can develop plans that will robustly ensure urea use and NOx control, the Agency will then be able to certify vehicles using urea SCR that include these provisions.

It is clearly not a foregone conclusion that manufacturers will be able to develop an acceptable plan for urea use on a limited basis in 2007. We have not yet seen a concrete proposal from industry on how they intend to address our concerns, and we will not make our decision regarding its acceptability prior to seeking broader stakeholder comment on such a proposal. We are looking forward to receiving industry's plan, recognizing that if solutions are found to the fundamental issues regarding urea SCR, it may provide yet another means for realizing very low NOx emissions in the future.

E. 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 first progress review. This was a concern of EPA's as well, and we therefore began working with industry to address this issue.

The American Petroleum Institute's (API) Diesel Engine Oil Advisory Panel (DEOAP) and American Society for Testing and Materials' (ASTM) Heavy-Duty Engine Oil Classification Panel (HDEOCP) have met regularly throughout 2003 to lay the ground work for development of the Proposed Category-10 (PC-10) lube oil formulation for the introduction of model year 2007 highway diesel engines. The PC-10 category will be a low sulfur, low ash, low phosphate (SAP) oil formulation for heavy-duty on highway and non-road diesel engines. EPA is represented on this panel and is working 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.

During 2003 the DEOAP has addressed issues pertaining to new test methods for development of PC-10 oils, funding of PC-10 development, and sulfur/ash/phosphate chemical limits for the PC-10 lube oil formulation. In addition, the DEOAP established a Supplemental Performance Designation process that allows for a fast-track category development process. This fast-track development process will allow enhancements to be made to an existing lube oil category, without engine OEMs having to make a formal request for a new lube oil category. Enhancement are currently being made for the existing CI-4 category and it is anticipated that enhancements will be needed for the PC-10 category as technologies mature.

At this time, the PC-10 development process in on track to deliver a new lube oil formulation on time for introduction of 2007 emissions compliant highway engines, with new lubricant licensing occurring in the third quarter of 2006.

IV. Conclusions

The Agency has completed a comprehensive technical review of progress by the manufacturers of diesel engines and emission control systems in developing technology to reduce engine exhaust pollutants for 2007. During this review, the Agency met with almost thirty companies and reviewed first-hand the confidential data and analyses that companies would use to make their own decisions for 2007. Further, the Agency has conducted its own research and has partnered with the Department of Energy to further advance emission control technologies for 2007. We have carefully reviewed all of the information shared with the Agency and summarized broadly in this report. From our analysis of both confidential business information and public information, we can conclude the following:

- Engine manufacturers are on track for 2007 implementation.
- CDPFs will be used by all manufacturers for PM control.
- Generally, manufacturers will treat the NOx standard as a two-step process and will meet a 1.2 g/bhp-hr NOx emission level in 2007.
- All manufacturers can comply in 2007 with existing proven technologies.
- NOx control should not adversely affect fuel consumption and improvement may be possible over today's engines.
- Engine manufacturers' 2007 compliance plans are a building block for the technology package they plan to use to meet the 0.20 g/bhp-hr NOx standard in 2010.
- Engine manufacturers have adequate time to implement their full product development plans (i.e., all planned testing will be completed as needed in advance of 2007).
- Engine manufacturers will provide prototype vehicles in 2005 for early customer fleet testing consistent with their product development plans.
- All engine manufacturers have, or will in the coming weeks, complete their initial product development gateway reviews for 2007 which means:
  1. They have known solutions for 2007 compliance.
  2. Their cost for 2007 compliance matches an approved business plan.
  3. They have allocated the necessary resources for 2007 introduction.
  4. They are on target for a successful 2007 program launch.

- NOx adsorbers continue to improve in effectiveness and durability.

- NOx adsorbers are in production today on light heavy-duty trucks in Japan.

- NOx adsorbers will be the primary NOx compliance path for light-duty diesel vehicles in Tier 2.

- We continue to believe that NOx adsorbers could be applied in 2007 for compliance with the heavy-duty 2007 NOx standard.

- The CDPF technology is maturing and will be broadly applicable by 2007 with the addition of backup active filter regeneration approaches.

- Catalyzed diesel particulate filters (CDPFs) continue to be successfully applied where 15 ppm sulfur diesel fuel is available.

Appendix A: List of Acronyms

ABT	Averaging, Banking, and Trading
ACERT™	Advanced Combustion Emissions Reduction Technology trademarked
AEO	Annual Energy Outlook
APBF – DEC	Advanced Petroleum Based Fuels – Diesel Emission Control
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
ATA	American Trucking Association
CAA or the Act	Clean Air Act
CARB	California Air Resources Board
CDPF	Catalyzed Diesel Particulate Filter
DASL	Diesel Aftertreatment Sensitivity to Lubricants
DEM	Delayed Extended Main
DPF	Diesel Particulate Filter
EIA	Energy Information Administration
EMA	Engine Manufacturers Association
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 NOx Reduction
FACA	Federal Advisory Committee Act
FR	Federal Register
FSN	Filter Smoke Number
GPA	Geographic Phase-in Area
GVWR	Gross Vehicle Weight Rating
HDE	Heavy-Duty Engine
HDEOCP	Heavy-Duty Engine Oil Classification Panel
HDV	Heavy-Duty Vehicle
LTC	Low Temperature Combustion
MECA	Manufacturers of Emission Control Association
NAC	NOx Adsorber Catalyst

NMHC	Non-methane Hydrocarbons
NOx	Oxides of Nitrogen
NPRM	Notice of Proposed Rulemaking
NTE	Not-to-exceed
NVFEL	National Vehicle and Fuel Emissions Laboratory
OBD	On-Board Diagnostics
OEM	Original Equipment Manufacturer
ORNL	Oak Ridge National Laboratory
PADD	Petroleum Administrative Districts for Defense
PC-10	Proposed Category 10
PM	Particulate Matter
ppm	Parts per Million
RIA	Regulatory Impact Analysis
SAP	Sulfur, Ash, Phosphate
SET	Supplemental Emission Test
SO_2	Sulfur Dioxide
SOx	Oxides of Sulfur
SwRI	Southwest Research Institute
TCO	Temporary Compliance Option
TMA	Truck Manufacturers Association
TRALA	Truck Renting and Leasing Association
VOC	Volatile Organic Compound

Appendix B: HD 2007 Progress Review Meetings

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

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)	Hilite International
EmeraChem	NGK
Engelhard Corporation	Dupont
International Truck and Engine Corp.	Nissan Motor Company, LTD.
Ford Motor Company	IBIDEN
General Motors Corporation	PSA/Peugeot
Argillon	Toyota Motor Corporation
HD Humirel	Rhodia
Umicore	Lubrizol
Tenneco	Faurecia

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