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Advanced Collaborative Emissions Study (ACES) Phase 3A: Characterization of U.S. 2007-Compliant Diesel Engine and Exposure System Operation

Joe L. Mauderly and Jacob D. McDonald

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ABOUT HEI

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- Identifies the highest-priority areas for health effects research;
- Competitively funds and oversees research projects;
- Provides intensive independent review of HEI-supported studies and related research;
- Integrates HEI's research results with those of other institutions into broader evaluations; and
- Communicates the results of HEI's research and analyses to public and private decision makers.

HEI receives its core funds for the Health Effects of Air Pollution program from the U.S. Environmental Protection Agency and the worldwide motor vehicle industry. Frequently, other public and private organizations in the United States and around the world support major projects and research programs. In the case of the ACES 3A project, funding was provided by the U.S. Department of Energy and members of the motor vehicle industry. HEI has funded more than 280 research projects in North America, Europe, Asia, and Latin America, the results of which have informed decisions regarding carbon monoxide, air toxics, nitrogen oxides, diesel exhaust, ozone, particulate matter, and other pollutants. These results have appeared in the peer-reviewed literature and in more than 200 comprehensive reports published by HEI.

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PREFACE

HEI's Advanced Collaborative Emissions Study

BACKGROUND

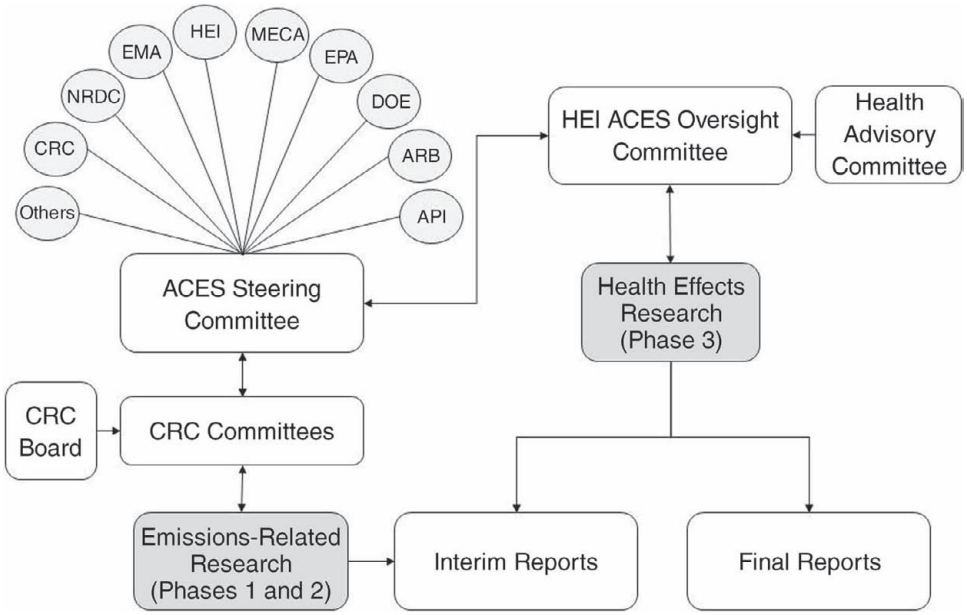
Because of health concerns related to exposure to diesel exhaust emissions, the U.S. Environmental Protection Agency (EPA*) and the California Air Resources Board (CARB) in 2001 adopted stringent new standards for diesel fuel and for heavy-duty diesel engine emissions. In 2007, engines were required to meet a new standard for particulate matter (PM) and, in 2010, to conform to an additional standard for nitrogen oxides (NO_x). In response, industry developed a combination of advanced-technology compression-ignition engines, exhaust aftertreatment systems, and reformulated fuels to meet these stringent standards, which were expected to result in substantially reduced emissions of PM, NO_x, and other exhaust constituents. The EPA and CARB projected that the targeted emissions reductions of about 90% (compared with emissions from pre-2007 heavy-duty diesel engine systems) will have substantial public health benefits.

The Advanced Collaborative Emissions Study (ACES) is a cooperative, multiparty effort conceptualized in 2005 to characterize the emissions and assess the safety of these new, advanced heavy-duty diesel engine systems and fuels. The ACES program consists of three phases:

- **Phase 1:** Extensive emissions characterization of four production-ready heavy heavy-duty diesel (HHDD; i.e., gross vehicle weight higher than 33,000 lb) engines equipped with control systems designed to meet the 2007 standards for reduced PM. This phase was conducted at Southwest Research Institute (SwRI) in 2007 and 2008 and was the basis for selecting one HHDD engine/control system for health testing in Phase 3.
- **Phase 2:** Extensive emissions characterization of a group of diesel engine and control systems intended for production that met the more stringent 2010 standards (including more advanced NO_x controls). This phase is being conducted at SwRI during 2012.
- **Phase 3:** Health effects assessment in rodents using one selected 2007-compliant heavy-duty diesel engine system. This phase started in 2008 with the installation of a specially designed emissions-generation and animal-exposure facility at the Lovelace Respiratory Research Institute (LRRI) and is being conducted in two parts. The 2007-compliant engine underwent emissions characterization (Phase 3A) before its use in an animal chronic-inhalation study with health measurements at several time periods (Phase 3B). The core of the ACES health assessment comprises a chronic-inhalation bioassay of cancer and noncancer endpoints in rats, similar to the standard National Toxicology Program (NTP) bioassay, and a 90-day inhalation study in mice. In addition to assessing the potential carcinogenicity of whole diesel exhaust (particles and gaseous components), these health studies will provide information on chronic toxicity (through histopathologic analyses of multiple organs at interim sacrifices and at the end of the study) and on in vivo genotoxicity, inflammation, and other noncancer health endpoints that have been associated with exposure to diesel exhaust.

The Figure in this Preface provides an overview of the ACES entities and stakeholders. The Coordinating Research Council (CRC) initiated and oversaw the emissions characterizations in Phases 1 and 2 of ACES under its committee structure for such projects. The design and implementation of the health effects research in Phase 3 and overall reporting of results for ACES are the responsibility of HEI and are overseen by

*A list of abbreviations and other terms appears at the end of the Project Report.



ACES flowchart including the ACES entities and stakeholders. API = American Petroleum Institute; ARB = Air Resources Board (California); CRC = Coordinating Research Council; DOE = U.S. Department of Energy; EMA = Truck & Engine Manufacturers Association; EPA = U.S. Environmental Protection Agency; HEI = Health Effects Institute; MECA = Manufacturers of Emission Controls Association; NRDC = Natural Resources Defense Council.

the HEI ACES Oversight Committee (a subset of the HEI Research Committee augmented by independent experts from several disciplines), with advice from a Health Advisory Committee of ACES stakeholder experts. The overall effort has been guided by an ACES Steering Committee consisting of representatives of HEI and CRC, along with the U.S. Department of Energy, U.S. EPA, engine manufacturers, the petroleum industry, CARB, emission control manufacturers, the National Resources Defense Council, and others. At the inception of ACES, the first step taken jointly by the CRC and HEI committees was the development of a detailed project plan that formed the basis for the subsequent requests for applications (RFAs) issued by CRC and HEI.

This Communication provides the results of the 2007-compliant engine exhaust characterization under various operating conditions in both the dilution tunnel and the animal-exposure chambers (Phase 3A) before the start of the inhalation exposures. The sections below provide some background on Phase 1, the process leading to the selection of the investigators for Phase 3, and the scope of Phase 3A activities.

PHASE 1

To implement this program, CRC issued a request for proposals (RFP) in January 2006 for an emissions characterization facility with demonstrated expertise to conduct emissions characterization following EPA regulations. After a CRC technical panel reviewed the responses, a team led by Dr. Imad Khalek at SwRI was selected by CRC to conduct Phases 1 and 2. In April 2007, four heavy-duty 2007-compliant engine and control systems (from Caterpillar Inc., Cummins Engine Company, Detroit Diesel Corporation, and Volvo Powertrain of North America) were delivered to SwRI for characterization of regulated and unregulated emissions during preselected test cycles as part of Phase 1. Throughout ACES, the engines were referred to as A, B, C, and D without revealing the identity of any of the manufacturers.

To cover a broad range of engine operating conditions, Khalek and colleagues used a number of test cycles:

- Federal Test Procedure (FTP), a transient cycle that is the basis for EPA engine certification and audit

- CARBx-ICT, which includes the idle, creep, and transient portions of the CARB heavy heavy-duty diesel engine (HHDDE)-5 Modes test cycle (CARB 5-Modes)
- CARBz-CH, which includes the cruise and high-speed cruise portions of the CARB 5-Modes
- A specially designed 16-hour cycle (described below), which includes four 4-hour segments consisting of FTP segments mixed with CARB 5-Modes

During the development of the ACES program, the HEI Oversight Committee decided that the animals would be exposed for 16 hours per day, similar to some earlier chronic-inhalation studies of diesel exhaust. This exposure regimen would maximize the received dose (duration × concentration) of diesel engine exhaust, given the expected very low particle concentrations produced by the 2007-compliant engine and after-treatment systems, and would still allow sufficient down-time for cage maintenance and animal husbandry. At the request of CRC, a team at West Virginia University developed a 16-hour engine operating cycle mainly for use in the Phase 3 health studies, but also to be used at SwRI during Phase 1 for comparison with the shorter cycles and to provide comparable information on system performance once the selected engine was moved to LRRI for the animal exposures. The 16-hour cycle was designed to be representative of modern truck usage and includes a broad range of engine activity reflecting both urban and rural (highway) driving. Details about the development of the cycle can be found in an article by Clark and colleagues (2007). The 16-hour cycle was also capable of adding useful information on emissions during particle filter regeneration, which does not occur during the shorter test cycles. As part of the 16-hour cycle tests, the diesel engine exhaust was delivered to an animal chamber for characterization of the exhaust under conditions similar to the animal exposures to be performed at LRRI (see later description). Details about the protocol, methods, and results of the Phase 1 study can be found in the final report, *Phase 1 of the Advanced Collaborative Emissions Study*, published by CRC (Khalek et al. 2009) and a subsequent paper by Khalek and colleagues (Khalek et al. 2011).

After the emissions characterization of the four 2007-compliant engines in May 2008, HEI randomly selected engine B for the health studies. The process for engine selection is described in the *Final Plan for Engine Selection* provided in Appendix A (available on the HEI Web site at *www.healtheffects.org*).

A duplicate engine (referred to as *engine B′*) of the same model and make as the engine selected was subsequently tested at SwRI using the same protocol as that for the original four engines. This engine was intended to serve as a backup in the event of a breakdown of the primary engine for which repairs were estimated to last more than one or two days. This backup engine underwent a set of emissions tests similar to those for engine B, with additional simulated high-altitude testing to mimic the conditions at LRRI, which is situated at an altitude of about 5300 ft (1600 m). In the summer of 2008, when testing was completed, SwRI delivered the two engines (B and B′) to LRRI.

PHASE 3

In 2006, HEI issued RFP 06-1, *Exposure Facility and Conduct of a Chronic Bioassay*, soliciting proposals for a multidisciplinary team to design and implement an engine facility with an engine dynamometer and a dilution system, to characterize the engine exhaust and animal chamber exposure, and to conduct an animal chronic-inhalation bioassay. The bioassay would include standard assessments of general health status, tumor incidence, and histopathologic changes in all major organs, as well as targeted measurements (such as inflammation and genotoxicity) that are not part of the standard NTP bioassays. For some of those additional endpoints, HEI issued RFA 06-2, *Additional Health Effects Measurements During the Chronic Bioassay and Short-Term Study*, to solicit applications for investigators to conduct the additional measurements in collaboration with the investigators funded under RFP 06-1.

A team led by Drs. Joseph Mauderly and Jacob McDonald at LRRI submitted a proposal for RFA 06-1 in July 2006. The proposal was reviewed by the HEI ACES Oversight Committee, which recommended the LRRI team for funding to conduct the core inhalation studies in Phase 3. A special facility was constructed at LRRI for housing the dynamometer and the 2007-compliant engine — which was considerably larger than engines previously tested at LRRI — and for delivering the exhaust to the animal-exposure chambers. A protocol for commissioning the dynamometer and characterizing the engine exhaust and the atmospheres in the

exposure chambers was developed by the LRRI team and approved by the HEI ACES Oversight Committee after receiving input from the Health Advisory Committee. The investigators at LRRI used a *mule* engine (a third engine, of the same make and model as the one selected at the end of Phase 1) for the initial commissioning of the test cell to verify that all parts of the system were operating correctly in order to avoid the unlikely event that test engine B or backup engine B′ would be damaged during the commissioning process. After several weeks of mule engine operation, which showed that all operating and control systems were functioning correctly, the LRRI investigators installed test engine B. They conducted initial tests to calibrate the engine and dynamometer control inputs, verify that the dynamometer was delivering the expected power during all segments of the engine map (i.e., the results of a procedure to determine the performance of an engine at selected operating points), and confirm that the engine was operating properly during various steady-state modes.

Once this component of the study was completed, the investigators started to characterize the engine B emissions, initially in the dilution tunnel using steady-states modes and the FTP cycle (to provide a more direct comparison with the Phase 1 results) and subsequently in the chambers using the 16-hour cycle. The fuel used in Phase 3A was provided by SwRI and was from the same batch as that used in Phase 1. (The fuel for Phase 3B is being provided by a local fuel supplier.)

Selection of Engine B′ as the Main Engine

At the inception of ACES, the plan for the Phase 3 animal exposures was to use the original test engine and to employ a backup engine only in the event that the main engine broke down and needed extensive repairs. Thus the backup engine B′ did not undergo the same detailed characterization at SwRI. During Phase 3A, the LRRI team first tested engine B, followed by engine B′. As shown in Tables 10 through 15 of this Communication, some differences between engines B and B′ were observed both at SwRI and at LRRI during the steady-state and FTP modes. However, the differences were small — given the low level of emissions from both engines — and could be due to interengine variability and to the fact that engine B′ was produced about a year after engine B and had updated engine and emissions controls. At the time Phase 3B was about to start, engine B′ had a larger share of the market for this model (more than two-thirds of the 2007-compliant engine market) than the original engine B, and its market share was expected to increase over time. Therefore, after consultation with the engine manufacturer, the HEI ACES Oversight Committee decided that engine B′ should be used as the main engine for the animal exposures at LRRI, with the original engine B serving as the backup. Thus, additional Phase 3A inhalation chamber characterizations were conducted using engine B′.

Exhaust Dilutions

Four chamber exposure levels were targeted for the animal bioassay: low, medium, and high diesel exhaust dilutions, and clean air. In previous diesel exhaust animal-exposure studies, dilution levels were based on particle mass concentrations. However, this approach was no longer viable because of the low particle concentrations in the exhaust of the 2007-compliant diesel engine and control systems (more than 90% lower than in the exhaust of older engines). The HEI ACES Oversight Committee therefore decided, after discussion with the investigators and the ACES stakeholders, to set dilutions based on predetermined NO_2 concentrations. This decision was made because NO_2 is the pollutant with the highest concentration in the exhaust of the 2007-compliant engines, and noncancer health effects have been observed with exposure to NO_2 and with whole diesel exhaust from older diesel engines in previous animal inhalation studies. The specifics of the decision about the NO_2 concentrations are as follows:

1. **The highest concentration of NO_2 would be 4.2 ppm.** This concentration was derived from the study by Mauderly and colleagues (1989) of chronic NO_2 exposures, in which animals were exposed to NO_2 at 9.5 ppm for 7 hours per day for 6 months; this concentration would serve as the maximum tolerated dose (MTD). The equivalent concentration for a 16-hour-per-day exposure duration is 4.15 ppm. However, given that actual concentrations vary during the 16-hour cycle and may end up slightly below or above the target, the HEI ACES Oversight Committee

recommended that concentrations should not go below 4.0 ppm. At this concentration, it was deemed possible to control the exposure chamber temperature to within the specified range.

2. **The lowest concentration would be 0.1 ppm**, or as close as possible to that concentration, in order to provide a likely no-observed-adverse-effect level (NOAEL). This concentration approaches the U.S. EPA ambient NO_2 air quality standard of 0.053 ppm. Concentrations in this range would be expected to be quite variable because of the high dilution ratio.
3. **The intermediate concentration would be 0.8 ppm.** Based on the highest and lowest concentrations, the HEI ACES Oversight Committee recommended targeting 0.8 ppm (but not exceeding it) and going no lower than 0.7 ppm.

An additional issue to consider in setting the highest chamber concentration was the chamber temperature. The acceptable range of temperatures with the animals in the chamber was set at 75° ± 3°F. A cooler was installed in the chamber to ensure that temperatures did not rise too high during the exposures.

SUMMARY

The results of Phase 3A of this study are described in this Communication. Initial results were presented to all ACES stakeholders in November 2009. After operating the engine for several additional weeks, the engine manufacturer certified that both engines B and B′ were operating properly. The HEI ACES Oversight Committee authorized the start of Phase 3B in April 2010.

This Communication provides important background information on the characterization of pollutant emissions and their concentrations in the animal-exposure chambers for a series of forthcoming ACES reports on the health effects of short-term and chronic inhalation in animals exposed to exhaust from a 2007-compliant diesel engine. A draft report of the Phase 3A results was received in August 2010 and was reviewed by members of the HEI ACES Oversight Committee and outside experts. Their comments were sent to the investigators, who provided a revised report in mid 2011. The revised report underwent minor editing for clarification; it has not been reviewed by the HEI Review Committee.

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APPENDICES AVAILABLE ON THE WEB

Appendix A contains a report describing the selection of the study engine. It is available on the HEI Web site, *http://pubs.healtheffects.org.*

Advanced Collaborative Emissions Study (ACES) Phase 3A: Characterization of U.S. 2007-Compliant Diesel Engine and Exposure System Operation

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EXECUTIVE SUMMARY

In Phase 3A of the Advanced Collaborative Emissions Study (ACES*), described in this Communication, a commissioning and characterization protocol was implemented at the Lovelace Respiratory Research Institute (LRRI) in order to evaluate the adequacy of the diesel engine operation and animal exposure systems for conducting a subsequent inhalation exposure study (Phase 3B). The objectives of this portion of the ACES program were to do the following:

1. Confirm proper performance of the engine and exposure systems during commissioning;
2. Compare emissions data at LRRI with comparable data from Southwest Research Institute (SwRI) to verify similar engine performance in both locations;
3. Fine-tune the dilution–exposure system and confirm stable operation;
4. Generate atmosphere data at dilution conditions specified for Phase 3B, the animal chronic-inhalation bioassay phase of the study; and
5. Assess system performance to enable development of criteria for validation of the entire exposure system.

The facility commissioning included assessments of engine and engine control system operation and the evaluation of predefined performance criteria for engine cooling, engine exhaust and dilution air, test cell ventilation, fuel conditioning, engine load and speed, data acquisition, and engine cycle performance as assessed by the 40 CFR Part 86 U.S. Federal Test Procedure (FTP). As a final verification of performance, the engine manufacturer reviewed all the data and confirmed proper performance of the engine and test system.

Diesel emissions data were collected to assess gas phase and particulate matter (PM) emissions under steady-state operation, during the FTP cycle, and using the 16-hour engine cycle that was adapted for the ACES program. Characterization was conducted on two engines, termed B and B′. The data from the steady-state and FTP cycles were considered the best representation for comparison with the studies conducted at SwRI in order to determine emission rates for the engines. Despite differences in dilution system configuration and altitude, the comparison to SwRI was conducted to ensure the engines were not performing outside of a normal range. Whereas there were some differences between the emissions observed at SwRI and LRRI, the results were considered to be reasonably similar, and sufficient to justify proceeding to Phase 3B. A slight concern was noted because the carbon dioxide (CO_2) concentrations reported at LRRI were as much as about 20% higher than those reported by SwRI. This was investigated further in a supplemental characterization, as described below.

This Project Report describes Phase 3A of Drs. Joe L. Mauderly and Jacob D. McDonald's 4-year study, "Development of a Diesel Exhaust Exposure Facility and Conduct of a Chronic Inhalation Bioassay in Rats and Mice." Phase 3A, "Development of a Diesel Exhaust Exposure Facility," began in October 2008. Total expenditures for Phase 3A were $398,588. The draft Project Report from Mauderly and McDonald was received for review in August 2010. The report was reviewed by technical experts identified by the Coordinating Research Council and the Health Effects Institute. A revised report, received in September 2011, was accepted for publication in October 2011. During the review process, the technical experts and the investigators had the opportunity to exchange comments and to clarify issues in the Project Report. The report was not reviewed by the HEI Health Review Committee. Correspondence concerning the Project Report may be addressed to Dr. Jacob McDonald, Lovelace Respiratory Research Institute, 2425 Ridgecrest Drive, S.E., Albuquerque, NM 87108.

Although this document was produced with partial funding by the United States Department of Energy (DOE), under the terms of Contract/Award Number DE-AC26-05NT42429, and certain motor vehicle and engine manufacturers, the opinions expressed herein are those of the authors and do not necessarily reflect the views of DOE or motor vehicle and engine manufacturers. This document has not been reviewed by public or private party institutions, including those that support the Health Effects Institute; therefore, it may not reflect the views of these parties, and no endorsements by them should be inferred.

* A list of abbreviations and other terms appears at the end of the Project Report.

The composition of the exposure chamber atmosphere was characterized in detail and the final dilution targets were set to concentrations of 4.2, 0.8, and 0.1 ppm nitrogen dioxide (NO_2). Most of the exposure system characterization was conducted at the 4.2 ppm NO_2 target. This included measurement of regulated gases, particle mass, size distribution, real-time mass, and detailed chemical composition. Particle penetration through the dilution system and exposure chamber performance were also assessed at the 4.2 ppm NO_2 level. The composition of the chamber atmosphere at the high-exposure level showed that the exposure system performed reproducibly, had sufficiently homogenous exposure atmospheres (only 0.36% spatial and 2.2% temporal variation within exposure chambers), and reached a steady state of 90% of concentration within 7 minutes. At an average of 4 ppm NO_2, the nitrogen monoxide (NO) concentration was 2.9 ppm, CO_2 was 2885 ppm, carbon monoxide (CO) was 3.1 ppm, total hydrocarbons (THC) were 0.1 ppm, and particle mass concentration was approximately 10 to 17 $\mu g/m^3$ on average. When measured in real time, most of the particle mass was observed during the 1 to 2 diesel particulate filter (DPF) regenerations that occurred during each 16-hour cycle. The particle number count also peaked during these periods and yielded particle size distributions that varied throughout the duty cycle, but were predominantly less than 50 nm in diameter.

The detailed composition of the test atmospheres is provided in Appendix D to this report (available on the Web only at www.healtheffects.org). As expected, most of the measured atmosphere constituents were low in concentration. Among the semivolatile organic compounds (SVOCs), hopanes and steranes were not detected. Of the remaining compounds, very little was observed on the filter, which was analyzed separately from the polyaromatic adsorbing resin (XAD) sorbent that captures the gas-phase SVOCs. The major classes of gas-phase SVOCs observed included the alphatic (straight chain and cyclic) SVOCs, acids, and lower molecular weight polycyclic aromatic hydrocarbons. Of the volatile organic compounds (VOCs), most were of low molecular weight (less than 5 carbon atoms) and were acetylene or alkanes/alkenes. Some aromatics were observed (e.g., toluene), but the benzene concentration was low. For the particle characterization, there was reasonable agreement (~10%) between weighed mass and the sum of measured species considering the uncertainty in each of the measurements. Appendix Figure D1 (see Appendix D) shows the composition of the PM in the exposure atmosphere. Carbon, which was primarily organic, accounted for approximately one-third of the mass. The inorganic ions (mostly sulfate and ammonium) made up about half of the mass; the remaining mass was made up of elements.

After execution of the primary study protocol, a supplementary characterization was conducted to further assess the robustness and reproducibility of the system, to further investigate the higher-than-expected CO_2 concentrations (compared with concentrations observed at SwRI), and to evaluate the particulate mass measurement technique. The results of this supplemental characterization showed adequate system stability (determined by consecutive days of operation and reasonable consistency in atmosphere composition). CO_2 was investigated by calculating the predicted CO_2 based on a mass balance of carbon in the fuel and dilution factors compared with the CO_2 measured in the exposure system. The measured CO_2 was within 3% of predicted in the steady-state tests and within 8% during the FTP cycle. These differences were considered similar enough to not merit further investigation into any variation in CO_2 between sites. The assessment of particle mass measurement technique involved comparing mass collected on the Teflon-membrane filters at variable frequencies and volumes. These results were also compared with PM mass measured with the Dekati mass monitor (DMM). The results from the DMM showed reasonable agreement with the filter measurements, although filters collected during a single day showed better agreement than those collected over multiple days. Filters collected on a single day also showed improved proportionality of concentrations across the three dilutions (based on NO_2 concentration). As a result, we selected a single-day time frame for future collections. In addition to these tests, we compared PM mass (on filters) and particle number (measured using a condensation particle counter [CPC]) at the exposure chamber inlet with concentrations measured in the chamber. Those tests showed an approximate 15% to 20% loss of PM mass and particle count from the inlet to the chamber.

In addition to the commissioning and characterization, a complementary component of the work — not defined originally in the Phase 3A protocol — was the evaluation of the robustness of the test facility. As part of the final commissioning phase, engine B was operated for 1 month with no failure that might require shutting down an inhalation exposure. In order to evaluate the second engine, engine B′ was then exchanged for engine B and was operated for 15 or more days. The resulting exposure characterization showed that, for engine B′, despite some variability, the average exposure targets of NO_2 were again achieved within 10%. Overall, the commissioning and characterization phase justified proceeding to the inhalation exposures to conduct Phase 3B.

BACKGROUND

ACES is a multidisciplinary program being carried out by HEI and the Coordinating Research Council (CRC) to better characterize the composition and potential toxicity of advanced technology compression ignition, engines, exhaust after treatment, and reformulated fuels that have been developed to meet 2007 and 2010 U.S. Environmental Protection Agency emissions standards. The program consists of several phases designed to characterize 2007-compliant emissions (Phase 1), characterize 2010-compliant emissions (Phase 2), and assess the toxicity of exhaust from both technologies (Phase 3). ACES Phase 3A comprises the development of an engine facility, conduct of emission and atmosphere generation trials, and production of data leading to the selection of animal exposure conditions and the conduct of an animal inhalation study (Phase 3B). This report describes the results of Phase 3A and, where appropriate, compares these results with data obtained during the Phase 1 characterizations at SwRI (Khalek et al. 2009). It summarizes (1) the commissioning and shakedown of the engine lab facility; (2) the development and testing of engine performance with three steady-state modes, the FTP cycle, and the ACES engine cycle; (3) the evaluation of emissions characteristics from the cycles; and (4) the development of test atmosphere characterizations relevant to the final inhalation protocol. The protocol and amendments to the protocol are provided as Appendices B and C, respectively, to this report (available on the HEI Web site at *www.healtheffects.org*). Detailed chemical characterization was performed under subcontract with the Desert Research Institute (DRI) (Barbara Zielinska, principal investigator).

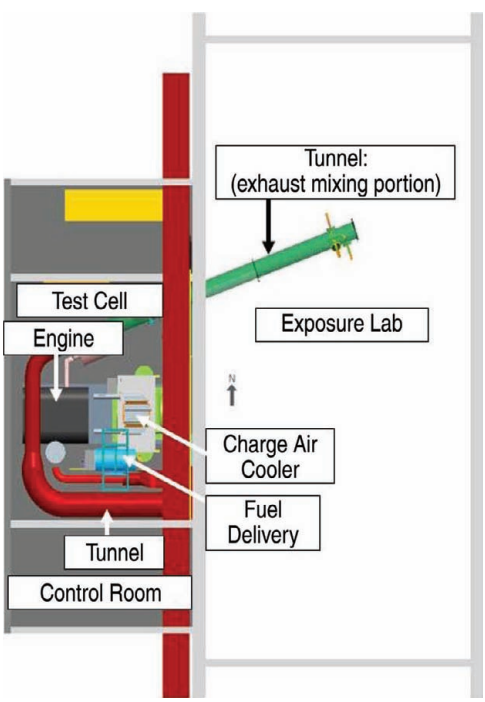


Figure 1. Overhead view of the engine laboratory and dilution tunnel. The tunnel portions shown in red are upstream from the engine exhaust mixing. The exhaust mixing portion is green, and the extraction point for the exposure chamber distribution system is at the end of the dilution tunnel (the remainder is routed to a waste stack). The charge air cooler is shown in grey. The engine is shown in black, and the fuel delivery system in blue. The dynamometer is shown in light green.

ENGINE AND EXPOSURE FACILITY

Figures 1 and 2 show schematics of the engine laboratory and dilution tunnel. The laboratory is equipped with a Dyne Systems Dymond series 550-horsepower–rated alternating-current dynamometer that has an Inter-Loc V Modular Multi-Loop Controller. The exhaust was transmitted through a 2007-compliant aftertreatment system provided by the engine manufacturer. The dilution tunnel was not a constant-volume system (as was used at SwRI). Rather, the tunnel operated at a constant pressure maintained by the presence of a supply air bypass that allowed excess air to be dumped to the engine room. The maximum combustion airflow was approximately 1300 cubic feet per minute (cfm). The nominal dilution tunnel flow was 2500 cfm.

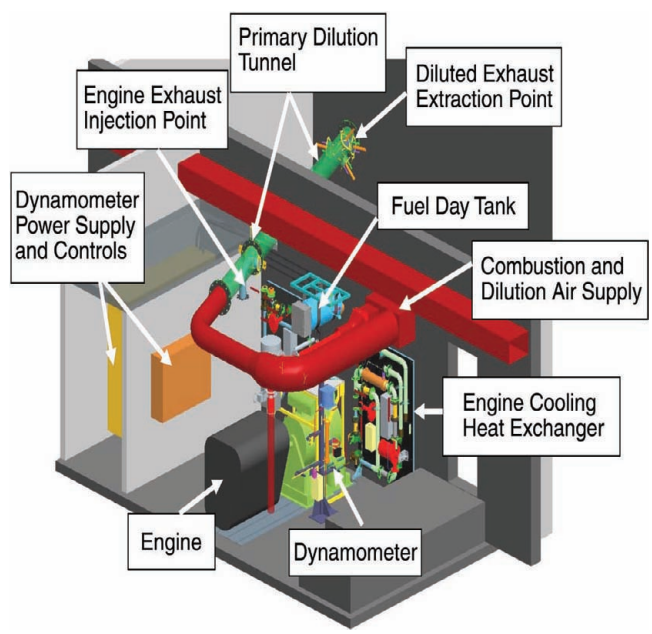


Figure 2. Front quarter view of engine laboratory and dilution tunnel. The tunnel portions shown in red come before the mixing of the engine exhaust. The green area shows the exhaust mixing section and the extraction point for the exposure chamber distribution system. The engine is shown in black, and the fuel delivery system in blue. The dynamometer is shown in light green.

Tunnel dilution air and combustion air were filtered via charcoal and high-efficiency particulate airfilters.

As described earlier, the engine manufacturer provided two engines, termed B and B′. The commissioning of the facility and the more detailed characterization were conducted with engine B. Engine B′ was successfully exchanged for engine B, and a more limited characterization of that engine was conducted. Chevron, No. 2, ultra-low sulfur diesel, was the fuel used for all testing and was supplied off the rack by a local Chevron distributor. Engine lubricating oil for ACES was donated by Lubrizol and was a proprietary blend.

Figure 3 shows photographs of the aerosol extraction point, and Figure 4 shows a schematic of the secondary and tertiary dilutions along with the inhalation exposure chamber. Aerosol was extracted from the dilution tunnel through probes that ranged in diameter from 0.9 to 5 cm. Aerosol then transited through a flow-through muffler before two more bypass and dilution steps. The distance from the extraction point to the exposure chamber was approximately 6 m. The transit line was composed of 5-cm diameter stainless steel tubing. The secondary and tertiary dilution air was medical-grade compressed air.

The extraction points for aerosol characterization from the chamber are shown as small circles (sample ports) on the front panels of the exposure chamber (Figure 4). Most of the chamber measurements were obtained from the middle ports. The gas analyzers resided on a platform above the exposure chambers.

COMMISSIONING OF ENGINE FACILITY

The objectives of the initial commissioning phase were to ensure (1) proper operation of the mechanical systems, (2) proper operation of the electrical systems, (3) proper

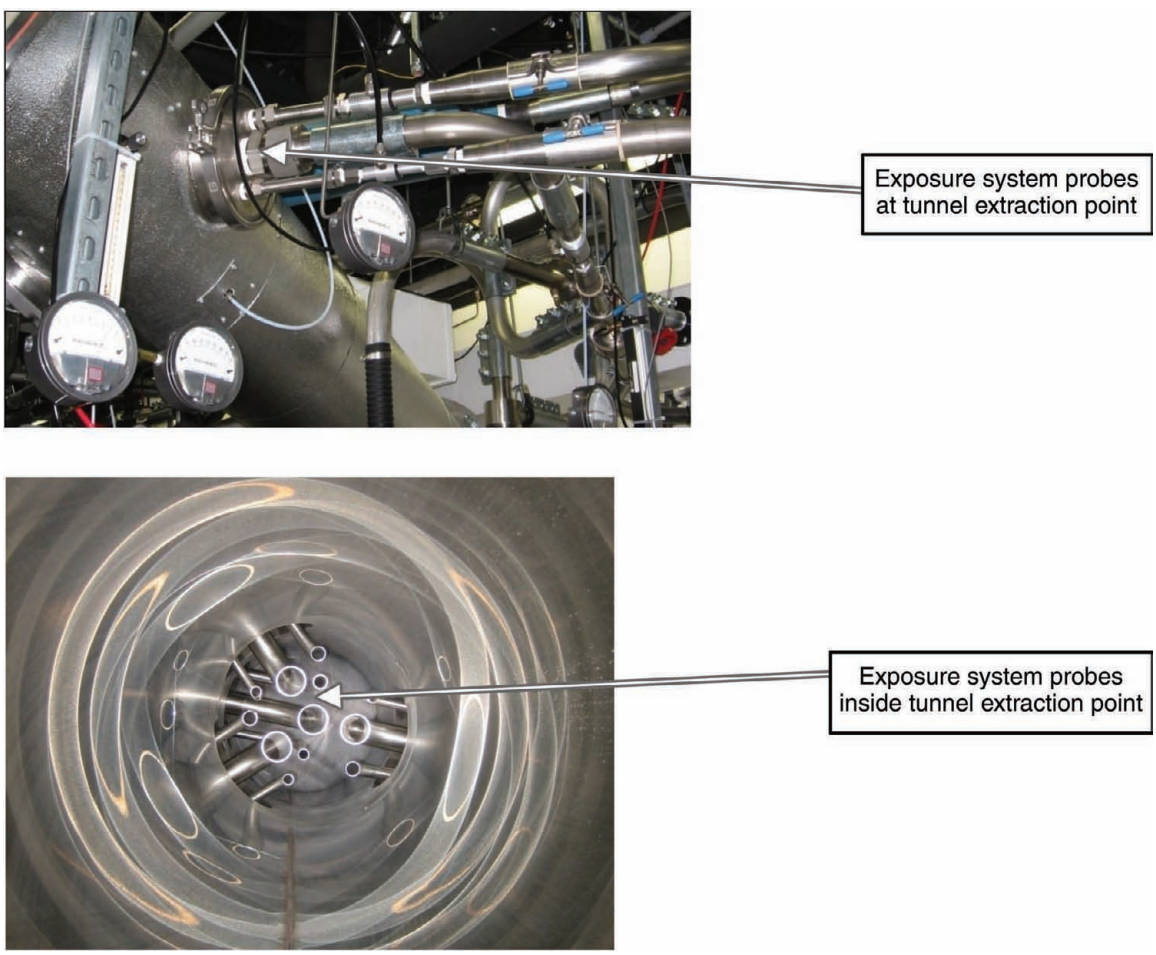


Figure 3. Photographs of sample probes on the outside and inside of the dilution tunnel at the exposure system aerosol extraction point.

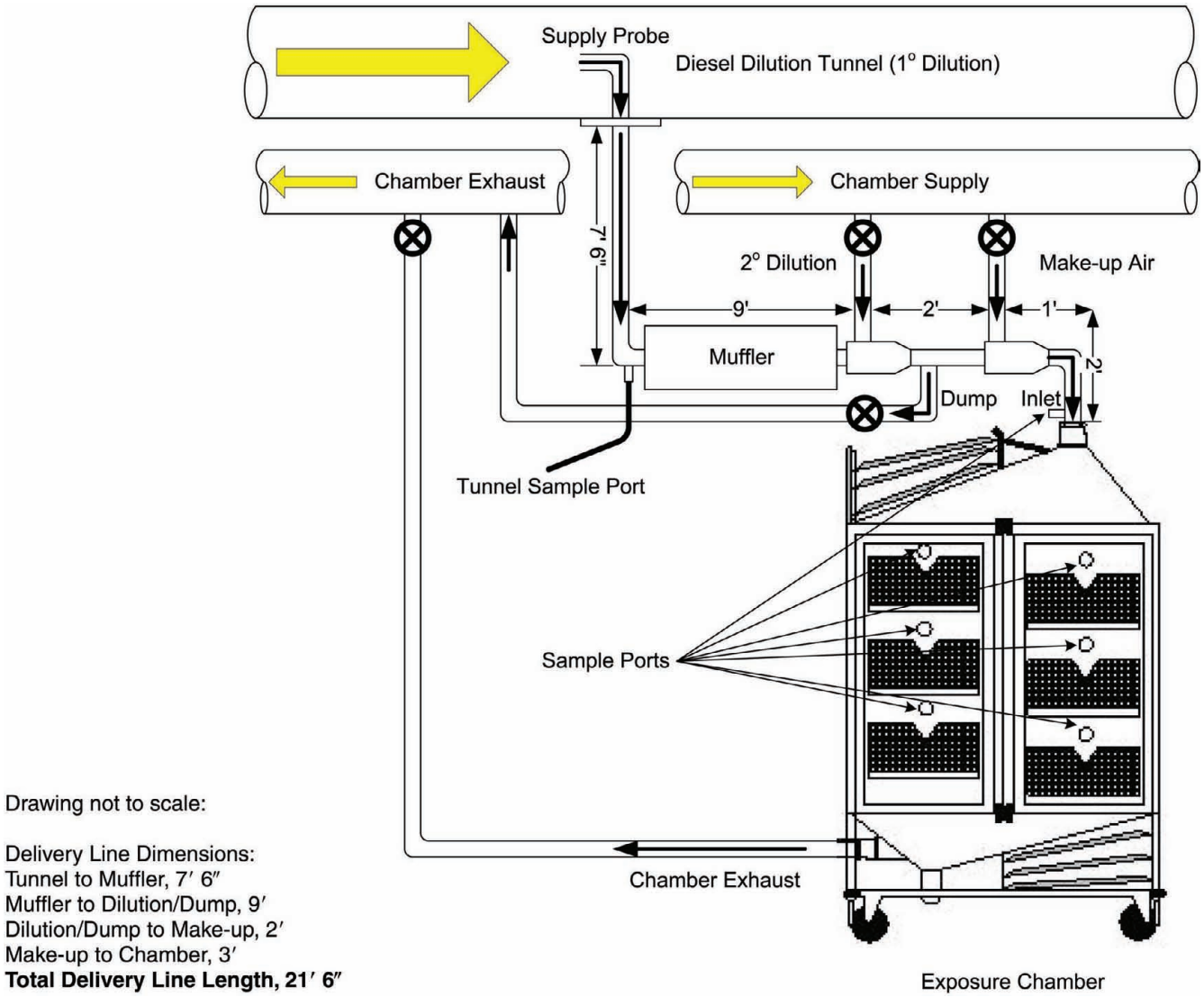


Figure 4. Schematic (not to scale) of secondary (2°) and tertiary (make-up air) dilution system before the inhalation exposure chamber. Diluted exhaust is extracted through a sampling probe. The probe size ranges from 0.95 to 5 cm, with the smallest size extraction for the lowest exposure level and the largest for the highest level. Flows to the chambers are extracted by house vacuum. Aerosol transits by way of a flow-through muffler before a series of two bypass and dilution legs.

operation of the engine and control system on the FTP cycle, and (4) verification of cycle performance for the 16-hour ACES engine cycle.

FACILITY AND CONTROL SYSTEMS PERFORMANCE

Results of the facility commissioning analysis are shown in Table 1. To verify the performance of the engine facility, engine and facility data recorded during a typical 4-hour segment of the 16-hour ACES cycle are reported. For the parameters for which the facility design criteria indicate a set point, the data average and standard deviation are shown. For the parameters for which the facility design criteria indicate a maximum or a minimum, the maximum or minimum from the data file is shown. The maximum-based values were also compared with the value measured while the engine was run at a rated load and speed in order to confirm operation of the test cell in the "worst case." If a value exceeded the facility design criteria, an explanation is provided. Failures to meet the original criteria occurred when the facility test required a high maximum set point for the parameters of engine airflow, fuel consumption, and engine outlet temperature. When these parameters were tested with the subject engine, the levels

Table 1. Summary of Facility Systems and Test Equipment for Associated Design Criteria Testing, and Results[a]

System	Objective	Design Criteria	Measurement During 4-Hour Test	Measurement Type	Measurement at Rated Condition	Accept-able?	Notes
Jacket water — engine block cooling	Verify proper installation and function of heat exchangers, pumps, control valves, current switches, and temperature and pressure indicators and elements	Engine outlet: 200°F	197°F ± 6°F	Avg ± SD		Y	
		Engine inlet: 180°F	184°F ± 6°F	Avg ± SD		Y	
		Chilled water flow rate: 97 gpm	100 gpm	NA		Y	Measured independent of engine condition
		Outlet: 70°F	177°F ± 12°F	Avg ± SD	72°F	Y	Measurement during 4-hour test is high due to controlled recirculation to maintain the engine side temperatures Measurements as rated were performed with supply valves 100% open, showing the minimum reachable temperature
		Inlet: 55°F	170°F ± 20°F	Avg ± SD	54°F	Y	Measurement during 4-hour test is high due to controlled recirculation to maintain the engine side temperatures Measurements as rated were performed with supply valves 100% open, showing the minimum reachable temperature
Charge air cooling — turbo compressed air temperature control	Verify proper installation and function of heat exchangers, pumps, control valves, current switches, temperature and pressure indicators and elements, balancing valves, and adjustment for proper flow rates of process fluids including tuning of system control loops	Engine flow rate max: 1330 cfm	56 scfm–915 scfm	Min/max	822 cfm	Y	Engine design limit below facility test criteria
		Engine outlet: 420°F	99°F–370°F	Min/max	384°F	Y	Engine design limit below facility test criteria
		Engine inlet: 80°F	72°F–86°F	Min/max		Y	
		Chilled water flow rate: 102 gpm	100 gpm	NA		Y	Measured independent of engine condition
		Outlet: 82°F	78°F ± 4°F	Avg ± SD		Y	
		Inlet: 77°F	77°F ± 2°F	Avg ± SD		Y	

(*Table continues next page*)

[a] cfm = cubic feet per minute; CV = coefficient of variation; ft-lb = foot pounds; gpm = gallons per minute; hp = horsepower; ISO = International Organization for Standardization; NA = not applicable; psi = pounds per square inch; rpm = revolutions per minute; scfm = standard cubic feet per minute; SD = standard deviation.

Table 1 (*Continued*). Summary of Facility Systems and Test Equipment for Associated Design Criteria Testing, and Results[a]

System	Objective	Design Criteria	Measurement During 4-Hour Test	Measurement Type	Measurement at Rated Condition	Accept-able?	Notes
Combustion air — engine intake air	Verify proper installation and function of heat exchangers, control valves, temperature and pressure indicators and elements, flow measurement devices, and adjustment for proper flow rates of process fluids including tuning of system control loops	Engine flow rate max: 1330 cfm	56 scfm–915 scfm	Min/max	822 cfm	Y	Engine design limit below facility test criteria
		Reheat coil outlet/engine inlet: 77°F	79°F ± 1°F	Avg ± SD		Y	
		Reheat coil inlet: 59°F	63°F ± 1°F	Avg ± SD		Y	
		Chilled water flow rate: 3.18 gpm	3 gpm	NA		Y	Measured independent of engine condition
Dilution air — mixing tunnel air to be mixed with the exhaust	Verify proper installation and function of temperature and pressure indicators and elements, flow measurement devices, and adjustment for proper flow rates of process fluids	Dilution air flow rate max: 3000 cfm	2500 scfm ± 25 scfm	Avg ± SD		Y	Sample temperature meets criteria at lower than design flow rate
		Inlet temperature: 59°F	63°F ± 1°F	Avg ± SD		Y	
		Sample zone temperature max: 375°F	342°F	Max		Y	Highest measurement observed over creep module
Cell ventilation — test cell air conditioning	Verify proper function of existing fans, dampers, temperature switches, and adjustment for proper flow rates of process fluids	Max temperature: 120°F	104°F	Max		Y	Maximum measurement recorded during commissioning (October through April 2009)
		Flow rate: 8500 cfm	8500 cfm	NA		Y	Measured independent of engine condition
Fuel conditioning — supply, recirculation, temperature, pressure, and measurement	Verify proper installation and function of heat exchangers, pumps, control valves, safety valves, safety interlocks, current switches, level controllers, level switches, level transmitters, temperature and pressure indicators and elements, balancing valves, and adjustment for proper flow rates of process fluids including tuning of system control loops	Engine fuel flow rate range: 26–120 gal/hour	0.4 gal/hour–45 gal/hour	Min/max	20.6 gal/hour	Y	Engine design limit below facility test criteria
		Engine fuel inlet pressure: −6 to 3 psig	0.1 psi–0.5 psi	Min/max		Y	
		Engine fuel inlet temperature: 104°F	107°F ± 2°F	Avg ± SD		Y	

(*Table continues next page*)

[a]cfm = cubic feet per minute; CV = coefficient of variation; ft-lb = foot pounds; gpm = gallons per minute; hp = horsepower; ISO = International Organization for Standardization; NA = not applicable; psi = pounds per square inch; rpm = revolutions per minute; scfm = standard cubic feet per minute; SD = standard deviation.

Table 1 (*Continued*). Summary of Facility Systems and Test Equipment for Associated Design Criteria Testing, and Results[a]

System	Objective	Design Criteria	Measurement During 4-Hour Test	Measurement Type	Measurement at Rated Condition	Accept-able?	Notes
Engine load and speed control — AC dynamometer, speed and torque measurement and control	Verify proper installation and function of alternating-current motor and variable frequency drive, cooling fans, temperature and pressure indicators and elements, and include the calibration of torque, speed, and throttle measurement and control devices using vendor-provided means and methods including tuning of system control loops	Engine power max: 500 hp	500 hp	Power map		Y	Meets engine performance requirements
		Engine peak torque: 1800 ft-lb	1650 ft-lb	Power map		Y	Meets engine performance requirements
		Engine max speed: 2300 rpm	2000 rpm	Power map		Y	Meets engine performance requirements
Data acquisition and control system	Verify proper installation and function of input and output modules, relays, power supplies, computer hardware, and software	Requested capabilities: Recording of facility and performance data typical of a transient test cell	NA			Y	
	Verify and calibrate all analog channels including pressure and temperature inputs using vendor-provided means and methods	ACES 16-hour test cycle	NA			Y	
		FTP test cycle	NA			Y	
		Modes 1, 3, and 5 of ISO 8178 8-mode test cycle	NA			Y	
	Verify proper function of safety systems and programmable logic controller including tuning of system control loops						
	Verify proper function of the requested test cycles						
Engine cycle performance	Verify performance of engine cycles by characterizing target versus actual engine power, torque, speed, air flow rates, fuel flow rates, temperatures, and pressures	Within 5% CV comparing target versus actual				Y	
		Within 5% precision for repeat of same engine cycles				Y	

[a]cfm = cubic feet per minute; CV = coefficient of variation; ft-lb = foot pounds; gpm = gallons per minute; hp = horsepower; ISO = International Organization for Standardization; NA = not applicable; psi = pounds per square inch; rpm = revolutions per minute; scfm = standard cubic feet per minute; SD = standard deviation.

Table 2. Engine Certification Regression Statistics from 40 CFR Part 86.1341-90[a]

	Regression Line Tolerances for Petroleum- and Methanol-Fueled Diesel Engines		
	Speed	Torque	Brake Horsepower
SEE of Y on X	100 rpm	13% power map maximum engine torque	8% of power map maximum bhp
Slope of the regression line (m)	0.970 to 1.030	0.83–1.03 (hot), 0.77–1.03 (cold)	0.89–1.03 (hot), 0.87–1.03 (cold)
Coefficient of determination (r^2)	0.970[b]	0.8800[b] (hot), 0.8500[b] (cold)	0.9100[b]
Y intercept of the regression line (b)	50 rpm	15 ft-lb	5.0

[a] bhp = brake horsepower; CFR = Code of Federal Regulations; ft-lb = foot pounds; rpm = revolutions per minute; SEE = standard error of estimate.
[b] Minimum.

were not high enough to allow testing to the maximum facility design criteria, given the design limits of the engine. However, *the performance of the facility for each parameter met the engine manufacturer's requirements at the rated condition.* Other limits that could not be tested using the original facility design criteria were peak torque and speed. The original facility performance test criterion was as follows: the engine had to operate within 5% of the maximum set points for these parameters. Since the capacity of the facility was designed to be much higher than the engine limits, this criterion could not be tested.

TEST CYCLE PERFORMANCE AND REGRESSION ANALYSIS

Cycle performance was characterized two ways. First, the cycle performance was evaluated by regression analysis, as defined below. Second, the performance criteria required that the precision of repeat cycles was within a 5% variation. As shown below, the engine cycle performance met both of these criteria.

Engine performance was validated by comparing speed, torque, and power demand with actual regression analysis per the procedure outlined for certification of heavy-duty, on-road engines by the U.S. Environmental Protection Agency in the Title 40 Code of Federal Regulations (CFR) Part 86. The control system for the engine and test cell was first tuned to meet the regression statistics prescribed by 40 CFR Part 86 for the U.S. FTP engine cycle. The CFR values for the required regression line tolerances that were applied are shown in Table 2. For standard error, the criteria listed are the maximum allowable.

As required by the 40 CFR Part 86, after each test the observed speed, torque, and power measurements were compared to the speed, torque, and power cycle demand values using the least-squares method. Before applying the regression, specific points from each signal were deleted as allowed per the CFR. The permitted point deletions are described in Table 3. After the data have been captured, it is also permissible to shift the speed and torque feedback in time relative to the demand before the regression was performed, but this was not found to be necessary to meet the required tolerances.

After the control system was tuned to consistently meet the regression statistic requirements, three consecutive FTP module cycles were conducted. The regression analysis results for these tests are shown in Table 4 for engine B and Table 5 for engine B′. The results indicate that each

Table 3. Permitted Point Deletions from Regression Analysis, from 40 CFR Part 86.1341-90[a]

Condition[b]	Points to Be Deleted
1. Wide open throttle and torque feedback < torque reference	Torque and/or bhp
2. Closed throttle, not an idle point, torque feedback > torque reference	Torque and/or bhp
3. Closed throttle, idle point, and torque feedback = curb idle transmission torque (10 ft-lb)	Speed and/or bhp

[a] bhp = brake horsepower; CFR = Code of Federal Regulations; ft-lb = foot pounds.
[b] For the purpose of this discussion, an *idle point* is defined as a point having a normalized reference torque of 0; a *normalized reference* as having speed of 0; and an *engine tested* as having a manual transmission with a curb idle transmission torque of 0. Point deletion may be applied either to the whole or to any part of the cycle.

Table 4. Regression Analysis Results for Engine B on the FTP Cycle[a,b]

Run	SEE		Regression Slope (m)		Y-Intercept (b)		r^2	
	Actual[c]	CFR Criteria	Actual[c]	CFR Criteria	Actual[c]	CFR Criteria	Actual[c]	CFR Criteria
Speed		100		0.97–1.03		50		0.97–1.00
LRRI 14Apr09 run 1	83.8080		0.9873		10.3342		0.9868	
LRRI 14Apr09 run 2	83.1087		0.9866		10.3639		0.9870	
LRRI 14Apr09 run 3	84.1699		0.9864		10.6081		0.9867	
Torque		13		0.83–1.03		15		0.88–1.00
LRRI 14Apr09 run 1	6.3906		0.9575		−7.8584		0.9373	
LRRI 14Apr09 run 2	7.4276		0.9120		−9.5326		0.9242	
LRRI 14Apr09 run 3	7.5939		0.9194		−8.4366		0.9223	
Power		8		0.89–1.03		5		0.91–1.00
LRRI 14Apr09 run 1	6.3352		0.9660		−1.3441		0.9412	
LRRI 14Apr09 run 2	6.3222		0.9436		−3.1884		0.9450	
LRRI 14Apr09 run 3	6.4059		0.9522		−3.0132		0.9449	

[a] All performance criteria were met.
[b] CFR = Code of Federal Regulations; FTP = Federal Test Procedure; LRRI = Lovelace Respiratory Research Institute; SEE = standard error of estimate.
[c] All passed regression.

Table 5. Regression Analysis Results for Engine B′ on the FTP Cycle[a,b]

Run	SEE		Regression Slope (m)		Y-Intercept (b)		r^2	
	Actual[c]	ACES Criteria	Actual[c]	ACES Criteria	Actual[c]	ACES Criteria	Actual[c]	ACES Criteria
Speed		100		0.97–1.03		50		0.97–1.00
LRRI 14Aug09 run 1	80.4747		0.9841		11.5821		0.9878	
LRRI 14Aug09 run 2	80.0700		0.9840		11.4170		0.9880	
LRRI 14Aug09 run 3	79.2452		0.9839		11.2522		0.9882	
Torque		13		0.83–1.03		15		0.88–1.00
LRRI 14Aug09 run 1	5.9410		0.9490		−10.0681		0.9431	
LRRI 14Aug09 run 2	7.7758		0.8980		−7.9746		0.9160	
LRRI 14Aug09 run 3	8.0878		0.8983		−8.5647		0.9071	
Power		8		0.89–1.03		5		0.91–1.00
LRRI 14Aug09 run 1	5.8959		0.9512		−2.0094		0.9463	
LRRI 14Aug09 run 2	6.5935		0.9314		−3.0711		0.9397	
LRRI 14Aug09 run 3	6.9120		0.9368		−3.6013		0.9324	

[a] All performance criteria were met.
[b] ACES = Advanced Collaborative Emissions Study; FTP = Federal Test Procedure; LRRI = Lovelace Respiratory Research Institute; SEE = standard error of estimate.
[c] All passed regression.

Table 6. Regression Analysis Results for Engine B for the 4-Hour ACES Engine Cycle[a,b]

Run	SEE		Regression Slope (m)		Y-Intercept (b)		r^2	
	Actual[c]	ACES Criteria	Actual[c]	ACES Criteria	Actual[c]	ACES Criteria	Actual[c]	ACES Criteria
Speed		100		0.97–1.03		50		0.97–1.00
LRRI 14Apr09 run 1	95.9941		0.9826		22.4724		0.9744	
LRRI 15Apr09 run 2	95.0691		0.9834		21.9758		0.9753	
LRRI 15Apr09 run 3	95.7424		0.9833		22.2813		0.9749	
Torque		13		0.83–1.03		15		0.88–1.00
LRRI 14Apr09 run 1	7.6972		0.9153		3.8493		0.9183	
LRRI 15Apr09 run 2	7.6442		0.9198		2.3122		0.9171	
LRRI 15Apr09 run 3	7.5305		0.9207		2.4876		0.9193	
Power		8		0.89–1.03		5		0.91–1.00
LRRI 14Apr09 run 1	6.7242		0.9204		0.4707		0.9223	
LRRI 15Apr09 run 2	6.7895		0.9281		−0.1107		0.9212	
LRRI 15Apr09 run 3	6.7061		0.9277		0.0572		0.9226	

[a] All performance criteria were met.
[b] ACES = Advanced Collaborative Emissions Study; LRRI = Lovelace Respiratory Research Institute; SEE = standard error of estimate.
[c] All passed regression.

test passed the criteria defined in the CFR. Table 6 summarizes the regression performance for engine B on three repetitions of a 4-hour segment of the ACES cycle.

As was true with the FTP, all cycle performance criteria were met for the CFR requirements, and precision to within 5% was seen among repeated runs. Figures 5 and 6 provide representative data for target versus actual performance for speed and torque during a 4-hour segment of the ACES cycle.

CHARACTERIZATION OF EXHAUST AND INHALATION EXPOSURE SYSTEM

The tests, objectives, and number of trials for each set of the tests conducted for engine B are summarized in Table 7. The testing of engine B′ was more limited and included tests 1, 2, and 7. A description of each test and the results are provided below. Where appropriate, comparisons with results obtained at SwRI are included. Measurements were taken from the SwRI full-flow constant

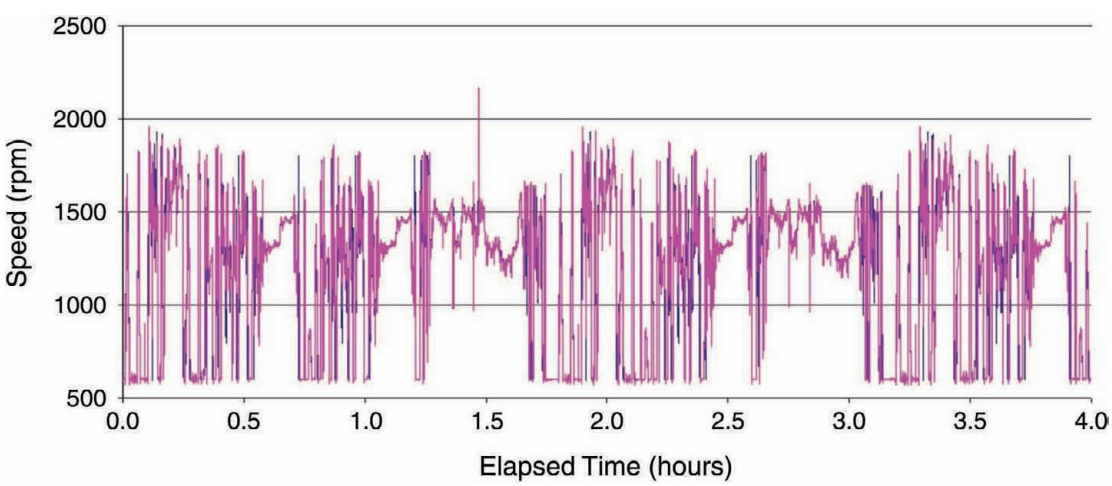


Figure 5. Target (blue) vs. actual speed (pink) during a representative 4-hour segment of the ACES transient cycle.

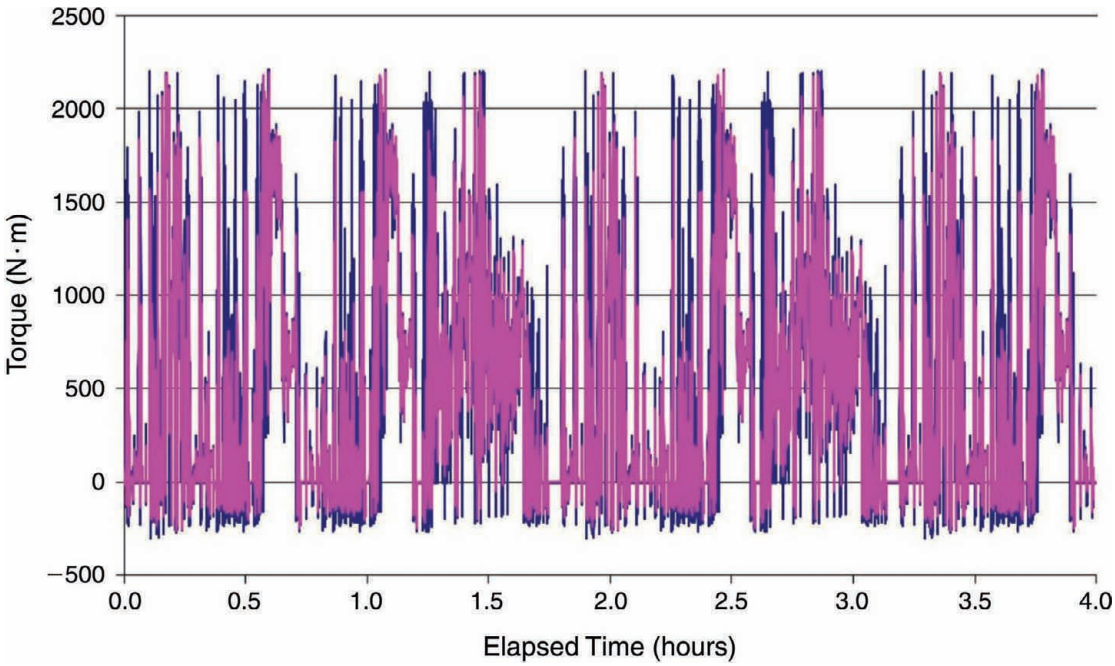


Figure 6. Target (blue) vs. actual torque (pink) during a representative 4-hour segment of the ACES transient cycle.

volume sampler (CVS) tunnel. Those results were obtained from the final Phase 1 report (Khalek et al. 2009), with the exception of the steady-state emissions data, which were not included in that report. Steady-state emissions data from SwRI were obtained directly from Dr. Imad Khalek of SwRI. The sampling equipment, conditions, and analyses used for the characterization are defined in Table 8.

EMISSIONS CHARACTERIZATION CALCULATIONS

Emissions Calculations

The primary dilution ratio was calculated from the following test cell parameters:

- Dilution air
- Fuel flow
- Combustion air flow

$$\text{Dilution Ratio}_{\text{primary}} = \frac{\text{Dilution Air} + \text{Combustion Air} + \text{Fuel Flow}}{\text{Combustion Air} + \text{Fuel Flow}}$$

The secondary dilution ratio was a ratio of tunnel nitrogen oxides (NO_x) to chamber NO_x:

$$\text{Dilution Ratio}_{\text{secondary}} = \frac{NO_{x_{\text{tunnel}}}}{NO_{x_{\text{chamber}}}}$$

The total dilution ratio was calculated by multiplying the primary and secondary dilution ratios:

$$\text{Dilution Ratio}_{\text{total}} = \text{Dilution Ratio}_{\text{primary}} \times \text{Dilution Ratio}_{\text{secondary}}$$

The engine output gas concentration was calculated from the chamber concentration by multiplying the chamber concentration by the total dilution ratio:

$$\text{Concentration}_{\text{engine}} = \text{Concentration}_{\text{chamber}} \times \text{Dilution Ratio}_{\text{total}}$$

Conversion of the gas concentration in ppm to mg/m^3 was calculated as follows:

$$\text{Gas Concentration (mg/m}^3\text{)} = \frac{\text{Gas Conc (ppm)} \times \text{MW} \div \text{(L/mole)} \times \frac{P_{\text{amb}}}{P_{\text{STP}}} \times \frac{T_{\text{STP}}}{T_{\text{amb}}}}{1000\ \text{L/m}^3}$$

where MW equals molecular weight (g), P_{amb} equals pressure ambient (mm Hg); P_{STP} equals pressure at standard temperature and pressure (mm Hg); T_{amb} equals temperature ambient (K); T_{STP} equals temperature at standard temperature and pressure (K); and L/mole equals liters occupied by 1 mole of gas at ambient pressure.

Table 7. Summary of Tests, Objectives, and Number of Trials for Characterization of the ACES Engine[a,b]

Test Number / Description	Objective	Number of Trials	Notes
1. Characterize exhaust on steady-state modes and FTP cycles	Evaluate exhaust characteristics to verify proper engine performance	3/cycle condition	Only regulated gases, particle mass, and size distribution
2. Determine composition and environmental conditions at dilution rate set to achieve 4.2 ppm NO_2	Compare SwRI exposure chamber composition to LRRI exposure chamber composition	3	SwRI chamber characterization used the 40× dilution rate; only regulated gases, particle mass, and size distribution
3. Determine minimum allowable dilution rate	Define highest concentration in exposure chamber at which temperature within the chamber is < 27°C (target = 24°C average temperature)	Iterative	Dilution rate must result in proper temperature; NO_2 and CO may also be considered as limiting factors
4. Determine chamber atmosphere composition at dilution to achieve 4.2 ppm NO_2	Verify repeatability of composition and environmental profile at proposed minimum allowable dilution	3	Will measure all components in Table 8
5. Determine chamber performance at dilution to achieve 4.2 ppm NO_2	Prevalidation to characterize T_{90}, chamber homogeneity, and repeatability	3	Only regulated gases, particle mass, and size distribution
6. Determine chamber atmosphere composition at dilution to achieve 0.1 and 0.8 ppm NO_2	Define atmosphere proportionality with dilution rate for key constituents	3	Only regulated gases, particle mass, and size distribution
7. Determine particle number-based size distribution in chamber and before exposure chamber at dilution set to achieve 4.2 ppm NO_2	Assess particle changes as a result of inhalation exposure chamber and aerosol transit lines	3	Determine with steady-state and FTP cycles

[a] Measurements conducted at the chamber sampling ports.
[b] ACES = Advanced Collaborative Emissions Study; FTP = Federal Test Procedure; LRRI = Lovelace Respiratory Research Institute; SwRI = Southwest Research Institute; T_{90} = time to reach 90% of target concentration.

Brake Horsepower · Hour Calculation

Brake horsepower · hour (bhp · hr; which indicates a unit of work [brake horsepower] integrated over 1 hour) was calculated as follows:

$$\text{Brake Horsepower} \cdot \text{Hour (bhp} \cdot \text{hr)} = \frac{\text{HP} \times \text{Test Time (min)}}{60 \text{ min/hr}}$$

Grams per brake horsepower · hour (g/bhp · hr) were calculated using the following:

$$\text{Grams per Brake Horsepower} \cdot \text{Hour (g/bhp} \cdot \text{hr)} = \frac{\text{Gas Conc (g/m}^3\text{)} \times \text{Exhaust Flow (m}^3\text{)}}{\text{bhp} \cdot \text{hr}}$$

ATMOSPHERE CHARACTERIZATION METHODS

The measurements and analytical techniques are summarized in Table 8. The procedures for performing these measurements are described in this section. Note that all real-time measurements were recorded once per second.

SAMPLE COLLECTION

Samples were collected for tunnel emissions measurements directly from the tunnel at the sample extraction point for the exposure chamber systems. Particle mass and size distribution were measured in the exposure chamber in all cases to allow sufficient dilution for those analyses. CO_2 was measured for engine B in an exposure chamber

Table 8. Summary of Analytical Techniques and Sampling Equipment Used to Characterize Exposure Chamber Atmospheres[a]

Analysis	Collection Device	Collection Media	Analytical Instrument
Continuous PM mass	DMM	NA	NA
Wet nitric oxides (NO_x, NO_2)	Chemiluminescence analyzer	NA	NA
Wet CO/CO_2	Infrared analyzer	NA	NA
THC	Heated flame ionization detector	NA	NA
Organic/elemental carbon	Aluminum in-line filter holder	Heat-treated quartz filter	TOR
Speciated metals	Teflon filter holder	Teflon membrane filter	XRF; ICP/MS
Speciated organic compounds			
Volatile hydrocarbons (C_1–C_{12})	VOC sampler	Electropolished canister	GC/MS
Volatile carbonyls	VOC sampler	DNPH cartridge	LC/UV
Semivolatile/fine particle organics	Tisch Environmental polyurethane foam sampler	TIGF filter/XAD-4	GC/MS
Size distribution			
0.5–20 µm aerodynamic distribution	Aerodynamic particle sizer	NA	NA
~5–500 nm particle number distribution/mass	Fast-mobility particle sizer	NA	NA

[a] DMM = Dekati mass monitor; DNPH = dinitrophenylhydrazine; GC/MS = gas chromatography/mass spectrometry; ICP/MS = inductively coupled plasma mass spectrometry; LC/UV = liquid chromatography/ultraviolet detection; NA = not applicable; THC = total hydrocarbon; TIGF = Teflon-impregnated glass fiber; TOR = thermal/optical reflectance; VOC = volatile organic compound; XAD-4 = sorbent resin; XRF = X-ray fluorescence.

because the range of the instrument (an infrared CO/CO_2 analyzer) was originally set too low to make the measurements from the tunnel. During CO_2 measurements, the chamber residence time was not accounted for, because the chamber residence time is not important for steady-state measurements. For the FTP cycle, we integrated the CO_2 measurements over the time of the cycle, so time delay was not an important factor for measurements from the chamber. The instrument was adjusted to a higher operating range before the engine B′ characterization, allowing the engine B′ measurements for CO_2 to be obtained directly from the dilution tunnel. The exposure chambers contained multiple sample ports that allowed samples to be taken directly from the breathing zone of the animals (immediately above the wire cages at different levels in the chamber), with the exception of the Teflon-membrane filter for metals and the filter and XAD-4 cartridge for SVOCs (see discussion later in this section). Samples from the Teflon-membrane filter and the SVOC filter and XAD-4 cartridge were taken out of an auxiliary sampling plenum, which was directly coupled to the chamber exhaust and was representative of the chamber atmosphere. The flow through these filters was high enough that the chamber distribution could be effected by drawing these samples directly from the chamber. (No animals were present during Phase 3A characterization.) The multiport design was used to characterize the homogeneity of the exposure atmosphere throughout the chambers. Samples were pulled through stainless-steel probes that were approximately 12 inches long and ¼ inch in diameter. Chamber uniformity assessments confirmed that samples could be collected in parallel ports and be representative of the same atmosphere.

PM MASS: REAL-TIME MASS AND SIZE DISTRIBUTION

Real-time PM mass was measured using a DMM-230. Real-time measurements were begun a minimum of 10 minutes before the initiation of a test in order to collect data on background PM in the exposure chambers.

Particle size was measured by a combination of a fast-response differential mobility analyzer (approximately 5–500 nm) and an aerodynamic particle sizer (0.5–20 microns). The fast-response differential mobility analyzer (DMA, Model 3091 Fast Response Particle Sizer Spectrometer, TSI, St. Paul, Minn.) also was used to measure particle number-based size distribution (in real time) with enhanced resolution for particle size (resolution, 1 second).

CHEMICAL CHARACTERISTICS OF PM

Elemental and Organic Carbon Masses

Elemental and organic carbon masses were determined at DRI with prebaked quartz-fiber filters using the modified Interagency Monitoring of Protected Visual Environments thermal/optical reflectance (TOR) method.

Organic Carbon Class and Species

Particulates and SVOCs were collected using Zefluor filters, followed by XAD-4 resin cartridges. The target analytes included compounds that were statistically above detection limits during the Phase 1 component of the ACES program. Organic analyses for SVOCs were conducted at DRI by gas chromatography/mass spectrometry (GC/MS).

Total Metals and Associated Elements

Samples for metal analysis were collected on clean Teflon-membrane filters and analyzed at DRI by energy-dispersive X-ray fluorescence (XRF). After this analysis, the Teflon-membrane filters were returned to their petri dishes and stored under refrigeration until the XRF data validation was completed and had indicated that the runs were acceptable. Selected samples were also analyzed by inductively coupled plasma mass spectrometry based on the results from the Phase 1 analysis.

Inorganic Ions: Ammonium (and Ammonia), Sulfate, and Nitrate

One-half of the quartz filters (and blanks) collected for the carbon analysis were extracted and analyzed at DRI for water-soluble chloride, nitrite, nitrate, sulfate, and formic and acetic acid by ion chromatography. This extract was also analyzed for ammonium by the indolphenol colorimetric method.

GASES AND VAPORS

Nitrogen Oxides, Total Hydrocarbons, Sulfur Dioxide, and Carbon Monoxide

Chemiluminescence analysis was used to measure NO_x (Teledyne Model 200 series; Ecophysics 700 series) and fluorescence analysis to measure SO_2 (Thermo Electron Corp.; Pulsed Fluorescence SO_2 Analyzer, Model 43i). CO and CO_2 concentrations were determined using a non-dispersive infrared gas analyzer (California Analytical Instruments, Model 600 series). THC was measured using a real-time flame ionization detector (California Analytical Instruments, Model 300H) calibrated against a certified propane standard. Analyzers were zeroed daily using ultra-zero air and calibrated with traceable span gases, as defined by the National Institute of Standards and Technology.

Gas Phase Hydrocarbon Speciation

VOCs (except acids and carbonyls, which are too polar for collection in and analysis from a canister) were collected using a custom-designed canister sampler (L. Sheetz Enterprises, Reno, Nev.). Samples were collected downstream of a NO_x denuder in a precleaned Summa canister and analyzed within 30 days of collection to ensure accurate characterization of polar compounds that may "stick" to the walls of the canister. The NO_x denuder reduced NO_x and ameliorated NO_x–VOC reactions that can lead to false low readings of concentrations of reactive compounds such as 1,3-butadiene and styrene. Analysis was conducted at DRI by GC/MS.

Analysis of Carbonyl Compounds

Carbonyl compounds were collected on dinitrophenylhydrazine (DNPH)-impregnated silica gel cartridges preceded by a commercially available oxidant scrubber and a Teflon-membrane prefilter to remove PM. To assess the trapping efficiency of the DNPH cartridge, two cartridges were used in a series, and the backup cartridge was analyzed to ensure that all carbonyls were trapped on the first cartridge. Analysis was conducted at DRI by liquid chromatography/ultraviolet testing (photodiode array).

RESULTS OF CHARACTERIZATION

TEST 1: DETERMINING EXHAUST CHARACTERISTICS DURING STEADY-STATE AND FTP CYCLES

In Test 1, exhaust characterization was conducted to measure NO_x, NO_2, CO, nonmethane hydrocarbons (NMHC), and particle number-based size distribution after primary dilution from the engine. This was conducted during selected steady-state modes (termed Modes 1, 3, and 5) and during the FTP cycle. The steady-state operating conditions in these modes are defined in Table 9.

Exhaust was extracted from the primary dilution tunnel for all gases, and it was further diluted with clean compressed air for the PM mass measurement. After an assessment of particle loss from the extraction point to the exposure chamber showed minimal to no loss or change in composition of the emissions, it was determined that all PM testing would be conducted from the exposure chamber from the sample ports shown in Figure 4. A manual regeneration of the DPF was conducted before each day of

Table 9. Parameters for Engine Steady-State Operations[a]

Mode 1:	Rated speed 1800 rpm 100% torque (2034 N·m, 100% throttle)
Mode 3:	Rated speed 1800 rpm 50% torque (1017 N·m, ~62% throttle)
Mode 5:	Peak torque speed 1200 rpm 100% torque (2237 N·m, 100% throttle)

[a] rpm = revolutions per minute.

steady-state or FTP characterizations. In addition, a power map was conducted before each characterization to confirm proper engine performance. For each condition, the engine was operated for a minimum of 40 minutes before the sampling. After the engine had warmed up and the chamber NO_x values had stabilized, samples were collected for 5-minute durations during the steady-state characterization and for 20-minute durations for the FTP characterization. Data are provided for both engine B and B′. In both cases, the results were compared with data obtained at SwRI, including results from SwRI tests conducted to simulate the lower barometric pressures at the higher-elevation LRRI site.

The results of the steady-state emissions testing for engines B and B′ are shown in Tables 10 and 11, respectively. Table 12 shows the results obtained from SwRI (Imad Khalek, personal communication, May 22, 2009). The data shown include average concentrations for three repeated tests of NO_x, CO_2, CO, hydrocarbons (NMHC for the LLRI testing; THC for the SwRI testing), and PM. The results show reasonable similarities between the two locations, and the LRRI data show good consistency of the emissions data from one test to the next. Testing for NO_x, which may be the analyte of most interest, showed results within 10% for Mode 1 for each engine and for both engines between locations. Both engines B and B′ showed lower NO_x emissions compared with the altitude-adjusted values for Mode 3. For Mode 5, engine B was within

Table 10. Summary of Steady-State Emissions Testing Results for LRRI (Engine B) as Measured from the Exposure Chamber[a,b]

	NO_x	CO	CO_2	NMHC	PM
Mode 1					
Test 1	1.78	0.00	667	0.025	0.0011
Test 2	1.77	0.00	661	0.025	0.0015
Test 3	1.75	0.00	657	0.025	0.0018
Average	1.77	0.00	662	0.025	0.0015
SD	0.02	0.00	5.011	0.000	0.0003
CV (%)	0.89	NA	0.76	1.76	22.49
Mode 3					
Test 1	0.88	0.00	754	0.237	0.00007
Test 2	0.88	0.00	757	0.240	0.00006
Test 3	0.88	0.00	756	0.240	0.00005
Average	0.88	0.00	756	0.239	0.00006
SD	0.001	0.00	1.516	0.002	0.00001
CV (%)	0.06	NA	0.20	0.76	20.09
Mode 5					
Test 1	1.71	0.00	570	0.038	0.00004
Test 2	1.84	0.00	569	0.038	0.00005
Test 3	1.89	0.00	569	0.045	0.00007
Average	1.81	0.00	569	0.040	0.00005
SD	0.09	0.00	0.776	0.004	0.00002
CV (%)	5.16	NA	0.14	9.52	34.60

[a] Data expressed in g/hp · hr.

[b] CV = coefficient of variation; g/hp · hr = grams per horsepower-hour; NMHC = nonmethane hydrocarbon; PM = particulate matter; SD = standard deviation.

Table 11. Summary of Steady-State Emissions Testing Results for LRRI (Engine B′) as Measured from the Exposure Chamber[a,b]

	NO_x	CO	CO_2	NMHC	PM
Mode 1					
Test 1	1.36	0.036	601	0.0002	0.0129
Test 2	1.36	0.036	602	0.0004	0.0122
Test 3	1.37	0.043	603	0.0005	0.0131
Average	1.36	0.038	602	0.0004	0.0127
SD	0.00	0.004	0.665	0.0002	0.0005
CV (%)	0.29	10.4	0.11	49.3	3.9
Mode 3					
Test 1	0.69	0.049	671	0.0017	0.00014
Test 2	0.70	0.053	670	0.0017	0.00012
Test 3	0.70	0.047	670	0.0020	0.00012
Average	0.70	0.050	670	0.0018	0.00013
SD	0.007	0.003	0.680	0.0001	0.00001
CV (%)	0.99	6.2	0.10	7.7	9.3
Mode 5					
Test 1	1.01	0.042	551	0.0016	0.00007
Test 2	1.27	0.044	552	0.0009	0.00006
Test 3	1.27	0.043	551	0.0013	0.00005
Average	1.18	0.043	551	0.0013	0.00006
SD	0.15	0.001	0.613	0.0004	0.00001
CV (%)	12.6	2.2	0.11	28.6	11.6

[a] Data expressed in g/hp · hr.

[b] CV = coefficient of variation; g/hp · hr = grams per horsepower-hour; NMHC = nonmethane hydrocarbon; PM = particulate matter; SD = standard deviation.

Table 12. Summary of Steady-State Emissions Testing Results for SwRI, as Measured from the CVS Tunnel[a,b]

	NO_x	CO	CO_2	THC	PM[c]
Mode 1					
Engine B	0.822	0.02	541	0.001	0.0010
Engine B′	0.784	0.02	491	0.012	0.0008
High Alt Engine B′	1.769	0.01	489	0.012	0.0006
Mode 3					
Engine B	0.771	0.03	629	0.004	0.0004
Engine B′	0.690	0.02	541	0.013	−0.0001
High Alt Engine B′	0.890	0.01	530	0.017	0.0001
Mode 5					
Engine B	1.135	0.03	494	0.002	0.0004
Engine B′	1.737	0.01	450	0.013	−0.0001
High Alt Engine B′	1.803	0.01	439	0.013	0.0000

[a] Data expressed in g/hp · hr.

[b] Alt = altitude; CVS = constant volume sampler; g/hp · hr = grams per horsepower-hour; PM = particulate matter; SwRI = Southwest Research Institute; THC = total hydrocarbons.

[c] PM measured from exposure chamber.

10% of the altitude-adjusted value, but B′ was 22% high. The CO_2 values obtained at LRRI were approximately 20% higher than those observed at SwRI. There is not yet a good explanation for this discrepancy. The other measured parameters had low concentrations and were not directly compared. Whereas these concentrations are low, the PM mass value measured during the third steady-state test of Mode 1 for engine B′ was noted to be above the 2007 PM mass standard. For all PM mass measurements, most of the variability can be explained by the fact that the PM mass values are at or near the limit of the sensitivity of the assay. We note that CO had values of zero in most tests because CO levels were at or near background. Figures 7 through 9 show particle size distribution and number count obtained during each of the tests (for engine B).

Tables 13 and 14 show results of the FTP emissions testing for engines B and B′. The results include average concentrations for three repeated tests of NO_x, CO, CO_2, NMHC, and PM. The NMHC values are corrected for background. Table 15 shows the results that were obtained at SwRI (Khalek et al. 2009). The results show reasonable similarities between the two locations, and the LRRI data show good consistency of the emissions from one test to the next, with the exception of data for Test 3 (see below for description). This is evaluated further in the section "Carbon Balance During Engine Cycle" later in this report. NO_x emissions, which as noted were likely of most interest, were an average of 14% higher at LRRI than at SwRI for engine B. The remaining measurements were not compared because the values were very low in all cases.

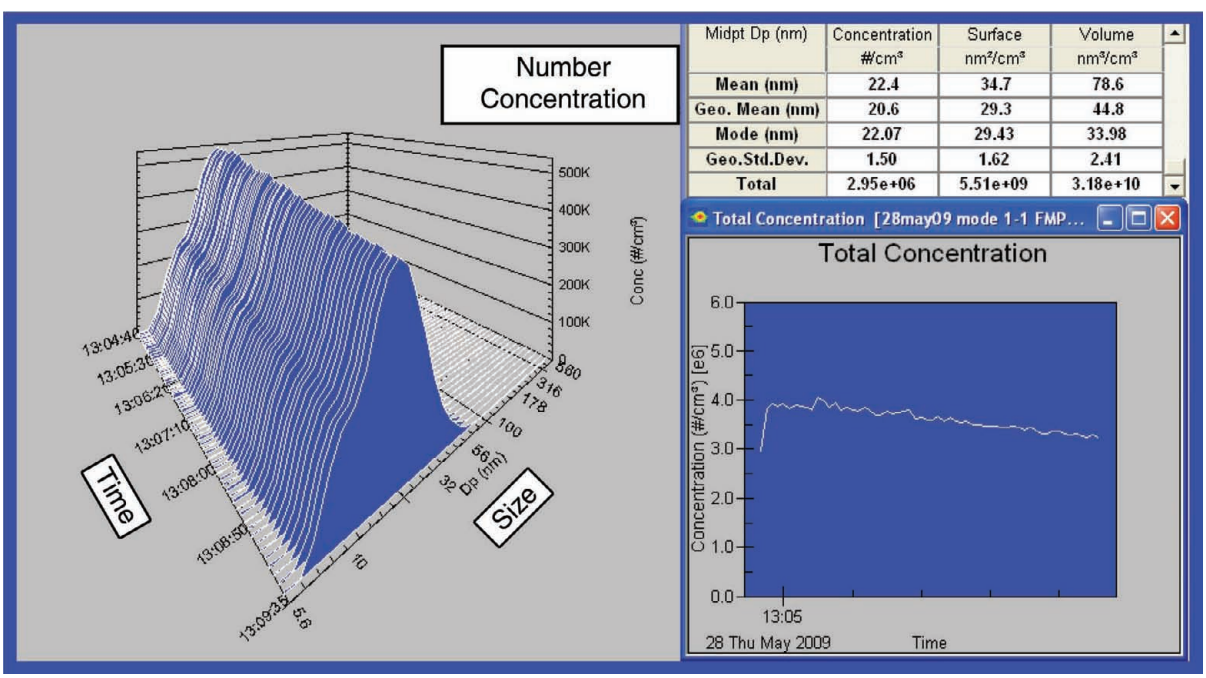
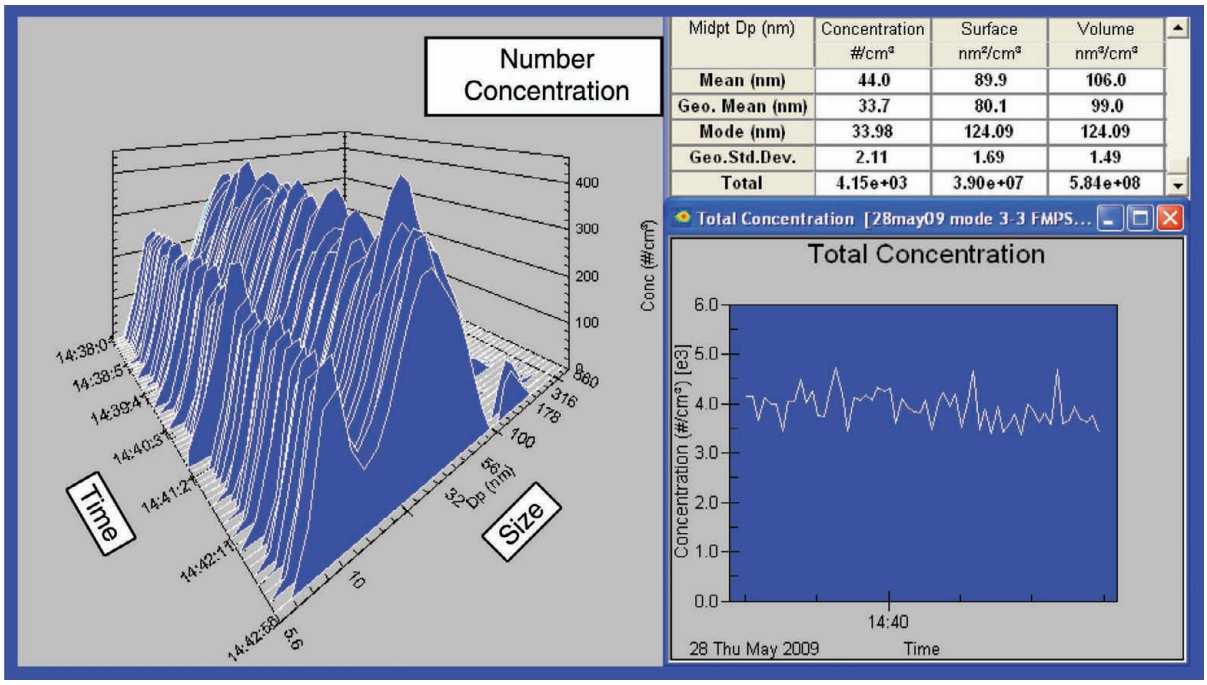
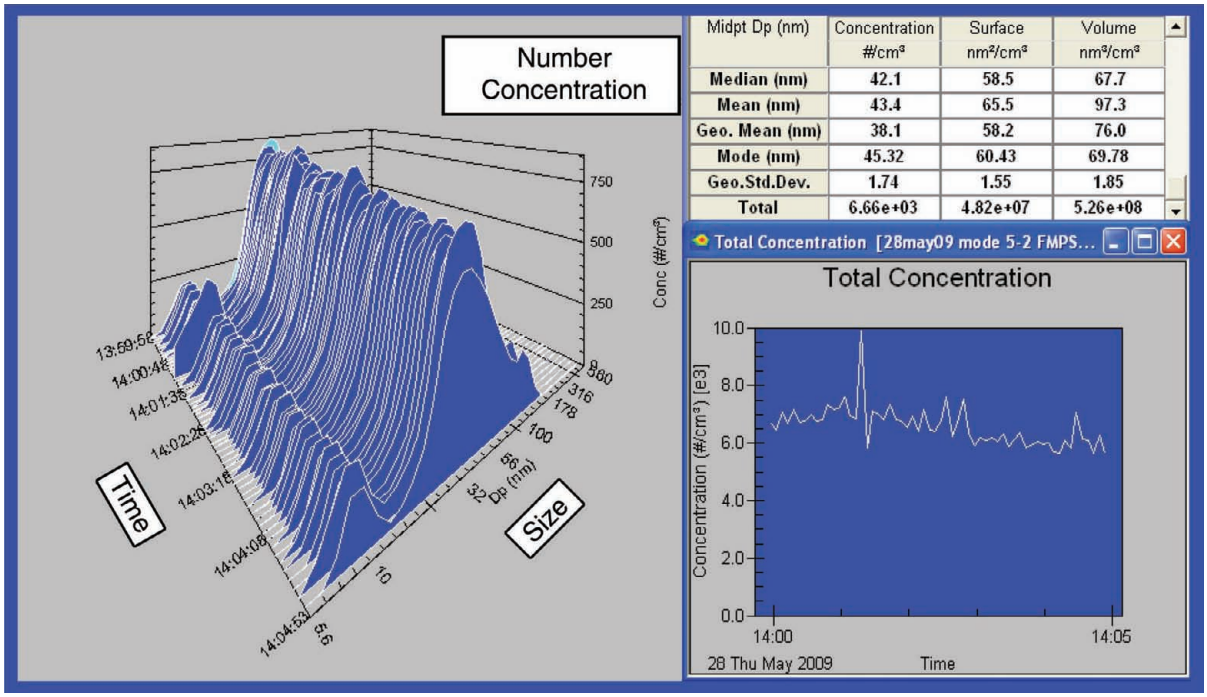


Figure 7. Sample particle size distribution for steady-state Mode 1 obtained from engine B.



Midpt Dp (nm)	Concentration #/cm³	Surface nm²/cm³	Volume nm³/cm³
Mean (nm)	44.0	89.9	106.0
Geo. Mean (nm)	33.7	80.1	99.0
Mode (nm)	33.98	124.09	124.09
Geo.Std.Dev.	2.11	1.69	1.49
Total	4.15e+03	3.90e+07	5.84e+08

Figure 8. Sample particle size distribution for steady-state Mode 3 obtained from engine B.



Midpt Dp (nm)	Concentration #/cm³	Surface nm²/cm³	Volume nm³/cm³
Median (nm)	42.1	58.5	67.7
Mean (nm)	43.4	65.5	97.3
Geo. Mean (nm)	38.1	58.2	76.0
Mode (nm)	45.32	60.43	69.78
Geo.Std.Dev.	1.74	1.55	1.85
Total	6.66e+03	4.82e+07	5.26e+08

Figure 9. Sample particle size distribution for steady-state Mode 5 obtained from engine B.

Table 13. Summary of FTP Emissions Testing Results at LRRI for Engine B as Measured from the Exposure Chamber[a,b]

	NO_x	CO	CO_2	NMHC	PM
FTP Test 1	1.43	0.074	679	0.011	0.00007
FTP Test 2	1.55	0.075	659	0.015	0.00009
FTP Test 3	1.66	0.065	819	0.010	0.00007
Average	1.55	0.071	719	0.012	0.00008
SD	0.11	0.006	87	0.003	0.00001
CV (%)	7.32	8.21	12.15	21.24	15.37

[a] Data expressed in g/hp • hr.

[b] CV = coefficient of variation; FTP = Federal Test Procedure; g/hp • hr = grams per horsepower-hour; LRRI = Lovelace Respiratory Research Institute; NMHC = nonmethane hydrocarbon; PM = particulate matter; SD = standard deviation.

Table 14. Summary of FTP Emissions Testing Results at LRRI for Engine B′ as Measured from the Exposure Chamber[a,b]

	NO_x	CO	CO_2	NMHC	PM
FTP Test 1	1.45	0.203	657	0.015	0.00039
FTP Test 2	1.52	0.168	655	0.014	0.00038
FTP Test 3	1.49	0.202	638	0.016	0.00037
Average	1.49	0.191	650	0.015	0.00038
SD	0.04	0.020	10.72	0.001	0.00001
CV (%)	2.53	10.47	1.65	8.92	2.68

[a] Data expressed in g/hp • hr.

[b] CV = coefficient of variation; FTP = Federal Test Procedure; g/hp • hr = grams per horsepower-hour; LRRI = Lovelace Respiratory Research Institute; NMHC = nonmethane hydrocarbon; PM = particulate matter; SD = standard deviation.

Table 15. Summary of the FTP Emissions Rates at SwRI for Engines B and B′, as Measured from the CVS Tunnel[a,b]

	NO_x	CO	CO_2	NMHC	PM
Engine B	0.89	0.11	647	−0.009	0.0013
Engine B′	0.98	0.08	615	0.011	0.0004
High Alt Engine B′	1.33	0.224	590	0.016	0.0002

[a] Data expressed in g/hp • hr.

[b] CVS = constant volume sampler; FTP = Federal Test Procedure; g/hp • hr = grams per horsepower-hour; NMHC = nonmethane hydrocarbon; PM = particulate matter; SwRI = Southwest Research Institute.

TESTS 2 AND 4: DETERMINING COMPOSITION AND ENVIRONMENTAL CONDITIONS AT A DILUTION RATE SET TO ACHIEVE 4.2 PPM NO_2

HEI defined the high-exposure level target as a dilution set to achieve an average exposure atmosphere concentration of 4.2 ppm NO_2. The original protocol was amended such that Tests 2 and 4 both involved repeated characterization of the exposure atmosphere under these dilution conditions. The original protocol specified that this testing would be conducted at a minimum allowable dilution that was presumed to be based on temperature. Test 4 extends the primary emissions measurements defined in Test 2 to include the detailed characterization of additional analytes and analyte classes, shown in Table 7. The detailed characterizations in Test 4 were conducted for only engine B, and those data are provided as Appendix D to this report. However, Test 2 was conducted for both engine B and B′. A single test consisted of a complete 16-hour ACES cycle, comprised of four 4-hour transient cycles. A power map was conducted daily to ensure proper engine operation. However, a manual regeneration was not performed before the testing.

Table 16 shows the average concentrations for three repeated tests of NO, NO_2, CO_2, CO, NMHC, and PM for engine B. Engine B′ data are provided in the section "Supplementary Characterization of System Performance" later in this report. The NMHC values are corrected for background. The average integrated concentrations for this characterization were approximately 12% above target. Of note is that the coefficient of variation (CV) between tests was less than 6% for NO, NO_2, and CO_2. No adjustments to the system were made between tests, in order to assess the unadjusted stability of the atmospheres from day to

Table 16. Integrated Average Concentrations of Gases and PM from 16-Hour Engine Cycle Measured in High-Level Exposure Chamber (Engine B)[a]

	NO (ppm)	NO_2 (ppm)	CO_2 (ppm)	CO (ppm)	NMHC (ppm)	PM ($\mu g/m^3$)
16-Jul-09	3.3	5.1	2926	0	0.29	6.3
17-Jul-09	3.1	4.6	2716	0.30	0	13.3
18-Jul-09	3.2	4.6	2714	0	0.35	8.0
Average	3.2	4.8	2785	0.10	0.21	9.2
SD	0.1	0.3	121	NA	0.19	3.6
CV (%)	2.6	5.7	4.4	NA	87.74	39.4

[a] CV = coefficient of variation; NMHC = nonmethane hydrocarbon; PM = particulate matter; SD = standard deviation.

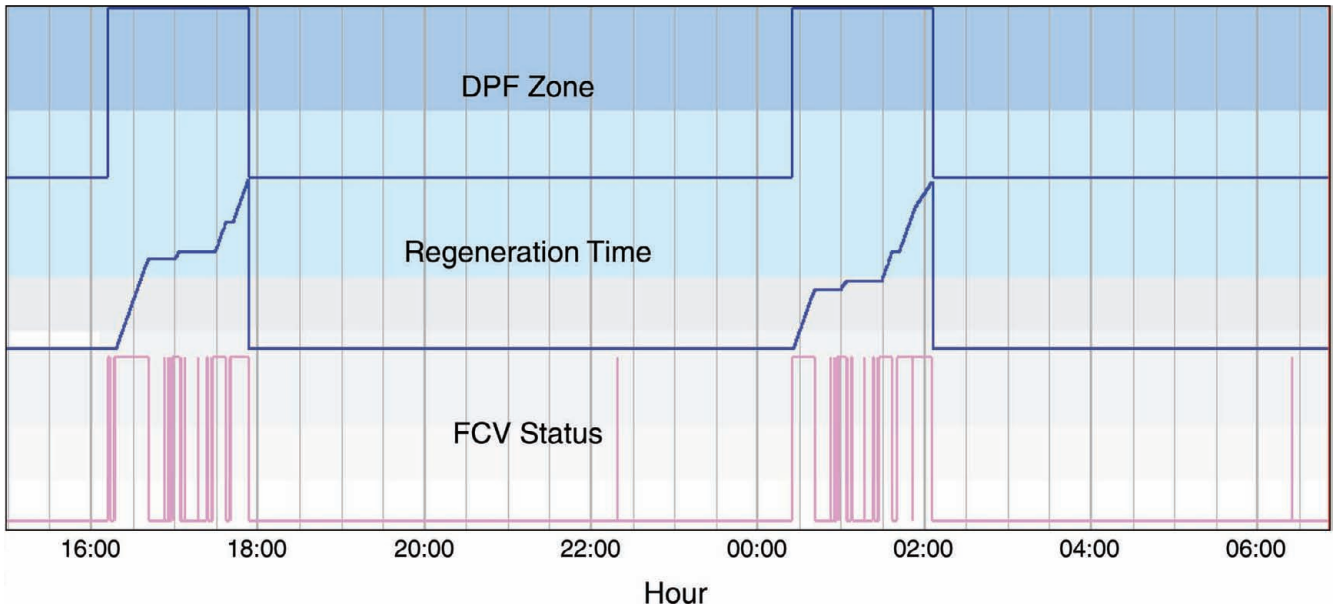


Figure 10. Indication of the DPF regeneration status during a representative 16-hour ACES cycle. During the cycle, two 90- to 120-minute regenerations occurred. This figure indicates DPF regeneration status (top), the regeneration time (middle), and the FCV status (bottom) during the cycle.

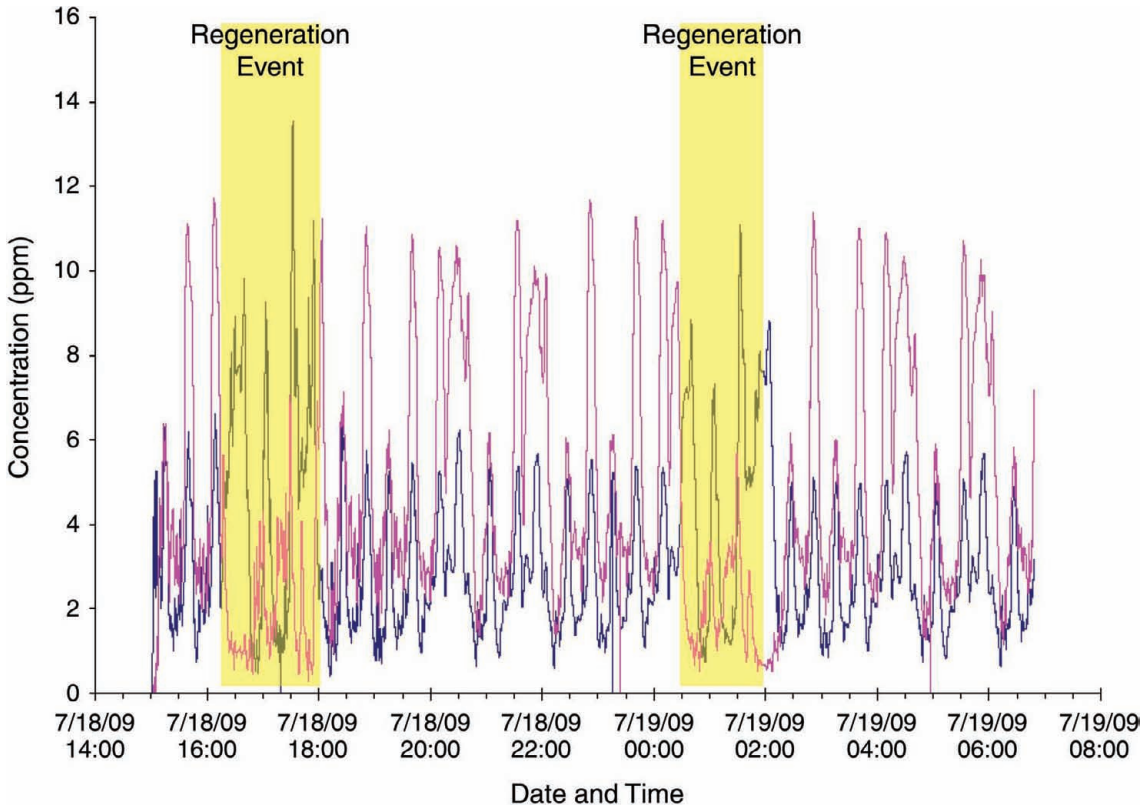


Figure 11. Representative real-time concentrations of NO (blue) and NO_2 (pink) during a 16-hour ACES transient cycle (with two regeneration events) at the high exposure level. The average concentrations of NO and NO_2 were 3.2 and 4.6 ppm.

day. The NO:NO_2 ratio was 40:60. CO and NMHC were at or near the background after the background was subtracted. The composition of NMHC is elucidated by the detailed speciation provided in Appendix D. PM had an average concentration of approximately 10 µg/m^3. As described later, most of the PM emissions occurred during DPF regeneration.

The 16-hour cycles at LRRI have consistently contained two trap regenerations during each test conducted during and subsequent to the emissions testing. Figure 10 shows control system data that illustrate points during the cycle where regenerations occurred. The data illustrate an on–off step in the DPF regeneration cycle, an indication of cumulative regeneration time, and an indication of the fuel cutoff valve status. The fuel cutoff valve (FCV) controls the fuel supply to the hydrocarbon doser and is the signal that is monitored by the control system to indicate regeneration status. Each regeneration took approximately 90 minutes. Of note is that this was the same regeneration time reported by SwRI.

Figures 11 and 12 indicate the real-time traces of the gases during the 16-hour ACES cycle. The plots show that, with the exception of THC, all of the gases varied throughout the cycle as a function of duty cycle and DPF status. NO_x concentrations did not exceed 15 ppm, and NO_2 concentrations did not exceed 12 ppm at any point during the cycle. During trap regeneration, NO became the dominant component of NO_x because the conditions during that period did not favor conversion of NO to NO_2. CO_2 concentrations showed changes that reflected primarily the changes in fuel consumption during the cycle. CO concentrations were the highest during the early part of the 16-hour cycle and decreased later, presumably due to the improved conversion efficiency of the aftertreatment system with the increasing temperature during warm-up. THC stayed reasonably constant throughout the cycle.

Figures 13 through 15 show the real-time particle mass, particle number, and particle number-based size distribution observed during the 16-hour transient cycle. As evident in the figures, particles were measurable primarily during the two, 90-minute regeneration periods. The particle mass concentration averaged approximately 50 µg/m^3 during this period, but peaked over 250 µg/m^3. For the two regeneration events shown, the average particle size was 22.1 (2.1) and 28.7 (1.5) nm (geometric standard deviation) for the first and second regeneration, respectively.

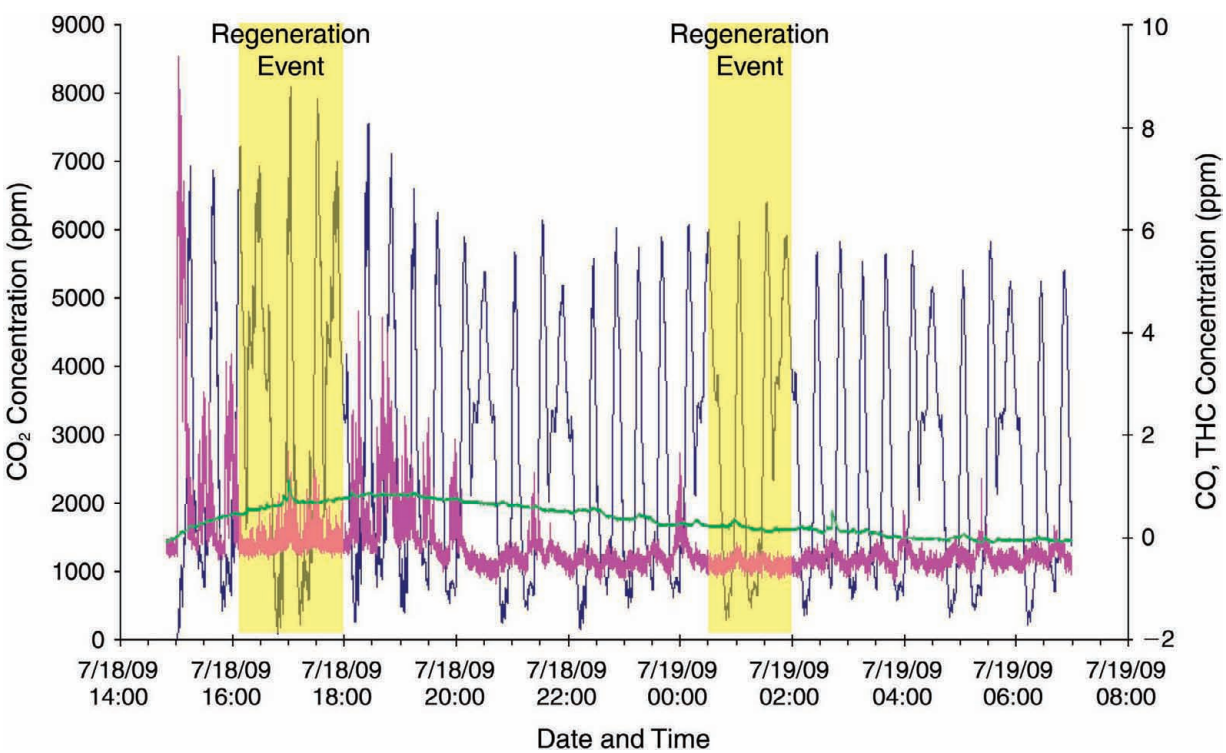


Figure 12. Representative real-time concentrations of CO_2 (blue), CO (pink), and THC (green) during a 16-hour ACES transient cycle (with two regeneration events) at the high exposure level. The average concentrations were 2714, −0.280, and 0.35 ppm.

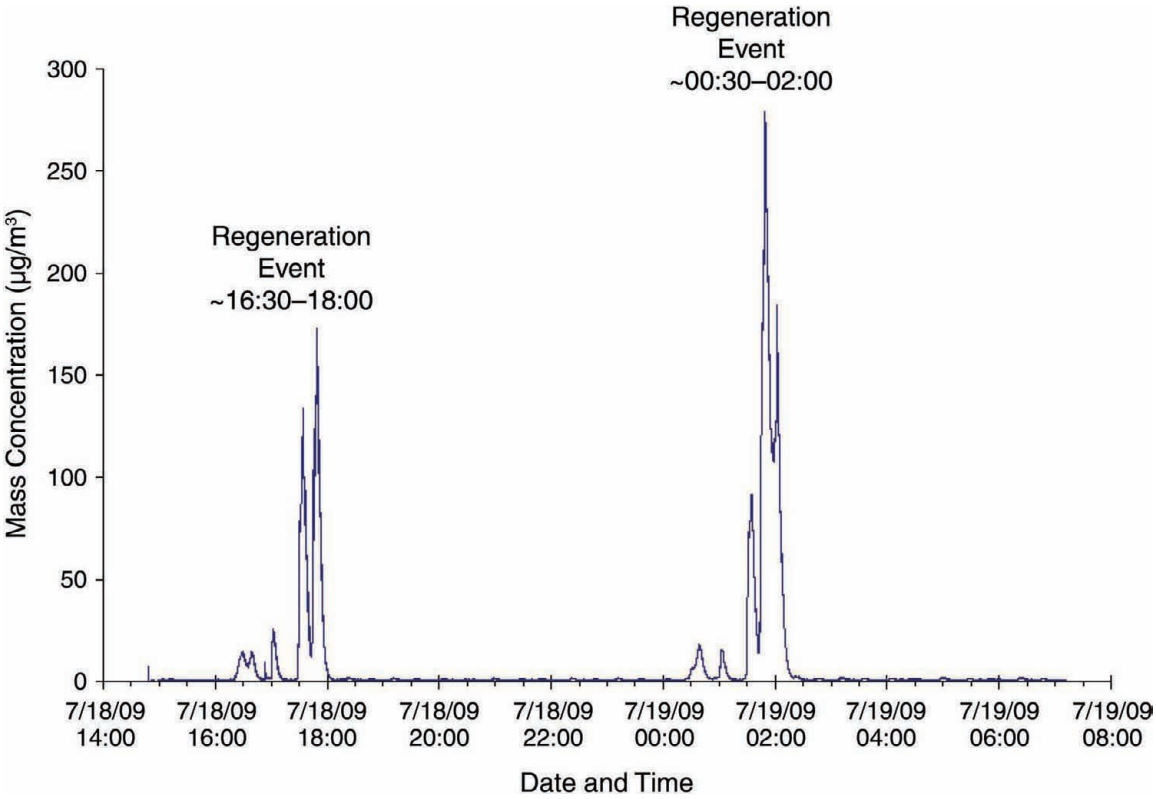


Figure 13. Representative real-time particle mass concentration measured by the DMM in the high-level chamber during the 16-hour ACES cycle. Particle concentrations peaked during the DPF regenerations. The approximate average concentrations during regenerations were 50 µg/m^3, and concentrations peaked as high as approximately 280 µg/m^3.

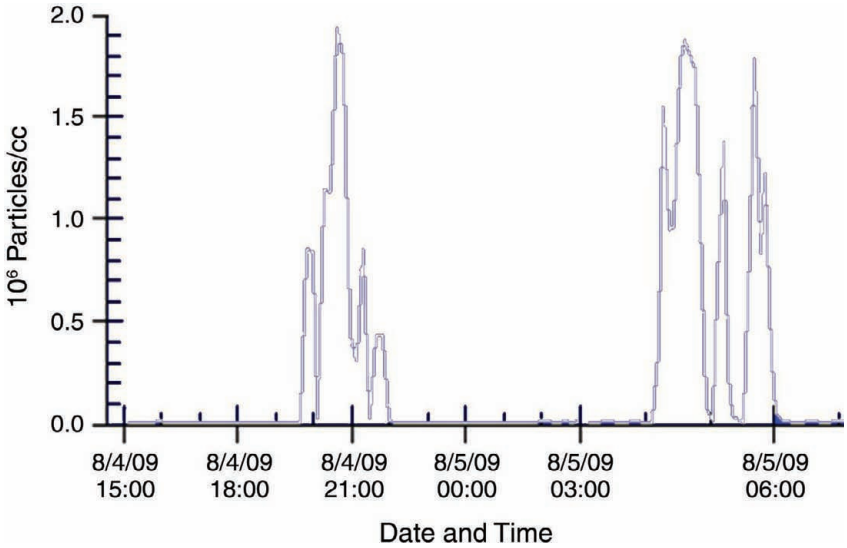


Figure 14. Representative real-time particle number concentration during a 16-hour ACES transient cycle. Particle number concentrations peaked during two trap regenerations.

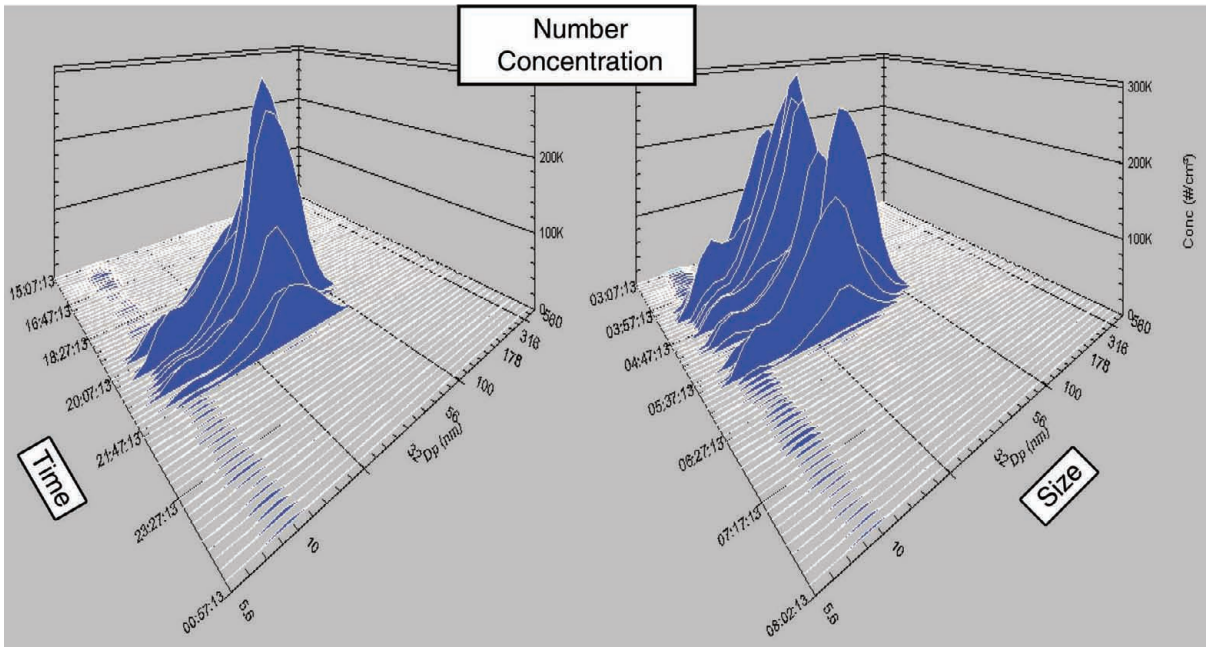


Figure 15. Representative real-time particle size distribution during a 16-hour ACES transient cycle with two regenerations (shown on the left and right). Particle concentrations were highest during DPF regeneration.

TEST 3: DETERMINING MINIMUM ALLOWABLE DILUTION RATE

As mentioned, HEI defined the minimum allowable dilution rate as the dilution set to achieve an average exposure atmosphere concentration of 4.2 ppm NO_2 in the high-level exposure chamber. At this target dilution, the ability to achieve animal welfare standards for temperature (24° ± 3°C) and relative humidity (< 70%) averaged throughout the ACES 16-hour transient cycle must be demonstrated. Figure 16 shows representative temperatures observed during a 16-hour cycle. Under these conditions the relative humidity of the chamber was less than 70% at all times. The criteria for both temperature and relative humidity were met. Since these data were generated, supplemental cooling has been added to the exposure room to ensure that there is sufficient control of temperature to meet the animal welfare guidelines once the animals are in place.

As mentioned earlier, the results in Table 15 show reasonable similarities between SwRI and LRRI, with the LRRI data showing consistency in the emissions between tests. However, one exception was noted in Test 3, where the CO_2 concentrations were approximately 20% higher than the average of the first two tests. This made the average CO_2 emissions for engine B substantially higher than those observed at SwRI. An assessment showed that the fuel consumption measurements at LRRI and SwRI were within 5% of each other, suggesting the CO_2 measurement in Test 3 was suspect since the differences in fuel consumption did not match differences in CO_2.

TEST 5: DETERMINING CHAMBER PERFORMANCE AT MINIMUM ALLOWABLE DILUTION RATE

Exposure Chamber Aerosol Distribution

In Test 5, we measured NO concentrations to demonstrate the uniformity of aerosol concentration in the exposure chambers. Four sampling ports located on the doors of the H-2000 chamber were used, and samples were taken at two positions, one at the front and one at the back of each of the four ports. A defined protocol was used in taking samples to allow determination of system homogeneity. The total variation of aerosol concentration was defined as the CV of samples taken in series at each sampling port during steady-state operation, and the temporal variation was the CV among the data referenced to one port sampled continuously throughout the test. The variation in NO concentrations among sample ports in the chamber is portrayed in Figure 17. The results demonstrated CVs of 0.36% and 2.2% for spatial and temporal

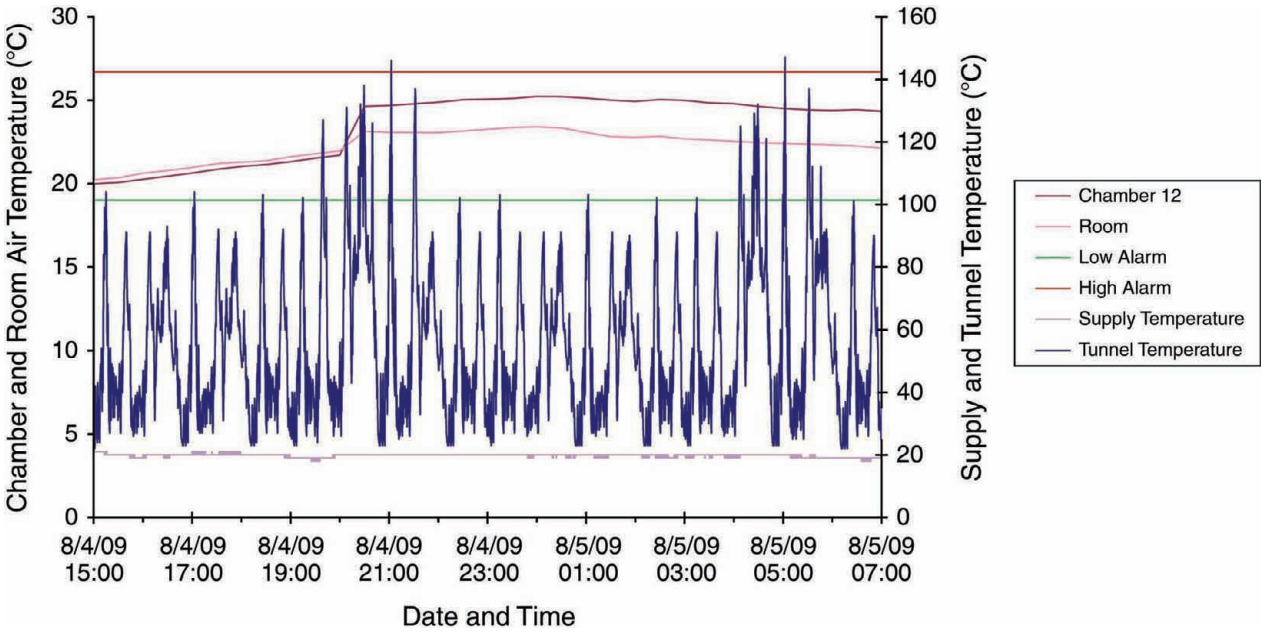


Figure 16. Temperature alarm limits, room temperature, and high-level exposure chamber temperature during a typical 16-hour transient cycle. Measurements were taken from exposure chamber 12, the room, the building supply air, and the dilution tunnel. Temperature alarms were set at 19.0°C (low) and 26.7°C (high).

distribution, respectively. As per the LRRI standard operating procedures, the acceptance criterion for chamber homogeneity CV is a CV of less than 10%. Therefore, no further statistical analysis on chamber homogeneity data was conducted.

Determination of T_{90}

The time to reach 90% of a target concentration (T_{90}), typically used to define exposure system characteristics in inhalation studies, cannot plausibly be defined during the 16-hour engine cycle (during which concentrations vary with engine load). In order to define a value for time to equilibrium, the T_{90} was measured with the engine operating in steady state. The time to system equilibrium (steady-state concentration) within the exposure chamber was 7 minutes. A real-time plot of time to equilibrium for NO concentration is shown in Figure 18.

Residual Aerosol Concentration During Nonexposure Hours

To define any background or re-entrainment of gaseous and particulate components during nonexposure hours, regulated pollutants in the exposure chambers were measured for the entire 8-hour nonexposure period on days following multiday operation of the system. All concentrations were at background levels.

Exposure System Stability

Exposure system stability was characterized during triplicate operations at the specified dilution conditions. LRRI standard operating procedures define that concentration CV for an exposure system be within 10% for system stability. As indicated in Table 13, the CV for NO_x for triplicate runs was 7.32%, which is considered good system stability.

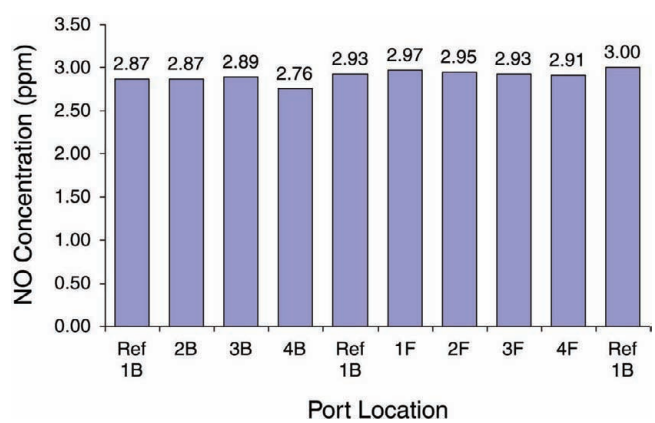


Figure 17. Chamber distribution of NO in the whole-body exposure chamber. "Ref" are reference ports to which the other exposure ports are compared. The labels 1B–4B indicate sampling locations in the back of the chamber. The labels 1F–4F indicate four different chamber sampling locations in the front of the chamber.

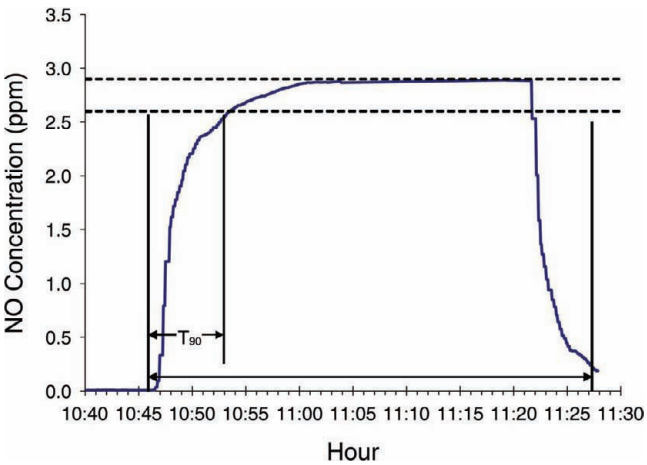


Figure 18. Time-to-chamber equilibrium for NO concentration. Chamber equilibrium was achieved 7 minutes after engine start.

Table 17. Concentration of NO and NO_2 During the 16-Hour Cycle at Proposed Mid and Low Exposure Levels (Engine B)[a]

	Mid-Level Chamber		Low-Level Chamber	
	NO (ppm)	NO_2 (ppm)	NO (ppb)	NO_2 (ppb)
16-Jul-09	0.53	0.89	28.39	79.39
17-Jul-09	0.52	0.84	26.60	98.43
18-Jul-09	0.54	0.84	30.43	98.21
Average	0.53	0.86	28.47	92.01
SD	0.013	0.026	1.917	10.931
CV (%)	2.4	3.1	6.7	11.9

[a] CV = coefficient of variation; SD = standard deviation.

TEST 6: DETERMINING COMPOSITION IN THE CHAMBER AT 0.8- AND 0.1-PPM EXPOSURE TARGETS

Table 17 shows the concentration of NO and NO_2 at the mid- and low-level exposure targets. Target concentrations within 10% were achieved at these exposure levels.

TEST 7: DETERMINING PARTICLE NUMBER-BASED SIZE DISTRIBUTION AT TUNNEL EXTRACTION POINT AND FROM EXPOSURE CHAMBER

Figures 19 and 20 show the particle size distribution measured at the tunnel extraction point and in the exposure chamber. The particle characteristics reported are particle number, surface area, and volume-weighted distributions. The data were collected during operation of the engine under steady-state conditions at 1800 revolutions per minute (rpm) and 75% throttle. The dilution ratio, defined by the NO_2 concentration in the tunnel versus that in the chamber, was approximately 2.7:1. The particle size distribution also showed reasonable similarity, with a slight difference in median diameter of 7 nm that may be within the measurement uncertainty for this determination. The changes based on mean size were greater, with an approximate 30-nm increase from the tunnel extraction point to the chamber. In addition, the surface and volume measurements did not scale with dilution, indicating that the particle characteristics are slightly modified with dilution.

As a follow-on to this experiment, particle count was measured at the tunnel extraction point and from the exposure chamber directly with a CPC. The engine was operated under steady-state Modes 1, 3, and 5. The particle count for each mode was decreased from 1.9×10^6 to 1.0×10^6 particles/cm^3, from 2.5×10^5 to 1.0×10^5 particles/cm^3, and from 13×10^3 to 6×10^3 particles/cm^3 for modes 1, 3, and 5, respectively, between the tunnel and the chamber. The dilution for each condition was 2.2:1, calculated by ratio of the NO_x concentrations at the two sampling points. With this dilution, the recovery of particles through the system was approximately 100% or higher than what was calculated, which suggests formation due to nucleation during the secondary dilution.

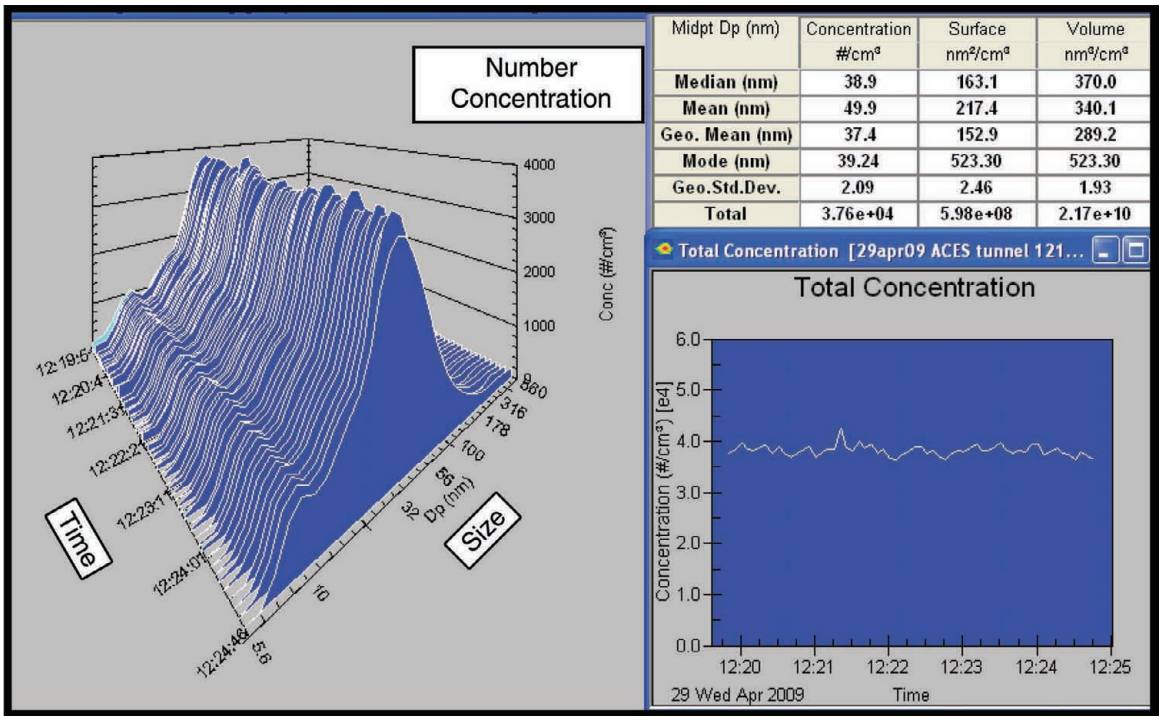
SUPPLEMENTARY CHARACTERIZATION OF SYSTEM PERFORMANCE

Additional characterization of test atmospheres and system performance was conducted to enhance the characterization efforts described earlier. The protocol was amended to include the tests described in Table 18.

CARBON BALANCE DURING ENGINE CYCLE

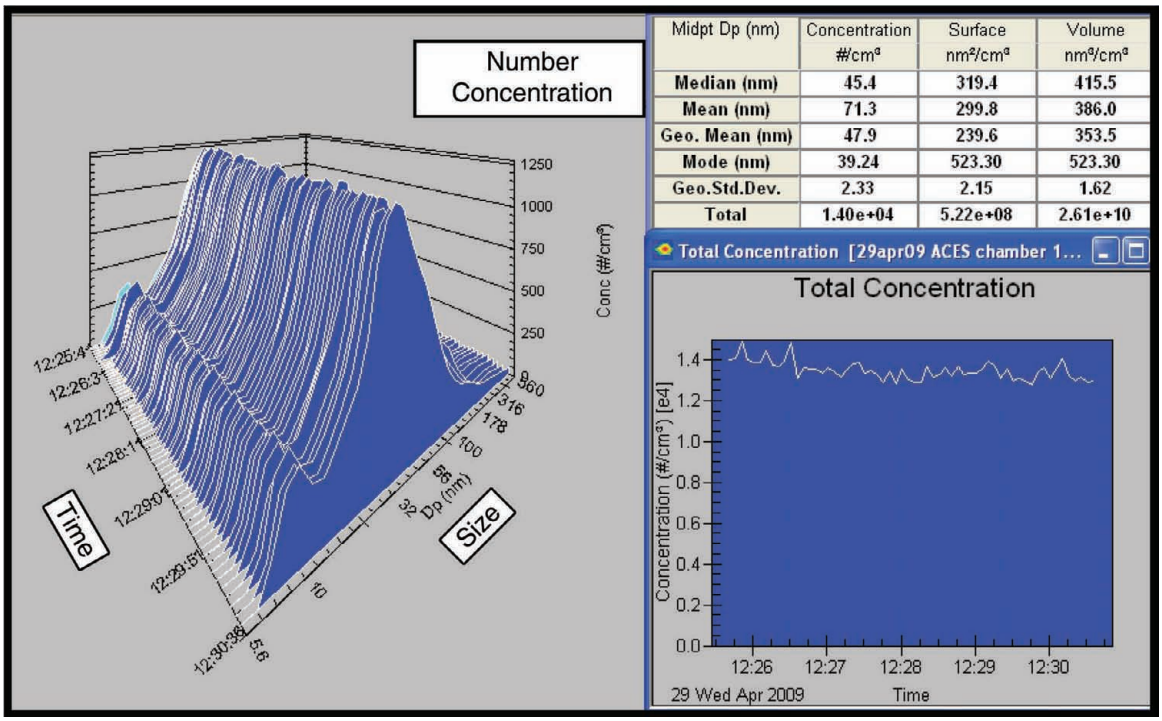
Carbon balance from fuel consumption data was conducted as a quality assurance check of the system. The goal of the test was to assess the reason for differences in CO_2 at LRRI during Phase 3A compared with the Phase 1 results. CO_2 was measured directly from the dilution tunnel and the fuel consumption was compared with the tunnel CO_2 concentrations in order to determine the carbon mass balance.

Measurements were conducted both on the steady-state and FTP engine cycles. Table 19 shows the fuel consumption, dilution factor, and CO_2 measured in the dilution tunnel. Table 20 shows the measured exhaust flow.



Midpt Dp (nm)	Concentration #/cm³	Surface nm²/cm³	Volume nm³/cm³
Median (nm)	38.9	163.1	370.0
Mean (nm)	49.9	217.4	340.1
Geo. Mean (nm)	37.4	152.9	289.2
Mode (nm)	39.24	523.30	523.30
Geo.Std.Dev.	2.09	2.46	1.93
Total	3.76e+04	5.98e+08	2.17e+10

Figure 19. An example of particle size distribution at the tunnel extraction point during steady-state engine operation. Particle characteristics reported are particle number, surface area, and volume-weighted distributions.



Midpt Dp (nm)	Concentration #/cm³	Surface nm²/cm³	Volume nm³/cm³
Median (nm)	45.4	319.4	415.5
Mean (nm)	71.3	299.8	386.0
Geo. Mean (nm)	47.9	239.6	353.5
Mode (nm)	39.24	523.30	523.30
Geo.Std.Dev.	2.33	2.15	1.62
Total	1.40e+04	5.22e+08	2.61e+10

Figure 20. An example of particle size distribution from the exposure chamber during steady-state operating conditions. Particle characteristics reported are particle number, surface area, and volume-weighted distributions.

Table 18. Summary of Tests and Objectives for Supplementary Characterization of Test Atmospheres and System Performance[a]

Test	Objective
1. Carbon balance during FTP cycle	Assess differences in CO_2 between SwRI and LRRI, and ensure equitable carbon balances between fuel consumption and CO_2 measurement in dilution tunnel
2. Determination of composition at dilution rate set to achieve 4.2, 0.8, and 0.1 ppm NO_2	Establish composition of exposure chamber atmospheres over an extended analysis period
3. Monitoring of environmental conditions in exposure chambers	Define highest concentration in exposure chamber at which temperature within the chamber is < 27°C (target = 23°C average temperature)
4. Assessment of particle mass measurement from multiday collections	Improve measurement of particle mass on filters and compare with Dekati mass monitor and CPC
5. Assessment of chamber inlet concentrations and comparison with chamber concentrations	Assess ability to measure PM concentration in chamber inlet to determine suitability to represent chamber engine exhaust composition

[a] CPC = condensation particle counter; FTP = Federal Test Procedure; LRRI = Lovelace Respiratory Research Institute; SwRI = Southwest Research Institute.

Predicted CO_2 tunnel concentration was calculated according to the following equation, where Rate in Exhaust is the volumetric flow rate of CO_2 produced in the exhaust:

kg of CO_2/kg of Exhaust =

$$\frac{CO_2 \text{ Rate in Exhaust}}{1° \text{ Dilution Factor} \times \text{Exhaust Rate}} \times \frac{MW_{CO_2}}{MW_{EXH}}$$

Steady-State Mode 1 = 442173.3 × 44/29 = 27768 ppm
Steady-State Mode 3 = 22822.9 × 44/29 = 15027 ppm
Steady-State Mode 5 = 29171.09 × 44/29 = 19206 ppm
FTP Cycle = 9537.8 × 44/29 = 6279 ppm

Table 19. Fuel Consumption, Dilution Ratio, and CO_2 Concentration in the Dilution Tunnel[a]

Cycle	Fuel Consumption (kg/min)	Primary Dilution Ratio (Tunnel)	Measured CO_2 (ppm; in Tunnel)
Steady-state Mode 1	1.45	3.9	28,600
Steady-state Mode 3	0.79	5.1	15,499
Steady-state Mode 5	0.98	5.4	19,550
FTP cycle	0.33	9.9	5,827

[a] FTP = Federal Test Procedure.

Table 21 shows the measured versus calculated CO_2 concentrations and the percentage difference between them. The agreement for the steady-state cycles was approximately 3% or better. A typical accepted difference is ≤ 2%. Ignoring THC and CO concentrations in exhaust as well as possible THC, CO, and CO_2 concentrations in dilution air may contribute to an additional 1% difference, as indicated in Table 21. The FTP cycle shows an approximate 8% difference in calculated versus measured CO_2. This larger difference may be attributed to different response rates between the combustion, dilution air, and fuel flow meters.

Overall, the differences shown here for calculated versus measured CO_2 were not enough to explain the observed difference in reported CO_2 between the Phase 1 and Phase 3 characterizations.

Table 20. Engine Exhaust Flow Rate[a]

Cycle	Exhaust Flow Rate (kg/min)
Steady-state Mode 1	28.15
Steady-state Mode 3	21.65
Steady-state Mode 5	19.87
FTP cycle	11.12

[a] FTP = Federal Test Procedure.

Table 21. Concentration of CO_2 in Tunnel, Calculated vs. Measured[a]

Cycle	Measured CO_2 (ppm)	Calculated CO_2 (ppm)	Difference, Measured − Calculated (%)
Steady-state Mode 1	28,600	27,768	3.0
Steady-state Mode 3	15,499	15,027	3.1
Steady-state Mode 5	19,550	19,206	1.8
FTP cycle	5,827	6,279	−7.5

[a] FTP = Federal Test Procedure.

EXPOSURE CHAMBER COMPOSITION AND ENVIRONMENTAL CONDITIONS

The objective was to augment data on the composition and stability of the exposure atmospheres, including composition of the atmosphere and chamber temperature over 15 days of operation of engine B′ at the 16-hour ACES test cycle. Tables 22 through 24 show concentrations of PM, NO, NO_2, NO_x, CO, CO_2, and THC along with the average chamber temperature and the number of DPF regenerations observed. For the high-level exposure, the concentration was measured gravimetrically at the chamber inlet (measured at the transit line immediately upstream of the exposure chamber) and within the exposure chamber, and also by DMM within the exposure chamber.

The primary dilution indicator for the exposure system performance was the integrated concentration of NO_2, with targets of 4.2, 0.8, and 0.1 ppm. The average concentration of NO_2 over the 15 days was within 10% of target at all exposure levels. There was variance outside of the 10% performance target on a few of the days. This may be attributable in part to the time it takes for the system operator to learn how to make accurate dilution adjustments, especially on a complex and variable cycle with constantly changing concentrations. In addition, the results of these trials led to the installation of an improved, finely tuned dilution on the lower exposure levels, which will provide additional system control during Phase 3B.

Concentrations of PM showed a CV of 25% to 30% for filter-based measurements and approximately 50% for

Table 22. High-Level Exposure Chamber PM, Gas, Temperature, and Regeneration Frequency (16-Hour Cycle)[a]

	Gravimetric Concentration		Measurements Collected from the Chamber Sampling Ports								
Test Day	Chamber PM (μg/m³)	Chamber Inlet PM (μg/m³)	DMM PM (μg/m³)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	CO (ppm)	CO_2 (ppm)	THC (ppm)	Chamber Temperature Average (°C)	Regen. (#/cycle)
1	10.6	—	—	2.77	4.12	6.89	—	—	0.28	20.7	1
2	8.3	—	—	2.87	4.22	7.09	—	—	0.26	21.4	1
3	8.0	13.5	10.5	3.14	4.21	7.35	2.92	3027	0.42	23.5	2
4	12.9	15.5	21.7	3.21	3.87	7.08	3.09	3013	0.00	23.0	2
5	6.4	11.5	11.3	3.31	4.57	7.88	3.30	3031	0.03	24.0	1
6	11.9	14.4	22.5	3.65	4.43	8.07	2.56	2994	0.00	20.7	2
7	7.2	8.7	13.2	3.41	4.80	8.21	3.25	2994	0.22	20.7	1
8	5.7	9.4	13.1	2.51	3.54	6.05	3.19	2647	0.04	21.1	1
9	7.7	11.0	14.8	2.54	3.53	6.07	2.33	2744	0.08	20.8	2
10	11.4	15.2	25.2	2.87	3.97	6.83	4.61	3013	0.00	22.1	1
11	13.4	15.8	9.16	2.45	3.56	6.01	3.32	2615	0.10	20.8	2
12	6.6	7.5	15.3	2.57	3.54	6.11	2.68	2619	0.07	20.8	1
13	14.2	16.4	38.0	2.90	4.15	7.05	3.05	2899	0.04	21.1	2
14	11.9	13.2	11.9	2.75	3.59	6.33	2.94	2918	0.00	21.2	2
15	9.0	10.4	13.4	3.05	4.07	7.11	3.49	2997	0.00	22.8	2
Average	9.7	12.5	16.9	2.9	4.0	6.9	3.1	2885.5	0.1	21.6	
SD	2.8	2.9	8.0	0.4	0.4	0.7	0.6	166.3	0.1	1.1	
CV (%)	28.9	23.5	47.4	12.2	10.2	10.6	17.6	5.8	128.3	5.2	

[a] CV = coefficient of variation; DMM = Dekati mass monitor; PM = particulate matter; Regen. = regeneration; SD = standard deviation; THC = total hydrocarbons; — = data not available.

Table 23. Mid-Level Exposure Chamber PM, Gas, Temperature, and Regeneration Frequency (16-Hour Cycle)[a]

Test Day	Gravimetric Chamber PM Concentration (μg/m^3)	Measurements Collected from the Chamber Sampling Ports			Chamber Temperature Average (°C)	Regen. (#/cycle)
		NO (ppm)	NO_2 (ppm)	NO_x (ppm)		
1	2.0	0.66	1.05	1.71	20.1	1
2	2.6	0.69	1.09	1.78	20.7	1
3	2.0	0.75	1.07	1.82	22.7	2
4	0.0	0.02	0.05	0.07	22.0	2
5	1.7	0.71	1.05	1.76	23.3	1
6	2.6	0.77	1.01	1.77	20.0	2
7	1.7	0.74	1.13	1.86	19.9	1
8	2.1	0.68	1.11	1.70	20.6	1
9	2.3	0.12	0.23	0.35	20.1	2
10	1.3	0.30	0.46	0.76	20.9	1
11	2.8	0.12	0.24	0.36	20.1	2
12	−0.1	0.28	0.45	0.73	20.2	1
13	2.8	0.48	0.75	1.23	20.5	2
14	0.9	0.47	0.65	1.12	20.6	2
15	1.4	0.52	0.73	1.25	22.0	2
Average	1.7	0.5	0.7	1.2	20.9	
SD	0.9	0.3	0.4	0.6	1.1	
CV (%)	53.1	53.3	50.5	51.2	5.1	

[a] CV = coefficient of variation; PM = particulate matter; Regen. = regeneration; SD = standard deviation.

Table 24. Low-Level Exposure Chamber PM, Gas, Temperature, and Regeneration Frequency (16-Hour Cycle)[a]

Test Day	Gravimetric Chamber PM Concentration (μg/m^3)	Measurements Collected from the Chamber Sampling Ports			Chamber Temperature Average (°C)	Regen. (#/cycle)
		NO (ppb)	NO_2 (ppb)	NO_x (ppb)		
1	1.1	15.43	71.20	86.62	19.1	1
2	1.9	16.36	72.27	88.62	19.6	1
3	0.6	26.45	93.35	119.83	21.2	2
4	0.7	30.33	88.39	118.72	20.7	2
5	1.0	29.46	103.17	132.68	21.5	1
6	0.4	27.70	96.01	123.68	18.6	2
7	0.8	23.80	96.37	120.16	18.5	1
8	0.0	62.03	122.23	184.19	19.4	1
9	1.6	26.63	95.04	121.64	18.8	2
10	0	117.22	227.32	344.51	18.8	1
11	1.3	71.27	167.75	239.00	19.0	2
12	0.7	53.32	112.58	165.82	19.1	2
13	0.3	35.53	88.88	124.42	20.5	2
Average	0.8	41.2	110.4	151.5	19.6	
SD	0.6	28.5	42.8	70.8	1.0	
CV (%)	72.0	69.2	38.8	46.7	5.2	

[a] CV = coefficient of variation; PM = particulate matter; Regen. = regeneration; SD = standard deviation.

DMM-based measurements. In addition, the PM average using the DMM was approximately 25% to 40% higher than the average of filter-based measurements at the high-exposure level. Using the high-level measurements, we compared the chamber inlet and exposure chamber concentrations to evaluate the ability of inlet concentration to represent the concentration of PM attributed to exhaust in the exposure chamber, discussed further below. In all cases, the average concentration at the high-exposure level was 10 to 20 µg/m^3. The filter-based measurements at the low-exposure levels in general trended with increases in dilution rate.

Concentrations of CO and CO_2 were consistent at approximately 3 and 3000 ppm throughout the 15 days of operation, and THC was 0.42 ppm or less. The THC measurement is highly variable due to the variance in the measurement method at these low concentrations.

The DPF was regenerated one to two times during each 16-hour cycle. There was no obvious trend between number of regenerations and the average concentrations of any measured constituent (PM and gases). However, as mentioned earlier, particle emissions occurred only during DPF regeneration. Figures 21 through 26, which show real-time particle number-based size distribution throughout the 16-hour cycle, further illustrate this: appreciable particle counts were observed in the exposure chamber only during periods of DPF regeneration. Most of these particles were less than 100 nm in diameter at all exposure levels.

Chamber temperature was targeted at 20°C without the animals, which are expected to add approximately 3°C to the heat load of the chambers. The range in temperature among the exposure levels was 19.5° to 21.6°C, with the warmest temperature observed at the highest exposure level. At these temperatures, the chamber environmental conditions are expected to be acceptable for the Phase 3B study.

COMPARISON OF CHAMBER INLET TO EXPOSURE CHAMBER ATMOSPHERE COMPOSITION

Because animals will contribute measurable PM to the exposure chamber atmosphere, it will be necessary to measure the concentration upstream of the exposure chamber to represent the amount of engine-exhaust–related PM in the chamber. Table 25 shows results of measurements made during the FTP cycle for gases, particle mass (measured by DMM), particle number concentration, and median diameter on engine B′. Because of instrument capacity, these measurements were not conducted in parallel, but rather in series. The results of the trials suggest good agreement between measurements made at the chamber inlet and exposure chamber. The DMM is capable of measuring particle mass between 1 µg/m^3 and 1000 µg/m^3. As shown in Table 25, all the particle mass measurements are at the

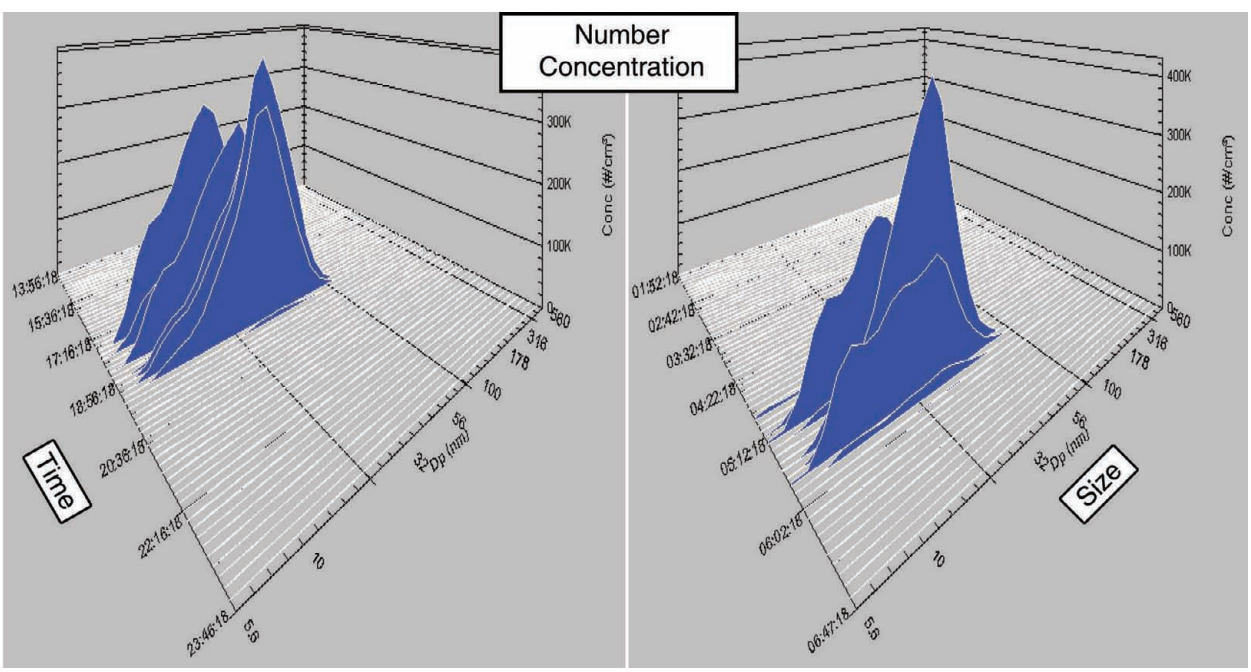


Figure 21. Real-time particle size distribution at the high-exposure level throughout the 16-hour cycle (September 28, 2009), which included two DPF regenerations (shown on the left and right).

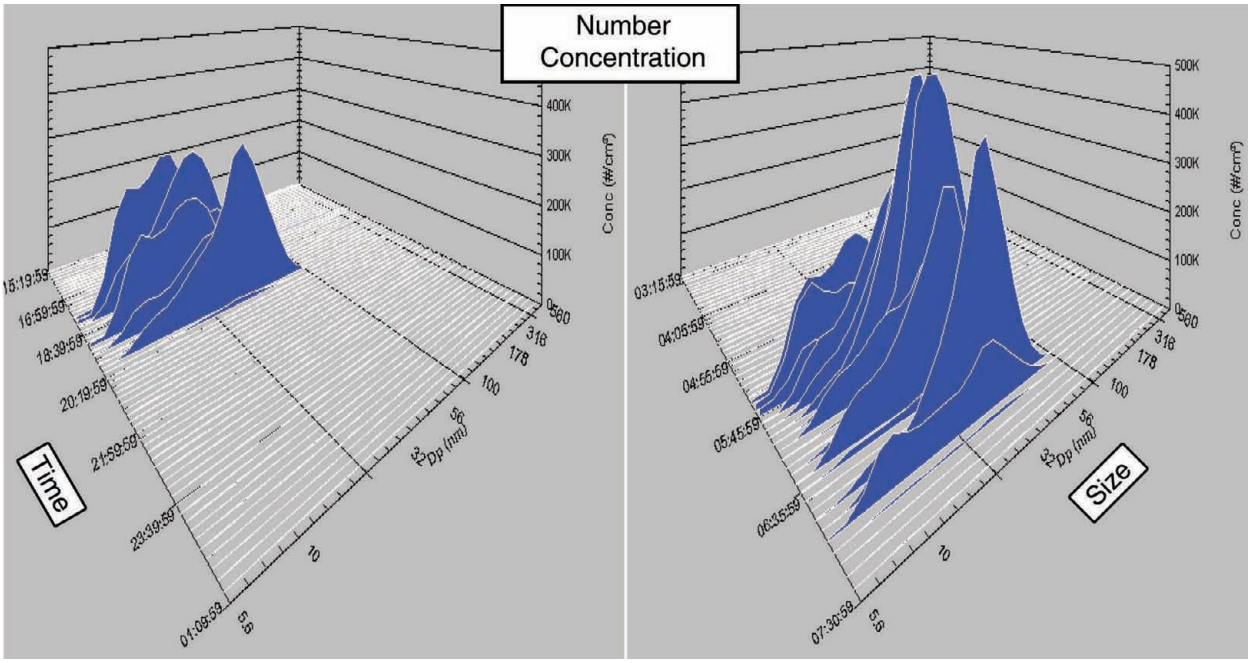


Figure 22. Another example of a real-time particle size distribution at the high-exposure level throughout the 16-hour cycle (October 1, 2009), which included two DPF regenerations (shown on the left and right).

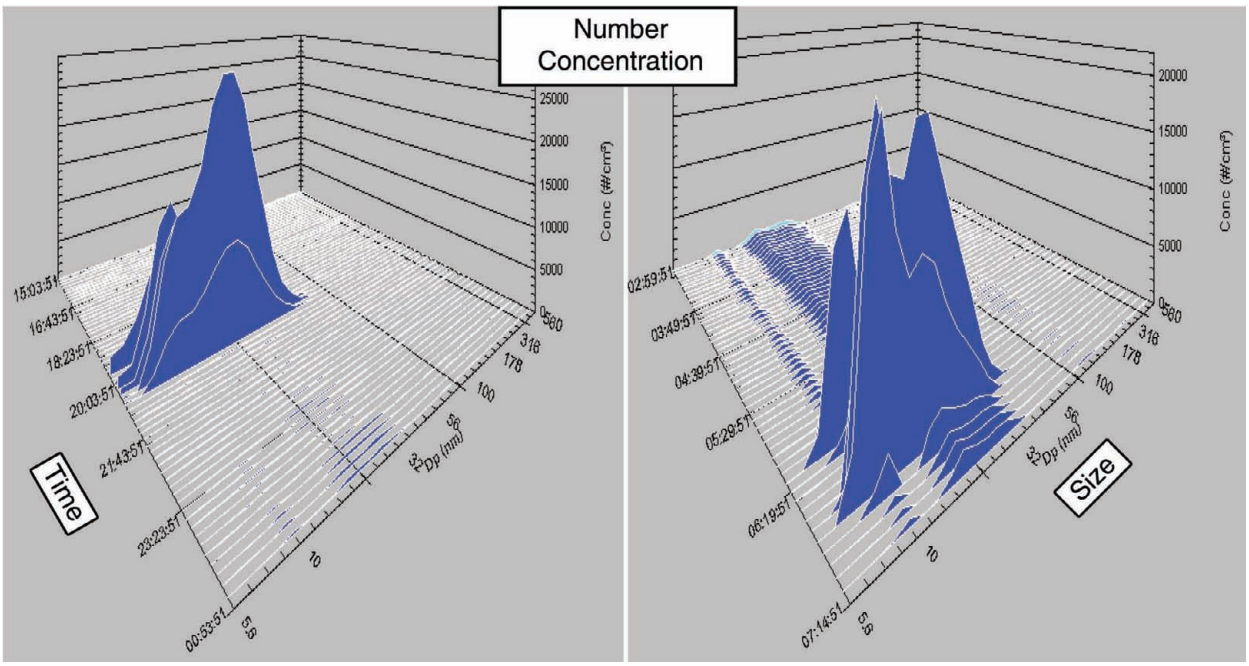


Figure 23. Real-time particle size distribution at the mid-exposure level throughout the 16-hour cycle (October 6, 2009), which included two DPF regenerations (shown on the left and right).

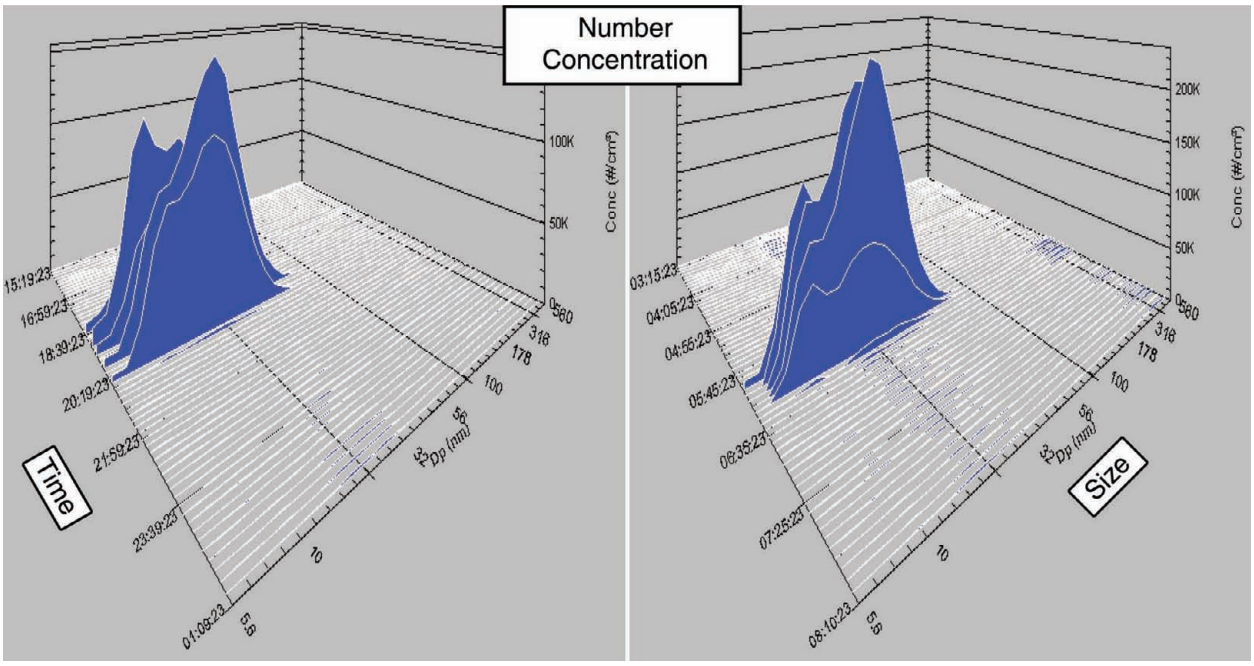


Figure 24. Another example of real-time particle size distribution at the mid-exposure level throughout the 16-hour cycle (October 12, 2009), which included two DPF regenerations (shown on the left and right).

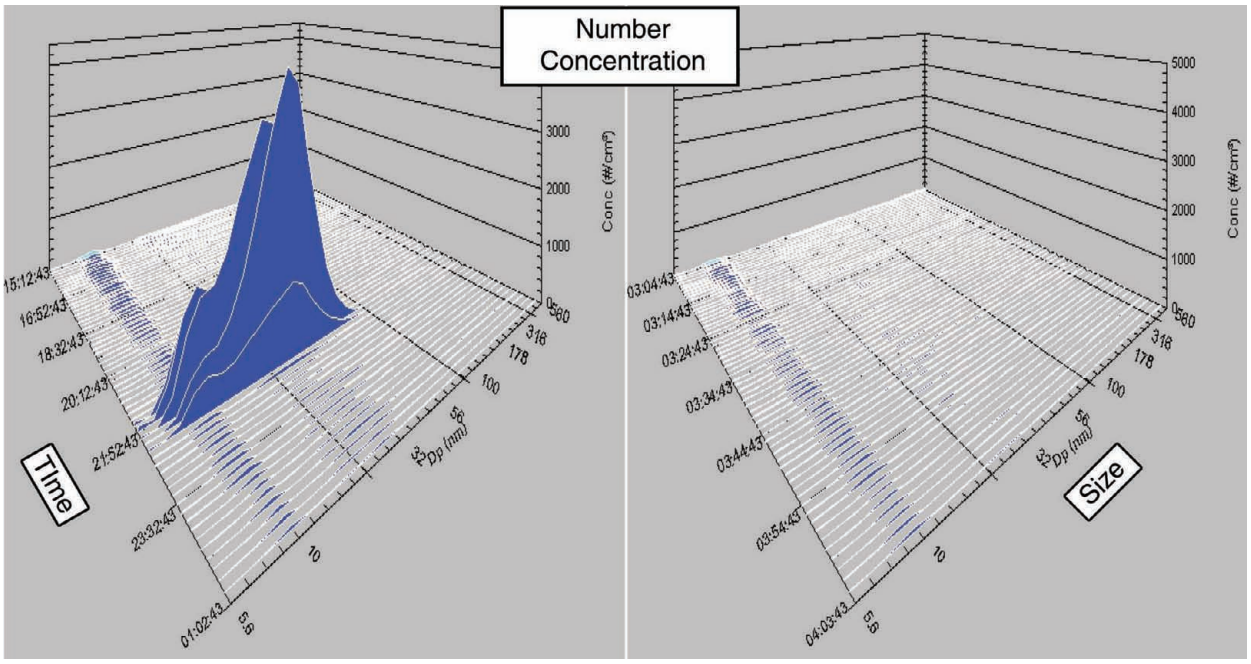


Figure 25. Real-time particle size distribution at the low-exposure level throughout the 16-hour cycle (September 24, 2009), which included one DPF regeneration (shown on the left).

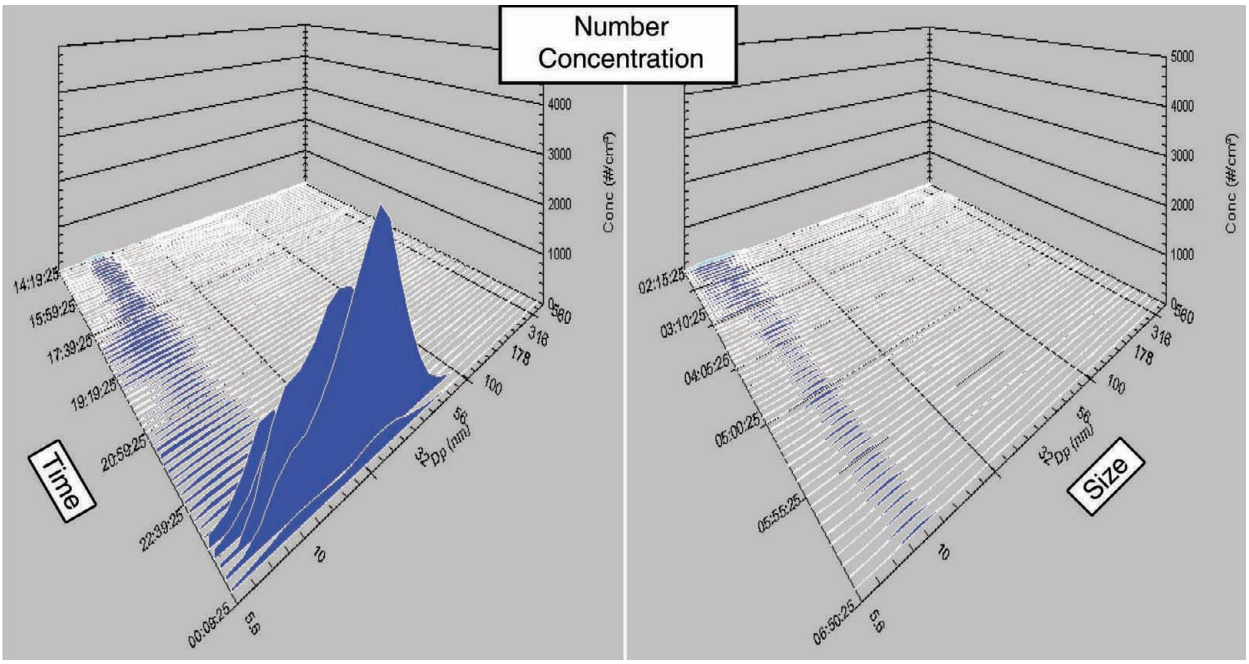


Figure 26. Another example of a real-time particle size distribution at the low-exposure level throughout the 16-hour cycle (September 25, 2009), which included one DPF regeneration (shown on the left).

lower end of the DMM measurement range. The previous section reported additional data comparing inlet and chamber particle gravimetric mass at the high-exposure level during each of the 15 trial days. In this test, the average concentration was approximately 20% higher at the chamber inlet (see Table 22), suggesting some potential loss of PM between these different sampling locations.

ASSESSMENT OF PARTICLE MEASUREMENT TECHNIQUE

It is difficult to measure PM at the concentrations in the ACES exposure atmospheres. The problem of low concentration is coupled with the requirement of collecting the samples at a low flow rate, so as not to disturb the balance in the exposure chamber. A standard protocol for measuring in exposure chambers is to sample at 10 liters per minute (3.3 cm/sec filter face velocity at ambient chamber temperature). Any more than that may disrupt the balance of the exposure chambers. This limitation reduces the accuracy of the measurement because of the low amount of mass that can be collected. Alternative strategies of collecting PM samples for either 1 or 3 days were evaluated. Table 26 shows the results of three trials at each exposure level using engine B′. The concentrations of PM either measured daily or using a 3-day average are compared. In all cases, the 3-day average concentration was significantly

Table 25. Chamber vs. Chamber Inlet Atmosphere: NO_2, NO_x, and Particle Mass, Number, and Size During the FTP Cycle Using Engine B′ [a]

	NO_2 (ppm)	NO_x (ppm)	Particle Mass (μg/m^3; DMM)	PM Number (#/cm^3)	Median PM Diameter (nm)
Chamber Test 1	4.68	7.40	1.71	1.79×10^5	43.9
Chamber Test 2	4.68	7.45	1.80	1.94×10^5	39.7
Inlet Test 1	4.44	7.18	1.71	1.95×10^5	45.4
Inlet Test 2	4.28	6.71	1.69	2.01×10^5	44.0

[a] DMM = Dekati mass monitor; FTP = Federal Test Procedure; PM = particulate matter.

Table 26. Daily (16 Hours) vs. 3-Day (16 Hours/Day) Sample Filter Analysis for PM Concentration[a] in Engine B′ Chamber

Test Day	High-Level Concentration		Mid-Level Concentration		Low-Level Concentration		Control Concentration	
	Daily	3-Day	Daily	3-Day	Daily	3-Day	Daily	3-Day
1	8.0	—	2.0	—	0.6	—	0.7	—
2	12.9	—	2.6	—	0.7	—	−0.1	—
3	6.4	—	2.0	—	1.0	—	1.0	—
Average	9.1	14.7	2.2	3.6	0.8	11.5	0.6	5.0
4	11.9	—	2.6	—	0.4	—	0.6	—
5	7.2	—	1.7	—	0.8	—	0.2	—
6	5.7	—	2.1	—	1.3	—	0.2	—
Average	8.3	11.0	2.1	3.3	0.8	3.9	0.3	2.4
7	7.7	—	2.3	—	0.2	—	0.3	—
8	11.4	—	1.3	—	0.0	—	0.5	—
9	13.4	—	2.8	—	1.6	—	1.6	—
Average	10.8	11.8	2.1	1.4	0.6	3.4	0.8	1.8
10	6.6	—	2.8	—	−0.1	—	0.1	—
11	14.2	—	0.9	—	1.3	—	1.4	—
12	11.9	—	1.4	—	0.7	—	0.3	—
Average	10.9	12.6	1.7	1.4	0.6	1.5	0.6	1.8

[a] Data expressed in $\mu g/m^3$.

higher than the single-day measurements. In addition, neither the single-day measurements nor the 3-day integrated measurement showed a trend with dilution. Finally, the 3-day measurement from the control chamber showed a measured value that was significantly higher than that of the single-day control measurement. The higher concentrations with the 3-day integrated samples may be due to the improved accuracy of the measurement. However, it is also possible that the 3-day integrated samples are affected by increased vapor adsorption artifact formation, where more time allows an increased concentration of non-PM material to accumulate on the filters. The single-day measurements seemed to show a more appropriate trend with dilution than the integrated measurements showed.

SUMMARY

A commissioning and characterization protocol was conducted to evaluate the adequacy of the ACES Phase 3 facility and exposure system for conducting the inhalation exposure study. The facility commissioning and emissions data were considered to represent acceptable performance based on review by the engine manufacturer. While there were some differences between the emissions observed at the two laboratories, SwRI and LRRI, the results were considered to be reasonably similar and sufficient to justify proceeding to Phase 3B. The differences must be viewed with the caveat that there were significant differences between the type of exhaust dilution and emissions sampling systems used at the two locations. Despite these differences, most data were within 20% variation for the key components. The final result is a proposed exposure atmosphere for the Phase 3B inhalation study based on targets of 4.2, 0.8, and 0.1 ppm NO_2. The exposure system performed reproducibly, had exposure atmospheres that were sufficiently homogeneous, and reached a steady state of 90% of concentration within 7 minutes.

In addition to the commissioning and characterization, a complementary component of the work, which was not defined in the original Phase 3A protocol, was the evaluation of the robustness of the test facility. As part of the final commissioning phase, engine B was operated for 1 month with no failures that would necessitate shutting down an exposure. Engine B′ was then exchanged for engine B and operated for more than 15 days; the resulting exposure characterization showed that, despite some variability, the average exposure targets of NO_2 were achieved within 10%. Repeated measurements showed that the CV of particle concentration throughout 15 days of operation was approximately 25%, substantially higher than the CV

of the gases (likely due to measurement variance). The PM mass measurement variance did not appear to improve with 3 days of sampling aimed at increasing the mass collected on the filter, possibly due to vapor measurement artifacts. Although exhaust concentrations can be measured at the inlet to the exposure chamber, this measurement may result in a concentration of PM that is high by more than 20%.

REFERENCE

Khalek IA, Bougher TL, Merritt PM. 2009. Phase 1 of the Advanced Collaborative Emissions Study. CRC Report: ACES Phase 1. Coordinating Research Council, Alpharetta GA. Available at www.crcao.org/publications/emissions/index.html. Accessed 1/10/11.

APPENDICES AVAILABLE ON THE WEB

The following material may be obtained from HEI's Web site, *www.healtheffects.org*:

Appendix A. Advanced Collaborative Emissions Study (ACES) Final Plan for Engine Selection (*part of the Preface to this Communication*)

Appendix B. Protocol

Appendix C. Protocol Amendments

Appendix D. Detailed Chamber Composition

ABOUT THE AUTHORS

Joe L. Mauderly, D.V.M., is an LRRI senior scientist emeritus. He was the original principal investigator for the ACES program and is now a consultant to the program. Mauderly was the principal investigator for all past subchronic and chronic inhalation studies of diesel emissions conducted at LRRI and has written extensively in the field. He supervised the assessments of respiratory function for this study.

Jacob D. McDonald received a Ph.D. in environmental chemistry with an emphasis in atmospheric chemistry from the University of Nevada–Reno. He is director of the Chemistry and Inhalation Exposure Program, as well as director of the Environmental Respiratory Health Program, both at LRRI. McDonald oversees exposure assessment and exposure atmosphere generation, inhalation toxicology, pharmacokinetics, and analytical/bioanalytical chemistry. He serves as principal investigator for Phase 3 of the ACES program.

ABBREVIATIONS AND OTHER TERMS

ACES	Advanced Collaborative Emissions Study
bhp · hr	brake horsepower integrated over 1 hour
CARB	California Air Resources Board
cfm	cubic feet per minute
CFR	Code of Federal Regulations
CO	carbon monoxide
CO_2	carbon dioxide
CPC	condensation particle counter
CRC	Coordinating Research Council
CV	coefficient of variation
CVS	constant volume sampler
DMM	Dekati mass monitor
DNPH	dinitrophenylhydrazine
DPF	diesel particulate filter
DRI	Desert Research Institute
EPA	U.S. Environmental Protection Agency
FCV	fuel cutoff valve
ft-lb	foot pounds
FTP	Federal Test Procedure
g/hp · hr	grams per horsepower · hour
GC/MS	gas chromatography/mass spectrometry
gpm	gallons per minute
HHDD	heavy heavy-duty diesel
HHDDE	heavy heavy-duty diesel engine
ISO	International Organization for Standards
LRRI	Lovelace Respiratory Research Institute
MTD	maximum tolerated dose
NMHC	nonmethane hydrocarbons
NO	nitrogen monoxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
NOAEL	no-observed-adverse-effect level
NTP	National Toxicology Program
PM	particulate matter
RFA	request for applications
RFP	request for proposals

rpm	revolutions per minute
scfm	standard cubic feet per minute
SVOC	semivolatile organic compound
SwRI	Southwest Research Institute
T_{90}	time to reach 90% of target concentration
THC	total hydrocarbons
TOR	thermal/optical reflectance
VOC	volatile organic compounds
XAD	polyaromatic adsorbing resins
XRF	X-ray fluorescence

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