APBF-DEC

Quarterly Update

**Advanced Petroleum-Based Fuels–
Diesel Emissions Control (APBF-DEC) Project**

#7, Fall 2002

Joint Meeting Provides Information on U.S., European & Japanese Fuels, Emissions Studies

Twenty-three speakers—representing the research programs of U.S., European, and Japanese companies, laboratories, and organizations—provided information about current research on fuels, vehicle systems, and emission effects at the *Motor Fuels: Effects on Energy Efficiency & Emissions in the Transportation Sector joint meeting in Washington, D.C.*, October 9-10.

The joint meeting was sponsored by the U.S. Department of Energy's (DOE) Advanced Petroleum-Based Fuels-Diesel Emissions Control (APBF-DEC) project, in collaboration with the Clean Air for Europe Program and the Japan Clean Air Program (JCAP).

Seventy-seven participants were welcomed by Steve Goguen on behalf of DOE's Energy Efficiency & Renewable Energy (EERE) Program. Mr. Goguen leads EERE's fuels technology team, which provides support for the APBF-DEC project. He cited the project's work to identify the best combination of low-sulfur (S) fuels, lubricants, and emission control systems and noted that non-petroleum fuels (e.g., synthetics and renewables) could become a reality by 2004 to 2010. He said the longer-term vision will be the FreedomCAR hydrogen/fuel cells program, which will mean freedom from petroleum dependence and pollutant emissions.

George Sverdrup, the APBF-DEC steering committee co-chair, described Phase I, which is focused on (1) vehicle systems, including two emission control devices, the selective catalytic reduction/diesel particle filter (SCR/DPF) and the nitrogen oxide (NO_x) adsorber/DPF, (2) sulfur effects from test fuels, and (3) emission measurements. He said the APBF-DEC team members have made considerable progress and were providing interim results at the joint meeting:

- Light- and heavy-duty platforms to measure the effects of fuel and lubricant composition on emissions under transient operations
- Comprehensive data on the status of fuel-engine-emission control technologies for reducing emissions
- Comprehensive data on the effects of fuel and lubricant properties on emissions of unregulated substances.

Members of the APBF-DEC project's steering committee and working group co-chairs plan to begin discussing the scope for Phase II, which starts in 2004 and continues through 2007. Several topics are being considered: continuing studies of the effects of sulfur (S) and other fuel properties (e.g., aromatics, oxygen, cetane); refinery process fuels from different refineries and Fischer-Tropsch fuels; and emissions measurements.

Summaries of presentations by representatives of APBF-DEC projects, the Clean Air for Europe Program, JCAP, and other combustion fuels research are provided on the following pages. The complete presentations are available at the following Web site: http://www.ott.doe.gov/motor_fuels.shtml.

BACKGROUND

The APBF-DEC is an industry/ government project to identify and evaluate (1) the optimal combinations of low-sulfur diesel fuels, lubricants, diesel engines, and emission control systems to meet projected emission standards for the 2000 to 2010 time period, while maintaining improvement in engine efficiency and durability and (2) properties of fuels and vehicle systems that could lead to even lower emissions beyond 2010.

Sulfur in the fuel is known to interfere with the functioning of most emission control technologies and has been implicated as a possible factor in the formation of ultrafine particulate matter (PM). A systems approach is being used, i.e., simultaneously investigating fuels, lubricants, engines, and emission control systems.

A government/industry steering committee and working groups are guiding the APBF-DEC project. Funding for the project is expected to total $33 million, including $19.3 million in cash ($14 million from the government) and $14 million in-kind contributions. The project is managed by DOE's National Renewable Energy Laboratory (NREL). Information about the APBF-DEC project is posted at: http://www.ott.doe.gov/apbf.shtml.

APBF-DEC is the successor to the Diesel Emissions Control-Sulfur Effects (DECSE) project. Its objective was to determine the impact of fuel sulfur levels on the performance and short-term durability of emission control systems, which could lower emissions of NO_x and PM from diesel-powered vehicles in the years 2002 to 2004. DECSE publications and technical reports are available at: http://www.ott.doe.gov/decse/.

For further information, contact either Wendy Clark at NREL, phone 303-275-4468, fax 303-275-4415, e-mail Wendy_clark@nrel.gov, or Helen Latham at Battelle, phone 614-424-4062, fax 614-424-5601, e-mail lathamh@battelle.org.

Selective catalytic reduction/diesel particle filter (SCR/DPF) technologies, fuels, engines– Southwest Research Institute (SwRI), San Antonio, TX, testing laboratory, test bed: Caterpillar C-12 engine.

Presenter: Magdi Khair, Southwest Research Institute.

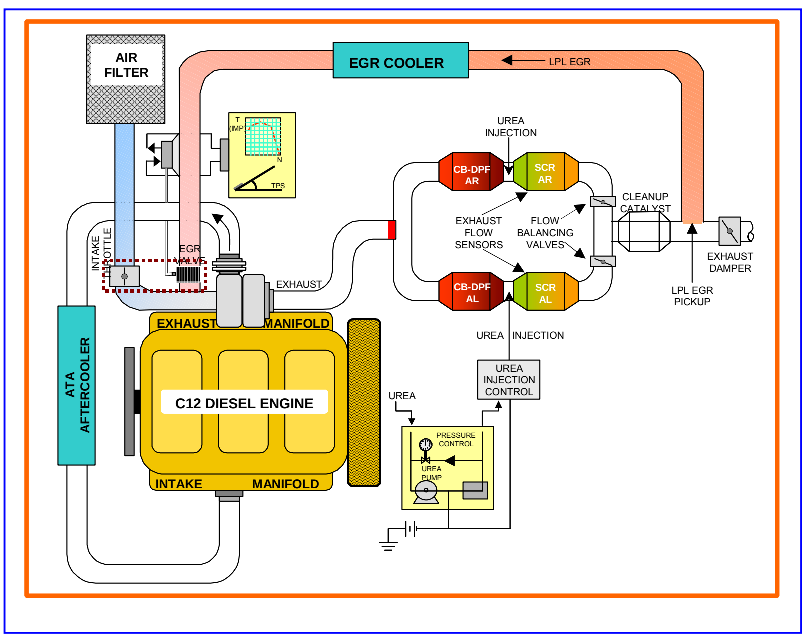
The technical approach for this project calls for 100 hours of testing during System A to compare the engine baseline (i.e., engine, steady-state and transient emission tests, 500 parts-per-million [ppm] S fuel) to a system designed to meet 2007 regulations*. The new system is testing 3-, 8-, and 15-ppm S fuel plus BP15 fuel under two protocols. All of the tests for unregulated emissions are being conducted with the BP15 fuel.

Several preliminary tests indicated:

- The Caterpillar test engine had transient NO_x/PM emissions of 3.5/0.07 grams per brake horsepower-hour (g/bhp-hr).**
- The low-pressure loop exhaust gas recirculation (EGR) system, with a DPF, was calibrated to yield more than a 50% reduction in NO_x and a 90% reduction in particulate matter (PM) when using 3-ppm S fuel and an exhaust gas recirculation system (EGR), in comparison to results when using 350-ppm S fuel.
- All low-sulfur fuels (e.g., 3-, 8-, 15-, and 30-ppm) using aftertreatment systems produced emissions below the 2007 regulatory standards for NO_x and PM for the steady-state emissions test.
- The transient emissions test showed that NO_x emissions were just over the 2007 limit, while the PM emissions were within the 2007 limit.

SCR/DPF. The selective catalytic reduction technology (SCR) is an emissions reduction device that, combined with a diesel particle filter (DPF) and advanced fuel formulations, has the potential to reduce regulated, unregulated, and toxic emissions. Two types of SCRs and DPFs are being evaluated.

The purpose of the test is to demonstrate the low diesel emissions possible by using the SCR/DPF, evaluate the sensitivity of emission controls to fuel variables, determine regulated and unregulated emissions with and without emission controls, and examine the emission control system's durability.



The test setup for the SCR/DPF project shows the Caterpillar C-12 diesel engine feeding the split exhausts, the urea injector, EGR, the equalizer cleanup catalyst, and other areas of the setup.

System A will be transferred to the durability cell for the last phase of its tests. Sensors will be recalibrated and placed in the test setup (see graphic at left). System B will analyze the advantages of adding the EGR to the SCR/DPF to provide a totally integrated system. The test setup features a split exhaust, a urea injection system, an EGR device, and a cleanup catalyst.

* The 2007 regulations limit emissions to 0.20 grams per brake horsepower-hour (g/bhp_hr NO_x and 0.01 g/bhp_hr PM).

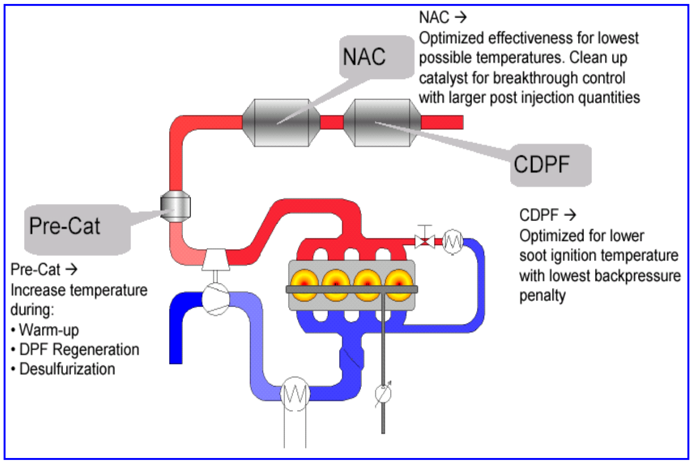
** U.S. EPA's emissions standards for trucks and buses are based on the amount of pollution emitted per unit of energy—expressed g/bhp_hr.

NO_x adsorber/diesel particle filter (DPF) technologies, fuels, engines – Staff from three laboratories reported on the progress of tests underway using NO_x adsorber/DPF technologies and three different platforms to assess the effects of fuel composition on the emission control systems' performances. Similar tasks are underway at each lab to: develop and refine regeneration and desulfurization strategies; measure regulated and unregulated engine-out baseline emissions; and evaluate the system's performance versus the fuel sulfur level over transient and steady-state cycles.

> **NO_x Adsorber/DPF.** The NO_x adsorber catalyst is a flow-through exhaust emissions control device with the potential to significantly reduce nitrogen oxides (NO_x) emissions in the exhaust from diesel engines. When combined with a DPF, the system also can oxidize the diesel particulate matter (PM), hydrocarbon (HC) and other unregulated emissions.
>
> The purpose of the three separate platforms is to demonstrate the potential of low-sulfur fuel to achieve stringent emission reductions from diesel engines of different power, using a system the includes the engine, fuel, NO_x adsorber, DPF, and thermal management technologies.

- **FEV Engine Technology, Inc., Auburn Hills, MI, test bed: a light-duty passenger car (Audi A4 Avant with a 1.9 liter (L) TDI engine). Presenter:** Dean Tomazic, FEV Engine Technology, Inc.

The project's goal is to demonstrate that the system (see graphic below) can meet the Tier 2, bin 5 light-duty vehicle emission standards for tailpipe emissions and evaluate the impact of varying sulfur levels on the systems performance. The test design considers strategies and tradeoffs, such as fuel economy versus emissions reduction.

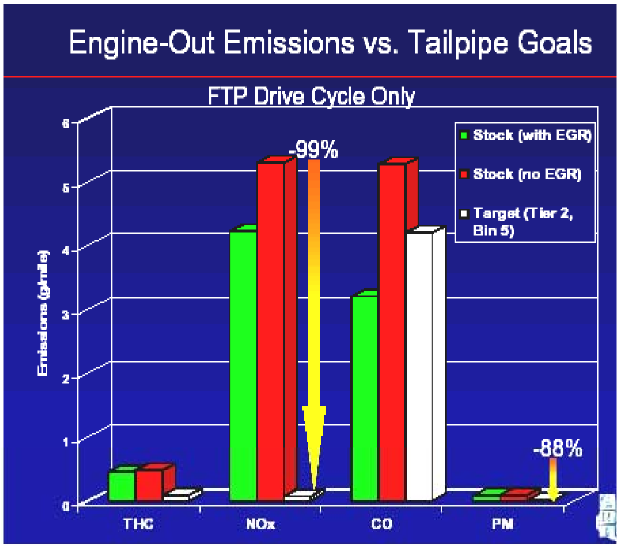


With the ECS system in place, the passenger car's NO_x and PM emissions will be reduced significantly.

One of the emission control systems being used during the aging and evaluation phase of the project combines a pre-catalyst (with oxidation and NO_x adsorbing capabilities), an underbody NO_x adsorber catalyst (NAC), and a catalyst-based diesel particulate filter (DPF). The second emission control system will be the same, except that the pre-catalyst will have only NO_x adsorbing capabilities. The graphic at left describes the functions of the first system's components. Initial test results, using a fresh emission control system, indicate that the system shows promise in achieving Tier 2 bin 5 regulations, although no aging studies have been conducted at this point.

- **SwRI, San Antonio, TX, test bed: a light-duty truck/SUV (a 2500 series Chevrolet Silverado, with a Duramax 6.6L engine). Presenter:** Cynthia Webb, Southwest Research Institute.

In addition to the key objective, which is to achieve proposed Tier 2 bin 5 emission levels using various fuel sulfur levels, this project is also determining whether regeneration and desulfurization strategies can be designed to maintain the tailpipe emission regulations. Two ECS configurations (single in-line and dual-branch)—with a NO_x adsorber catalyst and catalyzed DPF—are being tested for emission reduction capabilities. The systems will be used in conjunction with aggressive EGR for engine-out NO_x control. Enabling systems have been developed to modify the exhaust gas characteristics to help meet the emission control system's requirements. Steady-state strategies developed and refined in the test cell will be used as guidelines to be apply when the Silverado is tested over transient test cycles on a chassis dynamometer.



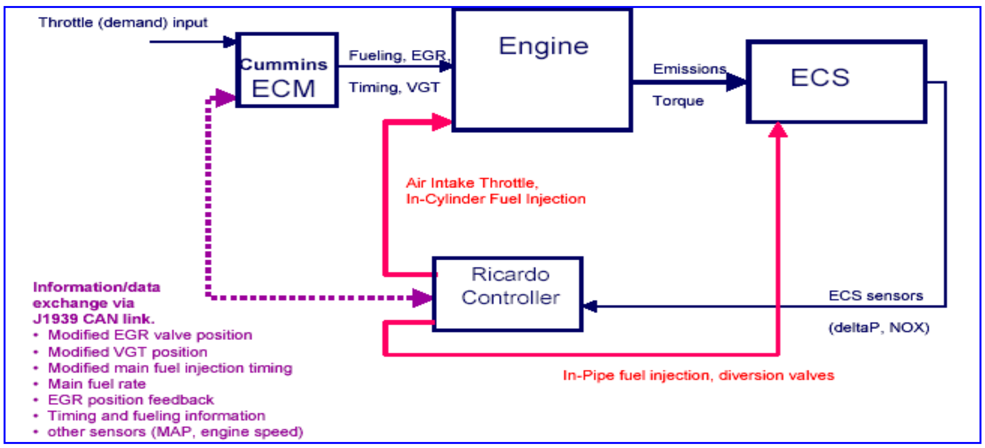
The engine-out emissions from the Duramax engine are reduced by using EGR, as indicated by the green bars. The "target" refers to the Tier 2 bin 5 emission standards.

Preliminary steady-state test results showed a potential NO_x emission reduction of more than 90% from the baseline of more than 4.9 grams per mile. The majority of the ECS calibration and fuel sulfur tests will be conducted during FY 2003.

- **Ricardo, Inc., Burr Ridge, IL, test bed: a heavy-duty engine (15L Cummins ISX, DOHC engine).**
  Presenter: Graham Weller, Ricardo, Inc.

The objectives of this project are similar to the two NO_x adsorber projects mentioned above (e.g., the effects of fuel S, engine durability, emissions, regeneration, desulfurization). However, the emissions goals are different because the 2007 emissions standards for heavy-duty engines are in brake-specific units and conducted on an engine dynamometer—0.20 grams per brake horsepower hour (g/bhp-hr) for NO_x and 0.01g/bhp-hr for PM. While this project does not include a vehicle integration task, attention will be given to designing a system that could be installed on a Class 8 truck. Two catalyst systems (single-leg and twin bed NO_x adsorber catalysts) are being tested up to 300 hours aging on 8- and 15-ppm S fuel to determine which system will then receive an additional 1,200 hours of aging.

Preliminary results indicate that the NO_x adsorber catalyst can reduce NO_x emissions by 85% and, at peak efficiency, by up to 98%. Early results also show that, using the federal test procedure (FTP), NO_x emissions can be reduced to 0.10-0.20 g/bhp-hr, nearing the 2007 targets. However, HC emissions were high (1.4 g/bhp-hr), and the associated fuel economy penalty is greater than desired (10%). Optimization of the rich regeneration strategy and addition of a downstream diesel oxidation catalyst (DOC) is required to minimize HC slip. The back pressure associated with the emission control devices has prohibited operating at high load conditions. Cycling the engine from lean to rich places additional demands on the engine, turbocharger, and EGR system, so durability effects on the engine may need to be evaluated further.



This schematic indicates pathways and controls in the test setup for the Cummins ISX heavy-duty engine.

Lubricants– Automotive Testing Laboratory (ATL), East Liberty, OH, test bed (Navistar T44E, 7.3L V8 engine, with retrofits).

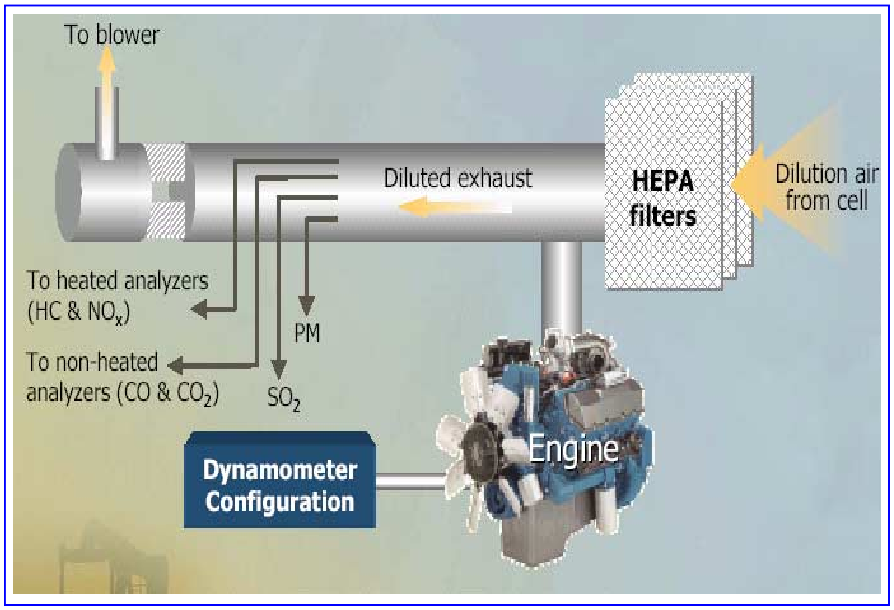
Presenters: Lisa Lanning, Automotive Testing Laboratories, Inc.; John Orban and Hsing-Chuan Tsai, Battelle.

Tests are being conducted with a medium-duty engine cell in two phases. Phase I focused on characterizing the effects of lubricant properties on engine-out emissions and developing methods to accelerate exposures of the ECS to lubricant-derived emissions. The objective of Phase II is to determine if lubricant formulations passing through the catalyst have any impact on the performance and durability of the diesel engine's ECS. The results will provide guidelines for catalyst-compatible lubricant formulation.

Lubricants. Testing of lubricant formulations is being conducted to determine which, if any, lubricant-derived components in the emissions are detrimental to the performance or durability of the emission control systems (ECS). The test engine is installed on a dynamometer combining a double-ended GE DC-electric brake (200hp) with a Go-Power DT-2000 water brake (800hp), which provides precise control and high torque/power absorption capability on a single in-line assembly.

The lubricants selected include four different base oils and 12 additive packages whose properties vary in elemental composition (e.g., sulfur, phosphorus) and ash levels. The test matrix included randomized test sequences, duplicate testing to evaluate repeatability, and periodic tests with a reference oil to account for testing trends. Emissions measurements for gases (HC, CO, CO_2, SO_2), and particulate matter (total PM [TPM], soluble organic fraction [SOF], sulfate [SO_4], metals, and polycyclic aromatic hydrocarbons [PAH]).

Testing was conducted on a 1999 International T444E engine (graphic on next page). Emissions measurements were taken during four steady-state test modes spanning a variety of operating conditions and exhaust temperatures. Among study questions were: (1) Are there significant differences in engine-out emissions attributable to oil properties; (2) If so, how much is due to properties of the additive package or base oil?



Test modes were conducted and emissions were measured for various gases and PM in the test cell pictured.

Preliminary conclusions were:

- Lubricant formulation has modest effects on regulated emissions (NO_x, HC, CO, PM).
- Sulfur content in oil has significant effects on sulfur emissions.
- Oil formulation (beyond its sulfur content) can have a significant impact on SO_2 emissions.
- Emissions from some metals (sulfur, phosphorus, zinc, calcium) correlate with their concentration in the oil.

Other Motor Fuels and Technologies Programs

An additional eight presentations described ongoing research on motor fuels and technologies affecting energy efficiency and on-road vehicle emissions. Here are brief summaries:

- **Overview of JCAP I and JCAP II. Presenter:** Yoshiaki Shibata, PEC.

The Japan Clean Air Program is a collaborative study by the automobile and petroleum industries in Japan that began in 1997 and continues to 2005. Additional support is provided by the national Agency of Natural Resources and Energy. The program, which is focused on reducing vehicle emissions, is researching gasoline and diesel fuels, engines, and emission control technologies to obtain information on related health effects, air quality, and costs. The first phase concentrated on achieving consensus among the collaborators, obtaining required data, and designing air quality modeling methods. The second phase of the program will conduct research to identify fuels and technologies that can ensure zero pollutants in vehicle emissions.

- **Overview of the Clean Air for Europe Activities. Presenter:** Giovanni DeSanti, Joint Research Center (JRC).

The program's objectives are to reduce pollutant emissions by optimizing engines and fuels, identifying the "fingerprints" of particulate matter sources, analyzing the samples, and determining the effects caused by the engine's operating conditions (with and without a catalyst or EGR) and the fuel's composition on particulate emissions. With the support of member states of the European Union, the program has developed an emissions policy for heavy-duty vehicles, is working on a multi-national strategy that will go into effect in 2004, is gathering technical information, and is disseminating information to stakeholders, policy makers, and the public. The first step, measuring the particulates, has been completed. The important effects on particulate matter from EGR-equipped engines and fuel quality (especially the oxygen content) are already apparent.

- **Status of Fuels and Lubricants for Diesel Engines (2002-2010). Presenters:** Karl Simon, U.S. EPA; Shuzo Nemoto, PEC; Giovanni DeSanti, JRC.

Mr. Simon discussed the U.S. EPA's mobile source emissions (both non-road and on-highway) and low sulfur fuel programs as well as progress toward meeting the 2007 regulations. He said the technology to limit PM in engine exhaust is becoming well established, but the NO_x adsorber technology is still in the development stage. He expects the NO_x catalysts to be available by 2007, but EPA is still learning about the technology's durability, especially as it relates to sulfur management. Mr. Nemoto said that his country's current regulations for PM are "more relaxed" than those in the U.S. or Europe, but during the past decade Japan's limits have become gradually stricter. By 2005, he said, Japan's regulations will be the most stringent in the world. Necessary technologies will then be in place to meet emission regulations, e.g., DPF traps to reduce PM, storage reduction catalyst to reduce NO_x, and a 50-ppm S cap by the end of 2005. Mr. DeSanti said that the current European Union regulations placed a limit of 2,000-ppm S on non-road fuels in January 2000 and will reduce that to 1,000-ppm by January 2006. Ultra-low sulfur fuels for the on-highway market will become more widely available in Europe over the next ten years. For instance, France is recommending that the EU set the maximum at 10-ppm S by 2006 instead of 2011, which is the EU's current plan. He said that France is also conducting life cycle assessments of alternative fuels to assist in making future decisions.

- **U.S. Fuels & NO_x Adsorber Projects.** **Presenters:** Nabil Hakim, DDC; Patrick Pierz, Cummins

Dr. Hakim presented information about the test of a NO_x adsorber catalyst in a heavy-duty truck engine, an engine that was not commercially available but part of an experimental design. The test design included both single and dual leg configurations. Results from the single leg test showed that when regeneration is occurring, NO_x is expelled and drivability suffers. The dual leg test revealed an extra fuel injection system was required and the reliability of the filter or catalyst is diminished. The NO_x sensor must be reliable if it is the only measuring instrument. Mr. Pierz summarized an evaluation of a NO_x adsorber system on a light-duty diesel vehicle, with the objective to develop generic aftertreatment subsystem technologies applicable for light-duty vehicle and truck engines. There were several conclusions. A NO_x conversion efficiency of 99% can be obtained with a preconditioned catalyst. Without preconditioning, a NO_x conversion efficiency of 89% could be achieved at about a 11.6% fuel penalty. The PM conversion was nearly 100%—below detection limits.

- **NO_x Catalyst Research.** **Presenter:** Richard Blint, General Motors Corp.

Dr. Blint described research that began in August under a cooperative agreement with the U.S. DOE to develop emission control strategies that may identify a new NO_x reduction catalyst for use in compression-ignition, direct-injection engines (CIDI). GM, the prime contractor (and ultimate customer), will provide diesel engines, exhaust system fabrication, catalyst validation, and emission control strategies. Accelrys will supply the software and informatics system. Engelhard will provide the exhaust system catalysts, catalytic materials, and testing. The tasks include design and synthesis of materials, searches for new materials, and development of tools (e.g., instrumentation) and exhaust systems. The goal is to have a new catalyst identified in 2002 to 2005 that will meet the 2007 regulations.

- **JCAP-I Diesel Engine Work Group Results.** **Presenter:** Toshiaki Kakegawa, PEC.

Mr. Kakegawa stated that the objective of JCAP was to examine the future direction of automobile and fuel technologies by evaluating exhaust emissions and the reliability for advanced types of fuel and engines. The NO_x storage reduction catalyst showed high NO_x efficiency—nearly undetectable NO_x emissions. But in a mileage accumulation test, NO_x tended to increase as the sulfur in the fuel increased. A similar result occurred in the CR-DPF test of PM. High NO_x reduction was obtained with the urea SCR, without a fuel economy penalty. Further work is required to stabilize the injection of urea and high NO_x efficiency in low temperature operation. Both the sulfur level and distillation characteristics of the fuel affected emissions.

- **Vehicle Emissions, Recent Results.** **Presenter:** Giovanni DeSanti, JRC.

Mr. DeSanti said that emissions from motorcycles significantly affect urban air quality, yet they do not fall under vehicle emission limits. In 1995, motorcycles accounted for 6.7% of the CO, 4.3% of the HC, and 0.2% of NO_x of the total road transport emissions, and their share of air pollution contribution is rising because of restrictions for other types of vehicles. Emissions from motorcycles are most significant during ozone-sensitive summer weekends. Motorcycle emissions were tested in comparison with an automobile, in two cycles, followed by a proposal to institute comparable emission limits.

- **U.S. Fuels Oxygenates.** **Presenters:** Tom Kenney, Ford; Charles Westbrook and Bruce Buchholz, Los Alamos National Laboratory.

Mr. Kenney described the Ad Hoc Auto/Energy CIDI R&D Program whose objectives are to determine the sensitivity of engine-out NO_x and PM to changes in diesel fuel in light-duty CIDI engines (Phase I) and demonstrate the potential of tailpipe emissions of advanced fuels in modern diesel vehicles with state-of-the-art controls and a PM/NO_x aftertreatment system (Phase II). Phase I results included: fuel properties can significantly affect diesel combustion and exhaust emissions; fuel reformulation alone is not sufficient to reach 2007 tailpipe emission standards; and an overall systems approach will be needed to address future tailpipe emission standards. Mr. Westbrook summarized his work involving diesel fuel chemistry modeling, whose objectives include using kinetic modeling to address problems in diesel and compression ignition engines, addressing specifically soot and NO_x production and ignition. Tri-propylene glycol mono-methyl ether (TPGME) reduces soot precursors, reinforcing the relationship of soot reduction to oxygen content in the fuel, and additives may be selected to optimize other operational characteristics. He concluded that it is now possible to rank oxygenates in order of their soot-producing tendency. Mr. Buchholz discussed the isotopic tracing of fuel components in combustion products, whose major objective is to determine the propensity of carbon in specific chemical structures to form certain emission products.