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Attachment 2. Khalek, Imad A., Matthew G. Blanks, and Patrick M. Merritt. 2013. *Phase 2 of the Advanced Collaborative Emissions Study.* CRC Report: ACES Phase 2. Coordinating Research Council, Alpharetta GA.

Attachment 3. Mauderly, Joe and Jacob D. McDonald. *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

The objective of the Advanced Collaborative Emissions Study (ACES) was to determine before widespread commercial deployment whether or not the new, energy-efficient, heavy duty diesel engines (2007 and 2010 EPA Emissions Standards Compliant) may generate anticipated toxic emissions that could adversely affect the environment and human health. ACES was planned to take place in three phases. In Phase 1, extensive emissions characterization of four production-intent prototype engine and control systems designed to meet 2007 standards for nitrogen oxides (NOx) and particulate matter (PM) was conducted at an existing emissions characterization facility: Southwest Research Institute (SwRI). One of the tested engines was selected (at random, after careful comparison of results) for health testing in Phase 3. In Phase 2, extensive emission characterization of three production-intent prototype engine and control systems meeting the 2010 standards (including more advanced NOx controls to meet the more stringent 2010 NOx standards) was conducted at the same test facility. In Phase 3, one engine/aftertreatment system selected from Phase 1 was further characterized during health effects studies (at an existing inhalation toxicology laboratory: Lovelace Respiratory Research Institute, [LRRI]) to form the basis of the ACES safety assessment. The Department of Energy (DOE) award provided funding for emissions characterization in Phases 1 and 2 as well as exposure characterization in Phase 3. The main health analyses in Phase 3 were funded separately and are not reported here.

The overall goal of ACES was to identify whether any toxic emissions are generated by the new technology diesel engines that might adversely affect the environment and human health. The overall hypotheses were as follows:

(1) Regulated and unregulated exhaust emissions from 2007/2010 compression ignition engine equipped vehicles will be greatly reduced compared to older vehicles.

(2) Exhaust emissions from these vehicles will not cause an increase in tumor formation or substantial toxicity to any organ or other serious health effects in rats and mice at the dilution ratios used compared to animals exposed to filtered air, although some biologic effects may occur.

In Phase 1A, funded separately, Dr. Nigel Clark and colleagues from West Virginia University (WVU) developed a transient 16-hour cycle for use in Phase 3 health testing, to provide more realistic exposure conditions for the animal inhalation studies. Thus, the 16-hour cycle was based on a combination of driving cycles from the California Air Resources Board (CARB) 5-mode test cycle to represent a mix of urban and highway driving conditions. The 16-hour cycle was approved for use in ACES in June 2007 and was subsequently added to the testing protocols for Phase 1 and 2.

In Phase 1, Dr. Imad Khalek and colleagues at SwRI and Desert Research Institute (DRI) characterized emission rates of regulated and unregulated pollutants from four 2007-compliant HHDDE tested on the heavy-duty FTP cycle, selected portions of the CARB heavy-duty cycle, and the specially developed 16-hour cycle. Four engines were procured from manufacturers of heavy-heavy duty diesel engines, i.e. Caterpillar, Cummins, Detroit Diesel, and Volvo. The engines were kept anonymous throughout the study as engines A, B, C, and D, randomly assigned. After careful comparison of emissions results, one engine (B) was selected for use in Phase 3; an identical back-up engine (B') was procured from the engine manufacturer and subjected to identical testing procedures as engines A-D. Additional testing was performed on engine B' to simulate high altitude conditions to be encountered in Phase 3. Furthermore, testing of all engines included sampling during a 16-hour cycle from an unoccupied animal inhalation chamber provided by LRRI to be used in Phase 3. All four 2007-compliant engines were shown to meet or exceed the 2007 EPA standards; regulated and unregulated emissions were 89-99% lower compared to a 2004 engine. Additional results were (a) detailed measurements of dioxins and furans, which were 99% lower than for 1996/1998 engines, (b) selection of engine B for use in Phase 3, (c) testing of an identical back-up engine B', including testing at simulated high altitude conditions and sampling inside an unoccupied animal inhalation chamber, and (d) development of an approach for biological screening, i.e. inclusion of short-term genotoxicity testing in Phase 3. Using the 16-hour cycle, it was shown that diesel PM filter regeneration for 2007 engines occurs between 1 and 3 times in 16 hours, which is when the

majority of PM emissions occur.

In Phase 2, Dr. Imad Khalek and colleagues at SwRI and DRI characterized emission rates of regulated and unregulated pollutants from three 2011 model HHDDE tested on the heavy-duty FTP cycle, selected portions of the CARB heavy-duty cycle, and the specially developed 16-hour cycle. Three engines were procured from Cummins, Detroit Diesel, and Volvo. Similarly to Phase 1, testing of all engines (randomly designated the letter X, Y, and Z) included sampling during a 16-hour cycle from an unoccupied animal inhalation chamber provided by LRRI to be used in Phase 3. ACES Phase 2 results demonstrate another drastic step in emissions reduction with 2010 EPA-compliant on-highway HHDDE. The three 2011 model engines showed substantially lower regulated emissions of NO_X, CO, NMHC, and PM relative to the 2010 standard. They also showed a substantial reduction in a very wide spectrum of particle and gas phase unregulated emissions species relative to pre-2007 and 2007 technology engines. There were no major increases in regulated or unregulated emissions.

In Phase 3A, Drs. Joe Mauderly and Jacob McDonald and colleagues at LRRI developed and characterized an exposure system for a chronic inhalation study of rats and mice exposed to exhaust from a 2007-compliant diesel engine. Considerable effort was made to upgrade the exposure facility at LRRI to accommodate a HHDDE because previously, the laboratory had only tested light-duty engines. Both engines B and B' were installed successfully and tested (sequentially); emissions were similar to what was reported in Phase 1. A decision was made to use engine B' for the animal exposures in Phase 3 because it was a slightly newer model. Some technical issues were encountered with the dynamometer and drive train set-up. This led to some delays in the project but the issues were resolved. The emissions generation system was functioning reliable and was shown to generate consistently the exposure atmospheres at the targeted NO_2 concentrations. Thus, a decision to go ahead with Phase 3B was approved.

In Phase 3B, Dr. McDonald and colleagues at LRRI measured daily exposure concentrations in the animal inhalation chambers to ensure proper system functioning at the targeted DEE concentrations, and conducted additional detailed exposure characterization at the beginning, middle, and end of the chronic inhalation study. The exposure system was shown to operate as designed throughout the animal inhalation study; the targeted DEE concentrations (at 4.2 ppm, 0.8 ppm, and 0.1 ppm NO_2) were met. Thus, animals were exposed to DEE successfully per study design specifications. The exposure system operated reliably although it was noted that the 16-hour cycle took a toll on the engine and dynamometer, which led to a switch from engine B' to engine B partway through the study. No major differences were found between the two engines in terms of daily and intensive emissions characterizations. Important information on durability and reliability of the engine/aftertreatment system was obtained, in addition to unique information on the frequency of diesel PM filter regenerations.

In addition, Phase 3B included short-term biological screening to determine whether exposure to DEE from a 2007-compliant engine produced changes in a limited set of biomarkers indicative of changes in mutagenicity and genotoxicity. Mice and rats that were exposed to DEE for up to 3 months showed no exposure-related changes in markers of genotoxicity compared to animals exposed to filtered air. Some small effects were noted in inflammatory markers and respiratory function, with fewer effects observed in mice compared to rats. Most of these small changes were thought to be due to (and were consistent with) exposure to NO_2. The primary importance of the biological screening results after 1 and 3 months of exposure is their demonstration that: 1) the great majority of health tests showed no effect of exposure; 2) several plausibly coherent responses may indicate early, exposure-related, subclinical impacts on lung inflammation, structure, and function of rats that are consistent with exposure to NO_2; 3) statistically significant effects were observed primarily at the highest exposure level (the lowest level has produced no observable effects).

In summary, the emissions characterization of 2007- and 2010 compliant engines has provided important data that confirm that these new technologies meet or are even below the Environmental Protection Agency (EPA) standards for PM and NOx emissions. Emissions of 2007-compliant engines were found to

be 90-99% below those of 2004 engines, with further reductions shown for 2010-compliant engines. There were no surprises in terms of increases in unregulated emissions due to PM or NOx control strategies. Thus, the study shows that emissions reductions have been met, as intended, and that the introduction of new technology heavy-duty diesel engines is providing health benefits by reducing exposure of human populations to PM, NOx, and many unregulated compounds, including designated air toxics.

We conclude that ACES has been completed successfully and has yielded important information on emissions from 2007- and 2010-compliant heavy-duty diesel engines and possible health effects resulting from exposure to those emissions. The results from Phase 1 and Phase 2 confirm Hypothesis 1, that "*regulated and unregulated exhaust emissions from 2007/2010 compression ignition engine equipped vehicles will be greatly reduced compared to older vehicles."* The results from Phase 3A and 3B indicate that engine/aftertreatment system performance has been reliable over the course of the 30-month study, although the intensive 16-hour cycle was shown to produce considerable wear and tear on the engine and dynamometer that called for repairs. Phase 3 biological screening after 1 and 3 months of exposure has shown that a small number of biological effects were seen, mostly related to mild inflammation of the lungs. No significant genotoxic and mutagenic changes or other serious adverse health outcomes were observed up to that time point. *Hypothesis 2, "Exhaust emissions from these vehicles will not cause an increase in tumor formation or substantial toxicity to any organ or other serious health effects in rats and mice at the dilution ratios used compared to animals exposed to filtered air, although some biologic effects may occur"* has thus been partially confirmed, although a full assessment will only occur upon completion of the final pathology analyses after 30 months of exposure.

Preliminary results indicate some mild exposure-related changes in the lungs after 3, 12, and 24 months of exposure that are consistent with effects seen after exposure to nitrogen dioxide (NO_2) alone (an exposure which, based on the Phase 2 results of 2010 engines, is expected to decrease substantially in all new engines going forward). These effects were seen only at the highest concentration of diesel engine exhaust (at 4.2 ppm NO_2). Results of the full assessment of health outcomes — which has been funded separately from this DOE-funded project — will be reported in late 2014. All this work has been conducted with input from the ACES stakeholders.

INTRODUCTION

Scope of Work

The objective of the Advanced Collaborative Emissions Study (ACES) project was to determine before widespread commercial deployment whether or not the new heavy-duty diesel engines (2007 and 2010 EPA Emissions Standards Compliant) may generate anticipated toxic emissions that could adversely affect the environment and human health. ACES was planned to take place in three phases. In Phase 1, extensive emissions characterization (at an existing emissions characterization facility: SwRI) of four production-intent prototype engine and control systems designed to meet 2007 standards for NOx and PM was conducted. One of the tested engines was selected randomly for health testing in Phase 3. In Phase 2, extensive emission characterization of three 2011 model engine and control systems meeting the 2010 standards (including more advanced NOx controls) was conducted at the same test facility. In Phase 3, one engine/aftertreatment system selected from Phase 1 was further characterized during health effects studies (at an existing inhalation toxicology laboratory: LRRI) to form the basis of the ACES safety assessment. The DOE award provided funding for emissions characterization in Phases 1 and 2 as well as exposure characterization in Phase 3. The main health analyses in Phase 3 were funded separately and are not reported in detail here.

Specific Aim and Hypothesis

The overall goal of ACES was to identify whether any toxic emissions are generated by the new technology diesel engines that might adversely affect the environment and human health. The overall hypotheses were as follows:

(1) Regulated and unregulated exhaust emissions from 2007/2010 compression ignition engine equipped vehicles will be greatly reduced compared to older vehicles.

(2) Exhaust emissions from these vehicles will not cause an increase in tumor formation or substantial toxicity to any organ or other serious health effects in rats and mice at the dilution ratios used compared to animals exposed to filtered air, although some biologic effects may occur.

Changes From the Original Scope of Work

There were several modest changes to the project, made in full consultation with DOE and all other sponsors. These included:

(1) Early in the project it was decided to add a component to the project before commencing Phase 1. This component, Phase 1A, entailed the development of a 16-hour cycle to combine urban and highway driving cycles for use in the chronic animal exposure studies in Phase 3, to be more representative of real-world emissions than the FTP steady-state cycle used for engine certification. This portion of the work was funded separately by the California Air Resources Board.

(2) Originally, the Scope of Work included health testing using exhaust from a 2010-compliant engine selected after completion of Phase 2. Instead, after consultation with DOE and all other sponsors, the ACES Steering Committee decided to commence health testing earlier in the project, i.e. using exhaust from a 2007-compliant engine selected after completion of Phase 1. This both reduced the time frame for the project by several years and took advantage of the higher exhaust exposure concentrations that could be achieved with a 2007-compliant engine compared to a 2010-compliant engine.

(3) Additional work was conducted in Phase 1 with separate funding to measure dioxins and furans in emissions of three 2007-compliant engines to complement the extensive measurements of unregulated emissions.

(4) Additional work was conducted in Phase 1 to conduct emissions characterization (a) at simulated high altitude conditions to reflect conditions during Phase 3 and (b) in an unoccupied animal inhalation chamber to provide comparable data for Phase 3.

Description of ACES Approach

Experimental work under ACES was performed in three phases. Through a competitive request for proposals from the Coordinating Research Council (CRC), an existing engine laboratory that meets the EPA specifications for 2007 and 2010 engine testing was selected, i.e. SwRI, to conduct Phase 1 and 2. In Phase 1, emissions from four 2007-compliant engine/control systems were characterized. One engine was selected for health testing in Phase 3. Additionally, a 16-hour test cycle was developed in Phase 1A. In Phase 2, emissions from three 2010-compliant engine/control systems were characterized using an identical approach as in Phase 1. The DOE grant supported all work conducted in Phase 1 and 2.

Through a competitive request from HEI (Request for Proposals 06-1), a health testing facility, i.e. LRRI was selected to conduct a chronic inhalation bioassay in rats and shorter-term biological screening in rats and mice exposed to diesel engine exhaust (DEE) in Phase 3. For this purpose, one selected 2007-compliant engine/control system was installed in a specially designed emission generation facility at LRRI. Through a second competitive request from HEI (Request for Applications 06-2), additional investigators were selected to conduct biological screening in mice and rats exposed to DEE for up to 3 months. During the biological screening and the 30-month bioassay, emissions were characterized at regular intervals throughout the testing. In Phase 3, the DOE grant supported the development of the exposure generation facility and the exposure characterization throughout the animal inhalation studies.

The emissions characterization work was overseen by CRC and its ACES Technical Panel. The health effects assessment was overseen by HEI and its ACES Oversight Committee. Additional input was provided by an HEI ACES Advisory Committee of stakeholders. Set-up of the emission generation facility at the health effects testing facility (for Phase 3) and finalizing the protocols for periodic emission characterization throughout Phase 3 was done with input from CRC and SwRI.

ACCOMPLISHMENTS

PHASE 1. EMISSIONS CHARACTERIZATION OF 2007 ENGINES AND CONTROL SYSTEMS

Phase 1A. Developing a 16-Hour Cycle

Goal: Develop a 16-hour test cycle to be used for animal exposures in Phase 3 (funded separately).

Accomplishments: A 16-hour test cycle was developed by Dr. Nigel Clark and colleagues at WVU. The cycle was based on a combination of driving cycles from the California Air Resources Board (CARB) 5-mode test cycle to represent a mix of urban and highway driving conditions. The 16-hour cycle was approved for use in ACES in June 2007 and was subsequently added to the testing protocols for Phase 1 and 2. The results were published in *CRC Report No. ACES 1a* (Clark et al 2007).

Approach: The WVU investigators developed a schedule of engine cycles representative of modern truck usage and demonstrated their application in an engine test cell. The motivation for developing a new test schedule was because the FTP is based on old engine technologies and represents a compromise of freeway and urban roadway (non-freeway) operation. The ACES test schedule was based on four active modes of truck operation including creep, transient, cruise, and high-speed cruise from the CARB 5-mode test cycle.

Results: Following test mode creation and initial testing, the final ACES cycle testing was performed at the WVU Research Center using a 2004 Cummins ISM370 heavy-duty diesel engine connected to a 500-hp GE dynamometer via a driveshaft and Vulcan coupling. The results indicated the ACES test modes are feasible on an engine dynamometer. It is the conclusion of the WVU investigators "that these new ACES modes better represent real world modern heavy-duty truck activity than the FTP and can better test newer engines for certification."

Conclusion: **Developing a 16-hour test cycle was an additional goal of ACES that was successfully completed. Two major benefits were: (a) It provided a combination of simulated driving conditions to better represent real-world emissions for the animal exposures in Phase 3. (b) It provided a unique opportunity to characterize emissions of 2007- and 2010-compliant engines in Phase 1 and 2 over a longer cycle than the FTP cycle used for engine certification. In particular, it allowed for the occurrence of diesel PM filter regenerations and emissions characterization during such regeneration events (see Phase 1 results below).**

Phase 1. Extensive emissions characterization and regulated and unregulated emissions data collection for the 2007 emissions engines

Goal: Characterize emission rates of regulated and unregulated pollutants from four 2007-compliant HHDDE tested on the heavy-duty FTP cycle, selected portions of the CARB heavy-duty cycle, and a 16-hour cycle specifically developed for use in Phase 3 animal exposures. Specific objectives were:

- Quantify the significant reduction in both regulated and unregulated emissions from advanced diesel engines,
- Provide regulated and unregulated emissions data for this new engine technology,
- Make data available to support the selection of one engine for ACES Phase 3 health study, and
- Provide initial guidance for ACES Phase 3 health study using the regulated and unregulated emissions information from ACES Phase 1.

Accomplishments: Four engines were procured from manufacturers of heavy-heavy duty diesel engines, i.e. Caterpillar, Cummins, Detroit Diesel, and Volvo. The engines were kept anonymous throughout the study as engines A, B, C, and D, randomly assigned; they were tested successfully by Dr. Imad Khalek and colleagues at SwRI and collaborators at DRI. One engine (B) was selected for use in Phase 3; an

identical back-up engine (B') was procured from the engine manufacturer and subjected to identical testing procedures as engines A-D. Additional testing was performed on engine B' to simulate high altitude conditions to be encountered in Phase 3. Furthermore, testing of all engines included sampling during a 16-hour cycle from an unoccupied animal inhalation chamber provided by LRRI to be used in Phase 3. The results were published in *CRC Report No. ACES 1* (Khalek et al. 2009) and Khalek et al. (2011). All data are available in an online database (see *Databases* below.)

Approach: To comply with 2007 EPA regulations, each engine was equipped with water-cooled exhaust gas recirculation or clean gas induction to reduce NO_x emissions, along with a catalyzed diesel PM filter (C-DPF), or a diesel oxidation catalyst (DOC) followed by a C-DPF to reduce PM emissions. DOCs were mainly used to increase NO_2 production to promote the oxidation of soot deposited in the C-DPF. Furthermore, a diesel fuel burner located upstream of the C-DPF, or a diesel fuel injector located upstream of the DOC, was used to elevate the exhaust temperature at the inlet of the C-DPF to actively regenerate and clean the C-DPF, as needed. Numerous additional improvements were also made by each engine manufacturer in relation to boost pressure and its response, fuel injection and combustion management, and system integration. Manufacturers also equipped engines with a crankcase ventilation system that has a filter to reduce PM emissions from the crankcase blow-by, which is vented to the atmosphere. The four 2007-compliant engines emissions were characterized on the following test cycles:

- FTP, the basis for engine certification and audit,
- CARBx-ICT, idle, creep and a transient portion of CARB HHDDE 5-Modes (CARB 5-Modes),
- CARBz-CH, cruise and high speed cruise of CARB 5-Modes, and
- 16-Hour cycle, four 4-hour segments consisting of FTPs and CARB 5-Modes.

FTP tests were performed to verify that they met applicable HC, CO, NOx, and PM emission standards. Tests included triplicate hot-start FTP tests, one cold-start FTP, and a single 'blank' test in association with each engine test sequence to quantify background emissions and tunnel / sampling system contamination levels.

For each cycle used, regulated emissions of CO, non-methane hydrocarbon (NMHC), NO_x, and PM, were measured. Unregulated emissions measured included total hydrocarbon (THC), methane (CH_4), CO_2, nitrogen monoxide (NO), nitrogen dioxide (NO_2), nitrous oxide (N_2O), particle size and number, organic carbon, elemental carbon, metals and elements, polynuclear aromatic hydrocarbon (PAH), nitro-PAH, oxy-PAH, polar compounds, alkanes, hopanes, steranes, cyanide, organic acids, gas phase acids, nitrosamines, auto/oil speciation of $C_2 - C_{12}$ hydrocarbons, aldehydes and ketones, volatile organic compounds, and dioxins/furans (only for the 16-Hour cycle) were a part of the unregulated emissions species measurement.

Samples of the different exhaust species were taken either directly from the sample zone of the full-flow constant volume sampler (CVS) dilution tunnel, or from locations that were linked to the sample zone by a dilution step with a dilution ratio of about 2. A unique sample location employed was an animal exposure chamber (unoccupied), provided by LRRI, to determine concentration levels that might be expected in Phase 3. Real time particle size and number, total PM, soot, organic carbon (OC), and elemental carbon (EC) measurements were taken only from the exposure chamber. All measurements were performed with engine blow-by routed to the exhaust downstream of the C-DPF. Selected FTP tests without blow-by were performed.

Results: Table 1 summarizes the average FTP regulated emissions relative to the EPA 2007 standards. Based on the average emissions from all four ACES engines, PM, CO, and NMHC emissions were at least 90 percent below the EPA limits. Average NO_x emissions were 10 percent below the standard. FTP transient cycle average PM emissions without crankcase blow-by were 38 percent lower than those with crank case blow-by. For the high altitude testing performed with the backup engine, NO_x emissions were about 34 percent higher than at normal altitude.

Table 1. Summary of average regulated emissions of four 2007-compliant engines over the FTP cycle

Pollutant	2007 Standard Limit (g/hp-hr)	Average ACES Engines Emissions (g/hp-hr)	ACES Emissions % Reduction Relative to the 2007 Limit
CO	15.5	0.33	98
NMHC	0.14	0.0064	95
PM	0.01	0.0011	89
NOx	1.2[1]	1.075	10
[1] Average value between 2007 and 2009, with full enforcement in 2010 at 0.20 g/hp-hr			

Average FTP NO_2 emissions, based on all four ACES engines, were 0.73 g/hp-hr, with an NO_2 to NO_x ratio of 68 percent. The NO_2 to NOx for 2004 technology engines is typically lower, 4 to 15 percent of the 2004 NOx limit of 2.4 g/hp-hr. Thus, the direct NO_2 emissions from these ACES engines can be more than a factor of two to eight times higher than 2004 technology engines, although the total NO_x emissions are lower. This rise of NO_2 emissions from heavy-duty diesel engines is temporary, and expected to go down below the EPA 2010 NO_x limit of 0.2 g/hp-hr. Average N_2O emissions were 0.008 g/hp-hr, about 0.8 percent of ACES engines NO_x emissions level.

During active regeneration, real time particle number emissions from 5.6 nm to 30 nm in diameter can be several orders of magnitude higher than the concentration without active regeneration. However, as shown in Figure 1, even when active regeneration occurred, the average particle number emissions were low, on the order of 90 percent below the level emitted by a 2004 technology engine, and a factor of 10 higher than the average emissions without regeneration, due to the low frequency of occurrence of active regeneration during the 16-hour cycle (1 to 3 times per 16-hour cycle).

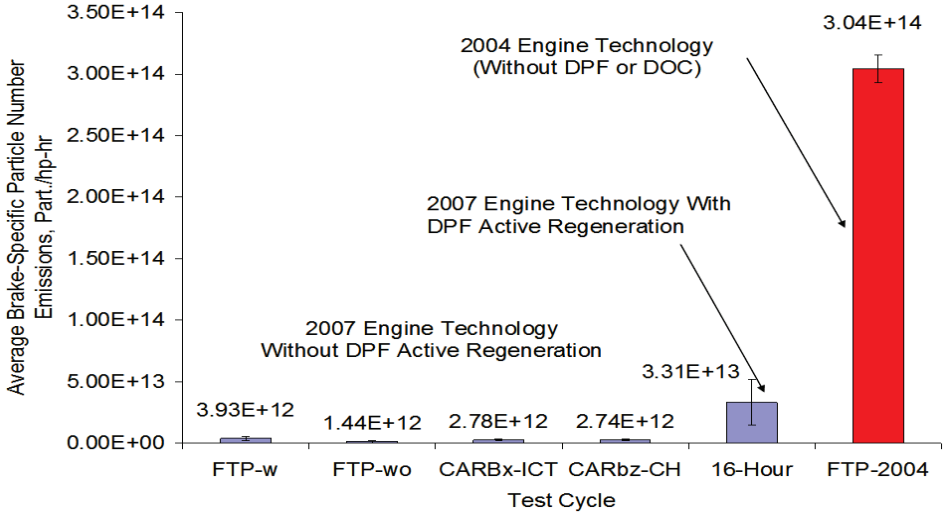

Figure 2. Average particle number emissions in Phase 1. (w = with crankcase blowby, wo = without crankcase blowby.)

Unregulated species showed reductions relative to a 2004 engine technology from 38 percent for inorganic ions to 99 percent for hopanes/steranes, elemental carbon, and dioxins/furans. For the metals, it is worth noting that no copper or vanadium were detected. 2007 technology engine PM composition was mainly dominated by sulfate and organic carbon, with a small fraction of elemental carbon and metals and

elements.

In summary, the ACES engines achieved more than 89 percent reductions in NMHC, CO, and PM emissions relative to the 2007 standards. Unregulated emissions were also substantially reduced relative to a 2004 technology engine. ACES engines NO_2 emissions were higher than those from 2004 engine technology due to the use of the DOC and C-DPF. NO_2 emissions will be considerably reduced when 2010 engines are introduced.

Testing emissions of dioxins and furans

With additional funding, samples were collected from Engines A, C, and D during the 16-hour cycle in order to collect enough material to measure dioxins and furans. The goal was to answer the questions whether or not the introduction of diesel PM filters would increase emissions of those compounds. Samples were analyzed using EPA method 8290. Concentrations of dioxins and furans were found to be 99% lower than levels in exhaust from 1996/1998 engines. The results are described in *CRC Report No. ACES 1* (Khalek et al 2009).

Selecting one 2007-compliant engine for use in Phase 3

The emission of selected compounds and classes of compounds for the 16-hour cycle (see Table 2) were used to rank the engines for engine selection. For the selection, the emission rates were ranked (normalized) using 4 methods, one parametric and three parametric. There was little or no difference in the total score among the engines, but one of the four engines (D) did happen to rank lowest in all four ranking methods. The ranking of the other three engines changed depending on the ranking method used and no engine was ranked highest with at least three of the four ranking methods. Based on the pre-determined rules, engine D was excluded from the selection and the selection among the other 3 engines was random; engine B was selected for use in Phase 3.

Table 2. Summary of 16-hour cycle emission rates for classes of compounds used for engine ranking

Emissions Components	Engine A	Engine B	Engine C	Engine D	Avg.	St. dev.
NO (g/hp-hr)	0.54	0.48	0.86	0.63	**0.63**	0.17
NO_2 (g/hp-hr)	0.95	0.91	0.56	0.56	**0.74**	0.21
CO (g/hp-hr)	0.09	0.08	0.46	0.15	**0.20**	0.18
PM Mass (g/hp-hr)	0.0013	0.0012	0.0011	0.0013	**0.0012**	0.0001
Particle number (N/hp-hr)	4.13×10^{13}	5.67×10^{13}	1.66×10^{13}	2.38×10^{13}	**3.46×10^{13}**	1.80×10^{13}
Elemental carbon (mg/hp-hr)	0.20	0.27	0.26	0.22	**0.24**	0.03
Organic carbon (mg/hp-hr)	1.53	0.24	0.26	0.52	**0.64**	0.61
Total metals (by XRF) (µg/hp-hr)	62.37	62.15	28.88	89.91	**60.82**	24.97
Inorganic ionic species (mg/hp-hr)	3.84	3.09	2.86	2.47	**3.06**	0.57
Carbonyl compounds (mg/hp-hr)	4.99	1.64	4.40	2.44	**3.37**	1.59
Single ring aromatic compounds (mg/hp-hr)	0.35	1.20	0.81	0.69	**0.76**	0.35
Total PAHs (mg/hp-hr)	0.55	0.73	0.84	0.80	**0.73**	0.13
Total nitro-PAHs (µg/hp-hr)	0.44	0.77	0.86	0.58	**0.66**	0.19
Total oxygenated PAHs (µg/hp-hr)	6.25	5.96	3.76	3.29	**4.82**	1.51
Nitrosamines (µg/hp-hr)	32.54	28.06	52.89	25.82	34.83	12.36

Characterizing emissions from the back-up engine B'

A fifth engine (the back-up engine B' for use in the chronic bioassay) was tested at SwRI to verify that its regulated emissions were similar to those of the selected engine B. Tests were conducted using the FTP test cycle and three steady-state tests modes. The emission rate of NOx was slightly higher than that of the selected engine B while the emissions of CO and PM were lower (see Table 3). To facilitate the comparison with the emissions characterization that will be done at LRRI using the selected engine, a set of tests was conducted under simulated high altitude conditions (the same as encountered at the LRRI facility). Higher altitude led to a small increase in NOx and CO emissions relative to emissions at sea level under some of the test conditions. Full results are presented in the *CRC Report No. ACES 1* (Khalek et al 2009).

Table 3: NOx emissions (g/hp-hr) of five 2007-compliant test engines over the FTP cycle and steady state modes

		SwRI Elevation					LRRI Elevation
Test Cycle		**Engine A**	**Engine B**	**Engine C**	**Engine D**	**Engine B'**	**Engine B'-Altitude**
FTP-with crank case blow-by	Avg.	1.26	0.89	1.03	1.12	0.98	1.33
	St.dev.	0.01	0.01	0.03	0.01	0.01	0.01
FTP-without crank case blowby	Avg.	1.25	0.90	1.05	1.11	0.97	1.31
	St.dev.	0.01	0.01	0.01	0.02	0.01	0.03

Development of testing methods for biological screening

An additional task outlined for Phase 1 was to develop methods for biological screening, using standard in vitro (i.e. test tube or cell culture) tests to evaluate toxicity of exhaust samples. Such limited biological evaluation were to be conducted during Phases 1 and 2, to further characterize the emissions and their potential biological activity to help in the selection of the engine to be used in Phase 3 and also to inform the final design of Phase 3. The results of these in vitro assays would not be used to assess health effects. Before the start of ACES, a Working Group was convened by HEI and CRC in 2005 to discuss options for in such vitro screening. The Working Group reviewed possible artifacts that could occur in collecting exhaust components for subsequent assay, discussed advantages and disadvantages of various approaches available for exposing cells to diesel exhaust (DE) or its components, and reviewed *in vitro* assays and exposure approaches and made recommendations about assays and exposure methods to be incorporated into biological screening.

A draft report from the Working Group was discussed by the HEI ACES Oversight Committee in September 2005. The Committee noted that in vitro assay are not reliable in predicting in vivo (i.e. inhaled) effects, although they may be useful in probing mechanisms of toxicity. A final consideration was the extensive and costly developmental work that was needed to set up and characterize relevant exposure systems and cell culture conditions, all efforts that did not appear to consistent with ACES and would divert resources from the main ACES studies. Because of the many issues surrounding in vitro testing of engine exhaust and the lack of sound testing procedures using whole exhaust (given very low PM levels in the exhaust), the Committee thought that such in vitro tests should not be performed as part of ACES. Instead, the Committee recommended to incorporate in vivo evaluation of genotoxicity into a set of short-term health effects evaluations. Thus, genotoxicity evaluation was included in Request for Applications 06-2. Two ancillary studies were funded, i.e. studies by Drs. Bemis and Hallberg. (A third study by Dr. John Veranth at the University of Utah encountered technical difficulties and was

terminated). The results from the biological screening studies by Drs. Bemis and Hallberg are described on pages 24 and 25.

Conclusions: **The goals for Phase 1 were met. Four 2007-compliant engines were tested and shown to meet or exceed the 2007 EPA standards; regulated and unregulated emissions were 89-99% lower compared to a 2004 engine. Additional results were (a) detailed measurements of dioxins and furans, which were 99% lower than for 1996/1998 engines, (b) the development of a 16-hour test cycle, (c) selection of engine B for use in Phase 3, (d) testing of an identical back-up engine B', including testing at simulated high altitude conditions and sampling inside an unoccupied animal inhalation chamber, and (e) development of an approach for biological screening, i.e. inclusion of short-term genotoxicity testing in Phase 3. Using the 16-hour cycle, it was shown that diesel PM filter regeneration for 2007 engines occurs between 1 and 3 times in 16 hours, which is when the majority of PM emissions occur.**

PHASE 2. EMISSIONS CHARACTERIZATION OF 2010 ENGINES AND CONTROL SYSTEMS

Goal: Characterize emission rates of regulated and unregulated pollutants from three 2010-compliant engines tested on the heavy-duty FTP cycle, selected portions of the CARB heavy-duty cycle, and a 16-hour cycle specifically developed for use in Phase 3 animal exposures.

Accomplishments: Three engines were procured from manufacturers of heavy-heavy duty diesel engines, i.e. Cummins, Detroit Diesel, and Volvo. The engines (randomly designated engines X, Y, and Z) were tested successfully by Dr. Imad Khalek and colleagues at SwRI and collaborators at DRI. Similarly to Phase 1, testing of all engines included sampling during a 16-hour cycle from an unoccupied animal inhalation chamber provided by LRRI to be used in Phase 3. The results were published as a CRC Report (posted on December 6, 2013). The Final Report is provided in Attachment 1. All data will be made in an online database (see *Databases* below.)

Approach: Phase 2 included detailed chemical characterization of exhaust species emitted from three 2011 model-year on-highway HHDDE in compliance with EPA 2010 emissions standards. Each engine had a total of 125 hours of manufacturer-run dynamometer operation prior to shipping to SwRI. Except for the urea-related compound analyses, the emissions characterizations performed under ACES Phase 2 were similar to those performed under ACES Phase 1 involving 2007 EPA-compliant on-highway HHDDE. According to the engine manufacturers, the 2010 ACES engines were obtained from the normal production supply, and are identical to those sold to customers during model year 2010. To comply with the 2010 NO_X limit, engine manufacturers utilized a urea-based selective catalytic reduction (SCR) catalyst in engine exhaust placed downstream of a diesel oxidation catalyst (DOC) and a catalyzed diesel PM filter (DPF) used for PM emissions control. Substantial efforts by the engine manufacturers went into the calibration of the urea dosing and mixing, SCR catalyst formulation, and engine control to achieve the desired NO_X reduction while maintaining a controlled level of ammonia slip using an ammonia oxidation (AMOX) catalyst downstream of the SCR catalyst. Improvements were also made in the area of PM emissions control, with the result that no active regeneration (onboard cleaning via exhaust fuel injection upstream of DOC) of the DPF was needed during ACES Phase 2 testing, compared to the several regeneration occurrences with the 2007 technology engines tested in ACES Phase 1.

Similar to Phase 1 testing, samples were taken from an unoccupied animal exposure chamber, to determine concentration levels that might be expected in future animal exposure studies. Real time particle size distribution and number concentration, total PM, soot (as measured by micro soot sensor) and OC/EC measurements were taken from the exposure chamber. All measurements were performed with engine blow-by routed to the exhaust downstream of the urea SCR/AMOX catalysts.

Results: Results of the three engines tested at SwRI indicated that the intended emissions reductions were met, and in most cases exceeded. Due to technical improvements, no active regeneration of the DPF was needed during ACES Phase 2 testing, compared to the several regeneration occurrences with the 2007 technology engines tested in ACES Phase 1. Table 4 summarizes the average weighted emissions for the FTP cold- and hot-start composite relative to the EPA 2010 standard. Substantial reductions were observed for CO (97%), NMHC (100%), PM (92%) and NO_X (61%). Relative to the 2004 standard, the reductions were 97% for CO, 97% for NO_X, 100% for NMHC, and over 99% for PM. In addition, substantial reductions in NO_X, NO_2, CO, NMHC, CH_4, PM, EC and OC mass, and particle number were observed. Greenhouse gas emissions based on CO_2, N_2O, and CH_4 led to no change in the 100 year global warming potential (GWP), as defined by the US EPA. The reduction in CH_4 and the slight reduction in CO_2 observed with 2010 technology engines (Figure 2) were offset by the increase in N_2O (not shown) leading to no change in the GWP.

Table 4. Summary of average weighted regulated emissions based on the FTP cold-start and hot-start composite

Pollutant	2010 EPA Standard (g/hp-hr)	[a] Weighted 2010 Engines Emissions (g/hp-hr)	Emissions % Reduction Relative to the 2010 Certification Standard
CO	15.5	0.50	97
NMHC	0.14	0.0000	100
PM	0.01	0.0008	92
NO_X	0.20	0.08	61
[a] (1/7×Cold-Start FTP) + (6/7×Hot-Start FTP)			

Although N_2O emissions were higher with the 2010 technology engines compared to the 2007 technology engines, they were still below the EPA 2014 N_2O emissions limit of 0.1 g/hp-hr (not shown). The average N_2O emissions ranged from 0.052 g/hp-hr and 0.054 g/hp-hr for Engines X and Z to 0.11 g/hp-hr for Engine Y. The N_2O limit is a "cap" standard designed to prevent major increases in N_2O. It was set at approximately twice the level of N_2O emissions from 2008 heavy-duty diesel and gasoline engines.

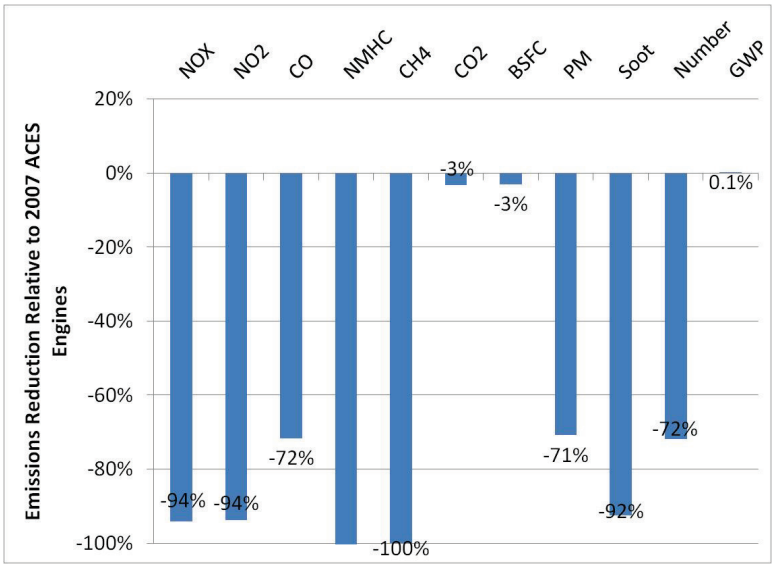

Figure 2. 2010 technology engines emissions reduction relative to 2007 technology engines for the 16-hour cycle

Table 5 shows the 2010 emissions reductions for several classes of unregulated emissions compounds relative to the 2007 technology engines used in ACES Phase 1, and to a 2004 technology engine used in the CRC E55/59 study, and also relative to a 1998 technology engine used for dioxins and furans. Very substantial reductions (91% to 100%) were observed relative to the 2004 technology engine. Substantial reductions (18% to 99%) were also observed relative to the 2007 technology engines. Out of six particle phase urea-related compounds for which we conducted analyses, only urea and cyanuric acid were detected. Even for those compounds, the emissions level was extremely low, with the highest cyanuric

acid mass concentration level being just about 18 ppb in the undiluted engine exhaust, and the emissions were in the range of 4.8 to 15.5 µg/hp-hr. The average exhaust concentration of ammonia (urea-related compound) due to ammonia slip ranged from 0.12 ppmv to 1.37 ppmv, depending on the engine and cycle used. This concentration range is much lower than the Euro VI limit of 10 ppm, and the potential US limit of 10 ppm to 15 ppm.

Table 5. Summary of unregulated emissions reduction for the 16-hour cycle

Pollutant	2010 % reduction relative to 2007 engines	2010 % reduction relative to 2004 engine	2007 % reduction relative to 2004 engine
Single Ring Aromatics	50	91	82
PAHs	97	99	79
Nitro-PAHs	99	100	81
Alkanes	93	99	85
Polar	96	99	81
Hopanes & Steranes	89	100	99
Carbonyls	80	100	98
Inorganic Ions	87	92	38
Metals and Elements	81	100	98
OC	18	97	96
EC	53	100	99
Dioxins and Furans[a]	97	100	99
[a] Relative to 1998 technology engine			

Figure 3 illustrates differences in composition of the PM emitted by 2010 technology engines compared to 2007 technology engines. For 2010 technology engines, the very low level of PM was dominated by OC (66%), followed by EC (16%) and nitrate (14%), in contrast with 2007 technology engines, where PM was dominated by sulfate (53%), followed by OC (30%) and EC (13%). Emissions of elements were substantially lower with the 2010 vs. 2007 technology engines. The non-metallic elements were dominated by sulfur (fuel and oil derived) and metallic elements were dominated by calcium and zinc (lube oil derived) followed by iron and aluminum (engine wear) (data not shown).

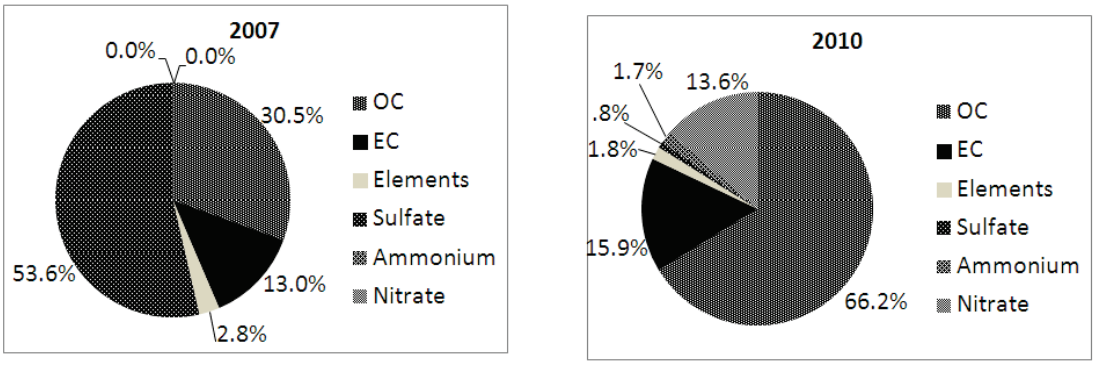

Figure 3. Summary of the percent composition of PM for 2007 (left) and 2010 (right) technology engines

Role of regeneration events in the observed PM concentrations

The observed reductions in PM (total mass, soot, and number) and unregulated emissions from 2007 to 2010 engines are likely due to differences in active DPF regeneration operation. The 2007 engines triggered multiple regeneration events during the 16-hour cycles, while the 2010 engines did not trigger any events. The improvement/reduction in regeneration was achieved through some combination of lower engine-out PM, increased passive regeneration and improved control strategies. PM emissions during regeneration events have been observed to be higher than normal operation for the 2007 engines used in ACES Phase 1. Unregulated emissions are believed to be higher during regeneration events. Thus, the results from the 2007 engines include emissions measured over both normal (no active regeneration) and regeneration operation, while the results from the 2010 engines only include emissions measured over normal operation. DPF active regeneration would have occurred had the 2010 engines been run for a much longer period of time (100 or more hours). The 2010 engines did not trigger a regeneration event even after three back-to-back 16-hour cycles (48 hours of operation). Full results are presented in the *CRC Report No. ACES 2* (Khalek et al 2013, in press; **see Attachment 1**).

Conclusions: **The goals for Phase 2 were met. ACES Phase 2 demonstrates another drastic step in emissions reduction with 2010 EPA-compliant on-highway HHDDE. The three 2011 model engines showed substantially lower regulated emissions of NO_X, CO, NMHC, and PM relative to the 2010 standard. They also showed a substantial reduction in a very wide spectrum of particle and gas phase unregulated emissions species relative to pre-2007 and 2007 technology engines.**

PHASE 3. EMISSIONS CHARACTERIZATION AND HEALTH EFFECTS TESTING OF SELECTED 2010 ENGINE AND CONTROL SYSTEMS

Phase 3A. Developing an Exposure System for a Chronic Inhalation Study in Animals

Goal: Develop and characterize an exposure system for a chronic inhalation study of rats and mice exposed to exhaust from a 2007-compliant diesel engine. Specific objectives were:

1) Confirm proper performance of the engine and exposure systems during commissioning;
2) Compare emissions data at LRRI with comparable data from 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.

Accomplishments: Considerable effort was made to upgrade the exposure facility at LRRI to accommodate a HHDDE because previously, the laboratory had only tested light-duty engines. Both engines B and B' were installed successfully and tested (sequentially); emissions were similar to what was reported in Phase 1. A decision was made to use engine B' for the animal exposures in Phase 3 because it was a slightly newer model.

Approach: Drs. Joe Mauderly and Jake McDonald worked with the manufacturers of engine B and the dynamometer to set up an appropriate exposure generation 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. 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 PM emissions under steady-state operation, during the FTP cycle, and using the 16-hour engine cycle that was developed for the ACES program. Characterization was conducted on two engines, termed B (main engine) and B' (back-up engine). 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.

Results: Emissions characterization of engines B and engine B' commenced in late 2008. Due to complications with the test set-up—most notably with the dynamometer and its back-up—testing of engine B was completed in July 2009; basic emissions and operating specifications were met and approved by the engine manufacturer. The tests revealed some concerns regarding high chamber temperature at the highest DEE concentration, which was close to what is allowed under animal care guidelines (data not shown). Levels of particles in the exposure chamber were very low except during trap regeneration (Figure 4).

Testing continued with engine B' at all dilution levels with additional room cooling in place to reduce the exposure chamber temperature. Based on the initial test results with both engines, final requirements for completion of Phase 3A were negotiated, including more detailed recording of trap regeneration events. A decision was made to conduct the Phase 3B health testing with engine B' because it is a newer version of engine B with updated emission controls and has a larger share in today's marketplace. Thus, the remaining inhalation chamber characterization was done with engine B' and was completed in November 2009 (Table 6). Subsequently, the data were reviewed and a decision was made to go ahead with animal exposures in Phase 3B in January 2010.

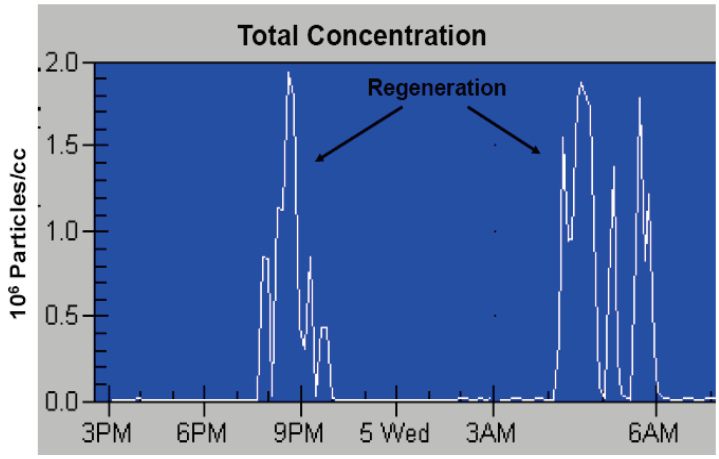

Figure 4: Real-time particle number concentrations in inhalation chamber during a 16-hr cycle

Table 6: Exposure chamber atmosphere at 3 dilution levels. (No animals present; engine B' operated on 15 consecutive days using a 16-hr cycle.)

	High DEE							Mid DEE			Low DEE		
	CO_2 (ppm)	CO (ppm)	THC (ppm)	PM chamb. ($\mu g/m^3$)	PM inlet ($\mu g/m^3$)	NO (ppm)	NO_2 (ppm)	PM chamb. ($\mu g/m^3$)	NO (ppm)	NO_2 (ppm)	PM chamb. ($\mu g/m^3$)	NO (ppb)	NO_2 (ppb)
Avg.	2885	3.1	0.1	9.7	12.5	2.9	4.0	1.7	0.5	0.7	0.8	35.8	98.5
St.dev.	166	0.6	0.1	2.8	2.9	0.4	0.4	0.9	0.3	0.4	0.6	30.0	50.7

The investigators noted that 1-2 diesel particle trap regenerations were observed during each 16-hr engine cycle, consistent with what was found in Phase 1. The majority of the particle number and mass was observed during the trap regenerations, and the composition of the PM was mostly organic carbon and sulfate. All measured particles were less than 500 nm in diameter, and varied substantially throughout the engine cycle.

Overall, the emissions characteristics reflected normal engine function and demonstrated successful commissioning of the engine test facility for the chronic bioassay. 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 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. Results are reported in *HEI Communication 17* (Mauderly and McDonald 2012).

Conclusions: **The goals of Phase 3A were met. Some technical issues were encountered with the dynamometer and drive train set-up. This led to some delays in the project but the issues were resolved. The emissions generation system was functioning reliable and was shown to generate consistently the exposure atmospheres at the targeted NO_2 concentrations. Thus, a decision to go ahead with Phase 3B was approved.**

Phase 3B. Exposure Characterization During the Chronic Inhalation Study in Animals

Goal: Measure daily exposure concentrations in the animal inhalation chambers to ensure proper system functioning at the targeted DEE concentrations. Conduct additional detailed exposure characterization at the beginning, middle, and end of the chronic inhalation study.

Accomplishments: The exposure system was shown to operate as designed throughout the animal inhalation study; the targeted DEE concentrations (at 4.2 ppm, 0.8 ppm, and 0.1 ppm NO_2) were met. Detailed information was obtained on long-term operation of the engines, including important information on the frequency of diesel PM filter regeneration.

Approach: The composition of the exposure chamber atmosphere was characterized in detail at the final dilutions of 4.2, 0.8, and 0.1 ppm NO_2. Most of the exposure system characterization was conducted at the 4.2 ppm NO_2 target. This included measurement of regulated gases, PM 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. Due to the low PM concentrations in DEE, PM mass measurements 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).

Results: The investigators continuously monitored the exposure atmospheres during the Phase 3B animal exposures, which started in February 2010 and ended in December 2012. Daily analysis of exposure atmospheres showed that the 2007-compliant engine system operated reliably and consistently provided the targeted exposure concentrations (at 4.2, 0.8, and 0.1 ppm of NO_2; see Table 7). However, in the summer of 2011 it became apparent that the specially-designed 16-hour test cycle was taking a toll on the engine and dynamometer. As a result, the back-up engine and back-up dynamometer were installed and the original engine and dynamometer were sent out for repair. During the remainder of the study no further problems were reported.

Table 7. Average daily concentrations of major DEE constituents in the animal inhalation chambers

Pollutant	High DEE	Mid DEE	Low DEE	Filtered Air
Gases:				
NO_2 (ppm)	4.23 ± 0.38	0.88 ± 0.10	0.105 ± 0.015	-0.005 ± 0.012
NO (ppm)	7.54 ± 1.88	1.68 ± 0.41	0.438 ± 0.278	0.001 ± 0.004
NO_x (ppm)	11.72 ± 2.14	2.55 ± 0.45	0.539 ± 0.268	-0.004 ± 0.014
CO (ppm)	6.0 ± 2.7	n/a	n/a	n/a
CO_2 (ppm)	5114 ± 468	n/a	n/a	n/a
THC (ppm)	0.45 ± 0.48	n/a	n/a	n/a
PM (filter-based):				
Inlet ($\mu g/m^3$)	12 ± 6	5 ± 4	3 ± 5	n/a
Chamber ($\mu g/m^3$)[a]	31 ± 16	30 ± 19	25 ± 16	27 ± 16

[a] Includes contributions from the animals (food, dander etc). Numbers are provided as mean ± standard deviation.

Four intensive exposure characterizations provided additional detailed information on the exposure atmospheres. One intensive characterization was conducted during the 3-month mouse inhalation study (April 2010); three were conducted during the beginning, middle, and towards the end of the chronic rat

inhalation study (September 2010, April 2011, and April 2012). Particle concentrations in the exposure chambers were very low, and only noticeable during trap regeneration, which took place on average once and sometimes twice per day. Figure 5 illustrates particle size distributions in the high diesel concentration exposure chamber, with 2 diesel PM filter generations that day (one shown on the left and the second on the right).

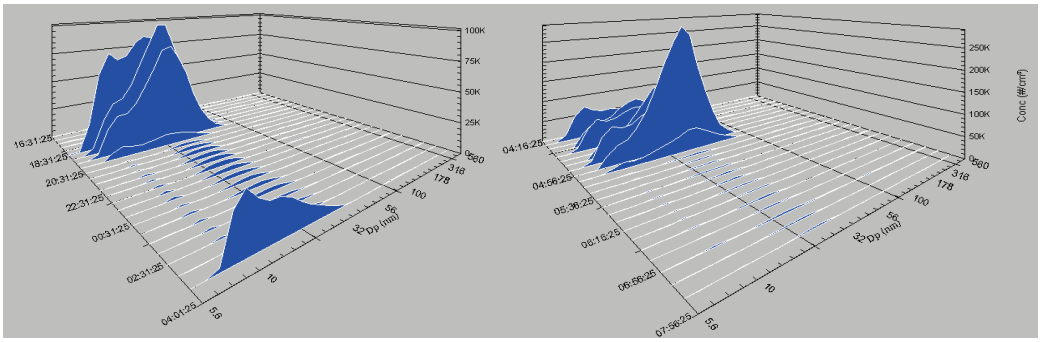

Figure 5. Particle size distribution at the high exposure level chamber

A selection of detailed data measured in the high diesel exposure chamber during the 4 intensive characterizations is presented in Table 8. Full data are included in the draft final report (McDonald et al, in press, see Attachment 2). Table 8 shows that exposure levels were fairly consistent throughout the entire study, although some variation was seen for certain pollutants. It should be noted that the characterizations were done on engine B' (April 2010, September 2010, April 2011) and engine B (April 2012), respectively.

Table 8. Detailed exposure characterization at the high exposure level chamber

Pollutant	Units	April 2010 (B')	September 2010 (B')	April 2011 (B')	April 2012 (B)
PM mass	$\mu g/m^3$	28.3 ± 23.0	20.0 ± 2.0	35 ± 44	26.0 ± 9.3
Particle number	N/cm^3	$0.97 \times 10^5 \pm 0.17 \times 10^5$	$23.7 \times 10^5 \pm 11.6 \times 10^5$	$5.2 \times 10^5 \pm 1.6 \times 10^5$	$3.3 \times 10^5 \pm 1.2 \times 10^5$
NO	ppm	4.8 ± 0.7	4.8 ± 0.7	7.2 ± 0.1	9.8 ± 1.9
NO_2	ppm	4.1 ± 0.9	4.3 ± 0.7	4.3 ± 0.1	4.8 ± 0.9
CO	ppm	6.2 ± 0.8	9.9 ± 1.8	5.9 ± 0.5	3.7 ± 0.4
CO_2	ppm	3,580 ± 228	5,947 ± 453	4,865 ± 39	4,784 ± 123
SO_2	ppb	23.6 ± 3.9	19.4 ± 5.2	32.3 ± 1.0	48 ± 1.6
EC	$\mu g/m^3$	2.7 ± 0.15	1.0	0.7 ± 0.02	0.4 ± 0.1
OC	$\mu g/m^3$	6.1 ± 0.20	2.6 ± 0.04	5.5 ± 0.3	8.5 ± 0.4
Ammonium	ng/m^3	1,740.4 ± 0.3	1,374.3 ± 27.3	679.4 ± 112.4	1,454.8 ± 5.4
Sulfate	ng/m^3	1,740.4 ± 0.9	2,863.7 ± 4.0	927.5 ± 0.1	2,952.6 ± 3.8
Nitrate	ng/m^3	1,193.3 ± 0.4	2,975 ± 0.5	2,298.4 ± 1.9	1,882.3 ± 50.9
Elements (Metals)	ng/m^3	823.8 ± 240.8	712.0 ± 226.2	451.7 ± 6.7	1,258.5 ± 29.2
Alkanes	$\mu g/m^3$	26.7 ± 1.5	16 ± 0.9	24.9 ± 1.3	38.6 ± 2
Carbonyl	$\mu g/m^3$	0.3 ± 1.0	3.3 ± 0.5	0.4 ± 0.4	0 ± 0.3
PAHs	$\mu g/m^3$	6.2 ± 0.3	3.8 ± 0.3	6 ± 0.33	2.89 ± 0.18
Nitro-PAHs	ng/m^3	6.5 ± 0.4	5.5 ± 0.3	8.6 ± 0.46	11.2 ± 1
Polars (Acids)	$\mu g/m^3$	24.8 ± 2.2	12.1 ± 1	15 ± 0.8	12.1 ± 1
Hopane and Steranes	ng/m^3	0.9 ± 0.1	1.3 ± 0.2	3.1 ± 0.2	9.3 ± 0.7
VOCs	$\mu g/m^3$	74.9 ± 12.8	73.6 ± 10	169.1 ± 17.3	277.8 ± 16.3

Figure 6 shows data at all exposure levels for total PAHs and volatile organic carbons (VOCs) as an example. 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 PAHs. Of the 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.

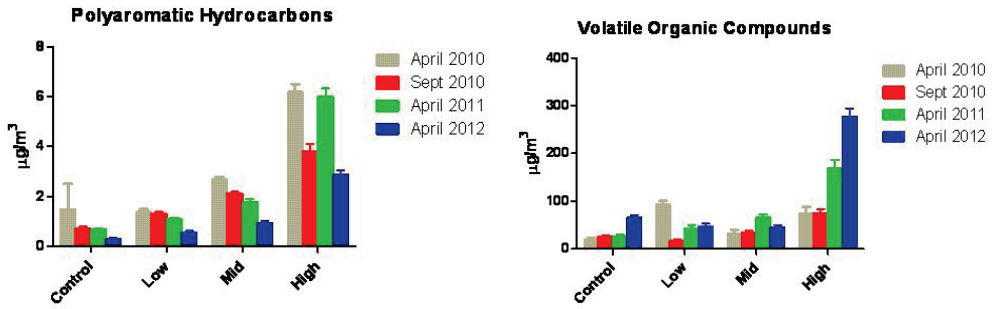

Figure 6. Total PAHs and VOCs measured during 4 intensive characterizations at the control, low, mid, and high exposure level chambers

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. Regarding PM mass measurements, 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). 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. All results are reported in the attached HEI Report (McDonald et al 2014; **see Attachment 2**), which will be published in 2014.

Conclusions: **The goals of exposure characterization during Phase 3B were met. Daily characterization of the exposure atmospheres showed that the exposure targets (based on NO_2 concentrations in the inhalation chambers) were met throughout the study. Thus, animals were exposed to DEE successfully per study design specifications. The exposure system operated reliably although it was noted that the 16-hour cycle took a toll on the engine and dynamometer, which led to a switch from engine B' to engine B partway through the study, and a switch to engine B' again during the final year. No major differences were found between the two engines in terms of daily and intensive emissions characterizations. Important information on durability and reliability of the engine/aftertreatment system was obtained, in addition to unique information on the frequency of diesel PM filter regenerations.**

Phase 3B. Biological Screening in Mice Exposed to Diesel Engine Exhaust for 1 and 3 months

Goal: To determine whether exposure to DEE from a 2007-compliant engine produced changes in a limited set of biomarkers indicative of changes in mutagenicity and genotoxicity.

Accomplishments: Mice and rats were successfully exposed to DEE for up to 3 months; they showed no exposure-related changes in markers of genotoxicity compared to animals exposed to filtered air. Some

small effects were noted in inflammatory markers and respiratory function, with fewer effects observed in mice compared to rats. Most of these small changes were thought to be due to (and were consistent with) exposure to NO_2.

Approach: Rats and mice exposed for 1 and 3 months to DEE were examined at LRRI for markers of inflammation in blood and lung lavage fluid. In addition, blood, lung, and brain samples were analyzed in two ancillary studies conducted by Drs. Jeffrey Bemis and Lance Hallberg for markers of genotoxicity and oxidative stress, which are early markers in the pathway leading towards eventual organ toxicity and tumor formation. Blood and tissue samples were analyzed using standard toxicologic assays.

Results: There were no exposure-related differences in mortality or clinically-evident morbidity in mice or rats after 1 or 3 months of exposure. Over 100 biologic response variables were assessed by McDonald and colleagues. Most indicators demonstrated no statistically significant differences from control as a result of exposure. Rats showed statistically significant responses in several indicators that correlate with oxidative stress in the lung, and also had increases in lung protein and cytokines that correlate with a mild inflammatory response. The mice showed fewer responses than the rats; specifically, the mice showed increases in neutrophil inflammation and an increase in the cytokine interleukin-6. There were mild histopathologic changes in the noses and lungs of rats (Table 9), but not in mice. Rats also showed slight but statistically significant decreases in pulmonary function.

Table 9. Incidence of selected lung findings in male and female Wistar Han rats after 3 months of DEE exposure

Exposure Level	Control	Low DEE	Mid DEE	High DEE
Male Lung				
Hyperplasia in Periacinar Epithelium	0/10	0/10	0/10	10/10
Macrophage Accumulation	0/10	0/10	0/10	3/10
Interstitial Fibrosis	0/10	0/10	0/10	4/10
Female Lung				
Hyperplasia in Periacinar Epithelium	0/10	0/10	0/10	9/10
Macrophage Accumulation	0/10	0/10	0/10	3/10
Interstitial Fibrosis	0/10	0/10	0/10	2/10

Bemis and colleagues evaluated the potential for DEE to elicit chromosome damage in rodents after 1- and 3-month exposure periods, using a well-established indicator (i.e., micronucleus formation in reticulocytes, a type of blood cell) measured by flow cytometry. Hallberg and colleagues evaluated genotoxicity, using a Comet assay to measure DNA strand breaks, and using a 8OH-dG assay to measure DNA-adduct formation; they also evaluated oxidative stress, using a TBARS assay. The overall conclusion was that there was no apparent effect of the specific DEE exposure conditions on any of these endpoints (data not shown). Results on the biological screening up to 3 months of exposure are presented in HEI Research Report 166 (McDonald et al [Part 1], Bemis et al [Part 2], Hallberg et al [Part 3]; 2012).

Conclusions **The primary importance of the biological screening results after 1 and 3 months of exposure is their demonstration that: 1) the great majority of health tests showed no effect of exposure; 2) several plausibly coherent responses may indicate early, exposure-related, subclinical impacts on lung inflammation, structure, and function of rats that are consistent with exposure to NO_2; 3) statistically significant effects were observed primarily at the highest exposure level (the lowest level has produced no observable effects).**

CONCLUSIONS

We conclude that ACES has been completed successfully and has yielded important information on emissions from 2007- and 2010-compliant heavy-duty diesel engines and possible health effects resulting from exposure to those emissions. The results from Phase 1 and Phase 2 confirm Hypothesis 1, that "*regulated and unregulated exhaust emissions from 2007/2010 compression ignition engine equipped vehicles will be greatly reduced compared to older vehicles."* Emissions characterization of both 2007- and 2010-compliant engines indicates that the standards are met or even exceeded. There were some differences in emissions among engines from different manufacturers, but those differences were generally small. In addition to detailed results presented in the Phase 1 and Phase 2 topical reports, the project has produced detailed databases on regulated and unregulated emissions under a variety of conditions (see Databases, below). These include testing with FTP (hot and cold starts) and selected CARB 5-mode cycles, repeated testing during the specially designed 16-hour cycle, and additional testing at simulated high altitude conditions.

The results from Phase 3A and 3B indicate that engine/aftertreatment system performance has been reliable over the course of the 30-month study, although the intensive 16-hour cycle was shown to produce considerable wear and tear on the engine and dynamometer that called for repairs. Phase 3 biological screening after 1 and 3 months of exposure has shown that a small number of biological effects were seen, mostly related to mild inflammation of the lungs. No significant genotoxic and mutagenic changes or other serious adverse health outcomes were observed up to that time point. *Hypothesis 2, "Exhaust emissions from these vehicles will not cause an increase in tumor formation or substantial toxicity to any organ or other serious health effects in rats and mice at the dilution ratios used compared to animals exposed to filtered air, although some biologic effects may occur"* has thus been partially confirmed, although a full assessment will only occur upon completion of the final pathology analyses after 30 months of exposure. Preliminary results indicate some mild exposure-related changes in the lungs after 3, 12, and 24 months of exposure that are consistent with effects seen after exposure to NO_2 alone (an exposure which, based on the Phase 2 results of 2010 engines, is expected to decrease substantially in all new engines going forward). These effects were seen only at the highest concentration of DEE (at 4.2 ppm NO_2). Results of the full assessment of health outcomes — which has been funded separately from this DOE-funded project — will be reported in late 2014. All this work has been conducted with input from the ACES stakeholders.

PRODUCTS

Publications

Reports and Journal Articles (by year)

1. Clark, Nigel N., Mridul Gautam, W. Scott Wayne, Gregory Thompson, Donald W. Lyons, , Feng Zhen, Clinton Bedick, Richard J. Atkinson, and David L. McKain. 2007. *Creation of the "Heavy Heavy-Duty Diesel Engine Test Schedule" for Representative Measurement of Heavy-Duty Engine Emissions*. CRC Report ACES 1a. Coordinating Research Council, Alpharetta, GA. Available from http://crcao.org/reports/recentstudies2007/ACES-1a/CRC%20ACES-1a%20Final%20Report%2007-11-2007.pdf.

2. Khalek, Imad A., Thomas L. Bougher, and Patrick M. Merritt. 2009. *ACES Phase 1. Phase 1 of the Advanced Collaborative Emissions Study*. CRC Report ACES Phase 1. Coordinating Research Council, Alpharetta GA. Available from http://www.crcao.org/reports/recentstudies2009/ACES%20Phase%201/ACES%20Phase1%20Final%20Report%2015JUN2009.pdf **SEE ATTACHMENT 1**

3. Mauderly, J.L. 2010. *Current Status of the Toxicology of Diesel Engine Exhaust – and the ACES Project*. Zentralblatt für Arbeitsmedizin, Arbeitsschutz, und Ergonomie 12; 412-417.

4. Khalek, Imad A., Thomas L. Bougher, Patrick M. Merritt, and Barbara Zielinska. 2011. *Regulated and Unregulated Emissions from Highway Heavy-Duty Diesel Engines Complying with U.S. Environmental Protection Agency 2007 Emissions Standards.* J. Air & Waste Manage. Assoc. 61:427–442.

5. Mauderly J.L., McDonald J.D. 2012. *Advanced Collaborative Emissions Study (ACES) Phase 3A: Characterization of U.S. 2007-Compliant Diesel Engine and Exposure System Operation.* Communication 17. Health Effects Institute, Boston, MA. Available from http://pubs.healtheffects.org/view.php?id=372. **SEE ATTACHMENT 3**

6. McDonald, Jacob D. et al. (Part 1); Jeffrey C. Bemis et al. (Part 2); Lance M. Hallberg et al. (Part 3); Daniel J. Conklin and Maiying Kong (Part 4). 2012. *Advanced Collaborative Emissions Study (ACES) Subchronic Exposure Results: Biologic Responses in Rats and Mice and Assessment of Genotoxicity.* Research Report 166. Health Effects Institute, Boston, MA. Available from http://pubs.healtheffects.org/view.php?id=377.

7. Khalek, Imad A., Matthew G. Blanks, and Patrick M. Merritt. 2013. *Phase 2 of the Advanced Collaborative Emissions Study*. CRC Report ACES Phase 2. Coordinating Research Council, Alpharetta GA. Available from www.crcao.org. **SEE ATTACHMENT 2**

8. McDonald Jacob D., Thomas Holmes, Richard K. White, Mark Gauna, Ramesh Chand, Judith Chow, Barbara Zielinska. In Press. *Health Effects Institute Advanced Collaborative Emissions Study (ACES). Phase 3B: Characterization of Exposure Atmospheres.* Health Effects Institute, Boston MA. Will be available from www.healtheffects.org in 2014. **SEE ATTACHMENT 4**

Webinars

1. Webinar organized by the Diesel Technology Forum: "Heavy-Duty Diesel Engine Emissions Research Webinar" (September 2009). Available at http://www.dieselforum.org/multimedia.

2. Seminar at CARB in Sacramento CA in February 2012 "Biological Response to Inhaled 2007 Compliant Diesel Emissions" (McDonald)

Conference Abstracts [a]

1. Poster Presentation at the Diesel Engine Emissions Reduction (DEER) meeting in Detroit MI, August 2006, P-11: "Status of the Advanced Collaborative Emissions Study (ACES)"
2. Platform Presentation at the HEI Annual Conference in San Francisco CA, April 2006, in the session "Hot Topics, Breaking News"
3. Poster Presentation at the CRC ON-Road Vehicle Emissions Workshop in San Diego, March 26-28 2007, "Status of the Advanced Collaborative Emissions Study (ACES)"
4. Poster Presentation at the HEI Annual Conference in Chicago IL, April 15-17 2007, "Status of the Advanced Collaborative Emissions Study (ACES)"
5. Poster Presentation at the Diesel Engine Emissions Reduction (DEER) meeting in Detroit MI, August 13-16 2007, P-23: "Status of the Advanced Collaborative Emissions Study (ACES)"
6. Poster presentation at the CRC On-Road Vehicle Emissions Workshop in San Diego CA, March 2008: "Advanced Collaborative Emissions Study."
7. Platform and poster presentations at the HEI Annual Conference in Philadelphia CA, April 2008: "Advanced Collaborative Emissions Study: Phase 1."
8. Platform presentation at the Diesel Engine Emissions Reduction (DEER) meeting in Detroit MI, August 2008: "Status of the Advanced Collaborative Emissions Study (ACES)."
9. Poster presentation at the CRC On-Road Vehicle Emissions Workshop in San Diego CA, March 2009: "Phase 1 of the Advanced Collaborative Emissions Study: Highlights of Project Findings."
10. Platform and poster presentations at the HEI Annual Conference in Portland OR, May 2009:
    a. "Advanced Collaborative Emissions Study (ACES)";
    b. "Status of ACES Phase 3: Chronic Inhalation Bioassay"; and
    c. "Advanced Collaborative Emissions Study (ACES): Additional Studies of Genotoxicity and Vascular Endpoints Funded Under RFA 06-2".
11. Platform presentations at the Air & Waste Management Association's 102nd Annual Conference & Exhibition in Detroit MI, June 2009:
    a. "Overview of the Advanced Collaborative Emissions Study (ACES)";
    b. "Advanced Collaborative Emission Studies - Regulated Emissions from 2007 Diesels";
    c. "Advanced Collaborative Emission Studies (ACES) - Unregulated Emissions from 2007 Diesel Engines";
    d. "Heavy-Duty Diesel Engine Test Cycles for the Advanced Collaborative Emissions Study";
    e. "Particle Number and Size Measurement Principles"; and
    f. "Particle Number Measurements from Filter-Equipped 2007 On-Highway Diesel Truck Engines."
12. Platform presentation at the ETH-Conference on Combustion Generated Nanoparticles June 2009, Zurich, Switzerland: "Particle Emissions from 2007 Heavy-Duty On-Highway Diesel Engines During Active Regeneration of Catalyzed DPF."
13. Platform and poster presentations at the Directions in Engine-Efficiency and Emissions Research (DEER) conference in Dearborn MI, August 2009:
    a. "Update on Phase 1 of the Advanced Collaborative Emissions Study (Aces Phase 1)"; and

[a] In addition, ACES results were presented annually at the DOE Merit Reviews during 2007–2013.

b. "Advanced Collaborative Emissions Study (ACES): Phase 3."

14. Poster presentation at the CRC On-Road Vehicle Emissions Workshop in San Diego CA, March 2010: "ACES: Characterization of Exposure Atmospheres and System Performance for a Chronic 2007 Compliant Diesel Exhaust Inhalation Study".
15. Platform and poster presentations at the HEI Annual Conference in Alexandria VA, April 2009:
    a. "Micronucleated Reticulocytes as an Indicator of Genotoxicity Following Exposure to Cyclophosphamide and Its Application to the Evaluation of Diesel Exhaust" (PI Bemis)
    b. "Effects of Diesel Emissions on Vascular Inflammation" (PI Conklin)
    c. "Assessment of the Genotoxicity of Diesel Exhaust/Diesel Exhaust Particulates from Improved Diesel Engines" (PI Hallberg)
    d. "Status of ACES Phase 3: Chronic Inhalation Bioassay" (PI Mauderly)
    e. "Diesel Exhaust Exposure and Cardiovascular Dysfunction: Part of ACES Phase 3" (PI Sun)
    f. "Lung Cell Gene Transcription Responses to Diesel Particulate" (PI Veranth).
16. Platform presentation at AK Fasern Stäube, Dortmund, Germany, September 2010: "Current Status of the Toxicology of Diesel Engine Exhaust – and the ACES Project."
17. Platform presentation at the Directions in Engine-Efficiency and Emissions Research (DEER) conference in Dearborn MI, September 2010: "Advanced Collaborative Emissions Study (ACES): Phase 3."
18. Platform and poster presentations at the HEI Annual Conference in Boston MA, May 2011:
    a. "Micronucleated Reticulocytes as an Indicator of Genotoxicity Following Exposure to Diesel Exhaust" (PI Bemis - poster)
    b. "Effects of Diesel Emissions on Vascular Inflammation" (PI Conklin - poster)
    c. "Assessment of the Genotoxicity of Diesel Exhaust/Diesel Exhaust Particulates from Improved Diesel Engines" (PI Hallberg - poster)
    d. "Phase 3B Update: Summary of 1 and 3 Month Exposures" (PI McDonald - platform)
    e. "ACES Phase 3: 4 and 13 Week Results from Rats and Mice Exposed to 2007 Compliant Diesel Emissions" (PI McDonald – poster)
    f. "Diesel Exhaust Exposure and Cardiovascular Dysfunction: Part of ACES Phase 3" (PI Sun - poster)
    g. "Lung Cell Gene Transcription Responses to Diesel Particulate" (PI Veranth - poster).
19. Platform presentations at the Directions in Engine-Efficiency and Emissions Research (DEER) conference in Dearborn MI, September 2010:
    a. "ACES Phase 3: 4 and 13 Week Results from Rats and Mice Exposed to 2007 Compliant Diesel Emissions, " and
    b. "Status of Phase 2 of the Advanced Collaborative Emissions Study (ACES)."
20. Platform and poster presentations at the HEI Annual Conference in Chicago, IL, April 2012:
    a. "Toxicologic Effects of Diesel Emissions: Historical Data and New Technology—Results from the HEI ACES Study" (McDonald - plenary)
    b. "Micronucleated Reticulocytes as an Indicator of Genotoxicity Following Exposure to Diesel Exhaust" (Bemis – poster)

c. "Effects of Diesel Engine Emissions on Systemic Inflammation in Rodents" (Conklin - poster)

d. "Assessment of the Genotoxicity of Diesel Exhaust and Diesel Exhaust Particulates from Improved Diesel Engines" (Hallberg - poster)

e. "One- and Three-Month Results from Rats and Mice Exposed to 2007-Compliant Diesel Emissions" (McDonald- poster)

f. "Diesel Exhaust Exposure and Cardiovascular Dysfunction" (Sun - poster)

g. "Status of ACES Phase 2" (Tennant – poster)

21. Platform presentation at the CRC Real Word Vehicle Emissions Workshop in San Diego CA in March 2012 "Update on Phase 2 of the Advanced Collaborative Emissions Study (ACES Phase 2)" (Tennant).

22. Platform presentations at the DEER meeting, Dearborn MI in October 2012:

    a. "Advanced Collaborative Emissions Study (ACES)" (Tennant)

    b. "ACES: Evaluation of Tissue Response to Inhaled 2007-Compliant Diesel Exhaust" (Shaikh)

23. Platform presentation at the CRC Mobile Source Air Toxics Workshop in Sacramento CA, February 2013: "ACES Phase 2: Study Update" (Tim French, Truck and Engine Manufacturers Association)

24. Platform and poster presentations at the Society of Toxicology annual meeting in San Antonio TX, March 2013:

    a. "IARC assessment of diesel and gasoline exhaust: overview of toxicologic evidence" (McDonald – plenary)

    b. "Biomarker-based evaluation of diesel exhaust emissions from 2007-compliant engines in rats and mice exposed for defined time periods" (Hallberg – poster)

25. Platform presentation at the Diesel, Transportation, Occupational Exposures, and Health meeting in New York City NY, April 2013: "A global perspective on improving diesel technology and fuel" (Greenbaum)

26. Platform presentation at the CRC Real World Emissions Workshop in San Diego CA, April 2013: "Phase 2 of the Advanced Collaborative Emissions Study (ACES): Highlights of Project Finding" (Khalek)

27. Platform and poster presentations at the HEI Annual Conference in San Francisco CA, April 2013:

    a. "Results from ACES Phase 2: Emissions Characterization of 2010-Compliant Engines" (Khalek – plenary)

    b. "Results from ACES Phase 3B: Health Effects of Chronic Exposure to Emissions from a 2007-Compliant Engine in Rats" (McDonald – plenary)

    c. "ACES: Micronucleated Reticulocytes As an Indicator of Genotoxicity Following Exposure to Diesel Exhaust" (Bemis – poster)

    d. "ACES: Effects of Chronic Diesel Engine Emissions on Systemic Inflammation in Rats" (Conklin – poster)

    e. "ACES: Genotoxicity of Diesel Exhaust from 2007-Compliant Diesel Engines: A Continuation of the Study" (Hallberg – poster)

    f. "ACES Phase 3: 52- and 104-Week Results from Rats Exposed to 2007-Compliant Diesel Emissions" (McDonald – poster)

    g. "ACES: Update on Phase 2 of the Advanced Collaborative Emissions Study" (Tennant – poster)

28. Platform presentation at the Emissions 2013 Conference and Exposition in Ypsilanti MI, June 2013: "Characterization and Health-Effects Testing of Emissions from Modern Diesel Engines" (Shaikh)

Networks and Collaborations Fostered

During the planning, conduct, and review of ACES, HEI and CRC have fostered multidisciplinary collaborations among scientists and engineers in the emissions characterization and toxicology communities. Examples are:

- Bringing together emissions experts in academia, industry, and government to serve on CRC's ACES Technical Panel to oversee Phase 1 and 2, with additional input from toxicology experts to advice on selection of engines and the development of exposure atmospheres for Phase 3.
- Bringing in additional emissions experts for specific tasks during Phases 1 and 2, including WVU collaborators to develop a 16-hour cycle in Phase 1A, and Oak Ridge National Laboratory collaborators to measure urea-related compounds in Phase 2.
- Bringing together emissions and toxicology experts to serve on the HEI ACES Oversight and Advisory Committees to provide input during planning and conduct of Phase 3.
- Organizing multi stakeholder workshops to design ACES and hold regular joint meetings of Oversight and Advisory Committees for input during the study.
- Fostering communications among the investigators conducting Phases 1 and 2 (at SwRI) and Phase 3 (at LRRI) to compare engine performance at both facilities.
- Funding a group of investigators to conduct biological screening in Phase 3 by measuring complementary health endpoints in organ and tissue samples from animals exposed to new technology diesel exhaust in ACES.
- Holding regular meetings among the Phase 3 investigators and educating them about engine technologies.
- Recruiting a group of additional toxicology experts to review the health effect analyses in Phase 3 and compare the ACES results with previous inhalation studies of old technology diesel exhaust, NO_2, and ozone.

Technologies / Techniques

As part of ACES, a special 16-hour cycle was developed that combined portions of CARB cycle (see description of Phase 1A on page 9). This specially-developed cycle was subsequently used in Phase 1 and 2 emissions characterization as well as Phase 3 health testing, and is available for other investigators for use in future studies. Details are available in the final report by Nigel Clark and colleagues (see

http://crcao.org/reports/recentstudies2007/ACES-1a/CRC%20ACES-1a%20Final%20Report%2007-11-2007.pdf.)

Databases

Databases with complete emissions data from Phases 1 and 2 can be found here:

- **Phase 1:** Final ACES Phase 1 Database. Available from:

  http://crcao.org/reports/recentstudies2009/ACES%20Phase%201/ACES_Final_Database_JUNE2010.zip
- **Phase 2:** Final ACES Phase 2 Database. Available from: http://crcao.org/reports/recentstudies2013/ACES%20Ph2/Database%202013.12.16.zip

Abbreviations

8OH-dG	8-hydroxy deoxyguanosine
ACES	Advanced Collaborative Emissions Study
AMOX	ammonia oxidation
Avg	average
C-DPF	catalyzed diesel PM filter
CFR	Code of Federal Regulations
CH	cruise and high speed
CH_4	methane
CO	carbon monoxide
CO	carbon dioxide
CRC	Coordinating Research Council
CVS	constant volume sampler
DEE	diesel engine exhaust
DEER	Directions in Engine-Efficiency and Emissions Research
DMM	Dekati mass monitor
DOC	diesel oxidation catalyst
DOE	Department of Energy
DPF	diesel PM filter
DRI	Desert Research Institute
EC	elemental carbon
EPA	Environmental Protection Agency
FTP	Federal Test Procedure
g/hp-hr	gram per horsepower-hour
GWP	global warming potential
HC	hydrocarbon
HEI	Health Effects Institute
HHDDE	heavy-heavy duty diesel engines
IARC	International Agency for Research on Cancer
ICT	idle, creep, and transient
LRRI	Lovelace Respiratory Research Institute
mg/hp-hr	milligram per horsepower-hour
µg/hp-hr	microgram per horsepower-hour
N/hp-hr	number per horsepower-hour
NMHC	non-methane hydrocarbon
NO	nitrogen oxide
NO_2	nitrogen dioxide
N_2O	nitrous oxide
NOx	nitrogen oxides
OC	organic carbon
PAH	polynuclear aromatic hydrocarbon
PM	particulate matter
ppb	parts per billion
ppm	parts per million
ppmv	parts per million by volume
stdev	standard deviation
SCR	selective catalytic reduction
SwRI	Southwest Research Institute
TBARS	thiobarbituric acid reactive substances
THC	total hydrocarbon
VOC	volatile organic compound
WVU	West Virginia University
XRF	X-ray fluorescence

CRC Report: ACES Phase 1

PHASE 1 OF THE ADVANCED COLLABORATIVE EMISSIONS STUDY

June 2009

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PHASE 1 OF THE ADVANCED COLLABORATIVE EMISSIONS STUDY

FINAL REPORT

SwRI® Project No. 03.13062

Prepared for and Sponsored by:

Coordinating Research Council, Inc.
3650 Mansell Road, Suite 140
Alpharetta, GA 30022

Health Effects Institute
101 Federal Street, Suite 500
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Corning Inc.
ArvinMeritor

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June 2009

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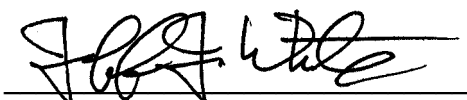
Prepared by:

Imad A. Khalek, Program Manager

Reviewed by:



Jeff J. White, Director

EMISSIONS RESEARCH AND DEVELOPMENT DEPARTMENT
ENGINE, EMISSIONS AND VEHICLE RESEARCH DIVISION

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Results and discussion given in this report relate only to the test items described in this report.

FOREWORD

Phase 1 of the Advanced Collaborative Emissions Study (ACES Phase 1) was performed by SwRI's Emissions Research and Development Department (ER&DD), in the Engine, Emissions and Vehicle Research Division.

SwRI's Principal Investigator and Project Manager was Dr. Imad Khalek, Program Manager. SwRI's Project Leader was Mr. Thomas Bougher, Research Engineer. The chemistry effort was coordinated by Mr. Patrick Merritt, Senior Research Scientist. Chemistry assistance was provided by Mr. Ken Jones, Senior Research Technologist, Mr. Tom Gabehart, Research Technologist, Ms. Yolanda Rodriguez, Staff Technician, Ms. Kelly Strate, Senior Technician, Mr. Chuan-Yi Tsai, Research Assistant, and Mr. Luis Sanchez, Principal Technician. Additional assistance was provided by Ms. Jacqueline Ranger, Group Leader, and Ms. Shraddha Quarderer, Senior Research Scientist. Laboratory assistance was provided by Mr. Ernie Krueger, Laboratory Manager, Mr. Keith Echtle, Assistant Manager, Mr. Danny Terrazas, Supervisor, Mr. Daniel Preece, Senior Technician, Mr. William Valuk, Staff Technician, Mr. Don Parker, Senior Technician, Mr. Joe Sosa, Principal Technician, Mr. Rudy Guerra, Senior Technician, Mr. Denny Zaske, Senior Technician, and Mr. Tim Milligan, Principal Technician.

Chemical analyses were performed by SwRI's ER&DD and SwRI's Chemistry and Chemical Engineering Division. Additional chemical analyses such as PAHs, polar compounds, elements, and OC/EC were performed by Desert Research Institute (DRI), with Dr. Barbara Zielinska as the Principal Investigator.

ACES Phase 1 was sponsored by CRC and HEI, with funding from the DOE Office of Vehicle Technologies, EPA, EMA, CARB, API, Corning Inc., and ArvinMeritor. The engines and engine support were provided by Caterpillar, Cummins, Detroit Diesel, and Volvo Powertrain. Key contacts were Mr. Reynaldo Agama, Caterpillar, Dr. Shirish Shimpi, Cummins, Mr. Don Keski-Hynnila, Detroit Diesel, and Mr. Steve Berry, Volvo Powertrain. The lube oil was provided by Lubrizol, and the key contact was Dr. Ewa Bardasz.

The sponsors' project coordinators were Dr. Chris Tennant from CRC and Dr. Maria Costantini from HEI. The CRC ACES Panel members included:

Mr. Reynaldo Agama, Caterpillar
Dr. James Ball, Ford Motor Company (now retired)
Dr. Nicholas Barsic, John Deere
Mr. Steve Berry, Volvo Powertrain
Dr. Steven Cadle, General Motors R&D Center (now retired)
Dr. Maria Costantini, Health Effects Institute
Dr. Annemoon van Erp, Health Effects Institute
Mr. Timothy French, Engine Manufacturers Association
Dr. Thomas Hesterberg, Navistar
Mr. Donald Keski-Hynnila, Detroit Diesel
Mr. Chris Laroo, US Environmental Protection Agency
Dr. Douglas Lawson, National Renewable Energy Laboratory
Mr. Hector Maldonado, California Air Resources Board

Dr. Matti Maricq, Ford Motor Company
Dr. Mani Natarajan, Marathon Petroleum Company LLC
Mr. Ralph Nine, US Department of Energy/National Energy Technology Laboratory
Dr. Robert Okamoto, California Air Resources Board
Mr. Charles Schleyer, ExxonMobil
Dr. Shirish Shimpi, Cummins
Dr. Joseph Somers, US Environmental Protection Agency
Dr. Chris Tennant, Coordinating Research Council
Mr. Steve Trevitz, Volvo Powertrain
Dr. Urban Wass, Volvo AB
Dr. Jane Warren, Health Effects Institute (now retired)

EXECUTIVE SUMMARY

Phase 1 of the Advanced Collaborative Emissions Study (ACES) included detailed chemical characterization of exhaust species emitted from four 2007 model-year heavy heavy-duty diesel engines (HHDDE) manufactured by Caterpillar, Cummins, Detroit Diesel, and Volvo. The work started in March, 2007, and was completed in August, 2008. ACES Phase 1 objectives were:

- To quantify the reduction in both regulated and unregulated emissions from advanced diesel engines,
- To provide regulated and unregulated emissions data for this new engine technology,
- Make data available to support the selection of one engine for the ACES Phase 3 health study,
- To provide initial guidance for the ACES Phase 3 health study using the regulated and unregulated emissions information from ACES Phase 1.

Based on the results of the exhaust emissions characterization, one of the four ACES engines, Engine B, was selected for the ACES Phase 3 health study to be conducted at Lovelace Respiratory Research Institute (LRRI). The engine selection process is described in a Health Effects Institute (HEI) Report, included in Appendix A. An additional backup engine to the one selected for the health study, Engine B', was provided by the engine manufacturer and was tested for regulated emissions at a barometric pressure of 99.3 kPa, representing SwRI's elevation in San Antonio, Texas, and at a simulated barometric pressure of 82.6 kPa, representing LRRI's higher elevation in Albuquerque, New Mexico. The high elevation simulation was performed on the backup engine only.

To comply with 2007 EPA regulations, each engine tested was equipped with water-cooled exhaust gas recirculation (EGR) or clean gas induction (CGI) to reduce NO_x emissions, along with a catalyzed diesel particulate filter (C-DPF), or a diesel oxidation catalyst (DOC) followed by a C-DPF to reduce PM emissions. DOCs were mainly used to increase nitrogen dioxide production to promote the oxidation of soot deposited in the C-DPF. Furthermore, a diesel fuel burner located upstream of the C-DPF, or a diesel fuel injector located upstream of the DOC, was used to elevate exhaust temperature at the inlet of the C-DPF to actively regenerate and clean the C-DPF, as needed. Numerous additional improvements were also made by each engine manufacturer to engine boost pressure and its response, fuel injection and combustion management, and system integration. Manufacturers also equipped engines with crankcase ventilation systems with filters to reduce PM emissions from the crankcase blow-by, which was vented to the atmosphere.

ACES engines emissions were characterized on the following test cycles:

- FTP, the basis for US EPA engine certification and audit.
- CARBx-ICT, idle, creep and a transient portion of the CARB HHDDE-5 Modes (CARB 5-Modes).
- CARBz-CH, cruise and high speed cruise of the CARB 5-Modes.

- 16-Hour Cycle, four 4-hour segments consisting of FTPs and CARB 5-Modes. (The 16-Hour cycle was developed mainly to be used in ACES Phase 1 and in the Phase 3 health study.)

For reference, the CARB 5-Modes were developed earlier by CARB and include curb idle, creep, transient, cruise, and high speed cruise modes.

Table ES-1 provides a summary of cycle time, average exhaust temperature, and percent power relative to the Federal Test Procedure (FTP) transient cycle.

TABLE ES-1. SUMMARY OF CYCLES TESTED

Test Cycles	Time, min	Average Exhaust Temperature, °C	% of FTP Average Power
FTP	20	243	100
CARBx-ICT	39	131	20
CARBz-CH	49	297	137
16-Hour [a]	960	277	110
[a] Four 4-hour segments that consist of repeats of the FTP and CARB-5 Modes			

For each cycle used, regulated emissions of carbon monoxide (CO), non-methane hydrocarbons (NMHC), oxides of nitrogen (NO_x), and particulate matter (PM), were measured. Unregulated emissions measured included total hydrocarbon (THC), methane (CH_4), carbon dioxide (CO_2), nitric oxide (NO), nitrogen dioxide (NO_2), nitrous oxide (N_2O), particle size and number, organic carbon (OC), elemental carbon (EC), metals and elements, polynuclear aromatic hydrocarbons (PAH), nitroPAH, oxyPAH, polar compounds, alkanes, hopanes, steranes, cyanide ion, organic acids, gas phase acids, nitrosamines, detailed speciation of $C_2 - C_{12}$ hydrocarbons, aldehydes and ketones, and dioxins/furans (only for the 16-Hour cycle).

Samples of the different exhaust species were taken either directly from the sample zone of the full-flow constant volume sampler (CVS) dilution tunnel, or from locations that were linked to the sample zone by a dilution step with a dilution ratio of about 2. A unique sample location employed was an animal exposure chamber (unoccupied), provided by LRRI, to determine concentration levels that might be expected in ACES Phase 3. Real time particle size and number, total PM, soot and OC/EC measurements were taken from the exposure chamber.

All measurements were performed with engine blow-by routed to the exhaust downstream of the C-DPF. Selected FTP tests without blow-by were also performed.

Table ES-2 summarizes the average FTP regulated emissions with blow-by relative to EPA 2007 standards. Based on the average emissions from all four ACES engines, PM, CO, and NMHC emissions were all at least 90 percent below the EPA standard. Average NO_x emissions were 10 percent below the standard.

FTP transient cycle average PM emissions without blow-by were 38 percent lower than that with blow-by. For the high elevation testing performed with the backup engine, NO_x emissions were about 34 percent higher than at normal elevation.

TABLE ES-2. SUMMARY OF AVERAGE REGULATED EMISSIONS BASED ON THE FTP CYCLE WITH BLOW-BY

	2007 EPA Standard (g/hp-hr)	Average ACES Engine Emissions (g/hp-hr)	ACES Emissions % Reduction Relative to the 2007 Certification Standard
CO	15.5	0.33	98
NMHC	0.14	0.0064	95
PM	0.01	0.0011	89
NO_X	1.2 [a]	1.075	10
[a] Average value between 2007 and 2009, with full enforcement in 2010 at 0.20 g/hp-hr			

Average FTP NO_2 emissions for the four ACES engines, were 0.73 g/hp-hr, with an NO_2 to NO_x ratio of 68 percent. The NO_2 to NO_X ratio for 2004 technology engines is typically lower, at 4 to 15 percent of the 2004 NO_X limit of 2.4 g/hp-hr. Thus, the direct NO_2 emissions from these ACES engines can be a factor of two to eight times higher than from 2004 technology engines, although the total NO_x emissions from the ACES engines are lower. This increase in NO_2 emissions from 2007 and later heavy-duty diesel engines is temporary, and is expected to be reduced below the EPA 2010 NO_x limit of 0.2 g/hp-hr when 2010 engines are introduced.

During active regeneration, real time particle number emissions from 5.6 nm to 30 nm in diameter can be several orders of magnitude higher than the concentration without active regeneration. However, as shown in Figure ES-1, even when active regeneration occurred, the average particle number emissions were low -- on the order of 90 percent below the level emitted by a 2004 technology engine. They were a factor of 10 higher than the average emissions without regeneration, in spite of the low frequency of occurrence of active regeneration during the 16-Hour cycle (1 to 3 times per 16-Hour cycle).

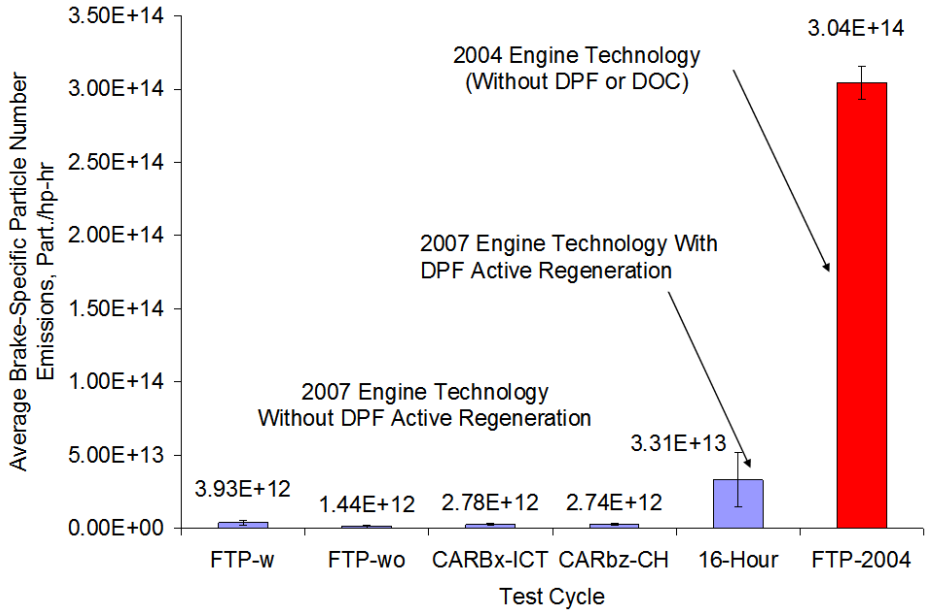

FIGURE ES-1. AVERAGE PARTICLE NUMBER EMISSIONS (W AND WO REPRESENT "WITH" AND "WITHOUT" ENGINE BLOW-BY, RESPECTIVELY)

Unregulated compounds in Table ES-3 show reductions relative to a 2004 technology engine used in the CRC E55/59 [1] study, and also relative to a 1998 technology engine [2] for dioxins/furans. Reductions ranged from 38 percent for inorganic ions to 99 percent for hopanes/steranes, elemental carbon, and dioxins/furans. No vanadium emissions were detected in the ACES engines, but copper emissions were detected during the 16-Hour cycle.

TABLE ES-3. SUMMARY OF UNREGULATED EMISSIONS REDUCTION FOR 16-HOUR CYCLE

Compounds	% Reduction Relative to 2004 Technology Engine
Single Ring Aromatics	82
PAH	79
NitroPAH	81
Alkanes	85
Polar	81
Hopanes/Steranes	99
Carbonyls	98
Inorganic Ions	38
Metals and Elements	98
Organic Carbon	96
Elemental Carbon	99
Dioxins/Furans [a]	99
[a] Relative to 1998 technology engine	

2007 technology engine PM was composed mainly of sulfate and organic carbon, with a small fraction of elemental carbon and metals and elements, as shown in Figure ES-2.

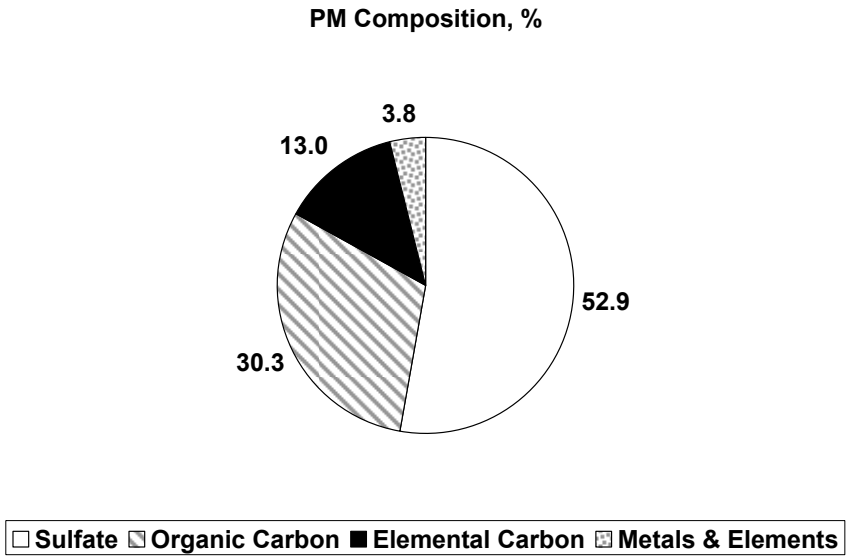

FIGURE ES 2. MEASURED PM COMPOSITION FOR 16-HOUR CYCLE

In summary, the ACES engines achieved more than 89 percent reductions in NMHC, CO, and PM emissions compared to the 2007 standards. Unregulated emissions were also substantially reduced relative to a 2004 technology engine. ACES engines NO_2 emissions were higher than those from 2004 technology engines due to the use of DOC and C-DPF technology. NO_2 emissions will likely be considerably reduced when 2010 engines are introduced.

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ACRONYMS AND ABBREVIATIONS

ACES	Advanced Collaborative Emissions Study
API	American Petroleum Institute
BG	Background (clean dilution air downstream of the HEPA filter of the full flow constant volume sampler tunnel)
BSE	Brake-Specific Emissions
BSFC	Brake Specific Fuel Consumption
CARB	California Air Resources Board
CARB 5-Modes	CARB Heavy Heavy-Duty Idle, Creep, Transient, Cruise, and High Speed Cruise modes
CARBx-ICT	Idle, Creep, and Transient of CARB 5-Modes
CARBz-CH	Cruise and High Speed Cruise of CARB 5-Modes
CFR	Code of Federal Regulations
CGI	Clean Gas Induction
CI	Chemical Ionization
CO	Carbon Monoxide
CRC	Coordinating Research Council
CVAAS	Cold Vapor Atomic Absorption Spectroscopy
CVS	Constant Volume Sampler
DCM	Dichloromethane
DMM	Dekati Mass Monitor
DNPH	Dinitrophenylhydrazine
DOE	Department of Energy
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
DR	Dilution Ratio
DRI	Desert Research Institute
DFI/GC	Direct Filter Injection Gas Chromatography
EC	Elemental Carbon
ECM	Engine Control Module
EDXRF	Energy Dispersive X-Ray Fluorescence
EEPS	Engine Exhaust Particle Sizer
EGR	Exhaust Gas Recirculation
EI	Electron Impact
EMA	Engine Manufacturers Association
EPA	Environmental Protection Agency
ER&DD	Emissions Research and Development Department
FD	Fuel Density
FID	Flame Ionization Detector
FM	Fuel Mileage
FTIR	Fourier Transform Infrared Spectroscopy
FTP	Federal Test Procedure
FTP-TC	Federal Test Procedure Transient Cycle
FTP-w	Federal Test Procedure Transient Cycle with Blow-By
FTP-woo	Federal Test Procedure Transient Cycle without Blow-By
GC-ECD	Gas Chromatography-Electron Capture Detection
GC/MS	Gas Chromatograph/Mass Spectroscopy

HDDE	Heavy-Duty Diesel Engine
HEI	Health Effects Institute
HEPA	High Efficiency Particulate Air
HHDDE	Heavy Heavy-Duty Diesel Engine
HPLC	High Performance Liquid Chromatography
HRGC	High Resolution Gas Chromatography
HRMS	High Resolution Mass Spectroscopy
VOC	Volatile Organic Compounds
IC	Ion Chromatography
ICP/MS	Inductively Coupled Plasma/Mass Spectroscopy
LRRI	Lovelace Respiratory Research Institute
MID	Multiple Ion Detection
N/A	Not Available
MSS	Micro-Soot Sensor
NDIR	Non-Dispersed Infrared
NIST	National Institute of Standards and Technology
NitroPAH	Nitrated Polycyclic Aromatic Hydrocarbon
NMHC	Non-Methane Hydrocarbon
NO	Nitric oxide
NO_2	Nitrogen Dioxide
N_2O	Nitrous Oxide
NO_X	Oxides of Nitrogen
OC	Organic Carbon
ODS	Octadecasilane
POC	Principle Organic Constituents
OxyPAH	Oxygenated Polycyclic Aromatic Hydrocarbon
PAH	Polycyclic Aromatic Hydrocarbon
PCDD	Polychlorinated Dibenzodioxins
PCDF	Polychlorinated Dibenzofurans
PM	Particulate Matter
PTFE	Polytetrafluoroethylene
PUF	Polyurethane Foam
SIS	Selective Ion Storage
S/N	Signal to Noise
SRM	Standard Reference Material
SVOC	Semivolatile Organic Compound
SwRI	Southwest Research Institute
TB	Tunnel Blank
TEF	Toxic Equivalency Factor
TEQ	Toxic Equivalent
THC	Total Hydrocarbon
TOR	Thermal Optical Reflectance
TOT	Thermal Optical Transmittance
ULSD	Ultra-low Sulfur Diesel
UV	Ultraviolet
VOST	Volatile Organic Sample Train
XAD™	"Polymeric Adsorbing Resins"
XRF	X-Ray Fluorescence

1.0 INTRODUCTION

Four heavy-duty diesel engine manufacturers, Caterpillar (CAT), Inc., Cummins, Inc., Detroit Diesel Corporation (DDC), and Volvo Powertrain, provided engines for Phase 1 of the ACES program. The engines were all 2007 model-year and included a CAT C13, Cummins ISX, DDC Series 60, and a Mack MP7. All four engines are considered to be heavy heavy-duty diesel engines that are currently being marketed in the US. The exhaust composition of these engines was characterized to verify that the concentration of regulated emissions were at or below the requirements of EPA's 2007 regulation and to provide data on emission concentrations of a large number of unregulated compounds. One of the four engines was selected for ACES Phase 3 exposure study based on ACES Phase 1 emission results, and according to the process described in Appendix A.

A backup engine to the one selected for ACES Phase 3 exposure study was provided by one of the manufacturers for regulated emissions testing at SwRI's elevation in San Antonio, Texas, (99.3 kpa), and at a simulated high elevation (82.6 kpa), similar to that of LRRI in Albuquerque, New Mexico, where the ACES Phase 3 exposure study will be conducted.

Throughout the ACES project, all engines have remained anonymous, and were designated as Engine A, Engine B, Engine C, Engine D, and Engine B' for the backup engine. It is understood that the identity of these engines will be revealed by CRC, after the ACES exposure study is completed.

The four primary engines (Engines A, B, C, and D) were tested for regulated and unregulated emissions, at SwRI's elevation, using the hot-start Federal Test Procedure transient cycle (FTP-TC), two composites of the CARB Heavy Heavy-Duty Diesel Engines (HHDDE) 5-Modes (CARB 5-Modes), and a 16-Hour transient cycle that was developed by West Virginia University for this program. This cycle was composed of the FTP-TC and the CARB 5-Modes [3]. The backup engine, Engine B', was tested for regulated emissions using the FTP-TC at SwRI's elevation and at LRRI's simulated elevation.

Regulated emissions measurement included carbon monoxide (CO), non-methane hydrocarbon (NMHC), oxides of nitrogen (NO_x), and particulate matter (PM). Unregulated emissions included total hydrocarbon (THC), methane (CH_4), carbon dioxide (CO_2), nitric oxide (NO), nitrogen dioxide (NO_2), particle size and number, organic carbon, elemental carbon, metals and elements, polynuclear aromatic hydrocarbon (PAH), nitroPAH, oxyPAH, polar compounds, alkanes, hopanes, steranes, cyanide ion, organic acids, gas phase acids, nitrosamines, detailed speciation of $C_2 - C_{12}$ hydrocarbons, aldehydes and ketones, and dioxins and furans.

All volumetric flows, volumes or concentrations shown in this report are based on a reference temperature of 20°C and a pressure of 101.3 kPa, used in 40 CFR Part 86. All averages, standard deviations, and error bars are based on three repeats of the FTPs, two repeats of CARBx-ICT, two repeats of the CARBz-CH, and three repeats of the 16-Hour cycle.

2.0 EXPERIMENTAL SETUP

2.1 Engines

Five 2007 model-year (MY 2007) HHDDEs were used in Phase 1 of the ACES program. One of the five engines was a duplicate backup engine. The engines included a CAT C13, Cummins ISX, DDC Series 60, and Mack MP7, as shown in Figures 1, 2, 3, and 4, respectively. All engines were equipped with a diesel oxidation catalyst (DOC) followed by a wall-flow catalyzed diesel particulate filter (DPF), or simply with a catalyzed DPF with a means of active regeneration via exhaust fuel injection or a burner. All engines were turbocharged with water-cooled intake air systems. Three of the engines were equipped with water-cooled high-pressure loop exhaust gas recirculation (EGR), where the exhaust gas is routed from before the DPF to the high pressure side of the intake air compressor. One engine was equipped with low-pressure loop water-cooled EGR or clean gas induction (CGI), where the exhaust gas is routed from downstream of the DPF to the inlet side of the intake air compressor.

The active regeneration strategy for each engine was different and may take into consideration such things as engine operating time, fuel used, DPF loading condition, DOC inlet temperature, DPF inlet temperature, and sophisticated accountability, soot loading, and other factors such as occurrence of passive regeneration during normal operation. All active regeneration events were triggered by the engine control module (ECM), without any interference by the engine operator, except during exhaust system conditioning, where the DPF went into a "forced" active regeneration event that was triggered by the engine operator.

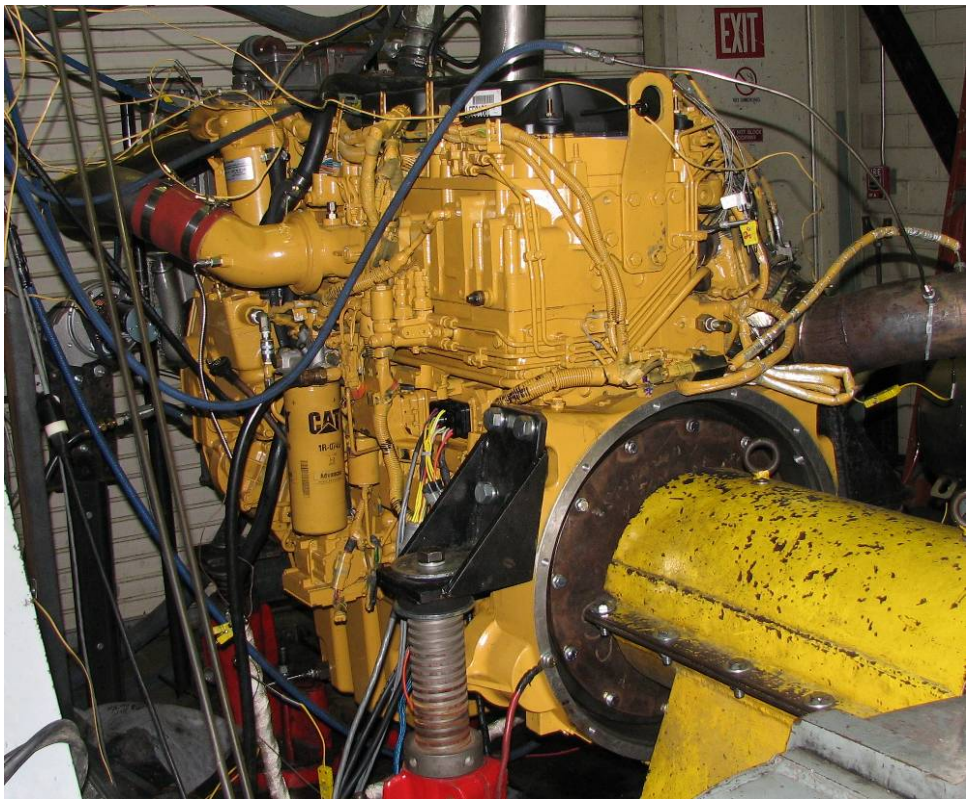


FIGURE 1. 2007 CATERPILLAR C13 ENGINE

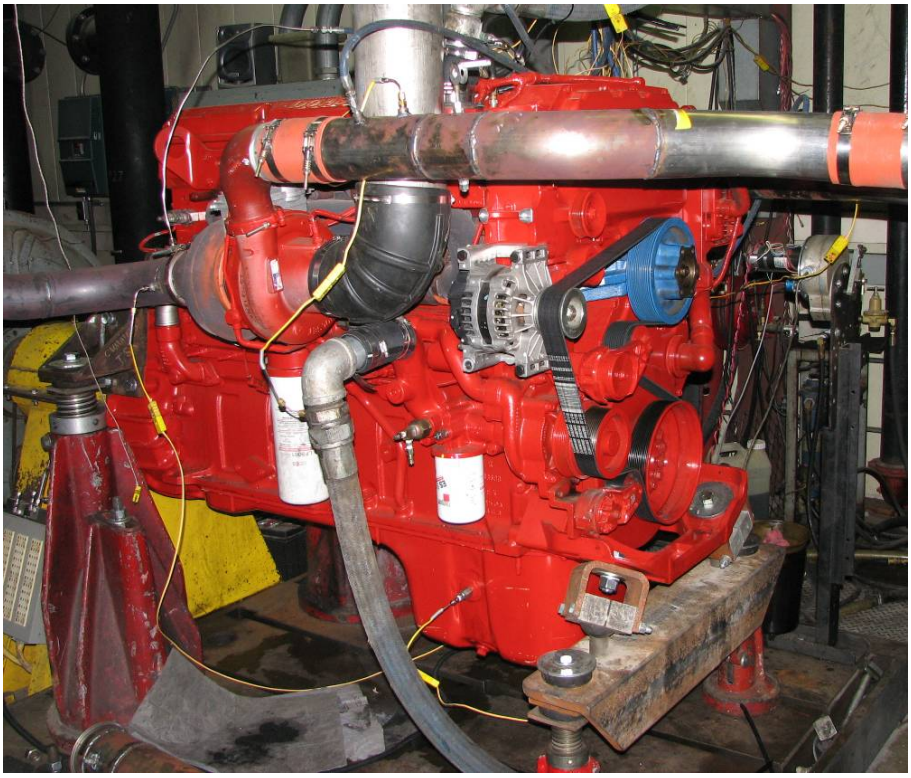


FIGURE 2. 2007 CUMMINS ISX ENGINE

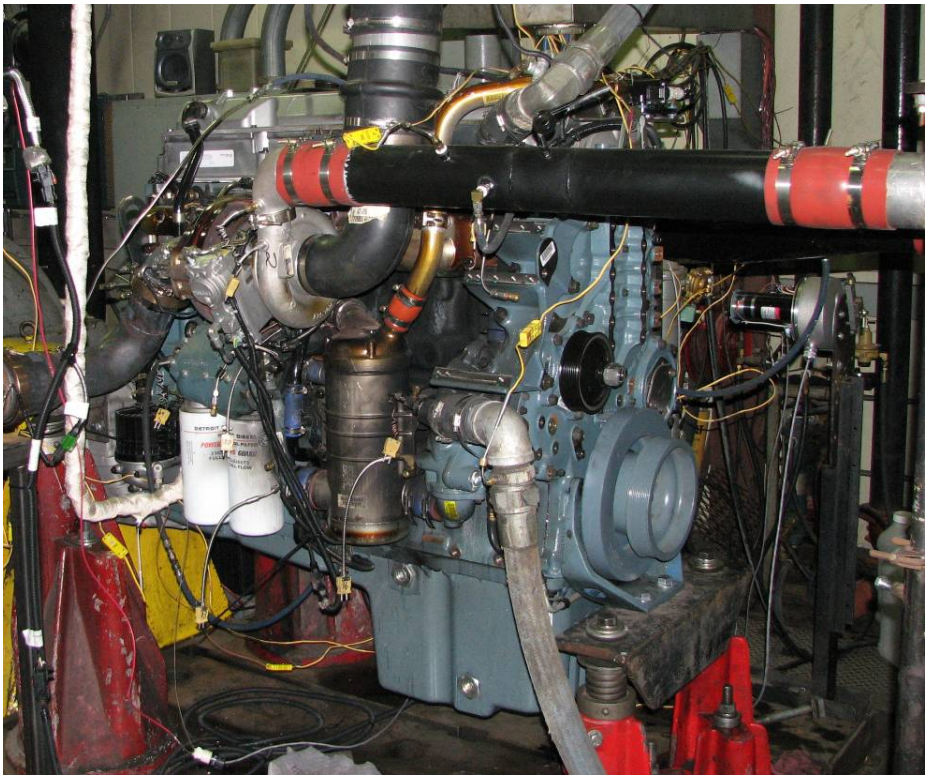


FIGURE 3. 2007 DETROIT DIESEL DDC SERIES 60 ENGINE

FIGURE 4. 2007 VOLVO POWERTRAIN MACK MP7

2.2 Fuel and Oil Properties

2.2.1 Fuel ASTM Properties and Elements

The ACES program fuel was provided by CRC through a commercial fuel supplier. It was an ultra-low sulfur diesel (ULSD) fuel that conformed to US EPA CFR Part 1065 ULSD fuel specifications. ASTM fuel properties are shown in Table 1. A sample was taken from the SwRI fuel tank where the ACES fuel was stored. The total aromatics content was 26.7 percent; the cetane number was 47.5; and the sulfur content was 4.50 ppm. Another sulfur analysis was performed on a fuel sample taken upstream of an engine fuel pump. The sulfur level was 5.20 ppm, which was comparable to that in the fuel tank, suggesting there was no sulfur contamination in the lines between the fuel tank and the engine fuel pump.

Table 2 shows the elements detected in the fuel. The most notable is the presence of residual lube oil elements such as calcium, phosphorus, and zinc. The presence of these elements was confirmed in two separate measurements. The sum of all measured elements' concentration in the fuel was about 9.5 ppm, with sulfur being the highest at 5.55 ppm, followed by phosphorus at 1.36 ppm, calcium at 1.38 ppm, zinc at 1.19 ppm, and lead at 6.28 ppb.

Mercury was not detected in the fuel.

TABLE 1. ASTM FUEL PROPERTIES

ASTM Test	Test Property / Description	Units	EM-6330-F Tank 37E
D86	Distillation		
	IBP	deg F	332
	10% Evaporated	deg F	420
	50% Evaporated	deg F	499
	90% Evaporated	deg F	585
	FBP	deg F	632
	Recovered	mL	97.6
	Residue	mL	1.5
	Loss	mL	0.9
D130	Copper Corrosion Strip	Rating	1A
D1319	Hydrocarbons by FIA		
	Aromatics	Vol %	26.7
	Olefins	Vol %	1.6
	Saturates	Vol %	71.7
D1796	Water & Sediment	mL	<0.02
D2500	Cloud Point	deg C	-24
D2622	Sulfur Content	wt %	<0.001
		ppm	<10
D5453	Sulfur Content	ppm	4.5
D4052	API Gravity at 60°F		33.8
	Specific Gravity at 60°F		0.8561
	Density at 15°C	grams/L	855.6
D445	Viscosity @ 40°C	cSt	2.613
D482	Ash Content	mass %	<0.001
D5291	Carbon Content	wt %	86.32
	Hydrogen Content	wt %	12.92
	Oxygen by Difference	wt %	0.76
D6079	Lubricity by HFRR		
	Major Axis	mm	0.38
	Minor Axis	mm	0.31
	Wear Scar Diameter	mm	0.345
	Wear Scar Description		evenly abraded oval
	Fuel Temperature	deg C	60
D613	Cetane Number		47.5
D93	Flash Point	deg F	149
	Flash Point	deg C	65
D976	Cetane Index (calculated)		44

TABLE 2. FUEL ELEMENTS

Element	Sample Result (mg/kg)	Reporting Limit[a] (mg/kg)	Method
Aluminum	<0.497	0.497	ICP
Antimony	<0.00198	0.00198	ICP/MS
Arsenic	<0.0494	0.0494	ICP/MS
Barium	<0.0794	0.0794	ICP
Beryllium	<0.00993	0.00993	ICP
Boron	<0.199	0.199	ICP
Cadmium	<0.00198	0.00198	ICP/MS
Calcium	1.38	0.497	ICP
Cerium	<0.000988	0.000988	ICP/MS
Chromium	<0.0497	0.0497	ICP
Cobalt	<0.000988	0.000988	ICP/MS
Copper	<0.0497	0.0497	ICP
Gallium	<0.000988	0.000988	ICP/MS
Gold	<0.00148	0.00148	ICP/MS
Indium	<0.000988	0.000988	ICP/MS
Iron	<0.497	0.497	ICP
Lanthanum	<0.000988	0.000988	ICP/MS
Lead	0.00628	0.00198	ICP/MS
Magnesium	<0.497	0.497	ICP
Manganese	<0.0497	0.0497	ICP
Molybdenum	<0.00494	0.00494	ICP/MS
Nickel	<0.00988	0.00988	ICP/MS
Palladium	0.00304	0.00198	ICP/MS
Phosphorus	1.36	0.199	ICP
Platinum	<0.000988	0.000988	ICP/MS
Potassium	<0.993	0.993	ICP
Rhodium	<0.000988	0.000988	ICP/MS
Rubidium	<0.000988	0.000988	ICP/MS
Selenium	0.00693	0.00494	ICP/MS
Silicon	<0.993	0.993	ICP
Silver	<0.00247	0.00247	ICP/MS
Sodium	<14.9	14.9	ICP
Strontium	0.00338	0.000988	ICP/MS
Sulfur	5.55	0.497	ICP
Thallium	<0.00198	0.00198	ICP/MS
Tin	0.00435	0.00198	ICP/MS
Titanium	<0.0497	0.0497	ICP
Tungsten	<0.00198	0.00198	ICP/MS
Uranium	<0.000988	0.000988	ICP/MS
Vanadium	<0.0497	0.0497	ICP
Yttrium	<0.0497	0.0497	ICP
Zinc	1.19	0.0497	ICP
Zirconium	<0.0497	0.0497	ICP

[a] Reporting limit is defined as 3 x the standard deviation of seven repeats of a NIST traceable concentration at the instrument minimum detection limit.

2.2.2 Lube Oil ASTM Analyses and Elemental Composition

Table 3 shows the ASTM analyses for the fresh lube oil, and for the used lube oil after 125 hours of degreening that was performed by the respective engine manufacturer. The dominant elements observed in the fresh lube oil were calcium (2268 ppm), phosphorus (1043 ppm), and zinc (1157 ppm). The used lube oil had higher levels of aluminum, barium, boron, copper, lead, magnesium, manganese, iron, and silicon, compared to the fresh oil, implying that these elements were accumulated in the oil during normal lubrication.

Mercury was not detected in the lube oil.

2.3 Sampling System

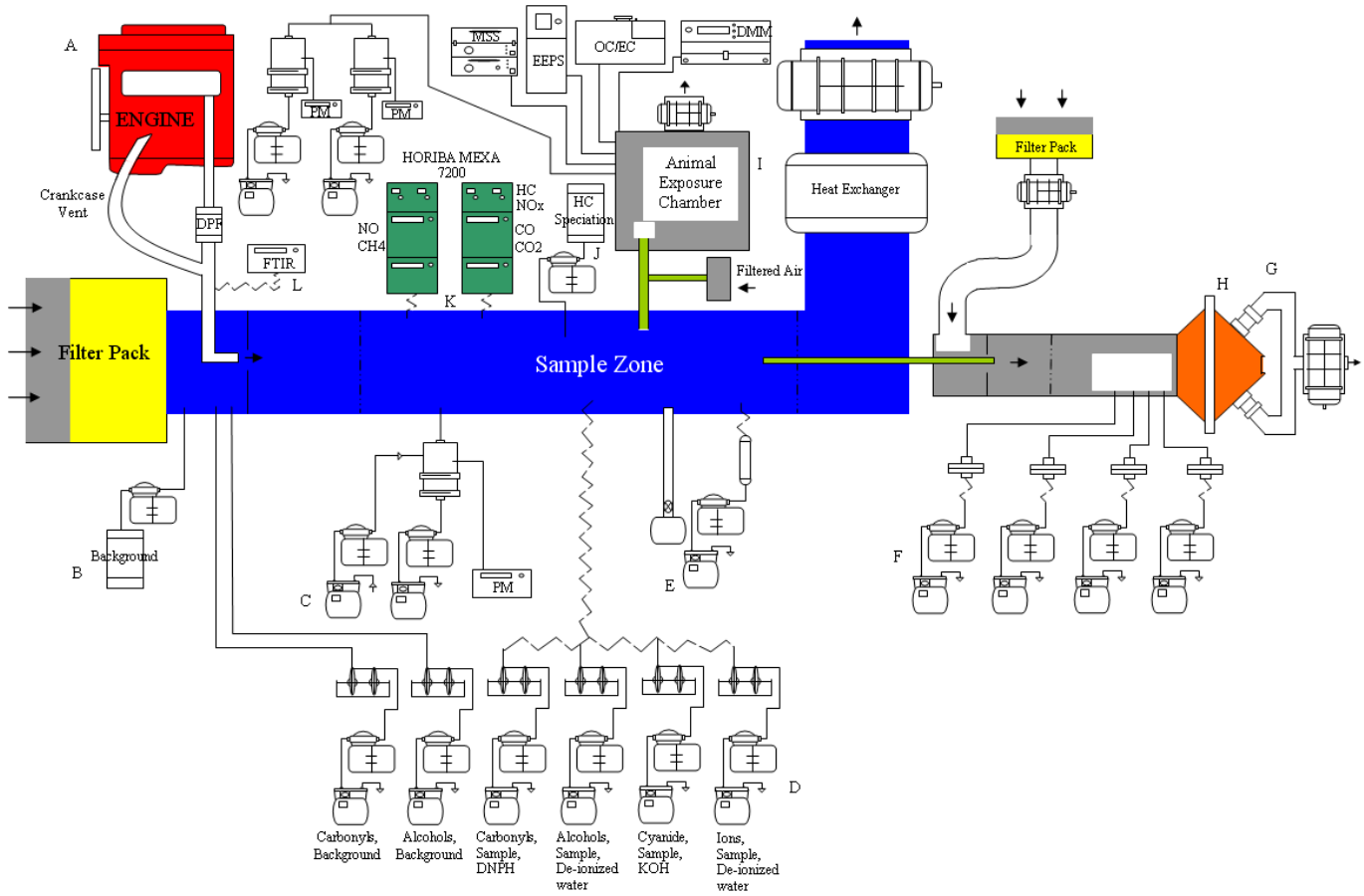
Figure 5 shows the overall sampling system of the experimental setup. Figure 6 shows a photograph of the exposure chamber along with the sample probes for the engine exhaust particle sizer (EEPS), Dekati Mass Monitor (DMM-230), micro-soot sensor (MSS), semi-continuous OC/EC, Teflo® filter sample train, and quartz filter sample train. The exposure chamber, provided by LRRI, was setup on the CVS tunnel. The nominal flow rate through the chamber was about 500 lpm. The 90 percent recovery residence time was on the order of four minutes, and the actual time to completely purge the chamber from any residuals was on the order of 20 minutes. Figure 7 shows the 8 x 10-inch Zefluor filter assembly followed by the four 4-inch XAD holders.

Referring to Figure 5, the dilution ratio between the constant volume sampler (CVS) tunnel and the exposure chamber was slightly less than 2:1, and the dilution ratio between the CVS tunnel and the 8 x 10 inch filter assembly was also about 2:1. The average dilution ratio between engine exhaust and CVS was about 20:1. Dilution ratio (DR) is defined as:

DR = (dilution air flow + sample flow)/(sample flow)

TABLE 3. LUBE OIL PROPERTIES FOR FRESH OIL AND AFTER 125 HOURS OF ENGINE AND DPF DEGREENING BY THE ENGINE MANUFACTURER

ASTM Test	Test Property / Description	Units	EM-3275-EO Fresh Lube Oil	EM-3276-EO Used Oil Engine A	EM-3278-EO Used Oil Engine B	EM-3277-EO Used Oil Engine C	EM-3282-EO Used Oil Engine D
D3524M	Fuel Dilution, Diesel	wt %	<0.3	<0.3	<0.3	1.2	<0.3
D4291	Glycol	ppm	<100	<100	<100	<100	<100
D445	Viscosity @ 100 °C	cSt	15.19	13.83	14.47	13.23	20.64
D445	Viscosity @ 40 °C	cSt	113.86	102.2	112.09	96.28	78.94
D4739	Total Base Number						
	Inflection	mg KOH/g	7.63	5.61	6.16	6.11	7.5
	Buffer	mg KOH/g	7.47	4.13	4.78	4.48	6.17
D5185	Element Analysis						
	Aluminum	ppm	2	3	2	2	2
	Antimony	ppm	<1	<1	<1	<1	<1
	Barium	ppm	<1	3	3	<1	<1
	Boron	ppm	<1	6	8	2	3
	Calcium	ppm	2268	2459	1879	2291	2350
	Chromium	ppm	<1	6	3	<1	2
	Copper	ppm	<1	12	13	8	96
	Iron	ppm	1	61	72	16	26
	Lead	ppm	<1	4	5	1	6
	Magnesium	ppm	5	8	261	32	125
	Manganese	ppm	<1	5	4	1	1
	Molybdenum	ppm	<1	9	<1	2	<1
	Nickel	ppm	<1	<1	<1	4	25
	Phosphorus	ppm	1043	978	1010	984	1125
	Silicon	ppm	3	36	36	23	68
	Silver	ppm	<1	<1	<1	<1	2
	Sodium	ppm	<5	10	8	6	7
	Tin	ppm	<1	4	4	1	4
	Zinc	ppm	1157	1209	1186	1133	1269
	Potassium	ppm	<5	<5	6	<5	<5
	Strontium	ppm	<1	<1	<1	<1	<1
	Vanadium	ppm	<1	<1	<1	<1	<1
	Titanium	ppm	<1	<1	<1	<1	<1
	Cadmium	ppm	<1	<1	<1	<1	<1
D664	Total Acid Number						
	Inflection	mg KOH/g	N/A	N/A	N/A	N/A	N/A
	Buffer	mg KOH/g	1.75	2.39	1.95	1.81	1.76
E168	FTIR (Oxidation & Nitration)						
	Diff. @ 5.8um	ABS/cm	0	2.86	0.18	2.14	0.37
	Diff. @ 6.1um	ABS/cm	0	0.28	0.18	0.09	0.09
TGA Soot	Residue	wt %	0.8	0.9	0.6	0.9	0.8
	Volatiles	wt %	99	98	97.1	98.8	98.9
	Soot	wt %	0.142	1.039	2.274	0.358	0.33



A 2007 Heavy-Duty Diesel Engine with DPF
B Background bag sample of dilution air for CO, CO_2, NO_X, NO, THC, CH_4, and C_2-C_{12} speciation
C Regulated PM following CFR Part 1065 using 47 mm Teflo filter
D Impingers for carbonyls, alcohols, ions, and cyanide ion
E Sorbent traps for nitrosamines and Summa canister for SVOC
F Auxiliary PM samples on 47mm filters for inorganic ions (Fluoropore Filter), XRF (Teflo Filter), and ICP-MS (Fluoropore Filter), DCI/GC (TX-40 filter)
G XAD traps for gas phase semi-volatile compounds: PAH, oxyPAH, nitroPAH, hopanes, steranes, carpanes, polar organics, high molecular weight alkanes and cycloalkanes, dioxins, furans
H Filter (8x10 inch Zefluor) for particulate-phase semi-volatile compounds: PAH, oxyPAH, nitroPAH, dioxins, furans, hopanes, steranes, carpanes, polar organics, high molecular weight alkanes and cycloalkanes, dioxins, furans
I Animal Exposure chamber (no animals present) PM mass using Teflo filter, size and number using EEPS, real time total PM using DMM-230, real-time soot using MSS, OC/EC collection using a pair of quartz filters, and semi-continuous OC/EC (very limited use)
J Proportional bag sample for hydrocarbon speciation of C_2 through C_{12} compounds
K Horiba MEXA 7200 for THC, CO, CO_2, NO_X , NO analyzer, and CH_4 analyzer
L FTIR for nitrogen compounds

FIGURE 5. OVERALL SAMPLING SYSTEM

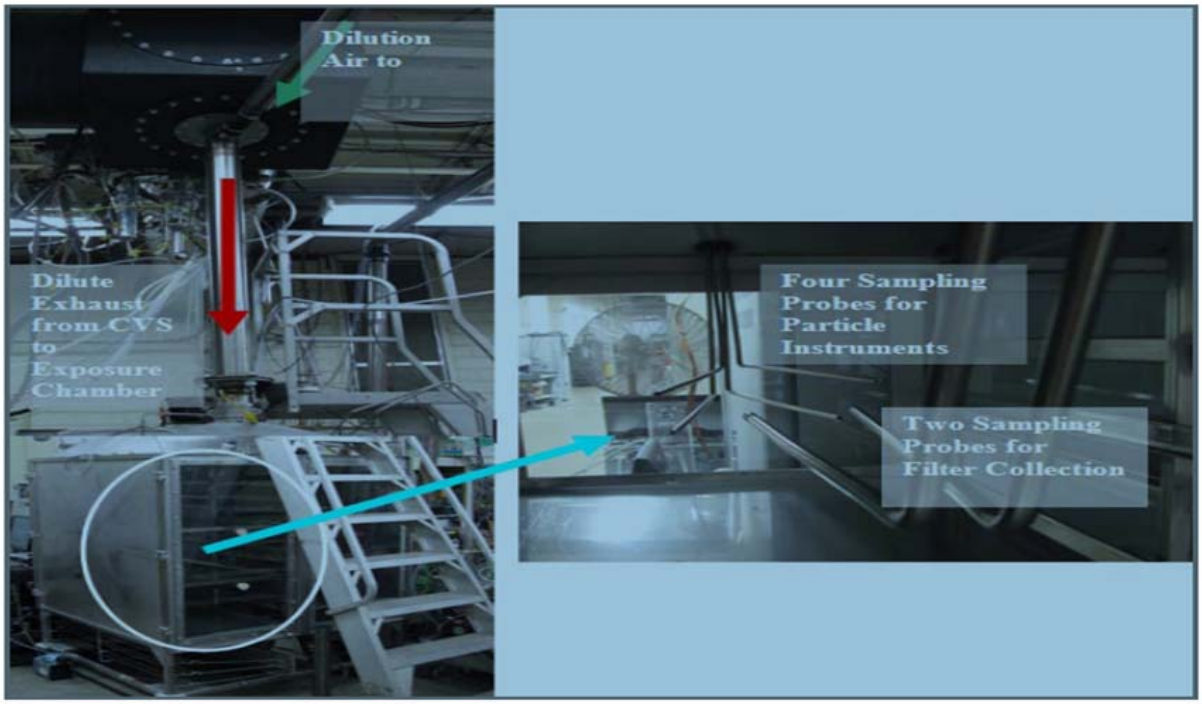


FIGURE 6. EXPOSURE CHAMBER

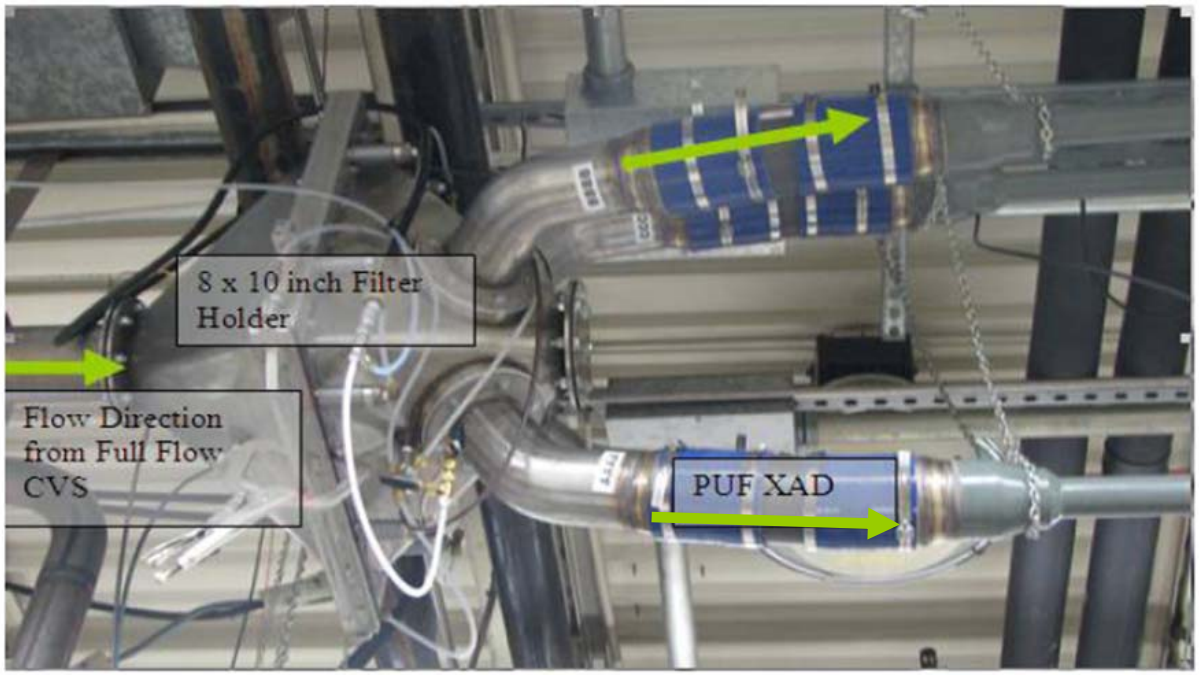


FIGURE 7. ZEFLUOR FILTER (8 X 10-INCH) AND XAD ASSEMBLY

3.0 TEST MATRIX

Table 4 shows the series of tests performed for each of the four candidate ACES engines. For the backup engine, the test included only regulated emissions using Modes 1, 3, and 5, and the hot-start FTP with and without blow-by at SwRI's San Antonio elevation, and at LRRI's, Albuquerque simulated elevation. Table 5 shows the detailed test matrix for each engine in the order it was tested, along with the length of each test cycle.

Table 6 shows the measurements done for each test performed on each engine. Figures 8 through 11 show the percent normalized torque and speed profiles for the different cycles used in ACES Phase 1. Normalized engine torque is defined as the actual torque over the maximum torque produced by the engine. Normalized engine speed is defined as (actual speed –warm-idle speed)/(rated power speed – warm-idle). Thus it is possible for the normalized speed to be over 100 percent, if the actual engine speed is higher than the rated speed.

TABLE 4. NUMBER OF REGULATED AND UNREGULATED EMISSIONS TESTS FOR EACH ENGINE

Cycle	Regulated Pollutants	Unregulated
Hot-Start FTP	3	[a,h]
Mode 1, rated speed, 100% load	3	[a,h]
Mode 3, rated speed, 50% load	3	[a,h]
Mode 5, peak torque speed, 100% load	3	[a,h]
Cold-Start FTP	1	[a,h]
Hot-Start FTP	6 [b]	6 [b]
Composite CARB HHDDE Cycle Mode 1, 2, and 5 (creep, transient, and idle), CARBX-ICT	2	2
Composite CARB HHDDE Cycle Mode 3 and 4 (cruise and high-speed cruise), CARBZ-CH	2	2
16-Hour Transient Cycle	3	3
Tunnel Blanks [c,d]	4 for Engine A and 3 for others	4 for Engine A and 3 for others
Tunnel Background [e,f]		1
Dioxins and Furans [g]		1

[a] Only real time particle size, number, total mass, and solid mass were performed for these tests.
[b] Three hot-start FTP runs with blow-by and three without blow-by.
[c] Tunnel blank is a 20-minute test run exactly like an engine test, except the engine is off.
[d] One tunnel blank after cleaning CVS tunnel but before running the Engine. A second tunnel blank after finishing the six hot-start FTP runs, which is also before starting the CARB composite modes. A third tunnel blank after finishing the CARB composite modes but before the 16-Hour transient cycle. A fourth tunnel blank after finishing the 16-Hour transient cycle.
[e] Tunnel background is a 16-Hour test where samples are taken from the dilution air immediately downstream of the CVS HEPA filter.
[f] Tunnel background dilution air was collected for 16 hours using 8 x 10 Zefluor filter followed by four XAD traps.
[g] Dioxins and furans were collected separately for 16 hours on Engines A, C, and D using 8 x 10 Zefluor filters followed by four XAD traps.
h Data were shared with each engine manufacturer to make sure that the engine emissions performance complied with the manufacturer's expectation and to get approval to proceed with the program.

TABLE 5. DETAILED TEST MATRIX FOR EACH ACES ENGINE

Test	Regulated Pollutants (No. of Runs)	Unregulated (No. of Runs)	Cycle Length
Tunnel Blank No. 1	1	1	20 minutes
Hot-Start FTP	3	[a]	20 minutes
Mode 1	3	[a]	20 minutes
Mode 3	3	[a]	20 minutes
Mode 5	3	[a]	20 minutes
Cold-Start FTP	1	[a]	20 minutes
Hot-Start FTP	6 [b]	6 [b]	20 minutes
Tunnel Blank No. 2	1	1	20 minutes
Composite CARB HHDDE Cycle Modes 1, 2, and 5 (idle, creep, transient), CARBx-ICT	2	2	39 minutes
Composite CARB HHDDE Cycle Modes 3 and 4 (cruise and high-speed cruise), CARBz-CH	2	2	48 minutes
Tunnel Blank No. 3	1	1	20 minutes
16-Hour Transient Cycle [c] (Three Repeats)	1 1 1	1 1 1	16 hours 16 hours 16 hours
Tunnel Blank No. 4	1	1	20 minutes
Tunnel Background No. 1	N/A	1	16 hours
Dioxins/Furans [d]			16 hours

[a] Only real time particle size, number, total mass, solid mass, and semi-continuous OC was performed for these modes.
[b] Three hot-start FTP runs with blow-by and three without blow-by.
[c] Each 16-Hour cycle (four runs of 4-hour segments), ran over a two-day period, at 8 hours per day.
[d] Dioxins/furans collection was performed on Engines A, C, and D only, along with a separate tunnel background for each run.

TABLE 6. SAMPLING/ANALYSIS MATRIX FOR REGULATED AND UNREGULATED EMISSIONS ON EACH ACES ENGINE

Parameter; Analytical Method(s)	Media	FTP Hot Start-W/O Blowby	FTP Hot Start-W Blowby	CARBx-ICT	CARBz-CH	16-Hr Transient Cycle	Tunnel Blank	16-Hr Tunnel Background	Background Corrected[a]?
Total Hydrocarbon (THC)	FID	3	3	2	2	3	3	0	Yes
Oxides of Nitrogen (NO_X)	Chemi-luminescent	3	3	2	2	3	3	0	Yes
Carbon Monoxide (CO)	NDIR	3	3	2	2	3	3	0	Yes
Particulate Matter (PM)	47 mm Teflon® membrane filter	3	3	2	2	3	3	0	No
NO_2	Chemi-luminescent	3	3	2	2	3	3	0	Yes
N_2O	FTIR	3	3	2	2	3	3	0	No
OC/EC	Quartz filter	3	3	2	2	3	3	0	No
Particle Size and Number	EEPS	3	3	2	2	3	3	0	No
Real Time PM	DMM-230	3	3	2	2	3	3	0	No
Metals, elements; ICP/MS	Fluoropore® filter + DI Water Impinger	3	3	2	2	3	3	0	No
Ca, P, S, K, Fe, Si, Na; EDXRF	Fluoropore® filter	3	3	2	2	3	3	0	No
Inorganic ions and acids; IC	Fluoropore® filter + DI Water Impinger	3	3	2	2	3	3	0	No
pH, H+; pH, Titration	DI Water Impinger	3	3	2	2	3	3	0	No
Cyanide, Cr(VI) ; GC-ECD, ICP/MS	KOH Impinger	3	3	2	2	3	3	0	No
SO_2; IC	H_2O_2 Impinger	3	3	2	2	3	3	0	No
Gas phase hydrocarbons (C2–C12a;GC-FID	Tedlar® Bag	3	3	2	2	3	3	0	Yes
Carbonyl compounds; HPLC-UV	DNPH Impinger	3	3	2	2	3	3	0	Yes
Alcohols; GC-FID	DI Water Impinger	3	3	2	2	3	3	0	Yes
Dioxins and Furans; HRGC/HRMS	Zefluor® Filter + XAD® Cartridge	0	0	0	0	1	0	1	Yes
Selected VOCs; GC/MS	SUMMA® Canister	3	3	2	2	1	3	0	No
PAH; GC/MS	Zefluor® Filter + XAD® Cartridge	3	3	2	2	3	3	1	No
nitroPAH; GC/MS		3	3	2	2	1	3	1	No
Hopane/Steranes/Carpanes; GC/MS		3	3	2	2	3	3	0	No
Alkanes, Alkenes, Alkynes, Cyclo- and branched (C14-C40); GC/MS		3	3	2	2	1	3	0	No
Polar compounds, Oxygenated PAH, Organic Acids; GC/MS		3	3	2	2	1	3	1	No
Nitrosamines; GC/MS	Thermosorb®	3	3	2	2	1	3	0	No

[a] Background corrected means that a sample of the background dilution air taken from downstream of the HEPA filter in the CVS tunnel is analyzed for the same species concentration measured in the dilute exhaust, and then subtracted from the dilute exhaust species concentration using the following equation: Xbgc=Xm –(1-1/DR)*Xbg, where Xbgc is the corrected concentration, Xm is the measured concentration, and Xbg is the background concentration of the species of interest.

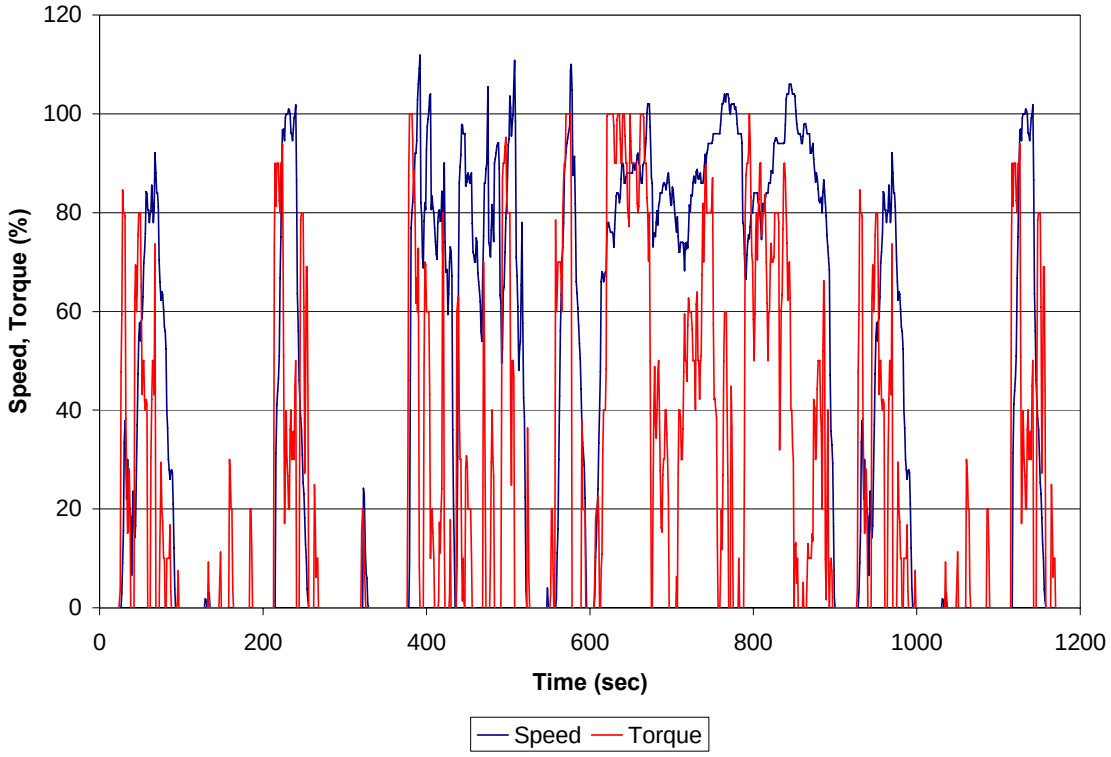


FIGURE 8. FTP TRANSIENT CYCLE NORMALIZED TORQUE AND SPEED PROFILES

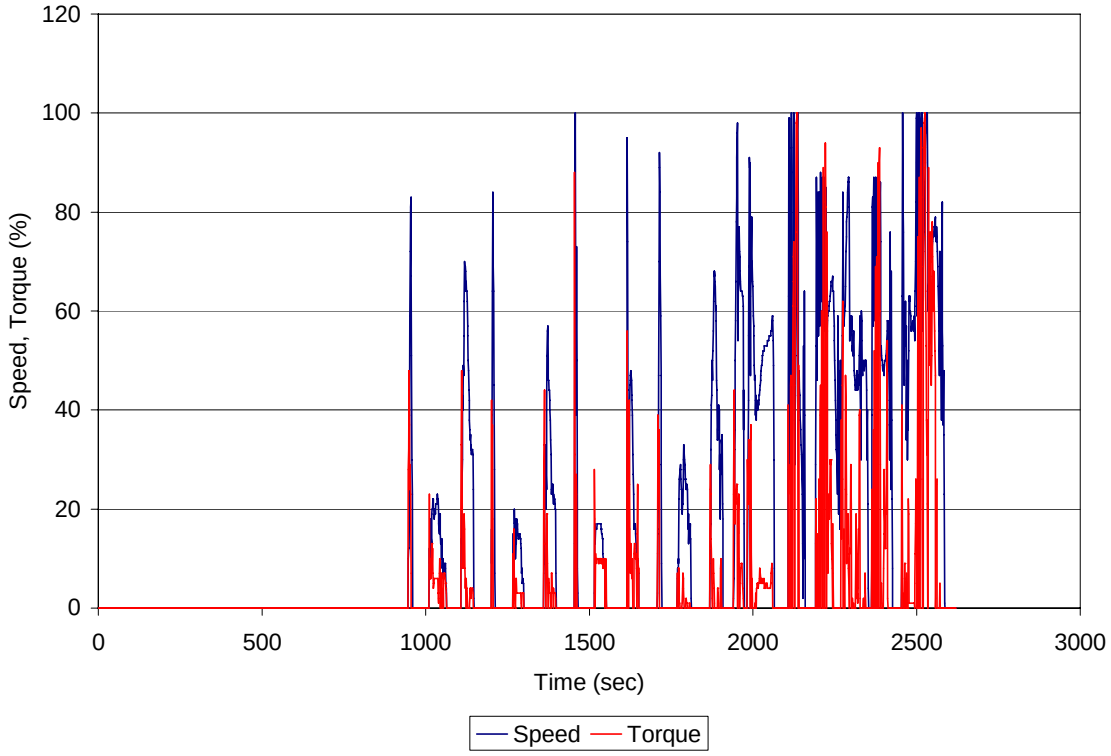


FIGURE 9. CARBX-ICT CYCLE NORMALIZED TORQUE AND SPEED PROFILES

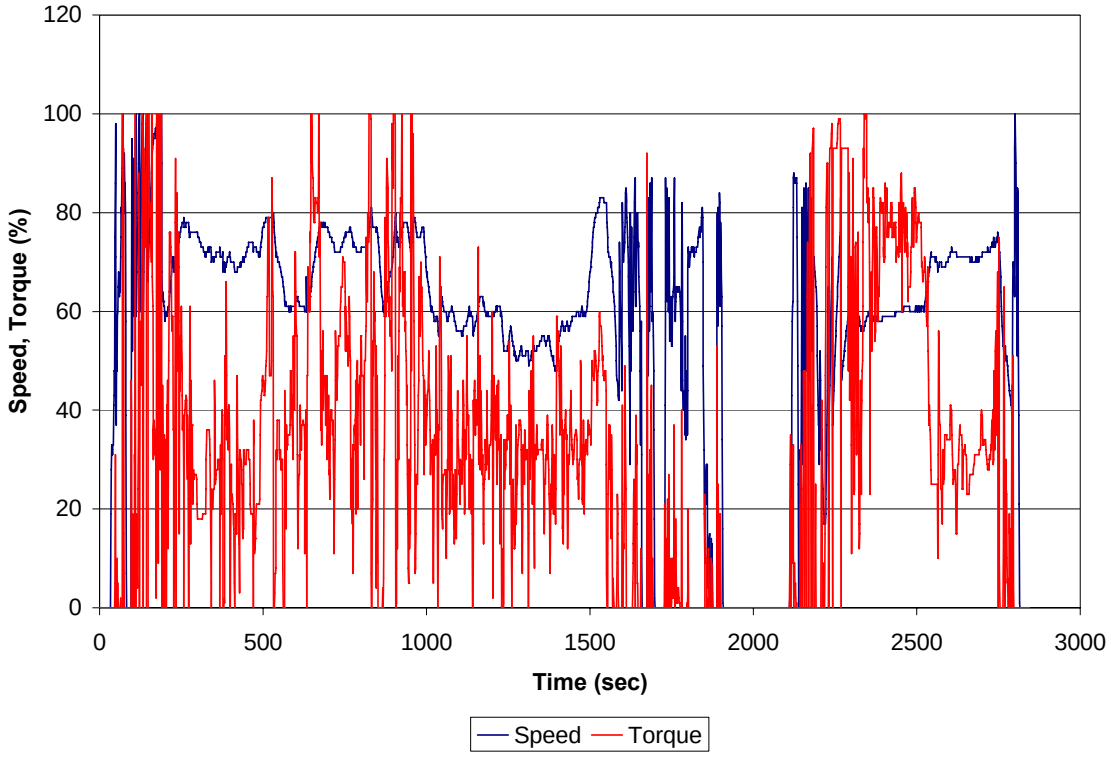


FIGURE 10. CARBZ-CH CYCLE NORMALIZED TORQUE AND SPEED PROFILES

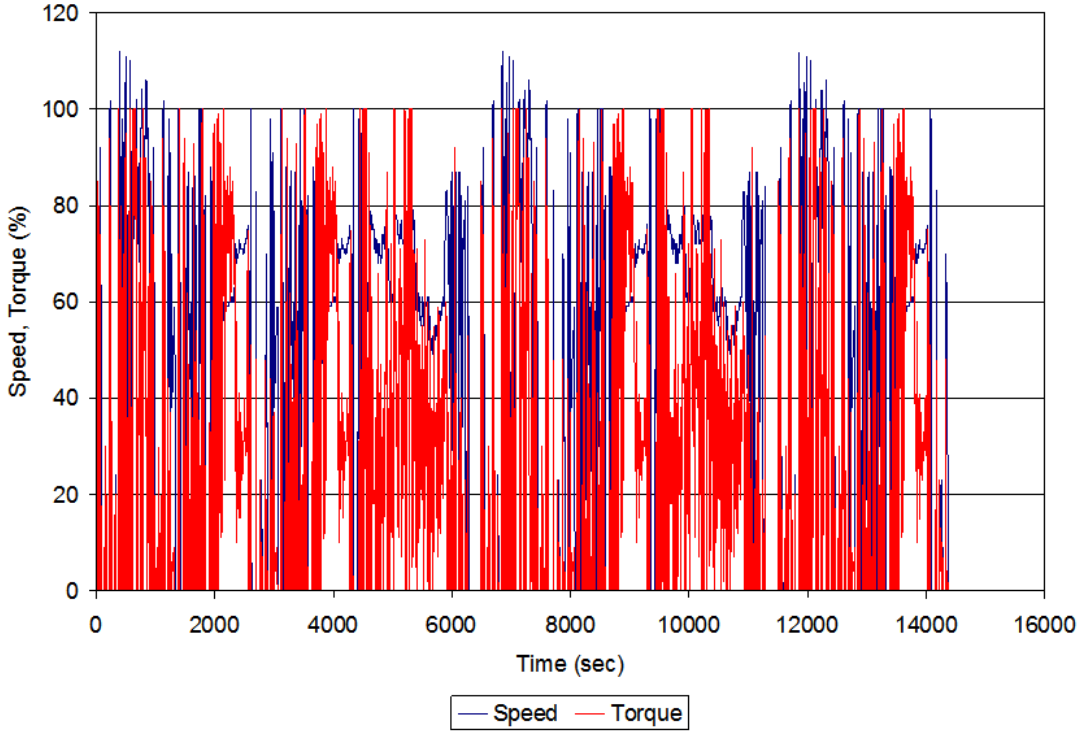


FIGURE 11. FOUR-HOUR REPEATED SEGMENT OF THE NORMALIZED TORQUE AND SPEED PROFILES FOR THE 16-HOUR CYCLE

4.0 PROCEDURES

Tasks performed prior to and during engine testing are described in this section.

4.1 Full Flow Constant Volume Sampler Tunnel Cleanup and Conditioning

In Project E-66, it was learned that the PM emissions reported using tunnel blank filter collection without engine operation is similar to that reported using a diesel engine equipped with a DPF. It is also known from previous work and from Project E-66 [4] that the history of operation of the full flow CVS using different technology engines affects the time required for unregulated and PM emission measurement stabilization. For example, during Project E-66, it took a total of 10 hours of continuous engine operation at rated power to stabilize PM emissions. Therefore, prior to test cell engine installation for the ACES project, a thorough full flow CVS tunnel cleaning was performed. Due to the very low PM and unregulated emission levels expected from the 2007 engines, it was important to clean the internal surface of the tunnel to remove any adsorbed material that could interfere with PM and unregulated emissions measurements. Volatile and semi-volatile materials that may have adsorbed onto the internal surface of the tunnel or the surface soot layer could desorb during an engine run or when sampling a tunnel blank. The tunnel was completely removed from the test cell and cleaned using a small amount of Simple Green detergent and power washed and rinsed using water. Figures 12 and 13 shows the CVS sample zone before and after cleaning.

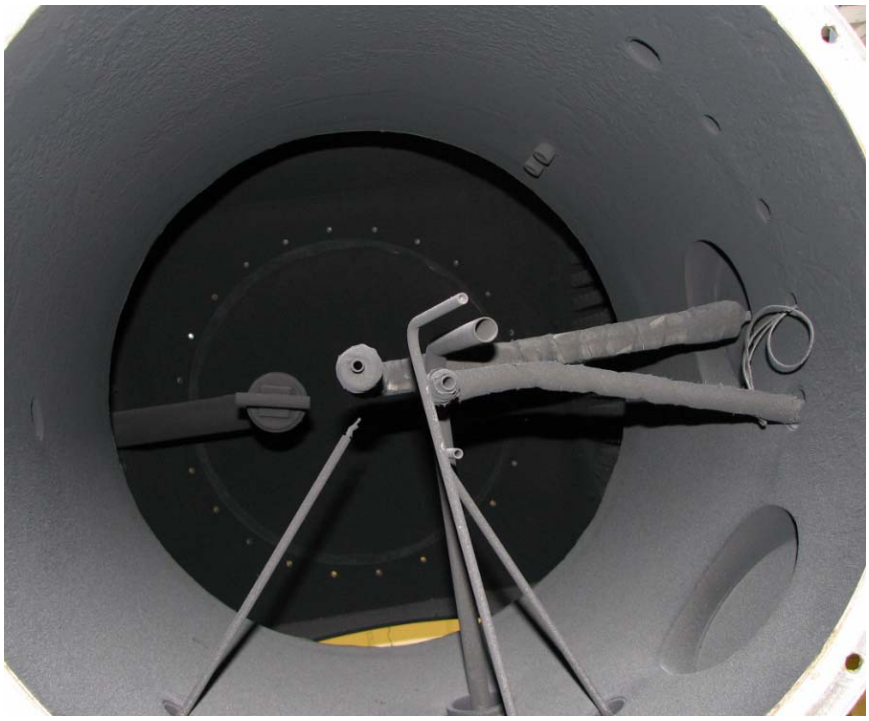


FIGURE 12. CVS SAMPLE ZONE BEFORE CLEANING

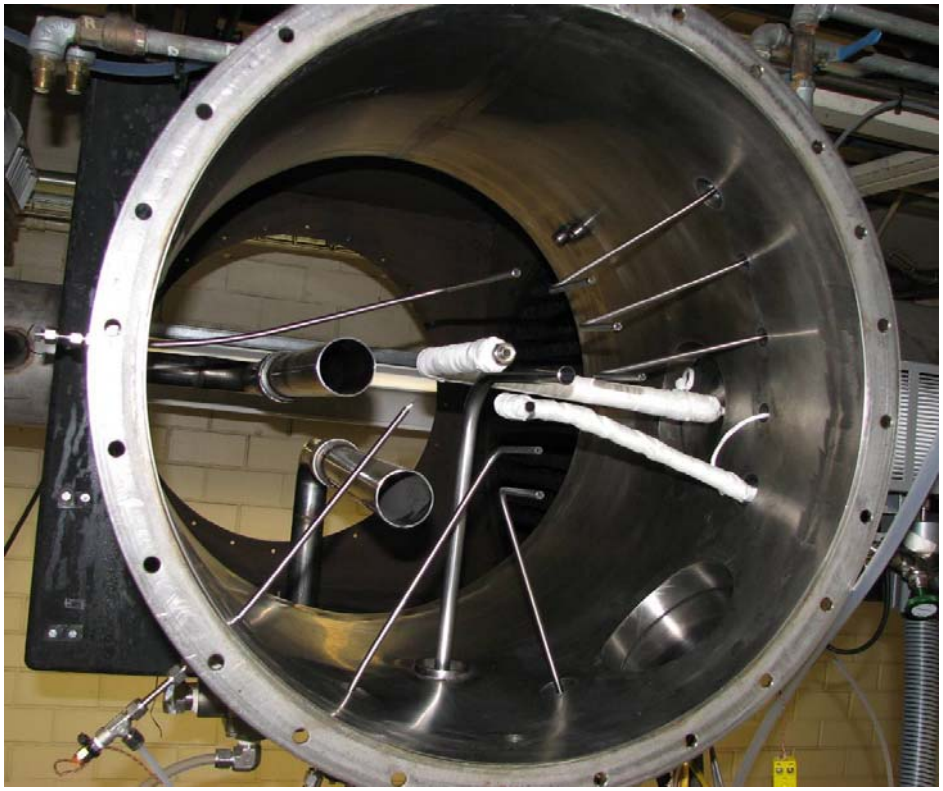


FIGURE 13. CVS SAMPLE ZONE AFTER CLEANING

After the tunnel was cleaned, reassembled, and verified via propane recovery checks, the first 2007 engine, Engine A, was installed in the test cell with new stainless steel exhaust piping to the CVS. The length of the exhaust pipe between the DPF exit and the CVS inlet was on the order of 12 feet. This section was heated or insulated. Next, the engine was power validated to make sure it performed as expected by the manufacturer. Engine and sampling system conditioning was then performed by running the engine at rated power while operating the sampling systems for a period of 10 hours. The test sequence for subsequent engines did not include tunnel cleaning, but did include tunnel conditioning, similar to the first engine.

4.2 Regulated Emissions Measurements

Regulated emissions including NO_x, CO, and NMHC were measured in accordance with CFR Part 1065 using a Horiba MEXA-7000 series emission bench. NO_x was measured using the chemiluminescent detection method. CO was measured using the non-dispersive infrared detection method, and NMHC was determined by taking the difference between THC and methane measurements using the flame ionization detection method.

Regulated PM was measured using a single Teflon® membrane (Pall Teflo®) filter, 47 mm in diameter that was maintained at $47^{o}C \pm 5°C$ in accordance with CFR Part 1065. The filter face velocity was maintained close to 100 cm/sec. The filter room used for filter conditioning and weighing was maintained in accordance with CFR Part 1065 requirements. The filter weighing procedure included three filter pre and three filter post weights. The averages of the pre and post weights were used to determine the filter weight gain. In Project E-66, SwRI

demonstrated a filter weighing variability of less than ±2.5 μg (one standard deviation) using Teflon® membrane filters.

4.3 Sampling and Analysis of Unregulated Emissions

Analysis of unregulated emissions was performed at SwRI and at DRI. A summary of analytical responsibilities and notes on methodology are presented in Table 7.

SwRI determined ions by ion chromatography, metals and other elements by inductively coupled plasma/mass spectroscopy (ICP/MS) and cold vapor atomic absorption spectroscopy (CVAAS); and selected air pollutants by gas chromatography/mass spectroscopy (GC/MS). Speciation of C_1 through C_{12} hydrocarbons including alcohols, aldehydes, and ketones was performed using GC and high performance liquid chromatography (HPLC). Fourier transform infrared spectroscopy (FTIR) was used primarily for continuous monitoring of N_2O. SwRI utilized dual chemiluminescent NO_x detectors, one operating in NO mode and one in NO_x mode, so an accurate determination of NO_2 could be made as the difference between NO_x and NO. Cyanide samples were collected in impingers and analyzed by GC-ECD. Dioxins and furans samples were collected on an 8 by 10-inch filter followed by four XAD traps, and were analyzed in accordance with EPA Method 8290 using high resolution gas chromatography (HRGC) and high resolution mass spectroscopy (HRMS).

For the animal exposure chamber, real-time particle size distribution was measured using the TSI engine exhaust particle sizer (EEPS); real time PM mass was measured with the Dekati DMM-230; real time soot mass was measured by the AVL micro-soot sensor (MSS); and organic carbon was measured using the Sunset Laboratories OC/EC instrument with Zefluor® filters. During engine and CVS conditioning and stabilization, OC/EC quartz filters were also used with the animal exposure chamber using a primary and a backup 47 mm quartz filter. The quartz filters were then analyzed for OC/EC by DRI.

DRI provided analyses for hopanes, steranes, polar compounds, heavy alkanes ($>C_{12}$), polycyclic aromatic hydrocarbons (PAH), nitroPAH, oxyPAH, and organic acids. DRI also provided analyses for OC/EC and nitrosamines, as well as a subset of metals and elements that were analyzed by energy dispersive X-ray fluorescence (EDXRF) spectroscopy.

4.3.1 Filter and XAD Sample Collection for Chemical Analysis

For the collection of filter and XAD® samples for chemical analysis, SwRI used a large supplemental secondary dilution tunnel that permitted the use of an 8 by 10-inch (203 by 254 mm) Zefluor® filter followed by four 4-inch diameter XAD® cartridges that were sampling in parallel, downstream of the filter. The nominal flow rate through the filter and four XAD® cartridges was about 1700 slpm.

TABLE 7. SUMMARY OF ANALYSIS METHODOLOGY AND RESPONSIBILITY

Analyte Class	Notes	Method	Laboratory
Metals and Elements	47 mm Teflo® filter, 28 slpm	ICP/MS, ICP	SwRI
Ions	Water Impinger (4 slpm), 47 mm TX-40 filter (28 slpm)	IC	SwRI
Fuel/Oil PM Contribution	47 mm TX-40 filter, selected samples only, 28 slpm	DFI/GC	SwRI
Hydrogen Ion	H^+, water impinger, 4 slpm	Titration	SwRI
Cyanide Ion	Impinger, 4 slpm	GC/ECD	SwRI
VOC ($C_1 - C_{12}$)	Tedlar ® bag	GC/FID	SwRI
Carbonyl compounds	DNPH impingers, 4 slpm	HPLC	SwRI
Alcohols	DI water impinger, 4 slpm	GC/FID	SwRI
Selected VOCs	Solid sorbent, 1 slpm (nitromethane, nitropropane, hydrogen sulfide, carbonyl sulfide)	GC/MS	SwRI
Dioxins/Furans	One sample per engine, on 16-hr integrated sample, gas- and particle-phase extracts analyzed together, 1700 slpm	GC/MS	SwRI
Real Time Total PM	1Hz, 10 slpm	DMM-230	SwRI
Real Time Soot	1Hz, 2 slpm	MSS	SwRI
Real Time PM Size and Number	1Hz, 10 slpm	EEPS	SwRI
Metals and Elements	47 mm Teflo® filter, 28 slpm	EDXRF	DRI
PAH	Gas- and particle-phase extracts analyzed together, except 16-Hour integrated sample, 1700 slpm	GC/MS	DRI
NitroPAH	Gas- and particle-phase extracts analyzed together, except 16-Hour integrated sample, 1700 slpm	GC/MS	DRI
Hopanes, Steranes	Gas- and particle-phase extracts analyzed together, except 16-Hour integrated sample, 1700 slpm	GC/MS	DRI
Polar compounds	Gas- and particle-phase extracts analyzed together, except 16-Hour integrated sample, 1700 slpm	GC/MS	DRI
Other SVOC (C_{14}-C_{40})	Gas- and particle-phase extracts analyzed together, except 16-Hour integrated sample, 1700 slpm	GC/MS	DRI
Nitrosamines	Thermosorb N®, 1 slpm	GC/MS	DRI
OC/EC	Quartz filters, 58 slpm	TOR and TOT	DRI

The breakthrough volume of semi-volatile and volatile components for XAD® adsorbent is not known. However, XAD® resins are known to have much higher collection efficiency for naphthalene and other volatile PAH than polyurethane foam (PUF) alone.[5, 6] Experiments performed at the University of California, Los Angeles with three layers of XAD®, 10 g each, showed that the first layer collected 93-97 percent of naphthalene and other semi-volatile PAH, such as fluoranthene and pyrene (24-hrs sampling, 113 LPM). Thus, 20 g of XAD® should be sufficient to collect most of the compounds of interest. However, to check the validity of this approach, primary and backup XAD® cartridges were used and extracted separately, and all primary and backup XAD® cartridges were analyzed for breakthrough for the 16-Hour cycle. For the rest of the cycles, backup XAD® cartridges were analyzed for three FTP runs performed on the first engine tested, Engine A. The remainder of the extracts for the rest of cycles and engines were saved by DRI, but not analyzed.

4.3.2 Ions and Inorganic Acids

Samples were collected in impingers containing a potassium hydroxide solution and analyzed for cyanide ion via GC-ECD (Electron Capture Detector). The GC-ECD procedure for cyanide analysis was developed at SwRI and published in EPA document 600-2-80-068, "Analytical Procedures for Characterizing Unregulated Emissions from Vehicles Using Middle-Distillate Fuels," 1980.

Hexavalent chromium Cr(VI) was collected using a modified EPA Method 061 and analyzed by EPA 7199. Similar to cyanide, an impinger filled with a potassium hydroxide solution was used to collect the Cr(VI), and the impinger solution was subsequently analyzed by ion chromatography.

Anions and cations (NH_4^+, NO_2^-, NO_3^-, SO_4^{2-}), and inorganic acids (HNO_2, HNO_3, H_2SO_4) samples were collected on Teflon membrane filters, and by water impingers. Filters were extracted to remove the analytes of interest, and the extract was analyzed using ion chromatography (IC). Impinger solutions were analyzed by IC as well; however, it was not possible to differentiate between anions and cations from ionic species versus inorganic acids. In addition, it should be noted that NO_2 passing through water may form HNO_2 and HNO_3. A titration to determine the H^+ concentration was performed, and the pH was measured.

4.3.3 Metals and Elements

Filter samples were analyzed with ICP/MS and EDXRF to ensure that analyses for all required elements were covered with adequate detection limits. Total Br, Cl, S, K, Na, P, Ca, Fe, and Si were determined by energy dispersive x-ray fluorescence (EDXRF).

The particulate filters for ICP/MS metals analysis were digested with high purity acids. The majority of the metals were analyzed via ICP/MS using EPA SW-846 Method 6020 to get the lowest possible detection limits. The ICP/MS method has been used for analysis of motor vehicle samples by several investigators [7]. Blank filters were analyzed to assess any contribution from the media and the extraction/digestion solutions.

The ICP/MS instrument is standardized using NIST traceable standard reference materials. Prior to analyzing any samples, the standardization is verified with a second NIST traceable reference material. This second standard is from a different lot or manufacturer than the first standardization material. Immediately after the second standard is run, a blank is run to verify the zero setting. The second standard is required to be within 90-110 percent recovery of the certified value. The absolute value of the check blank is required to be below the reporting limit for the analyte. If either condition has not been met, the analysis would be terminated and the instrument re-standardized and re-checked. The standard and check blank are re-run after every 10 samples, and at the end of the run to ensure that the instrument remains in control throughout the entire run. If a standard falls out of the control limits, the analysis is terminated, the instrument re-standardized, and all samples since the last compliant standard are re-run. As an internal check, duplicate analyses are performed on approximately ten percent of samples, selected at random.

Tunnel blank samples were collected for each analyte as designated in Table 6.

4.3.4 Selected Volatile Organic Compounds

Samples for the selected volatile organic compounds (nitromethane, nitropropane, hydrogen sulfide, carbonyl sulfide), were collected in sample bags and sorbent traps specific to the analytes. They were analyzed by GC/MS. SwRI Test and Analysis Procedures TAP 0404014 and 0404015 were utilized. TAP 0404014 is based upon EPA method TO-15, which uses a combination of multi-sorbent tubes and cryogenic focusing for sample concentration with subsequent analysis by GC/MS. TAP 0404015 is based upon SW-846 Method 5040 and covers the determination of volatile organic compounds (VOCs), collected on Tenax® and Tenax®/charcoal sorbent cartridges using a volatile organic sampling train (VOST). This method was utilized in conjunction with an appropriate analytical method, SW-846 8240, Volatile Analysis by GC/MS. Because a majority of gas streams sampled using VOST will contain a high concentration of water, the analytical method is based on the quantitative thermal desorption of volatile compounds from the Tenax® and Tenax®/charcoal traps with analysis by purge and trap GC/MS. The contents of the sorbent cartridges are spiked with an internal standard/surrogate solution and thermally desorbed with organic free nitrogen or helium, bubbled through organic-free water and trapped on an analytical absorbent trap. After the purge, the analytical trap is dry purged for two additional minutes, then heated rapidly to 240°C, with the carrier flow reversed so the effluent flow from the analytical trap is directed to the GC/MS. The VOCs are separated by temperature-programmed gas chromatography and detected by low-resolution mass spectrometry. The concentrations of VOCs are calculated using the internal standard technique. Tunnel blank samples were collected for each analyte as specified in Table 6.

4.3.5 Hydrocarbon Speciation of C_2 Through C_{12} Compounds

Vapor phase C_2 to C_{12} hydrocarbon species were sampled with Tedlar® bags from the primary dilution tunnel. Analysis of these samples was conducted within five to 10 minutes after collection to avoid degradation of the more reactive species, such as 1,3-butadiene. Carbonyls and alcohols were sampled from the primary dilution tunnel via impingers. Alcohols were collected in impingers filled with deionized water, and carbonyls with a solution of

dinitrophenylhydrazine (DNPH) in acetonitrile. To minimize degradation, aldehyde samples were analyzed as soon as the sampling was completed.

The analytical procedures used for conducting hydrocarbon speciation (C_2 to C_{12} hydrocarbons, aldehydes and ketones, and alcohols) are similar to the CRC Auto/Oil Phase II protocols. With these methods, exhaust emissions samples are analyzed for the presence of more than 200 different exhaust species. Four GC procedures and one HPLC procedure are used to identify and quantify compounds. A brief description of these procedures is given below.

The first GC procedure uses a 15 m x 0.53 mm I.D. DB-WAX (1μm film) pre-column and a 50 m x 0.53 mm I.D. (10 femtometer film) Alumina PLOT/KCI (Carbopack®) column to permit the separation and determination of exhaust concentrations of C_1-C_4 individual hydrocarbon species, including ethane, ethylene, acetylene, propane, propylene, propadiene, butane, trans-2-butene, 1-butyne, and cis-2-butene. Bag samples were analyzed using a gas chromatograph equipped with a flame ionization detector (FID). The gas chromatograph system utilizes two analytical columns. The carrier gas is helium. An external multiple component standard in zero air is used to quantify the results. Detection limits for the procedure are on the order of 5 ppbC in dilute exhaust for all compounds.

The second GC procedure uses a 60 m x 0.32 mm I.D. (10 μm film) DB-1 column to provide separation and exhaust concentrations for more than 100 C_5-C_{12} individual HC compounds. Bag samples are analyzed using a gas chromatograph equipped with a flame ionization detector (FID). The GC system utilizes a FID, a pneumatically operated and electrically controlled valve, and an analytical column. The carrier gas is helium. An external multiple component standard in zero air is used to quantify the results. Detection limits for the procedure are on the order of 10 ppbC in dilute exhaust for all compounds.

The third GC procedure uses a separate system configured similarly to the second GC method to determine individual concentrations of benzene and toluene according to CRC Auto/Oil Phase II Protocols. The third GC utilizes a 30 m x 0.25 mm I.D. (0.25 μm film) DB-5 column instead of a DB-1 column.

An HPLC with a Zorbax® octadecasilane (ODS) column was utilized for the analysis of aldehydes and ketones. Samples were collected in impingers with a solution of DNPH in acetonitrile. For analysis, a portion of the acetonitrile solution was injected into a liquid chromatograph equipped with an ultraviolet (UV) detector. External standards of the aldehyde and ketone DNPH derivatives were used to quantify the results.

For alcohols, sample collection was performed by bubbling diluted exhaust through deionized water in a series of impingers. An aliquot of the solution was subsequently analyzed for alcohols using a gas chromatograph equipped with a flame ionization detector. External standards were used to quantify the results.

For each sample set, a background (dilution air) sample was collected. Tunnel blank samples were collected for each analyte as specified in Table 6.

4.3.6 Dioxins and Furans

As discussed above, sampling for dioxins and furans utilized an 8 by 10-inch Zefluor® filter followed by four 4 inch XAD cartridges. This approach was required to achieve the extremely low detection limits required for these analytes. The analytical protocol followed for analysis of dioxins and furans (PCDD or PCDF) is EPA Method 8290. The instruments used included a VG AutoSpec high resolution gas chromatograph/high resolution mass spectrometer (HRGC/HRMS), a Fisons AutoSpec Ultima HRGC/HRMS, and a Micromass AutoSpec Ultima HRGC/HRMS. The sample was spiked with a solution containing specified amounts of each of the nine isotopically ($^{13}C_{12}$) labeled PCDDs/PCDFs listed in the method. The sample was then extracted according to a matrix-specific extraction procedure and analyzed.

A tunnel background sample was collected as specified in Table 4.

4.3.7 Elemental Carbon/Organic Carbon

SwRI used the Sunset Laboratories semi-continuous instrument with a Zefluor® filter for OC analysis during tunnel conditioning and stabilization. SwRI used this method extensively during Project E-66. The use of this instrument was intended to support the sampling system conditioning efforts by providing information on the stability of OC emissions. These efforts were not successful because the engines went into active DPF regeneration at least two times during the 10 hours of conditioning. Due to the high temperatures experienced during active regeneration, the 10 hours of conditioning was deemed to be sufficient prior to starting the official testing.

For OC/EC collection and analysis during official testing, SwRI did not use the semi-continuous OC/EC analyzer. Instead, SwRI collected PM from the animal exposure chamber on a primary and a backup quartz filter. These filters were analyzed for OC/EC by DRI using thermal optical reflectance (TOR) and thermal optical transmittance (TOT).

4.3.8 Particulate- and Gas-Phase Organic Compounds

Among the many particulate and semi-volatile organic compounds (SVOC) are the following groups of compounds: PAH, oxyPAH, nitroPAH, hopanes/steranes, higher molecular weight alkanes, cycloalkanes, higher molecular weight aromatics, and certain polar organic compounds. Sampling was performed with an 8 by 10 inch Zefluor PM filter followed by four, 4-inch traps containing XAD-4 resin. For analysis, a Varian 4000 Ion Trap in electron impact (EI) mode, and a Varian 1200 triple quadrupole GC/MS operating in negative chemical ionization (CI) mode was used for nitroPAH compounds. Negative CI offers a superior sensitivity for the analysis of nitroPAH (approximately 100 times higher than EI or positive CI) and other compounds with electron-withdrawing substituents, but not for regular PAH and hydrocarbons. Because nitroPAH are expected to be present at a very low level, this superior sensitivity and selectivity was necessary.

Sampling materials were prepared by DRI and shipped to SwRI. Prior to sampling, XAD-4 resins were extracted with methanol followed by dichloromethane (CH_2Cl_2), using an Accelerated Solvent Extractor (Dionex 3000). The cleaned resin was dried in a vacuum oven heated to 40 ºC and stored in sealed glass containers in a clean freezer. The filters were cleaned

by sonification in CH_2Cl_2 for 30 minutes, followed by another 30-minute sonification in methanol. The filters were then dried, placed in aluminum foil, and labeled. Each batch of pre-cleaned XAD-4 resin and approximately 10 percent of pre-cleaned filters was checked for purity by solvent extraction and GC/MS analysis of the extracts. The XAD-4 resins were assembled into glass cartridges (20 g of XAD) and stored in a clean freezer prior to shipment to SwRI.

All samples returned from SwRI were stored in a freezer prior to extraction. All samples were extracted within two weeks of being received at DRI.

Prior to extraction, the following deuterated internal standards were added to each filter and XAD sorbent: naphthalene-d8, biphenyl-d10, acenaphthene-d10, phenanthrene-d10, anthracene-d10, pyrene-d12, benz(a)anthracene-d12, chrysene-d12, benzo[e]pyrene-d12, benzo[a]pyrene-d12, benzo[g,h,i]perylene-d12, coronene-d12, cholestane-d6, hexadecane-d34, eicosane-d42, hexatriacontane-d74, 2-nitrodiphenyl-d9, 1-nitropyrne-d9, benzoic-d6 acid, phthalic 3,4,5,6-d4 acid, hexanoic-d11 acid, heptadecanoic-d33 acid, and myristic-d27 acid.

Filters and XAD-4 resins were extracted with dichloromethane using the Dionex ASE followed by acetone extraction under the same conditions. The dichloromethane extraction method has been reported to yield high recovery of PAH [8] and nitroPAH [9,10]. Dichloromethane extraction followed by acetone also gave good recovery for PAH, aliphatic hydrocarbons, cycloalkanes, hopanes, steranes, and polar organic compounds.

All extracts were then concentrated by rotary evaporation at 35°C under gentle vacuum to approximately 1 mL and filtered through a 0.2 μm PTFE disposal filter device (Whatman Pura discTM 25TF), rinsing the flask 3 times with 1 mL dichloromethane and acetone (50/50 by volume) each time. The extract was split into two fractions (polar and non-polar analyses) and was solvent exchanged to acetonitrile under ultra-high purity nitrogen.

The extracts were analyzed first by GC/MS for higher molecular weight (C>15) aliphatic hydrocarbons and cycloalkanes. Subsequently, the extracts were pre-cleaned by the solid-phase extraction technique. Superclean LC-SI SPE cartridges (Supelco) were sequentially eluted with hexane, and hexane/benzene (1:1). The hexane fraction contains the non-polar aliphatic hydrocarbons (alkanes), and hopanes and steranes, and the hexane/benzene fraction contains PAH and nitroPAH. These two fractions were concentrated to approximately 100 μL and analyzed by GC/MS for hopanes, steranes, PAH and oxyPAH. For nitroPAH, the extracts were further pre-cleaned by the solid-phase extraction technique, using aminopropyl (NH2) SPE cartridges (Waters), with sequential elution with hexane/DCM, 98/2 v/v and hexane/DCM 80/20 v/v as described by Bamford et al. [11]. For nitro- and dinitroPAH analysis, these fractions were further cleaned by semi-preparative normal-phase high performance liquid chromatography (HPLC) technique (Waters). The Chromegabond Amino Cyano 25 cm x 9.6 mm column (ES Industries, West Berlin, NJ) and isocratic elution with 20 percent DCM in hexane were used [11]. The fraction corresponding to nitro- and dinitroPAH was collected and analyzed by negative ion chemical ionization GC/MS. The fraction for the polar analysis was derivatized using a mixture of bis(trimethylsilyl)trifluoroacetamide and pyridine to convert the polar compounds into their trimethylsilyl derivatives for analysis of organic acids, phenol and cresol.

The filters and XAD® extracts were analyzed by GC/MS, using a Varian CP-3800 GC equipped with a CP8400 auto sampler and interfaced to a Varian 4000 Ion Trap. Due to the high sensitivity of Ion Trap MS, it was used for analysis of all gas-phase and particulate phase organic compounds, with the exception of the nitroPAH compounds, which utilized the electron impact (EI) ionization method. Injections (1 µL) were made in the splitless mode onto a 30m 5 percent phenylmethylsilicone fused-silica capillary column (DB-5ms, J&W Scientific or equivalent). Quantification of the individual compounds was obtained by the selective ion storage (SIS) technique, monitoring the molecular (or the most characteristic) ion of each compound of interest and the corresponding deuterated internal standard. Calibration curves for the GC/MS quantification were made for the most abundant and characteristic ion peaks of the compounds of interest using the deuterated species most closely matched in volatility and retention characteristics as internal standards. National Institute of Standards and Technology (NIST) Standard Reference Material (SRM) 1647 (certified PAH) with the addition of deuterated internal standards and of those compounds not present in the SRM (i.e., oxyPAH, nitroPAH, hopane, steranes, carpanes, hydrocarbons, cycloalkanes) were used to make calibration solutions. A six- to eight-level calibration was performed for each compound of interest and the calibration check (using median calibration standards) was run every 10 samples to check for accuracy of analyses. If the relative accuracy of measurement (defined as a percentage difference from the standard value) was greater than 20 percent, the instrument was recalibrated.

NitroPAH was analyzed using the Varian 1200 triple quadrupole gas chromatograph/mass spectrometer (GC/MS/MS) system with a CP-8400 auto sampler. The tandem MS/MS system allows for structural elucidation of unknown compounds with precursor, product and neutral loss scan. The GC interface allows for sensitive analyses of complex mixtures in electron impact (EI) as well as positive and negative chemical ionization (CI) mode. Negative CI offers superior sensitivity for the analysis of nitroPAH (approximately 100 times higher than EI or positive CI) that could be emitted from combustion sources, including motor vehicle engines. The sensitivity of this instrument in full scan EI/MS mode is approximately 1 pg/µl with a 20:1 signal-to-noise ratio (S/N). In EI/MS SIM mode it reaches 50 fg/ul with a 10:1 S/N. For negative CI, 10 fg/ul of octafluoronaphthalene gives a S/N of 20:1. This superior sensitivity offers the advantage of analyzing small samples collected during a short sampling time.

4.3.9 Nitrosamines

Nitrosamines were collected on Thermosorb/N adsorbent cartridges using a Teflon® sample probe. Samples were quantified using modified EPA Method TO-7, which specifies analysis by GC/MS. The cartridge samples were collected from the primary dilution tunnel. The cartridges were eluted with a mixture of 25 percent methanol and 75 percent dichloromethane. The first 1.8 ml was collected for the GC/MS analysis, using the Varian 1200 GC/MS/MS system operating in negative CI mode. Injections (1 ul) were made in the splitless mode onto a CP WAX 51 capillary column (25 m long, 0.25 mm id). Quantification of the individual compounds was obtained by the multiple ion detection (MID) technique, monitoring the molecular ion of each compound of interest and the corresponding deuterated internal standard.

4.3.10 Real Time PM Size, Number, Total and Soot Mass

Particle size distribution and number concentration were measured using a TSI EEPS, as shown in Figure 14. The instrument covers a particle size range from 5.6 nm to 560 nm, and reports the full size distribution measurement on a 10 Hz basis. The principle of operation is to charge particles and mobilize them to deposit on a series of electrometers, each representing a narrow particle size range. The current reading from each electrometer is converted to number concentration.

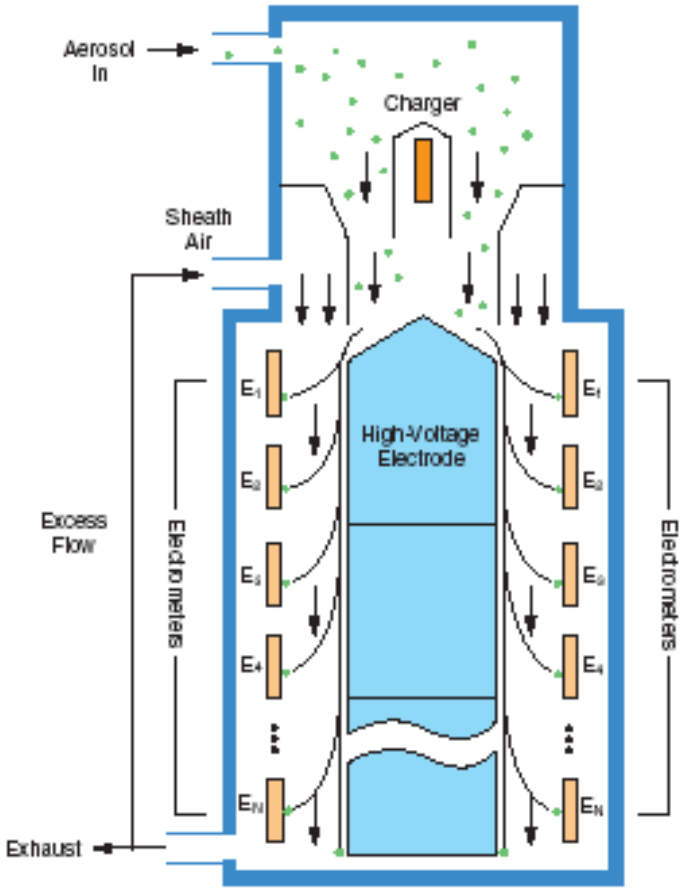


FIGURE 14. TSI ENGINE EXHAUST PARTICLE SIZER (EEPS)

The Dekati DMM-230, shown in Figure 15, was used for real time total particle mass emission measurement on a 1 Hz basis. The principle of operation is to charge particles and deposit the sub-30 nm particles on an electrometer by electric mobility and the rest of the particles on a series of electrometer stages by inertial impaction, with each electrometer representing a narrow aerodynamic size range. The current reading from each electrometer stage is converted into mass concentration using an average apparent density. The apparent density is determined by overlaying the calculated mobility diameter size distribution on top of the aerodynamic diameter size measured distribution.

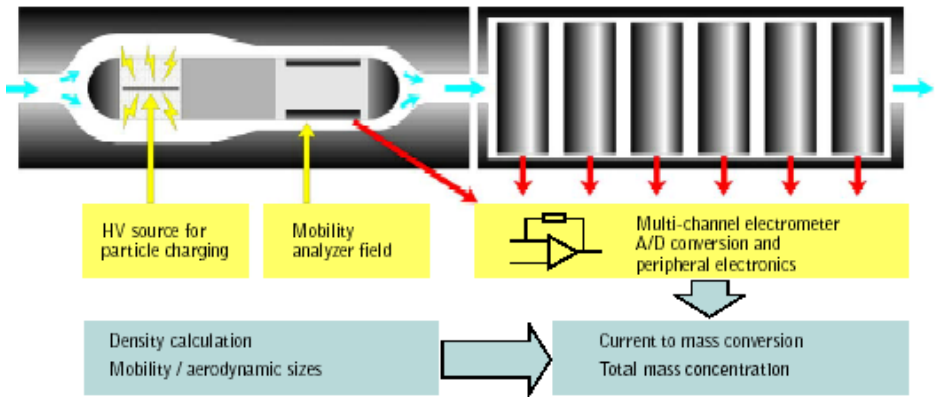


FIGURE 15. DEKATI MASS MONITOR (DMM-230)

An AVL MSS shown in Figure 16 was used for real time soot mass emission measurement on a 1 Hz basis. This instrument is widely used in engine emission activities focusing on the measurement of soot. The principle of operation is to slightly heat soot particles with a pulsed laser beam so the soot particles can generate a sound wave that can be detected by a sensitive microphone. The magnitude of the electric signal generated by the microphone indicates the mass concentration of soot.

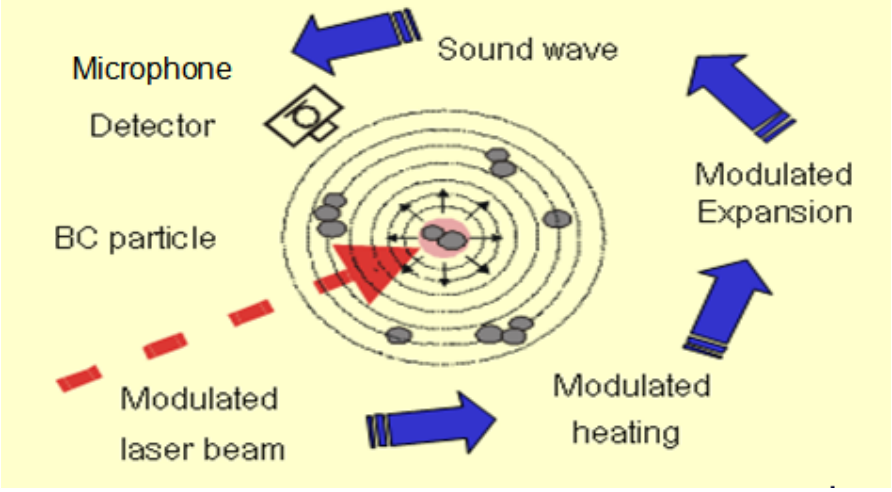


FIGURE 16. AVL MICRO-SOOT SENSOR (MSS)

4.4 Step-by-Step Engine Testing Procedures

Table 8 shows the general step-by-step procedures that were followed throughout the ACES program, including the various QA/QC checks used. Step 3 (tunnel blanks) were performed after tunnel clean up prior to testing Engine 1, and prior to testing Engine 5. The other steps applied to all engines. Each engine was conditioned for 20 minutes at rated engine power prior to performing the hot-start transient cycles. The engine was also conditioned for 20 minutes at rated engine power prior to performing one series of the CARB HHDDE 5-modes cycles.

TABLE 8. STEP-BY-STEP PROCEDURES

Steps	Action Items
1	Clean CVS tunnel (done only once before the first engine)
2	Set CVS flows as required
3	*Generate a tunnel blank with a sampling time of 20 minutes using a Teflo filter in accordance with Part 1065*
4	Perform all necessary calibration required under CFR Part 1065
5	Install engine in test cell
6	Power validate engine and compare the performance with that declared by the manufacturer
7	If Step 6 is acceptable, proceed to Step 8, otherwise resolve the performance issues
8	Condition engine and sampling system at near rated engine power for a period of 10 hours
9	Generate an engine torque map at wide open throttle in accordance with CFR Part 1065
10	Run practice FTP transient cycles, and perform the necessary tuning to pass cycle statistics
11	Perform three hot-start transient cycles and measure regulated emissions, particle size, number and mass using EEPS, DMM-230, and MSS if available
12	Perform three repeats of Mode 1, Mode 3, and Mode 5 taking regulated emissions with selected particle measurements as in Step 11
13	Compare all regulated brake specific emissions with those determined by the manufacturer
14	Resolve the differences, if any, between SwRI and the manufacturer results and proceed with the emission characterization
15	Condition engine and sampling system by performing an "forced" active DPF regeneration prior to an overnight soak
16	Perform one cold-start FTP while sampling for regulated and selected particle measurement as in Step 11
17	Perform three hot-start FTP cycles (without blow-by) with 20 minutes engine-off soak between cycles. Sample for all regulated and unregulated emission species on each run.
18	Condition engine and sampling system by performing an "forced" active DPF regeneration
19	Repeat Step 17, but route engine blow-by to the exhaust in accordance with CFR Part 1065
20	*Generate a tunnel blank with a sampling time of 20 minutes similar to that in Step 3*
21	Condition engine and sampling system by performing an "forced" active DPF regeneration
22	Perform two runs of CARBx-ICT for regulated and unregulated emissions with 20 minutes engine-off soak period between runs
23	Condition engine and sampling system by performing an "forced" active DPF regeneration
24	Perform two runs of CARBz-CH for regulated and unregulated emissions with 20 minutes engine-off soak between runs
25	*Generate a tunnel blank with a sampling time of 20 minutes, with similar measurements to that in Step 3*
26	Condition engine and sampling system by performing an "forced" active DPF regeneration
27	Perform one 16-Hour transient cycle over a period of two days. Sample for all regulated and unregulated emissions. On day 1, run a hot-start for the first 4-hour segment, bring the engine to low idle for 15 minutes, and run another 4-hour segment, then shut down engine. On day 2, run a cold-start for the first 4-hour segment, bring the engine to low idle for 15 minutes, and then run another 4-hour segment, and shut down engine.
28	Repeat Step 27 twice
29	Repeat Step 27 one more time and collect for dioxins/furans analysis only. (All engines, except Engine B)
30	*Generate a tunnel blank with a sampling time of 20 minutes while sampling as in Step 3*
31	*Generate a tunnel background for 16 hours while sampling as in Step 27*
32	*Generate a tunnel background for 16 hours while sampling as in Step 29*
33	*Repeats Steps 4 through 32 with Engine B, but skip Step 29*
34	*Repeats Steps 4 through 32 with Engine C*
35	*Repeats Steps 4 through 32 with Engine D*

5.0 RESULTS

This section includes all the regulated and unregulated emission species results. Active DPF regeneration took place during some of the runs, as indicated in Table 9. Active DPF regeneration is a state that is defined by the engine control module (ECM) attempting to regenerate the DPF by exhaust fuel injection (dosing), or by starting an exhaust burner, depending on the technology used. An active regeneration state may include times where dosing is not active due to a low exhaust temperature or other conditions. Although fuel injection may not be occurring, it is likely that the engine is still operating differently in an attempt to facilitate the regeneration process by intake air throttling or changing the EGR and VGT positioning. For engines using exhaust fuel injection, these measures are necessary to raise the exhaust temperature to the point where fuel injection may be enabled and the regeneration can proceed. An active regeneration state may include multiple, separate dosing events until the DPF is "clean." The length of the regeneration event thus is likely to depend on the duty cycle of the engine. More higher load (and therefore higher temperature) operation will allow the regeneration to proceed quicker, resulting in a shorter overall regeneration time. It should be emphasized that this does not necessarily apply to every regeneration method.

Engine C had a DPF crack failure during CARBx-ICT and CARBz-CH cycles; these data were excluded from the emission comparison results. The engine controller provided by the manufacturer was not properly configured for the test cell environment, and consequently would clear the DPF soot load status between tests. It is believed that the DPF failed when an uncontrolled regeneration event was triggered with an underestimated DPF soot load. Upon further investigation, the engine manufacturer identified a problem with the fuel injection system, and recommended replacing the engine. The engine was replaced with an identical engine, and testing resumed for the 16-Hour tests. The CARBx-ICT and CARBz-CH cycles were not re-run due to budgetary and project timing constraints.

Table 9 indicates when active regeneration occurred and how many times it occurred. The time listed for active regeneration is the time between the beginning and end of a regeneration state for the 16-Hour cycle. The regeneration state time listed could mean that exhaust fuel dosing is on continuously, or switched on and off, depending on engine load, speed, exhaust temperature, or other conditions. Thus, when an active regeneration state is triggered during the FTP cycle, it does not mean that active regeneration was occurring continuously for the entire FTP cycle time. It could be "on" for 1 to 5 minutes or for the entire time, again, depending on each engine manufacturer's strategy.

Because all the data in the results section will be reported on a brake-specific basis, Table 10 shows the average conversion multiplier for converting from brake-specific emissions to other units of interest such as fuel specific emissions, emissions rate, or concentration. The conversion multipliers were calculated based on the experimental data. For example, if the average brake-specific emission for Engine A, FTP-w, is 1 g/hp-hr for a particular compound, it will be 5.16 g/kg of fuel, 98.8 g/hr, and 172 mg/m³ in the exhaust. If one is interested in determining the average concentration in the exposure chamber for this particular compound, one can then divide the exhaust concentration over the exposure chamber dilution ratio (46.15). It should be noted that the conversion from brake-specific emissions (g/hp-hr) to emission rate (g/hr) is based simply on the average power (hp) of the cycle.

TABLE 9. NUMBER OF ACTIVE REGENERATIONS PER TEST

Test Cycle	Number of Cycles	Number of Regenerations per Cycle			
		Engine A	Engine B	Engine C	Engine D
FTP-w	3	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0
FTP-wo	3	1[c], 1[c], 1[c]	0, 0, 0	0, 0, 0	0, 0, 0
CARBx-ICT	2	0, 0	0, 0	DPF Crack	0, 0
CARBz-CH	2	0, 1[c]	0, 0, 0	DPF Crack	0, 0
16-Hour	3	1, 1, 1	2, 2, 3	1, 1, 1	1, 1, 1
Approximate Time of an Active Regeneration State, minutes (16-Hour Cycle Only)		75[a]	90[a]	30[a]	30[b]

[a] During this time, active regeneration via exhaust fuel injection or via an exhaust burner may or may not be on all the time. E.g. During the 75 minutes with Engine A, exhaust fuel injection may shut off at low exhaust temperature and may come back on at high temperature.
[b] For Engine D, this is the actual time of the active regeneration
[c] Dosing occurred during a portion of each FTP, but under the same active regeneration state.

TABLE 10. CONVERSION MULTIPLIER FROM BRAKE-SPECIFIC EMISSIONS TO OTHER UNITS

Test Name	Average Exhaust Temp, °C	Average Exhaust Flow, m³/hr	Average CVS Dilution Ratio	Average Exposure Chamber Dilution Ratio	Average 8x10 Dilution Ratio	Conversion from Brake Specific to Fuel Specific (g/hp-hr to g/kg of fuel)	Conversion from Brake Specific to Emission Rate (g/hp-hr to g/hr)	Conversion from Brake Specific to Concentration (g/hp-hr to mg/m³)
Engine A								
FTP-w	242	572	27.9	1.65	1.60	5.16	98.8	172.6
FTP-wo	246	572	28.7	1.63	1.62	4.89	98.3	171.7
CARBx-ICT	156	216	47.1	1.67	1.61	3.41	17.0	78.7
CARBz-CH	296	673	13.4	1.65	1.60	4.81	137.4	204.1
16 HR	273	550	24.6	1.62	1.89	5.31	108.4	197.0
Engine B								
FTP-w	239	513	29.9	1.60	1.84	4.94	94.7	184.7
FTP-wo	245	507	30.1	1.60	1.87	5.24	94.1	185.7
CARBx-ICT	99	275	34.6	1.70	1.77	4.49	19.6	71.4
CARBz-CH	299	588	16.0	1.73	1.90	5.64	138.5	235.4
16 HR	274	525	21.8	1.52	1.95	5.15	110.8	211.0
Engine C								
FTP-w	230	362	64.1	1.49	1.38	5.23	81.8	226.2
FTP-wo	230	359	64.1	1.49	1.56	5.27	81.0	225.7
CARBx-ICT	131	131	88.2	1.52	1.96	3.81	17.6	134.3
CARBz-CH	277	507	25.6	1.46	1.93	5.69	139.1	274.7
16 HR	260	402	42.7	1.59	2.10	5.64	105.5	262.3
Engine D								
FTP-w	262	482	42.4	1.57	1.86	5.52	101.5	210.5
FTP-wo	264	478	43.5	1.57	1.97	5.54	101.3	211.8
CARBx-ICT	138	262	39.3	1.61	1.94	4.21	20.5	78.4
CARBz-CH	314	594	19.5	1.59	1.84	5.82	147.5	248.2
16 HR	299	527	29.5	1.60	1.95	5.55	118.0	223.9

Based on Table 10, if the average brake-specific emissions for CARBx-ICT are a factor of 1.4 higher than the average emissions for the FTP, CARBz-CH, and the 16-Hour cycle, then the fuel-specific emissions for CARBx-ICT would be at levels similar to the other cycles because of the CARBx-ICT cycle's higher fuel consumption rate. CARBx-ICT brake-specific emissions, on average, would need to be a factor of 5.5, 8.3, and 6.5 higher than the brake-specific emissions for the FTP, CARBz-CH, and 16-Hour cycle, respectively, for the g/hr emissions rate to be the same. Thus, it is important to take into consideration these conversion factors when comparing emissions among the different engines and cycles.

If one assumes a typical fuel mileage (FM) for heavy-duty trucks, e.g. 6 miles per gallon, one can convert the brake specific emissions (BSE) from g/hp-hr to g/mile by using the following equation:

$$g/mile = [BSE]/[(BSFC/FD*FM]$$

BSFC is the measured brake specific fuel consumption in lb/hp-hr, and FD is the fuel density in lb/gallon (7.12 lb/gallon). The g/mile calculation conversion factor is not shown in Table 10. This was done to differentiate calculations based on measured values, such as those reported in Table 10, from calculations based on assumptions, such as the equation above.

Table 10 also includes the values of average exhaust temperature, exhaust flow rate, CVS dilution ratio, exposure chamber dilution ratio, and 8 x 10-inch filter dilution ratio. The average exhaust temperature is an indicator of the engine-out temperature before the aftertreatment system. This value indicates how much catalytic activity may occur in an aftertreatment system from one cycle to another. The average exhaust flow rate is given in units of standard cubic meters per hour, referenced to 20 degrees Celsius and 1 atmosphere pressure. The CVS dilution ratio (DR) is defined as follows:

$$CVS\ DR = Total\ CVS\ Flow/Exhaust\ Flow$$

where the total CVS flow includes both the CVS dilution air and the exhaust flow. The exposure chamber dilution ratio is the total dilution ratio from exhaust concentration to exposure chamber concentration and is defined as follows:

$$Exposure\ Chamber\ DR = CVS\ DR*Secondary\ Exposure\ Chamber\ DR$$

where the secondary exposure chamber DR is the ratio of the total exposure chamber flow to the sample flow extracted from the CVS. The 8 x 10-inch filter dilution ratio refers to the ratio from the exhaust concentration to the concentration measured by the 8 by 10-inch Zefluor® filter, XAD cartridges, and the four 47 mm filters. It is defined as:

$$8x10\ DR = CVS\ DR*Secondary\ 8\ x\ 10\ DR$$

where the 8 x 10 secondary DR is the ratio of the total flow of the 8 x 10 system to the sample flow extracted from the CVS.

5.1 Fuel and Oil PAHs, Hopanes and Steranes

Figures 17, 18, and 19 show PAH concentration in the fuel and in fresh and used lube oil after 125 hours of degreening. PAH in the lube oil was at a much lower concentration than the PAH in the fuel. However, for PAH species such as coronene, dibenzopyrene and dibenzofluoranthene; little to no presence was detected in the fuel, although some presence was observed in the lube oil. PAH concentration in the lube oil was less than 0.5 ppm, except for Engine B, where it was 7.5 ppm for coronene and 28 ppm for benzo (ghi) perylene. It is not clear why the Engine B lube oil exhibited different concentrations than the other lube oils.

Figures 20 and 21 show the hopanes and steranes present in fresh and used lube oil. The highest hopanes and steranes concentration was found in Engine D's lube oil. Engine B lube hopanes were on the same order as Engine D, but the steranes were lower. Hopanes and steranes may be a good indicator of the lube oil's contribution to emissions, since they were not measured in the fuel. Appendix C includes the data on fuel and lube oil PAHs, and hopanes and steranes.

Figures 17 through 21 give a visual indication of the differences in PAHs, hopanes, and steranes concentrations (ratio of mass of species and mass of bulk liquid) between oil and fuel and among the different lube oils. For in depth information, interested readers should look at Appendix C that includes the actual data on fuel and lube oil PAHs, hopanes and steranes, along with the uncertainty or the limit of detection for each compound. It is worth noting that the majority of the data reported are above the limit of detection.

5.2 Cycle Work

Table 11 shows the work performed by each engine for each cycle tested. The cycle length is 20 minutes for the FTP, 39 minutes for CARBx-ICT, 48 minutes for CARBz-CH, and 16 hours for the 16-Hour cycle. Relative to the average engine power produced during the FTP cycle, the 16-Hour cycle was 10 percent higher, the CARBz-CH cycle was 37.5 percent higher, and the CARBx-ICT was 80 percent lower. Essentially, CARBx-ICT was at a much lighter engine load than that of the FTP, and it will only produce 20 percent of the work produced by the FTP per unit time.

The cycle work for each engine was very consistent, and the coefficient of variation, based on three repeats for the FTP and 16-Hour cycle, and two repeats for CARBx-ICT and CARBz-CH, was less than one percent for the majority of the runs, as shown in Table 11.

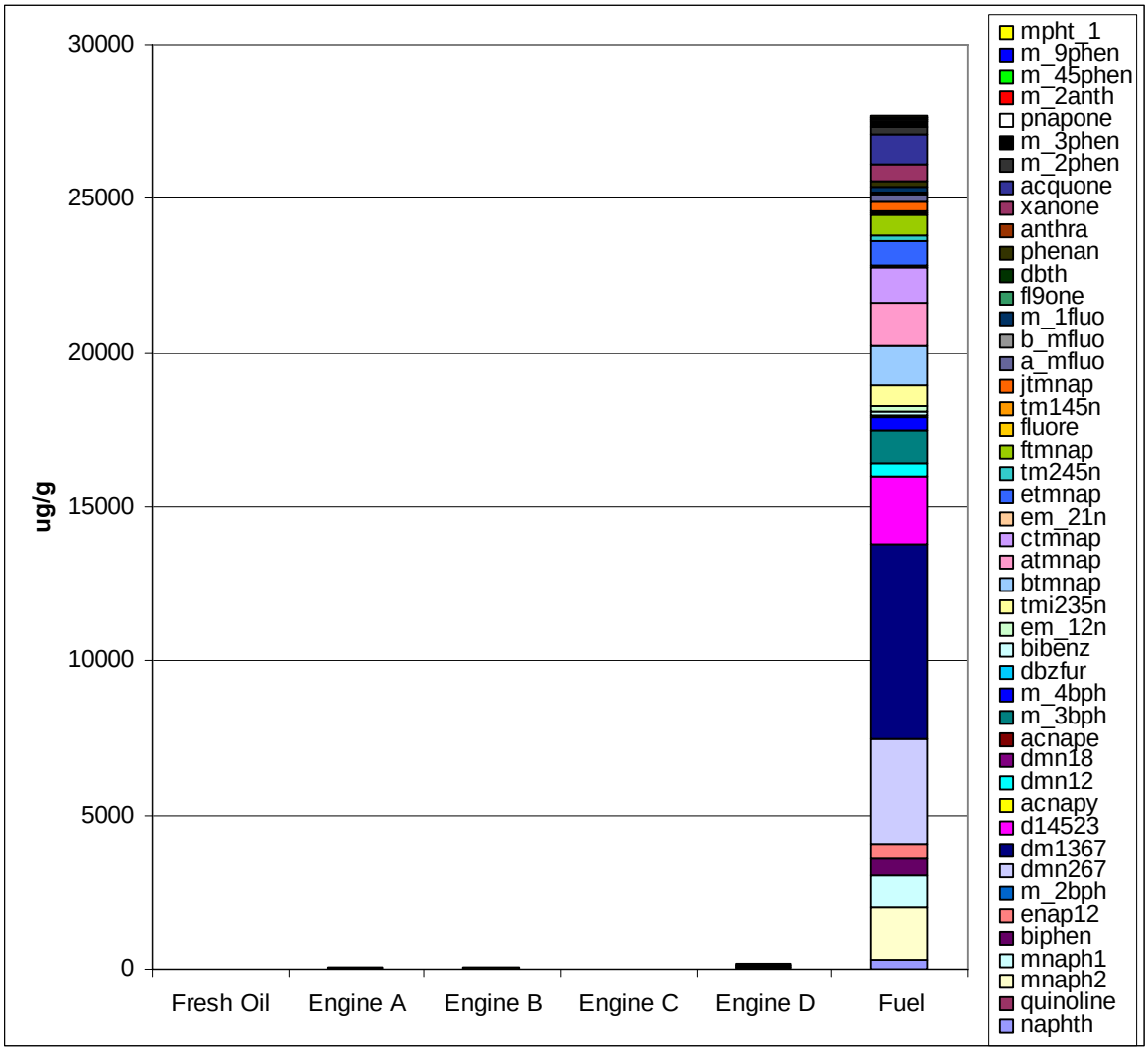


FIGURE 17. PAH CONCENTRATION IN LUBE OIL AND FUEL SHOWING A PARTIAL LIST OF FUEL PAH COMPOUNDS AT MUCH HIGHER CONCENTRATION THAN IN LUBE OIL

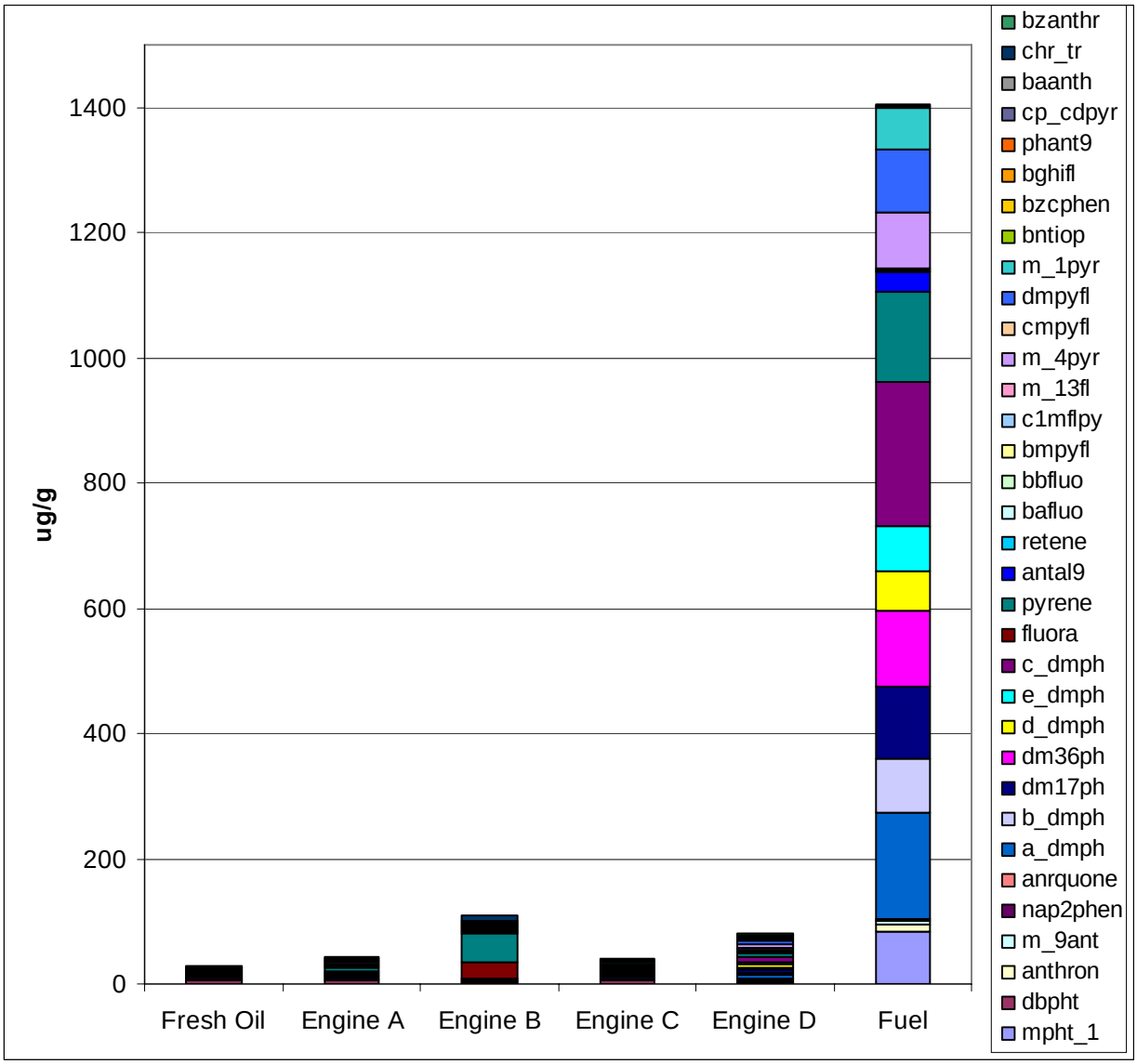


FIGURE 18. PAH CONCENTRATION IN LUBE OIL AND FUEL SHOWING A PARTIAL LIST OF FUEL PAH COMPOUNDS AT HIGHER CONCENTRATION THAN IN LUBE OIL

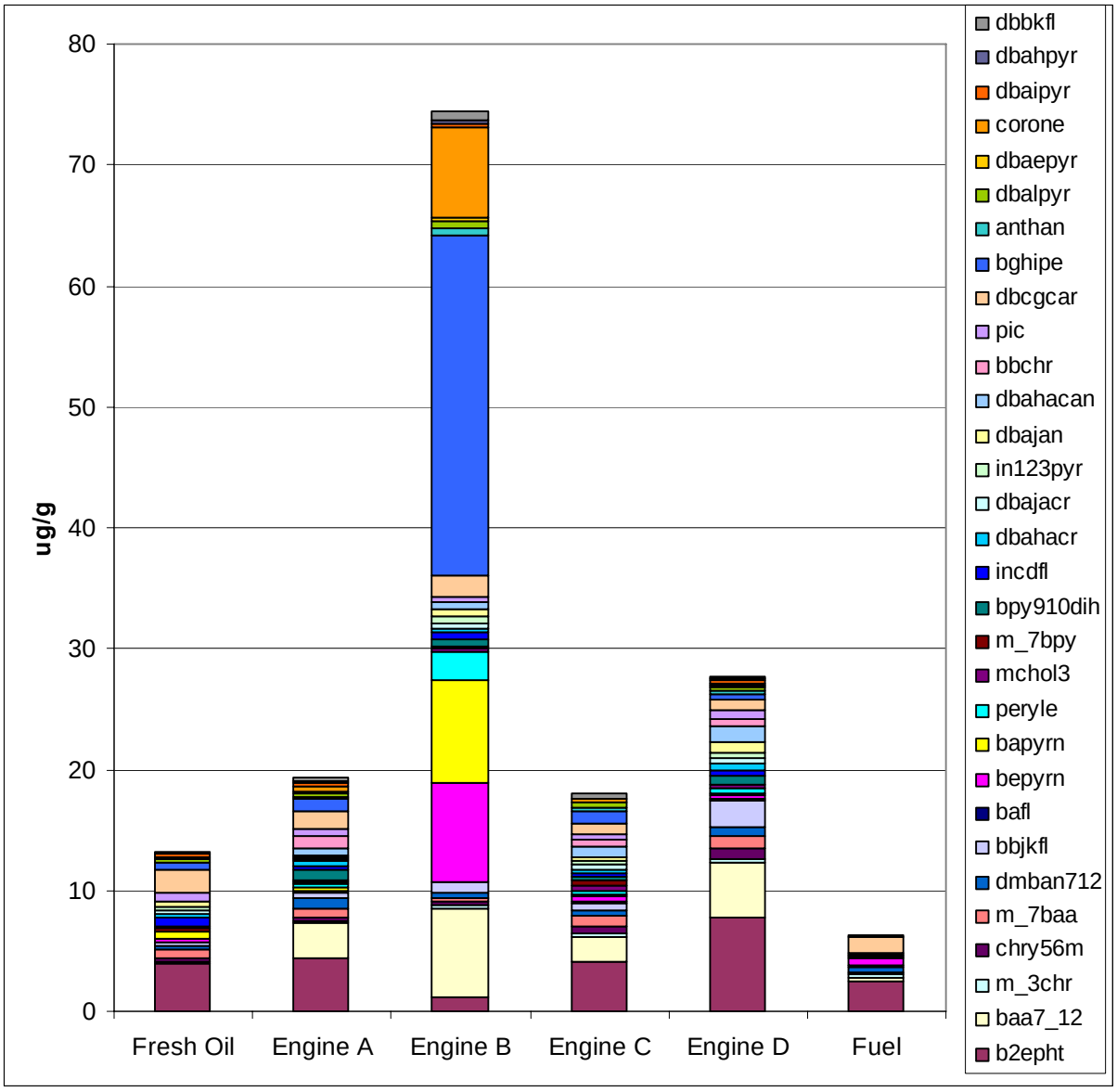


FIGURE 19. PAH CONCENTRATION IN LUBE OIL AND FUEL SHOWING A PARTIAL LIST OF FUEL PAH COMPOUNDS LOWER CONCENTRATION THAN IN LUBE OIL

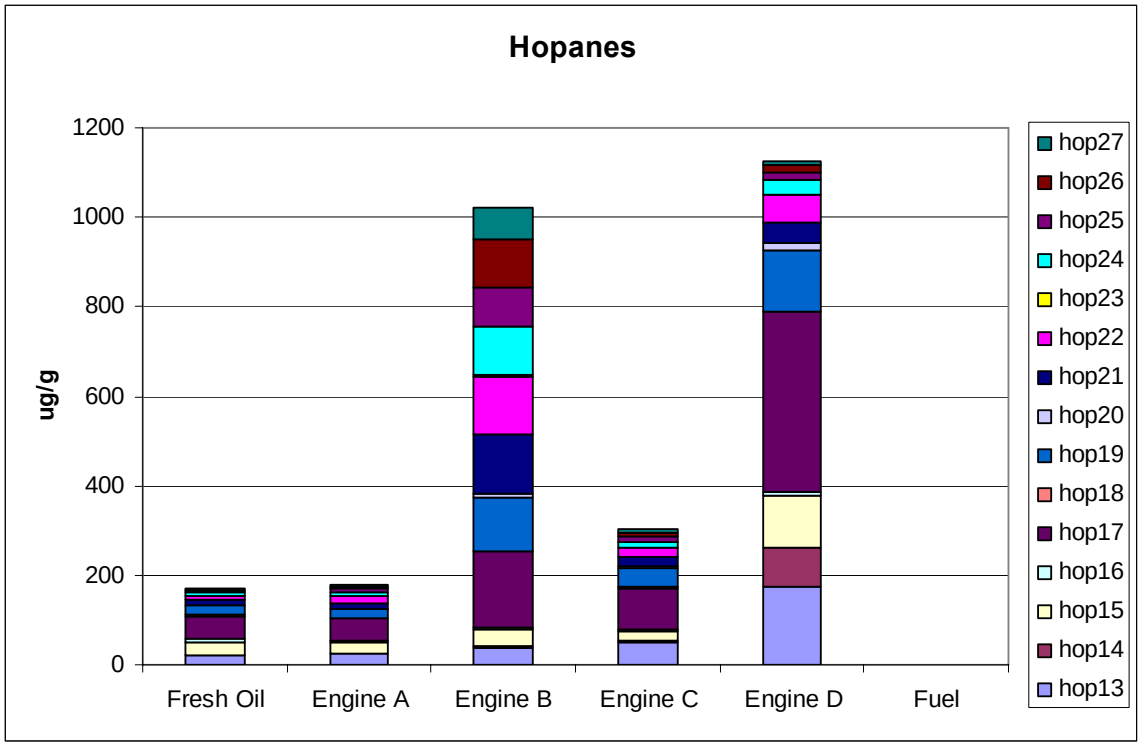


FIGURE 20. HOPANES CONCENTRATION IN LUBE OIL

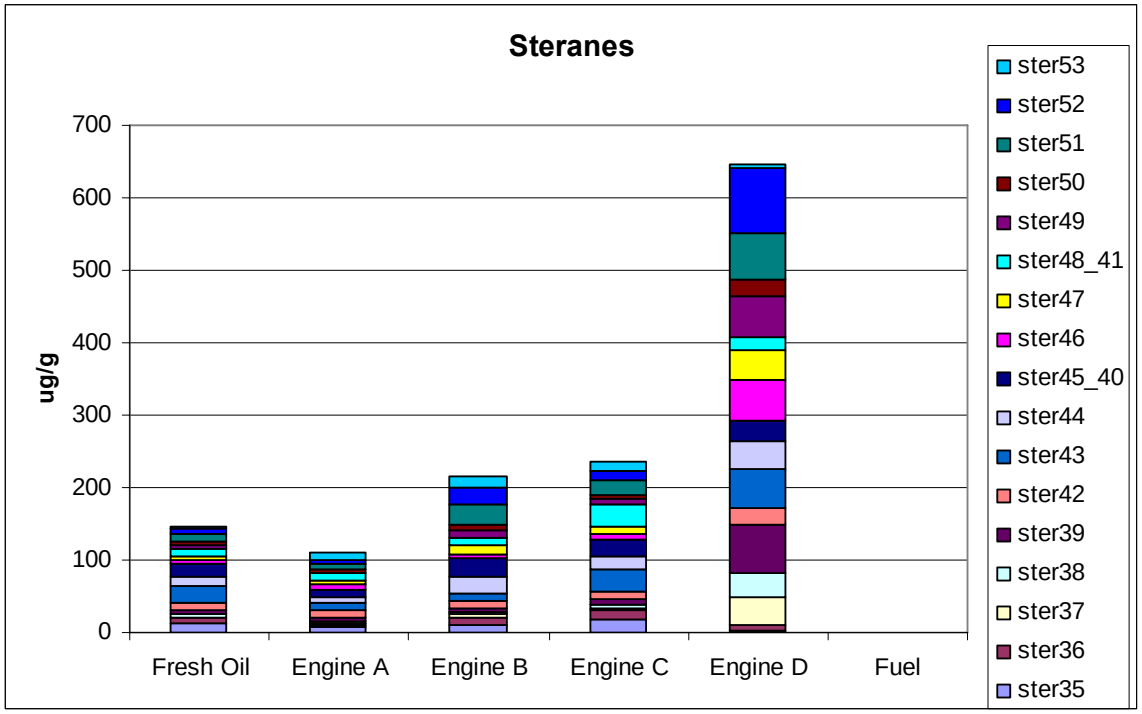


FIGURE 21. STERANES CONCENTRATION IN LUBE OIL

TABLE 11. ENGINE CYCLE WORK

Test Cycle	Test Number	Work, hp-hr					
		SwRI Elevation					Lovelace Elevation
		Engine A	Engine B	Engine C	Engine D	Engine B'	Engine B'
FTP-w	1	32.82	31.50	27.52	33.86	32.15	31.59
	2	32.93	31.45	27.13	33.72	32.12	31.57
	3	32.78	31.56	26.98	33.76	32.17	31.58
	Avg	**32.85**	**31.50**	**27.21**	**33.78**	**32.15**	**31.58**
	Stdev	**0.07**	**0.05**	**0.28**	**0.07**	**0.03**	**0.01**
	COV	**0.2%**	**0.2%**	**1.0%**	**0.2%**	**0.08%**	**0.03%**
FTP-wo	1	32.55	31.38	26.98	33.78	32.15	31.58
	2	32.74	31.26	26.95	33.71	32.14	31.55
	3	32.74	31.26	26.90	33.67	32.10	31.53
	Avg	**32.68**	**31.30**	**26.94**	**33.72**	**32.13**	**31.55**
	Stdev	**0.11**	**0.07**	**0.04**	**0.05**	**0.02**	**0.03**
	COV	**0.3%**	**0.2%**	**0.2%**	**0.2%**	**0.07%**	**0.08%**
CARBx-ICT	1	12.50	14.20	12.78	15.02	CARBx-ICT, CARBz-CH, and the 16-Hour cycle were not run with this engine	
	2	12.23	14.33	12.77	14.82		
	Avg	**12.36**	**14.26**	**12.78**	**14.92**		
	Stdev	**0.19**	**0.09**	**0.01**	**0.15**		
	COV	**1.6%**	**0.6%**	**0.0%**	**1.0%**		
CARBz-CH	1	108.71	109.60	103.42	116.39		
	2	108.10	108.98	107.61	116.38		
	Avg	**108.41**	**109.29**	**105.52**	**116.38**		
	Stdev	**0.43**	**0.44**	**2.97**	**0.01**		
	COV	**0.4%**	**0.4%**	**2.8%**	**0.0%**		
16-Hour	1	1711.28	1765.09	1686.03	1893.61		
	2	1728.85	1771.30	1687.33	1876.16		
	3	1753.33	1775.01	1687.78	1884.45		
	Avg	**1731.15**	**1770.47**	**1687.05**	**1884.74**		
	Stdev	**21.12**	**5.01**	**0.91**	**8.73**		
	COV	**1.2%**	**0.3%**	**0.1%**	**0.5%**		

5.3 Oxides of Nitrogen (Nitric Oxide, Nitrogen Dioxide, and Nitrous Oxide) Emissions

Table 12 and Figure 22 show the brake-specific NO_x emissions. Engine B', the backup engine, was tested at SwRI's elevation and at the Lovelace simulated elevation for regulated emissions only. At Lovelace elevation, the NO_x emission rate was 31 to 33 percent higher than that at SwRI's elevation.

Engine A through D showed different levels of NO_x emissions, depending on the cycle used. Average NO_x emissions ranged from 0.89 to 1.26 for the FTP-w, 2.97 to 5.22 for the CARBx-ICT, 0.93 to 1.72 for CARBz-CH, and from 1.19 to 1.49 for the 16-Hour cycle. The minimum increase of NO_x emissions between the FTP-w cycle and the 16 hour cycle was 6 percent for Engine D, while the maximum increase was 56 percent for Engine B. It is interesting to note that the brake specific NO_x emissions for Engines A and B increased by 37 and 35 percent, respectively for the CARBx-CH cycle relative to the FTP-w, while the emissions decreased by 17 percent for Engine D in the same comparison.

TABLE 12. BRAKE-SPECIFIC NO_X EMISSIONS

Test Cycle	Test Number	NO_x, g/hp-hr					
		SwRI Elevation					Lovelace Elevation
		Engine A	Engine B	Engine C	Engine D	Engine B'	Engine B'-Alt.
FTP-w	1	1.26	0.88	0.99	1.13	0.97	1.33
	2	1.25	0.89	1.05	1.11	0.97	1.31
	3	1.28	0.89	1.05	1.13	0.99	1.34
	Avg	**1.26**	**0.89**	**1.03**	**1.12**	**0.98**	**1.33**
	Stdev	**0.01**	**0.01**	**0.03**	**0.01**	**0.01**	**0.01**
	COV	**1.1%**	**0.8%**	**3.2%**	**0.9%**	**1.3%**	**1.0%**
FTP-wo	1	1.26	0.88	1.04	1.13	0.98	1.34
	2	1.25	0.91	1.04	1.10	0.96	1.29
	3	1.24	0.89	1.06	1.12	0.97	1.29
	Avg	**1.25**	**0.90**	**1.05**	**1.11**	**0.97**	**1.31**
	Stdev	**0.01**	**0.01**	**0.01**	**0.02**	**0.01**	**0.03**
	COV	**0.6%**	**1.5%**	**1.4%**	**1.6%**	**1.3%**	**2.1%**
CARBx-ICT	1	2.95	4.49	N/A	5.21		
	2	2.99	4.46	N/A	5.22		
	Avg	**2.97**	**4.48**	**N/A**	**5.22**		
	Stdev	**0.03**	**0.02**	**N/A**	**0.01**		
	COV	**1.0%**	**0.4%**	**N/A**	**0.1%**		
CARBz-CH	1	1.53	1.20	N/A	0.91		
	2	1.90	1.21	N/A	0.95		
	Avg	**1.72**	**1.20**	**N/A**	**0.93**		
	Stdev	**0.26**	**0.01**	**N/A**	**0.03**		
	COV	**15.0%**	**0.7%**	**N/A**	**3.1%**		
16-Hour	1	1.44	1.43	1.46	1.18		
	2	1.52	1.35	1.37	1.19		
	3	1.52	1.39	1.44	1.21		
	Avg	**1.49**	**1.39**	**1.42**	**1.19**		
	Stdev	**0.05**	**0.04**	**0.05**	**0.01**		
	COV	**3.2%**	**3.0%**	**3.5%**	**1.1%**		

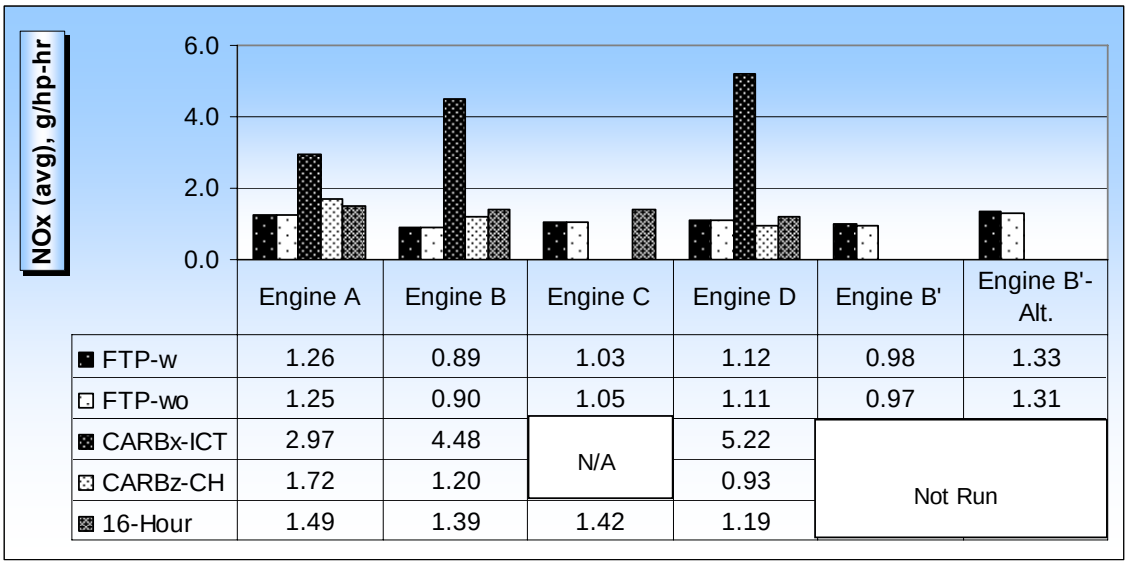


FIGURE 22. AVERAGE BRAKE-SPECIFIC NO_X EMISSIONS

Table 13 and Figure 23 show the NO emission results. Note that NO was not measured for Engine B'. The NO emissions profile may be different from the NO_x emissions profile, due to differences in NO_2 emissions, which are shown in Table 14 and Figure 24. NO_2 was not measured directly, but was calculated by taking the difference between NO_x and NO. Table 15 shows the NO_2 to NO_x ratio. The ratio ranged from 22 percent to 81 percent, depending on the cycle and engine used. Generally, the lowest ratio was observed with CARBx-ICT and the highest was observed with the FTP. NO_2 is produced in combustion, depending on the combustion strategy and temperature and the amount of EGR used. Furthermore, noble metals in the DOC and/or the DPF, particularly platinum, can convert NO to NO_2. Since the engine-out NO_2 is not known, it is unknown what the NO_2 percent increase is due to the catalyzed aftertreatment devices.

Table 16 and Figure 25 show the N_2O emissions. In general, the N_2O emissions represent less than one percent of total NO_x emissions.

5.4 Carbon Monoxide Emissions

The 2007 CO emission standard is 15.5 g/hp-hr. Table 17 and Figure 26 show the brake-specific CO emissions for all engines. Overall, CO emission levels were much lower than the standard for all engines and all cycles. The higher CO emissions with the CARBx-ICT cycle may suggest lower catalyst activity in oxidizing CO to CO_2 at the lower exhaust temperatures occurring during this low-power test cycle.

5.5 Total Hydrocarbon, Methane, and Non-Methane Hydrocarbon

The NMHC emission standard for 2007 and beyond is 0.14 g/hp-hr. NMHC was determined by taking the difference between THC and CH_4. Tables 18, 19, and 20 show the brake-specific emissions for THC, CH_4, and NMHC, respectively. Similarly, Figures 27, 28, and 29 show the average brake specific emissions for all engines and cycles tested. Because the concentrations in the CVS tunnel were very close to that in the CVS dilution air, the data were noisy after performing a background correction per CFR Part 1065. In general, NMHC emissions were much lower than the 2007 standard.

The same observation made about CO for the CARBx-ICT cycle can also be made about hydrocarbons. Due to the low exhaust temperatures of CARBx-ICT, the catalyzed DOC/DPF or DPF only may have provided less HC oxidation resulting in higher emissions than from the rest of the cycles. So, even on an emission rate basis in g/hr, CARBx-ICT will typically generate higher emissions than the rest of the cycles.

TABLE 13. NO EMISSIONS

Test Cycle	Test Number	NO, g/hp-hr			
		Engine A	Engine B	Engine C	Engine D
FTP-w	1	0.35	0.17	0.34	0.54
	2	0.37	0.11	0.34	0.50
	3	0.37	0.22	0.35	0.50
	Avg	**0.36**	**0.16**	**0.34**	**0.51**
	Stdev	**0.01**	**0.06**	**0.01**	**0.02**
	COV	**2.9%**	**33.8%**	**1.7%**	**3.9%**
FTP-wo	1	0.47	0.21	0.41	0.51
	2	0.44	0.21	0.35	0.53
	3	0.47	0.26	0.35	0.48
	Avg	**0.46**	**0.23**	**0.37**	**0.51**
	Stdev	**0.02**	**0.03**	**0.03**	**0.03**
	COV	**4.7%**	**11.8%**	**8.4%**	**5.2%**
CARBx-ICT	1	1.62	2.73	N/A	3.82
	2	1.87	2.54	N/A	4.36
	Avg	**1.75**	**2.64**	**N/A**	**4.09**
	Stdev	**0.18**	**0.13**	**N/A**	**0.38**
	COV	**10.3%**	**5.1%**	**N/A**	**9.3%**
CARBz-CH	1	0.64	0.29	N/A	0.42
	2	1.31	0.30	N/A	0.45
	Avg	**0.98**	**0.30**	**N/A**	**0.44**
	Stdev	**0.47**	**0.01**	**N/A**	**0.02**
	COV	**48.5%**	**3.2%**	**N/A**	**5.5%**
16-Hour	1	0.53	0.49	0.74	0.62
	2	0.57	0.45	0.87	0.62
	3	0.52	0.50	0.98	0.66
	Avg	**0.54**	**0.48**	**0.86**	**0.63**
	Stdev	**0.02**	**0.03**	**0.12**	**0.02**
	COV	**4.1%**	**5.4%**	**13.7%**	**3.5%**

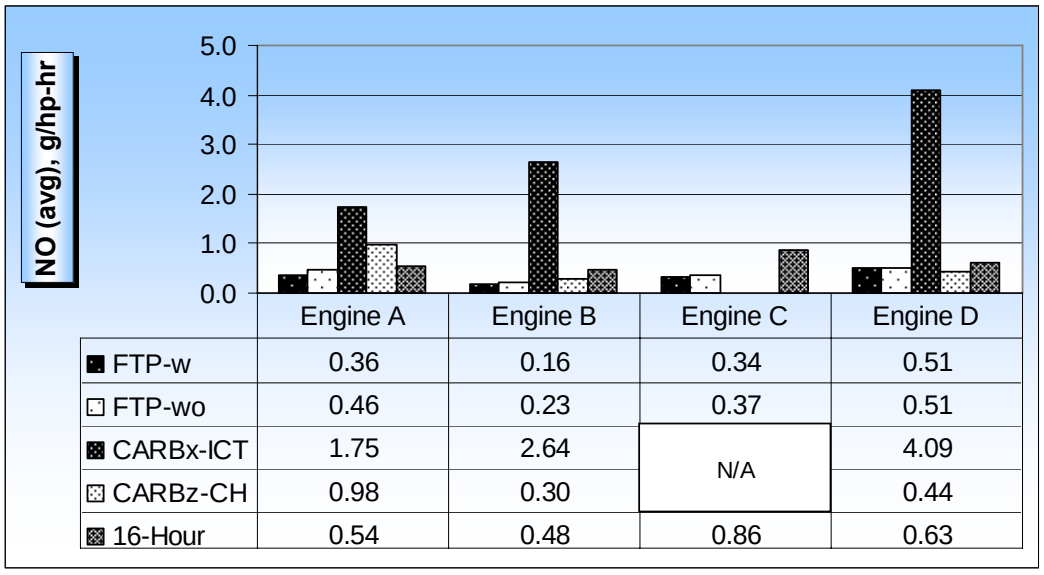


FIGURE 23. AVERAGE BRAKE-SPECIFIC NO EMISSIONS

TABLE 14. BRAKE-SPECIFIC NO_2 EMISSIONS

Test Cycle	Test Number	NO_2, g/hp-hr			
		Engine A	Engine B	Engine C	Engine D
FTP-w	1	0.90	0.71	0.65	0.59
	2	0.89	0.79	0.71	0.61
	3	0.90	0.68	0.70	0.62
	Avg	**0.90**	**0.72**	**0.69**	**0.61**
	Stdev	**0.01**	**0.06**	**0.03**	**0.02**
	COV	**1.0%**	**7.8%**	**5.0%**	**2.8%**
FTP-wo	1	0.79	0.67	0.64	0.60
	2	0.82	0.70	0.68	0.57
	3	0.77	0.64	0.71	0.64
	Avg	**0.79**	**0.67**	**0.68**	**0.60**
	Stdev	**0.02**	**0.03**	**0.04**	**0.04**
	COV	**2.9%**	**4.8%**	**5.9%**	**6.1%**
CARBx-ICT	1	1.33	1.75	N/A	1.38
	2	1.11	1.92	N/A	0.86
	Avg	**1.22**	**1.84**	**N/A**	**1.12**
	Stdev	**0.15**	**0.12**	**N/A**	**0.37**
	COV	**12.6%**	**6.6%**	**N/A**	**32.8%**
CARBz-CH	1	0.89	0.90	N/A	0.49
	2	0.59	0.90	N/A	0.50
	Avg	**0.74**	**0.90**	**N/A**	**0.50**
	Stdev	**0.22**	**0.00**	**N/A**	**0.00**
	COV	**29.4%**	**0.1%**	**N/A**	**0.9%**
16-Hour	1	0.90	0.94	0.72	0.56
	2	0.95	0.90	0.49	0.57
	3	1.00	0.89	0.46	0.55
	Avg	**0.95**	**0.91**	**0.56**	**0.56**
	Stdev	**0.05**	**0.03**	**0.14**	**0.01**
	COV	**4.9%**	**3.0%**	**25.1%**	**1.7%**

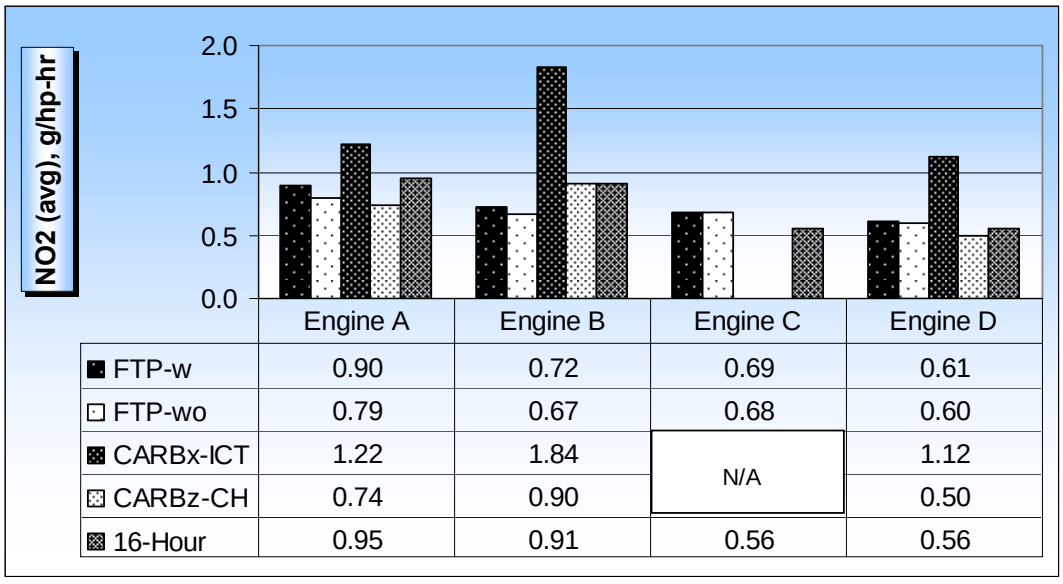


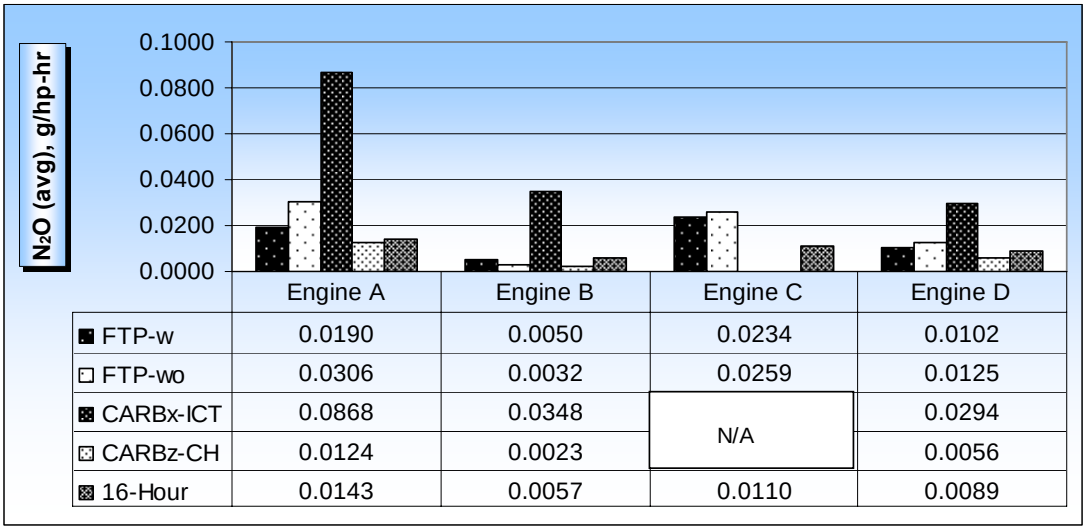
FIGURE 24. AVERAGE BRAKE-SPECIFIC NO_2 EMISSIONS

TABLE 15. NO_2/NO_X RATIO

NO_2/NO_x Ratio, %				
	Engine A	**Engine B**	**Engine C**	**Engine D**
FTP-w	71%	81%	67%	54%
FTP-wo	63%	75%	65%	54%
CARBx-ICT	41%	41%	N/A	22%
CARBz-CH	43%	75%	N/A	53%
16-Hour	64%	65%	39%	47%

TABLE 16. BRAKE-SPECIFIC N_2O EMISSIONS

Test Cycle	Test Number	N_2O, g/hp-hr SwRI Elevation			
		Engine A	**Engine B**	**Engine C**	**Engine D**
FTP-w	1	0.0192	0.0041	0.0285	0.0070
	2	0.0205	0.0031	0.0210	0.0117
	3	0.0175	0.0077	0.0206	0.0119
	Avg	**0.0190**	**0.0050**	**0.0234**	**0.0102**
	Stdev	**0.0015**	**0.0025**	**0.0044**	**0.0028**
	COV	**1.1%**	**0.8%**	**3.2%**	**0.9%**
FTP-wo	1	0.0339	0.0033	0.0390	0.0127
	2	0.0283	0.0030	0.0200	0.0123
	3	0.0296	0.0032	0.0187	0.0124
	Avg	**0.0306**	**0.0032**	**0.0259**	**0.0125**
	Stdev	**0.0030**	**0.0001**	**0.0114**	**0.0002**
	COV	**0.6%**	**1.5%**	**1.4%**	**1.6%**
CARBx-ICT	1	0.0871	0.0296	N/A	0.0295
	2	0.0866	0.0399	N/A	0.0294
	Avg	**0.0868**	**0.0348**	**N/A**	**0.0294**
	Stdev	**0.0003**	**0.0073**	**N/A**	**0.0000**
	COV	**1.0%**	**0.4%**	**N/A**	**0.1%**
CARBz-CH	1	0.0117	0.0023	N/A	0.0055
	2	0.0132	0.0023	N/A	0.0057
	Avg	**0.0124**	**0.0023**	**N/A**	**0.0056**
	Stdev	**0.0011**	**0.0000**	**N/A**	**0.0002**
	COV	**1.0%**	**0.4%**	**N/A**	**0.1%**
16-Hour	1	0.0140	0.0059	0.0130	0.0095
	2	0.0150	0.0054	0.0100	0.0078
	3	0.0141	0.0060	0.0099	0.0094
	Avg	**0.0143**	**0.0057**	**0.0110**	**0.0089**
	Stdev	**0.0006**	**0.0003**	**0.0017**	**0.0009**
	COV	**3.2%**	**3.0%**	**15.8%**	**1.1%**



	Engine A	Engine B	Engine C	Engine D
FTP-w	0.0190	0.0050	0.0234	0.0102
FTP-wo	0.0306	0.0032	0.0259	0.0125
CARBx-ICT	0.0868	0.0348	N/A	0.0294
CARBz-CH	0.0124	0.0023		0.0056
16-Hour	0.0143	0.0057	0.0110	0.0089

FIGURE 25. AVERAGE BRAKE-SPECIFIC N_2O EMISSIONS

TABLE 17. BRAKE-SPECIFIC CO EMISSIONS

Test Cycle	Test Number	CO, g/hp-hr					
		SwRI Elevation					Lovelace Elevation
		Engine A	Engine B	Engine C	Engine D	Engine B'	Engine B'-Alt.
FTP-w	1	0.11	0.12	1.14	0.36	0.089	0.334
	2	0.16	0.12	0.51	0.35	0.085	0.148
	3	0.12	0.10	0.51	0.33	0.066	0.189
	Avg	**0.13**	**0.11**	**0.72**	**0.35**	**0.080**	**0.224**
	Stdev	**0.02**	**0.01**	**0.37**	**0.01**	**0.012**	**0.097**
	COV	**17.7%**	**12.0%**	**51.0%**	**4.3%**	**15.0%**	**43.5%**
FTP-wo	1	0.09	0.02	0.49	0.35	0.020	0.189
	2	0.08	0.02	0.52	0.37	0.001	0.115
	3	0.05	0.03	0.44	0.36	0.005	0.060
	Avg	**0.08**	**0.02**	**0.48**	**0.36**	**0.009**	**0.121**
	Stdev	**0.02**	**0.01**	**0.04**	**0.01**	**0.010**	**0.065**
	COV	**27.6%**	**30.4%**	**8.2%**	**3.0%**	**119.3%**	**53.6%**
CARBx-ICT	1	2.32	0.24	N/A	2.04	CARBx-ICT, CARBz-CH, and the 16-Hour cycle were not run with this engine	
	2	2.07	0.30	N/A	1.81		
	Avg	**2.20**	**0.27**	**N/A**	**1.92**		
	Stdev	**0.18**	**0.04**	**N/A**	**0.16**		
	COV	**8.0%**	**16.2%**	**N/A**	**8.4%**		
CARBz-CH	1	0.04	0.05	N/A	0.10		
	2	0.05	0.06	N/A	0.07		
	Avg	**0.04**	**0.05**	**N/A**	**0.09**		
	Stdev	**0.00**	**0.00**	**N/A**	**0.01**		
	COV	**10.8%**	**9.5%**	**N/A**	**17.0%**		
16-Hour	1	0.09	0.09	0.43	0.15		
	2	0.10	0.08	0.48	0.16		
	3	0.10	0.07	0.46	0.14		
	Avg	**0.09**	**0.08**	**0.46**	**0.15**		
	Stdev	**0.00**	**0.01**	**0.03**	**0.01**		
	COV	**2.9%**	**12.0%**	**5.7%**	**7.9%**		

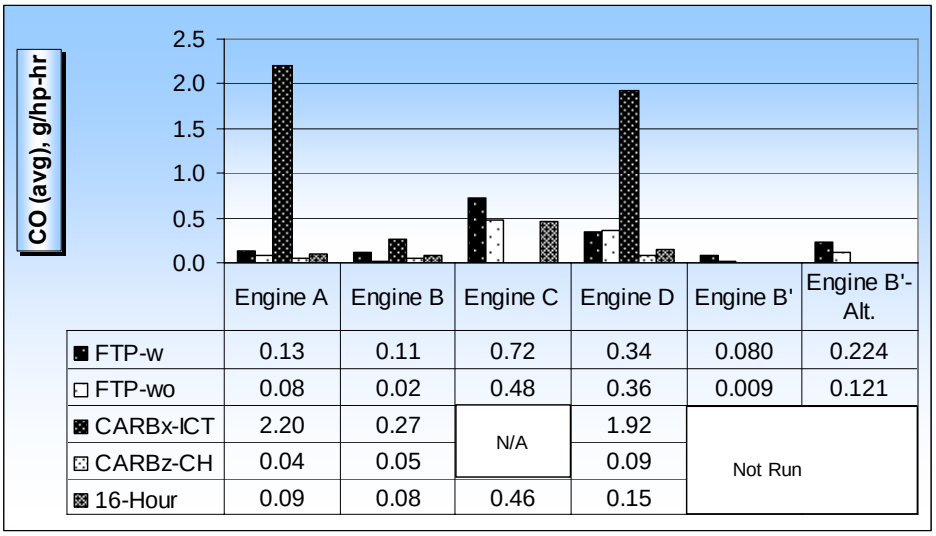


FIGURE 26. AVERAGE BRAKE-SPECIFIC CO EMISSIONS

TABLE 18. BRAKE-SPECIFIC THC EMISSIONS

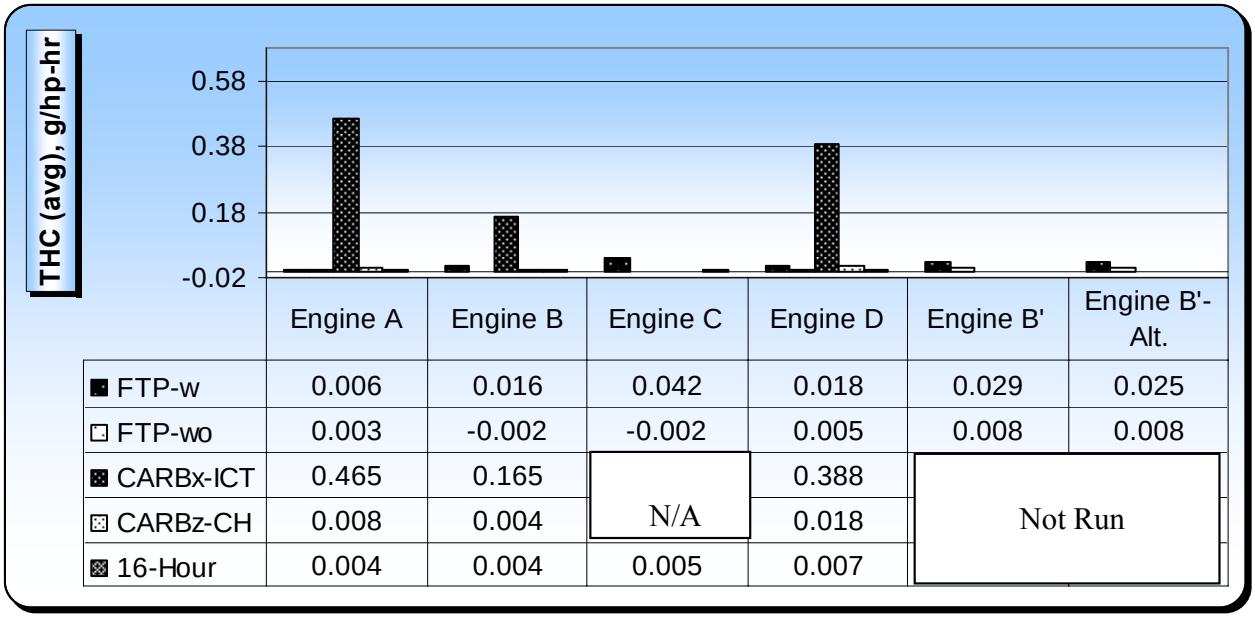
Test Cycle	Test Number	THC, g/hp-hr					
		SwRI Elevation					Lovelace Elevation
		Engine A	Engine B	Engine C	Engine D	Engine B'	Engine B'
FTP-w	1	0.005	0.020	0.055	0.016	0.035	0.029
	2	0.007	0.027	0.044	0.015	0.026	0.021
	3	0.007	0.002	0.026	0.023	0.025	0.024
	Avg	**0.006**	**0.016**	**0.042**	**0.018**	**0.029**	**0.025**
	Stdev	**0.001**	**0.013**	**0.015**	**0.005**	**0.005**	**0.004**
	COV	**18.4%**	**78.1%**	**35.7%**	**25.5%**	**18.6%**	**16.1%**
FTP-wo	1	0.006	0.008	-0.007	0.011	0.011	0.024
	2	0.001	-0.011	-0.001	0.004	0.005	0.001
	3	0.002	-0.004	0.002	-0.001	0.008	-0.001
	Avg	**0.003**	**-0.002**	**-0.002**	**0.005**	**0.008**	**0.008**
	Stdev	**0.002**	**0.010**	**0.005**	**0.006**	**0.003**	**0.014**
	COV	**79.2%**	**-426.3%**	**-236.9%**	**122.0%**	**35.5%**	**166.4%**
CARBx-ICT	1	0.455	0.131	N/A	0.407	CARBx-ICT, CARBz-CH, and the 16-Hour cycle were not run with this engine	
	2	0.475	0.199	N/A	0.368		
	Avg	**0.465**	**0.165**	**N/A**	**0.388**		
	Stdev	**0.014**	**0.048**	**N/A**	**0.027**		
	COV	**3.0%**	**29.3%**	**N/A**	**7.1%**		
CARBz-CH	1	0.008	0.005	N/A	0.017		
	2	0.008	0.004	N/A	0.018		
	Avg	**0.008**	**0.004**	**N/A**	**0.018**		
	Stdev	**0.001**	**0.001**	**N/A**	**0.000**		
	COV	**6.3%**	**23.3%**	**N/A**	**2.8%**		
16-Hour	1	0.007	0.006	-0.002	0.004		
	2	0.000	0.005	0.003	0.007		
	3	0.005	0.000	0.013	0.008		
	Avg	**0.004**	**0.004**	**0.005**	**0.007**		
	Stdev	**0.003**	**0.003**	**0.008**	**0.002**		
	COV	**80.7%**	**84.8%**	**160.6%**	**30.3%**		

TABLE 19. BRAKE-SPECIFIC CH_4 EMISSIONS

Test Cycle	Test Number	CH_4, g/hp-hr					
		SwRI Elevation					Lovelace Elevation
		Engine A	Engine B	Engine C	Engine D	Engine B'	Engine B'
FTP-w	1	0.009	0.019	0.024	0.007	0.026	0.011
	2	0.009	0.022	0.003	0.009	0.017	0.011
	3	0.010	0.036	0.013	0.010	0.017	0.009
	Avg	**0.009**	**0.025**	**0.014**	**0.009**	**0.020**	**0.010**
	Stdev	**0.001**	**0.009**	**0.011**	**0.002**	**0.005**	**0.001**
	COV	**6.6%**	**35.2%**	**77.8%**	**20.5%**	**27.0%**	**0.1%**
FTP-wo	1	-0.008	0.013	0.012	0.004	0.017	0.009
	2	0.012	0.012	0.003	0.008	0.011	0.006
	3	0.011	0.015	0.013	0.011	0.017	0.005
	Avg	**0.005**	**0.014**	**0.010**	**0.008**	**0.015**	**0.007**
	Stdev	**0.011**	**0.002**	**0.006**	**0.003**	**0.003**	**0.002**
	COV	**238.9%**	**11.5%**	**57.8%**	**42.6%**	**22.3%**	**28.0%**
CARBx-ICT	1	0.062	0.028	N/A	0.033	CARBx-ICT, CARBz-CH, and the 16-Hour cycle were not run with this engine	
	2	0.058	0.019	N/A	0.063		
	Avg	**0.060**	**0.023**	**N/A**	**0.048**		
	Stdev	**0.003**	**0.006**	**N/A**	**0.021**		
	COV	**5.3%**	**28.0%**	**N/A**	**44.9%**		
CARBz-CH	1	0.005	0.006	N/A	0.005		
	2	0.008	0.007	N/A	0.006		
	Avg	**0.007**	**0.007**	**N/A**	**0.006**		
	Stdev	**0.002**	**0.001**	**N/A**	**0.001**		
	COV	**30.1%**	**13.7%**	**N/A**	**9.6%**		
16-Hour	1	0.007	0.028	0.022	0.007		
	2	0.003	0.007	0.000	0.006		
	3	0.006	0.017	0.013	0.009		
	Avg	**0.005**	**0.017**	**0.012**	**0.007**		
	Stdev	**0.002**	**0.010**	**0.011**	**0.001**		
	COV	**42.8%**	**59.6%**	**94.1%**	**19.7%**		

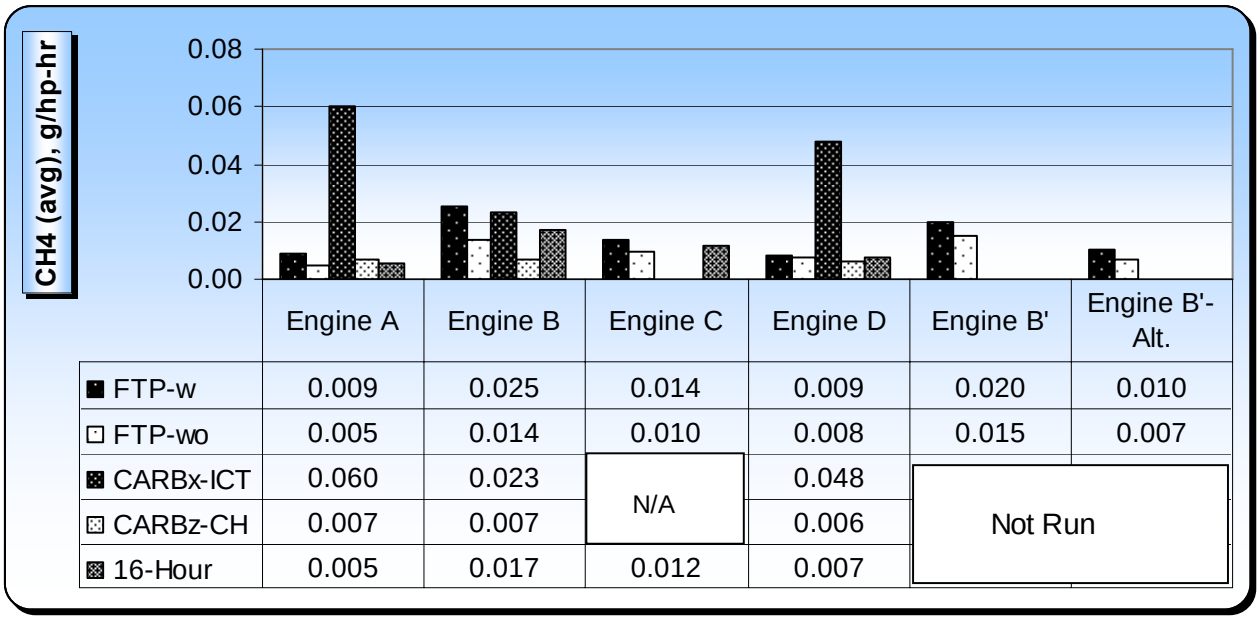
TABLE 20. BRAKE-SPECIFIC NMHC EMISSIONS

Test Cycle	Test Number	NMHC, g/hp-hr					
		SwRI Elevation					Lovelace Elevation
		Engine A	Engine B	Engine C	Engine D	Engine B'	Engine B'
FTP-w	1	-0.004	0.001	0.031	0.009	0.011	0.019
	2	-0.002	0.005	0.041	0.006	0.011	0.011
	3	-0.003	-0.034	0.013	0.013	0.010	0.017
	Avg	**-0.003**	**-0.009**	**0.028**	**0.010**	**0.011**	**0.016**
	Stdev	**0.001**	**0.021**	**0.014**	**0.004**	**0.001**	**0.004**
FTP-wo	1	0.014	-0.005	-0.020	0.007	-0.005	0.017
	2	-0.011	-0.024	-0.004	-0.004	-0.005	-0.005
	3	-0.009	-0.020	-0.011	-0.011	-0.008	-0.005
	Avg	**-0.002**	**-0.016**	**-0.012**	**-0.003**	**-0.006**	**0.002**
	Stdev	**0.014**	**0.010**	**0.008**	**0.009**	**0.001**	**0.012**
CARBx-ICT	1	0.392	0.103	N/A	0.375	CARBx-ICT, CARBz-CH, and the 16-Hour cycle were not run with this engine	
	2	0.417	0.181	N/A	0.305		
	Avg	**0.405**	**0.142**	**N/A**	**0.340**		
	Stdev	**0.017**	**0.055**	**N/A**	**0.049**		
CARBz-CH	1	0.003	-0.001	N/A	0.012		
	2	-0.001	-0.004	N/A	0.012		
	Avg	**0.001**	**-0.002**	**N/A**	**0.012**		
	Stdev	**0.003**	**0.002**	**N/A**	**0.000**		
16-Hour	1	0.000	-0.021	0.003	0.000		
	2	-0.002	-0.002	-0.024	0.002		
	3	-0.001	-0.017	0.000	-0.005		
	Avg	**-0.001**	**-0.013**	**-0.007**	**-0.001**		
	Stdev	**0.001**	**0.010**	**0.015**	**0.003**		



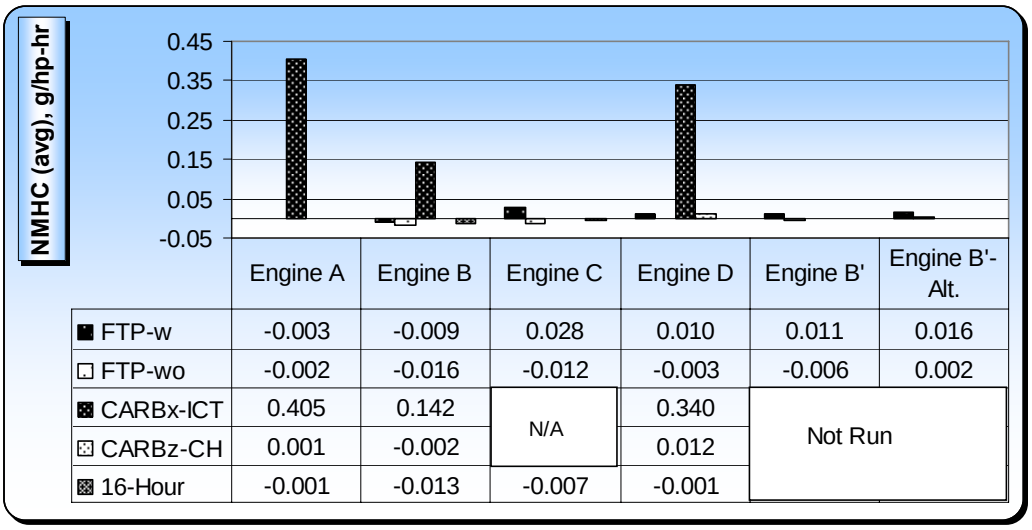
	Engine A	Engine B	Engine C	Engine D	Engine B'	Engine B'-Alt.
FTP-w	0.006	0.016	0.042	0.018	0.029	0.025
FTP-wo	0.003	-0.002	-0.002	0.005	0.008	0.008
CARBx-ICT	0.465	0.165	N/A	0.388	Not Run	
CARBz-CH	0.008	0.004		0.018		
16-Hour	0.004	0.004	0.005	0.007		

FIGURE 27. AVERAGE BRAKE-SPECIFIC THC EMISSIONS



	Engine A	Engine B	Engine C	Engine D	Engine B'	Engine B'-Alt.
FTP-w	0.009	0.025	0.014	0.009	0.020	0.010
FTP-wo	0.005	0.014	0.010	0.008	0.015	0.007
CARBx-ICT	0.060	0.023	N/A	0.048	Not Run	
CARBz-CH	0.007	0.007		0.006		
16-Hour	0.005	0.017	0.012	0.007		

FIGURE 28. AVERAGE BRAKE-SPECIFIC CH_4 EMISSIONS



	Engine A	Engine B	Engine C	Engine D	Engine B'	Engine B'-Alt.
FTP-w	-0.003	-0.009	0.028	0.010	0.011	0.016
FTP-wo	-0.002	-0.016	-0.012	-0.003	-0.006	0.002
CARBx-ICT	0.405	0.142	N/A	0.340	Not Run	
CARBz-CH	0.001	-0.002		0.012		
16-Hour	-0.001	-0.013	-0.007	-0.001		

FIGURE 29. AVERAGE BRAKE-SPECIFIC NMHC EMISSIONS

5.6 Carbon Dioxide Emissions and BSFC

CO_2 is becoming increasingly important because it is a major greenhouse gas. In the case of diesel engines, it is also indicative of fuel consumption. Table 21 and Figure 30 show the brake-specific CO_2 emissions, and Table 22 and Figure 31 show the brake-specific fuel consumption (BSFC), which is calculated based on emissions. CO_2 ranged from 547 g/hp-hr for Engine D, CARBz-CH, to 941 g/hp-hr for Engine A, CARBx-ICT. Generally, the lightest loaded cycle, CARBx-ICT, resulted in the highest $BSCO_2$ and BSFC, and the highest loaded cycle, CARBz-CH, resulted in the lowest $BSCO_2$ and BSFC.

5.7 Particulate Matter Emissions

Several metrics and methods were used to characterize PM. This section includes information on Teflon® membrane filter-based PM measurement, quartz filter-based OC/EC analysis, filter-based elemental EDXRF analysis, real time total PM using the DMM-230, real time soot using the MSS, and real time number and size using the EEPS.

5.7.1 Filter-Based PM Mass-CVS Tunnel and Exposure Chamber

Filter-based PM was collected from two locations. The first was the CVS tunnel sample zone, in accordance with CFR Part 1065, where the filter face temperature was maintained at 47°C ± 5°C, and total residence time (CVS plus secondary tunnel) was on the order of 3 seconds. The second location was the exposure chamber, where the dilution ratio from the CVS was about 2, the filter face temperature was about 28°C, and the residence time was on the order of 4 to 5 minutes to purge 90 percent of the volume entering the chamber. It takes an additional 15 minutes for the remaining 10 percent to be fully purged. The temperature of the exposure chamber filter was not actively controlled and was dictated by the temperature inside the exposure chamber. The total flow through each of the 47 mm filters was approximately 57 slpm, resulting in a filter face velocity near 100 cm/s. Table 23 and Figure 32, and Table 24 and Figure 33 show the brake-specific PM emissions from the CVS and the exposure chamber, respectively. Generally, PM emissions were very low, well below the 2007 PM standard of 0.01 g/hp-hr for the FTP.

TABLE 21. BRAKE-SPECIFIC CO_2 EMISSIONS

Test Cycle	Test Number	CO_2, g/hp-hr					
		SwRI Elevation					Lovelace Elevation
		Engine A	Engine B	Engine C	Engine D	Engine B'	Engine B'-Alt.
FTP-w	1	619	647	605	580	616	589
	2	620	650	613	575	616	590
	3	619	644	609	579	614	591
	Avg	**619**	**647**	**609**	**578**	**615**	**590**
	Stdev	**0**	**3**	**4**	**3**	**1**	**1**
	COV	**0.1%**	**0.4%**	**0.6%**	**0.5%**	**0.2%**	**0.1%**
FTP-wo	1	660	648	606	577	613	591
	2	650	649	604	576	613	597
	3	648	649	606	576	613	589
	Avg	**653**	**649**	**605**	**576**	**613**	**592**
	Stdev	**6**	**1**	**1**	**1**	**0**	**5**
	COV	**1.0%**	**0.1%**	**0.2%**	**0.1%**	**0.0%**	**0.8%**
CARBx-ICT	1	941	819	N/A	754	CARBx-ICT, CARBz-CH, and the 16-Hour cycle were not run with this engine	
	2	926	813	N/A	755		
	Avg	**934**	**816**	**N/A**	**754**		
	Stdev	**10**	**4**	**N/A**	**1**		
	COV	**1.1%**	**0.5%**	**N/A**	**0.1%**		
CARBz-CH	1	662	563	N/A	547		
	2	669	568	N/A	550		
	Avg	**665**	**565**	**N/A**	**549**		
	Stdev	**5**	**3**	**N/A**	**2**		
	COV	**0.8%**	**0.6%**	**N/A**	**0.3%**		
16-Hour	1	597	615	567	576		
	2	604	620	565	574		
	3	602	624	564	573		
	Avg	**601**	**620**	**565**	**574**		
	Stdev	**4**	**4**	**2**	**2**		
	COV	**0.6%**	**0.7%**	**0.3%**	**0.3%**		

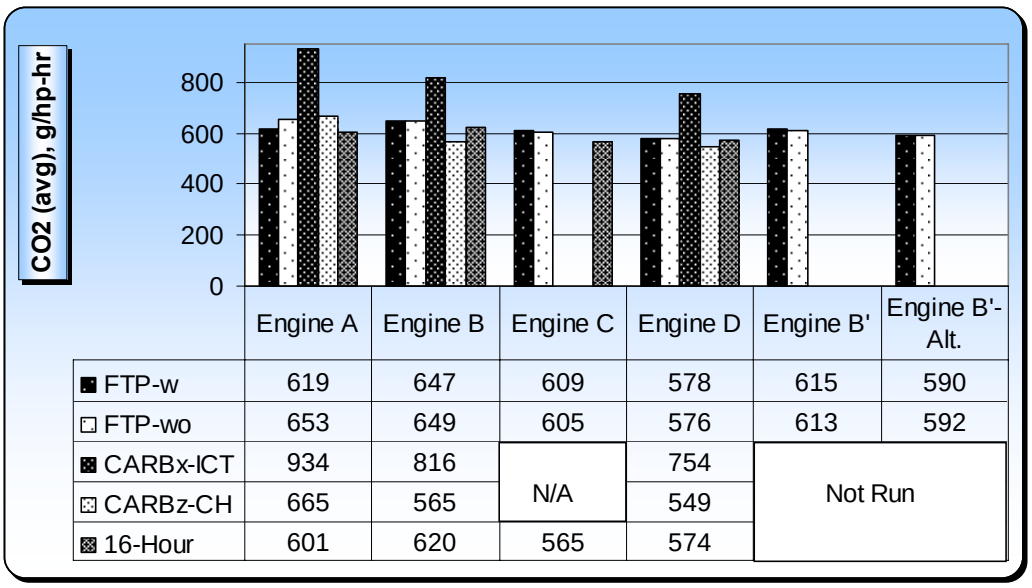


FIGURE 30. AVERAGE BRAKE-SPECIFIC CO_2 EMISSIONS

TABLE 22. BRAKE-SPECIFIC FUEL CONSUMPTION

Test Cycle	Test Number	BSFC, lb/hp-hr					
		SwRI Elevation					Lovelace Elevation
		Engine A	Engine B	Engine C	Engine D	Engine B'	Engine B'-Alt.
FTP-w	1	0.466	0.447	0.419	0.401	0.427	0.409
	2	0.428	0.449	0.423	0.397	0.427	0.409
	3	0.428	0.445	0.421	0.400	0.426	0.409
	Avg	**0.441**	**0.447**	**0.421**	**0.399**	**0.426**	**0.409**
	Stdev	**0.022**	**0.002**	**0.002**	**0.002**	**0.001**	**0.000**
	COV	**5.0%**	**0.5%**	**0.5%**	**0.5%**	**0.2%**	**0.1%**
FTP-wo	1	0.456	0.447	0.419	0.399	0.425	0.409
	2	0.449	0.448	0.417	0.398	0.425	0.414
	3	0.448	0.448	0.419	0.398	0.425	0.408
	Avg	**0.451**	**0.448**	**0.418**	**0.398**	**0.425**	**0.410**
	Stdev	**0.004**	**0.000**	**0.001**	**0.000**	**0.000**	**0.003**
	COV	**1.0%**	**0.1%**	**0.2%**	**0.1%**	**0.0%**	**0.8%**
CARBx-ICT	1	0.654	0.566	N/A	0.524	CARBx-ICT, CARBz-CH, and the 16-Hour cycle were not run with this engine	
	2	0.643	0.563	N/A	0.524		
	Avg	**0.649**	**0.564**	**N/A**	**0.524**		
	Stdev	**0.007**	**0.002**	**N/A**	**0.000**		
	COV	**1.1%**	**0.4%**	**N/A**	**0.1%**		
CARBz-CH	1	0.457	0.389	N/A	0.378		
	2	0.462	0.393	N/A	0.380		
	Avg	**0.460**	**0.391**	**N/A**	**0.379**		
	Stdev	**0.004**	**0.002**	**N/A**	**0.001**		
	COV	**0.8%**	**0.6%**	**N/A**	**0.3%**		
16-Hour	1	0.413	0.425	0.392	0.398		
	2	0.418	0.429	0.391	0.397		
	3	0.416	0.431	0.390	0.396		
	Avg	**0.416**	**0.428**	**0.391**	**0.397**		
	Stdev	**0.002**	**0.003**	**0.001**	**0.001**		
	COV	**0.5%**	**0.7%**	**0.3%**	**0.3%**		

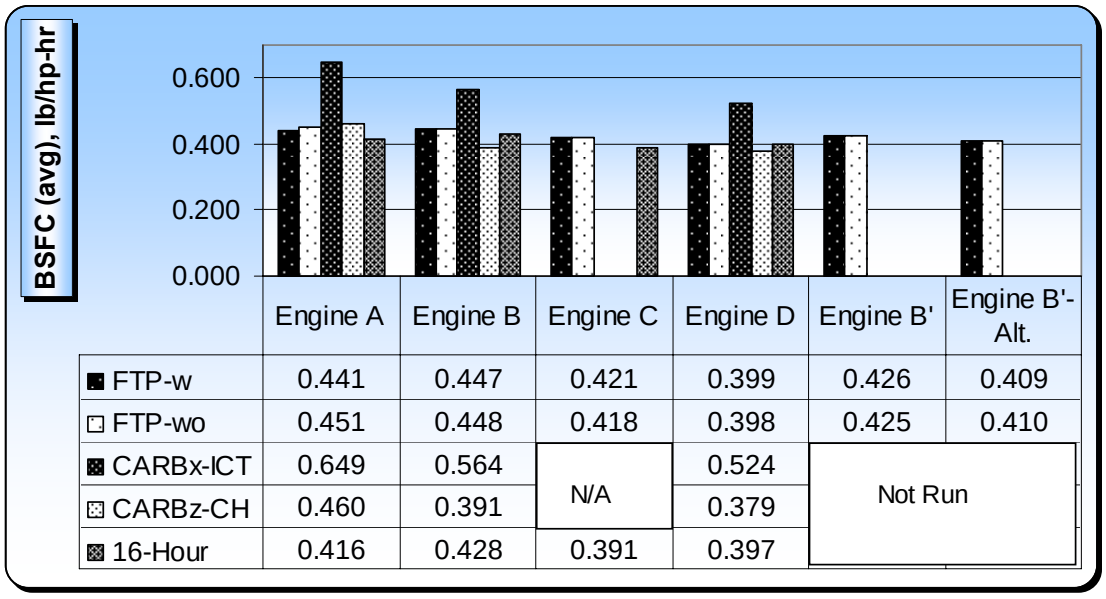


FIGURE 31. AVERAGE BRAKE-SPECIFIC FUEL CONSUMPTION

TABLE 23. BRAKE-SPECIFIC PM EMISSIONS (CVS TUNNEL, CFR PART 1065)

Test Cycle	Test Number	PM (Part 1065), g/hp-hr					
		SwRI Elevation					Lovelace Elevation
		Engine A	Engine B	Engine C	Engine D	Engine B'	Engine B'
FTP-w	1	0.0015	0.0013	0.0009	0.0005	0.0005	0.0004
	2	0.0013	0.0018	0.0005	0.0011	0.0003	0.0002
	3	0.0019	0.0008	0.0009	0.0007	0.0004	0.0001
	Avg	**0.0016**	**0.0013**	**0.0008**	**0.0008**	**0.0004**	**0.0002**
	Stdev	**0.0003**	**0.0005**	**0.0002**	**0.0003**	**0.0001**	**0.0001**
	COV	**17.0%**	**37.4%**	**31.7%**	**39.8%**	**23.0%**	**54.0%**
FTP-wo	1	0.0004	0.0004	0.0007	0.0008	0.0004	0.0001
	2	0.0010	0.0012	0.0008	0.0002	-0.0001	0.0005
	3	0.0003	0.0011	0.0006	0.0005	0.0002	0.0001
	Avg	**0.0006**	**0.0009**	**0.0007**	**0.0005**	**0.0002**	**0.0003**
	Stdev	**0.0004**	**0.0004**	**0.0001**	**0.0003**	**0.0002**	**0.0002**
	COV	**63.9%**	**45.6%**	**15.2%**	**54.3%**	**132.3%**	**78.1%**
CARBx-ICT	1	0.0074	0.0013	NA	0.0022	CARBx-ICT, CARBz-CH, and the 16-Hour cycle were not run with this engine	
	2	0.0092	0.0005	NA	0.0014		
	Avg	**0.0083**	**0.0009**	**NA**	**0.0018**		
	Stdev	**0.0013**	**0.0006**	**NA**	**0.0005**		
	COV	**16.2%**	**66.0%**	**NA**	**30.3%**		
CARBz-CH	1	0.0046	0.0007	NA	0.0003		
	2	0.0117	0.0006	NA	0.0002		
	Avg	**0.0082**	**0.0006**	**NA**	**0.0003**		
	Stdev	**0.0050**	**0.0001**	**NA**	**0.0001**		
	COV	**61.8%**	**12.8%**	**NA**	**24.0%**		
16-Hour	1	0.0003	0.0015	0.0017	0.0016		
	2	0.0019	0.0009	0.0012	0.0008		
	3	0.0016	0.0012	0.0004	0.0014		
	Avg	**0.0013**	**0.0012**	**0.0011**	**0.0013**		
	Stdev	**0.0009**	**0.0003**	**0.0006**	**0.0004**		
	COV	**67.8%**	**26.1%**	**58.4%**	**31.0%**		

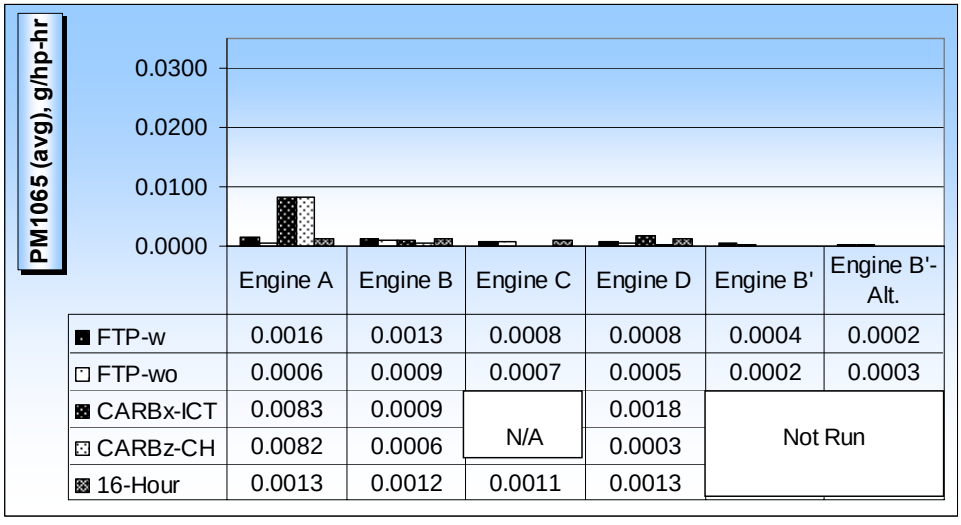


FIGURE 32. AVERAGE BRAKE-SPECIFIC PM EMISSIONS (CVS TUNNEL, CFR PART 1065)

TABLE 24. BRAKE-SPECIFIC PM EMISSIONS (EXPOSURE CHAMBER)

Test Cycle	Test Number	PM (Exp. Chamber), g/hp-hr			
		Engine A	Engine B	Engine C	Engine D
FTP-w	1	0.0018	0.0024	0.0003	0.0009
	2	0.0013	0.0013	0.0001	0.0009
	3	-	0.0007	0.0005	0.0009
	Avg	**0.0015**	**0.0015**	**0.0003**	**0.0009**
	Stdev	**0.0003**	**0.0009**	**0.0002**	**0.0000**
	COV	**20.7%**	**59.9%**	**57.0%**	**0.6%**
FTP-wo	1	0.0007	0.0006	0.0000	0.0006
	2	0.0008	0.0009	0.0007	0.0007
	3	0.0018	0.0007	0.0006	0.0003
	Avg	**0.0011**	**0.0007**	**0.0004**	**0.0005**
	Stdev	**0.0006**	**0.0001**	**0.0003**	**0.0002**
	COV	**58.0%**	**16.9%**	**82.5%**	**39.1%**
CARBx-ICT	1	0.0085	0.0010	N/A	-0.0036
	2	0.0073	0.0013	N/A	0.0015
	Avg	**0.0079**	**0.0011**	**N/A**	**0.0015**
	Stdev	**0.0008**	**0.0002**	**N/A**	**-**
	COV	**10.2%**	**21.3%**	**N/A**	**-**
CARBz-CH	1	0.0083	0.0008	N/A	0.0004
	2	0.0203	0.0007	N/A	0.0004
	Avg	**0.0143**	**0.0007**	**N/A**	**0.0004**
	Stdev	**0.0085**	**0.0001**	**N/A**	**0.0000**
	COV	**59.1%**	**8.6%**	**N/A**	**9.8%**
16-Hour	1	0.0005	0.0033	0.0020	0.0026
	2	0.0042	0.0022	0.0017	0.0015
	3	0.0042	0.0028	0.0005	0.0017
	Avg	**0.0030**	**0.0028**	**0.0014**	**0.0019**
	Stdev	**0.0021**	**0.0005**	**0.0008**	**0.0005**
	COV	**71.5%**	**19.2%**	**56.2%**	**28.0%**

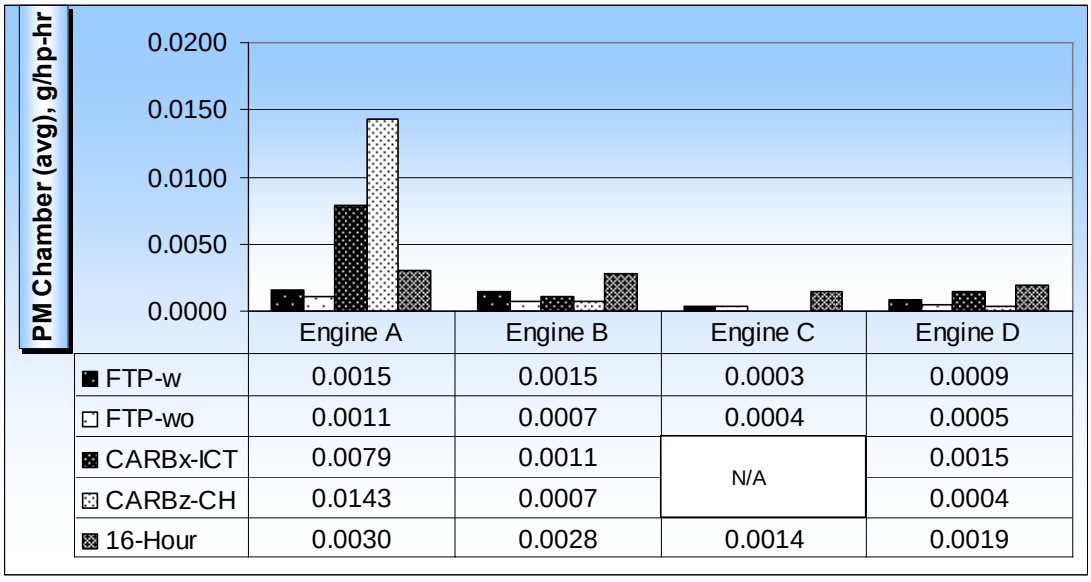


FIGURE 33. AVERAGE BRAKE-SPECIFIC PM EMISSIONS (EXPOSURE CHAMBER)

Figure 34 shows the ratio of PM with blow-by and PM without blow-by for the FTP. On average, across all engines, the PM with blow-by was about 50 percent higher based on both the CVS and exposure chamber PM results.

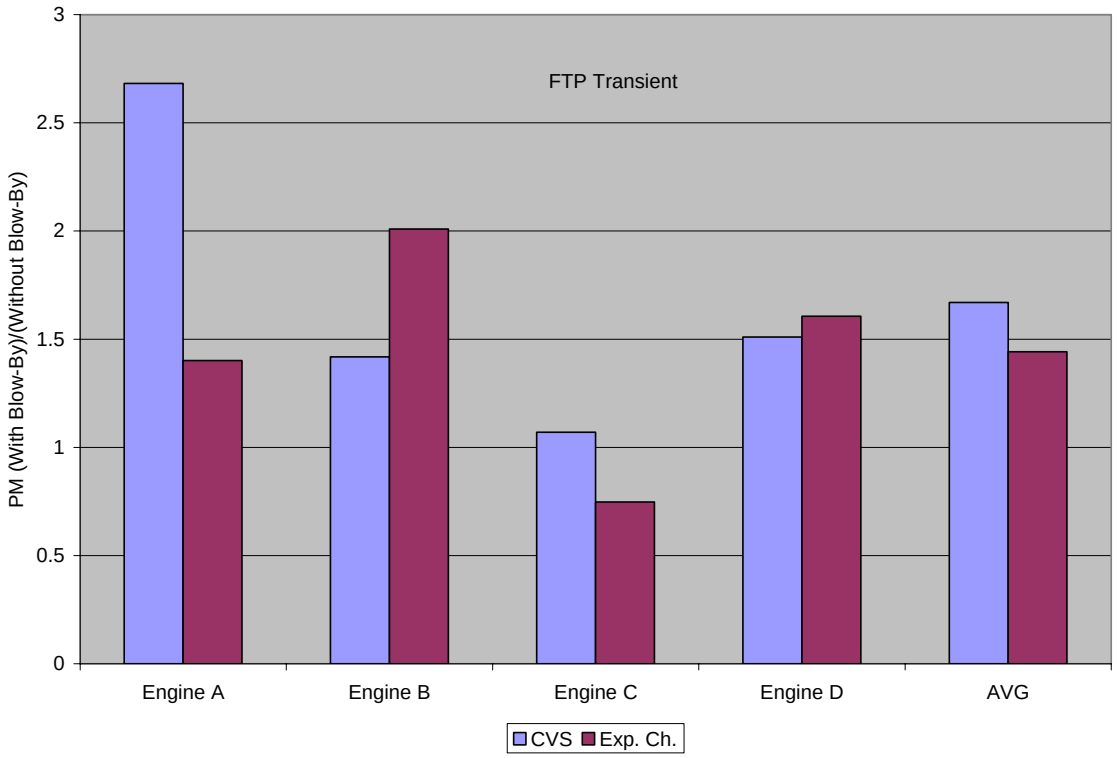


FIGURE 34. RATIO OF PM WITH BLOW-BY AND PM WITHOUT BLOW-BY

Figure 35 shows the ratio of exposure chamber-based PM and CVS-based PM. For the FTP and CARBx-ICT (light load cycles), there were no notable differences in PM between the two sampling locations. For the CARBz-CH and the 16-Hour cycle, the exposure chamber result was 50 to 100 percent higher, respectively, for these cycles. It is important to note that the 16-Hour cycle filter-based PM measurement should be considered the most precise due to the high level of PM accumulated on the sample filter. While the PM collected on an FTP sample filter was on the order of 10 µg, the 16-Hour cycle filter typically had more than 500 µg.

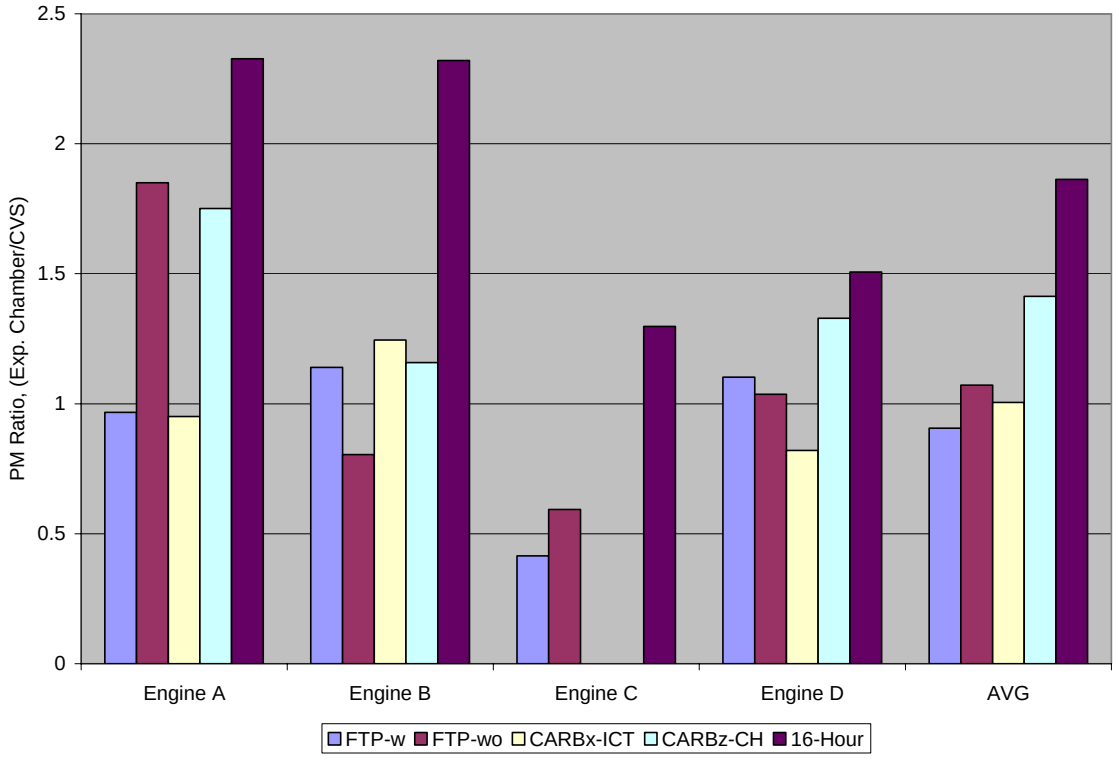


FIGURE 35. RATIO OF PM BASED ON EXPOSURE CHAMBER AND PM BASED ON CVS USING CFR PART 1065

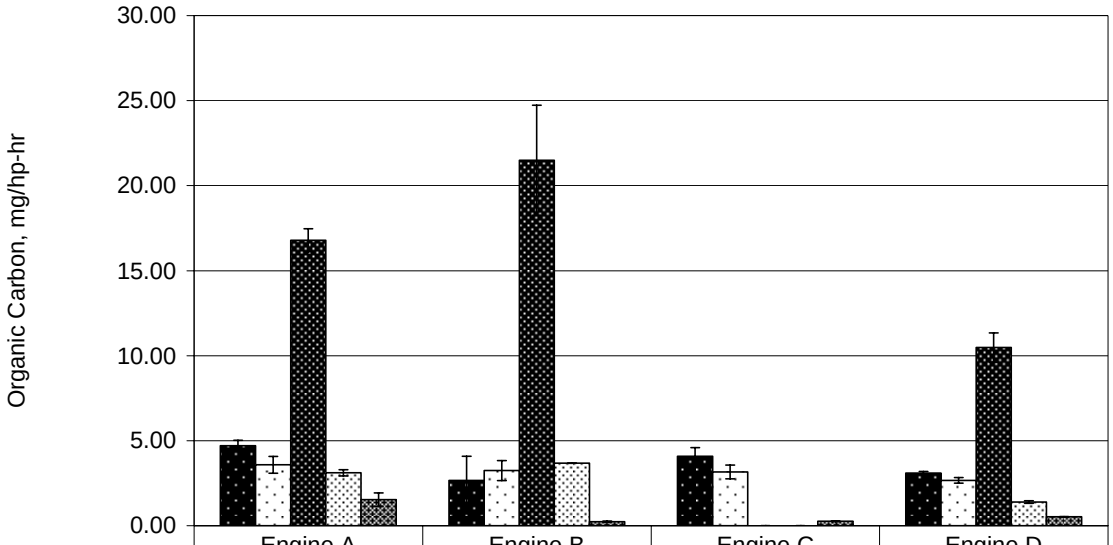
5.7.2 Quartz Filter-Based OC/EC-Exposure Chamber

PM was collected on quartz filters from the exposure chamber, and the filters were analyzed using the OC/EC reflectance method by DRI. Table 25, and Figures 36 and 37 show the average brake-specific OC/EC emissions. The 16-Hour cycle data are considered the most precise due to the long sampling time, where a larger PM quantity was collected on the filter. For the 16-Hour cycle, with the exception of OC for engine A, which was about 7 times higher than the mass of EC, the OC emissions were similar to EC with Engine B and C, and over twice the EC for Engine D. For the FTP, the EC represented less than 3 percent of the 2007 PM standard. The OC was comparable to tunnel blank levels, and it was on the order of 40 percent of the 2007 PM standard, perhaps due to positive gas phase artifact collection by the quartz filter material.

Based on all engines tested, the average EC to OC ratio was 4.1 percent for the FTP-w (with blow-by), 3.2 percent for the FTP-wo (without blow-by), 1.6 percent for CARBx-ICT, 12.1 percent for CARBz-CH, 37.3 percent for the 16-Hour cycle, and 3.6 percent for TB (tunnel blank). In principle, the longer the cycle the higher the EC to OC ratio, suggesting that with longer cycles, the accumulation of OC on the filter is decreasing as function of time due to perhaps the positive gas phase artifact reaching equilibrium with the filter media.

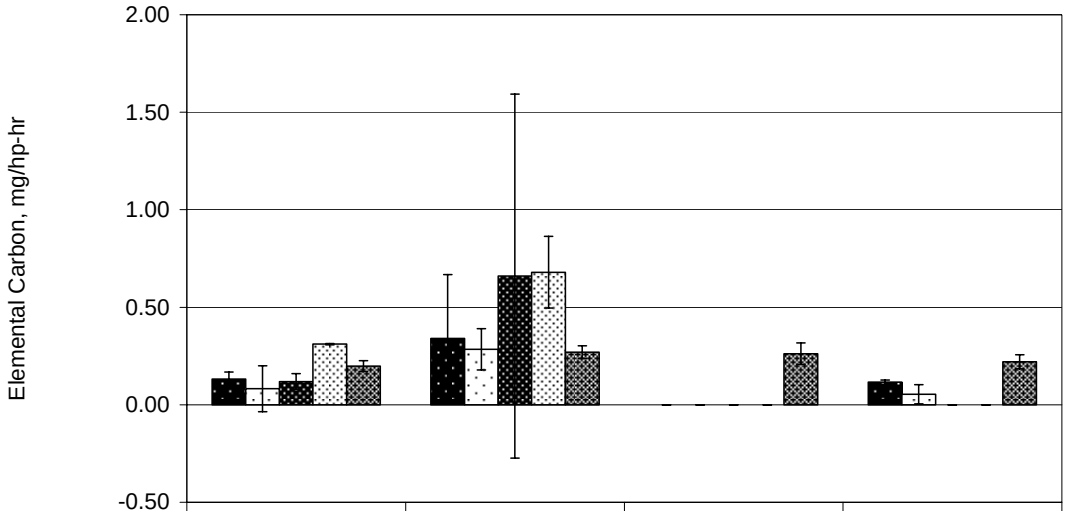
TABLE 25. AVERAGE BRAKE-SPECIFIC ELEMENTAL/ORGANIC CARBON EMISSIONS BASED ON FILTER COLLECTION FROM EXPOSURE CHAMBER

Test Cycle	Number of Repeats		Elemental/Organic Carbon, mg/hp-hr							
			Engine A		Engine B		Engine C		Engine D	
			EC	OC	EC	OC	EC	OC	EC	OC
FTP-w	3	Avg	0.13	4.70	0.34	2.67	0.00	4.08	0.12	3.10
		Stdev	0.04	0.32	0.33	1.41	0.00	0.52	0.01	0.09
		COV	27%	7%	97%	53%	0%	13%	9%	3%
FTP-wo	3	Avg	0.08	3.58	0.28	3.24	0.00	3.16	0.05	2.67
		Stdev	0.12	0.50	0.11	0.59	0.00	0.41	0.05	0.17
		COV	144%	14%	37%	18%	0%	13%	91%	6%
CARBx-ICT	2	Avg	0.12	16.79	0.66	21.49	N/A	N/A	0.00	10.48
		Stdev	0.04	0.68	0.93	3.24	N/A	N/A	0.00	0.87
		COV	34%	4%	141%	15%	N/A	N/A	0%	8%
CARBz-CH	2	Avg	0.31	3.11	0.68	3.68	N/A	N/A	0.00	1.39
		Stdev	0.00	0.19	0.18	0.01	N/A	N/A	0.00	0.07
		COV	0.0	0.1	0.3	0.0	N/A	N/A	0.0	0.1
16 Hour	3	Avg	0.20	1.53	0.27	0.24	0.26	0.26	0.22	0.52
		Stdev	0.03	0.40	0.03	0.04	0.06	0.02	0.04	0.01
		COV	14%	26%	12%	15%	21%	7%	16%	2%
TB	3	Avg	0.00	0.05	0.28	3.24	0.00	3.16	0.05	2.67
		Stdev	0.00	0.01	0.11	0.59	0.00	0.41	0.05	0.17
		COV	130%	13%	37%	18%	0%	13%	91%	6%



	Engine A	Engine B	Engine C	Engine D
FTP-w	4.70	2.67	4.08	3.10
FTP-wo	3.58	3.24	3.16	2.67
CARBx-ICT	16.79	21.49	N/A	10.48
CARBz-CH	3.11	3.68		1.39
16 Hour	1.53	0.24	0.26	0.52

FIGURE 36. AVERAGE ORGANIC CARBON EMISSIONS BASED ON FILTER COLLECTION FROM EXPOSURE CHAMBER



	Engine A	Engine B	Engine C	Engine D
FTP-w	0.13	0.34	0.00	0.12
FTP-wo	0.08	0.28	0.00	0.05
CARBx-ICT	0.12	0.66	N/A	0.00
CARBz-CH	0.31	0.68		0.00
16 Hour	0.20	0.27	0.26	0.22

FIGURE 37. AVERAGE ELEMENTAL CARBON EMISSIONS BASED ON FILTER COLLECTION FROM EXPOSURE CHAMBER

5.7.3 DMM-Based Total PM Mass-Exposure Chamber

Table 26 and Figure 38 summarize the DMM-based PM emissions for all engines and cycles tested. The DMM was very sensitive to regeneration events, particularly during the 16-Hour cycle, and also for the regeneration that occurred during CARBz-CH for Engine A.

Overall, the DMM gave higher PM mass emissions than that reported using the filter-based method, particularly when regeneration events occurred. This may be due to the high number of small particles generated during the active regeneration event, some of which may have diffused to the upper stages of the DMM, giving an apparent higher PM result.

5.7.4 MSS-Based Soot Mass-Exposure Chamber

Table 27 and Figure 39 summarize the soot emission results measured by the MSS. The soot concentration in the exposure chamber was very low -- on the order of 8 µg/m³, which is close to the detection limit of the MSS (~5 µg/m). Since the elemental carbon concentration was so low, the MSS measured directly from the exposure chamber without any addition of dilution air from its conditioning unit. For the FTP, the soot emissions were very low -- on the order of one percent of the total PM.

TABLE 26. DMM-BASED BRAKE-SPECIFIC PM MASS EMISSIONS - EXPOSURE CHAMBER

Test Cycle	Test Number	DMM-Mass, g/hp-hr			
		Engine A	Engine B	Engine C	Engine D
FTP-w	1	0.0005	0.0070	0.0003	0.0007
	2	0.0005	0.0011	0.0002	0.0007
	3	0.0005	0.0010	0.0002	0.0000
	Avg	**0.0005**	**0.0030**	**0.0002**	**0.0005**
	Stdev	**0.0000**	**0.0035**	**0.0001**	**0.0004**
	COV	**0.8%**	**114.0%**	**29.4%**	**86.9%**
FTP-wo	1	0.0000	0.0009	0.0002	0.0004
	2	0.0001	0.0008	0.0000	0.0004
	3	0.0002	0.0007	0.0000	0.0004
	Avg	**0.0001**	**0.0008**	**0.0001**	**0.0004**
	Stdev	**0.0001**	**0.0001**	**0.0001**	**0.0000**
	COV	**96.1%**	**7.9%**	**173.2%**	**7.7%**
CARBx-ICT	1	0.0016	0.0006	N/A	0.0060
	2	0.0019	0.0006	N/A	0.0008
	Avg	**0.0017**	**0.0006**	N/A	**0.0034**
	Stdev	**0.0002**	**0.0000**	N/A	**0.0037**
	COV	**12.9%**	**0.3%**	N/A	**108.1%**
CARBz-CH	1	0.0019	0.0007	N/A	0.0003
	2	0.0357	0.0007	N/A	0.0003
	Avg	**0.0188**	**0.0007**	N/A	**0.0003**
	Stdev	**0.0239**	**0.0000**	N/A	**0.0000**
	COV	**127.3%**	**4.9%**	N/A	**1.9%**
16-Hour	1	0.0062	0.0033	0.0034	0.0044
	2	0.0055	0.0059	0.0034	0.0006
	3	0.0112	0.0066	0.0008	0.0027
	Avg	**0.0076**	**0.0053**	**0.0049**	**0.0026**
	Stdev	**0.0031**	**0.0017**	**0.0064**	**0.0019**
	COV	**41.0%**	**32.4%**	**130.1%**	**75.0%**

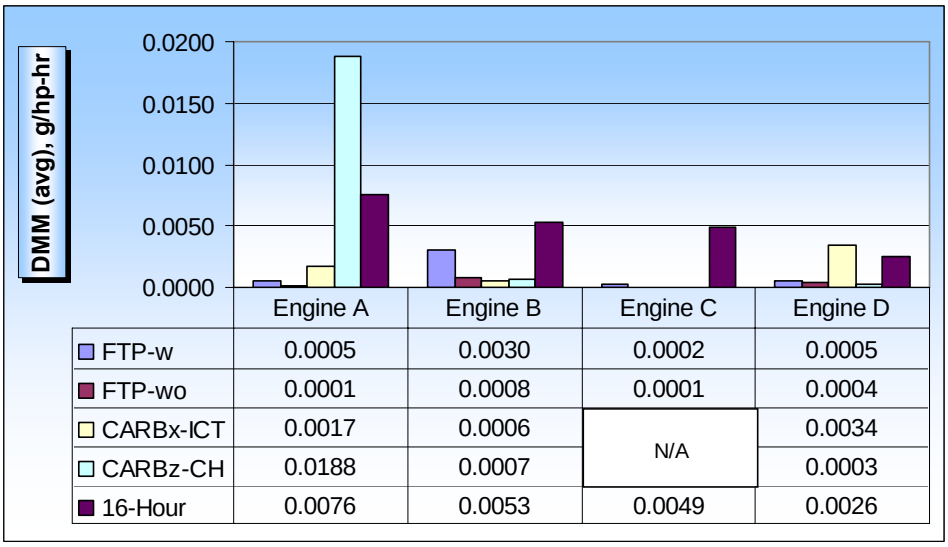


FIGURE 38. AVERAGE DMM-BASED BRAKE-SPECIFIC PM MASS EMISSIONS - EXPOSURE CHAMBER

TABLE 27. MSS-BASED BRAKE-SPECIFIC SOOT MASS EMISSIONS - EXPOSURE CHAMBER

Test Cycle	Test Number	MSS-Soot, g/hp-hr			
		Engine A	Engine B	Engine C	Engine D
FTP-w	1	0.0008	0.0013	0.0004	0.0004
	2	0.0008	0.0011	0.0003	0.0003
	3	-	0.0009	0.0003	0.0000
	Avg	**0.0008**	**0.0011**	**0.0004**	**0.0002**
	Stdev	**0.0000**	**0.0002**	**0.0001**	**0.0002**
	COV	**1.6%**	**17.1%**	**15.8%**	**86.9%**
FTP-wo	1	0.0008	0.0010	0.0004	0.0003
	2	0.0008	0.0010	0.0003	0.0003
	3	0.0008	0.0011	0.0003	0.0003
	Avg	**0.0008**	**0.0010**	**0.0003**	**0.0003**
	Stdev	**0.0000**	**0.0001**	**0.0000**	**0.0000**
	COV	**3.0%**	**5.7%**	**11.7%**	**9.1%**
CARBx-ICT	1	-	0.0021	N/A	0.0006
	2	0.0019	0.0021	N/A	0.0003
	Avg	**0.0019**	**0.0021**	N/A	**0.0004**
	Stdev	**-**	**0.0000**	N/A	**0.0002**
	COV	**-**	**0.1%**	N/A	**56.8%**
CARBz-CH	1	0.0005	0.0008	N/A	0.0002
	2	0.0006	0.0009	N/A	0.0002
	Avg	**0.0006**	**0.0008**	N/A	**0.0002**
	Stdev	**0.0001**	**0.0001**	N/A	**0.0000**
	COV	**12.0%**	**7.3%**	N/A	**11.7%**
16-Hour	1	0.0008	0.0010	0.0005	0.0005
	2	0.0007	0.0007	0.0005	0.0002
	3	0.0007	0.0009	0.0004	0.0006
	Avg	**0.0007**	**0.0009**	**0.0004**	**0.0004**
	Stdev	**0.0000**	**0.0001**	**0.0000**	**0.0002**
	COV	**3.8%**	**14.6%**	**8.9%**	**42.2%**

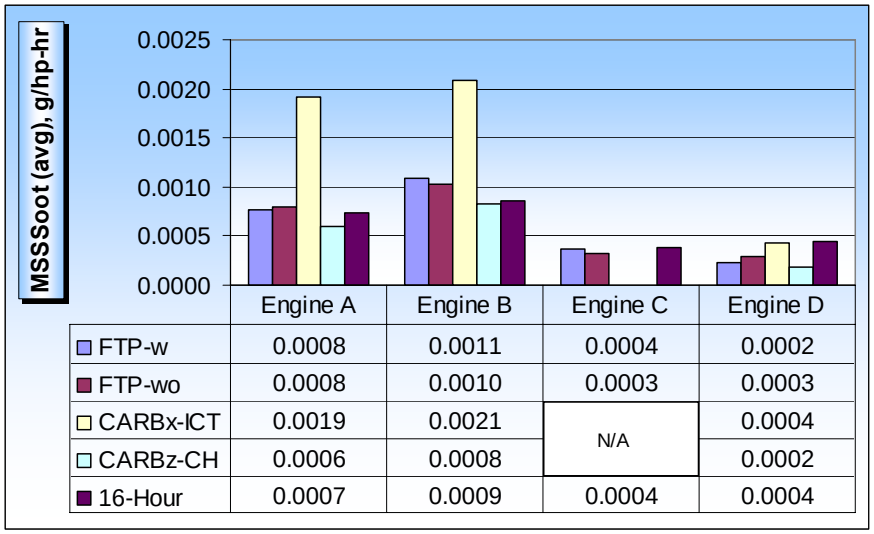


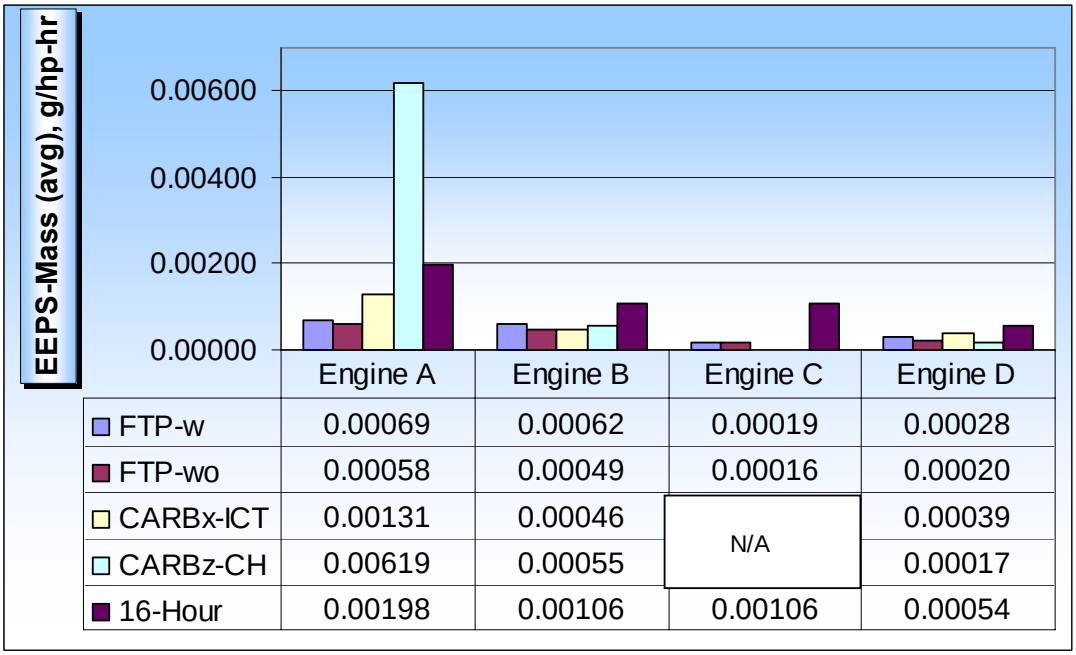
FIGURE 39. AVERAGE MSS-BASED BRAKE-SPECIFIC SOOT MASS EMISSIONS - EXPOSURE CHAMBER

5.7.5 EEPS-Based Particle Mass-Exposure Chamber

Table 28 and Figure 40 show the EEPS-based PM mass emissions from the exposure chamber. PM mass was calculated assuming spherical particles with a density of 1 g/cm³. The EEPS-based mass emissions were generally on the order of 20 to 75 percent of the PM emissions reported using the exposure chamber filter method.

TABLE 28. EEPS-BASED BRAKE-SPECIFIC PM MASS EMISSIONS - EXPOSURE CHAMBER

Test Cycle		EEPS-Mass, g/hp-hr			
		Engine A	**Engine B**	**Engine C**	**Engine D**
FTP-w	1	0.00070	0.00084	0.00019	0.00028
	2	0.00069	0.00056	0.00023	0.00030
	3	0.00069	0.00045	0.00015	0.00028
	Avg	**0.00069**	**0.00062**	**0.00019**	**0.00028**
	Stdev	**0.0000**	**0.0002**	**0.0000**	**0.0000**
	COV	**0.5%**	**32.4%**	**21.5%**	**4.0%**
FTP-wo	1	0.00020	0.00049	0.00019	0.00018
	2	-	0.00045	0.00011	0.00021
	3	0.00096	0.00054	0.00018	0.00020
	Avg	**0.00058**	**0.00049**	**0.00016**	**0.00020**
	Stdev	**0.0005**	**0.0000**	**0.0000**	**0.0000**
	COV	**93.0%**	**8.8%**	**26.2%**	**9.0%**
CARBx-ICT	1	0.00142	0.00046	N/A	0.00054
	2	0.00120	0.00046	N/A	0.00023
	Avg	**0.00131**	**0.00046**	N/A	**0.00039**
	Stdev	**0.0002**	**0.0000**	N/A	**0.0002**
	COV	**11.9%**	**0.2%**	N/A	**56.8%**
CARBz-CH	1	0.00371	0.00068	N/A	0.00016
	2	0.00867	0.00041	N/A	0.00018
	Avg	**0.00619**	**0.00055**	N/A	**0.00017**
	Stdev	**0.0035**	**0.0002**	N/A	**0.0000**
	COV	**56.7%**	**34.9%**	N/A	**9.0%**
16-Hour	1	0.00204	0.00096	0.00087	0.00079
	2	0.00184	0.00109	0.00078	0.00024
	3	0.00205	0.00113	0.00033	0.00061
	Avg	**0.00198**	**0.00106**	**0.00066**	**0.00054**
	Stdev	**0.0001**	**0.0001**	**0.00030**	**0.0003**
	COV	**6.0%**	**8.2%**	**44.3%**	**51.2%**



	Engine A	Engine B	Engine C	Engine D
FTP-w	0.00069	0.00062	0.00019	0.00028
FTP-wo	0.00058	0.00049	0.00016	0.00020
CARBx-ICT	0.00131	0.00046	N/A	0.00039
CARBz-CH	0.00619	0.00055		0.00017
16-Hour	0.00198	0.00106	0.00106	0.00054

FIGURE 40. AVERAGE EEPS-BASED PM MASS EMISSIONS - EXPOSURE CHAMBER

5.7.6 EEPS-Based Particle Number-Exposure Chamber

Table 29 and Figure 41 summarize the data on brake-specific PM number emissions in the exposure chamber. Particle number emissions were extremely sensitive to regeneration events. For Engine A, FTP-wo, where active regeneration events took place during a small portion of the cycle, the average particle number emissions was at least one order of magnitude higher than the average reported for the FTP-w, where no regeneration events occurred. The same thing can be said for Engine A, CARBz-CH, compared to the other ACES engines. For the 16-Hour cycle, the average particle number emission level was at least one order of magnitude higher than the FTP cycle because of the regeneration events that occurred during a fraction of the 16-Hour cycle. These ranged from less than 30 minutes to a few hours, depending on each engine manufacturer's regeneration strategy. Since the elemental carbon measured by the OC/EC method and the soot measured by the MSS remained low even during active regeneration, one can hypothesize that the majority of particle number emissions are volatile PM.

The effect of blow-by can also be seen with particle number measurement during the FTP transient runs, particularly for Engine C and D, where the average particle number emissions with blow-by were a factor of 2 to 7 higher than those without blow-by. Engine B showed a small increase -- on the order of 37 percent. For Engine A, no active regeneration took place for the without blow-by case, so no such comparison was made.

TABLE 29. EEPS-BASED BRAKE-SPECIFIC PM NUMBER EMISSIONS - EXPOSURE CHAMBER

Test Cycle	Test Number	Particle Number, part./hp-hr			
		Engine A	Engine B	Engine C	Engine D
FTP-w	1	4.48E+12	5.11E+12	1.83E+12	5.12E+12
	2	4.78E+12	3.26E+12	4.26E+12	5.02E+12
	3	5.16E+12	2.63E+12	6.81E+11	4.86E+12
	Avg	**4.81E+12**	**3.67E+12**	**2.26E+12**	**5.00E+12**
	Stdev	**3.41E+11**	**1.29E+12**	**1.83E+12**	**1.31E+11**
	COV	**7.1%**	**35.1%**	**81.0%**	**2.6%**
FTP-wo	1	4.52E+13	2.78E+12	6.09E+11	6.51E+11
	2	-	2.58E+12	5.66E+11	7.10E+11
	3	4.75E+13	2.63E+12	1.72E+12	7.16E+11
	Avg	**4.64E+13**	**2.66E+12**	**9.65E+11**	**6.92E+11**
	Stdev	**1.63E+12**	**1.06E+11**	**6.53E+11**	**3.58E+10**
	COV	**3.5%**	**4.0%**	**67.7%**	**5.2%**
CARBx-ICT	1	2.90E+12	2.14E+12	N/A	4.16E+12
	2	3.40E+12	2.15E+12	N/A	1.91E+12
	Avg	**3.15E+12**	**2.15E+12**	**N/A**	**3.03E+12**
	Stdev	**3.53E+11**	**7.51E+09**	**N/A**	**1.59E+12**
	COV	**11.2%**	**0.3%**	**N/A**	**52.4%**
CARBz-CH	1	1.36E+14	2.04E+12	N/A	3.21E+12
	2	3.68E+14	2.37E+12	N/A	3.33E+12
	Avg	**2.52E+14**	**2.21E+12**	**N/A**	**3.27E+12**
	Stdev	**1.64E+14**	**2.35E+11**	**N/A**	**9.06E+10**
	COV	**65.1%**	**10.6%**	**N/A**	**2.8%**
16-Hour	1	4.34E+13	4.82E+13	1.82E+13	2.48E+13
	2	3.90E+13	6.54E+13	2.18E+13	4.55E+12
	3	4.14E+13	5.59E+13	9.74E+12	2.47E+13
	Avg	**4.13E+13**	**5.65E+13**	**2.45E+13**	**1.80E+13**
	Stdev	**2.18E+12**	**8.62E+12**	**3.93E+13**	**1.17E+13**
	COV	**5.3%**	**15.3%**	**160.6%**	**64.8%**

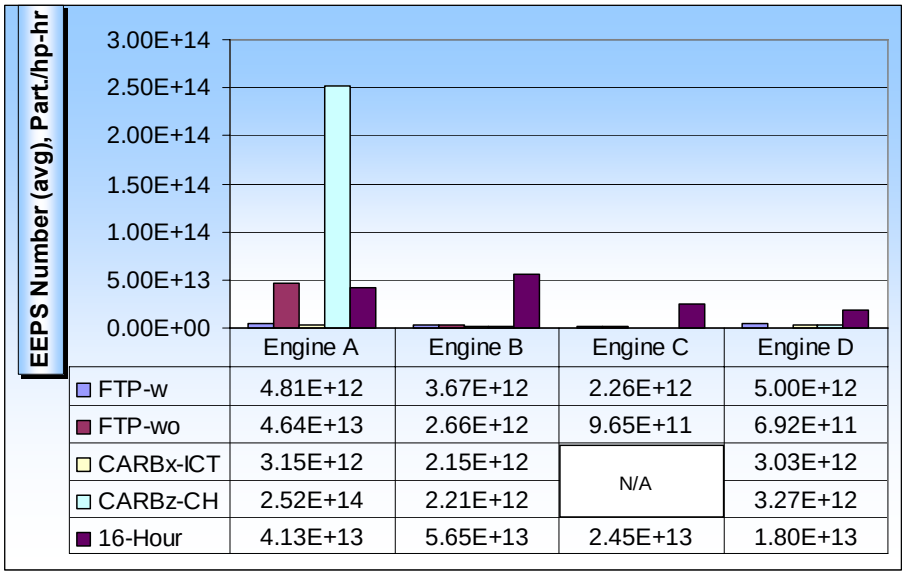


FIGURE 41. AVERAGE EEPS-BASED BRAKE-SPECIFIC PM NUMBER EMISSIONS - EXPOSURE CHAMBER

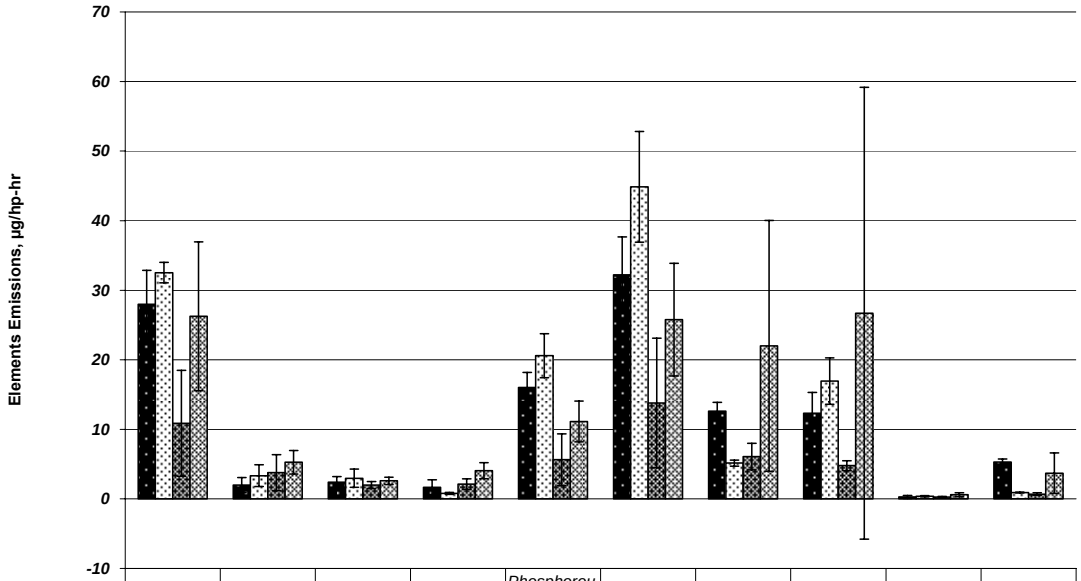
5.7.7 Metals and Other Elements

Table 30 shows a summary of total elements for all engines and cycles. It is important to note that the majority of the elements detected for the FTP, CARBx-ICT, and CARBz-CH were below the limit of detection for the X-ray fluorescence (XRF) analysis technique. Only the 16-Hour cycle presents data where the detected level was above the uncertainty level for certain elements (Figure 42). A more detailed list is included in Appendix D. Lube oil-derived elements such as phosphorus, sulfur, calcium, and zinc were observed, with the highest emissions from sulfur, which is also a fuel component. No vanadium was observed. Copper was only detected with the 16-Hour cycle.

TABLE 30. TOTAL ELEMENTAL BRAKE-SPECIFIC EMISSIONS

Test Cycle	Number of Repeats		Total Elements, µg/hp-hr			
			Engine A	Engine B	Engine C	Engine D
FTP-w[a]	3	Avg	805	1950	811	1449
		Stdev	11	49	68	98
		COV	1%	3%	8%	7%
FTP-wo[a]	3	Avg	745	2011	804	1343
		Stdev	71	217	14	297
		COV	9%	11%	2%	22%
CARBx-ICT[a]	2	Avg	3004	4293	3082	3592
		Stdev	814	67	972	526
		COV	27%	2%	32%	15%
CARBz-CH[a]	2	Avg	1625	587	551	393
		Stdev	570	38	281	33
		COV	35%	6%	51%	8%
16-Hour	3	Avg	413	541	185	376
		Stdev	62	85	109	77
		COV	15%	16%	59%	21%

[a] The great majority of the metallic elements detected were below the limit of the detection method.



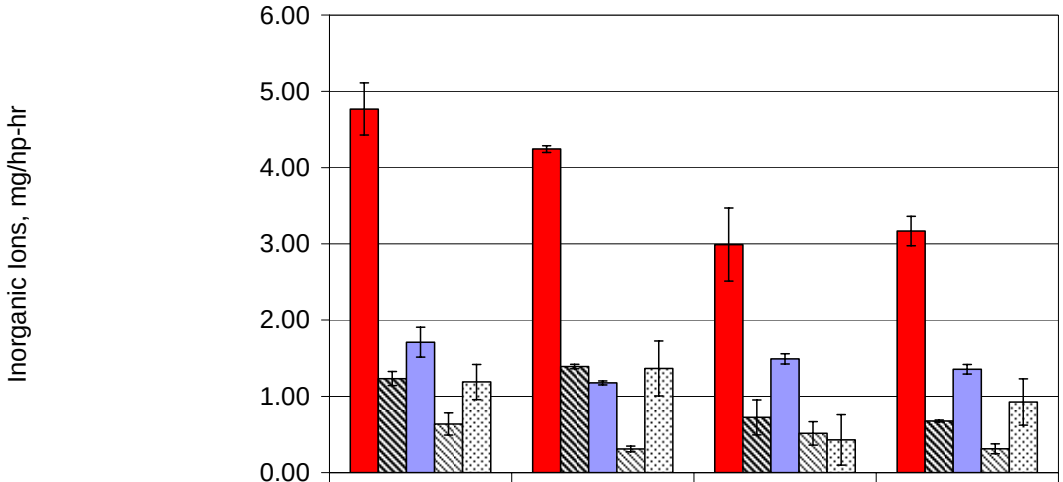
	Sodium	Magnesium	Aluminum	Silicon	Phosphorous	Sulfur/10	Calcium	Iron	Copper	Zinc
Engine A	27.99	1.99	2.41	1.67	16.02	32.22	12.61	12.32	0.28	5.29
Engine B	32.53	3.34	2.97	0.81	20.59	44.87	5.15	16.95	0.38	0.92
Engine C	10.87	3.78	1.98	2.12	5.62	13.78	6.09	4.79	0.26	0.70
Engine D	26.26	5.27	2.59	4.06	11.13	25.77	22.00	26.70	0.60	3.71

FIGURE 42. AVERAGE BRAKE-SPECIFIC ELEMENTS EMISSIONS FOR 16-HOUR CYCLE (ELEMENTS SHOWN ARE ABOVE LIMIT OF DETECTION)

5.8 Inorganic Ions Emissions

Inorganic ions were detected mainly in the 16-Hour cycle. Sulfate was the only ionic species that was detected in the particle phase. Inorganic ions collected in deionized water downstream of the sample filter were analyzed for chloride, nitrate, nitrite, sulfate, ammonium, and hydrogen ions, and pH. Only nitrate, nitrite, and sulfate, besides hydrogen ions, were detected in the water.

Figure 43 shows the brake-specific emissions of total inorganic ions (gas and particle phase), excluding hydrogen ions. Particle phase sulfate was two to three times higher than gas phase sulfate, except for Engine C, where the two had a similar level. Nitrate and nitrite were detected in the water downstream of the filter but neither of these species was observed on the filter. The average pH of the deionized water after collection during the 16-Hour cycle was about 4, as shown in Figure 44, suggesting that the solution was acidic. Figure 45 shows a comparison between measured filter-based sulfate as measured by IC and calculated sulfate from sulfur measured by the XRF method. Trends as well as the absolute emission levels were very similar between measured and calculated sulfate. Figure 46 shows a correlation between measured filter-based sulfate and sulfur. Good linear regression was observed with a coefficient of determination (R^2) of 0.93. The slope of the linear regression was 3, the same as the multiplier used to convert elemental sulfur into sulfate. This suggests that all the sulfur on the filter is in the form of SO_4^{2-}; providing evidence that there is little non-sulfate sulfur in the collected PM. In general, a large portion of PM emitted from 2007 engines is sulfate, which is derived from sulfur in the fuel and lube oil.



	Engine A	Engine B	Engine C	Engine D
Total Inorganic Ions	4.77	4.24	2.99	3.17
Gas Phase Nitrate	1.23	1.39	0.72	0.68
Gas Phase Nitrite	1.71	1.18	1.49	1.36
Gas Phase Sulfate	0.64	0.31	0.52	0.31
Particle Phase Sulfate	1.19	1.37	0.43	0.93

FIGURE 43. GAS AND PARTICLE PHASE INORGANIC IONS BRAKE-SPECIFIC EMISSIONS FOR THE 16-HOUR CYCLE

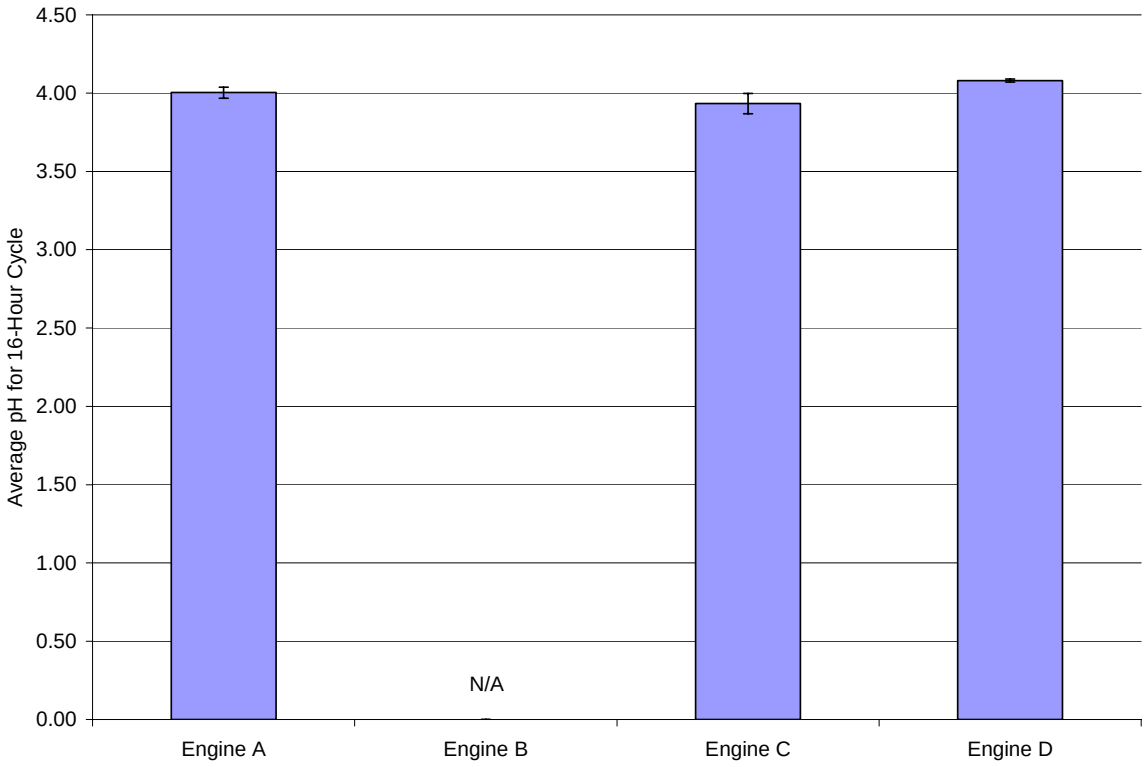
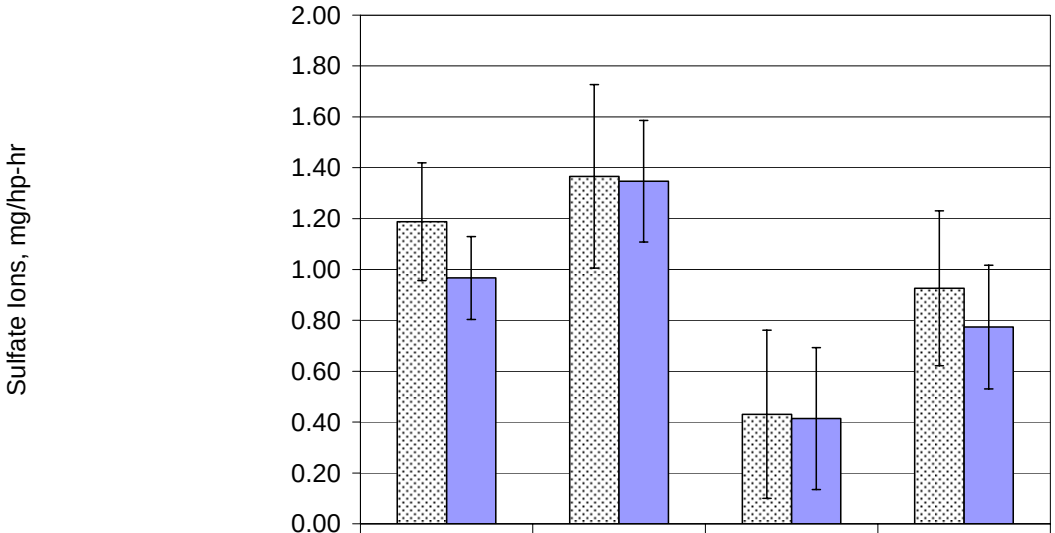


FIGURE 44. AVERAGE DEIONIZED WATER PH AFTER DILUTE EXHAUST COLLECTION DURING THE 16-HOUR CYCLE



	Engine A	Engine B	Engine C	Engine D
Measured Particle Phase Sulfate	1.19	1.37	0.43	0.93
Calculated Sulfate from Sulfur on Filter	0.97	1.35	0.41	0.77

FIGURE 45. MEASURED AND CALCULATED SULFATE PM FOR THE 16-HOUR CYCLE

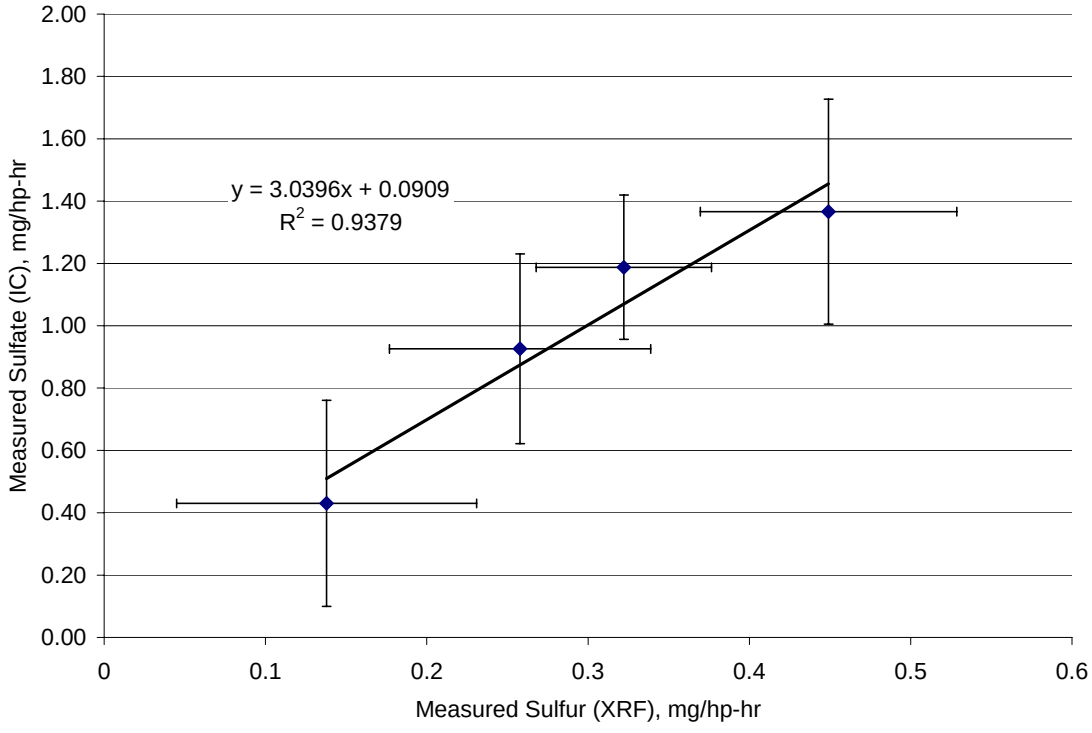


FIGURE 46. CORRELATION BETWEEN MEASURED FILTER-BASED SULFATE AND SULFUR

5.9 Carbonyl Emissions

Carbonyl compounds were detected mainly for the 16-Hour cycle and for the CARBx-ICT cycle. Figures 47 and 48 and Tables 31 and 32 show the carbonyl emissions species for all engines for the 16-Hour cycle and CARBx-ICT. Carbonyl emissions were dominated mainly by formaldehyde and acetaldehyde. Detailed carbonyl data are included in Appendix E. Figure 49 shows total carbonyl emissions for all engines and cycles. Brake-specific carbonyl emissions were the highest for the CARBx-ICT cycle. Generally, carbonyl compounds are either reported as negative values due to background subtraction or zero if the detection is below the laboratory blank.

5.10 Selected Hydrocarbon Speciation-C_1-C_{12}

Table 33 and Figure 50 summarize the BTEX (benzene, toluene, ethylbenzene, and mixed xylenes) emissions for the different engines and cycles. The lowest emission levels were from the 16-Hour cycle and ranged from 0.35 mg/hp-hr to 1.2 mg/hp-hr. CARBx-ICT again showed the highest emission levels. The highest emissions in the BTEX group were for m-& p-xylene. As for the other compounds, 1,3-butadiene was detected only for CARBx-ICT cycle. Ethylene was the highest hydrocarbon species emitted for the CARBx-ICT cycle, followed by propylene, on the order of 88 and 22 mg/hp-hr, respectively.

5.11 PAH Emissions

Table 34 and Figure 51 show a summary of total PAH, excluding any oxyPAH and nitroPAH. The sum of total brake-specific PAH emissions are the lowest for the CARBz-CH, which is the highest loaded cycle. The lightest loaded cycle, CARBx-ICT, showed the highest PAH emissions. PAH emissions were dominated by gas phase PAHs, and the largest contributors were naphthalene and F-trimethylnaphthalene (unspecified trimethyl naphthalene). Generally, higher molecular weight PAHs up to 4-ring showed higher emissions in the gas phase, compared to the particle phase. PAHs higher than 4-rings were mainly undetected.

Note that the tunnel blank (TB) PAH was based on a 20-minute run using the cycle work value of the FTP transient cycle. So, it is comparable with the FTP. The background (BG) run is based on a 16-Hour collection of CVS dilution air, from downstream of the HEPA filter. Note that the total PAH for the tunnel blank is similar to the levels with the FTP cycles. For the 16-Hour cycle, the BG emissions represents 50 to 100 percent of the 16-Hour cycle emissions.

5.12 OxyPAH Emissions

Table 35 and Figure 52 summarize the total oxyPAH emissions. Note that the sum of oxyPAHs is considerably lower than that of the PAHs.

The TB was comparable with FTP emission levels, but the 16-Hour cycle level was three to six times higher than that reported for BG dilution air, suggesting that oxyPAH formation is associated with engine operation or perhaps artifact formation during the long 16-Hour cycle. It is important to note that the oxyPAH emissions are reported in units of µg/hp-hr, while the total PAH emissions are reported in units of mg/hp-hr.

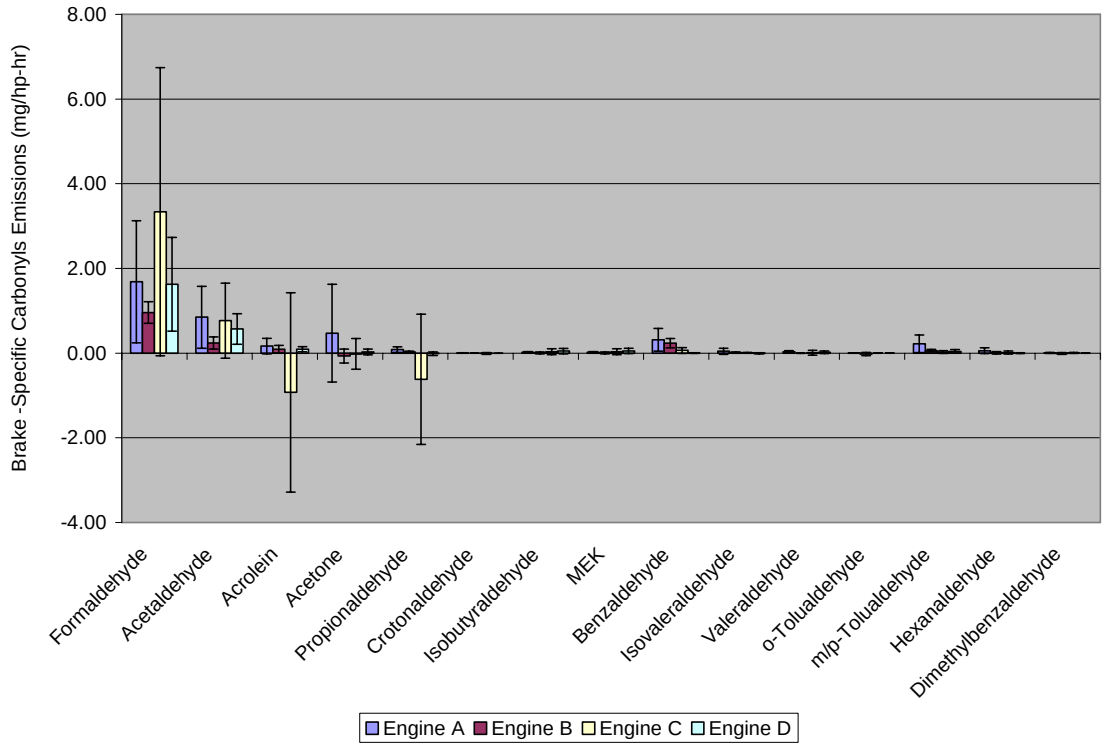


FIGURE 47. CARBONYL COMPOUND BRAKE-SPECIFIC EMISSIONS FOR 16-HOUR CYCLE

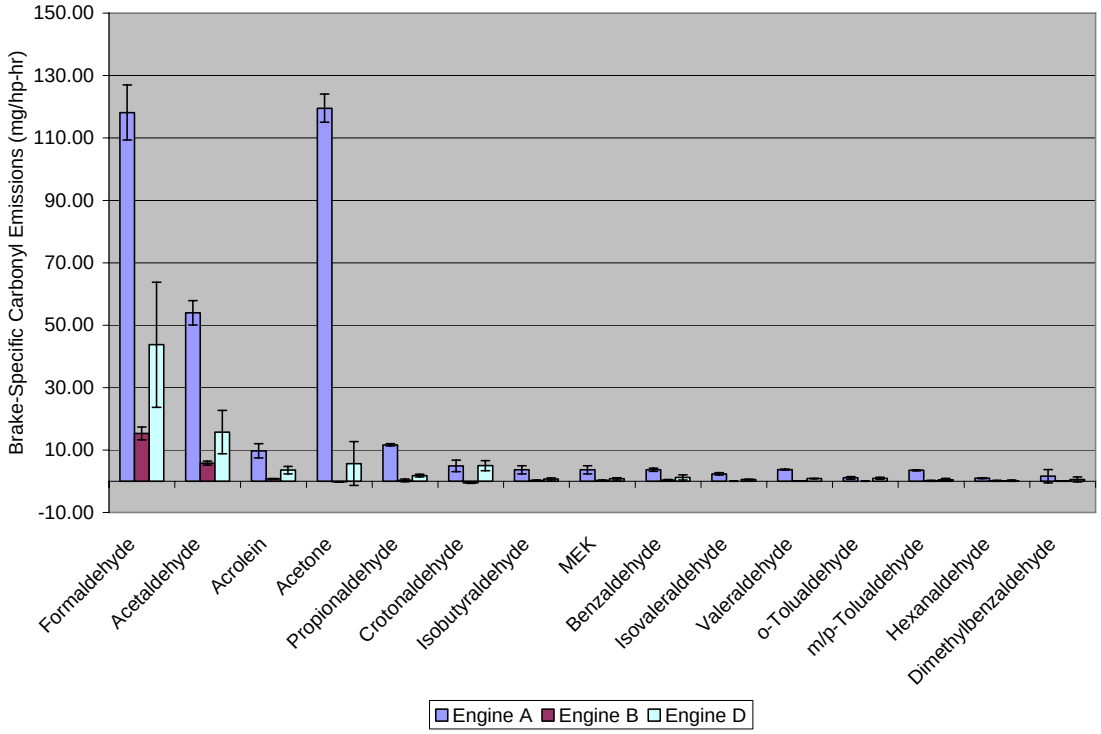


FIGURE 48. CARBONYL COMPOUND BRAKE-SPECIFIC EMISSIONS FOR CARBX-ICT

TABLE 31. CARBONYL COMPOUND BRAKE-SPECIFIC EMISSIONS FOR 16-HOUR CYCLE

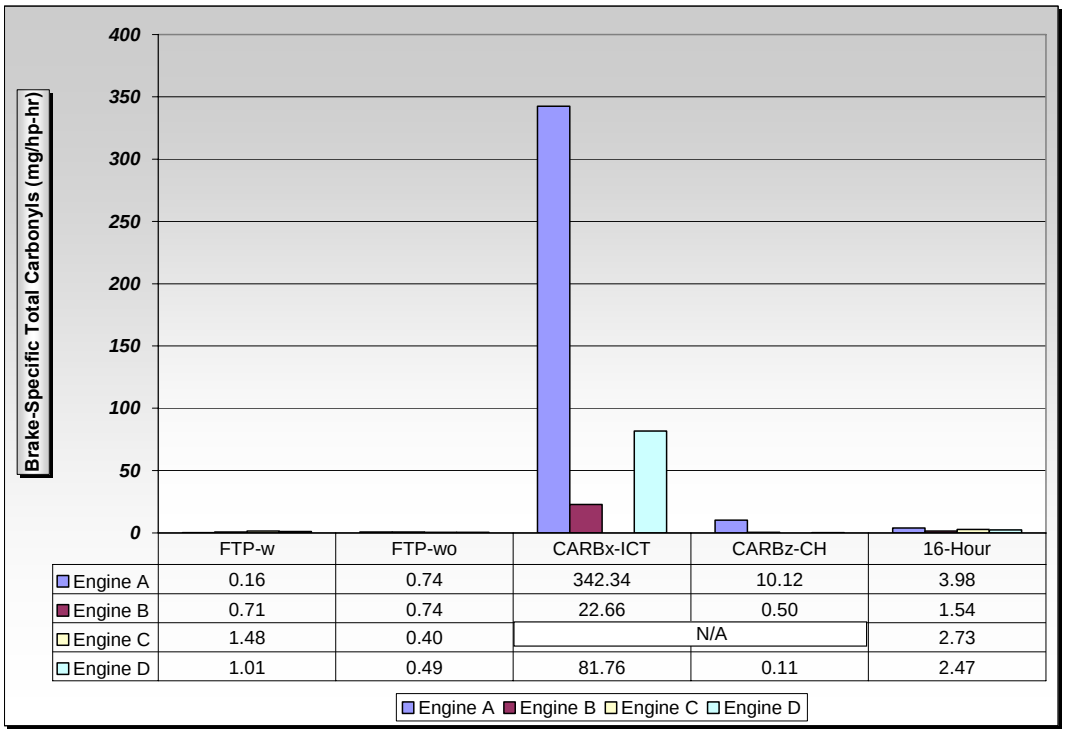
	Brake Specific Carbonyls, mg/hp-hr, 16-Hour cycle							
	Engine A		Engine B		Engine C		Engine D	
	Avg.	Stdev	Avg.	Stdev	Avg.	Stdev	Avg.	Stdev
Formaldehyde	1.69	1.44	0.96	0.25	3.34	3.40	1.63	1.11
Acetaldehyde	0.85	0.73	0.24	0.14	0.77	0.89	0.57	0.36
Acrolein	0.17	0.18	0.09	0.09	-0.93	2.35	0.09	0.06
Acetone	0.47	1.15	-0.07	0.17	-0.02	0.36	0.03	0.07
Propionaldehyde	0.08	0.07	0.03	0.02	-0.62	1.54	-0.01	0.04
Crotonaldehyde	0.00	0.00	0.00	0.00	-0.01	0.02	0.00	0.00
Isobutyraldehyde	0.02	0.02	0.01	0.02	0.03	0.07	0.05	0.06
MEK	0.02	0.02	0.01	0.02	0.03	0.07	0.05	0.06
Benzaldehyde	0.32	0.27	0.23	0.11	0.06	0.07	0.00	0.01
Isovaleraldehyde	0.04	0.07	0.01	0.01	0.01	0.01	0.00	0.01
Valeraldehyde	0.03	0.03	0.00	0.00	0.01	0.06	0.02	0.03
o-Tolualdehyde	0.00	0.00	-0.02	0.04	0.00	0.00	0.00	0.00
m/p-Tolualdehyde	0.22	0.21	0.06	0.03	0.03	0.03	0.04	0.04
Hexanaldehyde	0.06	0.07	0.01	0.03	0.01	0.03	0.00	0.01
Dimethylbenzaldehyde	0.00	0.01	-0.01	0.02	0.00	0.01	0.00	0.00

Negative values are due to background subtraction
Zero is reported if the measurement is below the analytical laboratory blank value

TABLE 32. CARBONYL COMPOUND BRAKE-SPECIFIC EMISSIONS FOR CARBX-ICT

	Brake Specific Carbonyls, mg/hp-hr, 16-Hour cycle							
	Engine A		Engine B		Engine C		Engine D	
	Avg.	Stdev	Avg.	Stdev	Avg.	Stdev	Avg.	Stdev
Formaldehyde	118.16	8.78	15.33	2.04	N/A	N/A	43.74	20.03
Acetaldehyde	54.00	3.91	5.78	0.66	N/A	N/A	15.73	6.95
Acrolein	9.76	2.25	0.79	0.04	N/A	N/A	3.55	1.21
Acetone	119.55	4.52	-0.18	0.00	N/A	N/A	5.66	7.05
Propionaldehyde	11.67	0.33	0.29	0.45	N/A	N/A	1.82	0.44
Crotonaldehyde	4.92	1.85	-0.55	0.15	N/A	N/A	5.00	1.59
Isobutyraldehyde	3.67	1.28	0.25	0.03	N/A	N/A	0.75	0.31
MEK	3.67	1.28	0.25	0.03	N/A	N/A	0.76	0.32
Benzaldehyde	3.70	0.51	0.37	0.17	N/A	N/A	1.22	0.84
Isovaleraldehyde	2.38	0.39	0.00	0.00	N/A	N/A	0.56	0.09
Valeraldehyde	3.73	0.17	0.03	0.04	N/A	N/A	0.85	0.09
o-Tolualdehyde	1.07	0.41	0.00	0.00	N/A	N/A	0.94	0.36
m/p-Tolualdehyde	3.47	0.17	0.11	0.15	N/A	N/A	0.45	0.43
Hexanaldehyde	0.96	0.15	0.12	0.17	N/A	N/A	0.18	0.21
Dimethylbenzaldehyde	1.62	2.15	0.06	0.09	N/A	N/A	0.55	0.78

Negative values are due to background subtraction
Zero is reported if the measurement is below the analytical laboratory blank value

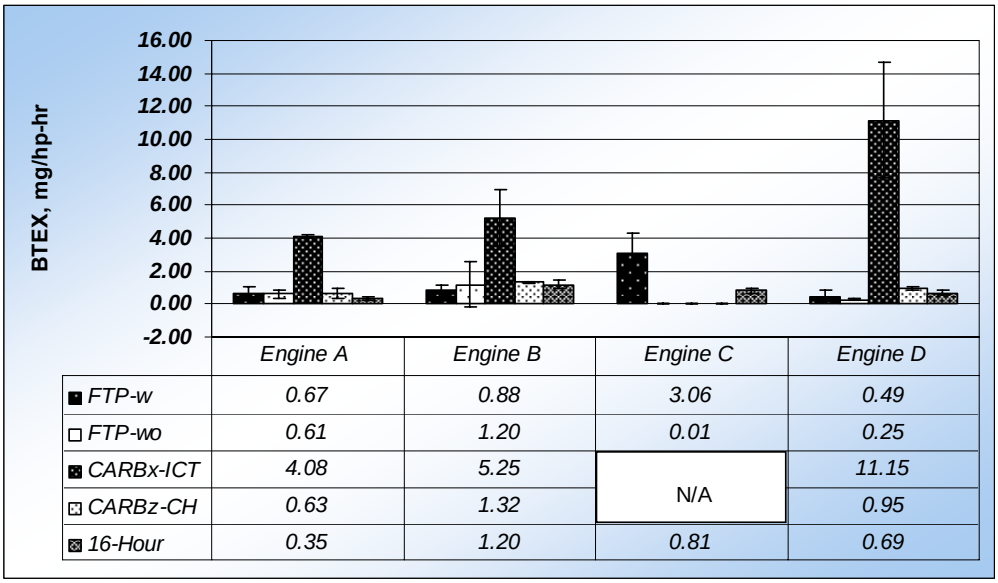


	FTP-w	FTP-wo	CARBx-ICT	CARBz-CH	16-Hour
Engine A	0.16	0.74	342.34	10.12	3.98
Engine B	0.71	0.74	22.66	0.50	1.54
Engine C	1.48	0.40	N/A		2.73
Engine D	1.01	0.49	81.76	0.11	2.47

FIGURE 49. TOTAL CARBONYL COMPOUND BRAKE-SPECIFIC EMISSIONS FOR ALL ENGINES AND CYCLES

TABLE 33. TOTAL BTEX COMPOUND BRAKE-SPECIFIC EMISSIONS

Test Cycle	Number of Repeats		BTEX, mg/hp-hr			
			Engine A	Engine B	Engine C	Engine D
FTP-w	3	**Avg**	0.67	0.88	3.06	0.49
		Stdev	0.36	0.23	1.27	0.40
		COV	53.0%	26.1%	41.4%	81.2%
FTP-wo	3	**Avg**	0.61	1.20	0.01	0.25
		Stdev	0.26	1.38	0.02	0.05
		COV	42.5%	115.4%	173.2%	20.2%
CARBx-ICT	2	**Avg**	4.08	5.25	N/A	11.15
		Stdev	0.11	1.75	N/A	3.50
		COV	2.7%	33.3%	N/A	31.4%
CARBz-CH	2	**Avg**	0.63	1.32	N/A	0.95
		Stdev	0.28	0.05	N/A	0.15
		COV	44.8%	4.1%	N/A	15.6%
16-Hour	3	**Avg**	0.35	1.20	0.81	0.69
		Stdev	0.11	0.22	0.14	0.17
		COV	32.8%	18.5%	16.8%	24.3%



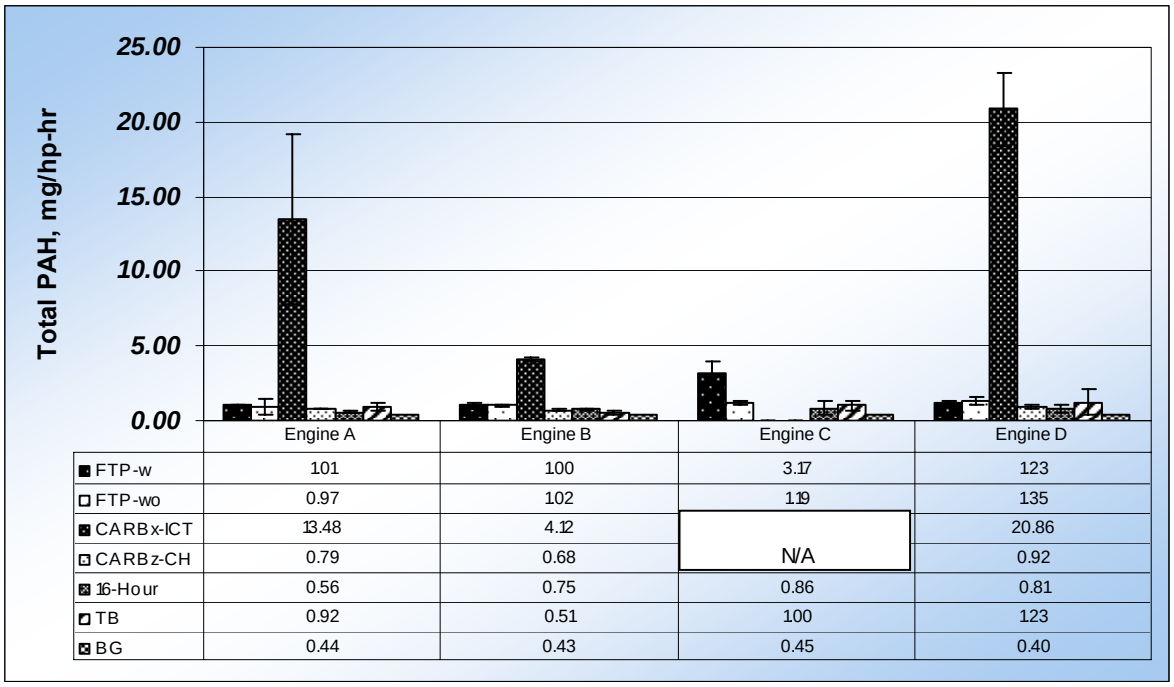
	Engine A	Engine B	Engine C	Engine D
FTP-w	0.67	0.88	3.06	0.49
FTP-wo	0.61	1.20	0.01	0.25
CARBx-ICT	4.08	5.25	N/A	11.15
CARBz-CH	0.63	1.32		0.95
16-Hour	0.35	1.20	0.81	0.69

FIGURE 50. AVERAGE TOTAL BTEX COMPOUND BRAKE-SPECIFIC EMISSIONS FOR DIFFERENT ENGINES AND CYCLES

TABLE 34. SUMMARY OF PAH COMPOUND BRAKE-SPECIFIC EMISSIONS

Test Cycle	Number of Repeats		Total PAH, mg/hp-hr			
			Engine A	Engine B	Engine C	Engine D
FTP-w	3	**Avg**	1.01	1.00	3.17	1.23
		Stdev	0.03	0.24	0.79	0.16
		COV	3.2%	24.3%	24.9%	12.8%
FTP-wo	3	**Avg**	0.97	1.02	1.19	1.35
		Stdev	0.55	0.10	0.13	0.26
		COV	56.2%	9.6%	11.2%	19.5%
CARBx-ICT	2	**Avg**	13.48	4.12	N/A	20.86
		Stdev	5.64	0.14	N/A	2.48
		COV	41.8%	3.3%	N/A	11.9%
CARBz-CH	2	**Avg**	0.79	0.68	N/A	0.92
		Stdev	0.02	0.05	N/A	0.18
		COV	3.0%	8.1%	N/A	19.4%
16-Hour	3	**Avg**	0.56	0.75	0.86	0.81
		Stdev	0.08	0.06	0.43	0.25
		COV	13.7%	8.0%	49.8%	30.8%
TB	3	**Avg**	0.92	0.51	1.00	1.23
		Stdev	0.25	0.10	0.34	0.84
		COV	27.6%	20.3%	33.8%	68.6%
BG	1	**Value**	0.44	0.43	0.45	0.40

Because the analytical lab reported data below the limit of detection, the actual values reported were included in the summation, regardless of whether or not the value is above or below the limit of detection. Except for the 16-Hour cycle, many compounds were below the limit of detection and can contribute to the total sum.



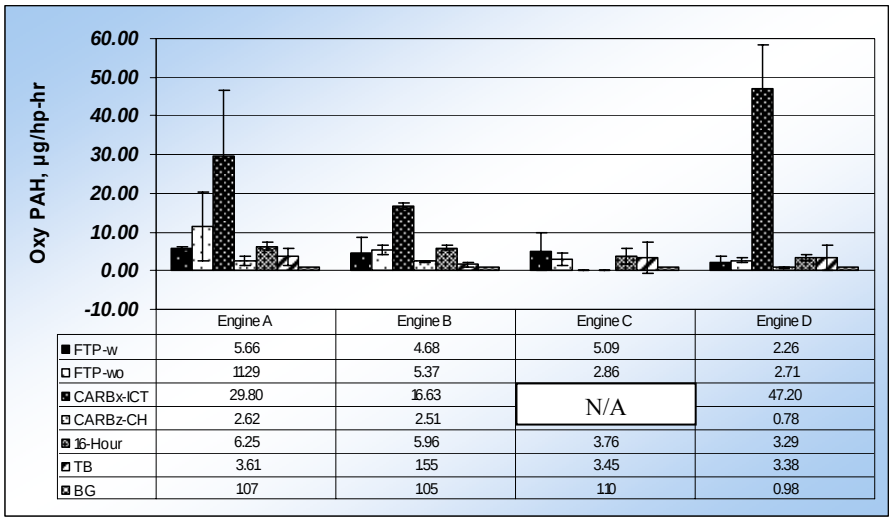
	Engine A	Engine B	Engine C	Engine D
FTP-w	1.01	1.00	3.17	1.23
FTP-wo	0.97	1.02	1.19	1.35
CARBx-ICT	13.48	4.12		20.86
CARBz-CH	0.79	0.68	N/A	0.92
16-Hour	0.56	0.75	0.86	0.81
TB	0.92	0.51	1.00	1.23
BG	0.44	0.43	0.45	0.40

FIGURE 51. PAH COMPOUND BRAKE-SPECIFIC EMISSIONS

TABLE 35. SUMMARY OF OXYPAH COMPOUND BRAKE-SPECIFIC EMISSIONS

Test Cycle	Number of Repeats		OxyPAH, µg/hp-hr			
			Engine A	Engine B	Engine C	Engine D
FTP-w	3	**Avg**	5.66	4.68	5.09	2.26
		Stdev	0.39	4.00	4.87	1.47
		COV	6.8%	85.5%	95.8%	65.1%
FTP-wo	3	**Avg**	11.29	5.37	2.86	2.71
		Stdev	8.88	1.26	1.69	0.54
		COV	78.7%	23.5%	59.1%	19.8%
CARBx-ICT	2	**Avg**	29.80	16.63	N/A	47.20
		Stdev	16.67	0.70	N/A	11.02
		COV	55.9%	4.2%	N/A	23.4%
CARBz-CH	2	**Avg**	2.62	2.51	N/A	0.78
		Stdev	1.18	0.19	N/A	0.30
		COV	45.1%	7.7%	N/A	39.0%
16-Hour	3	**Avg**	6.25	5.96	3.76	3.29
		Stdev	1.08	0.68	1.84	0.76
		COV	17.2%	11.5%	49.0%	23.0%
TB	3	**Avg**	3.61	1.55	3.45	3.38
		Stdev	2.23	0.64	4.11	3.26
		COV	61.8%	41.4%	119.1%	96.6%
BG	1	**Value**	1.07	1.05	1.10	0.98

Because the analytical lab reported data below the limit of detection, the actual values reported were included in the summation, regardless of whether or not the value is above or below the limit of detection. Except for the 16-Hour cycle, many compounds were below the limit of detection and can contribute to the total sum.



	Engine A	Engine B	Engine C	Engine D
FTP-w	5.66	4.68	5.09	2.26
FTP-wo	11.29	5.37	2.86	2.71
CARBx-ICT	29.80	16.63	N/A	47.20
CARBz-CH	2.62	2.51		0.78
16-Hour	6.25	5.96	3.76	3.29
TB	3.61	1.55	3.45	3.38
BG	1.07	1.05	1.10	0.98

FIGURE 52. OXYPAH COMPOUND BRAKE-SPECIFIC EMISSIONS

5.13 NitroPAH Emissions

Table 36 and Figure 53 show total brake-specific nitroPAH emissions. NitroPAH emissions for the 16-Hour cycle were a factor of 2 to 3 times higher than background levels. Also, FTP cycle emissions were more than a factor of 20 higher than the tunnel blank, but due to measurement uncertainty at such as low emission level, no conclusions can be drawn.

5.14 Alcohol and Organic Acid Compound Emissions

Table 37 and Figure 54 show a summary of alcohol and organic acid compound brake-specific emissions. For the 16-Hour cycle, alcohol and organic compound emissions were a factor of 43 to 100 higher than background. For the FTP, the emissions were only a factor of 1.1 to 4.3 higher than a tunnel blank. This suggests that during a short sampling time of 20 minutes, the outgassing of material can have a major contribution to the reported emissions value for cycles like the FTP, CARBx-ICT, and CARBz-CH.

5.15 Hopanes/Steranes Emissions

Table 38 and Figure 55, and Table 39 and Figure 56 summarize the results for hopanes and steranes. Hopanes and steranes were found in the lube oil. Since the FTP ran with and without blow-by, one would expect that the runs without blow-by would have had lower hopanes and steranes emissions. That was the case for Engines A, B, and D. Only Engine C had lower hopanes and steranes emissions when the engine ran with blow-by added to the exhaust. There were very little hopanes and steranes measured in the background air.

TABLE 36. SUMMARY OF NITROPAH COMPOUND BRAKE-SPECIFIC EMISSIONS

Test Cycle	Number of Repeats		NitroPAH, µg/hp-hr			
			Engine A	Engine B	Engine C	Engine D
FTP-w	3	**Avg**	2.36	1.51	4.17	0.57
		Stdev	0.08	0.44	0.57	0.34
		COV	3.5%	29.2%	13.6%	59.0%
FTP-wo	3	**Avg**	1.65	1.89	1.05	0.06
		Stdev	1.22	0.96	0.69	0.06
		COV	73.7%	50.6%	65.9%	93.2%
CARBx-ICT	2	**Avg**	7.71	7.83	N/A	10.86
		Stdev	3.95	1.20	N/A	6.06
		COV	51.3%	0.15	N/A	55.8%
CARBz-CH	2	**Avg**	1.50	1.91	N/A	0.51
		Stdev	0.44	0.17	N/A	0.05
		COV	29.6%	0.09	N/A	10.3%
16-Hour	3	**Avg**	0.40	0.77	0.86	0.58
		Stdev	0.20	0.38	0.23	0.04
		COV	50.5%	49.3%	26.6%	7.5%
TB	3	**Avg**	0.10	0.68	0.26	0.09
		Stdev	0.12	0.55	0.30	0.15
		COV	117.0%	81.1%	115.5%	164.6%
BG	1	**Value**	0.22	0.21	0.23	0.20

Because the analytical lab reported data below the limit of detection, the actual values reported were included in the summation, regardless of whether or not the value is above or below the limit of detection. Except for the 16-Hour cycle, many compounds were below the limit of detection and can contribute to the total sum.

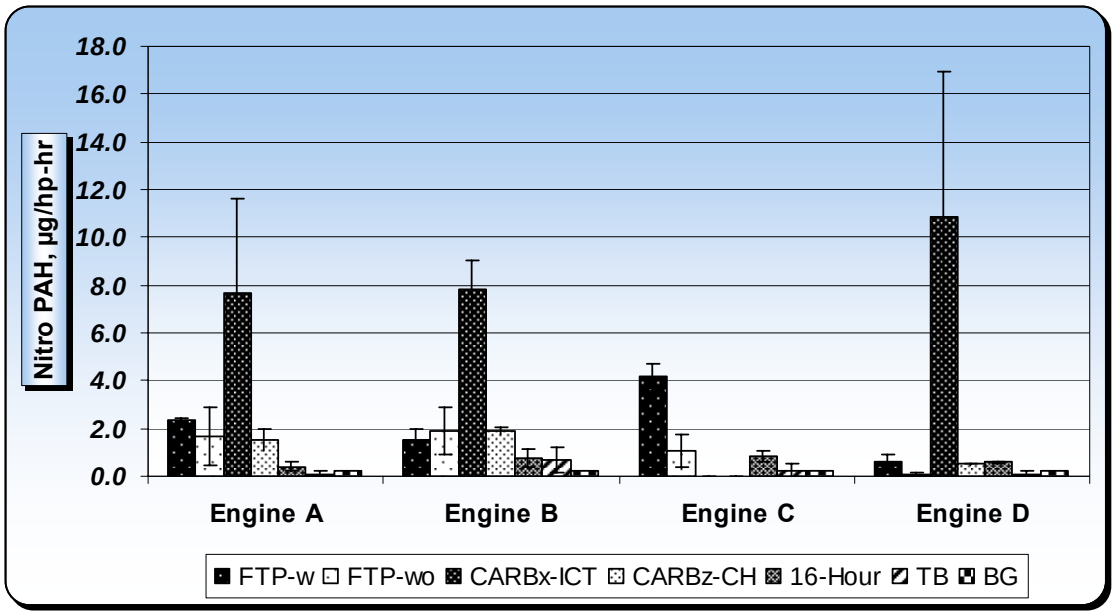


FIGURE 53. NITROPAH COMPOUND BRAKE-SPECIFIC EMISSIONS

TABLE 37. SUMMARY OF ALCOHOL AND ORGANIC ACID COMPOUND BRAKE-SPECIFIC EMISSIONS

Test Cycle	Number of Repeats		Alcohol and Organic Acid Compounds, mg/hp-hr			
			Engine A	Engine B	Engine C	Engine D
FTP-w	3	**Avg**	12.60	8.36	16.14	11.50
		Stdev	4.00	0.91	8.66	1.21
		COV	32%	11%	54%	10%
FTP-wo	3	**Avg**	11.88	12.16	9.75	7.92
		Stdev	2.50	3.16	5.57	6.04
		COV	21%	26%	57%	76%
CARBx-ICT	2	**Avg**	31.07	18.36	N/A	29.12
		Stdev	12.29	6.00	N/A	13.23
		COV	40%	33%	N/A	45%
CARBz-CH	2	**Avg**	7.17	2.84	N/A	2.52
		Stdev	1.55	0.19	N/A	0.22
		COV	22%	7%	N/A	9%
16-Hour	3	**Avg**	1.43	0.87	1.27	0.99
		Stdev	0.28	0.13	0.02	0.14
		COV	19%	15%	2%	15%
TB	3	**Avg**	4.55	7.54	3.68	7.79
		Stdev	2.20	2.83	4.71	5.57
		COV	48%	38%	128%	72%
BG	3	**Value**	0.084	0.082	0.086	0.077

Because the analytical lab reported data below the limit of detection, the actual values reported were included in the summation, regardless of whether or not the value is above or below the limit of detection. Except for the 16-Hour cycle, many compounds were below the limit of detection and can contribute to the total sum.

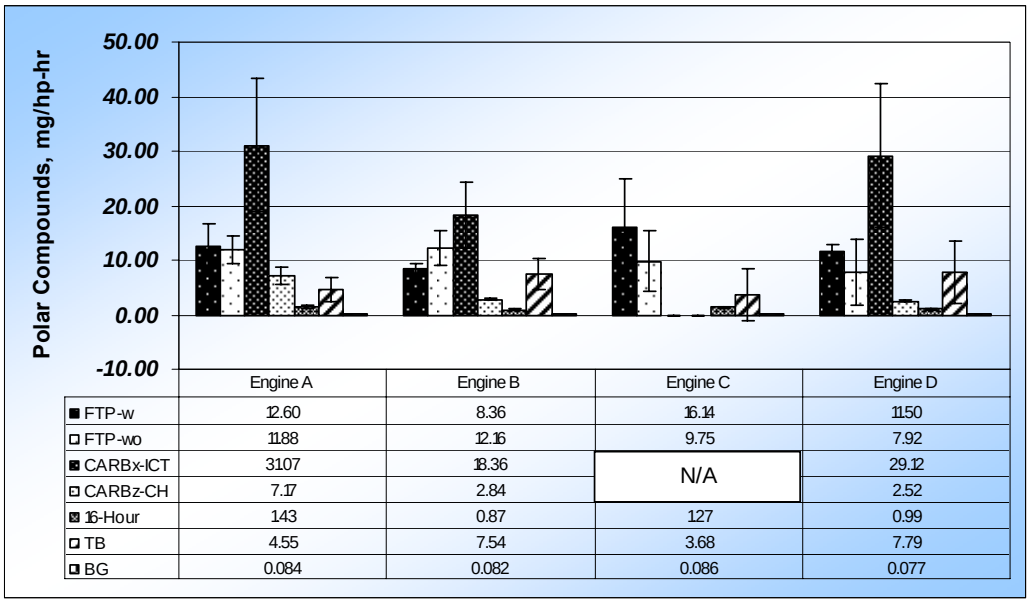


FIGURE 54. ALCOHOL AND ORGANIC ACID COMPOUNDS BRAKE-SPECIFIC EMISSIONS

TABLE 38. HOPANES BRAKE-SPECIFIC EMISSIONS

Test Cycle	Number of Repeats		Total Hopanes, µg/hp-hr			
			Engine A	Engine B	Engine C	Engine D
FTP-w	3	**Avg**	1.93	0.38	0.11	0.78
		Stdev	0.25	0.10	0.02	0.07
		COV	13.0%	26.0%	18.7%	8.7%
FTP-wo	3	**Avg**	0.65	0.22	0.48	0.58
		Stdev	0.23	0.05	0.10	0.04
		COV	35.7%	24.0%	21.6%	6.2%
CARBx-ICT	2	**Avg**	4.18	0.73	N/A	2.34
		Stdev	2.05	0.02	N/A	0.29
		COV	49.0%	2.7%	N/A	12.5%
CARBz-CH	2	**Avg**	0.79	0.14	N/A	0.31
		Stdev	0.14	0.00	N/A	0.02
		COV	17.8%	0.4%	N/A	7.1%
16-Hour	3	**Avg**	2.15	0.10	0.10	0.22
		Stdev	1.39	0.01	0.01	0.07
		COV	64.9%	8.8%	12.0%	29.9%
TB	3	**Avg**	0.97	0.07	0.07	0.49
		Stdev	0.58	0.02	0.02	0.22
		COV	60.0%	28.3%	28.3%	45.3%
BG	1	**Value**	0.02	0.02	0.02	0.02

Because the analytical lab reported data below the limit of detection, the actual values reported were included in the summation, regardless of whether or not the value is above or below the limit of detection. Except for the 16-Hour cycle, many compounds were below the limit of detection and can contribute to the total sum.

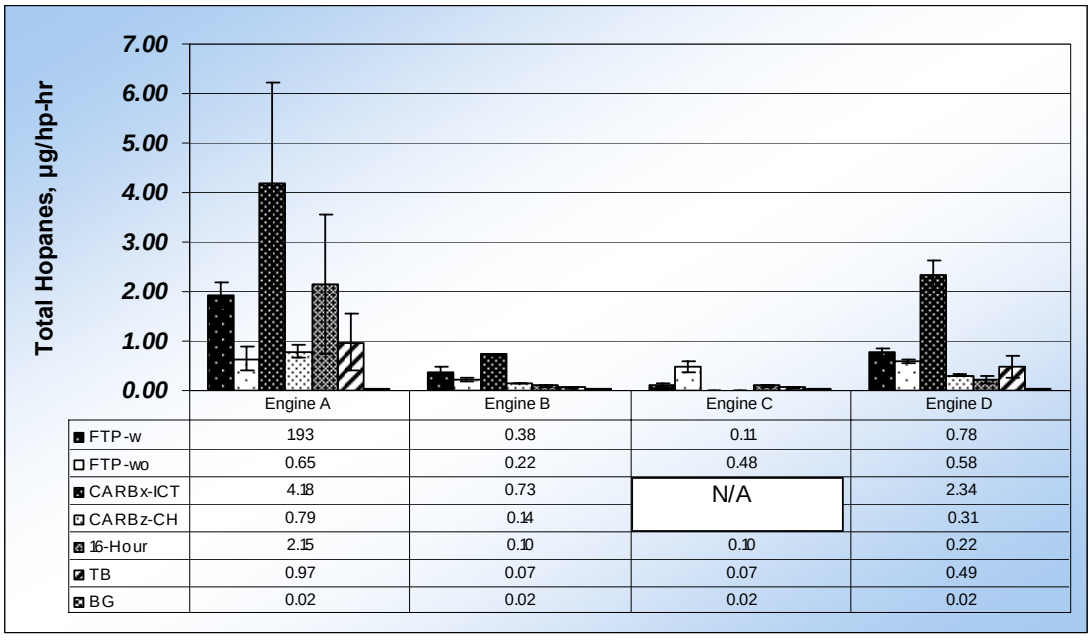


FIGURE 55. AVERAGE HOPANES BRAKE-SPECIFIC EMISSIONS

TABLE 39. STERANES BRAKE-SPECIFIC EMISSIONS

Test Cycle	Number of Repeats		Total Steranes, µg/hp-hr			
			Engine A	Engine B	Engine C	Engine D
FTP-w	3	**Avg**	0.54	0.14	0.08	0.17
		Stdev	0.09	0.03	0.01	0.04
		COV	17.1%	23.0%	8.2%	22.3%
FTP-wo	3	**Avg**	0.17	0.12	0.20	0.09
		Stdev	0.22	0.03	0.12	0.01
		COV	131.2%	21.9%	58.5%	11.6%
CARBx-ICT	2	**Avg**	0.93	0.25	N/A	0.60
		Stdev	1.32	0.00	N/A	0.08
		COV	141.4%	0.4%	N/A	13.9%
CARBz-CH	2	**Avg**	0.30	0.06	N/A	0.12
		Stdev	0.03	0.00	N/A	0.00
		COV	11.0%	3.3%	N/A	1.1%
16-Hour	3	**Avg**	1.56	0.03	0.05	0.11
		Stdev	1.07	0.00	0.01	0.04
		COV	68.7%	12.9%	13.4%	37.6%
TB	3	**Avg**	0.22	0.03	0.03	0.06
		Stdev	0.13	0.03	0.03	0.01
		COV	59.8%	83.6%	83.6%	24.3%
BG	1	**Value**	0.02	0.02	0.02	0.02
Because the analytical lab reported data below the limit of detection, the actual values reported were included in the summation, regardless of whether or not the value is above or below the limit of detection. Except for the 16-Hour cycle, many compounds were below the limit of detection and can contribute to the total sum.						

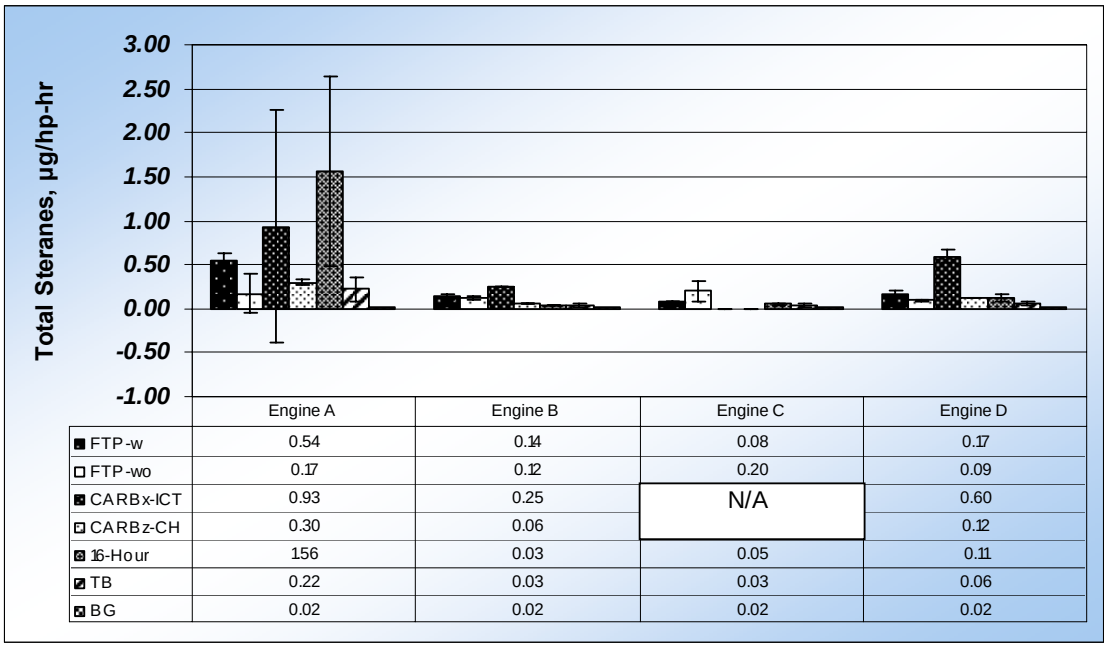


FIGURE 56. AVERAGE STERANES BRAKE-SPECIFIC EMISSIONS

5.16 Dioxins/Furans Emissions

Tables 40, 41, and 42 show the toxic equivalent (TEQ) mass of the 17 dioxin and furan compounds, for Engines A, C, and D, respectively. The toxic equivalency factor (TEF) is shown for each compound, along with the TEQ values in picograms. Essentially, the mass shown in the tables is the TEQ mass collected by an 8x10 filter and a PUF XAD during the16-Hour transient cycle, and during a 16 hour background air collection.

Table 43 shows TEQ brake-specific emissions for actual engine operation, background, and for net emissions determined by subtracting the background. The net brake-specific emissions level was below 0.5 picogram/hp-hr. The total TEQ of dioxins/furans emitted during the 16 hour cycle ranged from about 45 to 600 picograms. The average concentration in the exposure chamber ranged from about 0.006 to 0.08 picograms per cubic meter.

In a 1996 and 1998 on-highway diesel truck tunnel study [2], the TEQ was estimated to be about 946 picograms per liter of diesel fuel. The calculated TEQ emissions in this work ranges from 0.13 to 1.4 picogram per liter of diesel fuel, which represents a greater than 99.9 percent reduction.

Table 44 shows the sum of tetra-, penta-, hexa-, and hepta- dioxins/furans. Total dioxin/furan emissions are a factor of 100 higher than the toxic-equivalent dioxins/furans.

Table 45 shows the presence of total chlorine in fresh and used lube oil for Engine C and D. The concentration by mass is on the order of 120 ppm. Table 46 shows the concentration of chlorine and chloride, and total chlorine (sum of chlorine and chloride) in the background air and also in engine intake air. Engine intake air is typically humidified with a water spray to meet target levels of relative humidity and temperature required by CFR Part 1065. The elevated chlorine level in the intake air may be due to the chlorine contained in the water spray. Both intake air chlorine and chlorine in the lube oil may contribute to dioxin and furan formation.

5.17 Cyanide, Sulfide, and Hexavalent Chromium Emissions

The emissions for cyanide, sulfide, and hexavalent chromium were all below the lowest detection limit, which was about 0.6, 11.5, and 0.1 µg/hp-hr, respectively, for the 16-Hour cycle.

5.18 Nitrosamines Emissions

Table 47 and Figure 57 show a summary of total nitrosamines. For the 16-Hour cycle, N-nitrosodi-N-methylamine (NDMA) dominated the emissions. For the rest of the cycles and engines, the emissions mainly contained N-nitrosodi-N-ethylamine (NDEA) besides NDMA. Detailed data are included in Appendix F.

TABLE 40. TEQ MASS OF DIOXINS/FURANS COLLECTED DURING 16-HOUR CYCLE FOR ENGINE A AND BACKGROUND SAMPLE

Engine A TEQ Dioxins/Furans, ng/sample						
TEQ Summary		16-Hour Cycle XAD	16-Hour Cycle 8 x 10 Filter		16-Hour Background XAD	16-Hour Background 8 x 10 Filter
ANALYTE	TEF					
2,3,7,8-TCDD	1	0	0		0	0
1,2,3,7,8-PeCDD	0.5	0	0		0.0314	0
1,2,3,4,7,8-HxCDD	0.1	0.052	0		0	0
1,2,3,6,7,8-HxCDD	0.1	0.0908	0		0	0
1,2,3,7,8,9-HxCDD	0.1	0.145	0		0	0
1,2,3,4,6,7,8-HpCDD	0.01	0.0462	0		0.0408	0.0345
OCDD	0.001	0.02548	0.0177		0.00586	0
2,3,7,8-TCDF	0.1	1.56	0.172		0.808	0
1,2,3,7,8-PeCDF	0.05	0.3925	0.04625		0.1155	0
2,3,4,7,8-PeCDF	0.5	0	0		0.715	1.04
1,2,3,4,7,8-HxCDF	0.1	0.248	0.392		0.28	0.351
1,2,3,6,7,8-HxCDF	0.1	0.528	0.262		0.1315	0.21
1,2,3,7,8,9-HxCDF	0.1	0	0		0	0
2,3,4,6,7,8-HxCDF	0.1	0	0.286		0.0638	0
1,2,3,4,6,7,8-HpCDF	0.01	0	0		0	0
1,2,3,4,7,8,9-HpCDF	0.01	0	0		0	0
OCDF	0.001	0.00795	0.008		0.00587	0.00257
Total TEQ, ng/sample		**3.10**	**1.18**		**2.20**	**1.64**
TEQ: toxic equivalent mass that is obtained by multiplying the measured mass per sample of a particular compound by the toxic equivalent factor (TEF)						

TABLE 41. TEQ MASS OF DIOXINS/FURANS COLLECTED DURING 16-HOUR CYCLE FOR ENGINE C AND BACKGROUND SAMPLE

Engine C TEQ Dioxins/Furans, ng/sample						
TEQ Summary		16-Hour Cycle XAD	16-Hour Cycle 8 x 10 Filter		16-Hour Background XAD	16-Hour Background 8 x 10 Filter
ANALYTE	TEF					
2,3,7,8-TCDD	1	0	0		0	0
1,2,3,7,8-PeCDD	0.5	0	0		0	0
1,2,3,4,7,8-HxCDD	0.1	0.146	0.21		0	0
1,2,3,6,7,8-HxCDD	0.1	0	0.193		0	0
1,2,3,7,8,9-HxCDD	0.1	0.243	0.484		0.164	0
1,2,3,4,6,7,8-HpCDD	0.01	0.0761	0.0498		0.0505	0.0483
OCDD	0.001	0.0544	0.0126		0.03328	0.0135
2,3,7,8-TCDF	0.1	1.522	0.409		1.041	0
1,2,3,7,8-PeCDF	0.05	0.211	0.149		0.0705	0
2,3,4,7,8-PeCDF	0.5	4.215	2.48		3.005	1.39
1,2,3,4,7,8-HxCDF	0.1	0.825	0.719		0	0
1,2,3,6,7,8-HxCDF	0.1	0.296	0		0.1963	0
1,2,3,7,8,9-HxCDF	0.1	0.218	0		0	0
2,3,4,6,7,8-HxCDF	0.1	0.21	0		0.107	0
1,2,3,4,6,7,8-HpCDF	0.01	0	0		0	0
1,2,3,4,7,8,9-HpCDF	0.01	0.063	0		0	0
OCDF	0.001	0.00393	0.00715		0.00212	0.00481
Total TEQ, ng/sample		**8.08**	**4.71**		**4.67**	**1.46**
TEQ: toxic equivalent mass that is obtained by multiplying the measured mass per sample of a particular compound by the toxic equivalent factor (TEF)						

TABLE 42. TEQ MASS OF DIOXINS/FURANS COLLECTED DURING 16-HOUR CYCLE FOR ENGINE D AND BACKGROUND SAMPLE

Engine D TEQ Dioxins/Furans, ng/sample						
TEQ Summary		16-Hour Cycle XAD	16-Hour Cycle 8 x 10 Filter		16-Hour Background XAD	16-Hour Background 8 x 10 Filter
ANALYTE	**TEF**					
2,3,7,8-TCDD	1	0	0		0	0
1,2,3,7,8-PeCDD	0.5	0	0		0	0
1,2,3,4,7,8-HxCDD	0.1	0.037	0		0	0
1,2,3,6,7,8-HxCDD	0.1	0.088	0		0	0
1,2,3,7,8,9-HxCDD	0.1	0	0.679		0	0
1,2,3,4,6,7,8-HpCDD	0.01	0.0263	0.0881		0.0369	0.0689
OCDD	0.001	0.0468	0.0218		0.04597	0.0172
2,3,7,8-TCDF	0.1	1.282	0.24		0.72	0
1,2,3,7,8-PeCDF	0.05	0.105	0.161		0.182	0
2,3,4,7,8-PeCDF	0.5	5.69	3.005		0	1.775
1,2,3,4,7,8-HxCDF	0.1	0.3	0		0	0.443
1,2,3,6,7,8-HxCDF	0.1	0	0.616		0.244	0.304
1,2,3,7,8,9-HxCDF	0.1	0	0		0	0
2,3,4,6,7,8-HxCDF	0.1	0.0912	0		0.149	0.287
1,2,3,4,6,7,8-HpCDF	0.01	0	0		0	0
1,2,3,4,7,8,9-HpCDF	0.01	0	0		0	0
OCDF	0.001	0.00695	0.00426		0.00832	0.00624
Total TEQ, ng/sample		**7.67**	**4.82**		**1.39**	**2.90**
TEQ: toxic equivalent mass that is obtained by multiplying the measured mass per sample of a particular compound by the toxic equivalent factor (TEF)						

TABLE 43. TEQ DIOXINS/FURANS BRAKE-SPECIFIC EMISSIONS AND CONCENTRATION

	Engine picogram/hp-hr	Background picogram/hp-hr	Net[a] picogram/hp-hr	Net[a] per Cycle picograms	Net[a] Exposure Chamber picogram/m³
Engine A	0.36	0.34	0.04	70.72	0.0008
Engine C	1.51	0.38	1.15	1455.79	0.0161
Engine D	0.92	0.25	0.68	1282.34	0.0140

[a] The net value background corrected using Xnet = Xr-(1-1/DR)*Xbg, where Xr is the reported emissions without background correction, Xbg is the reported emissions for background, and DR is the average dilution ratio in the CVS during the 16-Hour cycle.

TABLE 44. TOTAL DIOXINS/FURANS BRAKE-SPECIFIC EMISSIONS AND CONCENTRATION

	Engine picogram/hp-hr	Background picogram/hp-hr	Net[a] picogram/hp-hr	Net[a] per Cycle picograms	Net[a] Exposure Chamber picogram/m³
Engine A	35.43	11.59	24.42	42732.34	0.4869
Engine C	30.55	15.58	15.71	19845.59	0.2199
Engine D	32.01	9.82	22.61	42609.63	0.4654

[a] The net value background corrected using Xnet = Xr-(1-1/DR)*Xbg, where Xr is the reported emissions without background correction, Xbg is the reported emissions for background, and DR is the average dilution ratio in the CVS during the 16-Hour cycle.

TABLE 45. TOTAL CHLORINE IN ENGINE LUBRICANT

SwRI Code	Source	Result, mg/kg
EM-3275-EO	New Oil	120
EM-3277-EO	Engine C	124
EM-3282-EO	Engine D	130
Duplicate result	Engine D	133

TABLE 46. TOTAL CHLORINE IN AIR

	Chlorine, Cl_2, µg/m³	Chloride, Cl^-, µg/m³	Total Chlorine, µg/m³
C16H-62 Engine C Intake Air	85	98	183
C16H-62-BG	61	75	136
D16H60 Engine D Intake Air	82	94	176
D16H60-BG	124	<69	~158

TABLE 47. NITROSAMINES BRAKE-SPECIFIC EMISSIONS

Test Cycle	Number of Repeats		Nitrosamines, µg/hp-hr			
			Engine A	Engine B	Engine C	Engine D
FTP-w	3	**Avg**	168.0	137.6	73.5	429.6
		Stdev	199.6	87.5	11.8	203.3
		COV	119%	64%	16%	47%
FTP-wo	3	**Avg**	N/A	105.0	118.2	179.0
		Stdev	N/A	64.8	78.7	310.0
		COV	N/A	61.7%	66.6%	173.2%
CARBx-ICT	2	**Avg**	442.8	60.3	N/A	839.5
		Stdev	626.2	85.2	N/A	1187.2
		COV	141%	141%	N/A	141%
CARBz-CH	2	**Avg**	114.6	86.0	N/A	29.6
		Stdev	89.3	36.8	N/A	0.2
		COV	78%	43%	N/A	1%
16-Hour	3	**Avg**	46.5	107.7	100.6	26.6
		Stdev	14.2	140.9	74.6	8.5
		COV	30%	131%	74%	32%

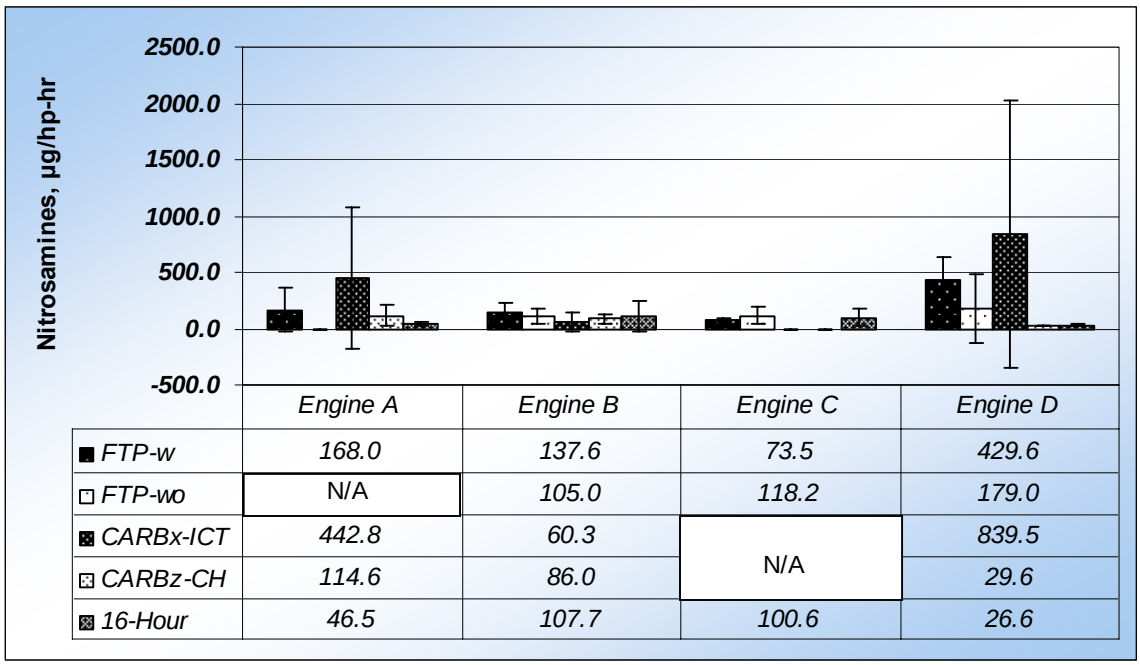


FIGURE 57. AVERAGE TOTAL NITROSAMINES EMISSIONS

5.19 Selected VOC Emissions

Table 48 and Figure 58 show the brake-specific emissions of selected VOCs. These included carbonyl sulfide (COS), nitromethane, nitroethane, 2-nitropropane, and 1-nitropropane. Generally, COS and nitromethane (CH_3NO_2) dominated the selected VOC compound emissions.

TABLE 48. SELECTED VOC COMPOUND BRAKE-SPECIFIC EMISSIONS

Test Cycle	Number of Repeats		HVOCs, mg/hp-hr			
			Engine A	Engine B	Engine C	Engine D
FTP-w	3	Avg	0.39	3.50	1.79	0.34
		Stdev	0.31	3.61	0.98	0.03
		COV	78.5%	103.1%	54.4%	8.6%
FTP-wo	3	Avg	0.93	7.45	1.07	0.45
		Stdev	0.29	11.01	0.73	0.19
		COV	30.9%	147.8%	67.6%	41.0%
CARBx-ICT	2	Avg	6.97	2.57	N/A	1.86
		Stdev	4.98	1.76	N/A	0.44
		COV	71.4%	68.5%	N/A	23.9%
CARBz-CH	2	Avg	1.29	3.50	N/A	2.28
		Stdev	0.44	0.19	N/A	0.50
		COV	34.3%	5.5%	N/A	22.0%
16-Hour	3	Avg	2.87	1.02	0.17	0.95
		Stdev	1.92	0.00	0.29	0.41
		COV	66.8%	0.2%	173.2%	42.8%

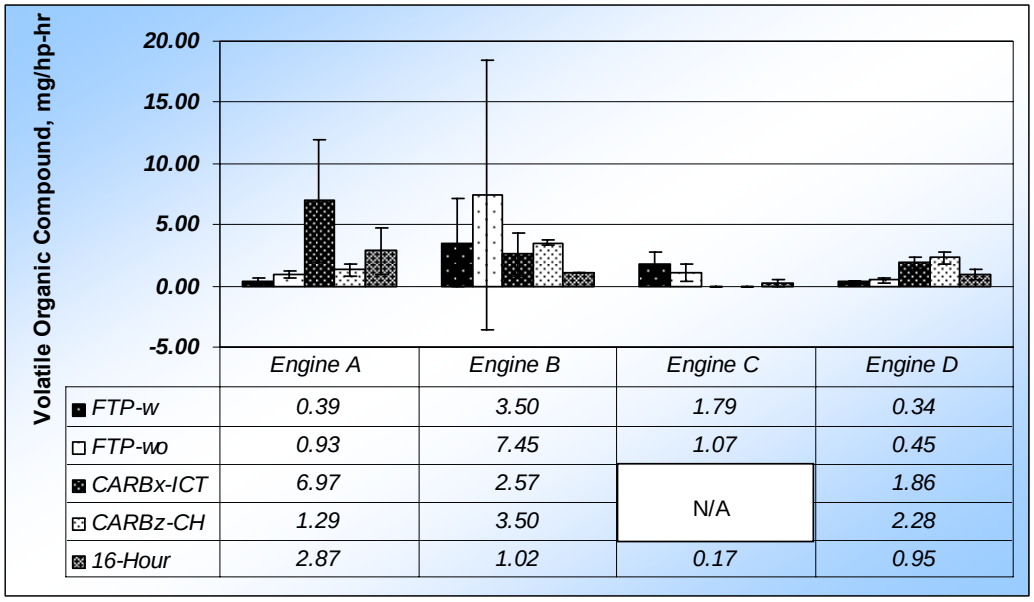


FIGURE 58. AVERAGE SELECTED VOC COMPOUND BRAKE-SPECIFIC EMISSIONS

6.0 SUMMARY

ACES Phase 1 engine testing started in March, 2007, and was completed in August, 2008. Four model year 2007 heavy-duty diesel engines were characterized for regulated and unregulated emissions using different cycles that included the FTP, CARBx-ICT, CARBz-CH, and the 16-Hour transient cycle. A backup engine was characterized for regulated emissions at SwRI's San Antonio, Texas, elevation (barometric pressure of 99.3 kPa) and at a simulated higher elevation (barometric pressure of 82.6 kpa) similar to that at LRRI in Albuquerque, New Mexico.

- Regulated emissions of NMHC, CO, and PM were 95, 98, and 89 percent below the EPA 2007 standard, respectively, and NO_x emissions were 10 percent below the standard.
- Unregulated emissions that included single ring aromatics, PAH, nitroPAH, alkanes, alcohol and organic acids, hopanes/steranes, carbonyls, metals and elements, organic carbon, elemental carbon, and dioxins/furans were 79 to 99 percent lower than the emissions from a similar 2004 technology engine. Inorganic ions were 38 percent lower.
- Average FTP NO_2 to NO_x ratio was 68 percent for the ACES engines, which is higher than the 4 to 15 percent expected in 2004 technology engines. The use of catalyzed aftertreatment devices for PM reduction in 2007 technology engines is causing the temporary increase in NO_2 to NO_x ratio, but in 2010, both the absolute level of NO_2 as well as NO_x emissions must be reduced to meet EPA 2010 NOx standard of 0.20 g/hp-hr, an 83 percent reduction from an average 2007 NOx emission level of 1.2 g/hp-hr.
- Higher elevation led to 34 percent increase in NO_x emissions for the FTP transient cycle.
- Lower exhaust temperature operation led to higher emissions of low and high molecular weight hydrocarbons, mainly due to the lower oxidation rates of the catalyzed aftertreatment systems.
- Average PM emissions with blowy-by was 50 percent higher than the PM emissions without blow-by.
- Average particle number emissions were one to two orders of magnitude lower than from typical 2004 technology engines. Active DPF regeneration events led to a more than one order of magnitude increase in cycle average particle number emissions, even though their occurrence was infrequent.
- Tunnel blank emission levels were similar to the emissions reported for the FTP cycle for many unregulated emissions species. CVS tunnel contamination, and storage and release of materials may impact the results for emissions measurements at extremely low levels. No tunnel blank corrections were performed during this work. Only tunnel background correction was performed when available.

Finally, some selected speciation data that are discussed in the body of the report are included in the designated appendices. All raw data will be transferred to a CRC website at http://www.crcao.org, which will be accessible to the public.

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APPENDIX A

HEI REPORT ON ENGINE SELECTION

Health Effects Institute

Report on Engine Selection
June 20, 2008

Engine Selection Process Group

REPORT ON ENGINE SELECTION
Prepared by the Engine Selection Process Group
June 20, 2008

INTRODUCTION

The Advanced Collaborative Emission Study (ACES) is a product stewardship initiative undertaken to characterize the emissions and assess the potential cancer and noncancer effects of the exhaust of heavy heavy-duty diesel engines and control systems designed to meet the 2007 and 2010 standards for particulate matter (PM) and nitrogen oxides (NOx). It is funded by U.S. DOE, U.S. EPA, the Engine Manufacturers Association, California ARB, the American Petroleum Institute, Corning, and the Coordinating Research Council. For this study, four manufacturers (Caterpillar, Cummins, Detroit Diesel, and Volvo) have voluntarily provided 2007-compliant production-ready engines for evaluation of emissions. The identity of the engines is being kept confidential, and the engines have been randomly assigned a letter from A to D.

In Phase 1 of ACES, which is completed, extensive characterization of the gaseous and particulate emissions of the four engines has been conducted at Southwest Research Institute (SwRI). A 16-Hour cycle, developed for use in Phase 3, was also used as one of the test cycles in the emissions characterization. The results from the triplicate 16-hr cycles have been the basis for selecting one heavy heavy-duty diesel engine/aftertreatment system for health testing. In Phase 3, the selected 2007-compliant engine system will be installed in a specially-designed emissions generation and animal exposure facility. Emissions will be characterized in the chambers prior to the engine's use in a chronic inhalation study with health measurements at several time periods. Phase 2 will involve characterization of emissions from 2010-compliant engines.

Phase 1 has been overseen by CRC and its ACES Panel; Phase 3 is overseen by HEI and its ACES Oversight Committee.

In March 2007, HEI set up an Engine Selection Process Group (ESPG) comprising a subset of members of the CRC ACES Panel and HEI ACES Oversight Committee to guide HEI in the process of engine selection. This report provides an overview of the process to develop and finalize the engine selection plan, a brief description of the Final Engine Selection Plan, a summary of the Phase 1 study results and the role of the CRC ACES Panel, and the process by which the ESPG made a recommendation for engine selection.

Attached to this document is the Final Plan for Engine Selection of May 29, 2008 (prepared by the ESPG).

A Summary of Exhaust Species Measurements and Calculations for ACES Phase 1 Engine Selection Process and the tables with emissions rates for all species used in engine selection (prepared by Dr. Imad Khalek of SwRI) are available on a secure web site upon request.

OVERVIEW OF PROCESS TO DEVELOP THE ENGINE SELECTION PLAN

The process by which the ESPG developed and modified the plan is described in the Final Plan for Engine Selection of May 29, 2008. That document represents the second revision of the Initial Draft Plan for Engine Selection (dated September 29, 2007), which was approved by the Steering Committee in October 2007. The first set of modifications to the plan were made in the winter of 2008 and resulted in the Final Initial Plan for Engine Selection of April 11, 2008. These included (1) removing dioxin and

furans (which were not analyzed in the 16-Hour cycle for all engines) from the list of components to be used in engine selection, (2) adding chloride (as a potential precursor of dioxin), and (3) adding a new section describing the protocol for engine selection. This document was approved by the ESPG and discussed at the Joint Meeting of the HEI ACES Oversight and Advisory Committees on April 29, 2008.

In establishing the Initial Plan, the ESPG kept the ability to refine it once the actual data became available for review. As described in more detail in the next section, the CRC Panel recommended some minor changes during one of their periodic meetings to review and discuss the results of Phase 1. These were approved by the ESPG and incorporated in the Final Plan for Engine Selection of May 29, 2008. They include: (1) clarifying how to report negative data resulting from background correction; (2) clarifying that total PAHs be referred to as "total PAHs with the exclusion of nitro-and oxygenated PAHs" to avoid double counting of those PAHs, which are in the list of compounds for engine selection on their own; and (3) adding a new rule for removing compounds for which measurements are at or below the LOD in each of the three replicates for three of the four engines. Because the changes made in the two subsequent revisions of the Initial Draft Plan for Engine Selection approved by the ESPG did not substantially alter the principles and rules laid out in the Initial Draft, those documents were not sent to the Steering Committee for approval.

The Initial Plan deferred the decision on all aspects of analyses of the emissions data to the CRC ACES Panel. At the May 7 and 8, 2008 meeting the CRC Panel agreed on the following:

- Background correction will be made for those measurements for which the EPA CFR prescribes such correction and for those exhaust measurements for which background emissions were measured simultaneously.
- Metals measurements will be reported based on the XRF method. Although two methods, XRF and ICP-MS, were used to measure metals, the panel members agreed that the XRF was more sensitive than the ICP-MS method for most metals.
- If no quality issues with the data could be identified, the data would not be removed on the basis of numerical value.

BRIEF DESCRIPTION OF ENGINE SELECTION PLAN

The plan set forth the following general principles:

- The study does not have adequate statistical power to distinguish among engines;
- All selected emission components should have the same weight in the total ranking because their relative toxicity cannot be assessed at low concentrations; and
- It is important to avoid choosing an engine with the lowest overall emissions, because it may lead to questions about effects of emissions from engines with higher overall emissions.

The plan states that the engine selection will use 4 ways of ranking the compounds, one nonparametric and three parametric. Regardless of the method, ranks of individual component or classes of components for each engine are added to obtain an overall score. The highest overall score for each method will have the highest rank (i.e. 4th).

- If 3 or 4 of the methods yield the same 4th ranking engine, that engine will be selected;
- If fewer than 3 methods identify the same 4th ranking engine, the engine would be selected randomly, with the following two caveats:
    - If 3 or 4 of the ranking methods yield the same 1st ranking engine, this engine will not be included in the random selection;

- If an engine is defined as an outlier, it will not be included in the random selection (because it would not be considered representative).

SUMMARY OF PHASE 1 STUDY AND ROLE OF THE CRC ACES PANEL

Phase 1 was carried at SwRI by Dr. Imad Khalek and collaborators at Desert Research Institute. The CRC Panel met regularly during the course of the testing to review and discuss the results of all test cycles (FTP, CARB and combined 16-Hour FTP/CARB cycles) as they became available. The final meeting of the Panel to discuss the 16-Hour emission data to be used for engine selection was held on May 7 and 8 at SwRI. Two members of the HEI Oversight Committee and a member of the HEI staff participated as well. The goal of the meeting was to review all data from the Phase 1 of ACES and clarify any questions about the results, in advance of HEI's ESPG meeting to select the engine.

A large part of the data were presented and reviewed at the CRC ACES Panel meeting. These included all the regulated pollutants, PAHs, carbonyls, and metals for all the cycles. Some of the data were still being processed (ionic inorganic species and EC/OC for engine B) and were not presented. Butadiene was not detected in any of the samples. Most of the data reported were not considered final. It was agreed that Dr. Imad Khalek and his collaborators would continue the data review, focusing on the 16-Hour cycle, and would post the data on an FTP site so all Panel members could review them as well. Once the CRC Panel and Dr. Khalek felt confident that all data transformation steps were right, errors had been corrected, and predetermined rules for eliminating values below the LOD had been applied appropriately, the final average emission rates for each compound and class of compounds for each engine data (see Table 1) were provided to Dr. Robert Mason (the SwRI statistician) for ranking according to the methods described in the Engine Selection Plan. The overall ranking of the four engines is provided in Table 3. The four ranking tables are provided in on pages 7 and 8 of this document.

Table 1. Summary of Emission Rates for Compounds and Classes of Compounds Used for Engine Ranking (6/4/08)

Emissions Components	Engine A	Engine B	Engine C	Engine D	AVG.	St. dev.
NO (g/hp-hr)	0.54	0.48	0.86	0.63	**0.63**	**0.17**
NO_2 (g/hp-hr)	0.95	0.91	0.56	0.56	**0.74**	**0.21**
Carbon Monoxide (g/hp-hr)	0.09	0.08	0.46	0.15	**0.20**	**0.18**
PM Mass (g/hp-hr)	0.0013	0.0012	0.0011	0.0013	**0.0012**	**0.0001**
PM Number (Part./hp-hr)	4.13E+13	5.67E+13	1.66E+13	2.38E+13	**3.46E+13**	**1.80E+13**
EC (mg/hp-hr)	0.20	0.27	0.26	0.22	**0.24**	**0.03**
OC (mg/hp-hr)	1.53	0.24	0.26	0.52	**0.64**	**0.61**
Total Metals (by XRF) (µg/hp-hr)	62.37	62.15	28.88	89.91	**60.82**	**24.97**
Inorganic Ionic Species (mg/hp-hr)	3.84	3.09	2.86	2.47	**3.06**	**0.57**
Carbonyl compounds (mg/hp-hr)	4.99	1.64	4.40	2.44	**3.37**	**1.59**
Single ring aromatic compounds (mg/hp-hr)	0.35	1.20	0.81	0.69	**0.76**	**0.35**
Total PAHs (mg/hp-hr)	0.55	0.73	0.84	0.80	**0.73**	**0.13**
Total Nitro PAHs (µg/hp-hr)	0.44	0.77	0.86	0.58	**0.66**	**0.19**
Total oxygenated PAHs (µg/hp-hr)	6.25	5.96	3.76	3.29	**4.82**	**1.51**
Nitrosamines (µg/hp-hr)	32.54	28.06	52.89	25.82	**34.83**	**12.36**

MEETING OF THE ESPG TO SELECT THE ENGINE

On June 6, 2008, the ESPG met at HEI to review the final set of data and select the engine for Phase 3 based on the final ranking of the four engines. The list of all ESPG members and those who participated is provided in Table 2. Other participants included: Robert Mason (SwRI) and members of the HEI staff (Maria Costantini, Daniel Greenbaum, Robert O'Keefe, and Annemoon van Erp).

Table 2. List of ESPG members at the June 6 meeting

	Present	On the phone
Reynaldo Agama, Caterpillar	Y	
James Ball, Ford	N	
Melvyn Branch, HEI Oversight Committee	N	
Steve Cadle (retired), representing General Motors	Y	
Kenneth Demerjian, HEI Oversight Committee	N	
Timothy French, EMA		Y
Helmut Greim, HEI Oversight Committee	N	
Thomas Hesterberg, International	N	
Donald Keski-Hynnila, Detroit Diesel	Y	
David Kittelson, HEI Oversight Committee	Y	
Douglas Lawson, NREL	Y	
Hector Maldonado, CARB		Y
Mani Natarajan, Marathon Petroleum Co	N	
Howard Rockette, HEI Oversight Committee	Y	
Shirish Shimpi, Cummins	Y	
Joseph Somers, EPA	Y	
Chris Tennant, CRC	Y	
Mark Utell (Chair), HEI Oversight Committee	Y	
Urban Wass, Volvo	N	Y
Kenneth Wright, Conoco Phillips	Y	

The meeting started with an overview of the results of Phase 1 by Dr. Tennant. He explained how the 16-Hour cycle was selected and developed and noted that it was designed to capture a cold start. Regeneration occurred at least once during the 16-Hour cycle. For this testing, the CVS was also connected to an exposure chamber (without animals). Most of the measurements were made in samples taken from the CVS, but some (EC, OC, and PM number) were made in samples taken from the exposure chamber. The emission rates of the regulated pollutants were well below the 2007 standards. For a few species (CO, EC, toluene, and iron) an unusual variance was noted that could not be explained by issues in sample collection or analyses.

The ESPG members noted that both EC and OC were higher than the PM filter mass. This could have been due to the fact that they were measured in the chamber while the PM mass was measured in the CVS or to artifacts in collecting PM on a filter. Another observation was that the mass of total inorganic ions was higher than that of the PM filter mass. This could not be explained. The ESPG decided to leave this class of compounds in the list because, even if there were an error, it appeared to be systematic and thus was unlikely to bias the engine selection. The ESPG noted that two engines had higher NO_2 emissions (A and B) compared to the other two (C and D) and that, if an engine with higher NO_2 were selected, its exhaust may need to be diluted more. With regard to elements, the ESPG was surprised to find that

sodium was the most abundant one. It was not clear whether sodium was a contaminant or whether it was coming from lube oil. In the absence of a valid reason for removing this element, it was left in the list.

Dr. Mason summarized how the measurements below the LOD had been treated based on the rules set in the Final Engine Selection Plan. He noted that chloride was the only species removed because for at least 3 engines, all three measurements were below the LOD. He also explained that none of the engines met the criteria for being defined as an outlier. The results supported the initial hypotheses that no engine had higher or lower emissions for all the components than the other engines. Dr. Rockette (the biostatistician of the ESPG) applied two tests that are used to determine whether there are differences among groups of measurements (Friedman's two-way analysis of variance and ANOVA). The tests did not show statistically significant differences among the four engines, although the small number of samples limited the ability to detect a difference even if one did exist.

The ESPG noted that the results show that, based on the engine selection rules, there is little or no difference in the total ranking among the engines, but one of the four engines (D) did happen to rank lowest in all four ranking methods (see Table 3). This finding excluded this engine from being included in the random selection. The ranking of the other three engines changed depending on the ranking method used and no engine was ranked highest with at least three of the four ranking methods.

Table 3. Summary of total ranking (6/4/2008)

	Engine A	**Engine B**	**Engine C**	**Engine D**
Method 1	40.5	36.0	39.5	34.0
Method 2a	15.96	14.83	15.89	13.33
Method 2b	59.31	60.12	60.12	54.61
Method 2c	0.77	1.58	1.58	-3.93

Highest
Lowest

Some ESPG members expressed concern about the fact that two of the four ranking methods (2b – which corrects by the standard deviation, and 2c – which corrects by the mean and the standard deviation) give rise to exactly the same rank order among the four engines and only one should have been used. However, all ESPG members agreed that the group should not create new rules *post-hoc*. Dr. Mason commented that, if one used only method 1 (which ranks the data from lowest to highest and ignores the actual values) and 2c (which is the most common standardization method and uses both the mean and the standard deviation) the results would not change.

Given the ranking results, the ESPG – including the representatives of all four engine manufacturers – agreed that the selection should be random among engines A, B, and C. This was done by random drawing by Dr. Mark Utell, Chair of the HEI Research Committee. The engine that was randomly selected was Engine B; hence the ESPG recommends that Engine B be used for Phase 3.

RANKING TABLES

Ranking Method 1

6/4/08	Engine A		Engine B		Engine C		Engine D		
Emissions Components	**Emissions**	**Rank**	**Emissions**	**Rank**	**Emissions**	**Rank**	**Emissions**	**Rank**	**Total Rankings**
NO, g/hp-hr	0.54	2.0	0.48	1.0	0.86	4.0	0.63	3.0	10.0
NO2, g/hp-hr	0.95	4.0	0.91	3.0	0.56	1.5	0.56	1.5	10.0
Carbon Monoxide, g/hp-hr	0.09	2.0	0.08	1.0	0.46	4.0	0.15	3.0	10.0
PM Mass, g/hp-hr	0.0013	3.5	0.0012	2.0	0.0011	1.0	0.0013	3.5	10.0
PM Number, Part./hp-hr	4.13E+13	3.0	5.67E+13	4.0	1.66E+13	1.0	2.38E+13	2.0	10.0
EC (mg/hp-hr)	0.20	1.0	0.27	4.0	0.26	3.0	0.22	2.0	10.0
OC (mg/hp-hr)	1.53	4.0	0.24	1.0	0.26	2.0	0.52	3.0	10.0
Total Metals, mg/hp-hr	62.37	3.0	62.15	2.0	28.88	1.0	89.91	4.0	10.0
Inorganic Ionic Species, mg/hp-hr	3.84	4.0	3.09	3.0	2.86	2.0	2.47	1.0	10.0
Carbonyl compounds (mg/hp-hr)	4.99	4.0	1.64	1.0	4.40	3.0	2.44	2.0	10.0
Single ring aromatic compounds, mg/hp-hr	0.35	1.0	1.20	4.0	0.81	3.0	0.69	2.0	10.0
Total PAHs (mg/hp-hr)	0.55	1.0	0.73	2.0	0.84	4.0	0.80	3.0	10.0
Total Nitro PAHs (µg/hp-hr)	0.44	1.0	0.77	3.0	0.86	4.0	0.58	2.0	10.0
Total oxygenated PAHs (µg/hp-hr)	6.25	4.0	5.96	3.0	3.76	2.0	3.29	1.0	10.0
Nitrosamines (µg/hp-hr)	32.54	3.0	28.06	2.0	52.89	4.0	25.82	1.0	10.0
Total Ranking		40.5		36.0		39.5		34.0	

Ranking Method 2a

6/4/08	Engine A		Engine B		Engine C		Engine D		
Emissions Components	**Emissions**	**Rank**	**Emissions**	**Rank**	**Emissions**	**Rank**	**Emissions**	**Rank**	**Mean of 4 Engines**
NO, g/hp-hr	0.54	0.86	0.48	0.76	0.86	1.37	0.63	1.00	0.63
NO2, g/hp-hr	0.95	1.28	0.91	1.22	0.56	0.75	0.56	0.75	0.75
Carbon Monoxide, g/hp-hr	0.09	0.46	0.08	0.41	0.46	2.36	0.15	0.77	0.20
PM Mass, g/hp-hr	0.0013	1.06	0.0012	0.98	0.0011	0.90	0.0013	1.06	0.0012
PM Number, Part./hp-hr	4.13E+13	1.19	5.67E+13	1.64	1.66E+13	0.48	2.38E+13	0.69	3.46E+13
EC (mg/hp-hr)	0.20	0.84	0.27	1.14	0.26	1.09	0.22	0.93	0.24
OC (mg/hp-hr)	1.53	2.40	0.24	0.38	0.26	0.41	0.52	0.82	0.64
Total Metals, mg/hp-hr	62.37	1.03	62.15	1.02	28.88	0.47	89.91	1.48	60.83
Inorganic Ionic Species, mg/hp-hr	3.84	1.25	3.09	1.01	2.86	0.93	2.47	0.81	3.07
Carbonyl compounds (mg/hp-hr)	4.99	1.48	1.64	0.49	4.40	1.31	2.44	0.72	3.37
single ring aromatic compounds, mg/hp-hr	0.35	0.46	1.20	1.57	0.81	1.06	0.69	0.90	0.76
Total PAHs (mg/hp-hr)	0.55	0.75	0.73	1.00	0.84	1.15	0.80	1.10	0.73
Total Nitro PAHs (µg/hp-hr)	0.44	0.66	0.77	1.16	0.86	1.30	0.58	0.88	0.66
Total oxygenated PAHs (µg/hp-hr)	6.25	1.30	5.96	1.24	3.76	0.78	3.29	0.68	4.82
Nitrosamines (µg/hp-hr)	32.54	0.93	28.06	0.81	52.89	1.52	25.82	0.74	34.83
Total Ranking		15.96		14.83		15.89		13.33	

Ranking Method 2b

6/4/08	Engine A		Engine B		Engine C		Engine D		
Emissions Components	**Emissions**	**Rank**	**Emissions**	**Rank**	**Emissions**	**Rank**	**Emissions**	**Rank**	**Std. Dev. Of 4 Engines**
NO, g/hp-hr	0.54	3.24	0.48	2.88	0.86	5.16	0.63	3.78	0.17
NO2, g/hp-hr	0.95	4.43	0.91	4.25	0.56	2.61	0.56	2.61	0.21
Carbon Monoxide, g/hp-hr	0.09	0.50	0.08	0.45	0.46	2.56	0.15	0.84	0.18
PM Mass, g/hp-hr	0.0013	13.58	0.0012	12.53	0.0011	11.49	0.0013	13.58	0.0001
PM Number, Part./hp-hr	4.13E+13	2.29	5.67E+13	3.15	1.66E+13	0.92	2.38E+13	1.32	1.80E+13
EC (mg/hp-hr)	0.20	6.05	0.27	8.17	0.26	7.87	0.22	6.66	0.03
OC (mg/hp-hr)	1.53	2.51	0.24	0.39	0.26	0.43	0.52	0.85	0.61
Total Metals, mg/hp-hr	62.37	2.50	62.15	2.49	28.88	1.16	89.91	3.60	24.97
Inorganic Ionic Species, mg/hp-hr	3.84	6.66	3.09	5.36	2.86	4.96	2.47	4.28	0.58
Carbonyl compounds (mg/hp-hr)	4.99	3.15	1.64	1.03	4.40	2.77	2.44	1.54	1.59
single ring aromatic compounds, mg/hp-hr	0.35	1.00	1.20	3.42	0.81	2.31	0.69	1.97	0.35
Total PAHs (mg/hp-hr)	0.55	4.29	0.73	5.69	0.84	6.55	0.80	6.23	0.13
Total Nitro PAHs (µg/hp-hr)	0.44	2.33	0.77	4.08	0.86	4.56	0.58	3.07	0.19
Total oxygenated PAHs (µg/hp-hr)	6.25	4.15	5.96	3.96	3.76	2.50	3.29	2.18	1.51
Nitrosamines (µg/hp-hr)	32.54	2.63	28.06	2.27	52.89	4.28	25.82	2.09	12.36
Total Ranking		59.31		60.12		60.12		54.61	

Ranking Method 2c

6/4/08	Engine A		Engine B		Engine C		Engine D			
Emissions Components	**Emissions**	**Rank**	**Emissions**	**Rank**	**Emissions**	**Rank**	**Emissions**	**Rank**	**Mean of 4 Engines**	**Std. Dev. Of 4 Engines**
NO, g/hp-hr	0.54	-0.52	0.48	-0.88	0.86	1.39	0.63	0.01	0.63	0.17
NO2, g/hp-hr	0.95	0.96	0.91	0.77	0.56	-0.86	0.56	-0.86	0.75	0.21
Carbon Monoxide, g/hp-hr	0.09	-0.59	0.08	-0.64	0.46	1.48	0.15	-0.25	0.20	0.18
PM Mass, g/hp-hr	0.0013	0.78	0.0012	-0.26	0.0011	-1.31	0.0013	0.78	0.0012	0.00
PM Number, Part./hp-hr	4.13E+13	0.37	5.67E+13	1.23	1.66E+13	-1.00	2.38E+13	-0.60	3.46E+13	1.80E+13
EC (mg/hp-hr)	0.20	-1.13	0.27	0.98	0.26	0.68	0.22	-0.53	0.24	0.03
OC (mg/hp-hr)	1.53	1.47	0.24	-0.65	0.26	-0.62	0.52	-0.19	0.64	0.61
Total Metals, mg/hp-hr	62.37	0.06	62.15	0.05	28.88	-1.28	89.91	1.16	60.83	24.97
Inorganic Ionic Species, mg/hp-hr	3.84	1.34	3.09	0.04	2.86	-0.36	2.47	-1.03	3.07	0.58
Carbonyl compounds (mg/hp-hr)	4.99	1.02	1.64	-1.09	4.40	0.65	2.44	-0.58	3.37	1.59
single ring aromatic compounds, mg/hp-hr	0.35	-1.18	1.20	1.25	0.81	0.14	0.69	-0.21	0.76	0.35
Total PAHs (mg/hp-hr)	0.55	-1.40	0.73	0.00	0.84	0.86	0.80	0.55	0.73	0.13
Total Nitro PAHs (µg/hp-hr)	0.44	-1.18	0.77	0.57	0.86	1.05	0.58	-0.44	0.66	0.19
Total oxygenated PAHs (µg/hp-hr)	6.25	0.95	5.96	0.76	3.76	-0.70	3.29	-1.01	4.82	1.51
Nitrosamines (µg/hp-hr)	32.54	-0.19	28.06	-0.55	52.89	1.46	25.82	-0.73	34.83	12.36
Total Ranking		0.77		1.58		1.58		-3.93		

APPENDIX B

ADDITIONAL ABBREVIATIONS LIST

Polycyclic Aromatic Hydrocarbons

NAPHTH	Naphthalene
NAPHTHU	Naphthalene uncertainty
QUINOLINE	Quinoline
QUINOLINEU	Quinoline uncertainty
MNAPH2	2-methylnaphthalene
MNAPH2U	2-Methylnaphthalene uncertainty
MNAPH1	1-Methylnaphthalene
MNAPH1U	1-Methylnaphthalene uncertainty
BIPHEN	Biphenyl
BIPHENU	Biphenyl uncertainty
ENAP12	1+2Ethylnaphthalene
ENAP12U	1+2Ethylnaphthalene uncertainty
M_2BPH	2-Methylbiphenyl
M_2BPHU	2-Methylbiphenyl uncertainty
DMN267	2,6+2,7-Dimethylnaphthalene
DMN267U	2,6+2,7-Dimethylnaphthalene uncertainty
DM1367	1,3+1,6+1,7-Dimethylnaphthalene
DM1367U	1,3+1,6+1,7-Dimethylnaphth uncertainty
D14523	1,4+1,5+2,3-Dimethylnaphthalene
D14523U	1,4+1,5+2,3-Dimethylnaphth uncertainty
ACNAPY	Acenaphthylene
ACNAPYU	Acenaphthylene uncertainty
DMN12	1,2-Dimethylnaphthalene
DMN12U	1,2-Dimethylnaphthalene uncertainty
DMN18	1,8-Dimethylnaphthalene
DMN18U	1,8-Dimethylnaphthalene uncertainty
ACNAPE	Acenaphthene
ACNAPEU	Acenaphthene uncertainty
M_3BPH	3-Methylbiphenyl
M_3BPHU	3-Methylbiphenyl uncertainty
M_4BPH	4-Methylbiphenyl
M_4BPHU	4-Methylbiphenyl uncertainty
DBZFUR	Dibenzofuran
DBZFURU	Dibenzofuran uncertainty
EM_12N	1-ethyl-2-methylnaphthalene
EM_12NU	1-ethyl-2-methylnaphthalene uncertainty
TMI235N	2,3,5+I-trimethylnaphthalene
TMI235NU	2,3,5+I-trimethylnaphthalene uncertainty
BTMNAP	B-Trimethylnaphthalene
BTMNAPU	B-Trimethylnaphthalene uncertainty
ATMNAP	A-Trimethylnaphthalene
ATMNAPU	A-Trimethylnaphthalene uncertainty
CTMNAP	C-Trimethylnaphthalene
CTMNAPU	C-Trimethylnaphthalene uncertainty
EM_21N	2-Ethyl-1-methylnaphthalene
EM_21NU	2-Ethyl-1-methylnaphthalene uncertainty

ETMNAP	E-Trimethylnaphthalene
ETMNAPU	E-Trimethylnaphthalene uncertainty
TM245N	2,4,5-Trimethylnaphthalene
TM245NU	2,4,5-Trimethylnaphthalene uncertainty
FTMNAP	F-Trimethylnaphthalene
FTMNAPU	F-Trimethylnaphthalene uncertainty
FLUORE	Fluorene
FLUOREU	Fluorene uncertainty
TM145N	1,4,5-Trimethylnaphthalene
TM145NU	1,4,5-Trimethylnaphthalene uncertainty
JTMNAP	J-Trimethylnaphthalene
JTMNAPU	J-Trimethylnaphthalene uncertainty
A_MFLUO	A-Methylfluorene
A_MFLUOU	A-Methylfluorene uncertainty
B_MFLUO	B-Methylfluorene
B_MFLUOU	B-Methylfluorene uncertainty
M_1FLUO	1-Methylfluorene
M_1FLUOU	1-Methylfluorene uncertainty
DBTH	Dibenzothiophene
DBTHU	Dibenzothiophene uncertainty
PHENAN	Phenanthrene
PHENANU	Phenanthrene uncertainty
ANTHRA	Anthracene
ANTHRAU	Anthracene uncertainty
ACQUONE	Acenaphthenequinone
ACQUONEU	Acenaphthenequinone uncertainty
M_2PHEN	3-Methylphenanthrene
M_2PHENU	3-Methylphenanthrene uncertainty
M_3PHEN	2-Methylphenanthrene
M_3PHENU	2-Methylphenanthrene uncertainty
M_2ANTH	2-Methylanthracene
M_2ANTHU	2-Methylanthracene uncertainty
M_45PHEN	4,5-Methylenephenanthrene
M_45PHENU	4,5-Methylenephenanthrene uncertainty
M_9PHEN	9-Methylphenanthrene
M_9PHENU	9-Methylphenanthrene uncertainty
MPHT_1	1-Methylphenanthrene
MPHT_1U	1-Methylphenanthrene uncertainty
DBPHT	Dibutyl phthalate
DBPHTU	Dibutyl phthalate uncertainty
ANTHRON	Anthrone
ANTHRONU	Anthrone uncertainty
M_9ANT	9-Methylanthracene
M_9ANTU	9-Methylanthracene uncertainty
NAP2PHEN	2-Phenylnaphthalene
NAP2PHENU	2-Phenylnaphthalene uncertainty
A_DMPH	A-Dimethylphenanthrene
A_DMPHU	A-Dimethylphenanthrene uncertainty

B_DMPH	B-Dimethylphenanthrene
B_DMPHU	B-Dimethylphenanthrene uncertainty
DM17PH	1,7-Dimethylphenanthrene
DM17PHU	1,7-Dimethylphenanthrene uncertainty
DM36PH	3,6-Dimethylphenanthrene
DM36PHU	3,6-Dimethylphenanthrene uncertainty
D_DMPH	D-Dimethylphenanthrene
D_DMPHU	D-Dimethylphenanthrene uncertainty
E_DMPH	E-Dimethylphenanthrene
E_DMPHU	E-Dimethylphenanthrene uncertainty
C_DMPH	C-Dimethylphenanthrene
C_DMPHU	C-Dimethylphenanthrene uncertainty
FLUORA	Fluoranthene
FLUORAU	Fluoranthene uncertainty
PYRENE	Pyrene
PYRENEU	Pyrene uncertainty
RETENE	Retene
RETENEU	Retene uncertainty
BAFLUO	Benzo(a)fluorene
BAFLUOU	Benzo(a)fluorene uncertainty
BBFLUO	Benzo(b)fluorene
BBFLUOU	Benzo(b)fluorene uncertainty
BMPYFL	B-MePy/MeFl
BMPYFLU	B-MePy/MeFl uncertainty
C1MFLPY	1-MeFl+C-MeFl/Py
C1MFLPYU	1-MeFl+C-MeFl/Py uncertainty
M_13FL	1+3-methylfluoranthene
M_13FLU	1+3-methylfluoranthene uncertainty
M_4PYR	4-methylpyrene
M_4PYRU	4-methylpyrene uncertainty
CMPYFL	C-MePy/MeFl
CMPYFLU	C-MePy/MeFl uncertainty
DMPYFL	D-MePy/MeFl
DMPYFLU	D-MePy/MeFl uncertainty
M_1PYR	1-Methylpyrene
M_1PYRU	1-Methylpyrene uncertainty
BNTIOP	Benzonaphthothiophene
BNTIOPU	Benzonaphthothiophene uncertainty
BZCPHEN	Benzo(c)phenanthrene
BZCPHENU	Benzo(c)phenanthrene uncertainty
BGHIFL	Benzo(ghi)fluoranthene
BGHIFLU	Benzo(ghi)fluoranthene uncertainty
PHANT9	9-Phenylanthracene
PHANT9U	9-Phenylanthracene uncertainty
CP_CDPYR	Cyclopenta(c,d)pyrene
CP_CDPYRU	Cyclopenta(c,d)pyrene uncertainty
BAANTH	Benz(a)anthracene
BAANTHU	Benz(a)anthracene uncertainty

CHR_TR	Chrysene-Triphenylene
CHR_TRU	Chrysene-Triphenylene uncertainty
B2EPHT	Bis[2-ethylhexyl]phthalate
B2EPHTU	Bis[2-ethylhexyl]phthalate uncertainty
M_3CHR	3-Methylchrysene
M_3CHRU	3-Methylchrysene uncertainty
CHRY56M	5+6-Methylchrysene
CHRY56MU	5+6-Methylchrysene uncertainty
M_7BAA	7-Methylbenz(a)anthracene
M_7BAAU	7-Methylbenz(a)anthracene uncertainty
DMBAN712	7,12-Dimethylbenz(a)anthracene
DMBAN712U	7,12-Dimethylbenz(a)anthracene uncertainty
BBJKFL	Benzo(b+j+k)fluoranthene
BBJKFLU	Benzo(b+j+k)fluoranthene uncertainty
BAFL	Benzo(a)fluoranthene
BAFLU	Benzo(a)fluoranthene uncertainty
BEPYRN	Benzo(e)pyrene
BEPYRNU	Benzo(e)pyrene uncertainty
BAPYRN	Benzo(a)pyrene
BAPYRNU	Benzo(a)pyrene uncertainty
PERYLE	Perylene
PERYLEU	Perylene uncertainty
MCHOL3	3-Methylcholanthrene
MCHOL3U	3-Methylcholanthrene uncertainty
M_7BPY	7-Methylbenzo(a)pyrene
M_7BPYU	7-Methylbenzo(a)pyrene uncertainty
INCDFL	Indeno[123-cd]fluoranthene
INCDFLU	Indeno[123-cd]fluoranthene uncertainty
DBAHACR	Dibenz(a,h)acridine
DBAHACRU	Dibenz(a,h)acridine uncertainty
DBAJACR	Dibenz(a,j)acridine
DBAJACRU	Dibenz(a,j)acridine uncertainty
IN123PYR	Indeno[123-cd]pyrene
IN123PYRU	Indeno[123-cd]pyrene uncertainty
DBAJAN	Dibenzo(a,j)anthracene
DBAJANU	Dibenzo(a,j)anthracene uncertainty
DBAHACAN	Dibenzo(ah+ac)anthracene
DBAHACANU	Dibenzo(ah+ac)anthracene uncertainty
BBCHR	Benzo(b)chrysene
BBCHRU	Benzo(b)chrysene uncertainty
PIC	Picene
PICU	Picene uncertainty
DBCGCAR	7H-dibenzo[c,g]carbazole
DBCGCARU	7H-dibenzo[c,g]carbazole uncertainty
BGHIPE	Benzo(ghi)perylene
BGHIPEU	Benzo(ghi)perylene uncertainty
ANTHAN	Anthanthrene
ANTHANU	Anthanthrene uncertainty

DBALPYR	Dibenzo(a,l)pyrene
DBALPYRU	Dibenzo(a,l)pyrene uncertainty
DBAEPYR	Dibenzo(a,e)pyrene
DBAEPYRU	Dibenzo(a,e)pyrene uncertainty
CORONE	Coronene
CORONEU	Coronene uncertainty
DBAIPYR	Dibenzo(a,i)pyrene
DBAIPYRU	Dibenzo(a,i)pyrene uncertainty
DBAHPYR	Dibenzo(a,h)pyrene
DBAHPYRU	Dibenzo(a,h)pyrene uncertainty
DBBKFL	Dibenzo(b,k)fluoranthene
DBBKFLU	Dibenzo(b,k)fluoranthene uncertainty

Oxygenated PAHs

FL9ONE	9-Fluorenone
FL9ONEU	9-Fluorenone uncertainty
XANONE	Xanthone
XANONEU	Xanthone uncertainty
PNAPONE	Perinaphthenone
PNAPONEU	Perinaphthenone uncertainty
ANTHRON	Anthrone
ANTHRONU	Anthrone uncertainty
ANRQUONE	Anthraquinone
ANRQUONEU	Anthraquinone uncertainty
ANTAL9	9-Anthraaldehyde
ANTAL9U	9-Anthraaldehyde uncertainty
BZANTHR	Benzanthrone
BZANTHRU	Benzanthrone uncertainty
BAA7_12	Benz(a)anthracene-7,12-dione
BAA7_12U	Benz(a)anthracene-7,12-dione uncertainty
BPY910DIH	9,10-dihydrobenzo(a)pyrene-7(8H)-one
BPY910DIHU	9,10-dihydrobenzo(a)pyrene-7(8H)-one uncertainty

Nitrogenated PAHs

NI4PHOL	4-Nitrophenol
NI4PHOLU	4-Nitrophenol uncertainty
NI1NAPTH	1-Nitronaphthalene
NI1NAPTHU	1-Nitronaphthalene uncertainty
NI1ME5N	1-Methyl-5-nitronaphthalene
NI1ME5NU	1-Methyl-5-nitronaphthalene uncertainty
NI2NAPTH	2-Nitronaphthalene
NI2NAPTHU	2-Nitronaphthalene uncertainty
NI2BIPH	2-Nitrobiphenyl
NI2BIPHU	2-Nitrobiphenyl uncertainty
NI4ME2N	2-Methyl-4-nitronaphthalene
NI4ME2NU	2-Methyl-4-nitronaphthalene uncertainty

NI4ME1N	1-Methyl-4-nitronaphthalene
NI4ME1NU	1-Methyl-4-nitronaphthalene uncertainty
MXNIYNAP	x-Methyl-y-nitronaphthalene
MXNIYNAPU	x-Methyl-y-nitronaphthalene uncertainty
NI6ME1N	1-Methyl-6-nitronaphthalene
NI6ME1NU	1-Methyl-6-nitronaphthalene uncertainty
NI3BIPH	3-Nitrobiphenyl
NI3BIPHU	3-Nitrobiphenyl uncertainty
NI4BPH	4-Nitrobiphenyl
NI4BPHU	4-Nitrobiphenyl uncertainty
NI13NAP	1,3-Dinitronaphthalene
NI13NAPU	1,3-Dinitronaphthalene uncertainty
NI15NAP	1,5-Dinitronaphthalene
NI15NAPU	1,5-Dinitronaphthalene uncertainty
NI5ACEN	5-Nitroacenaphthene
NI5ACENU	5-Nitroacenaphthene uncertainty
NI2FLUO	2-Nitrofluorene
NI2FLUOU	2-Nitrofluorene uncertainty
NI4PHEN	4-Nitrophenanthrene
NI4PHENU	4-Nitrophenanthrene uncertainty
NI9ANTHR	9-Nitroanthracene
NI9ANTHRU	9-Nitroanthracene uncertainty
NI9PHEN	9-Nitrophenanthrene
NI9PHENU	9-Nitrophenanthrene uncertainty
NI18NAP	1,8-Dinitronaphthalene
NI18NAPU	1,8-Dinitronaphthalene uncertainty
NI3PHEN	3-Nitrophenanthrene
NI3PHENU	3-Nitrophenanthrene uncertainty
NI2PHEN	2-Nitrophenanthrene
NI2PHENU	2-Nitrophenanthrene uncertainty
NI2ANTHR	2-Nitroanthracene
NI2ANTHRU	2-Nitroanthracene uncertainty
NI1FLUOR	1-Nitrofluoranthene
NI1FLUORU	1-Nitrofluoranthene uncertainty
NI7FLUOR	7-Nitrofluoranthene
NI7FLUORU	7-Nitrofluoranthene uncertainty
NI2FLUOR	2-Nitrofluoranthene
NI2FLUORU	2-Nitrofluoranthene uncertainty
NI3FLUOR	3-Nitrofluoranthene
NI3FLUORU	3-Nitrofluoranthene uncertainty
NI4PYRE	4-Nitropyrene
NI4PYREU	4-Nitropyrene uncertainty
NI8FLUOR	8-Nitrofluoranthene
NI8FLUORU	8-Nitrofluoranthene uncertainty
NI1PYRE	1-Nitropyrene
NI1PYREU	1-Nitropyrene uncertainty
NI2PYRE	2-Nitropyrene
NI2PYREU	2-Nitropyrene uncertainty

NI27FLUO	2,7-Dinitrofluorene
NI27FLUOU	2,7-Dinitrofluorene uncertainty
NI27FL9ON	2,7-Dinitrofluoren-9-one
NI27FL9ONU	2,7-Dinitrofluoren-9-one uncertainty
NI7BZANTH	7-Nitrobenz(a)anthracene
NI7BZANTHU	7-Nitrobenz(a)anthracene uncertainty
NI6CHRY	6-Nitrochrysene
NI6CHRYU	6-Nitrochrysene uncertainty
NI3BZANTH	3-Nitrobenzanthrone
NI3BZANTHU	3-Nitrobenzanthrone uncertainty
NI13PYR	1,3-Dinitropyrene
NI13PYRU	1,3-Dinitropyrene uncertainty
DNIFLUORA	A-Dinitrofluoranthene
DNIFLUORAU	A-Dinitrofluoranthene uncertainty
NI16PYR	1,6-Dinitropyrene
NI16PYRU	1,6-Dinitropyrene uncertainty
NI18PYR	1,8-Dinitropyrene
NI18PYRU	1,8-Dinitropyrene uncertainty
DNIFLUORB	B-Dinitrofluoranthene
DNIFLUORBU	B-Dinitrofluoranthene uncertainty
DNIFLUORC	C-Dinitrofluoranthene
DNIFLUORCU	C-Dinitrofluoranthene uncertainty
NI6A3EBP	6a+3e-nitrobenzpyrene
NI6A3EBPU	a+3e-nitrobenzpyrene uncertainty
NI1BEP	1-nitrobenzo[e]pyrene
NI1BEPU	1-nitrobenzo[e]pyrene uncertainty

Polar Compounds

PHENOL	Phenol
PHENOLU	Phenol uncertainty
HEXAC	Hexanoic acid (c6)
HEXACU	Hexanoic acid (c6) uncertainty
OCRESOL	o-Cresol
OCRESOLU	o-Cresol uncertainty
MCRESOL	m-Cresol
MCRESOLU	m-Cresol uncertainty
PCRESOL	p-Cresol
PCRESOLU	p-Cresol uncertainty
HEPTAC	Heptanoic acid (c7)
HEPTACU	Heptanoic acid (c7) uncertainty
ANILINE	Aniline
ANILINEU	Aniline uncertainty
BENAC	Benzoic acid
BENACU	Benzoic acid uncertainty
OCTANAC	Octanoic acid (c8)
OCTANACU	Octanoic acid (c8) uncertainty
OTOLUIC	o-Toluic

OTOLUICU	o-Toluic uncertainty
MTOLUIC	m-Toluic
MTOLUICU	m-Toluic uncertainty
NONAC	Nonanoic acid (c9)
NONACU	Nonanoic acid (c9) uncertainty
PTOLUIC	p-Toluic
PTOLUICU	p-Toluic uncertainty
DECAC	Decanoic acid (c10)
DECACU	Decanoic acid (c10) uncertainty
UNDECAC	Undecanoic acid (c11)
UNDECACU	Undecanoic acid (c11) uncertainty
LAUAC	Dodecanoic (lauric) acid (c12)
LAUACU	Dodecanoic (lauric) acid (c12) uncertainty
TDECAC	Tridecanoic acid (c13)
TDECACU	Tridecanoic acid (c13) uncertainty
MYRAC	Myristic acid (c14)
MYRACU	Myristic acid (c14) uncertainty
PDECAC	Pentadecanoic acid (c15)
PDECACU	Pentadecanoic acid (c15) uncertainty
PALAC	Palmitic acid (c16)
PALACU	Palmitic acid (c16) uncertainty
HEPTADAC	Heptadecanoic acid (c17)
HEPTADACU	Heptadecanoic acid (c17) uncertainty
OLAC	Oleic acid
OLACU	Oleic acid uncertainty
STEAC	Stearic acid (c18)
STEACU	Stearic acid (c18) uncertainty
NDECAC	Nonadecanoic acid (c19)
NDECACU	Nonadecanoic acid (c19) uncertainty
ECOSAC	Eicosanoic acid (c20)
ECOSACU	Eicosanoic acid (c20) uncertainty
OCTDECDI	Octadecanedioic acid
OCTDECDIU	Octadecanedioic acid uncertainty

Alkanes

NORFARN	Norfarnesane
NORFARNU	Norfarnesane uncertainty
DODEC	Dodecane
DODECU	Dodecane uncertainty
TRIDEC	Tridecane
TRIDECU	Tridecane uncertainty
HPYCYHX	Heptylcyclohexane
HPYCYHXU	Heptylcyclohexane uncertainty
FARNES	Farnesane
FARNESU	Farnesane uncertainty
TDEC	Tetradecane
TDECU	Tetradecane uncertainty

OCYCYHX	Octylcyclohexane
OCYCYHXU	Octylcyclohexane uncertainty
PENTAD	Pentadecane
PENTADU	Pentadecane uncertainty
NOYCYHX	Nonylcyclohexane
NOYCYHXU	Nonylcyclohexane uncertainty
HEXAD	Hexadecane
HEXADU	Hexadecane uncertainty
NORPRST	Norpristane
NORPRSTU	Norpristane uncertainty
DECYHX	Decylcyclohexane
DECYHXU	Decylcyclohexane uncertainty
HEPTAD	Heptadecane
HEPTADU	Heptadecane uncertainty
HEPTDPRIS	Heptadecane_Pristane
HEPTDPRISU	Heptadecane_Pristane uncertainty
DEC1YHX	Undecylcyclohexane
DEC1YHXU	Undecylcyclohexane uncertainty
OCTAD	Octadecane
OCTADU	Octadecane uncertainty
PHYTAN	Phytane
PHYTANU	Phytane uncertainty
DEC2YHX	Dodecylcyclohexane
DEC2YHXU	Dodecylcyclohexane uncertainty
NONAD	Nonadecane
NONADU	Nonadecane uncertainty
DEC3YHX	Tridecylcyclohexane
DEC3YHXU	Tridecylcyclohexane uncertainty
EICOSA	Eicosane
EICOSAU	Eicosane uncertainty
DEC4YHX	Tetradecylcyclohexane
DEC4YHXU	Tetradecylcyclohexane uncertainty
HENEIC	Heneicosane
HENEICU	Heneicosane uncertainty
DEC5YHX	Pentadecylcyclohexane
DEC5YHXU	Pentadecylcyclohexane uncertainty
DOCOSA	Docosane
DOCOSAU	Docosane uncertainty
DEC6YHX	Hexadecylcyclohexane
DEC6YHXU	Hexadecylcyclohexane uncertainty
TRICOSA	Tricosane
TRICOSAU	Tricosane uncertainty
DEC7YHX	Heptadecylcyclohexane
DEC7YHXU	Heptadecylcyclohexane uncertainty
TETCOS	Tetracosane
TETCOSU	Tetracosane uncertainty
DEC8YHX	Octadecylcyclohexane
DEC8YHXU	Octadecylcyclohexane uncertainty

PENCOS	Pentacosane
PENCOSU	Pentacosane uncertainty
HEXCOS	Hexacosane
HEXCOSU	Hexacosane uncertainty
DEC9YHX	Nonadecylcyclohexane
DEC9YHXU	Nonadecylcyclohexane uncertainty
HEPCOS	Heptacosane
HEPCOSU	Heptacosane uncertainty
CYHXEIC	Eicosylcyclohexane
CYHXEICU	Eicosylcyclohexane uncertainty
OCTCOS	Octacosane
OCTCOSU	Octacosane uncertainty
NONCOS	Nonacosane
NONCOSU	Nonacosane uncertainty
CYHXHEN	Heneicosylcyclohexane
CYHXHENU	Heneicosylcyclohexane uncertainty
TRICONT	Triacontane
TRICONTU	Triacontane uncertainty
HTRICONT	Hentriacontane
HTRICONTU	Hentriacontane uncertainty
DTRICONT	Dotriacontane
DTRICONTU	Dotriacontane uncertainty
TTRICONT	Tritriacontane
TTRICONTU	Tritriacontane uncertainty
TETRICONT	Tetratriacontane
TETRICONTU	Tetratriacontane uncertainty
PTRICONT	Pentatriacontane
PTRICONTU	Pentatriacontane uncertainty
HXTRICONT	Hexatriacontane
HXTRICONTU	Hexatriacontane uncertainty
HPTRICONT	Heptatriacontane
HPTRICONTU	Heptatriacontane uncertainty
OTRICONT	Octatriacontane
OTRICONTU	Octatriacontane uncertainty
NTRICONT	Nonatriacontane
NTRICONTU	Nonatriacontane uncertainty
TECONT	Tetracontane
TECONTU	Tetracontane uncertainty

Hopanes and Steranes

HOP13	18α(H)-22,29,30-Trisnorhopane
HOP13U	18α(H)-22,29,30-Trisnorhopane uncertainty
HOP14	17α(H),18α(H),21β(H)-25,28,30-Trisnorhopane
HOP14U	17α(H),18α(H),21β(H)-25,28,30-Trisnorhopane uncertainty
HOP15	17α(H)-22,29,30-Trisnorhopane
HOP15U	17α(H)-22,29,30-Trisnorhopane uncertainty

HOP16	17α(H),18α(H),21ß(H)-28,30-Bisnorhopane
HOP16U	17α(H),18α(H),21ß(H)-28,30-Bisnorhopane uncertainty
HOP17	17α(H),21β(H)-29-Norhopane
HOP17U	17α(H),21β(H)-29-Norhopane uncertainty
HOP18	18α(H)- 29-Norneohopane
HOP18U	18α(H)- 29-Norneohopane uncertainty
HOP19	17α(H),21β(H)-Hopane
HOP19U	17α(H),21β(H)-Hopane uncertainty
HOP20	17β(H),21α(H)-Hopane
HOP20U	17 β(H),21α(H)-Hopane uncertainty
HOP21	22S-17α(H),21β(H)-30-Homohopane
HOP21U	22S-17α(H),21β(H)-30-Homohopane uncertainty
HOP22	22R-17α(H),21β(H)-30-Homohopane
HOP22U	22R-17α(H),21β(H)-30-Homohopane uncertainty
HOP23	17β(H),21 β(H)-Hopane
HOP23U	17β(H)),21 β(H)-Hopane uncertainty
HOP24	22S-17α(H),21β(H)-30,31-Bishomohopane
HOP24U	22S-17α(H),21β(H)-30,31-Bishomohopane uncertainty
HOP25	22R-17α(H),21β(H)-30,31-Bishomohopane
HOP25U	22R-17α(H),21β(H)-30,31-Bishomohopane uncertainty
HOP26	22S-17α(H),21β(H)-30,31,32-Trisomohopane
HOP26U	22S-17α(H),21β(H)-30,31,32-Trisomohopane uncertainty
HOP27	22R-17α(H),21β(H)-30,31,32-Trishomohopane
HOP27U	22R-17α(H),21β(H)-30,31,32-Trishomohopane uncertainty
STER35	20S-13ß(H),17α(H)-Diacholestane
STER35U	20S-13ß(H),17α(H)-Diacholestane uncertainty
STER36	20R-13ß(H),17α(H)-Diacholestane
STER36U	20R-13ß(H),17α(H)-Diacholestane uncertainty
STER37	20S-13α(H),17ß(H)-Diacholestane
STER37U	20S-13α(H),17ß(H)-Diacholestane uncertainty
STER38	20R-13α(H),17ß(H)-Diacholestane
STER38U	20R-13α(H),17ß(H)-Diacholestane uncertainty
STER39	20S-13ß(H),17α(H)-Diaergostane
STER39U	20S-13ß(H),17α(H)-Diaergostane uncertainty
STER42	20S5α(H),14α(H)-Cholestane
STER42U	20S5α(H),14α(H)-Cholestane uncertainty
STER43	20R5α(H),14β(H)-Cholestane
STER43U	20R5α(H),14β(H)-Cholestane uncertainty
STER44	20S5α(H),14β(H),17β(H)-Cholestane
STER44U	20S5α(H),14β(H),17β(H)-Cholestane uncertainty
STER45_40	20R-5α(H),14α(H),17α(H)-Cholestane & 20S-13ß(H),17α(H)-diastigmastane
STER45_40U	20R-5α(H),14α(H),17α(H)-Cholestane & 20S-13ß(H),17α(H)-diastigmastane uncertainty
STER46	20S5α(H),14α(H),17α(H)-Ergostane
STER46U	20S5α(H),14α(H),17α(H)-Ergostane uncertainty
STER47	20R5α(H),14β(H),17β(H)-Ergostane
STER47U	20R5α(H),14β(H),17β(H)-Ergostane uncertainty

STER48_41	20S-5α(H),14ß(H),17ß(H)-Ergostane&20R-13α(H),17ß(H) diastigmastane
STER48_41U	20S-5α(H),14ß(H),17ß(H)-Ergostane & 20R-13α(H),17ß(H)-diastigmastane uncertainty
STER49	20R5α(H),14α(H),17α(H)-Ergostane
STER49U	20R5α(H),14α(H),17α(H)-Ergostane uncertainty
STER50	20S5α(H),14α(H),17α(H)-Stigmastane
STER50U	20S5α(H),14α(H),17α(H)-Stigmastane uncertainty
STER51	20R5α(H),14β(H),17β(H)-Stigmastane
STER51U	20R5α(H),14β(H),17β(H)-Stigmastane uncertainty
STER52	20S5α(H),14β(H),17β(H)-Stigmastane
STER52U	20S5α(H),14β(H),17β(H)-Stigmastane uncertainty
STER53	20R5α(H),14α(H),17α(H)-Stigmastane
STER53U	20R5α(H),14α(H),17α(H)-Stigmastane uncertainty

Nitrosamines

NDMA	N-nitrosodi-N-methylamine
NDMAU	N-nitrosodi-N-methylamine uncertainty
NDEA	N-nitrosodi-N-ethylamine
NDEAU	N-nitrosodi-N-ethylamine uncertainty
NDPA	N-nitrosodi-N-propylamine
NDPAU	N-nitrosodi-N-propylamine uncertainty
NNMUR	N-nitroso-N-methylurea
NNMURU	N-nitroso-N-methylurea uncertainty
NDBA	N-nitrosodi-N-butylamine
NDBAU	N-nitrosodi-N-butylamine uncertainty
NPPD	N-nitrosopiperidine
NPPDU	N-nitrosopiperidine uncertainty
NPYR	N-nitrosopyrrolidine
NPYRU	N-nitrosopyrrolidine uncertainty
NMRP	N-nitrosomorpholine
NMRPU	N-nitrosomorpholine uncertainty

Metals and Elements

NAXC	Sodium concentration (µg/filter) (qualitative only)
NAXU	Sodium concentration (µg/filter) uncertainty
MGXC	Magnesium concentration (µg/filter) (qualitative only)
MGXU	Magnesium concentration (µg/filter) uncertainty
ALXC	Aluminum concentration (µg/filter)
ALXU	Aluminum concentration (µg/filter) uncertainty
SIXC	Silicon concentration (µg/filter)
SIXU	Silicon concentration (µg/filter) uncertainty
PHXC	Phosphorous concentration (µg/filter)
PHXU	Phosphorous concentration (µg/filter) uncertainty
SUXC	Sulfur concentration (µg/filter)
SUXU	Sulfur concentration (µg/filter) uncertainty

CLXC	Chlorine concentration (µg/filter)
CLXU	Chlorine concentration (µg/filter) uncertainty
KPXC	Potassium concentration (µg/filter)
KPXU	Potassium concentration (µg/filter) uncertainty
CAXC	Calcium concentration (µg/filter)
CAXU	Calcium concentration (µg/filter) uncertainty
SCXC	Scandium concentration (µg/filter)
SCXU	Scandium concentration (µg/filter) uncertainty
TIXC	Titanium concentration (µg/filter)
TIXU	Titanium concentration (µg/filter) uncertainty
VAXC	Vanadium concentration (µg/filter)
VAXU	Vanadium concentration (µg/filter) uncertainty
CRXC	Chromium concentration (µg/filter)
CRXU	Chromium concentration (µg/filter) uncertainty
MNXC	Manganese concentration (µg/filter)
MNXU	Manganese concentration (µg/filter) uncertainty
FEXC	Iron concentration (µg/filter)
FEXU	Iron concentration (µg/filter) uncertainty
COXC	Cobalt concentration (µg/filter)
COXU	Cobalt concentration (µg/filter) uncertainty
NIXC	Nickel concentration (µg/filter)
NIXU	Nickel concentration (µg/filter) uncertainty
CUXC	Copper concentration (µg/filter)
CUXU	Copper concentration (µg/filter) uncertainty
ZNXC	Zinc concentration (µg/filter)
ZNXU	Zinc concentration (µg/filter) uncertainty
GAXC	Gallium concentration (µg/filter)
GAXU	Gallium concentration (µg/filter) uncertainty
ASXC	Arsenic concentration (µg/filter)
ASXU	Arsenic concentration (µg/filter) uncertainty
SEXC	Selenium concentration (µg/filter)
SEXU	Selenium concentration (µg/filter) uncertainty
BRXC	Bromine concentration (µg/filter)
BRXU	Bromine concentration (µg/filter) uncertainty
RBXC	Rubidium concentration (µg/filter)
RBXU	Rubidium concentration (µg/filter) uncertainty
SRXC	Strontium concentration (µg/filter)
SRXU	Strontium concentration (µg/filter) uncertainty
YTXC	Yttrium concentration (µg/filter)
YTXU	Yttrium concentration (µg/filter) uncertainty
ZRXC	Zirconium concentration (µg/filter)
ZRXU	Zirconium concentration (µg/filter) uncertainty
NBXC	Niobium concentration (µg/filter)
NBXU	Niobium concentration (µg/filter) uncertainty
MOXC	Molybdenum concentration (µg/filter)
MOXU	Molybdenum concentration (µg/filter) uncertainty
PDXC	Palladium concentration (µg/filter)
PDXU	Palladium concentration (µg/filter) uncertainty

AGXC	Silver concentration (µg/filter)
AGXU	Silver concentration (µg/filter) uncertainty
CDXC	Cadmium concentration (µg/filter)
CDXU	Cadmium concentration (µg/filter) uncertainty
INXC	Indium concentration (µg/filter)
INXU	Indium concentration (µg/filter) uncertainty
SNXC	Tin concentration (µg/filter)
SNXU	Tin concentration (µg/filter) uncertainty
SBXC	Antimony concentration (µg/filter)
SBXU	Antimony concentration (µg/filter) uncertainty
CSXC	Cesium concentration (µg/filter)
CSXU	Cesium concentration (µg/filter) uncertainty
BAXC	Barium concentration (µg/filter)
BAXU	Barium concentration (µg/filter) uncertainty
LAXC	Lanthanum concentration (µg/filter)
LAXU	Lanthanum concentration (µg/filter) uncertainty
CEXC	Cerium concentration (µg/filter)
CEXU	Cerium concentration (µg/filter) uncertainty
SMXC	Samarium concentration (µg/filter)
SMXU	Samarium concentration (µg/filter) uncertainty
EUXC	Europium concentration (µg/filter)
EUXU	Europium concentration (µg/filter) uncertainty
TBXC	Terbium concentration (µg/filter)
TBXU	Terbium concentration (µg/filter) uncertainty
HFXC	Hafnium concentration (µg/filter)
HFXU	Hafnium concentration (µg/filter) uncertainty
TAXC	Tantalum concentration (µg/filter)
TAXU	Tantalum concentration (µg/filter) uncertainty
WOXC	Tungsten concentration (µg/filter)
WOXU	Tungsten concentration (µg/filter) uncertainty
IRXC	Iridium concentration (µg/filter)
IRXU	Iridium concentration (µg/filter) uncertainty
AUXC	Gold concentration (µg/filter)
AUXU	Gold concentration (µg/filter) uncertainty
HGXC	Mercury concentration (µg/filter)
HGXU	Mercury concentration (µg/filter) uncertainty
TLXC	Thallium concentration (µg/filter)
TLXU	Thallium concentration (µg/filter) uncertainty
PBXC	Lead concentration (µg/filter)
PBXU	Lead concentration (µg/filter) uncertainty
URXC	Uranium concentration (µg/filter)
URXU	Uranium concentration (µg/filter) uncertainty

APPENDIX C

PAH, HOPANES, AND STERANES MASS CONCENTRATION IN FUEL AND LUBE OIL

TABLE C-1. FUEL AND LUBE OIL PAH

	Fresh Oil	Engine A	Engine B	Engine C	Engine D	Fuel
	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g
naphth	0.00	0.13	1.66	0.00	12.14	291.86
naphthu	0.04	0.04	0.09	0.04	0.65	15.84
quinoline	0.00	0.00	0.00	0.00	0.00	41.08
quinolineu	0.04	0.04	0.04	0.04	0.04	5.26
mnaph2	0.00	0.35	0.00	0.16	20.06	1695.80
mnaph2u	0.04	0.04	0.04	0.04	0.96	80.81
mnaph1	0.00	0.17	0.12	0.04	7.96	1000.20
mnaph1u	0.04	0.04	0.04	0.04	0.42	52.76
biphen	0.00	0.56	0.12	0.00	0.69	548.93
biphenu	0.04	0.05	0.04	0.04	0.04	24.76
enap12	0.00	0.61	0.04	0.08	2.54	473.80
enap12u	0.04	0.09	0.04	0.04	0.34	64.94
m_2bph	0.00	0.22	0.00	0.00	0.36	13.94
m_2bphu	0.04	0.04	0.04	0.04	0.04	0.56
dmn267	0.00	5.13	0.04	0.78	7.30	3403.16
dmn267u	0.04	0.28	0.04	0.05	0.41	184.80
dm1367	0.00	6.47	0.39	1.60	14.32	6299.48
dm1367u	0.04	0.34	0.04	0.09	0.75	334.84
d14523	0.00	0.91	0.04	0.47	3.45	2196.19
d14523u	0.04	0.05	0.04	0.04	0.22	127.01
acnapy	0.00	0.00	3.55	0.00	0.07	1.37
acnapyu	0.04	0.04	0.74	0.04	0.04	0.28
dmn12	0.00	0.04	0.00	0.16	1.05	439.35
dmn12u	0.04	0.04	0.04	0.04	0.11	51.75
dmn18	0.00	0.00	0.00	0.00	0.00	0.90
dmn18u	0.04	0.04	0.04	0.04	0.04	0.16
acnape	0.19	0.04	0.04	0.12	0.04	10.31
acnapeu	0.04	0.04	0.04	0.04	0.04	1.64
m_3bph	0.00	7.78	0.15	0.35	5.71	1044.48
m_3bphu	0.04	0.26	0.04	0.04	0.19	35.37
m_4bph	0.00	0.17	0.00	0.00	1.16	462.90
m_4bphu	0.04	0.04	0.04	0.04	0.05	20.95
dbzfur	0.00	0.13	0.00	0.00	0.11	46.08
dbzfuru	0.04	0.04	0.04	0.04	0.04	1.64
bibenz	0.00	0.09	0.00	0.00	0.73	131.01
bibenzu	0.04	0.04	0.04	0.04	0.11	16.22
em_12n	0.00	0.48	0.04	0.04	0.69	195.29
em_12nu	0.04	0.09	0.04	0.04	0.15	37.40
tmi235n	0.00	1.00	0.15	0.39	2.36	657.96
tmi235nu	0.04	0.05	0.04	0.04	0.13	34.89
btmnap	0.00	5.47	0.08	1.91	10.90	1293.11
btmnapu	0.04	0.51	0.04	0.17	1.05	122.41
atmnap	0.00	4.30	0.12	1.01	5.34	1373.16
atmnapu	0.04	0.23	0.04	0.08	0.28	74.99

TABLE C-1 (CONT'D.) FUEL AND LUBE OIL PAH

	Fresh Oil	Engine A	Engine B	Engine C	Engine D	Fuel
	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g
ctmnap	0.00	5.39	0.08	2.30	10.32	1162.57
ctmnapu	0.04	0.25	0.04	0.11	0.45	51.13
em_21n	0.04	0.13	0.12	0.00	0.15	26.01
em_21nu	0.04	0.04	0.04	0.04	0.04	3.77
etmnap	0.00	2.56	0.12	0.70	7.49	817.75
etmnapu	0.04	0.12	0.04	0.05	0.33	35.49
tm245n	0.00	0.17	0.12	0.16	0.22	150.42
tm245nu	0.04	0.04	0.04	0.04	0.04	8.83
ftmnap	0.00	3.48	0.15	0.86	2.40	678.42
ftmnapu	0.04	0.17	0.04	0.05	0.14	33.85
fluore	0.00	0.78	0.46	0.12	0.87	79.43
fluoreu	0.04	0.18	0.12	0.04	0.18	15.50
tm145n	0.00	0.87	0.00	0.31	1.45	34.52
tm145nu	0.04	0.13	0.04	0.08	0.22	5.51
jtmnap	0.23	1.30	0.19	0.43	2.83	311.04
jtmnapu	0.04	0.14	0.04	0.04	0.27	29.42
a_mfluo	0.19	0.43	0.00	0.16	0.47	255.62
a_mfluou	0.04	0.05	0.04	0.04	0.04	22.92
b_mfluo	0.00	0.17	0.00	0.04	0.25	93.41
b_mfluou	0.04	0.04	0.04	0.04	0.04	11.26
m_1fluo	0.15	1.00	0.00	0.58	1.24	146.99
m_1fluou	0.04	0.13	0.04	0.08	0.19	21.65
fl9one	0.00	0.22	0.08	0.16	0.51	12.54
fl9oneu	0.04	0.04	0.04	0.04	0.04	1.03
dbth	0.00	0.00	0.00	0.04	0.07	8.63
dbthu	0.04	0.04	0.04	0.04	0.04	1.36
phenan	0.00	1.82	14.85	0.43	3.67	144.80
phenanu	0.04	0.11	0.79	0.04	0.19	7.71
anthra	0.00	0.17	0.08	0.16	0.76	22.77
anthrau	0.04	0.04	0.04	0.04	0.18	4.90
xanone	0.00	1.91	0.15	0.19	8.10	558.11
xanoneu	0.04	0.83	0.08	0.08	3.50	240.76
acquone	0.00	0.00	0.58	0.62	12.17	968.80
acquoneu	0.04	0.04	0.04	0.04	0.74	58.20
m_2phen	0.00	1.74	0.50	1.01	8.69	222.59
m_2phenu	0.04	0.31	0.08	0.16	1.45	36.68
m_3phen	0.27	1.09	0.50	1.36	8.07	216.53
m_3phenu	0.08	0.22	0.12	0.24	1.48	40.10
pnapone	0.00	0.39	0.54	0.78	1.05	22.18
pnaponeu	0.04	0.09	0.08	0.12	0.15	2.94
m_2anth	0.08	0.09	0.00	0.12	0.18	2.15
m_2anthu	0.04	0.04	0.04	0.04	0.04	0.47
m_45phen	0.00	0.43	4.63	0.23	1.05	1.17
m_45phenu	0.04	0.09	1.05	0.08	0.22	0.28

TABLE C-1 (CONT'D.) FUEL AND LUBE OIL PAH

	Fresh Oil	Engine A	Engine B	Engine C	Engine D	Fuel
	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g
m_9phen	0.38	0.52	0.58	1.09	2.98	82.44
m_9phenu	0.08	0.09	0.12	0.20	0.55	15.63
mpht_1	0.00	0.39	0.66	0.62	3.71	82.44
mpht_1u	0.04	0.05	0.08	0.08	0.45	9.95
dbpht	4.66	3.13	2.58	6.38	2.62	1.33
dbphtu	0.55	0.36	0.32	0.77	0.30	0.16
anthron	0.57	0.74	0.35	1.13	0.51	12.22
anthronu	0.15	0.18	0.08	0.27	0.11	2.88
m_9ant	0.00	0.13	0.12	0.35	0.18	4.02
m_9antu	0.04	0.04	0.04	0.08	0.04	0.56
nap2phen	0.30	0.22	1.23	0.12	0.22	0.31
nap2phenu	0.04	0.04	0.16	0.04	0.04	0.04
anrquone	0.27	0.70	0.15	0.47	0.29	4.06
anrquoneu	0.08	0.13	0.04	0.12	0.07	0.83
a_dmph	0.42	1.04	0.19	1.13	6.80	169.09
a_dmphu	0.08	0.13	0.04	0.16	0.90	22.13
b_dmph	0.00	1.22	0.31	0.82	3.89	86.54
b_dmphu	0.04	0.22	0.08	0.16	0.67	15.19
dm17ph	1.29	0.83	0.89	0.47	5.63	114.22
dm17phu	0.16	0.09	0.12	0.08	0.65	12.84
dm36ph	0.27	0.26	0.12	0.16	2.76	120.55
dm36phu	0.04	0.04	0.04	0.04	0.41	17.46
d_dmph	0.49	1.09	0.12	0.47	4.11	64.86
d_dmphu	0.15	0.31	0.04	0.16	1.17	18.52
e_dmph	0.42	0.39	0.15	0.43	3.53	71.97
e_dmphu	0.08	0.09	0.04	0.08	0.63	13.03
c_dmph	2.65	2.74	2.08	3.23	9.41	230.40
c_dmphu	0.46	0.44	0.35	0.56	1.59	38.69
fluora	0.00	0.43	24.65	0.93	0.29	0.74
fluorau	0.04	0.09	5.39	0.20	0.07	0.16
pyrene	1.02	1.91	46.17	1.17	4.18	142.89
pyreneu	0.16	0.31	7.26	0.20	0.67	22.50
antal9	0.72	0.96	0.89	3.42	2.22	30.34
antal9u	0.12	0.18	0.16	0.56	0.37	5.02
retene	0.08	0.09	0.12	0.31	0.15	0.62
reteneu	0.04	0.04	0.04	0.04	0.04	0.04
bafluo	1.70	2.78	0.93	0.93	1.89	2.19
bafluou	0.46	0.74	0.23	0.24	0.51	0.59
bbfluo	0.19	0.52	0.62	1.63	0.33	0.20
bbfluou	0.08	0.13	0.16	0.43	0.11	0.08
bmpyfl	0.83	0.35	0.58	1.25	1.42	0.94
bmpyflu	0.15	0.09	0.12	0.24	0.26	0.16
c1mflpy	0.98	0.83	2.24	0.74	1.56	2.93
c1mflpyu	0.15	0.13	0.39	0.12	0.26	0.52

TABLE C-1 (CONT'D.) FUEL AND LUBE OIL PAH

	Fresh Oil	Engine A	Engine B	Engine C	Engine D	Fuel
	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g
m_13fl	0.57	0.61	0.62	1.28	1.02	1.37
m_13flu	0.15	0.17	0.19	0.39	0.29	0.39
m_4pyr	0.68	1.65	1.12	1.36	5.42	88.92
m_4pyru	0.04	0.10	0.09	0.09	0.28	4.57
cmpyfl	0.34	1.09	1.20	3.23	0.65	0.35
cmpyflu	0.11	0.31	0.35	0.94	0.18	0.12
dmpyfl	1.33	1.09	1.35	0.74	7.01	98.68
dmpyflu	0.19	0.18	0.20	0.12	1.04	14.48
m_1pyr	0.98	1.17	2.70	1.13	1.85	66.27
m_1pyru	0.19	0.22	0.51	0.24	0.37	12.84
bntiop	1.17	0.74	1.74	0.97	1.02	0.16
bntiopu	0.23	0.18	0.35	0.20	0.22	0.04
bzcphen	0.61	0.78	1.27	0.54	1.53	0.16
bzcphenu	0.23	0.31	0.46	0.20	0.55	0.08
bghifl	1.33	1.39	0.85	0.51	0.25	2.93
bghiflu	0.16	0.18	0.12	0.08	0.04	0.36
phant9	0.45	0.26	0.12	0.12	0.22	0.00
phant9u	0.11	0.09	0.04	0.04	0.07	0.04
cp_cdpyr	0.45	0.48	0.58	0.16	0.55	0.16
cp_cdpyru	0.08	0.09	0.12	0.04	0.11	0.04
baanth	0.00	0.39	3.90	0.27	0.29	0.23
baanthu	0.04	0.09	0.86	0.08	0.07	0.08
chr_tr	2.31	0.83	7.56	1.13	1.05	1.41
chr_tru	0.31	0.13	1.00	0.16	0.15	0.20
bzanthr	0.91	2.13	2.24	1.79	3.42	0.51
bzanthru	0.19	0.48	0.51	0.39	0.77	0.12
b2epht	3.94	5.17	1.23	4.05	7.78	2.42
b2ephtu	0.40	0.51	0.12	0.41	0.77	0.25
baa7_12	0.00	1.69	7.29	2.18	4.54	0.35
baa7_12u	0.04	0.44	1.79	0.55	1.10	0.08
m_3chr	0.19	0.22	0.31	0.23	0.33	0.27
m_3chru	0.04	0.04	0.04	0.04	0.07	0.04
chry56m	0.27	0.35	0.27	0.51	0.80	0.08
chry56mu	0.04	0.04	0.04	0.04	0.05	0.04
m_7baa	0.68	0.39	0.35	0.90	1.05	0.16
m_7baau	0.12	0.09	0.08	0.16	0.19	0.04
dmban712	0.34	1.35	0.35	0.51	0.80	0.39
dmban712u	0.04	0.14	0.04	0.04	0.08	0.04
bbjkfl	0.27	0.43	0.85	0.58	2.07	0.12
bbjkflu	0.04	0.05	0.12	0.08	0.23	0.04
bafl	0.00	0.13	0.08	0.08	0.15	0.00
baflu	0.04	0.04	0.04	0.04	0.04	0.04
bepyrn	0.30	0.35	8.14	0.51	0.33	0.62
bepyrnu	0.11	0.13	2.71	0.16	0.11	0.20

TABLE C-1 (CONT'D.) FUEL AND LUBE OIL PAH

	Fresh Oil	Engine A	Engine B	Engine C	Engine D	Fuel
	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g
bapyrn	0.57	0.39	8.52	0.08	0.18	0.08
bapyrnu	0.04	0.05	0.68	0.04	0.04	0.04
peryle	0.11	0.17	2.43	0.31	0.40	0.08
peryleu	0.04	0.04	0.14	0.04	0.04	0.04
mchol3	0.00	0.52	0.23	0.54	0.29	0.12
mchol3u	0.04	0.09	0.08	0.12	0.07	0.04
m_7bpy	0.15	0.09	0.19	0.43	0.11	0.08
m_7bpyu	0.04	0.04	0.04	0.08	0.04	0.04
bpy910dih	0.23	0.30	0.54	0.19	0.62	0.00
bpy910dihu	0.08	0.09	0.12	0.04	0.15	0.04
incdfl	0.68	0.52	0.58	0.31	0.47	0.00
incdflu	0.04	0.05	0.04	0.04	0.04	0.04
dbahacr	0.38	1.00	0.27	0.39	0.62	0.00
dbahacru	0.04	0.09	0.04	0.04	0.04	0.04
dbajacr	0.19	1.04	0.42	0.31	0.36	0.00
dbajacru	0.08	0.26	0.12	0.08	0.11	0.04
in123pyr	0.30	1.35	0.69	0.39	0.44	0.00
in123pyru	0.04	0.06	0.04	0.04	0.04	0.04
dbajan	0.42	1.43	0.46	0.31	0.98	0.00
dbajanu	0.08	0.31	0.12	0.08	0.18	0.04
dbahacan	0.00	2.09	0.58	0.78	1.27	0.00
dbahacanu	0.04	0.08	0.04	0.05	0.06	0.04
bbchr	0.00	0.96	0.08	0.58	0.62	0.00
bbchru	0.04	0.05	0.04	0.04	0.04	0.04
pic	0.87	0.70	0.46	0.54	0.65	0.00
picu	0.23	0.22	0.12	0.16	0.18	0.04
dbcgcar	1.82	1.00	1.74	0.90	0.98	1.37
dbcgcaru	0.46	0.26	0.43	0.24	0.26	0.35
bghipe	0.64	0.39	28.08	0.93	0.44	0.04
bghipeu	0.12	0.09	5.44	0.20	0.07	0.04
anthan	0.00	0.39	0.58	0.35	0.25	0.00
anthanu	0.04	0.05	0.04	0.04	0.04	0.04
dbalpyr	0.19	0.22	0.69	0.47	0.29	0.00
dbalpyru	0.04	0.04	0.04	0.04	0.04	0.04
dbaepyr	0.19	0.13	0.19	0.00	0.18	0.04
dbaepyru	0.08	0.04	0.08	0.04	0.07	0.04
corone	0.00	0.13	7.56	0.23	0.15	0.04
coroneu	0.04	0.04	1.91	0.08	0.04	0.04
dbaipyr	0.27	0.04	0.19	0.00	0.18	0.00
dbaipyru	0.04	0.04	0.04	0.04	0.04	0.04
dbahpyr	0.00	0.22	0.31	0.00	0.15	0.00
dbahpyru	0.04	0.04	0.04	0.04	0.04	0.04
dbbkfl	0.23	0.13	0.81	0.43	0.22	0.00
dbbkflu	0.04	0.04	0.05	0.04	0.04	0.04
Sum PAH	**42.72**	**115.35**	**215.07**	**76.31**	**279.66**	**29049.4**
u is designated for measurement uncertainty or limit of detection						

TABLE C-2. OIL AND FUEL HOPANES AND STERANES

	Fresh Oil	Engine A	Engine B	Engine C	Engine D	Fuel
	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g
hop13	20.59	23.71	38.10	51.36	173.45	0.00
hop13u	2.44	2.81	4.52	6.10	20.59	0.00
hop14	2.15	2.44	5.00	3.68	87.94	0.00
hop14u	0.09	0.10	0.21	0.15	3.65	0.00
hop15	28.81	24.75	33.88	20.02	116.96	0.04
hop15u	1.72	1.48	2.02	1.20	10.17	0.00
hop16	5.91	4.21	5.63	5.29	6.96	0.00
hop16u	0.38	0.27	0.36	0.34	0.45	0.00
hop17	51.92	48.69	170.39	89.73	404.51	0.06
hop17u	2.18	2.05	7.16	3.77	17.00	0.00
hop18	4.80	2.01	1.63	4.84	0.00	0.00
hop18u	0.24	0.10	0.08	0.24	0.00	0.00
hop19	17.79	19.38	120.42	40.54	134.20	0.00
hop19u	1.11	1.21	7.51	2.53	8.37	0.00
hop20	2.91	1.26	8.13	3.26	20.29	0.00
hop20u	0.38	0.16	1.06	0.42	2.65	0.00
hop21	12.19	12.61	131.39	21.26	44.87	0.00
hop21u	0.77	0.79	8.26	1.34	2.82	0.00
hop22	8.21	13.05	128.54	21.16	61.06	0.00
hop22u	0.55	0.87	8.61	1.42	4.09	0.00
hop23	0.00	0.00	2.78	2.08	1.33	0.00
hop23u	0.00	0.00	0.14	0.10	0.07	0.00
hop24	5.86	10.43	111.78	12.90	33.16	0.00
hop24u	0.70	1.25	13.42	1.55	3.98	0.00
hop25	3.98	6.28	84.95	8.58	15.81	0.00
hop25u	0.47	0.74	9.99	1.01	1.86	0.00
hop26	2.79	5.23	108.96	10.25	16.86	0.00
hop26u	0.51	0.96	19.95	1.88	3.09	0.00
hop27	1.76	3.56	70.32	7.32	7.51	0.00
hop27u	0.09	0.17	3.40	0.35	0.36	0.00
sum hopanes	**169.66**	**177.61**	**1021.89**	**302.27**	**1124.91**	**0.1**
u is designated for measurement uncertainty or limit of detection						

TABLE C-2 (CONT'D.) OIL AND FUEL HOPANES AND STERANES

	Fresh Oil	Engine A	Engine B	Engine C	Engine D	Fuel
	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g
ster35	12.70	7.39	11.22	17.99	3.24	0.00
ster35u	0.36	0.21	0.32	0.52	0.09	0.00
ster36	6.91	3.94	9.70	12.13	6.52	0.00
ster36u	0.69	0.39	0.97	1.21	0.65	0.00
ster37	1.81	2.46	3.71	2.70	39.11	0.00
ster37u	0.13	0.17	0.26	0.19	2.75	0.00
ster38	4.30	2.48	3.51	5.67	32.59	0.00
ster38u	0.58	0.33	0.47	0.76	4.39	0.00
ster39	5.27	4.00	5.78	8.46	66.23	0.00
ster39u	0.51	0.38	0.56	0.81	6.36	0.00
ster42	10.86	9.53	10.29	10.33	25.28	0.00
ster42u	1.14	1.00	1.08	1.08	2.65	0.00
ster43	21.63	12.49	10.47	30.23	51.89	0.00
ster43u	0.91	0.53	0.44	1.27	2.18	0.00
ster44	12.63	7.38	21.04	18.11	39.79	0.00
ster44u	1.44	0.84	2.39	2.06	4.53	0.00
ster45_40	18.90	8.39	27.24	22.60	27.22	0.00
ster45_40u	0.55	0.24	0.79	0.66	0.79	0.00
ster46	5.34	8.65	5.09	7.53	55.87	0.00
ster46u	0.35	0.57	0.33	0.49	3.66	0.00
ster47	4.42	6.32	11.41	11.45	42.08	0.00
ster47u	0.38	0.54	0.98	0.98	3.61	0.00
ster48_41	10.90	8.62	11.97	29.67	16.90	0.00
ster48_41u	1.09	0.87	1.20	2.98	1.70	0.00
ster49	4.51	0.18	9.49	7.07	58.03	0.00
ster49u	1.23	0.05	2.60	1.93	15.87	0.00
ster50	4.27	4.32	7.39	5.80	22.13	0.00
ster50u	0.37	0.37	0.64	0.50	1.92	0.00
ster51	10.64	8.55	27.93	19.63	64.91	0.00
ster51u	1.68	1.35	4.40	3.09	10.22	0.00
ster52	7.93	5.73	22.87	13.40	88.23	0.00
ster52u	1.04	0.75	3.01	1.76	11.60	0.00
ster53	3.75	9.02	17.00	12.11	4.99	0.00
ster53u	0.50	1.21	2.28	1.62	0.67	0.00
sum steranes	**146.77**	**109.45**	**216.13**	**234.89**	**645.02**	**0**
u is designated for measurement uncertainty or limit of detection						

APPENDIX D

METALS AND ELEMENTS EMISSIONS IN µG/HP-HR

TABLE D-1. ENGINE A METALS AND ELEMENTS

	FTP-w-1	FTP-w-2	FTP-w-3	FTP-wo-1	FTP-wo-2	FTP-wo-3	CARBx-1	CARBx-2	CARBz-1	CARBz-1	16-Hour-1	16-Hour-2	16-Hour-3	TB-1	TB-2	TB-3	TB-4
	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr
NAXC	0.00	0.00	128.82	88.89	53.67	42.58	0.00	0.00	75.29	32.57	32.70	22.99	28.29	0.00	0.00	457.06	0.00
NAXU	509.87	509.87	528.00	437.25	386.22	386.60	1481.69	1498.13	146.39	123.70	7.71	6.19	6.18	1623.90	450.86	469.12	456.30
MGXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.82	2.39	0.76	811.76	0.00	0.00	0.00
MGXU	273.91	272.67	280.23	231.18	204.20	204.98	789.05	796.40	76.93	65.32	3.77	3.07	2.99	341.67	244.97	245.27	244.18
ALXC	28.53	0.00	0.00	20.79	0.00	21.40	0.00	176.77	13.23	7.03	2.34	1.64	3.24	0.00	0.00	0.00	18.43
ALXU	45.25	44.91	46.24	38.32	33.68	33.94	130.79	133.12	12.84	10.83	0.63	0.51	0.51	576.38	40.22	40.22	40.47
SIXC	44.08	0.00	0.00	0.00	0.00	58.04	0.00	51.99	0.00	3.83	2.40	0.45	2.16	0.00	0.00	0.00	0.00
SIXU	50.73	50.34	51.51	42.68	37.75	38.26	145.68	148.17	14.20	12.14	0.70	0.56	0.56	3206.69	45.08	45.08	45.08
PHXC	0.00	9.45	8.76	1.31	0.00	0.00	13.40	34.07	37.38	73.08	18.45	15.27	14.34	55.30	1.38	21.41	80.23
PHXU	14.43	14.74	15.08	12.22	10.80	10.82	41.70	43.10	4.24	3.75	0.27	0.23	0.22	13.03	12.90	13.20	13.20
SUXC	0.00	106.86	0.00	77.99	88.65	71.68	242.08	386.78	846.94	1710.74	383.70	302.24	280.54	0.00	52.54	51.37	1844.69
SUXU	40.29	40.56	41.17	34.39	30.62	30.46	117.38	119.44	15.35	18.50	2.74	2.17	2.03	36.03	36.32	36.32	44.45
CLXC	0.00	1.78	0.00	5.24	3.65	5.27	2.57	130.66	0.00	0.01	0.19	0.23	0.17	0.00	8.67	0.00	0.00
CLXU	9.93	9.92	10.15	8.41	7.44	7.45	28.70	29.00	2.80	2.38	0.14	0.11	0.11	10.56	8.88	8.88	8.88
KPXC	10.96	2.62	4.45	0.00	4.24	2.95	0.00	158.71	0.12	1.67	0.82	0.36	0.61	213.76	1.17	0.00	5.49
KPXU	9.28	9.26	9.48	7.85	6.95	6.96	26.81	27.09	2.61	2.22	0.13	0.10	0.10	360.48	8.30	8.30	8.30
CAXC	34.01	12.49	17.28	0.00	0.84	7.10	79.20	188.94	10.94	14.11	13.81	11.29	12.73	1894.51	2.93	2.56	91.96
CAXU	11.15	11.13	11.39	9.44	8.35	8.36	32.22	32.56	3.14	2.67	0.17	0.14	0.14	356.63	9.97	9.97	10.26
SCXC	1.97	0.00	6.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.14	0.06	7.46	0.00	0.00	0.00
SCXU	36.59	36.54	37.39	30.98	27.40	27.44	105.74	106.85	10.31	8.75	0.50	0.41	0.40	33.85	32.72	32.72	32.72
TIXC	2.62	8.28	0.00	0.00	3.61	0.32	0.00	12.72	0.00	0.00	0.07	0.06	0.33	68.21	0.00	0.38	1.17
TIXU	6.84	6.83	6.99	5.79	5.12	5.13	19.77	19.98	1.93	1.64	0.09	0.08	0.07	41.06	6.12	6.12	6.12
VAXC	2.20	0.00	0.00	1.47	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.01	0.00	3.14	0.00	0.38
VAXU	0.61	0.61	0.62	0.52	0.46	0.46	1.76	1.78	0.17	0.15	0.01	0.01	0.01	4.44	0.54	0.54	0.54
CRXC	0.66	0.00	5.60	0.00	0.00	0.00	0.00	8.35	1.29	1.00	0.37	0.24	1.28	0.00	0.00	0.59	31.97
CRXU	6.23	6.22	6.37	5.28	4.67	4.67	18.01	18.20	1.76	1.49	0.09	0.07	0.07	5.57	5.57	5.57	5.57
MNXC	0.47	5.71	0.00	5.59	0.00	0.00	29.24	0.00	2.48	1.37	0.19	0.11	0.23	78.05	0.00	0.00	0.00
MNXU	13.07	13.05	13.36	11.07	9.79	9.80	37.77	38.17	3.68	3.13	0.18	0.15	0.14	14.12	11.69	11.69	11.69
FEXC	17.52	37.24	19.29	13.37	12.49	13.14	87.46	240.80	16.92	13.01	12.07	9.46	15.42	289.80	0.00	2.35	203.91
FEXU	16.77	16.75	17.14	14.20	12.56	12.58	48.47	49.80	4.80	4.08	0.25	0.20	0.21	56.56	15.00	15.00	15.25
COXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
COXU	0.61	0.61	0.62	0.52	0.46	0.46	1.76	1.78	0.17	0.15	0.01	0.01	0.01	0.54	0.54	0.54	0.54
NIXC	0.00	2.01	0.00	0.00	0.00	0.00	0.00	0.00	0.44	0.00	0.00	0.01	0.41	17.26	0.00	2.97	13.16
NIXU	3.09	3.09	3.16	2.62	2.32	2.32	8.94	9.03	0.87	0.74	0.04	0.03	0.03	2.77	2.77	2.77	2.77
CUXC	0.00	1.96	5.60	0.00	1.16	0.00	0.00	17.38	1.80	1.42	0.15	0.16	0.53	816.87	0.21	4.90	25.68
CUXU	5.57	5.57	5.70	4.72	4.17	4.18	16.11	16.28	1.57	1.33	0.08	0.06	0.06	7.29	4.99	4.99	4.99
ZNXC	28.29	16.42	6.94	0.00	2.81	20.91	22.20	72.38	8.34	7.40	4.94	5.14	5.80	727.04	0.00	0.00	31.59
ZNXU	5.57	5.57	5.70	4.72	4.17	4.18	16.11	16.28	1.57	1.33	0.09	0.07	0.07	1136.09	4.99	4.99	4.99
GAXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.15	0.00	0.00	0.00	0.00
GAXU	19.86	19.84	20.30	16.82	14.87	14.90	57.40	58.01	5.60	4.75	0.27	0.22	0.22	22.75	17.76	17.76	17.76
ASXC	0.00	0.00	0.00	0.00	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ASXU	0.61	0.61	0.62	0.52	0.46	0.46	1.76	1.78	0.17	0.15	0.01	0.01	0.01	0.88	0.54	0.54	0.54
SEXC	7.26	0.00	0.24	0.00	3.12	0.00	10.83	0.00	0.00	1.21	0.00	0.00	0.03	0.00	8.84	0.00	11.19
SEXU	13.07	13.05	13.36	11.07	9.79	9.80	37.77	38.17	3.68	3.13	0.18	0.15	0.14	11.69	11.69	11.69	11.69
BRXC	10.54	0.00	0.00	2.98	2.63	0.67	0.00	0.00	0.00	0.73	0.00	0.02	0.07	5.87	3.52	0.00	5.49
BRXU	9.28	9.26	9.48	7.85	6.95	6.96	26.81	27.09	2.61	2.22	0.13	0.10	0.10	8.30	8.30	8.30	8.30
RBXC	1.31	3.46	0.00	0.36	0.00	0.00	0.00	17.92	0.00	0.73	0.00	0.00	0.03	10.98	0.00	0.00	4.27
RBXU	6.84	6.83	6.99	5.79	5.12	5.13	19.77	19.98	1.93	1.64	0.09	0.08	0.07	7.25	6.12	6.12	6.12
SRXC	0.00	0.89	4.45	2.58	4.91	9.21	3.79	2.60	2.97	0.94	0.43	0.30	0.22	5283.92	8.63	8.21	3.90
SRXU	12.37	12.35	12.64	10.47	9.26	9.28	35.74	36.12	3.48	2.96	0.17	0.14	0.13	63.43	11.06	11.06	11.06
YTXC	1.12	4.16	2.06	6.51	3.47	0.00	0.00	5.88	0.20	1.21	0.05	0.11	0.08	0.00	2.97	3.73	2.18
YTXU	9.28	9.26	9.48	7.85	6.95	6.96	26.81	27.09	2.61	2.22	0.13	0.10	0.10	8.88	8.30	8.30	8.30
U is designated for measurement uncertainty or limit of detection																	

TABLE D-1 (CONT'D.) ENGINE A METALS AND ELEMENTS

	FTP-w-1	FTP-w-2	FTP-w-3	FTP-wo-1	FTP-wo-2	FTP-wo-3	CARBx-1	CARBx-2	CARBz-1	CARBz-1	16-Hour-1	16-Hour-2	16-Hour-3	TB-1	TB-2	TB-3	TB-4
	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr
ZRXU	21.74	21.71	22.21	18.41	16.28	16.30	62.82	63.48	6.12	5.20	0.30	0.24	0.24	40.22	19.44	19.44	19.44
NBXC	0.00	0.00	6.27	3.73	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.03	10.98	0.00	6.28	11.40
NBXU	16.77	16.75	17.14	14.20	12.56	12.58	48.47	48.98	4.73	4.01	0.23	0.19	0.18	15.25	15.00	15.00	15.00
MOXC	2.44	0.00	11.01	0.00	4.14	0.00	0.00	3.28	0.00	0.06	0.00	0.06	0.00	0.00	0.00	8.04	6.12
MOXU	14.90	14.88	15.22	12.61	11.16	11.17	43.05	43.51	4.20	3.56	0.20	0.17	0.16	13.87	13.32	13.32	13.32
PDXC	12.27	0.00	4.93	0.00	0.00	0.00	0.00	0.00	1.23	1.68	0.00	0.00	0.03	0.00	0.00	0.00	0.00
PDXU	28.58	28.54	29.20	24.20	21.40	21.64	82.59	83.46	8.05	6.84	0.39	0.32	0.31	25.56	25.56	25.56	25.56
AGXC	0.00	4.16	5.60	6.86	0.49	0.81	0.00	0.00	0.00	0.47	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AGXU	26.05	26.01	26.62	22.06	19.50	19.54	75.28	76.07	7.34	6.23	0.36	0.29	0.28	23.29	23.29	23.29	23.29
CDXC	0.00	5.71	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CDXU	32.56	32.80	33.27	27.57	24.38	24.42	94.10	95.09	9.17	7.86	0.45	0.36	0.35	28.87	29.12	29.12	29.37
INXC	0.00	2.62	0.00	4.84	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.52	0.00	0.00	0.00
INXU	19.21	19.18	19.63	16.26	14.38	14.41	55.51	56.09	5.41	4.60	0.26	0.21	0.21	17.18	17.18	17.18	17.18
SNXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
SNXU	24.78	24.75	25.04	20.98	18.35	18.59	71.62	72.38	6.98	5.86	0.34	0.27	0.27	22.16	22.16	22.16	22.16
SBXC	0.00	0.00	0.00	33.60	0.00	0.00	46.30	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00	32.34	0.00
SBXU	45.91	45.85	46.91	38.87	34.38	34.43	132.68	134.08	12.94	10.98	0.63	0.51	0.50	40.77	41.06	41.06	41.06
CSXC	7.21	0.00	0.00	3.89	0.00	0.00	0.00	0.00	0.30	0.00	0.00	0.03	0.04	0.00	0.59	0.00	0.00
CSXU	7.40	7.39	7.56	6.27	5.54	5.55	21.39	21.62	2.09	1.77	0.10	0.08	0.08	6.62	6.62	6.62	6.62
BAXC	1.31	0.00	0.00	0.00	0.00	1.65	0.00	0.00	0.37	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BAXU	3.70	3.70	3.78	3.13	2.77	2.78	10.70	10.81	1.04	0.89	0.05	0.04	0.04	1724.78	3.31	3.31	3.31
LAXC	0.00	0.00	5.60	0.00	0.00	0.00	0.68	13.41	0.30	0.00	0.00	0.00	0.00	0.00	0.96	4.90	0.00
LAXU	5.57	5.57	5.70	4.72	4.17	4.18	16.11	16.28	1.57	1.33	0.08	0.06	0.06	4.99	4.99	4.99	4.99
CEXC	1.36	0.89	0.00	0.00	4.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CEXU	8.10	8.09	8.28	6.86	6.07	6.08	23.42	23.67	2.28	1.94	0.11	0.09	0.09	7.25	7.25	7.25	7.25
SMXC	4.17	0.00	0.00	9.08	8.03	0.00	23.42	27.50	0.67	2.15	0.00	0.00	0.00	0.00	0.00	6.45	8.42
SMXU	11.15	11.13	11.39	9.44	8.35	8.36	32.22	32.56	3.14	2.67	0.15	0.12	0.12	16.93	9.97	9.97	9.97
EUXC	0.00	0.00	4.26	0.00	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	13.11	2.93	0.00
EUXU	40.29	40.24	41.17	34.11	30.17	30.22	116.43	117.66	11.35	9.64	0.55	0.45	0.44	50.44	36.32	36.03	36.03
TBXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.89	0.00	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00
TBXU	13.63	13.61	13.93	11.54	10.21	10.22	39.40	39.81	3.84	3.26	0.19	0.16	0.15	14.12	12.19	12.19	12.19
HFXC	0.00	3.56	23.31	6.35	0.00	30.92	142.02	0.00	8.53	16.06	0.00	0.08	0.32	0.00	0.00	0.00	0.00
HFXU	88.35	87.91	89.95	74.53	65.91	66.02	255.34	257.08	24.80	21.14	1.21	0.98	0.96	90.12	78.72	78.72	78.47
TAXC	0.00	42.48	0.00	57.56	47.60	39.81	172.35	65.40	18.90	0.00	0.00	0.26	0.21	0.00	39.22	15.29	21.20
TAXU	74.11	73.69	75.73	62.75	55.50	55.59	214.19	215.48	20.88	17.73	1.02	0.82	0.80	74.03	65.99	65.99	65.99
WOXC	47.17	0.00	0.00	8.01	0.00	0.00	0.00	0.00	0.00	0.90	1.06	0.00	0.00	0.00	0.00	46.13	16.30
WOXU	106.53	106.06	108.52	90.20	79.52	79.65	306.93	310.16	29.83	25.49	1.46	1.18	1.15	105.66	95.53	95.27	95.27
IRXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.98	16.09
IRXU	22.91	22.88	23.41	19.40	17.15	17.18	66.21	66.90	6.45	5.48	0.31	0.25	0.25	20.49	20.49	20.49	20.78
AUXC	4.59	0.00	9.19	0.95	16.59	32.08	0.00	21.21	6.24	0.00	0.00	0.38	0.20	0.00	0.00	0.00	0.00
AUXU	48.95	48.89	50.02	41.45	36.90	36.96	141.48	142.97	13.89	11.71	0.67	0.55	0.54	43.78	43.78	43.78	43.78
HGXC	0.00	0.00	0.00	0.00	0.00	0.98	0.00	0.00	0.00	0.21	0.19	0.00	0.00	0.00	0.00	6.66	0.00
HGXU	14.90	14.88	15.22	12.61	11.16	11.17	43.05	43.51	4.29	3.56	0.20	0.17	0.16	13.32	13.32	13.32	13.32
TLXC	0.00	0.65	2.01	0.91	0.49	0.00	0.00	30.10	1.91	1.10	0.00	0.00	0.00	4.32	0.00	12.36	0.21
TLXU	15.51	15.49	15.84	13.13	11.61	11.63	44.81	45.29	4.37	3.71	0.21	0.17	0.17	13.87	13.87	13.87	13.87
PBXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	293.33	9.40	0.00	0.00	0.24	0.02	0.00	0.00	0.00	0.00
PBXU	16.11	16.09	16.47	13.65	12.07	12.09	46.57	48.02	4.63	3.86	0.22	0.18	0.18	15.00	14.41	14.41	14.41
URXC	0.00	8.33	0.00	0.00	8.21	10.86	41.84	69.23	0.00	3.88	0.00	0.00	0.00	0.00	3.52	0.00	0.00
URXU	26.05	26.01	26.62	22.06	19.50	19.54	75.28	76.07	7.34	6.23	0.36	0.29	0.29	24.38	23.29	23.29	23.29
U is designated for measurement uncertainty or limit of detection																	

TABLE D-2. ENGINE B METALS AND ELEMENTS

	FTP-w-1	FTP-w-2	FTP-w-3	FTP-wo-1	FTP-wo-2	FTP-wo-3	CARBx-1	CARBx-2	CARBz-1	CARBz-2	16-Hour-1	16-Hour-2	16-Hour-3	TB-1	TB-2	TB-3	TB-4
	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr
NAXC	0.00	0.00	0.00	110.12	0.00	0.00	56.42	0.00	62.09	0.00	33.52	30.82	33.25	0.00	0.00	0.00	36.41
NAXU	315.30	296.94	283.96	309.43	305.50	304.34	653.12	637.27	89.06	91.04	6.57	6.51	6.52	303.40	303.93	299.94	304.67
MGXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.78	1.69	3.55	0.00	0.00	0.00	0.00
MGXU	168.01	159.00	151.04	163.63	163.98	162.95	346.84	341.24	46.65	48.59	3.17	3.15	3.14	161.71	161.71	161.54	161.71
ALXC	14.59	37.29	0.00	47.69	15.81	0.00	24.47	0.00	0.00	0.94	4.47	2.13	2.31	0.00	0.00	0.00	29.82
ALXU	27.85	26.55	24.88	27.23	27.18	27.04	57.37	56.56	7.73	8.05	0.54	0.53	0.52	26.75	26.58	26.58	26.94
SIXC	0.00	0.00	15.91	17.69	0.00	0.00	0.00	0.00	0.00	0.00	0.95	0.80	0.67	0.00	1.19	0.00	0.00
SIXU	31.02	29.36	28.07	30.31	30.27	30.12	63.49	63.00	8.60	8.96	0.58	0.58	0.57	29.79	29.79	29.79	29.60
PHXC	53.30	48.40	50.59	55.41	53.09	42.61	101.50	135.14	11.12	16.57	22.77	16.95	22.03	61.06	50.17	60.28	41.87
PHXU	9.08	8.59	8.32	8.98	8.86	8.82	18.71	18.79	2.52	2.67	0.26	0.24	0.26	8.89	8.72	8.89	8.72
SUXC	1247.19	1177.98	1137.19	1212.49	1244.08	1096.54	2475.93	2668.93	337.06	350.41	498.22	356.97	490.77	1170.96	1094.78	1179.79	1168.38
SUXU	30.59	28.95	27.50	29.69	30.11	29.08	62.60	62.65	8.43	8.78	3.35	2.51	3.31	29.19	28.99	29.38	29.19
CLXC	0.00	4.09	0.00	0.00	0.00	1.06	0.00	0.00	0.01	0.24	0.00	0.11	0.00	0.00	40.18	0.00	0.00
CLXU	6.11	5.78	5.49	5.93	5.96	5.93	12.59	12.41	1.70	1.77	0.11	0.11	0.11	5.87	6.06	5.87	5.87
KPXC	4.30	7.91	11.87	13.60	1.83	4.45	9.44	7.08	1.27	2.02	0.65	0.33	0.42	7.50	36.02	3.88	3.88
KPXU	5.71	5.40	5.13	5.54	5.57	5.54	11.76	11.59	1.58	1.65	0.11	0.11	0.11	5.48	5.48	5.48	5.48
CAXC	107.01	71.64	68.29	107.55	62.04	60.13	143.13	140.58	20.85	19.69	5.64	5.00	4.81	101.21	67.54	63.91	59.23
CAXU	7.06	6.68	6.35	6.86	6.89	6.86	14.55	14.34	1.96	2.04	0.13	0.13	0.13	6.78	6.78	6.78	6.78
SCXC	0.00	0.00	0.00	1.71	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SCXU	22.52	21.31	20.24	21.86	21.97	21.86	46.38	45.73	6.25	6.50	0.42	0.42	0.41	21.63	21.63	21.63	21.63
TIXC	1.87	0.76	0.00	0.00	2.36	0.00	4.39	4.92	0.00	0.31	0.31	0.04	0.10	2.58	1.27	2.33	1.55
TIXU	4.21	3.98	3.78	4.09	4.11	4.09	8.67	8.55	1.17	1.22	0.08	0.08	0.08	4.04	4.04	4.04	4.04
VAXC	0.00	1.01	0.00	0.00	0.00	0.00	0.53	0.00	0.00	0.00	0.01	0.00	0.01	0.53	0.78	0.25	0.00
VAXU	0.37	0.35	0.34	0.36	0.37	0.36	0.77	0.76	0.10	0.11	0.01	0.01	0.01	0.36	0.36	0.36	0.36
CRXC	21.19	21.33	25.11	26.59	23.58	26.59	50.30	57.26	6.48	6.59	0.51	0.67	0.68	29.16	21.65	20.60	21.65
CRXU	3.83	3.63	3.45	3.72	3.74	3.72	7.90	7.79	1.06	1.11	0.07	0.07	0.07	3.68	3.68	3.68	3.68
MNXC	5.68	5.37	5.11	0.00	3.97	14.95	0.00	12.06	2.62	0.00	0.31	0.54	0.21	12.18	11.93	5.45	5.21
MNXU	8.04	7.61	7.23	7.81	7.85	7.81	16.57	16.34	2.23	2.32	0.15	0.15	0.15	7.73	7.73	7.73	7.73
FEXC	152.19	128.96	136.32	141.18	136.43	139.13	292.38	295.92	41.02	45.14	13.14	18.31	19.39	160.44	136.07	124.16	132.19
FEXU	10.70	9.93	9.61	10.19	10.24	10.19	21.62	21.31	2.91	3.09	0.21	0.22	0.22	10.27	10.08	10.08	10.08
COXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
COXU	0.37	0.35	0.34	0.36	0.37	0.36	0.77	0.76	0.10	0.11	0.01	0.01	0.01	0.36	0.36	0.36	0.36
NIXC	6.37	8.84	7.65	6.97	12.80	8.54	19.24	15.11	3.04	3.31	0.23	0.25	0.26	10.00	7.67	8.69	7.39
NIXU	1.90	1.80	1.71	1.85	1.86	1.85	3.92	3.86	0.53	0.55	0.04	0.04	0.04	1.83	1.83	1.83	1.83
CUXC	12.83	8.57	14.44	62.21	16.99	30.79	34.74	22.19	4.38	3.39	0.32	0.48	0.33	18.52	15.42	14.12	28.63
CUXU	3.43	3.25	3.08	3.53	3.35	3.33	7.07	6.97	0.95	0.99	0.06	0.06	0.06	3.30	3.30	3.30	3.30
ZNXC	15.51	14.43	34.34	53.56	13.56	26.06	25.83	36.48	5.28	4.17	0.86	0.93	0.97	18.03	22.15	14.90	28.38
ZNXU	3.43	3.25	3.27	3.53	3.35	3.33	7.07	6.97	0.95	0.99	0.07	0.07	0.07	3.30	3.30	3.30	3.30
GAXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.00	1.97	1.97	0.00	0.00
GAXU	12.22	11.57	10.99	11.87	11.93	11.87	25.18	24.83	3.39	3.53	0.23	0.23	0.23	11.74	11.74	11.74	11.74
ASXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ASXU	0.37	0.35	0.34	0.36	0.37	0.36	0.77	0.76	0.10	0.11	0.01	0.01	0.01	0.36	0.36	0.36	0.36
SEXC	0.00	1.15	5.47	2.24	0.00	8.79	12.53	6.32	0.00	0.00	0.00	0.06	0.00	8.42	4.02	0.00	5.59
SEXU	8.04	7.61	7.23	7.81	7.85	7.81	16.57	16.34	2.23	2.32	0.15	0.15	0.15	7.73	7.73	7.73	7.73
BRXC	0.00	0.00	5.34	1.57	0.00	4.45	0.00	0.00	0.38	0.23	0.00	0.00	0.06	2.33	7.78	0.00	1.02
BRXU	5.71	5.40	5.13	5.54	5.57	5.54	11.76	11.59	1.58	1.65	0.11	0.11	0.11	5.48	5.48	5.48	5.48
RBXC	0.00	1.53	0.00	1.82	0.51	1.82	0.00	14.75	0.00	0.00	0.00	0.00	0.02	0.50	1.55	0.00	0.00
RBXU	4.21	3.98	3.78	4.09	4.11	4.09	8.67	8.55	1.17	1.22	0.08	0.08	0.08	4.04	4.04	4.04	4.04
SRXC	5.13	13.01	3.16	0.00	4.73	0.78	1.66	6.03	2.54	0.31	0.20	0.09	0.10	4.65	7.25	5.95	3.38
SRXU	7.61	7.20	6.84	7.39	7.43	7.39	15.68	15.46	2.11	2.20	0.14	0.14	0.14	7.31	7.31	7.31	7.31
YTXC	0.00	2.43	0.39	0.00	0.00	1.46	0.00	1.41	1.24	0.90	0.00	0.09	0.10	0.00	1.97	0.00	1.44
YTXU	5.71	5.40	5.13	5.54	5.57	5.54	11.76	11.59	1.58	1.65	0.11	0.11	0.11	5.48	5.48	5.48	5.48
U is designated for measurement uncertainty or limit of detection																	

TABLE D-2 (CONT'D.) ENGINE B METALS AND ELEMENTS

	FTP-w-1	FTP-w-2	FTP-w-3	FTP-wo-1	FTP-wo-2	FTP-wo-3	CARBx-1	CARBx-2	CARBz-1	CARBz-2	16-Hour-1	16-Hour-2	16-Hour-3	TB-1	TB-2	TB-3	TB-4
	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr
ZRXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.14
ZRXU	13.38	12.66	12.03	12.98	13.06	12.99	27.56	27.17	3.71	3.86	0.25	0.25	0.25	12.85	12.85	12.85	12.85
NBXC	1.10	2.05	5.60	0.00	0.00	0.00	10.04	1.64	2.02	0.00	0.00	0.14	0.00	0.00	0.00	0.28	0.00
NBXU	10.32	9.77	9.28	10.02	10.07	10.02	21.26	20.96	2.86	2.98	0.19	0.19	0.19	9.91	9.91	9.91	9.91
MOXC	0.00	0.00	4.98	0.00	0.00	0.00	14.19	0.29	0.00	0.00	0.00	0.00	0.00	0.42	0.00	0.14	0.00
MOXU	9.17	8.68	8.24	8.90	8.95	8.90	18.89	18.62	2.54	2.65	0.17	0.17	0.17	8.81	8.81	8.81	8.81
PDXC	0.00	3.82	12.13	9.68	7.09	0.00	7.19	0.00	0.00	0.00	0.00	0.00	0.25	0.00	12.18	5.43	4.15
PDXU	17.59	16.64	15.81	17.07	17.16	17.08	36.23	35.72	4.88	5.08	0.33	0.33	0.32	16.89	16.89	16.89	16.89
AGXC	5.25	0.00	6.43	6.41	0.00	0.00	0.00	30.39	0.00	2.92	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AGXU	16.03	15.17	14.41	15.56	15.64	15.56	33.02	32.55	4.45	4.63	0.30	0.30	0.30	15.40	15.40	15.40	15.40
CDXC	0.00	0.00	0.00	0.00	0.00	0.00	1.13	0.00	0.00	0.00	0.00	0.00	0.00	3.66	0.00	0.00	3.66
CDXU	20.04	18.96	18.17	19.45	19.55	19.46	41.63	40.69	5.56	5.79	0.37	0.37	0.37	19.41	19.24	19.24	19.41
INXC	0.00	0.00	8.50	0.00	0.00	0.25	7.25	12.06	0.38	2.42	0.00	0.00	0.00	0.00	10.88	5.70	0.00
INXU	11.82	11.19	10.63	11.47	11.54	11.48	24.35	24.01	3.28	3.41	0.22	0.22	0.22	11.35	11.35	11.35	11.35
SNXC	0.00	0.00	0.00	0.00	0.00	0.28	18.95	0.00	3.45	1.49	0.00	0.15	0.00	0.00	3.13	0.00	0.00
SNXU	15.25	14.43	13.71	14.80	14.88	14.81	31.42	30.62	4.23	4.41	0.28	0.28	0.28	14.48	14.65	14.65	14.65
SBXC	0.00	3.71	13.48	0.00	0.00	0.00	53.10	1.35	3.48	3.16	0.00	0.20	0.00	6.34	3.77	0.00	12.57
SBXU	28.43	26.74	25.40	27.42	27.74	27.43	58.20	57.38	7.84	8.16	0.52	0.52	0.52	27.14	27.14	27.30	27.14
CSXC	0.00	0.38	0.00	1.43	0.00	0.00	3.62	0.00	0.00	0.00	0.00	0.04	0.03	0.00	0.00	1.16	0.00
CSXU	4.55	4.31	4.09	4.42	4.45	4.42	9.38	9.25	1.26	1.32	0.08	0.08	0.08	4.38	4.38	4.38	4.38
BAXC	0.00	0.00	0.00	0.00	0.25	0.00	3.86	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
BAXU	2.28	2.16	2.05	2.21	2.22	2.21	4.69	4.63	0.63	0.66	0.04	0.04	0.04	2.19	2.19	2.19	2.19
LAXC	0.40	0.90	0.36	0.00	0.00	0.39	0.00	0.00	0.00	0.00	0.01	0.01	0.04	2.19	0.00	0.64	0.00
LAXU	3.43	3.25	3.08	3.33	3.35	3.33	7.07	6.97	0.95	0.99	0.06	0.06	0.06	3.30	3.30	3.30	3.30
CEXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.00	0.00	0.00	4.68	0.00	0.00	0.00
CEXU	4.99	4.72	4.48	4.84	4.87	4.84	10.27	10.13	1.38	1.44	0.09	0.09	0.09	4.79	4.79	4.79	4.79
SMXC	6.60	3.71	2.05	0.00	0.00	0.00	5.82	12.35	0.26	0.00	0.00	0.00	0.00	1.94	5.84	3.24	0.00
SMXU	6.86	6.49	6.17	6.66	6.70	6.66	14.13	13.94	1.90	1.98	0.13	0.13	0.13	6.59	6.59	6.59	6.59
EUXC	0.00	0.00	0.00	2.74	0.00	0.00	39.73	26.58	0.00	0.00	0.00	0.06	0.00	0.00	0.00	6.34	0.00
EUXU	24.79	23.46	22.29	24.07	24.20	24.07	51.49	50.76	6.88	7.16	0.46	0.46	0.46	23.81	23.81	24.01	23.81
TBXC	0.00	6.63	0.00	0.00	0.00	0.00	2.73	9.84	0.00	0.00	0.00	0.00	0.00	0.00	4.13	4.13	0.00
TBXU	8.39	8.13	7.54	8.14	8.19	8.15	17.28	17.04	2.33	2.42	0.16	0.16	0.16	8.06	8.06	8.06	8.06
HFXC	0.00	31.95	0.00	13.12	16.88	7.36	98.41	0.00	0.00	0.00	0.48	0.00	0.00	0.00	0.00	22.82	16.09
HFXU	54.17	51.45	48.70	52.58	52.87	52.60	112.01	109.67	15.03	15.65	1.01	1.01	0.99	52.22	51.86	52.03	52.03
TAXC	0.00	19.42	11.40	24.88	22.40	0.00	80.59	9.31	12.58	0.00	0.00	0.48	0.28	27.99	13.24	0.00	17.89
TAXU	45.61	42.97	40.82	44.08	44.31	44.09	93.96	92.22	12.65	13.12	0.84	0.84	0.84	43.61	43.61	43.81	43.61
WOXC	0.00	0.00	0.00	0.00	0.00	10.89	46.44	37.59	0.00	0.00	0.00	0.00	0.00	12.60	11.05	0.00	0.00
WOXU	65.35	61.85	58.75	63.25	63.78	63.66	135.05	133.14	18.13	18.88	1.21	1.21	1.20	62.97	62.97	62.77	62.77
IRXC	0.00	10.20	0.00	0.00	0.00	10.22	0.00	9.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.73	0.00
IRXU	14.10	13.53	12.85	13.68	13.76	13.88	29.04	28.63	3.91	4.07	0.26	0.26	0.26	13.54	13.54	13.54	13.54
AUXC	12.54	0.00	0.00	0.00	3.83	0.00	0.00	0.00	1.16	0.00	0.56	0.00	0.02	0.00	0.00	0.00	0.00
AUXU	30.33	28.51	27.08	29.44	29.40	29.25	62.06	61.19	8.36	8.70	0.56	0.56	0.55	28.94	28.94	29.13	28.94
HGXC	0.00	0.00	0.00	0.00	5.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HGXU	9.17	8.68	8.24	8.90	8.95	8.90	18.89	18.62	2.54	2.65	0.17	0.17	0.17	8.81	8.81	8.81	8.81
TLXC	0.00	4.20	2.80	0.00	0.65	0.00	17.52	0.00	0.00	0.90	0.00	0.00	0.11	0.00	0.00	8.69	0.00
TLXU	9.54	9.03	8.58	9.26	9.31	9.27	19.66	19.38	2.65	2.76	0.18	0.18	0.18	9.17	9.17	9.17	9.17
PBXC	0.00	0.00	8.50	0.28	11.09	0.00	13.90	6.62	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.80	0.00
PBXU	9.92	9.39	8.92	9.63	9.68	9.63	20.43	20.14	2.75	2.87	0.18	0.18	0.18	9.53	9.53	9.53	9.53
URXC	0.00	11.49	11.40	8.90	8.95	0.00	0.00	10.95	1.58	2.11	0.00	0.23	0.00	14.26	0.00	0.00	0.00
URXU	16.20	15.17	14.41	15.56	15.64	15.56	33.38	32.55	4.45	4.63	0.30	0.30	0.30	15.40	15.56	15.56	15.40
U is designated for measurement uncertainty or limit of detection																	

TABLE D-3. ENGINE C METALS AND ELEMENTS

	FTP-w-1	FTP-w-2	FTP-w-3	FTP-wo-1	FTP-wo-2	FTP-wo-3	CARBx-1	CARBx-2	CARBz-1	CARBz-2	16-Hour-1	16-Hour-2	16-Hour-3	TB-1	TB-2	TB-3	TB-4
	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr
NAXC	147.77	0.00	0.00	0.00	0.00	0.00	937.75	255.16	0.00	237.48	6.14	12.54	2.55	0.00	0.00	306.48	220.65
NAXU	365.58	342.12	355.83	359.55	362.01	361.55	834.78	814.02	87.95	153.03	5.93	5.98	5.61	357.11	359.92	366.50	360.59
MGXC	12.69	31.70	0.00	0.00	63.14	0.00	433.37	148.30	10.14	61.17	2.73	1.78	2.85	24.87	0.00	69.72	270.86
MGXU	191.79	182.10	191.05	191.65	194.20	191.00	434.09	428.33	47.32	78.79	3.09	3.06	2.98	190.54	190.13	190.99	191.31
ALXC	10.06	28.62	0.00	17.79	0.00	0.00	89.38	159.62	2.33	8.79	2.42	2.37	1.40	0.00	0.00	44.37	56.98
ALXU	31.91	30.51	31.85	31.95	32.27	31.69	72.31	72.18	7.86	13.14	0.52	0.52	0.50	31.70	31.70	31.92	31.83
SIXC	18.86	25.54	0.61	34.37	29.08	16.71	82.08	166.86	14.63	15.04	1.96	2.00	1.44	32.24	21.48	50.37	54.52
SIXU	35.28	33.50	35.03	35.33	35.68	35.29	79.40	79.27	8.76	14.43	0.57	0.57	0.56	35.05	35.05	35.31	35.40
PHXC	0.00	0.00	0.00	0.00	0.00	1.06	26.03	67.88	11.77	9.79	0.56	7.16	1.37	0.00	6.61	19.79	9.07
PHXU	10.73	10.40	10.71	10.75	10.85	10.96	24.66	24.44	2.70	4.48	0.18	0.20	0.17	10.66	10.89	10.89	10.76
SUXC	32.77	225.43	161.70	163.14	125.08	199.77	457.74	253.80	66.43	81.15	8.91	161.09	35.42	182.12	163.70	131.77	333.20
SUXU	40.97	39.75	41.57	41.70	41.92	41.88	94.22	92.46	10.37	17.12	0.70	1.50	0.79	41.37	41.37	41.18	41.59
CLXC	0.00	4.39	6.48	3.09	0.00	0.61	38.98	22.72	18.66	6.82	0.21	0.92	3.00	4.60	2.46	8.91	15.67
CLXU	7.00	6.65	6.99	7.01	7.08	7.01	15.76	15.63	1.78	2.86	0.11	0.12	0.12	6.96	6.96	6.96	6.96
KPXC	0.00	0.00	0.00	0.00	0.00	0.00	14.61	13.76	1.68	4.55	0.76	0.53	0.58	6.13	5.84	5.24	5.71
KPXU	6.55	6.22	6.54	6.56	6.63	6.56	14.75	14.62	1.62	2.68	0.11	0.10	0.10	6.51	6.51	6.51	6.51
CAXC	16.07	2.04	6.16	6.50	3.12	10.22	73.76	62.07	33.29	14.79	4.67	5.73	4.38	19.66	25.51	26.72	62.79
CAXU	8.32	7.90	8.31	8.33	8.42	8.33	18.73	18.56	2.05	3.40	0.14	0.14	0.13	8.27	8.27	8.27	8.27
SCXC	0.00	0.00	9.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.64	0.00	0.00
SCXU	25.80	24.50	25.76	25.84	26.09	25.81	58.07	57.56	6.36	10.64	0.42	0.41	0.40	25.63	25.63	25.63	25.63
TIXC	7.10	2.04	0.00	3.41	5.00	6.17	24.37	20.71	3.58	4.05	0.32	0.21	0.15	0.00	7.05	10.76	9.23
TIXU	4.82	4.58	4.81	4.83	4.87	4.82	10.85	10.75	1.19	1.97	0.08	0.08	0.07	4.79	4.79	4.79	4.79
VAXC	0.00	0.00	0.93	0.00	2.50	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.61	2.46	3.38	0.00
VAXU	0.45	0.43	0.45	0.45	0.45	0.45	1.01	1.00	0.11	0.18	0.01	0.01	0.01	0.45	0.45	0.45	0.45
CRXC	6.20	5.00	9.59	8.69	8.16	10.86	44.54	37.99	4.66	6.33	0.61	0.37	0.28	11.68	14.78	26.43	15.67
CRXU	4.37	4.15	4.36	4.38	4.42	4.37	9.83	9.75	1.08	1.79	0.07	0.07	0.07	4.34	4.34	4.34	4.34
MNXC	0.45	0.00	0.00	5.73	0.00	4.47	7.30	27.24	2.02	4.99	0.25	0.00	0.08	0.45	8.14	3.51	6.77
MNXU	9.19	8.73	9.17	9.20	9.29	9.19	20.68	20.50	2.26	3.76	0.15	0.15	0.14	9.13	9.13	9.13	9.13
FEXC	63.68	64.59	45.68	76.16	57.84	65.25	139.85	67.59	28.11	29.19	6.31	4.56	4.20	65.73	70.32	52.83	93.37
FEXU	12.69	12.05	12.67	12.71	12.84	12.70	28.56	28.31	3.13	5.19	0.21	0.21	0.20	12.61	12.61	12.61	12.61
COXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
COXU	0.45	0.43	0.45	0.45	0.45	0.45	1.01	1.00	0.11	0.18	0.01	0.01	0.01	0.45	0.45	0.45	0.45
NIXC	4.63	7.05	3.40	6.82	10.01	10.22	18.80	4.16	4.19	5.06	0.19	0.20	0.10	7.98	4.31	7.69	4.76
NIXU	2.18	2.07	2.18	2.19	2.21	2.19	4.92	4.87	0.54	0.89	0.04	0.03	0.03	2.17	2.17	2.17	2.17
CUXC	6.20	7.08	4.33	9.94	3.77	4.05	28.56	30.39	5.19	23.27	0.41	0.35	0.16	5.24	10.76	13.53	10.76
CUXU	3.95	3.75	3.95	3.96	4.00	3.95	8.89	8.82	0.97	1.71	0.06	0.06	0.06	3.93	3.93	3.93	3.93
ZNXC	9.74	8.08	6.03	8.21	3.61	6.04	35.14	23.80	15.73	19.16	0.67	0.63	0.55	8.75	7.82	12.74	6.29
ZNXU	3.95	3.75	3.95	3.96	4.00	3.95	8.89	8.82	1.03	1.71	0.07	0.07	0.06	3.93	3.93	3.93	3.93
GAXC	0.00	8.94	2.63	11.91	12.35	0.00	3.11	0.00	0.00	0.00	0.03	0.14	0.00	0.00	0.00	0.00	0.00
GAXU	14.01	13.30	13.99	14.03	14.17	14.21	31.53	31.25	3.45	5.73	0.22	0.22	0.22	13.92	13.92	13.92	13.92
ASXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ASXU	0.45	0.43	0.45	0.45	0.45	0.45	1.01	1.00	0.11	0.18	0.01	0.01	0.01	0.45	0.45	0.45	0.45
SEXC	2.02	7.78	14.66	0.00	3.61	6.98	0.36	0.00	0.00	1.33	0.05	0.11	0.00	5.39	0.00	1.09	9.39
SEXU	9.19	8.73	9.17	9.20	9.29	9.19	20.68	20.50	2.26	3.76	0.15	0.15	0.14	9.13	9.13	9.13	9.13
BRXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00
BRXU	6.55	6.22	6.54	6.56	6.63	6.56	14.75	14.62	1.62	2.68	0.11	0.10	0.10	6.51	6.51	6.51	6.51
RBXC	0.00	5.86	3.40	0.00	0.29	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	5.52	0.00	0.00	4.92
RBXU	4.82	4.58	4.81	4.83	4.87	4.82	10.85	10.75	1.19	1.97	0.08	0.08	0.07	4.79	4.79	4.79	4.79
SRXC	8.06	0.31	4.01	0.00	8.16	3.73	0.00	0.00	0.61	0.00	0.00	0.14	0.00	0.00	9.54	0.00	0.00
SRXU	8.74	8.30	8.73	8.75	8.84	8.74	19.67	19.50	2.15	3.57	0.14	0.14	0.14	8.68	8.68	8.68	8.68
YTXC	5.11	1.04	0.00	0.00	3.61	1.09	0.00	0.00	0.00	0.00	0.00	0.06	0.05	0.00	4.15	0.00	0.00
YTXU	6.55	6.22	6.54	6.56	6.63	6.56	14.75	14.62	1.62	2.68	0.11	0.10	0.10	6.51	6.51	6.51	6.51
U is designated for measurement uncertainty or limit of detection																	

TABLE D-3 (CONT'D.) ENGINE C METALS AND ELEMENTS

	FTP-w-1	FTP-w-2	FTP-w-3	FTP-wo-1	FTP-wo-2	FTP-wo-3	CARBx-1	CARBx-2	CARBz-1	CARBz-2	16-Hour-1	16-Hour-2	16-Hour-3	TB-1	TB-2	TB-3	TB-4
	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr
ZRXC	2.15	0.00	0.00	0.00	10.30	10.19	26.47	8.24	9.75	1.77	0.24	0.05	0.06	1.53	20.27	18.13	0.00
ZRXU	15.33	14.55	15.30	15.35	15.50	15.33	34.49	34.19	3.82	6.27	0.25	0.24	0.24	15.23	15.23	15.23	15.23
NBXC	0.00	5.13	0.00	5.41	1.10	6.65	7.30	0.00	0.00	2.09	0.00	0.00	0.14	0.00	0.00	5.68	3.83
NBXU	11.82	11.23	11.80	11.84	11.96	11.83	26.61	26.38	2.91	4.83	0.19	0.19	0.18	11.75	11.75	11.75	11.75
MOXC	6.94	0.00	0.00	0.00	0.00	4.47	34.42	3.08	0.00	1.33	0.00	0.00	0.00	3.54	0.00	7.21	0.00
MOXU	10.51	9.98	10.49	10.52	10.63	10.51	23.65	23.44	2.59	4.30	0.17	0.17	0.16	10.44	10.44	10.44	10.44
PDXC	4.63	0.00	0.00	0.00	0.00	9.29	42.45	41.36	0.00	5.56	0.32	0.00	0.00	0.00	0.00	0.00	15.96
PDXU	20.11	19.10	20.30	20.14	20.34	20.12	45.27	44.87	4.96	8.22	0.32	0.32	0.31	19.98	19.98	19.98	19.98
AGXC	0.00	0.00	0.00	0.00	0.00	0.00	18.80	0.00	3.66	0.51	0.00	0.01	0.00	0.00	0.00	0.00	13.22
AGXU	18.35	17.42	18.32	18.37	18.56	18.35	41.29	40.93	4.52	7.50	0.29	0.29	0.28	18.23	18.23	18.23	18.23
CDXC	0.00	0.00	0.00	11.62	0.00	0.00	0.00	0.00	0.00	0.83	0.31	0.12	0.17	0.00	0.00	18.26	0.00
CDXU	22.72	21.57	22.90	22.75	22.98	22.73	51.13	50.67	5.60	9.29	0.37	0.36	0.35	22.57	22.57	22.79	22.57
INXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.27	0.00	0.00	0.00	0.00	5.20	0.00	0.00	0.00
INXU	13.53	12.84	13.50	13.55	13.68	13.53	30.44	30.18	3.40	5.53	0.22	0.22	0.21	13.44	13.44	13.44	13.44
SNXC	2.47	12.33	0.00	0.00	0.00	3.09	14.61	0.00	0.00	6.82	0.00	0.01	0.09	0.00	0.32	17.21	0.00
SNXU	17.38	16.50	17.13	17.18	17.58	17.39	39.12	38.78	4.23	7.11	0.27	0.28	0.27	17.05	17.27	17.27	17.27
SBXC	0.00	0.00	0.00	19.21	0.00	0.00	0.00	0.00	2.90	8.47	0.00	0.00	0.00	21.83	8.01	8.62	0.00
SBXU	32.36	30.72	32.30	32.40	32.72	32.37	72.82	72.18	7.97	13.23	0.52	0.52	0.50	32.15	32.15	32.15	32.15
CSXC	0.00	2.50	0.00	3.57	0.00	0.00	0.36	0.00	0.96	0.00	0.00	0.00	0.06	1.40	0.48	0.00	0.00
CSXU	5.24	4.97	5.23	5.24	5.30	5.24	11.79	11.68	1.29	2.14	0.08	0.08	0.08	5.20	5.20	5.20	5.20
BAXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BAXU	2.63	2.50	2.63	2.64	2.66	2.64	5.93	5.88	0.65	1.08	0.04	0.04	0.04	2.62	2.62	2.62	2.62
LAXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.04	0.00	0.00	0.00	0.00
LAXU	3.95	3.75	3.95	3.96	4.00	3.95	8.89	8.82	0.97	1.62	0.06	0.06	0.06	3.93	3.93	3.93	3.93
CEXC	0.93	0.00	0.00	0.00	0.00	0.00	11.86	11.75	0.46	2.02	0.00	0.00	0.04	0.00	0.00	2.46	0.00
CEXU	5.69	5.40	5.68	5.70	5.75	5.69	12.80	12.69	1.40	2.33	0.09	0.09	0.09	5.65	5.65	5.65	5.65
SMXC	4.34	1.46	0.00	2.80	7.51	0.00	7.01	0.00	0.00	2.15	0.11	0.05	0.00	1.24	4.31	0.00	0.00
SMXU	7.87	7.47	7.86	7.88	7.96	7.88	17.72	17.56	1.94	3.22	0.13	0.13	0.12	7.82	7.82	7.82	7.82
EUXC	0.00	17.94	16.39	2.19	12.84	0.00	0.00	0.00	2.22	1.41	0.21	0.00	0.00	11.40	0.00	4.02	0.00
EUXU	28.40	26.97	28.36	28.44	28.73	28.41	63.92	63.36	7.00	11.61	0.46	0.45	0.44	28.22	28.22	28.22	28.22
TBXC	7.55	0.73	8.79	3.86	0.00	9.42	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.00	4.79
TBXU	9.64	9.15	9.62	9.65	9.75	9.64	22.13	21.93	2.42	3.94	0.16	0.16	0.15	9.77	9.58	9.77	9.58
HFXC	0.00	0.00	0.00	0.00	0.00	3.86	0.00	0.00	0.00	0.00	0.00	0.87	0.86	0.00	7.53	0.00	0.00
HFXU	62.08	58.94	62.20	62.17	62.78	62.10	141.15	139.91	15.40	25.55	1.00	1.00	0.97	61.45	61.67	62.09	62.22
TAXC	0.00	0.00	0.00	0.00	0.00	0.00	16.34	0.00	6.06	13.83	0.00	0.00	0.00	0.00	0.00	0.00	32.88
TAXU	52.44	49.61	52.35	52.51	52.84	52.26	118.01	116.97	12.92	21.44	0.84	0.83	0.81	51.91	52.10	52.10	52.00
WOXC	40.81	39.33	33.04	36.23	45.04	17.94	148.89	98.63	0.00	12.01	0.00	0.00	0.00	66.97	0.00	0.00	0.00
WOXU	74.64	70.87	74.52	74.75	75.49	74.67	168.49	166.50	18.45	30.52	1.19	1.20	1.17	74.38	74.38	74.38	74.47
IRXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.00	0.00	12.58	0.00
IRXU	16.29	15.47	16.26	16.31	16.48	16.30	37.17	36.34	4.01	6.75	0.26	0.26	0.25	16.41	16.41	16.41	16.06
AUXC	17.48	3.69	14.98	0.00	6.73	0.00	72.02	10.75	3.70	0.00	0.00	0.05	0.36	8.14	0.00	21.96	28.73
AUXU	34.86	32.89	34.80	34.69	35.03	34.65	78.46	77.27	8.59	14.16	0.56	0.55	0.54	34.41	34.41	34.64	34.64
HGXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.99	0.00
HGXU	10.60	10.07	10.59	10.62	10.72	10.61	24.37	24.15	2.61	4.43	0.17	0.17	0.16	10.53	10.53	10.53	10.44
TLXC	0.00	0.00	1.25	0.00	0.00	0.00	9.04	0.00	2.06	0.00	0.00	0.00	0.00	3.70	0.00	0.00	4.44
TLXU	10.96	10.40	10.94	10.97	11.08	10.96	24.66	24.44	2.70	4.48	0.18	0.18	0.17	10.89	10.89	10.89	10.89
PBXC	0.00	6.16	17.90	0.00	12.51	2.15	69.57	33.11	2.82	6.44	0.59	0.50	0.00	0.00	3.67	5.84	12.29
PBXU	11.37	10.80	11.36	11.39	11.50	11.38	26.10	25.37	2.80	4.65	0.19	0.19	0.18	11.30	11.30	11.30	11.30
URXC	11.60	0.00	0.00	0.00	5.78	4.79	0.00	0.00	0.00	0.00	0.00	0.00	0.01	17.97	9.67	0.00	0.00
URXU	18.35	17.42	18.32	18.37	18.56	18.35	41.29	40.93	4.52	7.50	0.29	0.29	0.28	18.45	18.23	18.23	18.23
U is designated for measurement uncertainty or limit of detection																	

TABLE D-4. ENGINE D METALS AND ELEMENTS

	FTP-w-1	FTP-w-2	FTP-w-3	FTP-wo-1	FTP-wo-2	FTP-wo-3	CARBx-1	CARBx-2	CARBz-1	CARBz-2	16-Hour-1	16-Hour-2	16-Hour-3	TB-1	TB-2	TB-3
	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr
NAXC	416.96	295.45	284.72	152.45	94.98	444.53	1288.91	193.52	39.69	108.28	28.88	35.42	14.48	226.90	35.38	178.88
NAXU	296.90	293.62	293.13	306.73	301.75	319.56	691.51	719.99	89.77	78.79	6.35	6.44	6.05	300.74	296.92	299.84
MGXC	185.29	156.71	133.26	176.39	192.27	197.85	433.75	402.50	51.92	39.10	4.47	7.22	4.13	73.55	199.45	19.93
MGXU	154.60	153.95	153.60	162.68	160.63	166.40	356.64	383.25	47.67	41.01	3.09	3.08	3.09	157.99	158.89	157.65
ALXC	68.28	56.65	80.87	41.49	0.00	71.88	198.24	153.42	15.84	18.26	2.18	3.18	2.40	45.34	53.75	39.47
ALXU	25.78	25.70	25.67	26.93	26.40	27.74	59.88	63.97	7.95	6.84	0.52	0.52	0.52	26.28	26.46	26.28
SIXC	64.81	59.64	8.32	33.65	27.80	48.34	99.60	20.73	12.70	8.75	2.87	4.16	5.15	31.30	33.34	28.99
SIXU	28.67	28.58	28.37	29.98	29.60	30.86	66.14	70.71	8.84	7.57	0.58	0.58	0.59	29.25	29.25	29.25
PHXC	16.80	26.42	19.46	2.23	19.02	24.24	73.77	70.71	5.10	8.36	10.34	14.37	8.68	14.94	12.16	26.44
PHXU	8.71	8.69	8.68	8.98	9.05	9.38	20.10	21.62	2.69	2.31	0.21	0.23	0.20	8.95	8.95	8.95
SUXC	304.91	376.90	333.12	361.44	260.47	344.27	779.71	997.50	91.87	87.77	223.96	350.16	199.07	255.62	320.23	356.75
SUXU	33.89	34.15	33.93	35.86	34.84	36.48	78.60	85.02	10.45	9.00	1.87	2.61	1.73	34.43	34.80	34.99
CLXC	11.45	4.48	14.88	3.16	8.54	6.18	21.23	19.76	2.07	4.17	0.36	2.95	3.12	3.85	0.00	2.81
CLXU	5.64	5.62	5.61	5.93	5.86	6.07	13.00	13.99	1.74	1.50	0.11	0.12	0.12	5.79	5.79	5.79
KPXC	12.56	8.81	6.33	2.77	1.96	5.51	10.68	23.81	2.19	2.62	0.68	1.14	6.59	10.86	6.53	5.26
KPXU	5.27	5.26	5.25	5.55	5.48	5.68	12.17	13.09	1.63	1.40	0.11	0.11	0.12	5.41	5.41	5.41
CAXC	56.57	28.87	26.36	21.33	28.28	26.10	55.94	97.79	12.31	11.79	8.89	14.57	42.55	59.62	25.40	89.24
CAXU	6.70	6.68	6.67	7.05	6.96	7.21	15.45	16.62	2.06	1.78	0.14	0.15	0.21	6.87	6.87	6.87
SCXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SCXU	20.94	20.88	20.67	21.85	21.57	22.34	47.89	51.97	6.40	5.51	0.41	0.41	0.42	21.31	21.31	21.31
TIXC	15.93	0.00	3.99	0.00	3.89	6.71	15.51	15.46	1.62	2.31	0.28	0.94	1.87	8.44	8.95	3.85
TIXU	3.88	3.87	3.86	4.08	4.03	4.17	8.95	9.62	1.20	1.03	0.08	0.08	0.08	3.98	3.98	3.98
VAXC	0.00	0.00	2.47	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.06	0.00	0.00	0.00
VAXU	0.36	0.36	0.36	0.38	0.38	0.39	0.83	0.90	0.11	0.10	0.01	0.01	0.01	0.37	0.37	0.37
CRXC	11.71	8.94	18.85	9.17	6.74	16.61	26.42	29.07	2.61	3.90	0.50	0.38	2.37	12.53	8.71	10.48
CRXU	3.52	3.51	3.50	3.70	3.65	3.78	8.11	8.73	1.08	0.93	0.07	0.07	0.07	3.61	3.61	3.61
MNXC	9.95	0.75	1.98	0.00	2.85	8.04	0.60	0.00	1.08	0.00	0.04	0.06	0.82	0.00	8.95	1.04
MNXU	7.39	7.37	7.36	7.78	7.68	7.96	17.06	18.35	2.28	1.96	0.15	0.15	0.15	7.59	7.59	7.59
FEXC	26.63	27.04	42.87	31.94	34.11	19.03	34.47	80.27	5.45	12.62	7.11	8.79	64.20	51.34	16.11	93.22
FEXU	10.21	10.18	10.17	10.75	10.61	10.99	23.56	25.34	3.15	2.71	0.21	0.22	0.32	10.48	10.48	10.67
COXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
COXU	0.36	0.36	0.36	0.38	0.38	0.39	0.83	0.90	0.11	0.10	0.01	0.01	0.01	0.37	0.37	0.37
NIXC	0.00	1.62	0.62	0.00	7.63	0.00	13.48	7.76	0.81	0.00	0.06	0.04	1.07	1.41	2.95	9.08
NIXU	1.76	1.75	1.75	1.85	1.83	1.89	4.06	4.36	0.54	0.47	0.04	0.03	0.04	1.80	1.80	1.80
CUXC	11.43	11.39	9.91	6.80	11.63	9.38	25.82	22.84	2.07	3.70	0.41	0.46	0.94	13.27	9.95	4.33
CUXU	3.18	3.17	3.17	3.35	3.30	3.42	7.34	7.89	0.98	0.84	0.06	0.06	0.07	3.26	3.26	3.26
ZNXC	6.08	11.78	7.80	6.67	7.87	6.01	26.66	24.96	4.49	3.40	1.71	2.36	7.04	8.55	9.32	8.28
ZNXU	3.18	3.17	3.17	3.35	3.30	3.42	7.34	7.89	0.98	0.84	0.07	0.07	0.08	3.26	3.26	3.26
GAXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.56	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00
GAXU	11.27	11.24	11.22	11.86	11.71	12.13	26.00	27.98	3.48	2.99	0.22	0.22	0.22	11.57	11.57	11.57
ASXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ASXU	0.36	0.36	0.36	0.38	0.38	0.39	0.83	0.90	0.11	0.10	0.01	0.01	0.01	0.37	0.37	0.37
SEXC	3.88	5.10	6.08	7.48	3.49	10.32	0.00	19.44	6.86	0.00	0.00	0.31	0.05	4.49	3.98	0.00
SEXU	7.39	7.37	7.36	7.78	7.68	7.96	17.06	18.35	2.28	1.96	0.15	0.15	0.15	7.59	7.59	7.59
BRXC	2.84	8.56	3.84	1.96	0.64	3.87	2.56	15.08	1.04	0.49	0.11	0.01	0.00	0.00	8.55	0.37
BRXU	5.27	5.26	5.25	5.55	5.48	5.68	12.17	13.09	1.63	1.40	0.11	0.10	0.11	5.41	5.41	5.41
RBXC	0.00	4.46	0.00	0.00	1.80	0.00	0.00	0.00	1.61	0.60	0.06	0.00	0.00	0.27	0.00	0.00
RBXU	3.88	3.87	3.86	4.08	4.03	4.17	8.95	9.62	1.20	1.03	0.08	0.08	0.08	3.98	3.98	3.98
SRXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.21	0.34	0.00	0.00	0.00
SRXU	7.03	7.01	7.00	7.40	7.31	7.57	16.22	17.45	2.17	1.87	0.14	0.14	0.14	7.22	7.22	7.22
YTXC	0.00	0.00	2.24	1.58	0.00	1.09	0.00	0.00	0.00	0.00	0.00	0.14	0.05	0.00	0.00	1.78

U is designated for measurement uncertainty or limit of detection

TABLE D-4 (CONT'D.) ENGINE D METALS AND ELEMENTS

	FTP-w-1	FTP-w-2	FTP-w-3	FTP-wo-1	FTP-wo-2	FTP-wo-3	CARBx-1	CARBx-2	CARBz-1	CARBz-2	16-Hour-1	16-Hour-2	16-Hour-3	TB-1	TB-2	TB-3
	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr
YTXU	5.27	5.26	5.25	5.55	5.48	5.68	12.17	13.09	1.63	1.40	0.11	0.10	0.11	5.41	5.41	5.41
ZRXC	0.00	4.97	11.92	7.62	0.00	6.98	2.92	16.75	0.85	0.00	0.00	0.00	0.72	0.00	7.67	8.44
ZRXU	12.33	12.29	12.28	12.98	12.81	13.27	28.45	30.61	3.80	3.27	0.25	0.24	0.25	12.66	12.66	12.66
NBXC	0.00	2.84	0.00	9.55	6.31	6.54	0.00	0.00	0.00	0.36	0.08	0.02	0.02	8.04	0.00	3.19
NBXU	9.51	9.49	9.47	10.01	9.88	10.24	21.95	23.61	2.93	2.53	0.19	0.19	0.19	9.77	9.77	9.77
MOXC	0.00	5.44	0.00	3.13	0.00	0.00	13.18	10.46	0.07	0.00	0.00	0.00	0.00	7.14	0.00	1.78
MOXU	8.45	8.43	8.42	8.90	8.78	9.10	19.50	20.98	2.61	2.24	0.17	0.17	0.17	8.68	8.68	8.68
PDXC	0.00	0.00	0.00	0.00	0.00	7.23	0.00	0.00	1.15	0.00	0.00	0.18	0.01	0.00	0.00	5.63
PDXU	16.18	16.13	16.12	17.22	17.00	17.42	37.33	40.17	4.99	4.30	0.32	0.32	0.32	16.80	16.62	16.62
AGXC	0.00	0.00	4.71	0.00	0.00	1.61	0.00	24.70	0.00	0.00	0.00	0.04	0.00	11.49	0.00	0.00
AGXU	14.76	14.72	14.70	15.53	15.34	15.89	34.05	36.64	4.61	3.92	0.29	0.29	0.30	15.16	15.16	15.16
CDXC	0.00	10.18	11.92	0.00	0.00	6.46	0.00	0.00	5.60	0.00	0.00	0.13	0.00	0.00	1.30	9.98
CDXU	18.28	18.22	18.38	19.42	18.99	19.67	42.16	45.81	5.69	4.85	0.36	0.36	0.36	18.95	18.77	18.77
INXC	0.00	0.00	0.00	0.79	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.20	0.08	0.00	0.00	0.00
INXU	10.88	10.85	10.84	11.45	11.52	11.72	25.11	27.01	3.36	2.89	0.22	0.22	0.22	11.18	11.18	11.18
SNXC	0.00	0.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SNXU	13.81	13.94	13.93	14.53	14.53	15.05	31.85	34.26	4.26	3.71	0.28	0.28	0.28	14.17	14.17	14.36
SBXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SBXU	26.03	25.95	25.93	27.39	27.05	28.02	60.06	64.61	8.03	6.91	0.52	0.52	0.52	26.73	26.73	26.73
CSXC	0.00	0.00	1.75	0.00	0.00	0.00	0.00	3.14	0.23	0.07	0.00	0.00	0.00	1.30	0.00	0.00
CSXU	4.21	4.20	4.20	4.43	4.38	4.54	9.72	10.46	1.30	1.12	0.08	0.08	0.08	4.33	4.33	4.33
BAXC	0.00	0.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BAXU	2.12	2.11	2.11	2.23	2.20	2.28	4.89	5.26	0.65	0.56	0.04	0.04	0.04	2.18	2.18	2.18
LAXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.54	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LAXU	3.18	3.17	3.17	3.35	3.30	3.42	7.34	7.89	0.98	0.84	0.06	0.06	0.06	3.26	3.26	3.26
CEXC	0.00	0.00	2.11	2.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.08	0.00	0.00	2.44
CEXU	4.58	4.56	4.56	4.82	4.75	4.93	10.56	11.36	1.41	1.22	0.09	0.09	0.09	4.70	4.70	4.70
SMXC	2.61	6.31	4.09	4.33	5.80	6.01	5.43	0.00	0.65	0.00	0.04	0.00	0.00	0.00	1.41	6.26
SMXU	6.33	6.31	6.31	6.67	6.58	6.82	14.61	15.72	1.95	1.68	0.13	0.13	0.13	6.50	6.50	6.50
EUXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.00	0.00	0.00	4.46
EUXU	22.85	22.78	22.76	24.05	23.74	24.60	52.72	56.72	7.05	6.07	0.46	0.46	0.46	23.46	23.46	23.65
TBXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00
TBXU	7.91	7.89	7.88	8.32	8.06	8.51	18.25	19.63	2.44	2.10	0.16	0.15	0.16	8.12	8.12	8.12
HFXC	0.00	13.25	0.00	41.49	12.52	0.00	89.76	0.00	0.00	10.33	0.00	0.03	0.61	0.00	0.00	0.00
HFXU	50.57	50.05	50.18	52.83	52.16	54.23	115.82	125.06	15.59	13.33	1.00	0.99	1.00	51.73	51.73	51.18
TAXC	0.00	0.00	0.00	36.64	0.00	19.56	27.02	60.51	0.00	0.00	0.05	0.00	0.00	0.00	0.00	24.26
TAXU	41.93	41.81	41.76	44.32	43.76	45.33	97.15	104.52	13.04	11.23	0.84	0.83	0.84	43.24	43.05	43.24
WOXC	0.00	0.00	0.00	0.00	0.00	4.03	0.00	147.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WOXU	60.32	60.13	60.42	63.47	62.67	65.14	139.14	150.59	18.60	16.07	1.20	1.19	1.21	61.93	61.93	61.93
IRXC	1.37	0.00	10.27	0.00	1.93	0.95	9.48	1.54	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.58
IRXU	13.00	12.96	12.95	13.90	13.51	14.00	30.00	32.27	4.01	3.51	0.26	0.26	0.26	13.35	13.35	13.35
AUXC	14.32	0.00	0.00	1.47	20.55	18.37	3.22	4.04	3.11	5.85	0.34	0.00	0.53	23.39	6.26	0.00
AUXU	27.87	27.97	27.75	29.33	29.14	30.19	64.29	69.17	8.59	7.45	0.56	0.55	0.56	28.80	28.61	28.61
HGXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HGXU	8.45	8.43	8.42	8.90	8.78	9.10	19.50	20.98	2.61	2.29	0.17	0.17	0.17	8.87	8.68	8.68
TLXC	7.34	2.11	0.00	6.67	7.09	5.20	3.70	0.00	0.00	0.00	0.13	0.11	0.08	3.19	0.37	0.00
TLXU	8.82	8.79	8.78	9.28	9.16	9.49	20.34	21.88	2.72	2.34	0.18	0.17	0.18	9.05	9.05	9.05
PBXC	1.24	3.71	3.96	0.00	1.02	11.52	16.04	8.02	4.45	4.16	0.01	0.00	0.13	8.41	11.73	0.00
PBXU	9.15	9.12	9.11	9.63	9.51	9.85	21.11	22.71	2.82	2.43	0.18	0.18	0.18	9.40	9.40	9.40
URXC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.17	0.00	0.00	0.00	7.03
URXU	14.76	14.72	14.70	15.53	15.34	15.89	34.05	36.64	4.55	3.92	0.29	0.29	0.30	15.16	15.16	15.16

U is designated for measurement uncertainty or limit of detection

APPENDIX E

CARBONYL COMPOUNDS AND ALCOHOLS

TABLE E-1. ENGINE A CARBONYLS AND ALCOHOLS

mg/hp-hr	FTP-w-1	FTP-w-2	FTP-w-3	FTP-wo-1	FTP-wo-2	FTP-wo-3	CARBX-1	CARBX-2	CARBZ-1	CARBZ-2	16-hour-1a	16-Hour-1b	16-hour-2a	16-hour-2b	16-hour-3a	16-hour-3b	TB-1	TB-2	TB-3	TB-4
Methanol	0.00	0.00	0.00	0.00	0.00	0.00	10.26	4.66	0.00	0.00	0.00	0.14	0.05	0.01	0.00	0.35	0.00	0.00	0.00	0.00
Ethanol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.00	0.00	0.00	0.00	0.00	0.00
2-Propanol	0.00	0.00	0.00	0.00	0.00	0.00	18.20	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.06	0.00	3.07	3.07	1.04	0.00
1-Propanol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1-Butanol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Formaldehyde	0.00	0.00	0.00	0.00	0.00	0.00	124.37	111.95	0.60	0.87	3.76	2.88	0.77	0.00	1.95	0.75	1.76	1.76	0.00	0.00
Acetaldehyde	0.25	0.12	0.07	0.14	0.06	0.19	56.77	51.23	0.47	0.38	1.35	2.04	0.66	0.00	0.67	0.38	0.09	0.09	0.00	0.00
Acrolein	0.00	0.00	0.00	0.00	0.00	0.00	11.35	8.16	0.02	0.04	0.09	0.15	0.00	0.31	0.00	0.45	0.00	0.00	0.00	0.00
Acetone	0.00	0.04	0.00	1.53	0.16	0.00	122.75	116.35	8.48	7.48	0.00	0.00	0.00	0.00	0.00	2.82	0.00	0.00	0.00	0.00
Propionaldehyde	0.00	0.00	0.00	0.00	0.00	0.00	11.90	11.43	0.25	0.22	0.14	0.14	0.11	0.00	0.00	0.10	0.00	0.00	0.00	0.00
Crotonaldehyde	0.00	0.00	0.00	0.11	0.00	0.00	3.61	6.23	0.00	0.09	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Isobutyraldehyde	0.00	0.00	0.00	0.00	0.00	0.00	4.58	2.76	0.09	0.07	0.02	0.02	0.00	0.05	0.00	0.03	0.00	0.00	0.00	0.00
MEK	0.00	0.00	0.00	0.00	0.00	0.00	4.58	2.76	0.09	0.07	0.02	0.02	0.00	0.05	0.00	0.03	0.00	0.00	0.00	0.00
Benzaldehyde	0.00	0.00	0.00	0.02	0.00	0.00	4.07	3.34	0.17	0.06	0.22	0.54	0.34	0.00	0.09	0.71	0.96	0.96	0.00	0.00
Isovaleraldehyde	0.00	0.00	0.00	0.00	0.00	0.00	2.66	2.11	0.01	0.01	0.09	0.18	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00
Valeraldehyde	0.00	0.00	0.00	0.00	0.00	0.00	3.86	3.61	0.09	0.05	0.06	0.06	0.04	0.00	0.00	0.03	0.00	0.00	0.00	0.00
o-Tolualdehyde	0.00	0.00	0.00	0.00	0.00	0.00	1.37	0.78	0.01	0.02	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
m/p-Tolualdehyde	0.00	0.00	0.00	0.00	0.00	0.00	3.60	3.35	0.27	0.17	0.25	0.40	0.52	0.00	0.11	0.04	0.00	0.00	0.00	0.00
Hexanaldehyde	0.00	0.00	0.00	0.00	0.00	0.00	1.06	0.86	0.07	0.00	0.14	0.15	0.01	0.00	0.04	0.00	0.00	0.00	0.00	0.00
Dimethylbenzaldehyde	0.00	0.00	0.00	0.00	0.00	0.00	3.14	0.10	0.07	0.01	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nominal Limit of Detection	0.60	0.60	0.60	0.60	0.60	0.60	1.77	1.77	0.77	0.77	0.01	0.01	0.01	0.01	0.01	0.01	0.60	0.60	0.60	0.60

Footnotes: Negative values are due to background subtraction
Zero is reported if measurement is below the blank value

TABLE E-2. ENGINE B CARBONYLS AND ALCOHOLS

mg/hp-hr	FTP-w-1	FTP-w-2	FTP-w-3	FTP-wo-1	FTP-wo-2	FTP-wo-3	CARBX-1	CARBX-2	CARBZ-1	CARBZ-2	16-hour-1a	16-hour-1b	16-hour-2a	16-hour-2b	16-hour-3a	16-hour-3b	TB-1	TB-2	TB-3	TB-4
Methanol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14	-0.15	0.00	-0.17	-0.06	0.00	0.00	0.00	0.00
Ethanol	0.00	0.00	0.00	0.00	0.00	0.00	-0.22	-0.71	0.00	0.00	0.00	0.00	-0.16	-0.11	0.12	-0.02	0.00	0.00	0.00	0.00
2-Propanol	-1.74	-0.25	0.00	4.75	-0.45	-0.65	0.00	0.00	0.00	0.00	0.00	0.33	-0.20	0.00	0.17	-0.06	0.00	0.00	0.00	0.00
1-Propanol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1-Butanol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Formaldehyde	0.92	0.54	0.54	0.30	0.16	0.22	13.88	16.77	0.33	0.39	0.47	1.07	1.01	0.94	1.06	1.20	1.19	1.44	0.43	0.61
Acetaldehyde	0.35	0.18	0.18	0.10	0.01	0.04	5.31	6.25	0.14	0.10	0.16	0.26	0.33	0.28	0.00	0.40	0.16	0.21	0.20	0.25
Acrolein	0.00	0.00	0.01	0.00	0.00	0.00	0.77	0.82	0.00	0.00	0.02	0.05	0.24	0.18	0.03	0.04	0.00	0.06	0.01	0.00
Acetone	0.00	0.00	-0.86	0.00	0.00	0.00	-0.18	-0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.41	0.94	0.00	0.00	0.00
Propionaldehyde	0.00	-0.01	0.01	-0.01	-0.01	-0.01	-0.03	0.61	-0.01	-0.01	0.02	0.03	0.02	0.00	0.06	0.03	0.01	0.04	0.07	0.00
Crotonaldehyde	0.00	0.00	0.00	0.00	0.00	0.00	-0.44	-0.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.03	0.00	0.04	0.00
Isobutyraldehyde	-0.01	-0.01	0.00	0.00	0.00	0.00	0.28	0.23	-0.01	-0.01	0.00	0.00	0.00	0.05	0.00	-0.01	0.00	0.00	0.01	0.00
MEK	-0.01	-0.01	0.00	0.00	0.00	0.00	0.28	0.23	-0.01	-0.01	0.00	0.00	0.00	0.05	0.00	-0.01	0.00	0.00	0.01	0.00
Benzaldehyde	0.09	0.04	0.01	0.17	-0.01	-0.01	0.49	0.24	0.03	0.03	0.33	0.38	0.26	0.09	0.17	0.18	0.04	0.09	0.09	0.03
Isovaleraldehyde	0.00	0.00	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.01	-0.01	0.02	0.03	0.00	0.00	0.00	0.11	0.00
Valeraldehyde	-0.03	-0.03	0.00	0.12	0.04	-0.01	0.06	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.09	0.00
o-Tolualdehyde	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.08	0.00	0.00	-0.05	0.01	0.00	0.01	0.00	0.01
m/p-Tolualdehyde	0.00	0.00	0.00	0.38	0.22	0.07	0.21	0.00	0.00	0.00	0.09	0.06	0.05	0.01	0.05	0.08	0.00	0.11	0.06	0.00
Hexanaldehyde	0.03	0.00	0.00	-0.01	-0.02	-0.02	0.24	0.00	0.00	0.00	0.01	0.04	-0.01	0.01	-0.04	0.03	0.00	0.04	0.02	0.04
Dimethylbenzaldehyde	0.00	0.00	0.00	0.36	0.13	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	-0.05	0.00	0.00	0.01	0.00
Nominal Limit of Detection	0.60	0.60	0.60	0.60	0.60	0.60	1.77	1.77	0.77	0.77	0.01	0.01	0.01	0.01	0.01	0.01	0.60	0.60	0.60	0.60

Footnotes: Negative values are due to background subtraction
Zero is reported if measurement is below the blank value

TABLE E-3. ENGINE C CARBONYLS AND ALCOHOLS

mg/hp-hr	FTP-w-1	FTP-w-2	FTP-w-3	FTP-wo-1	FTP-wo-2	FTP wo-3	CARBX-1	CARBX-2	CARBZ-1	CARBZ-2	16-hour-1a	16-hour-1b	16-hour-2a	16-hour-2b	16-hour-3a	16-hour-3b	TB-1	TB-2	TB-3	TB-4
Methanol	1.15	0.18	0.68	0.09	0.43	0.90	N/A	N/A	N/A	N/A	-0.02	0.12	0.21	0.20	0.85	0.10	0.00	0.59	0.84	0.49
Ethanol	1.44	0.89	0.00	0.00	0.19	0.31	N/A	N/A	N/A	N/A	-0.03	0.09	0.24	0.14	0.21	-0.05	0.00	0.00	0.00	0.50
2-Propanol	1.85	1.35	-0.48	0.04	0.43	0.94	N/A	N/A	N/A	N/A	-0.15	0.02	-0.12	0.01	0.31	-0.05	0.00	0.18	1.24	0.47
1-Propanol	0.00	0.00	0.00	0.00	0.00	0.00	N/A	N/A	N/A	N/A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1-Butanol	0.00	0.00	0.00	0.00	0.00	0.00	N/A	N/A	N/A	N/A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Formaldehyde	0.91	0.56	0.18	0.19	0.07	0.09	N/A	N/A	N/A	N/A	1.65	3.77	6.26	8.28	0.21	-0.13	0.79	0.00	0.42	0.00
Acetaldehyde	0.29	0.25	0.10	0.14	0.02	0.04	N/A	N/A	N/A	N/A	0.29	0.50	1.60	2.14	0.07	0.01	0.08	0.00	0.20	0.03
Acrolein	0.00	0.00	0.00	0.10	0.00	0.00	N/A	N/A	N/A	N/A	0.05	0.02	-5.73	0.11	-0.01	0.00	0.06	0.00	0.01	0.00
Acetone	1.25	0.04	0.00	0.00	0.00	0.00	N/A	N/A	N/A	N/A	-0.62	0.00	0.00	0.51	0.00	0.00	0.00	5.46	0.00	0.00
Propionaldehyde	0.00	0.00	0.00	0.00	0.00	0.00	N/A	N/A	N/A	N/A	0.02	-3.76	0.00	0.04	0.00	0.00	0.03	0.47	0.06	0.00
Crotonaldehyde	-0.19	-0.19	-0.19	0.00	0.00	0.00	N/A	N/A	N/A	N/A	0.00	0.00	0.00	-0.05	0.00	0.00	0.00	0.00	0.04	0.00
Isobutyraldehyde	0.00	0.00	0.00	0.00	0.00	0.00	N/A	N/A	N/A	N/A	-0.01	0.00	0.05	0.16	0.00	-0.02	0.03	0.00	0.01	0.00
MEK	0.00	0.00	0.00	0.00	0.00	0.00	N/A	N/A	N/A	N/A	-0.01	0.00	0.05	0.16	0.00	-0.02	0.03	0.00	0.01	0.00
Benzaldehyde	0.20	0.00	0.00	0.00	0.00	0.00	N/A	N/A	N/A	N/A	0.08	0.05	0.18	0.07	-0.01	0.00	0.37	0.11	0.09	0.00
Isovaleraldehyde	0.00	0.00	0.00	0.10	0.00	0.00	N/A	N/A	N/A	N/A	0.00	0.02	0.00	0.01	0.00	0.00	0.18	0.00	0.11	0.00
Valeraldehyde	0.08	0.17	-0.04	0.00	0.00	0.00	N/A	N/A	N/A	N/A	-0.08	0.08	-0.02	0.05	0.01	0.01	0.00	0.13	0.09	0.00
o-Tolualdehyde	0.00	0.00	0.00	0.00	0.00	0.00	N/A	N/A	N/A	N/A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00
m/p-Tolualdehyde	0.54	0.33	0.09	0.00	0.00	0.00	N/A	N/A	N/A	N/A	0.02	0.08	0.00	0.06	0.00	0.00	0.00	0.17	0.06	0.00
Hexanaldehyde	0.07	0.00	0.00	0.20	-0.01	-0.01	N/A	N/A	N/A	N/A	0.03	0.05	-0.03	0.01	0.04	-0.02	0.00	0.00	0.02	0.00
Dimethylbenzaldehyde	0.00	0.00	0.00	0.28	0.00	0.00	N/A	N/A	N/A	N/A	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.17	0.01	0.00
Nominal Limit of Detection	0.60	0.60	0.60	0.60	0.60	0.60	1.77	1.77	0.77	0.77	0.01	0.01	0.01	0.01	0.01	0.01	0.60	0.60	0.60	0.60

Footnotes: Negative values are due to background subtraction
Zero is reported if measurement is below the blank value

TABLE E-4. ENGINE D CARBONLYS AND ALCOHOLS

mg/hp-hr	FTP-w-1	FTP-w-2	FTP-w-3	FTP-wo-1	FTP-wo-2	FTP wo-3	CARBX-1	CARBX-2	CARBZ-1	CARBZ-2	16-hour-1a	16-hour-1b	16-hour-2a	16-hour-2b	16-hour-3a	16-hour-3b	TB-1	TB-2	TB-3
Methanol	0.46	0.35	0.39	-0.11	-0.10	0.57	4.78	4.01	-0.04	-0.05	0.02	-0.03	0.00	0.01	0.05	-0.06	0.32	0.44	0.60
Ethanol	0.00	0.00	0.47	0.52	0.34	0.18	0.89	2.97	-0.03	-0.06	0.08	-0.02	0.31	0.21	0.03	-0.04	0.41	0.00	0.00
2-Propanol	0.24	0.00	0.86	-0.76	1.11	0.08	6.82	-7.81	-0.16	0.16	0.09	0.01	-0.01	-0.02	0.05	0.02	0.29	0.57	0.42
1-Propanol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1-Butanol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Formaldehyde	0.35	0.40	0.37	0.47	0.33	0.32	57.91	29.58	-0.29	0.44	1.78	1.36	1.31	1.28	3.67	0.35	0.52	0.36	0.35
Acetaldehyde	0.16	0.16	0.15	-0.16	0.01	-0.04	20.64	10.81	-0.20	0.21	0.61	0.19	0.47	0.46	1.25	0.46	0.20	0.33	0.11
Acrolein	0.03	0.00	0.00	0.00	0.00	0.00	4.40	2.69	-0.01	0.00	0.06	0.13	0.03	0.08	0.19	0.07	0.04	0.00	0.00
Acetone	0.00	0.00	0.00	0.00	0.00	0.00	10.64	0.68	-0.07	0.07	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00
Propionaldehyde	0.00	0.00	0.00	0.00	0.00	0.00	2.13	1.51	0.00	0.00	0.01	0.00	0.01	0.00	0.00	-0.09	0.01	0.01	0.18
Crotonaldehyde	0.00	0.00	0.00	0.01	0.01	-0.08	6.12	3.87	-0.04	-0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Isobutyraldehyde	0.25	0.28	0.31	0.00	0.00	0.00	0.98	0.53	-0.02	0.08	0.06	0.03	0.17	0.04	0.00	0.00	0.00	0.06	0.59
MEK	0.24	0.29	-0.08	0.00	0.00	0.00	0.99	0.53	-0.03	0.08	0.07	0.04	0.17	0.04	0.00	0.00	0.00	0.06	0.00
Benzaldehyde	0.06	0.01	-0.03	0.15	0.31	0.24	1.81	0.63	0.00	0.03	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.11	0.00
Isovaleraldehyde	0.01	0.04	0.04	0.00	0.00	0.00	0.50	0.62	-0.01	-0.01	-0.01	0.00	0.00	-0.01	0.02	-0.01	0.03	0.02	0.00
Valeraldehyde	-0.05	0.03	-0.01	-0.02	-0.03	-0.04	0.79	0.92	-0.03	0.05	0.00	0.06	0.00	0.06	0.00	0.00	0.00	0.12	0.00
o-Tolualdehyde	0.00	0.00	0.00	0.00	0.00	0.00	1.20	0.68	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00
m/p-Tolualdehyde	0.00	0.00	0.00	0.00	0.00	0.00	0.76	0.15	0.00	0.00	0.05	0.03	0.00	0.09	0.09	0.00	0.00	0.04	0.00
Hexanaldehyde	0.02	0.00	0.00	0.02	0.00	0.00	0.32	0.03	0.00	0.00	0.00	0.01	0.01	-0.02	0.00	0.00	0.00	0.04	0.00
Dimethylbenzaldehyde	0.00	0.00	0.00	0.00	0.00	0.00	1.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00
Nominal Limit of Detection	0.60	0.60	0.60	0.60	0.60	0.60	1.77	1.77	0.77	0.77	0.01	0.01	0.01	0.01	0.01	0.01	0.60	0.60	0.60

Footnotes: Negative values are due to background subtraction
Zero is reported if measurement is below the blank value

APPENDIX F

NITROSAMINES

TABLE F-1. ENGINE A NITROSAMINES

	NDMA	NDMAU	NDEA	NDEAU	NDPA	NDPAU	NNMUR	NNMURU	NDBA	NDBAU	NPPD	NPPDU	NPYR	NPYRU	NMRP	NMRPU
	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr
FTP-w-1	0.0	3.1	0.0	2.6	0.0	1.3	0.0	31.5	0.0	8.4	0.0	4.4	0.0	5.4	0.0	17.1
FTP-w-2	0.0	3.2	3.9	2.6	0.0	1.3	0.0	31.8	0.0	8.5	0.0	4.5	0.0	5.5	0.0	17.3
FTP-w-3	0.0	3.3	3.7	2.7	0.0	1.3	0.0	32.7	0.0	8.7	0.0	4.6	0.0	5.6	0.0	17.7
FTP-wo-2	0.0	3.4	0.0	2.8	0.0	1.4	0.0	34.5	0.0	9.2	0.0	4.8	0.0	5.9	0.0	18.7
FTP-wo-3	0.0	3.0	0.0	2.5	0.0	1.2	0.0	30.5	0.0	8.1	0.0	4.3	0.0	5.2	0.0	16.6
FTP-wo-4	4.6	3.1	0.0	2.5	0.0	1.2	0.0	30.7	0.0	8.2	0.0	4.3	0.0	5.3	0.0	16.7
CARBX-1	15.2	20.9	43.7	17.6	22.8	9.7	0.0	209.9	0.0	56.0	0.0	29.4	0.0	36.1	0.0	114.0
CARBX-2	0.0	20.8	0.0	17.1	0.0	8.5	0.0	209.4	0.0	55.9	0.0	29.4	0.0	36.0	0.0	113.7
CARBZ-1	5.6	2.2	3.8	1.8	0.0	0.9	0.0	22.2	0.0	5.9	0.0	3.1	0.0	3.8	0.0	12.1
CARBZ-2	3.0	2.3	0.0	1.9	0.0	0.9	0.0	23.0	0.0	6.1	0.0	3.2	0.0	4.0	0.0	12.5
16-Hour-1	24.3	2.5	1.8	1.7	0.0	0.9	0.0	21.2	0.0	5.7	0.0	3.0	0.0	3.6	0.0	11.5
16-Hour-2	22.9	2.4	0.0	1.7	0.0	0.9	0.0	21.3	0.0	5.7	2.0	3.0	0.0	3.7	0.0	11.6
16-Hour-3	21.3	2.4	0.0	1.7	0.0	0.9	0.0	21.1	0.0	5.6	0.0	3.0	0.0	3.6	0.0	11.4
TB-1	0.0	3.2	0.0	2.6	0.0	1.3	0.0	31.9	0.0	8.5	0.0	4.5	0.0	5.5	0.0	17.3
TB-2	0.0	3.2	5.6	2.6	0.0	1.3	0.0	31.9	0.0	8.5	0.0	4.5	0.0	5.5	16.5	17.3
TB-3	0.0	3.2	2.2	2.6	0.0	1.3	0.0	31.9	0.0	8.5	0.0	4.5	0.0	5.5	0.0	17.3
TB-4	0.0	3.2	0.0	2.6	0.0	1.3	0.0	31.9	0.0	8.5	0.0	4.5	0.0	5.5	0.0	17.3

u is designated for measurement uncertainty or limit of detection
TB emissions is based on the FTP transient cycle information

TABLE F-2. ENGINE B NITROSAMINES

	NDMA	NDMAU	NDEA	NDEAU	NDPA	NDPAU	NNMUR	NNMURU	NDBA	NDBAU	NPPD	NPPDU	NPYR	NPYRU	NMRP	NMRPU
	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr
FTP-w-1	3.1	2.7	3.3	2.2	0.0	1.1	0.0	27.1	0.0	7.2	0.0	3.8	0.0	4.7	0.0	14.7
FTP-w-2	0.0	2.5	1.5	2.0	0.0	1.0	0.0	25.2	0.0	6.7	2.8	3.5	0.0	4.3	0.0	13.7
FTP-w-3	1.3	2.4	0.0	2.0	0.0	1.0	0.0	24.4	0.0	6.5	0.0	3.4	0.0	4.2	0.0	13.3
FTP-wo-2	0.0	2.6	3.2	2.1	0.0	1.1	0.0	26.0	0.0	6.9	0.0	3.6	0.0	4.5	0.0	14.1
FTP-wo-3	0.0	2.6	3.3	2.1	0.0	1.1	0.0	26.0	0.0	6.9	0.0	3.6	0.0	4.5	0.0	14.1
FTP-wo-4	0.0	2.6	2.6	2.1	0.0	1.1	0.0	26.0	0.0	6.9	0.0	3.6	0.0	4.5	0.0	14.1
CARBX-1	0.0	11.9	8.7	9.8	0.0	4.9	0.0	119.9	0.0	32.0	0.0	16.8	0.0	20.6	0.0	65.1
CARBX-2	0.0	11.8	0.0	9.7	0.0	4.8	0.0	119.0	0.0	31.8	0.0	16.7	0.0	20.5	0.0	64.6
CARBZ-1	2.7	1.8	2.5	1.5	0.0	0.7	0.0	17.6	3.7	4.7	0.0	2.5	0.0	3.0	0.0	9.6
CARBZ-2	3.0	1.8	1.7	1.5	0.0	0.7	0.0	18.4	0.0	4.9	0.0	2.6	0.0	3.2	0.0	10.0
16-Hour-1	15.4	2.4	5.0	1.9	0.0	0.9	0.0	22.8	0.0	6.1	0.0	3.2	0.0	3.9	0.0	12.4
16-Hour-2	13.3	2.4	5.7	1.9	0.0	0.9	0.0	22.7	0.0	6.1	0.0	3.2	0.0	3.9	0.0	12.3
16-Hour-3	11.5	2.3	4.7	1.9	0.0	0.9	0.0	22.7	0.0	6.1	0.0	3.2	0.0	3.9	0.0	12.3
TB-1	0.0	2.6	3.1	2.1	0.0	1.0	0.0	25.8	0.0	6.9	0.0	3.6	0.0	4.4	0.0	14.0
TB-2	0.0	2.6	2.7	2.1	0.0	1.0	0.0	25.8	0.0	6.9	0.0	3.6	0.0	4.4	0.0	14.0
TB-3	0.0	2.6	1.2	2.1	0.0	1.0	0.0	25.8	0.0	6.9	0.0	3.6	0.0	4.4	0.0	14.0
TB-4	0.0	2.6	0.0	2.1	0.0	1.0	22.6	27.1	0.0	6.9	0.0	3.6	0.0	4.4	0.0	14.0

u is designated for measurement uncertainty or limit of detection
TB emissions is based on the FTP transient cycle information

TABLE F-3. ENGINE C NITROSAMINES

	NDMA	NDMAU	NDEA	NDEAU	NDPA	NDPAU	NNMUR	NNMURU	NDBA	NDBAU	NPPD	NPPDU	NPYR	NPYRU	NMRP	NMRPU
	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr
FTP-w-1	84.9	139.1	0.0	113.7	0.0	56.9	0.0	1416.0	0.0	372.8	0.0	195.9	0.0	240.1	0.0	758.2
FTP-w-2	61.4	159.2	0.0	130.2	0.0	65.1	0.0	1621.8	0.0	426.9	0.0	224.3	0.0	275.0	0.0	868.3
FTP-w-3	74.3	154.1	0.0	126.1	0.0	63.0	0.0	1569.8	0.0	413.2	0.0	217.1	0.0	266.2	0.0	840.5
FTP-wo-2	88.6	172.4	0.0	141.0	116.3	74.3	0.0	1755.5	0.0	462.1	0.0	242.8	0.0	297.6	0.0	939.9
FTP-wo-3	51.4	160.0	0.0	130.9	0.0	65.5	0.0	1630.1	0.0	429.1	0.0	225.5	0.0	276.4	0.0	872.8
FTP-wo-4	98.2	160.9	0.0	131.6	0.0	65.8	0.0	1638.7	0.0	431.4	0.0	226.7	0.0	277.8	0.0	877.4
CARBX-1	160.2	311.7	0.0	254.9	721.0	196.0	0.0	3173.9	0.0	835.5	0.0	439.0	0.0	538.1	0.0	1699.4
CARBX-2	58.6	304.0	0.0	248.7	468.9	157.9	0.0	3096.4	0.0	815.1	0.0	428.3	0.0	525.0	0.0	1657.9
CARBZ-1	29.9	31.1	0.0	25.4	0.0	12.7	0.0	315.8	0.0	83.1	0.0	43.7	0.0	53.5	0.0	169.1
CARBZ-2	24.4	29.2	0.0	23.9	38.5	14.4	0.0	297.3	0.0	78.3	0.0	41.1	0.0	50.4	0.0	159.2
16-Hour-1	98.4	278.5	0.0	227.8	0.0	113.9	0.0	2797.2	0.0	746.8	35.8	392.4	0.0	481.0	0.0	1518.8
16-Hour-2	30.8	8.1	0.0	6.4	0.0	3.2	0.0	79.0	0.0	21.1	0.0	11.1	0.0	13.6	0.0	42.9
16-Hour-3	170.8	12.5	1.7	4.8	0.0	2.4	0.0	59.4	0.0	15.8	0.0	8.3	0.0	10.2	0.0	32.2
TB-1	39.3	81.4	0.0	66.6	0.0	33.3	0.0	829.4	0.0	218.3	0.0	114.7	0.0	140.6	0.0	444.1
TB-2	40.9	115.7	0.0	94.7	0.0	47.3	0.0	1178.7	0.0	310.3	0.0	163.0	0.0	199.8	0.0	631.1
TB-3	81.9	10.5	2.0	7.4	1.2	3.7	0.0	91.4	27.5	24.6	0.0	12.8	0.0	15.7	0.0	49.6

u is designated for measurement uncertainty or limit of detection
TB emissions is based on the FTP transient Cycle

TABLE F-4. ENGINE D NITROSAMINES

	NDMA	NDMAU	NDEA	NDEAU	NDPA	NDPAU	NNMUR	NNMURU	NDBA	NDBAU	NPPD	NPPDU	NPYR	NPYRU	NMRP	NMRPU
	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr	µg/hp-hr
FTP-w-1	0.0	32.6	0.0	26.7	0.0	13.3	0.0	334.7	0.0	87.5	0.0	46.0	0.0	56.3	0.0	177.9
FTP-w-2	0.0	33.2	0.0	27.1	0.0	13.6	308.1	349.3	0.0	89.0	0.0	46.7	0.0	57.3	0.0	180.9
FTP-w-3	22.5	36.9	10.7	30.2	8.3	15.2	0.0	380.0	0.0	98.9	0.0	52.0	0.0	63.7	0.0	201.1
FTP-wo-2	26.1	38.7	22.4	31.8	0.0	15.8	0.0	398.3	0.0	103.8	0.0	54.5	0.0	66.8	0.0	211.0
FTP-wo-3	0.0	90.5	0.0	74.1	0.0	37.0	692.6	949.6	0.0	242.8	0.0	127.6	0.0	156.4	0.0	493.8
FTP-wo-4	0.0	91.6	64.8	75.2	0.0	37.5	317.9	951.9	0.0	245.6	0.0	129.1	0.0	158.2	0.0	499.6
CARBX-1	0.0	439.1	324.6	360.7	0.0	179.6	1044.4	4554.2	0.0	1177.6	0.0	618.7	0.0	758.5	0.0	2395.2
CARBX-2	0.0	468.1	496.5	386.0	0.0	191.5	2256.8	4878.4	0.0	1255.4	0.0	659.6	0.0	808.6	0.0	2553.3
CARBZ-1	0.0	60.2	0.0	49.3	0.0	24.6	0.0	616.3	0.0	161.5	0.0	84.8	0.0	104.0	0.0	328.4
CARBZ-2	0.0	56.0	0.0	45.8	0.0	22.9	0.0	570.5	0.0	150.2	0.0	78.9	0.0	96.7	0.0	305.4
16-Hour-1	15.7	2.7	2.9	2.0	0.7	1.0	0.0	25.1	0.0	6.6	0.0	3.5	0.0	4.2	0.0	13.4
16-Hour-2	32.6	3.5	2.6	2.1	0.7	1.1	0.0	26.1	0.0	6.9	0.0	3.6	0.0	4.4	0.0	14.0
16-Hour-3	14.9	2.8	3.3	2.2	1.0	1.1	0.0	26.4	0.0	7.0	0.0	3.7	0.0	4.5	5.3	14.2
TB-1	0.0	88.7	0.0	72.6	0.0	36.3	0.0	909.2	0.0	238.0	0.0	125.0	0.0	153.3	0.0	484.0
TB-2	0.0	93.5	0.0	76.5	0.0	38.3	0.0	952.8	0.0	250.8	0.0	131.8	0.0	161.6	0.0	510.2
TB-3	0.0	648.0	0.0	530.2	0.0	265.1	7010.6	6892.8	0.0	1737.9	0.0	913.1	0.0	1119.3	0.0	3534.8

u is designated for measurement uncertainty or limit of detection
TB emissions is based on the FTP transient cycle information

CRC Report: ACES Phase 2

PHASE 2 OF THE ADVANCED COLLABORATIVE EMISSIONS STUDY

NOVEMBER 2013

COORDINATING RESEARCH COUNCIL, INC.
5755 NORTH POINT PARKWAY SUITE 265·ALPHARETTA, GA 30022

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PHASE 2 OF THE ADVANCED COLLABORATIVE EMISSIONS STUDY

FINAL REPORT

SwRI® Project No. 03.17124

Prepared for and Sponsored by:

Coordinating Research Council, Inc.
5755 North Point Parkway Suite 265
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Health Effects Institute
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Funded by:

Department of Energy, Office of Vehicle Technologies
Environmental Protection Agency
Truck and Engine Manufacturers Association
California Air Resources Board
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November 2013

SOUTHWEST RESEARCH INSTITUTE®
SAN ANTONIO, TX • HOUSTON, TX • WASHINGTON, DC

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Results and discussion given in this report relate only to the test items described in this report.

FOREWORD

Phase 2 of the Advanced Collaborative Emissions Study (ACES Phase 2) was performed by the Department of Emissions R&D in the Engine, Emissions and Vehicle Research Division of Southwest Research Institute (SwRI).

SwRI's Principal Investigator and Project Manager was Dr. Imad Khalek (Senior Program Manager). Mr. Matt Blanks (Senior Research Engineer) was the Project Leader. Mr. Patrick Merritt (Principal Scientist) assisted in and coordinated the chemistry work. Mr. Vinay Premnath (Engineer), Mr. Richard Mechler (Senior Research Technologist), and Mr. Daniel Preece (Research Assistant) assisted in the particle measurement activities. Chemistry assistance was provided by Ms. Svitlana Kroll (Senior Research Scientist), Mr. Nolan Wright (Research Scientist), Ms. Yolanda Rodriguez (Staff Technician), Ms. Kelly Strate (Senior Technician), Mr. Chuan-Yi Tsai (Research Assistant), and Mr. Luis Sanchez (Assistant Supervisor). Additional assistance was provided by Mr. Chris Gourley (Senior Research Scientist), Ms. Shraddha Quarderer (Senior Research Scientist), and Ms. Jacqueline Ranger (Group Leader). Laboratory technical assistance was provided by Mr. Keith Echtle (Manager), Mr. David Elizondo (Supervisor), Mr. Tim Milligan (Staff Technician), Mr. Danny Terrazas (Supervisor), Mr. Joe Sosa (Principal Technician), and Mr. Rudy Guerra (Senior Technician).

The chemical analyses were performed by SwRI's Department of Emissions R&D and SwRI's Chemistry and Chemical Engineering Division. Additional chemical analyses such as PAHs, hopanes, steranes, alkanes, polar compounds, elements, and organic carbon/elemental carbon (OC/EC) were performed by Desert Research Institute (DRI), with Dr. Barbara Zielinska as the Principal Investigator. Urea related particle phase compounds were analyzed by Oak Ridge National Laboratory (ORNL), with Dr. John Storey as the Principal Investigator.

ACES Phase 2 was sponsored by the Coordinating Research Council and the Health Effects Institute (HEI), with funding from the DOE Office of Vehicle Technologies, Truck and Engine Manufacturers Association (EMA), Environmental Protection Agency (EPA), California Air Resources Board (CARB), and the American Petroleum Institute (API). The engines and engine support were provided by Cummins, Detroit Diesel, and Volvo Powertrain. Key contacts were Dr. Shirish Shimpi (Cummins), Mr. Don Keski-Hynnila (Detroit Diesel) and Mr. Jeff Shaffer (Volvo Powertrain). The lube oil was provided by Lubrizol, with Dr. Ewa Bardasz as a key contact.

The sponsors' project coordinators were Dr. Christopher Tennant from CRC, Dr. Maria Costantini and Dr. Rashid Shaikh from HEI. The CRC ACES Panel members included:

CRC ACES Panel

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Ewa Bardasz	Lubrizol Corporation	Carl Maronde	National Energy Technology Laboratory
Nick Barsic	John Deere	Mani Natarajan	Marathon Petroleum Company LP
Maria Costantini	Health Effects Institute	Ralph Nine	National Energy Technology Laboratory
Christopher Dea	Caterpillar, Inc.	Jeff Shaffer	Volvo Powertrain North America
Dominic DiCicco	Ford Motor Company	Rashid Shaikh	Health Effects Institute
Timothy A. French	Truck & Engine Mfrs Association	Shirish Shimpi	Cummins, Inc.
Rob Graze	Caterpillar, Inc.	Joseph H. Somers	US Environmental Protection Agency
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EXECUTIVE SUMMARY

Introduction

Phase 2 of the Advanced Collaborative Emissions Study (ACES Phase 2) included detailed chemical characterization of exhaust species emitted from three 2011 model-year on-highway heavy heavy-duty diesel engines (HHDDE) in compliance with US Environmental Agency (EPA) 2010 emissions standards. The engines were supplied by Cummins, Detroit Diesel, and Volvo. They were randomly designated as Engine X, Engine Y, and Engine Z in this program to remain anonymous. Each engine had a total of 125 hours of manufacturer-run dynamometer operation prior to shipping to Southwest Research Institute® (SwRI®). Except for the urea-related compound analyses, the emissions characterizations performed under ACES Phase 2 were similar to those performed under ACES Phase 1 involving 2007 EPA-compliant on-highway HHDDE. According to the engine manufacturers, the 2011 ACES engines were obtained from the normal production supply, and are identical to those sold to customers during model year 2010. Throughout this report, the engines are referred to as 2010 engines to reflect the 2010 emissions compliance.

In 2010, EPA's stringent NO_X limit of 0.20 g/hp-hr became fully enforceable whereby the NO_X emissions limit decreased from an average level of 1.2 g/hp-hr between 2007 and 2009 to a level less than or equal to 0.20 g/hp-hr in 2010. To comply with the 2010 NO_X limit, on-highway heavy-duty engine manufacturers utilized a urea-based selective catalytic reduction (SCR) catalyst in engine exhaust placed downstream of a diesel oxidation catalyst (DOC) and a catalyzed diesel particulate filter (DPF) used for particulate matter (PM) emissions control. The engine manufacturers devoted substantial efforts to calibration of the urea dosing and mixing, SCR catalyst formulation, and engine control to achieve the desired NO_X reduction while maintaining a controlled level of ammonia slip using an ammonia oxidation (AMOX) catalyst downstream of the SCR catalyst. Improvements were also made in PM emissions control, eliminating the need for active regeneration (onboard cleaning via exhaust fuel injection upstream of DOC) of the DPF during ACES Phase 2 testing, compared to the several regeneration occurrences with the 2007 technology engines tested in ACES Phase 1.

In ACES Phase 1, we reported substantially lower regulated and unregulated emissions relative to the 2007 standard and to pre-2007 technology engines. With the anticipated changes in engine technology between 2009 and 2010, particularly the addition of the urea-based SCR catalyst in engine exhaust, the ACES Panel recognized earlier (before the launching of ACES Phase 1) the importance of documenting the emissions of 2010 technology engines through ACES Phase 2. With ACES Phase 1 and Phase 2 in place, one would have a more thorough and complete emissions characterization of modern heavy-duty on-highway diesel engines for the period between 2007 and 2009 (ACES Phase 1) and for post-2010 (ACES Phase 2).

Test Cycles and Emissions Measurements

We used the cold-start and hot-start Federal Test Procedures (FTP) transient cycle to determine if the engines met the applicable standard on regulated emissions species. We conducted three separate runs of the hot-start FTP and the 16-hour transient cycle (16-Hour), similar to ACES Phase 1, to characterize the regulated and unregulated emissions species in engine exhaust. Each 16-Hour ran over two 8-hour days with Day 1 as a hot-start and Day 2 as a cold-start. For each cycle, regulated emissions of carbon monoxide (CO), non-methane hydrocarbons (NMHC), oxides of nitrogen (NO_x) and particulate matter (PM) were measured. Unregulated emissions measurement included total hydrocarbons (THC), methane (CH_4), carbon dioxide (CO_2), nitric oxide (NO), nitrogen dioxide (NO_2), nitrous oxide (N_2O), ammonia (NH_3), particle size distribution and number concentration, organic carbon (OC), elemental carbon (EC), metals and elements, inorganic ions, polynuclear aromatic hydrocarbons (PAH), nitroPAH, oxyPAH, polar compounds, alkanes, hopanes, steranes, cyanide ions, organic acids, gas phase acids, nitrosamines, detailed speciation of C_2 to C_{12} hydrocarbons, and carbonyls. Dioxins, furans and particle phase urea-related compounds were analyzed for the 16-Hour only.

Samples of the different exhaust species were taken either directly from the sample zone of the full-flow constant volume sampler (CVS) dilution tunnel (with a dilution ratio of 5 to 8) or from locations that were linked to the sample zone by a dilution step with a dilution ratio of approximately 2. Similar to ACES Phase 1, one sample location was an animal exposure chamber (unoccupied), provided by Lovelace Laboratory Research Institute (LRRI), to determine concentration levels that might be expected in future animal exposure such as those conducted in ACES Phase 3 on a 2007 technology engine. Real-time particle size distribution and number concentration, total PM, soot (as measured by MSS) and OC/EC measurements were taken from the exposure chamber. All measurements were performed with engine blow-by routed to the exhaust downstream of the urea SCR/AMOX catalysts.

Throughout this document, the emissions are reported on a work-specific basis (g/hp-hr) to represent the mass of emitted species over the brake-work produced by the engine during either the FTP or the 16-Hour. This is the official metric used in US EPA engine emissions regulations.

Reduction in Regulated Emissions for FTP Composite

Table ES-1 summarizes the average weighted brake-specific emissions for the FTP cold- and hot-start composite relative to the EPA 2010 standard. Brake-specific emission is a typical reported metric for engine emissions. Substantial reductions were observed for CO (97%), NMHC (>99.9%), PM (92%) and NO_X (61%). Figure ES-1 summarizes the emissions reduction relative to 2010, 2007, and 2004 standards. Relative to the 2004 standard, the reductions were 97% for CO, 97% for NO_X, >99.99% for NMHC, and 99% for PM.

TABLE ES-1. SUMMARY OF AVERAGE WEIGHTED REGULATED EMISSIONS BASED ON THE FTP COLD-START AND HOT-START COMPOSITE

	2010 EPA Standard (g/hp-hr)	[a]Weighted 2010 Engines Emissions (g/hp-hr)	Emissions % Reduction Relative to the 2010Standard
CO	15.5	0.50	97
NMHC	0.14	<0.001	>99
PM	0.01	0.0008	92
NO_X	0.20	0.08	61
[a](1/7×Cold-Start FTP) + (6/7×Hot-Start FTP)			

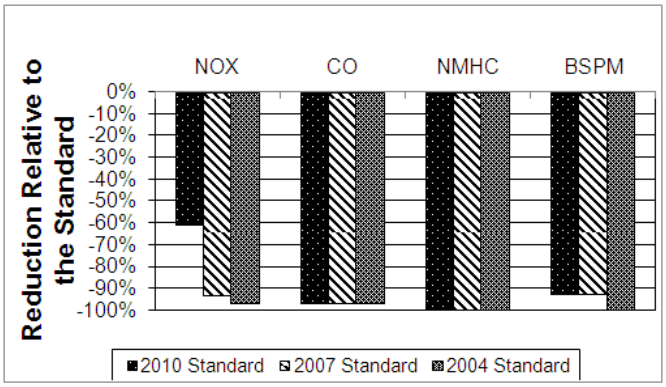

FIGURE ES-1. REGULATED EMISSIONS PERFORMANCE OF 2010 ENGINES RELATIVE TO 2010, 2007, AND 2004 EPA STANDARDS

Reduction in Regulated and Unregulated Average Emissions

Figure ES-2 summarizes the reductions in average emissions observed with the three 2010 technology engines relative to the average emissions of the four 2007 technology engines used in ACES Phase 1 for the 16-Hour. Substantial reductions in NO_X, NO_2, CO, NMHC, CH_4, PM, EC and OC mass, and particle number were observed. Greenhouse gas emissions based on CO_2, N_2O, and CH_4 led to no change in the 100-year global warming potential (GWP), as defined by the EPA. The reduction in CH_4 and the slight reduction in CO_2 observed with 2010 technology engines (Figure ES-2) were offset by the increase in N_2O (Figure ES-3) leading to no change in the GWP. Figure ES-3 shows that although N_2O emissions were higher with the 2010 technology engines compared to the 2007 technology engines, they were still below the EPA 2014 N_2O emissions limit of 0.1 g/hp-hr. The average N_2O emissions ranged from 0.052 g/hp-hr and 0.054 g/hp-hr for Engines X and Z to 0.11 g/hp-hr for Engine Y. The N_2O limit is a "cap" standard designed to prevent major increases in N_2O. The cap was set at approximately twice the level of N_2O emissions from 2008 heavy-duty diesel and gasoline engines[1].

[1] CFR 76 179, page 1790, September 15, 2011

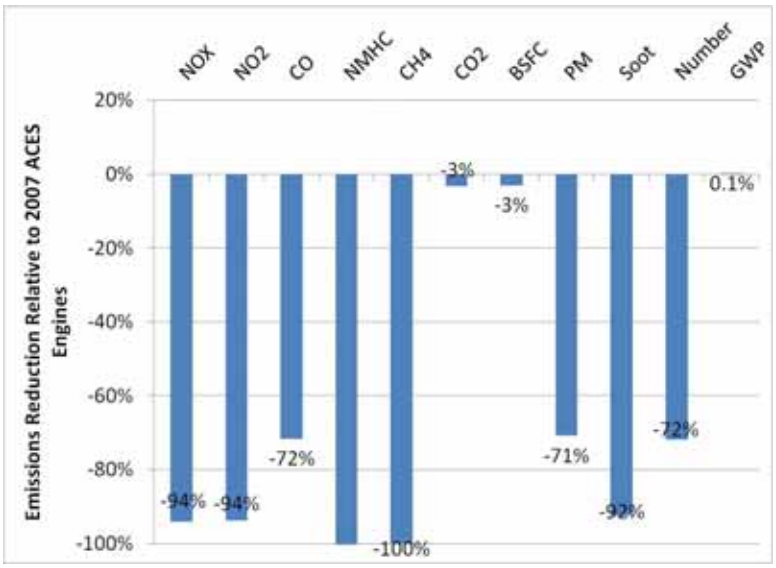

FIGURE ES-2. 2010 TECHNOLOGY ENGINES EMISSIONS REDUCTION RELATIVE TO 2007 TECHNOLOGY ENGINES FOR THE 16-HOUR

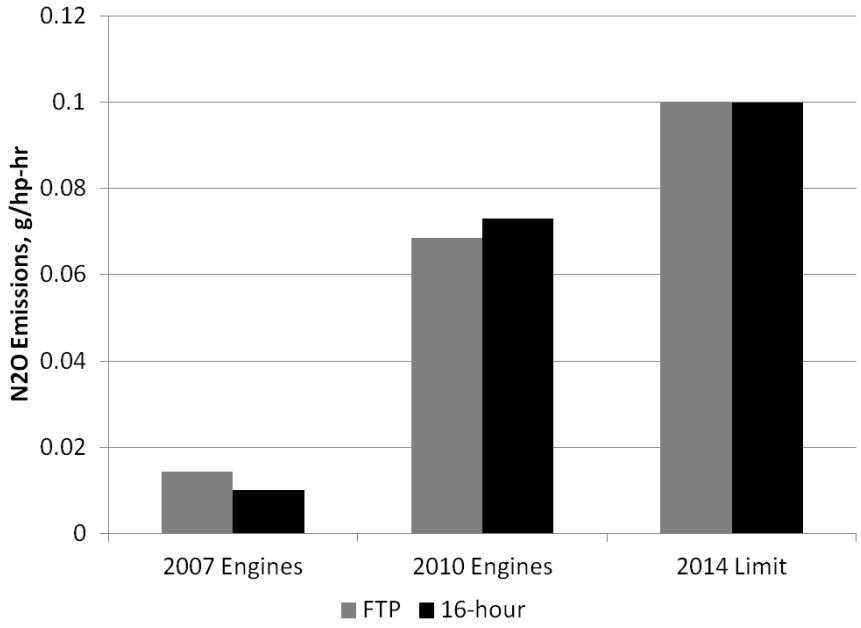

FIGURE ES-3. AVERAGE N_2O EMISSIONS COMPARISON FOR 2010 AND 2007 TECHNOLOGY ENGINES RELATIVE TO THE 2014 LIMIT

Table ES-2 shows the 2010 emissions reductions for several classes of unregulated emissions compounds relative to the 2007 technology engines used in ACES Phase 1, to a 2004 technology engine used in the CRC E55/59 study, and to a 1998 technology engine used for dioxins and furans. Very substantial reductions (91% to 100%) were observed relative to the 2004 technology engine. Substantial reductions (36% to 99%) were also observed relative to the 2007 technology engines.

TABLE ES-2. SUMMARY OF UNREGULATED EMISSIONS REDUCTION FOR 16-HOUR

	2010 % reduction relative to 2007 engines	2010 % reduction relative to 2004 engine
Single Ring Aromatics	50	91
PAH	97	99
NitroPAH	99	100
Alkanes	93	99
Polar	96	99
Hopanes & Steranes	89	100
Carbonyls	80	100
Inorganic Ions	87	92
Metals and Elements	81	100
Organic Carbon	36	97
Elemental Carbon	53	100
Dioxins and Furans[a]	88	100
[a]Relative to 1998 Technology Engine		

Urea-related Compounds

Out of six particle phase urea-related compounds for which we conducted analyses, only urea and cyanuric acid were detected. Even for those compounds, the emissions level was extremely low, with the highest cyanuric acid mass concentration level being just about 18 ppb in the undiluted engine exhaust, and the emissions in the range of 4.8 to 15.5 µg/hp-hr. The average exhaust concentration of ammonia (urea-related compound) due to ammonia slip ranged from 0.12 ppmv to 1.37 ppmv, depending on the engine and cycle used. This concentration range is much lower than the Euro VI limit of 10 ppm, and the potential US limit of 10 ppm to 15 ppm.

Particle Number Emissions

Interesting distinctions in particle number emissions and PM composition were observed between the 2010 and 2007 technology engines. Figure ES-4 (A) shows the total (solid + volatile) particle number emissions for the 2010, 2007, and 2004[2] technology engines for the FTP. Both the 2010 and 2007 had no active DPF regeneration events during the FTP. Substantial reduction (99%) in particle number was observed with the 2010 compared to the 2004 technology engine. Also, 2010 engines showed a 41% reduction in particle number relative to ACES Phase 1 2007 technology engines. Furthermore, a more substantial reduction of 72% was observed with the 2010 vs. 2007 engines when comparing the particle number emissions for the 16-Hour, shown in Figure ES-4 (B). For the 16-Hour, one distinction between the two technologies is that the 2010 engines DPF never actively regenerated during the entire ACES Phase 2 program, compared to 1 to 3 active regeneration events over one 16-Hour for the 2007 engines in ACES Phase 1. In ACES

[2] SwRI Internal Data

Phase 1, active regeneration during 4-hour segments of the 16-Hour led to a one-order-of-magnitude increase in particle number emissions over 4-hour segments without active regeneration. Thus, it is not surprising that the particle number emissions reduction with the 2010 engines was higher for the 16-Hour, compared to the FTP, as shown in Figure ES-4.

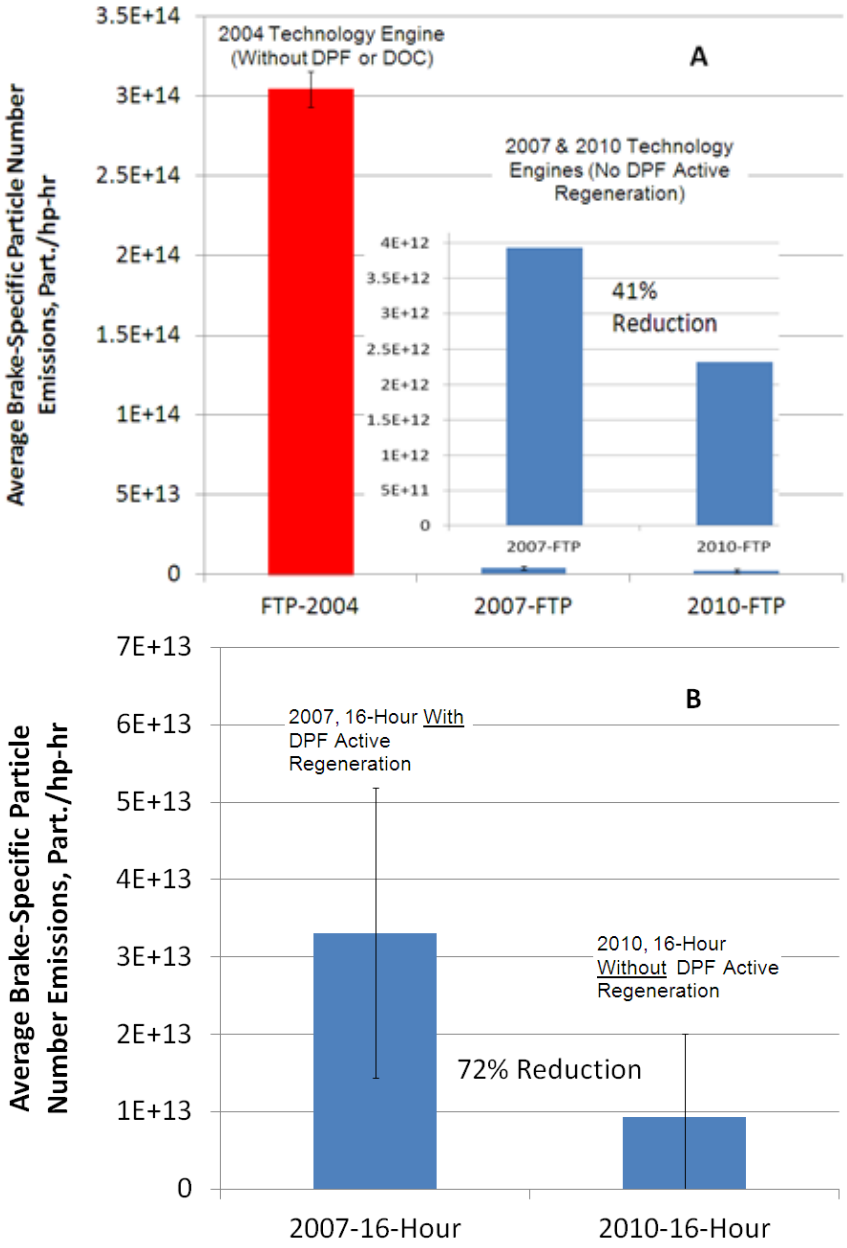

FIGURE ES-4. TOTAL (SOLID + VOLATILE) PARTICLE NUMBER EMISSIONS COMPARISON (A FOR FTP AND B FOR 16-HOUR)

PM Mass Emissions and Composition

Figure ES-5 and Table ES-3 show the main particle phase species contributing to PM emissions for the 2010 and 2007 technology engines. The reduction in PM mass in 2010 was mainly due to inorganic sulfate (SO_4^{2-}) ions, along with some elemental carbon (EC) and organic

carbon (OC) reductions. PM composition in the 2010 technology engines also showed some levels of nitrate (NO_3^-) and ammonium ($NH4^+$) ions that were absent from the PM in 2007 technology engines. Nitrate and ammonium are likely to be derived products of the urea and SCR system interactions.

The substantial reduction in sulfate was intriguing. Since sulfur content in the fuel and lube oil was no different between 2007 and 2010, it is highly likely that the reduction in sulfate is due to sulfur adsorption by the various aftertreatment systems used in the engine exhaust, especially the DOC and DPF. Due to the lack of active DPF regeneration encountered with the 2010 engines, compared to 2007 technology engines, it is likely that the internal surfaces of the DOC and DPF never got hot enough for the adsorbed sulfur to be released in high concentration. This same phenomenon is also likely responsible for the additional reduction observed in particle number between 2010 and 2007 during the 16-Hour, where the additional reduction in particle number with the 2010 engines could be mainly due to the lack of sulfuric acid particle nucleation.

Figure ES-6 and Table ES-3 show the PM composition as a percent of total PM. For 2010 technology engines, the very low level of PM was dominated by OC (66%) followed by EC (16%) and nitrate (14%), compared to sulfate (53%) followed by OC (30%) and EC (13%) for the 2007 technology engines. Figures ES-5 and ES-6 also indicate that elements emissions were substantially lower with the 2010 vs. 2007 technology engines. The non-metallic elements were dominated by sulfur (fuel and oil derived) and metallic elements were dominated by calcium and zinc (lube oil derived) followed by iron and aluminum (engine wear).

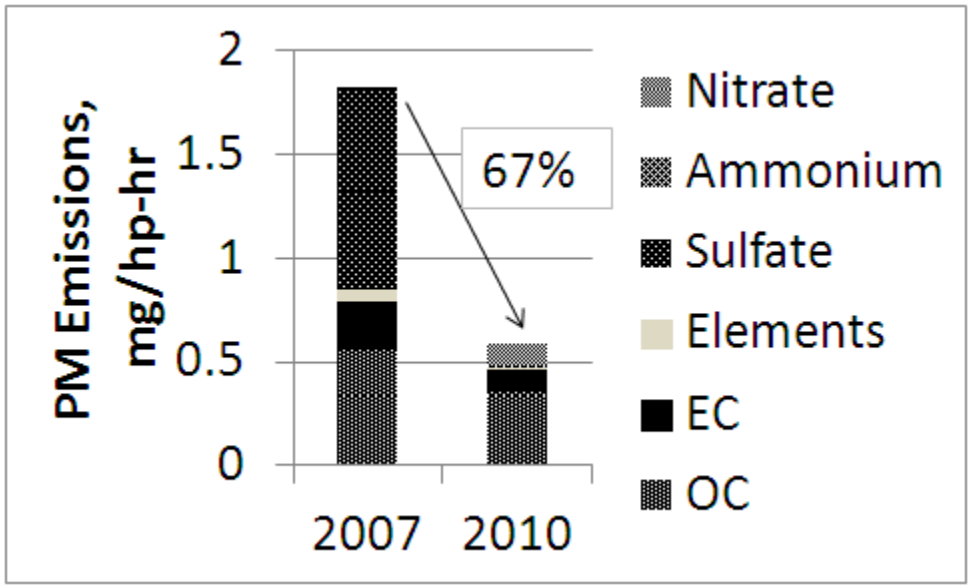

FIGURE ES-5. PM EMISSIONS COMPARISON BETWEEN 2010 AND 2007 TECHNOLOGY ENGINES (16-HOUR)

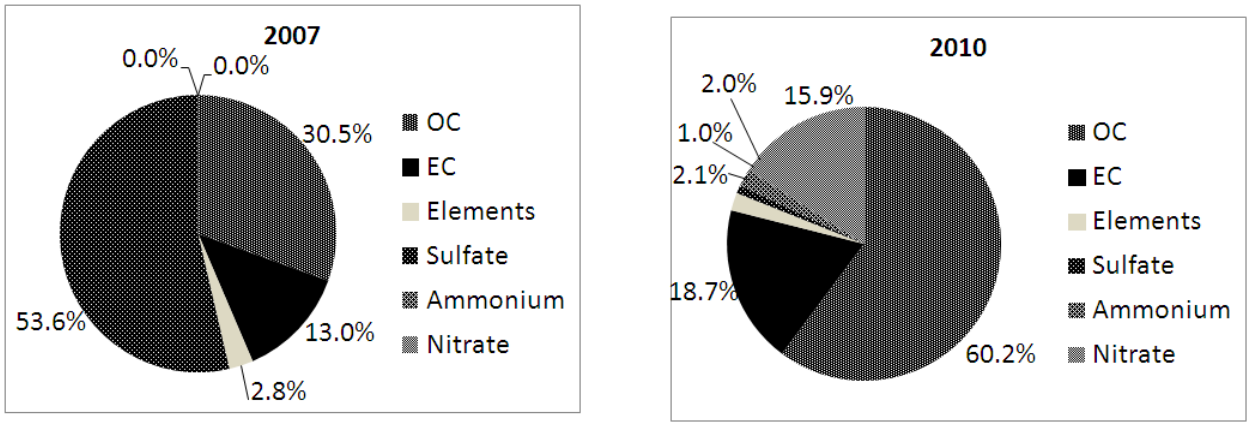

FIGURE ES-6. SUMMARY OF THE PM PERCENT COMPOSITION FOR 2010 AND 2007 TECHNOLOGY ENGINES

TABLE ES-3. SUMMARY OF PM EMISSIONS AND COMPOSITION FOR 2010 AND 2007 ENGINES

	OC	EC	Elements	Sulfate	Ammonium	Nitrate
	mg/hp-hr					
2007	0.556	0.238	0.052	0.978	0.000	0.000
2010	0.457	0.110	0.012	0.006	0.012	0.094
	% of total					
2007	30.5%	13.0%	2.8%	53.6%	0.0%	0.0%
2010	66.2%	15.9%	1.8%	0.8%	1.7%	13.6%

Summary

ACES Phase 2 demonstrates another large step in emissions reduction with 2010 EPA-compliant on-highway heavy heavy-duty diesel engines. The 2010-compliant engines showed substantially lower regulated emissions of NO_X, CO, NMHC, and PM relative to the 2010 standard. They also showed a substantial reduction in a very wide spectrum of particle and gas phase unregulated emissions species relative to pre-2007 and 2007 technology engines.

The observed reductions in PM (total mass, soot, and number) and unregulated emissions from 2007 to 2010 engines are likely due to differences in active DPF regeneration operation. The 2007 engines triggered multiple regeneration events during the 16-hour cycles, while the 2010 engines did not trigger any events. The improvement/reduction in regeneration was achieved through some combination of lower engine-out PM, increased passive regeneration and improved control strategies. PM emissions during regeneration events have been observed to be higher than normal operation for the 2007 engines used in ACES Phase 1. Unregulated emissions are believed to be higher during regeneration events. Thus, the results from the 2007 engines

include emissions measured over both normal (no active regeneration) and regeneration operation, while the results from the 2010 engines only include emissions measured over normal operation. DPF active regeneration would have occurred had the 2010 engines been run for a much longer period of time (100 or more hours). The 2010 engines did not trigger a regeneration event even after three back-to-back 16-hour cycles (48 hours of operation).

According to the engine manufacturers, the process and length of time for DPF active regeneration is expected to be similar for 2010 and 2007 engines. Therefore, the emissions during regeneration events are expected to be similar except for any differences due to increased loading of certain species like sulfur and heavy molecular weight hydrocarbons that are not oxidized by the aftertreatment system. Since 2010 engines have fewer regeneration events, the PM and unregulated emissions averaged over both normal and active regeneration operation are expected to be lower than 2007 engines. While it is not known how much the average PM and unregulated emissions on the 2010 engines may have increased if the test were continued to include regeneration events, the consensus of this study's principal investigator and its sponsors is that the 2010 engines' PM and unregulated emissions averaged over both normal and active regeneration operation are somewhere between the results measured during normal operation and the results measured on the 2007 engines over both normal and active regeneration operation.

Finally, all analyzed species including second-by-second data will be posted on the publically accessible CRC website at http://www.crcao.org.

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ACRONYMS AND ABBREVIATIONS

ACES	Advanced Collaborative Emissions Study
API	American Petroleum Institute
AMOX	Ammonia Oxidation Catalyst
BG	Background (clean dilution air downstream of the HEPA filter of the full flow constant volume sampler tunnel)
BSE	Brake-Specific Emissions
BSFC	Brake Specific Fuel Consumption
CARB	California Air Resources Board
CFR	Code of Federal Regulations
CI	Chemical Ionization
CO	Carbon Monoxide
CRC	Coordinating Research Council
CVAAS	Cold Vapor Atomic Absorption Spectroscopy
CVS	Constant Volume Sampler
DCM	Dichloromethane
DMM	Dekati Mass Monitor
DNPH	Dinitrophenylhydrazine
DOE	Department of Energy
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
DR	Dilution Ratio
DRI	Desert Research Institute
DFI/GC	Direct Filter Injection Gas Chromatography
EC	Elemental Carbon
ECM	Engine Control Module
EDXRF	Energy Dispersive X-Ray Fluorescence
EEPS	Engine Exhaust Particle Sizer
EGR	Exhaust Gas Recirculation
EI	Electron Impact
EMA	Truck and Engine Manufacturers Association
EPA	Environmental Protection Agency
ER&DD	Emissions Research and Development Department
FD	Fuel Density
FID	Flame Ionization Detector
FM	Fuel Mileage
FTIR	Fourier Transform Infrared Spectroscopy
FTP	Federal Test Procedure Transient Cycle
GC-ECD	Gas Chromatography-Electron Capture Detection
GC/MS	Gas Chromatograph/Mass Spectrometry
HDDE	Heavy-Duty Diesel Engine
HEI	Health Effects Institute
HEPA	High Efficiency Particulate Air
HHDDE	Heavy Heavy-Duty Diesel Engine
HPLC	High Performance Liquid Chromatography
HRGC	High Resolution Gas Chromatography
HRMS	High Resolution Mass Spectroscopy

IC	Ion Chromatography
ICPMS	Inductively Coupled Plasma/Mass Spectroscopy
LRRI	Lovelace Respiratory Research Institute
MID	Multiple Ion Detection
N/A	Not Available
MSS	Micro-Soot Sensor
NDIR	Non-Dispersed Infrared
NIST	National Institute of Standards and Technology
NitroPAH	Nitrated Polycyclic Aromatic Hydrocarbon
NMHC	Non-Methane Hydrocarbon
NO	Nitric oxide
NO_2	Nitrogen Dioxide
N_2O	Nitrous Oxide
NO_X	Oxides of Nitrogen
OC	Organic Carbon
ODS	Octadecasilane
ORNL	Oak Ridge National Laboratory
POC	Principle Organic Constituents
OxyPAH	Oxygenated Polycyclic Aromatic Hydrocarbon
PAH	Polycyclic Aromatic Hydrocarbon
PCDD	Polychlorinated Dibenzodioxins
PCDF	Polychlorinated Dibenzofurans
PM	Particulate Matter
PTFE	Polytetrafluoroethylene
PUF	Polyurethane Foam
SCFM	Standard Cubic Feet per Minute
SIS	Selective Ion Storage
SLPM	Standard Liters per Minute
S/N	Signal to Noise
SRM	Standard Reference Material
SVOC	Semivolatile Organic Compound
SwRI	Southwest Research Institute
TB	Tunnel Blank
TEF	Toxic Equivalency Factor
TEQ	Toxic Equivalent
THC	Total Hydrocarbon
TOR	Thermal Optical Reflectance
TOT	Thermal Optical Transmittance
ULSD	Ultra-low Sulfur Diesel
UV	Ultraviolet
VOC	Volatile Organic Compounds
VOST	Volatile Organic Sample Train
XAD™	"Polymeric Adsorbing Resins"
XRF	X-Ray Fluorescence

1.0 INTRODUCTION

Significant changes in on-highway, heavy-duty diesel engine technology took place between 1998 and 2010. While there were many improvements made in engine combustion, injection systems, turbochargers, and exhaust gas recirculation to reduce emissions, such improvements alone were not sufficient to meet EPA 2007 and 2010 emissions standards. Engine manufactures utilized four forms of aftertreatment technologies to assist in meeting the 2007 and 2010 emissions limits. As depicted in Figure 1, in 2007, due to a very stringent PM standard, diesel oxidation catalysts (DOC) followed by high efficiency catalyzed diesel particle filters (DPF) were introduced to diesel engine exhaust. A diesel injection system was also added upstream of the DOC to assist in regenerating or cleaning the DPF as needed. By injecting fuel upstream of a hot DOC, an exothermic reaction can take place raising the temperature upstream of the DPF to help oxidize the trapped EC and heavy molecular weight hydrocarbons. To meet the 2010 NO_X standards, a urea-based SCR system was also introduced to the exhaust downstream of the DPF for NO_X reduction. A separate urea dosing system upstream of the SCR along with a urea tank were also required. An ammonia oxidation (AMOX) catalyst was also added downstream of the SCR to minimize ammonia slip.

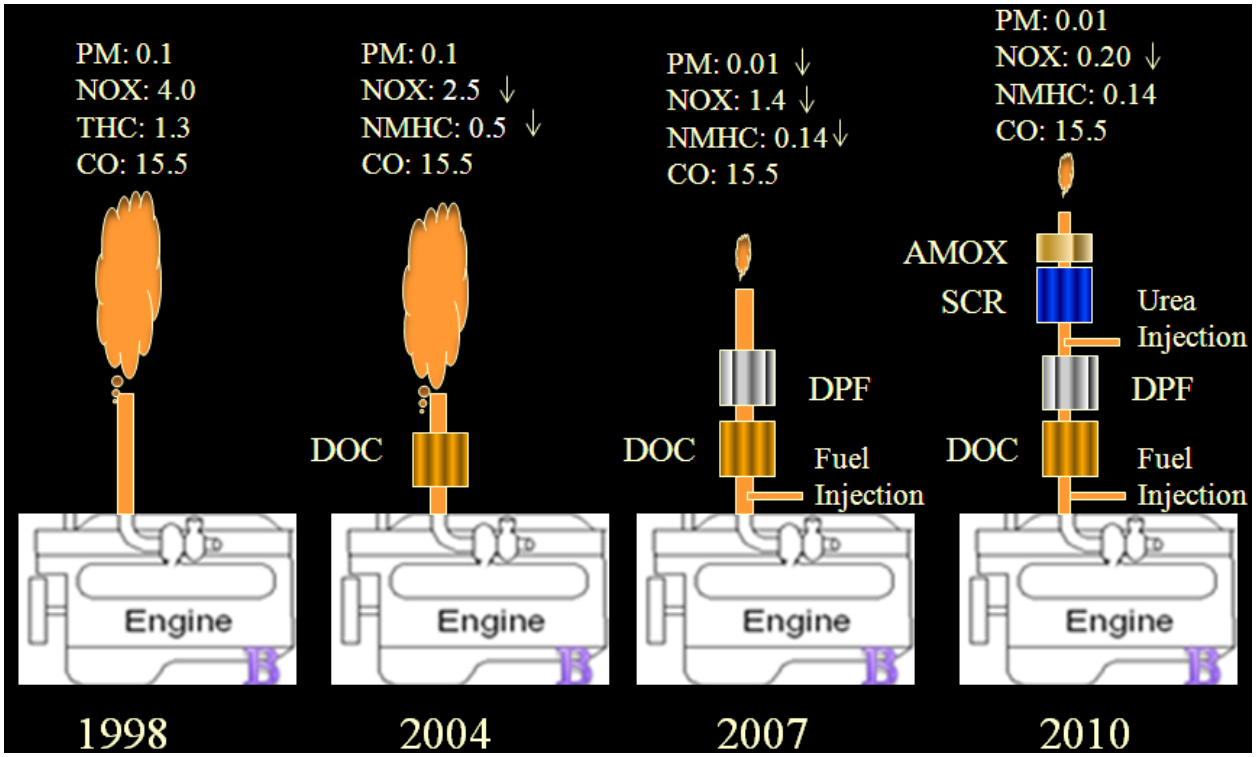

FIGURE 1. CHANGES IN THE EXHAUST OF ON-HIGHWAY HEAVY-DUTY DIESEL ENGINE TECHNOLOGY BETWEEN 1998 AND 2010

In anticipation of these technological changes in 2007 and later in 2010, there was a strong interest in thoroughly documenting the regulated and unregulated emissions impact of these engine technologies along with their impacts on potential health effects. In 2007, the ACES panel launched the ACES Phase 1 project[3,4], where we performed a detailed emissions

[3] Khalek et al., CRC ACES Phase 1 Final Report, 2009,

characterization on four 2007 heavy-duty on-highway technology engines. One of the engines was selected for a detailed health study by the Lovelace Respiratory Research Institute (LRRI) as a part of the ACES Phase 3[5]. In 2010, the ACES panel launched ACES Phase 2 as a continuation of ACES Phase 1 to fully characterize the emissions from 2010 EPA-compliant heavy-duty, on-highway technology engines. In both ACES Phase 1 and ACES Phase 2, the engines were brand new with only 125 hours of engine operation prior to testing at SwRI.

Three diesel engine manufacturers (Cummins, Inc., Detroit Diesel Corporation (DDC) and Volvo Powertrain) provided engines and engine support for the ACES Phase 2 program. The engines were all 2011 model-year and included a Cummins ISX, Detroit Diesel DD15, and a Mack MP8. All three engines are considered to be heavy heavy-duty on-highway diesel engines that are currently being marketed in the United States (US). The engines were all brand new, but had 125 hours of a manufacturer-run break-in and degreening operation prior to shipping to SwRI for testing. Throughout the ACES Phase 2 project, all engines remained anonymous, and were randomly designated as Engine X, Engine Y, and Engine Z. It is understood that the identity of the engines will be revealed by CRC at a later time

The three engines (Engines X, Y, and Z) were tested for regulated and unregulated emissions using the hot-start Federal Test Procedure (FTP) and the 16-Hour[6] (16-Hour) that was used in ACES Phase 1. Prior to using the engines for official measurement of regulated and unregulated emissions, the engines were tested using a composite of a cold-start and a hot-start FTP to verify their compliance with the 2010 standard.

Regulated emissions measurements included carbon monoxide (CO), non-methane hydrocarbon (NMHC), oxides of nitrogen (NO_x), and particulate matter (PM). Unregulated emissions included total hydrocarbon (THC), methane (CH_4), carbon dioxide (CO_2), nitric oxide (NO), nitrogen dioxide (NO_2), ammonia (NH_3), particle size distribution and number concentration, organic carbon, elemental carbon, metals and elements, inorganic ions, polynuclear aromatic hydrocarbon (PAH), nitroPAH, oxyPAH, polar compounds, alkanes, hopanes, steranes, cyanide ion, organic acids, gas phase acids, nitrosamines, detailed speciation of $C_2 - C_{12}$ hydrocarbons, aldehydes and ketones, dioxins and furans, and six particle phase urea-related compounds.

All volumetric flows, volumes or concentrations shown in this report are based on a reference temperature of 20°C and a pressure of 101.3 kPa. All averages, standard deviations, and error bars are based on three repeats of the FTP and three repeats of the 16-Hour.

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http://www.crcao.org/reports/recentstudies2009/ACES%20Phase%201/ACES%20Phase1%20Final%20Report%2015JUN2009.pdf

[4] Khalek I, T. Bougher, P. Merritt, and B. Zielinska, "Regulated and Unregulated Emissions from Highway Heavy-Duty Diesel Engines Complying with U.S. Environmental Protection Agency 2007 Emissions Standards," Submitted to *Journal of Air & Waste Management Association, March 2011*

[5] McDonald et al., "Advanced Collaborative Emissions Study (ACES) Subchronic Exposure Results: Biologic Responses in Rats and Mice and Assessment of Genotoxicity," HEI Research Report No. 166
http://www1.eere.energy.gov/vehiclesandfuels/pdfs/deer_2010/thursday/presentations/deer10_greenbaum.pdf

[6] Clark, N.N., F. Zhen, C. Bedick, M. Gautam, W. Wayne, G. Thompson, and D. Lyons, "Creation of the 16-Hour Engine Test Schedule from the Heavy Heavy-Duty Diesel Engine Test Schedule," CRC Report No. ACES-1-a, CRC Website at crcao.org, 2007

2.0 EXPERIMENTAL SETUP

2.1 Engines

Three 2011 model year (MY2011) on-highway, heavy-duty diesel engines, described in Table 1, were used in ACES Phase 2. They included a Cummins ISX (Cummins, Inc), Detroit Diesel DD15 (Detroit Diesel Corporation), and Mack MP8-415C (Volvo Powertrain). The power rating for the inline 6-cylinder engines ranged from 415 to 500 horsepower. The exhaust aftertreatment configuration included a DOC, DPF, SCR and an AMOX. Urea dosing was used for the SCR system, and diesel fuel injection was used when needed to actively regenerate the DPF. The exhaust system also included a turbocharger, a high-pressure loop exhaust gas recirculation (EGR) system with an EGR cooler, and NO_X sensors for active emissions control. The blow-by stream path included a separator before being vented to the atmosphere. The induction system was air to air cooled in a truck operation, but was water-cooled in the laboratory setting.

TABLE 1. ENGINE SPECIFICATIONS

Engine Series	ISX	DD15	MP8-415C
Manufacturer	Cummins	Detroit Diesel	Volvo Powertrain
Emissions Compliance	2010	2010	2010
Model year	2011	2011	2011
Displacement, liter	15	15	13
Rated Power, hp	500	455	415
Exhaust System	Turbocharged	Turbocharged	Turbocharged
Induction System	Compressed/Air to Air Cooled	Compressed/Air to Air Cooled	Compressed/Air to Air Cooled
Exhaust Configuration	(DOC+DPF)+SCR+AMOX	(DOC+DPF)+SCR+AMOX	(DOC+DPF)+SCR+AMOX
Exhaust NOX Sensors	Yes	Yes	Yes
Blow-By Configuration	Separator/Vented to Atmosphere	Separator/Vented to Atmosphere	Separator/Vented to Atmosphere
SCR Exhaust Fluid	Urea	Urea	Urea
DPF Active Regneration Exhaust Fluid	Diesel	Diesel	Diesel

2.2 Fuel, Urea, and Oil Properties

2.2.1 Fuel ASTM Properties and Elements

The ACES program fuel was provided by CRC through a commercial fuel supplier. It was a typical refinery commercial ultra-low sulfur diesel (ULSD) fuel that conformed to US EPA CFR Part 1065[7] ULSD fuel specifications. ASTM fuel properties are shown in Table 2. To ensure that no fuel contamination was introduced between the fuel tank and the engine, we changed all fuel sampling infrastructure into stainless steel tubing, similar to that done in ACES Phase 1. As shown in Table 2, no differences were observed in fuel properties between what was sampled directly from the fuel tank and what was sampled from the fuel system at the engine before the injection pump. The fuel has a sulfur level of 6.5 ppm, a cetane number of 48, and total aromatics of 32% (by volume). The cetane number was similar to that of the ACES Phase 1 fuel, but the sulfur level was 44% higher and the aromatics were 20% higher than those reported for ACES Phase 1 fuel. Higher initial and final boiling points of about 20°F to 30°F were also observed in ACES Phase 2 fuel, compared to ACES Phase 1 fuel.

[7] http://www.ecfr.gov/cgi-bin/text-idx?c=ecfr&tpl=/ecfrbrowse/Title40/40cfr1065_main_02.tpl

TABLE 2. ASTM FUEL PROPERTIES

			Fuel Tank	Engine Pump
ASTM Method	**Test Property**	**Test Units**	**EM-8050-F**	
D86	**Distillation**		**Results**	**Results**
	IBP	deg F	346	342
	5% Evaporated	degF	384	378
	10% Evaporated	degF	403	402
	15% Evaporated	degF	421	419
	20% Evaporated	degF	436	435
	30% Evaporated	degF	465	463
	40% Evaporated	degF	490	488
	50% Evaporated	degF	512	511
	60% Evaporated	degF	533	533
	70% Evaporated	degF	555	555
	80% Evaporated	degF	578	578
	90% Evaporated	degF	607	608
	95% Evaporated	degF	632	633
	FBP	degF	655	657
	Vol% Recovered	mL	97.5	96.7
	Vol% Residue	mL	1.4	1.5
	Vol% Loss	mL	1.1	1.8
D130	Copper Corrosion Strip	rating	1A	1A
D1319	Aromatics	vol%	32.7	31.9
	Olefins	vol%	2.6	2.5
	Saturates	vol%	64.7	65.6
D1796	Water & Sediment	mL	0.0	0.0
D2500	Cloud Point	°C	-11	-12
D4052s	API Gravity		36.6	36.5
	Specific Gravity		0.8418	0.842
D445	Viscosity at 40°C	cSt	2.631	2.616
D482	Ash Content	mass%	<0.001	<0.001
D5291	Carbon Content	wt%	86.56	86.44
D5291	Hydrogen Content	wt%	13.35	13.3
D5453	Sulfur Content	ppm	6.5	6.5
D6079	Lubricity by HFRR			
	Major Axis	mm	0.473	0.483
	Minor Axes	mm	0.399	0.41
	Wear Scar Diameter	mm	0.436	0.447
	Wear Scar Description		evenly abraded oval	evenly abraded oval
	Fuel Temperature	degC	60	60
D613	Cetane Number		48	48.1
D93	Flash Point	degF	148	147
D93	Flash Point	degC	65	64
D976	Cetane Index	calculated	50.4	50.5

2.2.2 Urea for SCR

The urea was obtained from Brenntag, a major supplier of diesel exhaust fluid (DEF) in North America. It is a TerraCair Ultrapure DEF (32.5% aqueous urea solution) that meets ISO 22241-1:2006. TerraCair Ultrapure DEF is also certified by API and meets the quality standard set by the engine manufacturers' service warranties.

2.2.3 Lube Oil ASTM Analyses and Elemental Composition

The lube oil was provided by Lubrizol. It is an API CJ-4 lube oil, which is typically used in post 2007 technology on-highway diesel engines. Table 3 shows the ASTM analyses for the fresh lube oil, and for the used lube oil after 125 hours of break-in and degreening that was performed by the respective engine manufacturers. The dominant elements observed in the fresh lube oil were calcium (2233 ppm), phosphorus (1020 ppm), zinc (1157 ppm), and sulfur (4018 ppm). These were very similar to ACES Phase 1 lube oil, although sulfur was not measured in ACES Phase 1. The used lube oil had some higher levels of boron, copper, magnesium, iron, and silicon, compared to the fresh oil, implying that these elements were accumulated in the oil during normal lubrication. Sulfur in the used oil was about 10% lower for Engine X and Y, compared to fresh oil, and it was 22% lower for Engine Z. There is no clear understanding and/or explanation for the differences observed, nor how they impact emissions if any.

2.3 Sampling System

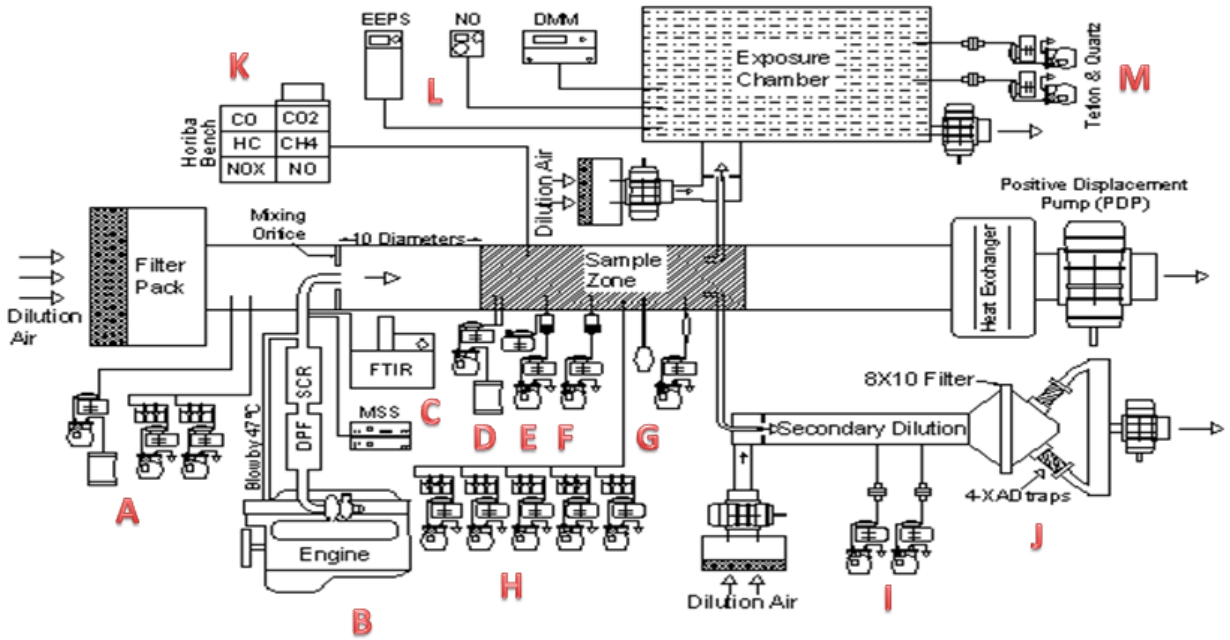
The sampling system for ACES Phase 2 is shown in Figure 2. It is similar to that used in Phase 1, with the exception of the additional 90 mm TX-40 filter collection for the urea-related particle phase compounds such as urea, melamine, cyanuric acid, ammelide, ammeline, and biuret which were analyzed by ORNL. In addition, the FTIR instrument was used for the measurement of ammonia and N_2O in the raw engine exhaust. Measurements and collection for different species from various locations along the sampling system are described below the schematic in Figure 1. Note that the filtered blow-by from the crankcase vent was routed to a location downstream of the SCR catalyst using a 47°C stainless steel sample line for all experiments conducted under ACES Phase 2. This is an EPA requirement to account for the filtered blow-by emissions contribution along with exhaust emissions since the filtered blow-by is routed to the atmosphere in heavy heavy-duty trucks.

The combustion intake air was humidity and temperature controlled in accordance with CFR Part 1065. The CVS air was a HEPA filtered air drawn from outside the airconditioned laboratory envrionment outside the test cell. The constant volume sampler (CVS) was maintained at a nominal flow rate of 1650 sfm for all three engines tested in this program. The relative humdity was in the range of 40% to 60%, but was uncontrolled. The minimum dilution ratio between the engine exhaust and the 47 mm filter (CVS dilution mutiplied by 47 mm filter dilution) was set between a dilution ratio of 5 and 7 at rated engine power operation, in accordance with the new requirement in 40 CFR Part 1065. The minimum dilution ratio in ACES Phase 2 was nearly a factor of 2 lower than that used in ACES Phase 1 to enhance the detection limit of the emissions measurements and to conform to the latest minimum dilution ratio requirement in CFR Part 1065 that was still under development during ACES Phase 1. The average dilution ratio between the engine exhaust and the CVS for the FTP and 16-Hours was

between 5 and 8, depending on the engine used. The dilution ratio between the CVS tunnel and various filter locations such as the exposure chamber filters (M), auxiliary filters (I), 8 x 10 inch filter assembly (J) and 47 mm CFR Part 1065 filter (E) was set to a nominal dilution ratio of 2. For the urea collected compounds, a special sampling system was developed with no dilution ratio step between the CVS and the 90 mm filter (F). This was used to improve the detection limit of these compounds since they have high boiling point temperatures and the dilution ratio should have no effect on them. The dilution ratio DR is defined as: DR = (dilution air flow + sample flow)/(sample flow)

TABLE 3. LUBE OIL PROPERTIES FOR FRESH OIL AND AFTER 125 HOURS OF ENGINE AND DPF DEGREENING BY THE ENGINE MANUFACTURER

ASTM Test	Test Property / Description	Units	EM-3380-EO Fresh Lube Oil	EM-3382-EO Used Oil Engine X	EM-3381-EO Used Oil Engine Y	EM-3379-EO Used Oil Engine Z
D3524M	Fuel Dilution, Diesel	wt %		0.6	<0.3	<0.3
D4291	Glycol	ppm	<100	<100	<100	<100
D445	Viscosity @ 100 °C	cSt	15.38	13.37	14.18	13.56
D445	Viscosity @ 40 °C	cSt	116.8	97	103.8	101.4
D5185S	Sulfur by ICP	Wt. %	0.402	0.366	0.36	0.314
	Sulfur by ICP	ppm	4018	3660	3596	3144
D5185	Element Analysis					
	Aluminum	ppm	2	2	3	3
	Antimony	ppm	<1	<1	<1	2
	Barium	ppm	<1	<1	<1	3
	Boron	ppm	1	3	10	2
	Calcium	ppm	2233	2212	2022	2115
	Chromium	ppm	<1	<1	<1	<1
	Copper	ppm	<1	9	98	8
	Iron	ppm	2	13	17	15
	Lead	ppm	<1	2	<1	3
	Magnesium	ppm	6	71	190	112
	Manganese	ppm	<1	<1	2	6
	Molybdenum	ppm	<1	4	11	6
	Nickel	ppm	<1	3	1	<1
	Phosphorus	ppm	1020	981	969	964
	Silicon	ppm	4	30	4	30
	Silver	ppm	<1	<1	<1	<1
	Sodium	ppm	<5	5	5	8
	Tin	ppm	<1	<1	3	<1
	Zinc	ppm	1157	1187	1136	1168
	Potassium	ppm	6	<5	<5	<5
	Strontium	ppm	<1	<1	<1	<1
	Vanadium	ppm	<1	<1	<1	<1
	Titanium	ppm	<1	<1	<1	3
	Cadmium	ppm	<1	<1	<1	<1
D4739	Total Base Number					
	Inflection	mg KOH/g	7.74	6.18	6.78	6.62
	Buffer	mg KOH/g	7.62	4.91	5.5	5.83
D664	Total Acid Number					
	Inflection	mg KOH/g	N/A	N/A	N/A	N/A
	Buffer	mg KOH/g	1.25	1.94	1.94	1.85
E168	FTIR (Oxidation & Nitration)		0	2.83	2.37	0.67
	Diff. @ 5.8um	ABS/cm	0	0.09	0	0
	Diff. @ 6.1um	ABS/cm	0.7	0.7	0.8	0.7
TGA	Residue	wt %	0.109	0.41	0.473	0.339
	Volatiles	wt %	99.2	98.9	98.8	98.9
	Elemental Carbon	wt %		0.6	<0.3	<0.3



A Background bag sample of dilution air for CO, CO_2, NO_X, NO, NO_2, total hydrocarbon, CH_4, and C_2-C_{12} speciation. Impingers for Carbonyls & Alcohols

B 2010 Heavy-Duty Diesel Engine with DOC-DPF-SCR

C FTIR for NH_3 and N_2O measurements

D Proportional bag sample for hydrocarbon speciation of C_2-C_{12} compounds

E Regulated PM followed CFR Part 1065 using 47mm Teflon membrane filter (Whatman). The same filter is also used for elemental analysis using EDXRF and ICP-MS

F 90mm TX-40 filter system, which will be used for particle phase urea-related compounds (Urea, melamine, cyanuric acid, ammelide and ammeline

G Sorbent traps for nitrosamines and Summa canister for SVOC

H Impingers for carbonyls using DNPH, alcohols using de-ionized water, cyanide ions using KOH, SO_2 using H_2O_2, and NH_3+ using H_2SO_4

I Auxiliary PM samples on 47mm filters for inorganic ions (TX-40 filter), DFI GC/SOF (TX-40 filter)

J Filter (8"x10" Zefluor) for particulate-phase semi-volatile compounds: PAH, oxyPAH, nitroPAH, dioxins, furans, hopanes, steranes, carpanes, polar organics, high molecular weight alkines and cycloalkanes, dioxins, furans. Four XAD traps for gas phase semi-volatile compounds: PAH, oxyPAH, nitroPAH, hopanes, steranes, carpanes, polar organics, high molecular weight alkanes and cycloalkanes, dioxins, furans

K Horiba MEXA 7200 for total hydrocarbon, CH_4, CO, CO_2, Nox, and NO measurements

L PM mass size and number using EEPS, real time total PM using DMM-230, real time soot using MSS, NO Measurement using chemiluminescent analyzer

M PM mass using Teflon membrane filter (Whatman), OC/EC collection using a pair of quartz filters

FIGURE 2. ACES PHASE 2 OVERALL SAMPLING SYSTEM

3.0 TEST MATRIX

Table 4 shows the series of tests that were performed for each of the three ACES Phase 2 engines. The first series of regulated emissions testing is to confirm the engine emission levels with the engine manufacturer and to ensure that the engine compares well to the emissions produced or expected by the engine manufacturer. It also serves the purpose of conditioning the engine and emission control system prior to starting the official regulated and unregulated emissions testing. Table 5 shows the detailed breakdown of the test matrix for each engine tested, along with the length of each test cycle. Table 6 shows the measurements done for each test performed on each engine. Table 6 also shows the sample location for each of the measurement. The CFR Part 1065 filter, exposure chamber, auxiliary filters, and the 8" by 10" filter and XADs assembly had a similar dilution ratio of about 2 relative to the CVS. They also had a similar mixing time on the order of one second. Figures 3 and 4 show the percent normalized torque and speed profiles for the different cycles used in ACES Phase 2. Normalized engine torque is defined as the actual torque over the maximum torque produced by the engine at the designated speed. Normalized engine speed is defined as (actual speed – warm-idle speed)/(max speed – warm-idle speed).

TABLE 4. NUMBER OF REGULATED AND UNREGULATED EMISSIONS TESTS FOR EACH ENGINE

Cycle	Regulated Pollutants	Unregulated
Mode 1, rated speed, 100% load	3	[a, b]
Mode 3, rated speed, 50% load	3	[a, b]
Mode 5, peak torque speed, 100% load	3	[a, b]
One Cold-Start + three Hot-Start FTP	4	[a ,b]
Hot-Start FTP	3	3
16-Hour	3	3
Tunnel Blanks [c, d]	3 for Engine X and 2 for others	3 for Engine X and 2 for others
16-Hour for Dioxins/Furans [e]		1
16-Hour Tunnel Background for Dioxins/Furans[f]		1

[a] Only real time particle size, number, total mass, and soot mass were performed for these tests.
[b] Data to be shared with each engine manufacturer to make sure that the engine emissions performance complied with the manufacturer's expectation and to get approval to proceed with the program.
[c] Tunnel blank is a 20-minute test run exactly like an engine FTP test, except the engine is off.
[d] One tunnel blank after cleaning CVS tunnel but before running the engine. A second tunnel blank after finishing the three hot-start FTP runs. A third tunnel blank after finishing the three 16-Hours.
[e] Dioxins and furans were collected separately for 16 hours on Engines X, Y, and Z using 8 x 10 Zefluor filters followed by four XAD traps.
[f] Tunnel background is a 16-Hour test where samples are taken from the dilution air immediately downstream of the CVS HEPA filter.

TABLE 5. DETAILED MATRIX FOR EACH ACES ENGINE

Test	Regulated Pollutants (No. of Runs)	Unregulated (No. of Runs)	Cycle Length
Tunnel Blank No. 1	1	1	20 minutes
Mode 1	3	[a]	20 minutes
Mode 3	3	[a]	20 minutes
Mode 5	3	[a]	20 minutes
Cold-Start followed by three Hot-Start FTP	4	[a]	20 minutes
Tunnel Blank No. 2	1	1	20 minutes
Hot-Start FTP	3	3	20 minutes
16-Hour [b] Day 1&2 (Three Repeats)	1	1	16 hours
Day 3&4	1	1	16 hours
Day 5&6	1	1	16 hours
Tunnel Blank No. 3	1	1	20 minutes
16-Hour for Dioxins&Furans [c] Day 7&8		1	16 hours
Tunnel Background for Dioxins&Furans[c]	N/A	1	16 hours

[a] Only real time particle size, number, total mass, and soot mass were taken from exposure chamber.
[b] Each 16-Hour (four runs of 4-hour segments), accumulates over a two-day period (two 4-hour segments per day). Days 1, 3, 5, and 7 begins as a hot-start after warm-up, and Days 2, 4, 6, and 8 begins as a cold-start
[c] For each engine, one 16-Hour engine cycle and one 16-Hour background test were collected for dioxins & furans analysis.

TABLE 6. SAMPLING/ANALYSIS MATRIX FOR REGULATED AND UNREGULATED EMISSIONS ON EACH ENGINE

Parameter; Analytical Method(s)	Media	FTP Hot Start	16-Hr Transient Cycle	Tunnel Blank	16-Hr Tunnel Background	Background Corrected[a]?	Sample Location
Total Hydrocarbon (THC), CH_4	FID	3	3	3	0	Yes	CVS tunnel
Oxides of Nitrogen (NO_X)	Chemi-luminescent	3	3	3	0	Yes	CVS tunnel
Carbon Monoxide (CO)	NDIR	3	3	3	0	Yes	CVS tunnel
Particulate Matter (PM), elements and metals (XRF, ICPMS)	47 mm Teflon® membrane Whatman filter	3	3	3	0	No	CVS+dilution step of ~2 (CFR Part 1065, 47°C)
Particulate Matter	47 mm Teflon® membrane Whatman filter	3	3	3	0	No	Exposure Chamber[b] (~28°C)
Nitrogen Dioxide ($NO2$)	Chemi-luminescent	3	3	3	0	Yes	CVS tunnel
N_2O, NH_3	FTIR	3	3	3	0	No	Engine Exhaust
OC/EC	47 mm Quartz filter	3	3	3	0	No	Exposure Chamber[b]
SOF/DFIGC	47 mm TX-40 Filter	3	3	3	0	No	
Particle Size and Number	EEPS	3	3	3	0	No	Exposure Chamber[b]
Real Time PM	DMM-230	3	3	3	0	No	Exposure Chamber[b]
Inorganic ions and acids; IC	47 mm TX-40® filter, DI Water Impinger	3	3	3	0	No	CVS+dilution step of ~2
NH_4^+; IC	47 mm TX-40 filter, H_2SO_4 impinger	3	3	3	0	No	CVS+dilution step of ~2
pH, H^+; pH, Titration	DI Water Impinger	3	3	3	0	No	CVS tunnel
Cyanide, Cr(VI) ; colorimetric	KOH Impinger	3	3	3	0	No	CVS tunnel
SO_2; IC	H_2O_2 Impinger	3	3	3	0	No	CVS tunnel
Gas phase hydrocarbons (C_2–C_{12});GC-FID	Tedlar® Bag	3	3	3	0	Yes	CVS tunnel
Carbonyl compounds; HPLC-UV	DNPH Impinger	3	3	3	0	Yes	CVS tunnel
Alcohols; GC-FID	DI Water Impinger	3	3	3	0	Yes	CVS tunnel
Dioxins and Furans; HRGC/HRMS	Zefluor® Filter + XAD® Cartridge	0	1	0	1	Yes	CVS+dilution step of 2
Selected VOCs; GC/MS	SUMMA® Canister	3	3	3	0	No	CVS tunnel
PAH; GC/MS	Zefluor® Filter + XAD® Cartridge	3	3	3	0	No	CVS+dilution step of 2
nitroPAH; GC/MS		3	3	3	0	No	CVS+dilution step of 2
Hopane/Steranes/Carpanes; GC/MS		3	3	3	0	No	CVS+dilution step of 2
Alkanes, Alkenes, Alkynes, Cyclo- and branched (C_{14}-C_{40}); GC/MS		3	3	3	0	No	CVS+dilution step of 2
Polar compounds, Oxygenated PAH, Organic Acids; GC/MS		3	3	3	0	No	CVS+dilution step of 2
Nitrosamines; GC/MS	Thermosorb®	3	3	3	0	No	CVS tunnel
Urea Compounds	90 mm TX-40 Filter	0	3	0	0	No	CVS tunnel

[a] Background corrected means that a sample of the background dilution air taken from downstream of the HEPA filter in the CVS tunnel is analyzed for the same species concentration measured in the dilute exhaust, and then subtracted from the dilute exhaust species concentration using the following equation: Xbgc=Xm –(1-1/DR)*Xbg, where Xbgc is the corrected concentration, Xm is the measured concentration, and Xbg is the background concentration of the species of interest.

[b] The dilution ratio between the CVS tunnel and exposure chamber was ~2.

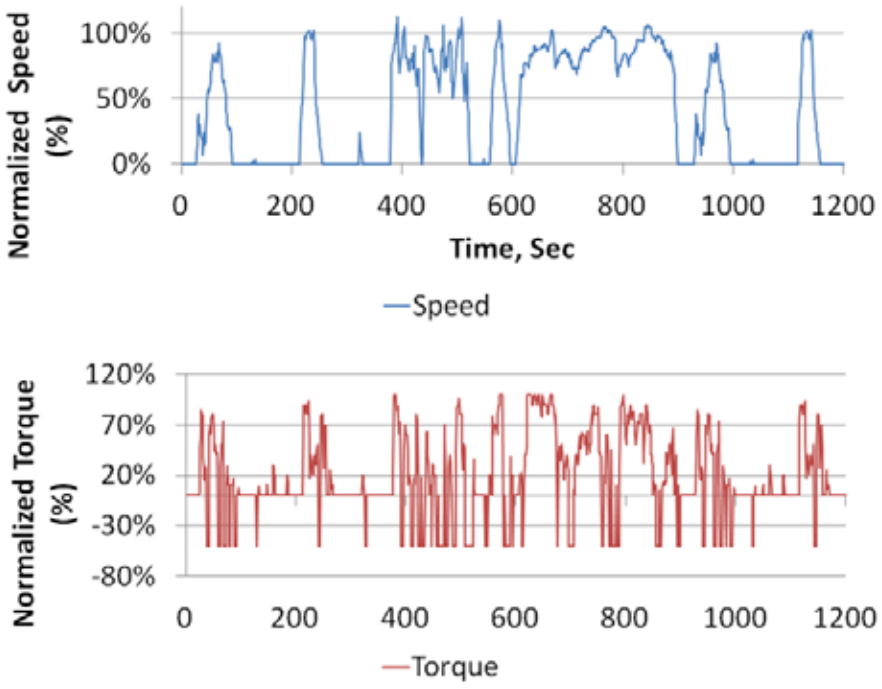


FIGURE 3. EXAMPLE OF FTP NORMALIZED SPEED AND TORQUE PROFILES

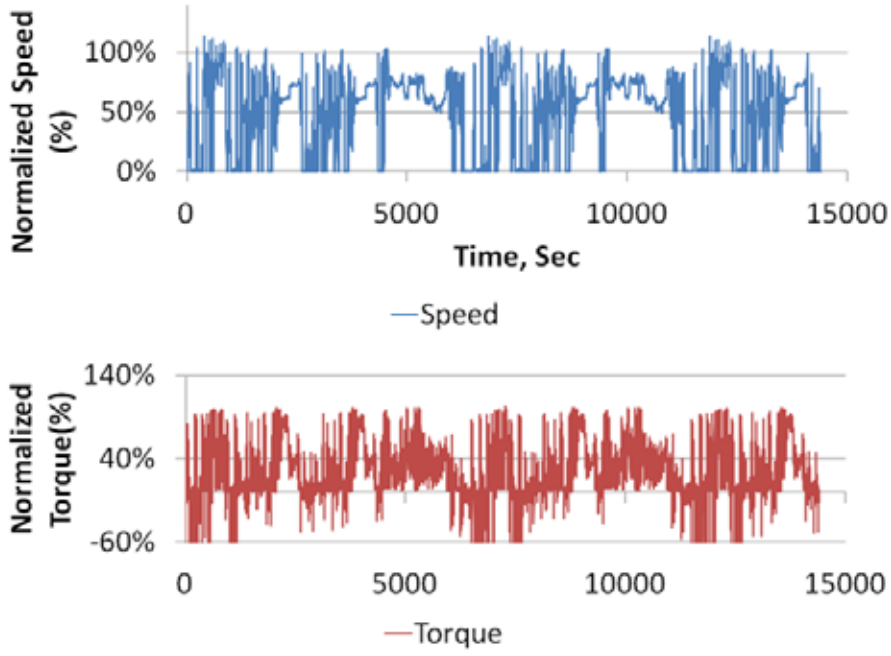


FIGURE 4. EXAMPLE OF FOUR-HOUR REPEATED SEGMENTS OF THE NORMALIZED SPEED AND TORQUE PROFILES FOR THE 16-HOUR

4.0 SPECIES AND ANALYTICAL TECHNIQUES

4.1 Regulated Emissions Measurements

Regulated emissions including NO_x, CO, and non-methane hydrocarbons (NMHC) were measured in the CVS in accordance with CFR Part 1065 using a Horiba MEXA-7200 emission bench. NO_x was measured using the chemiluminescent detection method. CO was measured using the non-dispersive infrared detection method, and NMHC was determined by taking the difference between CVS total hydrocarbons (THC) measurement and methane measurement using a non-methane cutter and the flame ionization detection method. For diesel engine test, heated sample line is required for NO_X and NMHC, and heated FID is required for NMHC.

Regulated PM was measured using a single Teflon® membrane filter (Whatman), 47 mm in diameter that is maintained at $47^oC \pm 5^oC$ in accordance with CFR Part 1065. The nominal dilution ratio between the filter and the CVS tunnel was 2. The filter face velocity was maintained close to 100 cm/sec. The filter room used for filter conditioning and weighing was maintained in accordance with CFR Part 1065 requirements. The filter weighing procedure includes three filter pre and three filter post weights. The averages of the pre and post weights were used to determine the filter weight gain. In Project E-66, SwRI demonstrated a filter weighing variability of less than ±2.5 μg (one standard deviation) using Teflon® membrane filters. Since then, our typical variability is within less than ±1 μg for three repeated weighings.

4.2 Sampling and Analysis of Unregulated Emissions

Analysis of unregulated emissions was performed by SwRI, DRI, and ORNL. A summary of analytical responsibilities and notes on methodology are presented in Table 7.

Greenhouse gases of methane, CO_2, and N_2O were measured. They are unregulated for 2010 engines but subject to EPA emissions standards starting with 2014 model year engines. CO_2 was measured in the CVS using the non-dispersive infrared detection method. Methane was measured in the CVS using the FID method. N_2O was measured in engine exhaust using a Fourier Transform Infrared (FTIR) detector.

SwRI determined particle and gas phase ions by ion chromatography. Selected air pollutants were analyzed using gas chromatography/mass spectrometry (GC/MS). Speciation of C_1 through C_{12} hydrocarbons including alcohols, aldehydes, and ketones was performed using GC and high performance liquid chromatography (HPLC). Fourier transform infrared spectroscopy (FTIR) was used primarily for continuous monitoring of N_2O and NH_3. SwRI utilized dual chemiluminescent NO_x detectors, one operating in NO mode and one in NO_x mode, so an accurate determination of NO_2 could be made as the difference between NO_x and NO. Cyanide samples were collected in impingers and analyzed by an automated colorimetric procedure. Dioxins and furans samples were collected on an 8 by 10-inch Zefluor filter followed by four XAD traps, and were analyzed in accordance with EPA Method 8290 using high resolution gas chromatography (HRGC) and high resolution mass spectroscopy (HRMS).

For sampling in the animal exposure chamber, real-time particle size distribution was measured using the TSI engine exhaust particle sizer (EEPS); real time PM mass was measured

with the Dekati DMM-230; and real time soot mass was measured with the AVL micro-soot sensor (MSS). OC and EC were collected from the exposure chamber on 47 mm quartz filters.

DRI provided analyses for hopanes, steranes, polar compounds, heavy alkanes (>C_{12}), polycyclic aromatic hydrocarbons (PAH), nitroPAH, oxyPAH, organic acids, and any unresolved complex mixtures, which were collected on an 8 by 10-inch Zefluor filter followed by four XAD traps. DRI provided analyses for OC/EC and nitrosamines, as well as metals and elements, which were analyzed by energy dispersive X-ray fluorescence (EDXRF) spectroscopy and induced coupled plasma mass spectroscopy (ICPMS).

ORNL provided analyses for particle phase urea related compounds that were collected on a 90 mm TX-40 filter during the 16-Hour. The nominal flow rate was 12 scfm targeting a filter face velocity of 100 cm/sec.

4.2.1 Filter and XAD Sample Collection for Chemical Analysis

For the collection of filter and XAD® samples for chemical analyses of semi-volatile compounds, SwRI used a large supplemental secondary dilution tunnel that permitted the use of an 8 by 10-inch (203 by 254 mm) Zefluor® filter followed by four 4-inch diameter XAD® cartridges that were sampled in parallel, downstream of the filter. The nominal flow rate through the filter and four XAD® cartridges was about 1700 slpm.

TABLE 7. SUMMARY OF ANALYSIS METHODOLOGY AND RESPONSIBILITY

Analyte Class	Notes	Method	Laboratory
Regulated Emissions	Dilute Exhaust	Various	SwRI
CO_2	Dilute Exhaust	NDIR	SwRI
CH_4	Dilute Exhaust	FID	SwRI
N_2O, NH_3	Raw Exhaust	FTIR	SwRI
Real Time PM	Size, Number, Soot mass, total mass	EEPS, DMM, MSS	SwRI
Sulfate, Nitrate, Ammonium ions	Water Impinger (4 slpm), 47 mm TX-40 filter (58 slpm)	IC	SwRI
Fuel/Oil PM Contribution (DFI/GC), and SOF	47 mm TX-40 filter, selected samples only, 58 slpm	DFI/GC	SwRI
Hydrogen Ion	H^+, water impinger, 4 slpm	Titration	SwRI
Cyanide Ion	KOH Impinger, 4 slpm	Colorimetry	SwRI
VOC ($C_1 - C_{12}$)	Tedlar® bag	GC/FID	SwRI
Carbonyl compounds	DNPH impinger, 4 slpm	HPLC	SwRI
Alcohols	DI water impinger, 4 slpm	GC/FID	SwRI
SO_2	H_2O_2 impinger, 4 slpm	IC	SwRI
NH_4^+	H_2SO_4 impinger, 4 slpm	IC	SwRI
Other Ions	De-ionized water impinger, 4 slpm	IC	SwRI
Selected VOCs	SUMMA Canister	GC/MS	SwRI
Dioxins/Furans	8 x 10 inch Zefluor filter followed by four XAD traps. One sample and one tunnel background per engine, on 16-hr integrated sample, gas- and particle-phase extracts analyzed together, 1700 slpm	GC/MS	SwRI
Real Time Total PM	1Hz, 10 slpm	DMM-230	SwRI
Real Time Soot	1Hz, 2 slpm	MSS	SwRI
Real Time PM Size and Number	1Hz, 10 slpm	EEPS	SwRI
Metals and Elements	47 mm Teflo® filter, 28 slpm	EDXRF/ICPMS	DRI
PAH	Gas- and particle-phase extracts analyzed together, except 16-Hour integrated sample, 1700 slpm	GC/MS	DRI
NitroPAH	Gas- and particle-phase extracts analyzed together, except 16-Hour integrated sample, 1700 slpm	GC/MS	DRI
Hopanes, Steranes	Gas- and particle-phase extracts analyzed together, except 16-Hour integrated sample, 1700 slpm	GC/MS	DRI
Polar compounds	Gas- and particle-phase extracts analyzed together, except 16-Hour integrated sample, 1700 slpm	GC/MS	DRI
Other SVOC (C_{14}-C_{40}) and unresolved complex mixtures	Gas- and particle-phase extracts analyzed together, except 16-Hour integrated sample, 1700 slpm	GC/MS	DRI
Nitrosamines	Thermosorb N®, 1 slpm	GC/MS	DRI
OC/EC	Quartz filters, 58 slpm	TOR and TOT	DRI
Particle Phase Urea Compounds	90 mm Zefluor Filter, ~300 slpm	APCI-MS	ORNL

4.2.2 Ions and Inorganic Acids

Samples were collected in impingers containing a potassium hydroxide solution and analyzed for cyanide ion pursuant of a colorimetric procedure described in EPA Method 335.4, "Determination of Total Cyanide by Semi-Automated Colorimetry."

Hexavalent chromium Cr(VI) was collected using a modified EPA Method 061 and analyzed by EPA 7199. Similar to cyanide, an impinger filled with a potassium hydroxide solution was used to collect the Cr(VI), and the impinger solution was subsequently analyzed by ion chromatography.

Anions and cations (NH_4^+, NO_2^-, NO_3^-, SO_4^{2-}), and inorganic acids (HNO_2, HNO_3, H_2SO_4) samples were collected on TX-40 filters, utilizing water and dilute sulfuric acid impingers. Filters were extracted to remove the analytes of interest, and the extract was analyzed using ion chromatography (IC). Impinger solutions were analyzed by IC as well; however, it is not possible to differentiate between anions and cations from ionic species versus inorganic acids. In addition, it should be noted that NO_2 passing through water may form HNO_2 and HNO_3. A titration to determine the H^+ concentration was performed, and the pH was measured.

4.2.3 Metals and Elements

Filter samples were analyzed with ICPMS and EDXRF to ensure that analyses for all required elements were covered with adequate detection limits. The CFR Part 1065 Teflon membrane filter was used for these analyses. The filter was sampling from the CVS with a dilution ratio of ~2 between the filter and the CVS tunnel.

The particulate filters for ICPMS metals analysis were digested with high purity acids. The majority of the metals were analyzed via ICPMS using EPA SW-846 Method 6020 to get the lowest possible detection limits. Blank filters were analyzed to assess any contribution from the media and the extraction/digestion solutions.

The ICPMS instrument was standardized using NIST traceable standard reference materials. Prior to analyzing any samples, the standardization was verified with a second NIST traceable reference material. This second standard was from a different lot or manufacturer than the first standardization material. Immediately after the second standard was run, a blank was run to verify the zero setting. The second standard was required to be within 90-110 percent recovery of the certified value. The absolute value of the check blank was required to be below the reporting limit for the analyte. If either condition was not met, the analysis would be terminated and the instrument re-standardized and re-checked. The standard and check blank were re-run after every 10 samples, and at the end of the run to ensure that the instrument remains in control throughout the entire run. If a standard falls out of the control limits, the analysis was terminated, the instrument re-standardized, and all samples since the last compliant standard were re-run. As an internal check, duplicate analyses were performed on approximately ten percent of samples, selected at random.

4.2.4 Selected Volatile Organic Compounds

Samples for the selected volatile organic compounds (nitromethane, nitropropane, hydrogen sulfide, carbonyl sulfide), were collected in sample bags and sorbent traps specific to the analytes. They were analyzed by GC/MS. SwRI Test and Analysis Procedures TAP 0404014 and 0404015 were utilized. TAP 0404014 is based upon EPA method TO-15, which uses a combination of multi-sorbent tubes and cryogenic focusing for sample concentration with subsequent analysis by GC/MS. TAP 0404015 is based upon SW-846 Method 5040 and covers the determination of volatile organic compounds (VOCs), collected on Tenax® and Tenax®/charcoal sorbent cartridges using a volatile organic sampling train (VOST). This method was utilized in conjunction with an appropriate analytical method, SW-846 8240, Volatile Analysis by GC/MS. Because a majority of gas streams sampled using VOST will contain a high concentration of water, the analytical method is based on the quantitative thermal desorption of volatile compounds from the Tenax® and Tenax®/charcoal traps with analysis by purge and trap GC/MS. The contents of the sorbent cartridges are spiked with an internal standard/surrogate solution and thermally desorbed with organic free nitrogen or helium, bubbled through organic-free water and trapped on an analytical absorbent trap. After the purge, the analytical trap is dry purged for two additional minutes, then heated rapidly to 240°C, with the carrier flow reversed so the effluent flow from the analytical trap is directed to the GC/MS. The VOCs are separated by temperature-programmed gas chromatography and detected by low-resolution mass spectrometry. The concentrations of VOCs are calculated using the internal standard technique. Tunnel blank samples were collected for each analyte as specified in Table 5.

4.2.5 Hydrocarbon Speciation of C_2 Through C_{12} Compounds

Vapor phase C_2 to C_{12} hydrocarbon species were sampled with Tedlar® bags from the CVS tunnel. Analyses of these samples were conducted within five to 10 minutes after collection to avoid degradation of the more reactive species, such as 1,3-butadiene. Carbonyls and alcohols were sampled from the CVS tunnel utilizing impingers. Alcohols were collected in impingers filled with deionized water, and carbonyls with a solution of dinitrophenylhydrazine (DNPH) in acetonitrile. To minimize degradation, aldehyde samples were analyzed as soon as the sampling was completed.

The analytical procedures used for conducting hydrocarbon speciation (C_2 to C_{12} hydrocarbons, aldehydes and ketones, and alcohols) were similar to the CRC Auto/Oil Phase II protocols. With these methods, exhaust emissions samples were analyzed for the presence of more than 200 different exhaust species. Four GC procedures and one HPLC procedure were used to identify and quantify compounds. A brief description of these procedures is given below.

The first GC procedure uses a 15 m x 0.53 mm I.D. DB-WAX (1μm film) pre-column and a 50 m x 0.53 mm I.D. (10 femtometer film) Alumina PLOT/KCI (Carbopack®) column to permit the separation and determination of exhaust concentrations of C_1-C_4 individual hydrocarbon species, including ethane, ethylene, acetylene, propane, propylene, propadiene, butane, trans-2-butene, 1-butyne, and cis-2-butene. Bag samples are analyzed using a gas chromatograph equipped with a flame ionization detector (FID). The gas chromatograph system utilizes two analytical columns. The carrier gas is helium. An external multiple component standard in zero air is used to quantify the results. Detection limits for the procedure are on the order of 5 ppbC in dilute exhaust for all compounds.

The second GC procedure uses a 60 m x 0.32 mm I.D. (10 μm film) DB-1 column to provide separation and exhaust concentrations for more than 100 C_5-C_{12} individual HC compounds. Bag samples are analyzed using a gas chromatograph equipped with a flame ionization detector (FID). The GC system utilizes a FID, a pneumatically operated and electrically controlled valve, and an analytical column. The carrier gas is helium. An external multiple component standard in zero air is used to quantify the results. Detection limits for the procedure are on the order of 10 ppbC in dilute exhaust for all compounds.

The third GC procedure uses a separate system configured similarly to the second GC method to determine individual concentrations of benzene and toluene according to CRC Auto/Oil Phase II Protocols. The third GC utilizes a 30 m x 0.25 mm I.D. (0.25 μm film) DB-5 column instead of a DB-1 column.

The fourth GC is used for alcohols. For alcohols, sample collection was performed by bubbling diluted exhaust through deionized water in a series of impingers. An aliquot of the solution was subsequently analyzed for alcohols using a gas chromatograph equipped with a flame ionization detector. External standards were used to quantify the results.

An HPLC with a Zorbax® octadecasilane (ODS) column was utilized for the analyses of aldehydes and ketones. Samples were collected in impingers with a solution of DNPH in acetonitrile. For analyses, a portion of the acetonitrile solution was injected into a liquid chromatograph equipped with an ultraviolet (UV) detector. External standards of the aldehyde and ketone DNPH derivatives were used to quantify the results.

4.2.6 Dioxins and Furans

As discussed above, sampling for dioxins and furans utilized an 8 by 10-inch Zefluor® filter followed by four 4 inch XAD cartridges. The dilution ratio between the CVS and the filter/XAD assembly was about 2. This approach is required to achieve the extremely low detection limits required for these analytes. The analytical protocol followed for analysis of dioxins and furans (PCDD or PCDF) is EPA Method 8290. The instruments include a Fisons AutoSpec Ultima high resolution gas chromatograph/high resolution mass spectrometer (HRGC/HRMS), a Micromass AutoSpec HRGC/HRMS, and a Micromass AutoSpec Premier HRGC/HRMS. The sample was spiked with a solution containing specified amounts of each of the nine isotopically ($^{13}C_{12}$) labeled PCDDs/PCDFs listed in the method. The sample was extracted according to a matrix-specific extraction procedure and analyzed. A tunnel background sample was collected as specified in Table 5.

4.2.7 Elemental Carbon/Organic Carbon

PM from the animal exposure chamber were collected on a primary and a backup quartz filter. Those filters were provided by DRI after being pre-fired at 900°C to remove organic contaminants. Quartz fiber filters absorb organic gases from ambient air and organic artifacts from the manufacturing process. By pre-firing the quartz filters before sampling, the absorbed gases and artifacts are reduced to constant insignificant levels. After collection, the filters were analyzed for OC/EC by DRI using the thermal optical reflectance (TOR) and the thermal optical transmittance (TOT) methods. This is a thermal desorption process subjecting the filters to

temperatures between 25°C and 800°C. The results are reported using the primary filter only similar to what was done during ACES Phase 1.

4.2.8 Particulate- and Gas-Phase Organic Compounds

Among the many particulate and semi-volatile organic compounds (SVOC) are the following groups of compounds: PAH, oxyPAH, nitroPAH, hopanes/steranes, higher molecular weight alkanes, cycloalkanes, higher molecular weight aromatics, certain polar organic compounds, and unresolved complex mixtures. Sampling was performed with an 8 by 10 inch Zefluor PM filter followed by four, 4-inch traps containing XAD-4 resin. The dilution ratio between the CVS and the filter/XAD assembly was about 2.

Sampling materials were prepared by DRI and shipped to SwRI. Prior to shipping, XAD-4 resins were extracted with methanol followed by dichloromethane (CH_2Cl_2), using an Accelerated Solvent Extractor (Dionex 3000). The cleaned resin was dried in a vacuum oven heated to 40 ºC and stored in sealed glass containers in a clean freezer. The filters were cleaned by sonification in CH_2Cl_2 for 30 minutes, followed by another 30-minute sonification in methanol. The filters were then dried, placed in aluminum foil, and labeled. Each batch of pre-cleaned XAD-4 resin and approximately 10 percent of pre-cleaned filters were checked for purity by solvent extraction and GC/MS analysis of the extracts. The XAD-4 resins were assembled into glass cartridges (20 g of XAD) and stored in a clean freezer prior to shipment to SwRI.

All samples returned from SwRI to DRI were stored in a freezer prior to extraction. All samples were extracted within two weeks of being received at DRI.

Prior to extraction, the following deuterated internal standards were added to each filter and XAD sorbent: naphthalene-d8, biphenyl-d10, acenaphthene-d10, phenanthrene-d10, anthracene-d10, pyrene-d12, benz(a)anthracene-d12, chrysene-d12, benzo[e]pyrene-d12, benzo[a]pyrene-d12, benzo[g,h,i]perylene-d12, coronene-d12, cholestane-d6, hexadecane-d34, eicosane-d42, hexatriacontane-d74, 2-nitrodiphenyl-d9, 1-nitropyrne-d9, benzoic-d6 acid, phthalic 3,4,5,6-d4 acid, hexanoic-d11 acid, heptadecanoic-d33 acid, and myristic-d27 acid.

Filters and XAD-4 resins were extracted with dichloromethane using the Dionex ASE followed by acetone extraction under the same conditions. The dichloromethane extraction method has been reported to yield high recovery of PAH[8] and nitroPAH[9,10]. Dichloromethane extraction followed by acetone also gives good recovery for PAH, aliphatic hydrocarbons, cycloalkanes, hopanes, steranes, and polar organic compounds.

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[8] Chuang, J.C., M.R. Kuhlman, and N. Wilson, "Evaluation of methods for simultaneous collection and determination of nicotine and polynuclear aromatic hydrocarbons in indoor air," *Environ. Sci. Technol.,* **24**, 661-665, 2006.

[9] Atkinson, R., J. Arey, A.M. Winer and B. Zielinska, "A survey of ambient concentrations of selected polycyclic aromatic hydrocarbons (PAH) at various locations in California." Final Report, prepared under Contract No. A5-185-32, for the California Air Resources Board, Sacramento, CA, by Statewide Air Pollution Research Center, University of California, Riverside, CA, 1988.

[10] Zielinska, B., J. Arey, R. Atkinson, and A.M. Winer, "The nitroarenes of molecular weight 247 in ambient particulate samples collected in Southern California," *Atmos. Environ.,* **23,** 223-229, 1989.

All extracts were then concentrated by rotary evaporation at 35°C under gentle vacuum to approximately 1 mL and filtered through a 0.2 μm PTFE disposal filter device (Whatman Pura discTM 25TF), rinsing the flask 3 times with 1 mL dichloromethane and acetone (50/50 by volume) each time. The extract was split into two fractions (polar and non-polar analyses) and was solvent exchanged to acetonitrile under ultra-high purity nitrogen.

The extracts were analyzed first by GC/MS for higher molecular weight (C>15) aliphatic hydrocarbons and cycloalkanes. Subsequently, the extracts were pre-cleaned by the solid-phase extraction technique. Superclean LC-SI SPE cartridges (Supelco) were sequentially eluted with hexane, and hexane/benzene (1:1). The hexane fraction contains the non-polar aliphatic hydrocarbons (alkanes), and hopanes and steranes, and the hexane/benzene fraction contains PAH and nitroPAH. These two fractions are concentrated to approximately 100 μL and analyzed by GC/MS for hopanes, steranes, PAH and oxyPAH. For nitroPAH, the extracts are further pre-cleaned by the solid-phase extraction technique, using aminopropyl (NH2) SPE cartridges (Waters), with sequential elution with hexane/DCM, 98/2 v/v and hexane/DCM 80/20 v/v. For nitro- and dinitroPAH analysis, these fractions are further cleaned by semi-preparative normal-phase high performance liquid chromatography (HPLC) technique (Waters). The Chromegabond Amino Cyano 25 cm x 9.6 mm column (ES Industries, West Berlin, NJ) and isocratic elution with 20 percent DCM in hexane was used. The fraction corresponding to nitro- and dinitroPAH was collected and analyzed by negative ion chemical ionization GC/MS. The fraction for the polar analysis is derivatized using a mixture of bis(trimethylsilyl)trifluoroacetamide and pyridine to convert the polar compounds into their trimethylsilyl derivatives for analysis of organic acids, phenol and cresol.

The filters and XAD® extracts were analyzed by GC/MS, using a Varian CP-3800 GC equipped with a CP8400 auto sampler and interfaced to a Varian 4000 Ion Trap. Due to the high sensitivity of Ion Trap MS, it was used for analysis of all gas-phase and particulate phase organic compounds, with the exception of the nitroPAH compounds, which utilized the electron impact (EI) ionization method. Injections (1 μL) were made in the splitless mode onto a 30m 5 percent phenylmethylsilicone fused-silica capillary column (DB-5ms, J&W Scientific or equivalent). Quantification of the individual compounds was obtained by the selective ion storage (SIS) technique, monitoring the molecular (or the most characteristic) ion of each compound of interest and the corresponding deuterated internal standard. Calibration curves for the GC/MS quantification were made for the most abundant and characteristic ion peaks of the compounds of interest using the deuterated species most closely matched in volatility and retention characteristics as internal standards. National Institute of Standards and Technology (NIST) Standard Reference Material (SRM) 1647 (certified PAH) with the addition of deuterated internal standards and of those compounds not present in the SRM (i.e., oxyPAH, nitroPAH, hopanes, steranes, carpanes, hydrocarbons, cycloalkanes) were used to make calibration solutions. A six- to eight-level calibration was performed for each compound of interest and the calibration check (using median calibration standards) was run every 10 samples to check for accuracy of analyses. If the relative accuracy of measurement (defined as a percentage difference from the standard value) was greater than 20 percent, the instrument was recalibrated.

NitroPAH compounds were analyzed using the Varian 1200 triple quadruple gas chromatograph/mass spectrometer (GC/MS/MS) system with a CP-8400 auto sampler. The tandem MS/MS system allows for structural elucidation of unknown compounds with precursor, product and neutral loss scan. The GC interface allows for sensitive analyses of complex

mixtures in electron impact (EI) as well as positive and negative chemical ionization (CI) mode. Negative CI offers superior sensitivity for the analysis of nitroPAH (approximately 100 times higher than EI or positive CI) that could be emitted from combustion sources, including motor vehicle engines. The sensitivity of this instrument in full scan EI/MS mode was approximately 1 pg/µl with a 20:1 signal-to-noise ratio (S/N). In EI/MS SIM mode it reaches 50 fg/ul with a 10:1 S/N. For negative CI, 10 fg/ul of octafluoronaphthalene gives an S/N of 20:1. This superior sensitivity offers the advantage of analyzing small samples collected during a short sampling time.

4.2.9 Nitrosamines

Nitrosamines were collected on Thermosorb/N adsorbent cartridges using a Teflon® sample probe. Samples are quantified using modified EPA Method TO-7, which specifies analyses by GC/MS. The cartridge samples were collected from the CVS tunnel. The cartridges were eluted with a mixture of 25 percent methanol and 75 percent dichloromethane. The first 1.8 ml was collected for the GC/MS analyses, using negative CI mode. Injections (1 ul) are made in the splitless mode onto a CP WAX 51 capillary column (25 m long, 0.25 mm id). Quantification of the individual compounds was obtained by the multiple ion detection (MID) technique, monitoring the molecular ion of each compound of interest and the corresponding deuterated internal standard.

As to the modifications - the elution solvent was 25% methanol and 75% dichloromethane, instead of acetone and no dichloromethane pre-elution was used. Also, DRI used their new, very sensitive GC/MS – Scion TQ (triple quad) interfaced to 456 GC and fitted with Chrompack CPWAX 51 capillary column (25 m long, 0.25 mm id). They also used chemical ionization (CI) with methane and single ion monitoring (SIM) technique. Deuterated nitrosodiethylamine (d10) was used as internal standard for nitrosoamines quantification. The total volume was about 20 liter for the FTP, and 240 liter for the 16-Hour. The total volume was less than the maximum volume of 300 liter, recommended for the TO-7 method.

4.2.10 Particle Phase Urea-Related Compounds

Particle phase urea-related compounds such as urea, melamine, cyanuric acid, ammelide, ammeline, and biuret were analyzed by ORNL using atmospheric pressure chemical ionization mass spectroscopy (APCI-MS). The materials were extracted from a 90 mm TX-40 (Teflon coated borosilicate glass fiber filter) sample filter that was used to collect PM from the CVS tunnel during the 16-Hour. The nominal flow through the filter was set to 340 lpm, resulting in a filter face velocity close to a 100 cm/sec. This high flow increased the chance of detecting these compounds if they exist at a detection limit of 5 µg/filter.

Urea and its common decomposition products can be separated into acids and bases. Urea and melamine are bases and cyanuric acid, ammelide, and ammeline are acids. Urea and melamine are soluble in formic acid solutions and form $M\text{-}H^+$ ions by positive atmospheric pressure chemical ionization (APCI). Cyanuric acid, ammelide and ammeline are soluble in diethyl amine solutions and form M^- ions by negative APCI-MS. Below is a description of the extraction method:

- Extraction method:
  - Each filter was cut into two pieces.
  - Acid extraction
    - 1 ml of a 0.5% formic acid in 50:50 methanol:water
    - Sonicate 20 minutes
    - Extract is spiked with arginine (I.S.) and analyzed by APCI-MS
  - Base extraction
    - 1ml of a 0.5% diethyl amine in 50:50 methanol:water
    - Sonicate for 20 minutes
    - Extract is spiked with lactic acid (I.S.) and analyzed by APCI-MS

For the APCI-MS parameters, samples were infused urea and melamine were analyzed in positive ion mode and cyanuric acid, ammelide, and ammeline were analyzed in negative ion mode. Some of the characteristics of the APCI-MS used for the urea-related compounds by ORNL are shown below:

- Bruker Ion Trap MS-MS with electrospray ionization and APCI sources at FEERC
  - model year 2001; 2005 software update
- Direct infusion of solution
- Low fragmentation by ionization process
  - important because low end mass is 60 amu so fragments might be too small
- Discrimination between positive and negative ionization can identify functional groups
- Can switch between positive and negative ion mode without changing other mass spec parameters
- May be possible to identify size of complexes (i.e. number of melamine and cyanuric acid units)

4.2.11 Real Time PM Size, Number, Total and Soot Mass

Each of the instruments described below was cleaned and flow-calibrated prior to any engine testing. All instruments were set up to collect from the exposure chamber.

Particle size distribution and number concentration was measured using a TSI EEPS, as shown in Figure 5. The instrument covers a particle size range from 5.6 nm to 560 nm, and reports the full size distribution measurement on a 10 Hz basis. The principle of operation is to charge particles and mobilize them to deposit on a series of electrometers, each representing a narrow particle size range. The current reading from each electrometer is converted to number concentration.

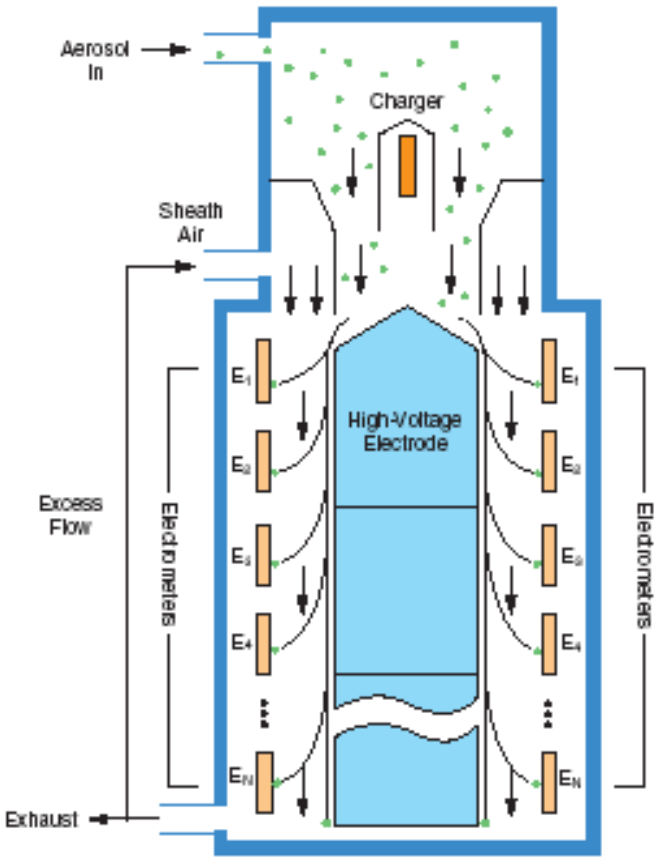

FIGURE 5. TSI ENGINE EXHAUST PARTICLE SIZER (EEPS)

The Dekati DMM-230, shown in Figure 6, was used for real time total particle mass emission measurement on a 1 Hz basis. The principle of operation is to charge particles and deposit the sub-30 nm particles on an electrometer by electric mobility and the rest of the particles on a series of electrometer stages by inertial impaction, with each electrometer representing a narrow aerodynamic size range. The current reading from each electrometer stage is converted into mass concentration using an average apparent density. The apparent density is determined by overlaying the calculated mobility diameter size distribution on top of the aerodynamic diameter size measured distribution.

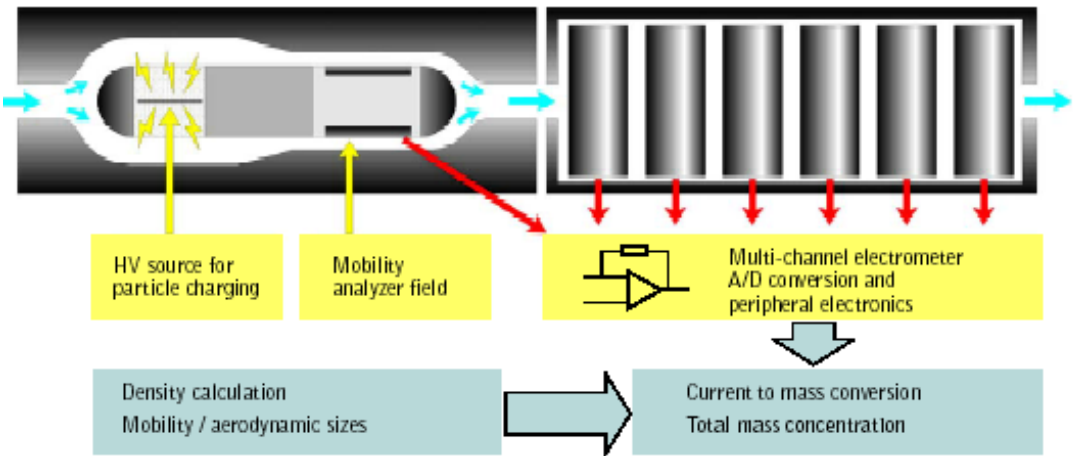

FIGURE 6. DEKATI MASS MONITOR (DMM-230)

An AVL micro-soot sensor (MSS), shown in Figure 7, was used for real time soot mass emission measurement on a 1 Hz basis. This instrument is widely used in engine emission activities focusing on the measurement of soot. The principle of operation is to slightly heat soot particles with a pulsed laser beam so the soot particles can heat the surrounding gas and generate a sound wave that can be detected by a sensitive microphone. The magnitude of the electric signal generated by the microphone is correlated with the mass concentration of soot.

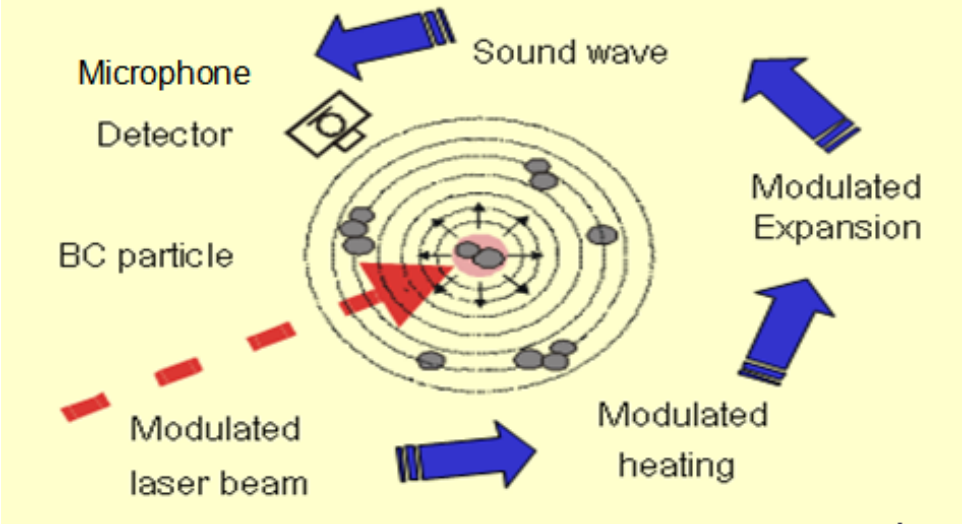

FIGURE 7. AVL MICRO-SOOT SENSOR (MSS)

5.0 PROCEDURES

5.1 Important Procedural Differences from ACES Phase 1

The following two sub-sections focus on important procedural differences between ACES Phase 2 and ACES Phase 1 that may have impact on emissions. Other procedural differences include the additional measurement of ammonia and urea-related compounds in ACES Phase 2. The potential presence of these compounds is derived from the use of urea-based SCR catalyst in the exhaust of 2010 technology engines. This is why their measurement was added to ACES Phase 2. One more difference was the CVS operation, where the average CVS dilution ratio in ACES Phase 2 was about half that of ACES Phase 1. This was done to adhere to CFR Part 1065 minimum dilution ratio requirement, as discussed in Section 2.3. This also helps improving the detection limit of various compounds. The dilution steps between the CVS and various other systems were kept at a nominal dilution ratio of 2, similar to that used in ACES Phase 1. Thus, with the reduced average CVS dilution ratio (5 to 8) by half, all other dilution ratios in exposure chamber, CFR Part 1065 filter, semivolatile filter assembly and auxiliary filter assembly was also reduced by half.

5.1.1 DPF Active Regeneration with 2010 Engines

In ACES Phase 1 testing of 2007 technology engines, the DPF actively regenerated on its own through a command from the engine control module (ECM) one to three times during the 16-Hour, depending on the engine used. To minimize variability in engine emissions and ensure consistency among engines using a common baseline, we performed a forced active regeneration on the DPF prior to starting a 16-Hour. Such a strategy did not prevent the capturing of emissions during a full cycle of DPF operation that included particle loading and active regeneration of at least once per 16-Hour.

Due to improvement in engine and aftertreatment emissions control, 2010 engines self-trigger much less frequent active DPF regenerations, compared to 2007 technology engines. As a result, no active DPF regeneration was expected to take place in a 16-Hour. Since there was a high degree of interest in capturing emissions on cycles with and without DPF active regenerations, the ACES panel endorsed the idea of removing any forced active regeneration between the three 16-Hour runs used in official testing to increase the probability of encountering an active DPF regeneration in one of them. While this approach did not guarantee the occurrence of an active regeneration, it was the best approach to implement on this program without changing the original scope of work. But, even with this approach, no active regeneration was encountered during the 16-Hour testing of the 2010-compliant engines. This was a distinct difference between ACES Phase 1 and ACES Phase 2.

5.1.2 Engine Preconditioning Prior to Official Testing

In ACES Phase 1, we performed forced active regeneration of the DPF followed by an overnight soak, prior to official testing of the cold-start/hot-start FTP. This was done for consistency among engines and to avoid active regeneration from occurring during an official FTP. For engines equipped with SCR catalysts, ammonia storage by the SCR catalyst at low temperature is a key in reducing cold-start NO_X emissions. Thus, the history of the SCR catalyst prior to a cold-start FTP or a hot-start FTP can affect NO_X emissions substantially. A forced

active regeneration of the DPF prior to official testing, similar to that done in ACES Phase 1, may deprive the SCR catalyst from stored ammonia due to high exhaust temperature. If the SCR catalyst has no stored ammonia prior to a cold-start FTP, the engine might fail the standard on NO_X. To avoid such issue that was under discussion between EMA and EPA, under the Emission Measurement and Testing Committee (EMTC), we used an approach where we conditioned the aftertreatment system using a forced active regeneration followed by three runs of the FTP. This strategy was intended to equilibrate the catalyst with some ammonia storage prior to official testing to avoid failing NO_X emissions. So, in ACES Phase 2 work, the engine and emission control system were conditioned prior to any official cold-start and hot-start FTP testing using the following conditioning strategy:

1. Perform a forced DPF active regeneration to clean the DPF
2. Run three back-to-back hot-start FTP to condition the SCR Catalyst with ammonia storage
3. Shut down the engine for an overnight soak
4. Run a cold-start followed by a hot-start FTP for official emission reporting

The forced active regeneration was triggered by the engine ECM using the manufacturer proprietary software. A set of instructions were given by each manufacturer to SwRI for the forced active regeneration procedure. The time for forced active regeneration took between 20 to 40 minutes, depending on the engine being tested. The end of regeneration was dictated by the engine ECM. The procedures for forced active regeneration were similar to those used in ACES Phase 1. The time it took to complete an active regeneration was also similar.

For the hot-start FTP for regulated and unregulated emissions measurement, we ran Step 1 and Step 2 above, and then started official testing. For the 16-Hour, Day 1 was run as a hot-start after conditioning using Step 1 and Step 2 above and Day 2 continued as a cold-start after an overnight soak. For the second and third 16-Hour runs (Day 3, 4, 5, and 6), Step 1 and Step 2 were omitted to increase the probability of active DPF regeneration as discussed in Section 5.1.1.

For dioxins and furans (Day 7 and 8) Steps 1 and 2 were performed prior to starting the 16-Hour. Since only one 16-Hour is run per engine for dioxins and furans, the ACES panel agreed to perform a forced DPF active regeneration prior to any testing for to ensure better consistency among engines.

5.2 Full Flow Constant Volume Sampler Tunnel Cleanup and Conditioning

Similar to what was done in ACES Phase 1 project prior to test cell engine installation, a thorough full flow CVS tunnel cleaning was performed in ACES Phase 2. Due to the very low PM and unregulated emission levels expected from the 2010 engines, it was important to clean the internal surface of the tunnel to remove any adsorbed material that could interfere with PM and unregulated emissions measurements. Volatile and semi-volatile materials that may have adsorbed onto the internal surface of the tunnel or the surface of particles could desorb during an engine run or when sampling a tunnel blank. The tunnel was completely removed from the test cell and cleaned using a small amount of Simple Green detergent and power washed and rinsed using water. According to the manufacturer's Material Safety Data Sheet(MSDS)[11], it is

[11]

composed of water (≥78%), 2-butoxyethanol (≤5%), ethoxylate alcohol (≤5%), tetrapotassium pyrophosphate (≤5%), sodium citrate (≤5%), fragrance (≤1%), colorant (≤1%).

5.3 Step-By-Step Procedure for Testing

In ACES Phase 2, we adhered to a specific test procedure for all engines and cycles tested. This is to make sure that all engines and cycles were run in a similar manner for a particular engine and among all three engines. All testing was done with engine blow-by routed to a location downstream of the SCR catalyst, in accordance with CFR Part 1065. Similar to ACES Phase 1, three hot-start FTP and three 16-Hour were run for regulated and unregulated emissions, and one 16-Hour was run for dioxins and furans collection. The reason for the separate 16-Hour for dioxins and furans is because the extraction and analyses for dioxins and furans were done at SwRI and the rest of the semi-volatile extraction and analyses were done at DRI.

Table 8 shows the step-by-step procedure for conducting the official regulated and unregulated testing for each 2010-compliant engine. This is similar to what was used in ACES Phase 1, except for the differences discussed above.

TABLE 8. STEP-BY-STEP PROCEDURES

Steps	Action Items
1	Clean CVS tunnel (done only once before the first engine)
2	Set CVS flows as required by CFR Part 1065
3	Perform all necessary calibration required under CFR Part 1065
4	*Generate a tunnel blank with a sampling time of 20 minutes before any engine exhaust run through the tunnel*
5	Install engine in test cell
6	Power validate engine and compare the performance with that declared by the manufacturer
7	If Step 6 is acceptable, proceed to Step 8, otherwise resolve the performance issues with the engine manufacturer
8	Generate an engine torque map at wide open throttle in accordance with CFR Part 1065
9	Run practice FTP, and perform the necessary tuning to pass cycle statistics
10	Perform "forced" active DPF regeneration followed by three back-to-back hot-start FTP to condition the engine and emission control system
11	Perform three repeats of Mode 1, Mode 3, and Mode 5 taking regulated emissions with selected real time particle measurement in exposure chamber (EEPS, DMM-230, MSS)
12	Repeat Step 10 and soak the engine overnight. Perform a cold-start FTP followed by three hot-start transient cycles and measure regulated emissions along with EEPS, DMM-230, and MSS measurements in exposure chamber. Shut down the engine for 20 minutes in between cycles
13	Compare all regulated brake specific emissions with those determined by the manufacturer
14	Resolve the differences, if any, between SwRI and the manufacturer results and proceed with the emission characterization
15	Condition engine and sampling system by performing a "forced" active DPF regeneration followed by three back-to-back hot-start FTPs
16	Perform three hot-start FTP cycles with 20 minutes engine-off soak between cycles. Sample for all regulated and unregulated emission species on each run.
18	*Generate a tunnel blank with a sampling time of 20 minutes similar to that in Step 4*
19	Condition engine and sampling system by performing a "forced" active DPF regeneration followed by three hot-start FTP
20	Perform one 16-Hour over a period of two days. Sample for all regulated and unregulated emissions. On day 1, warm up engine and bring it to idle for 15 minutes then run two 4-hour hot-start segments of the 16-Hour with 15 minutes idle time in between segments, followed by an overnight shut-down. On day 2, run a cold-start for the first 4-hour segment, bring the engine to low idle for 15 minutes, and then run another 4-hour segment, and shut down engine
21	Repeat Step 20 twice for Day 3&4 and for Day 5&6 , but without Step 19
22	Repeat Step 19, and then Repeat Step 20 one more time and collect for dioxins/furans analysis only using Day 7 and Day 8
23	*Generate a tunnel blank with a sampling time of 20 minutes similar to that in Step 4*
24	*Generate a tunnel background for 16 hours while sampling as in Step 22 only*
26	*Repeats Steps 5 through 24 for Engine Y*
27	*Repeats Steps 5 through 24 for Engine Z*
***Warm-Up Procedure**: Start-up engine and run it at intermediate speed, 50% load, until the coolant thermostat open. Run engine at rated power for 5 minutes, then bring it down to idle, before you start a test.*	

6.0 RESULTS

Because the power rating, displacement volume, and the engine model are known, we excluded from this report any information on cycle work and other related variables so the engines designated as Engine X, Y, and Z can remain anonymous. All detailed regulated and unregulated emissions species will be accessed through a CRC database that is available to the public along with this report.

This results section includes information on the regulated and unregulated emissions from each of the engines tested. Also, we include emissions comparisons between 2010 technology engines used in ACES Phase 2 and 2007 technology engines used in ACES Phase 1, where applicable. The main focus will be on the three repeats of the hot-start FTP and the three repeats of the 16-Hour performed on each engine. However, prior to proceeding with the results section, it is important to show that the engines are in full compliance with the respective EPA standards based on the FTP cold-start and hot-start composite that is typically used for engine certification in the laboratory.

Table 9 and Figure 8 summarize the FTP composite results for regulated emissions for Engines X, Y, and Z, along with % reduction relative to the 2010 standards. All of the engines' emissions were well below the 2010 standard. NO_X reduction ranged from 24% for Engine Y to 67% and 76% for Engine X and Z, respectively. The reduction in CO ranged from 91% for Engine X to 99% and 100% for Engines Y and Z, respectively. The reduction in NMHC was a 100% and the reduction in PM ranged from 84% for Engine Z to 97% for Engines Y and Z. Using Table 9 to determine the average emissions from all three engines, the emissions reductions relative to the 2010 standard were 61%, 97%, 100%, and 92% for NO_X, CO, NMHC, and PM, respectively. This demonstrates that there is a very good margin of compliance relative to the 2010 standards.

TABLE 9. SUMMARY OF FTP COMPOSITE REGULATED EMISSIONS

Engine X, g/hp-hr					
	Cold FTP	Hot FTP	Composite	2010	% Reduction
	102_C1	103_H1	1/7C+6/7 hot	Standard	Rel. 2010 Std.
NOX	0.301	0.026	0.065	0.200	67%
CO	2.84	1.07	1.32	15.50	91%
NMHC	0.000	0.000	0.000	0.140	100%
BSPM	0.0001	0.0003	0.0003	0.0100	97%
Engine Y, g/hp-hr					
	Cold FTP	Hot FTP	Composite	2010	% Reduction
	Y_259_C1	Y_260_H1	1/7C+6/7 hot	Standard	Rel. 2010 Std.
NOX	0.490	0.096	0.153	0.200	24%
CO	0.62	0.06	0.143	15.50	99%
NMHC	0.002	0.000	0.000	0.140	100%
BSPM	0.0004	0.0003	0.000	0.0100	97%
Engine Z, g/hp-hr					
	Cold FTP	Hot FTP	Composite	2010	% Reduction
	Z_283_C1	Z_284_H1	1/7C+6/7 hot	Standard	Rel. 2010 Std.
NOX	0.268	0.012	0.049	0.200	76%
CO	0.16	0.03	0.05	15.50	100%
NMHC	0.000	0.000	0.000	0.140	100%
BSPM	0.0066	0.0008	0.0016	0.0100	84%

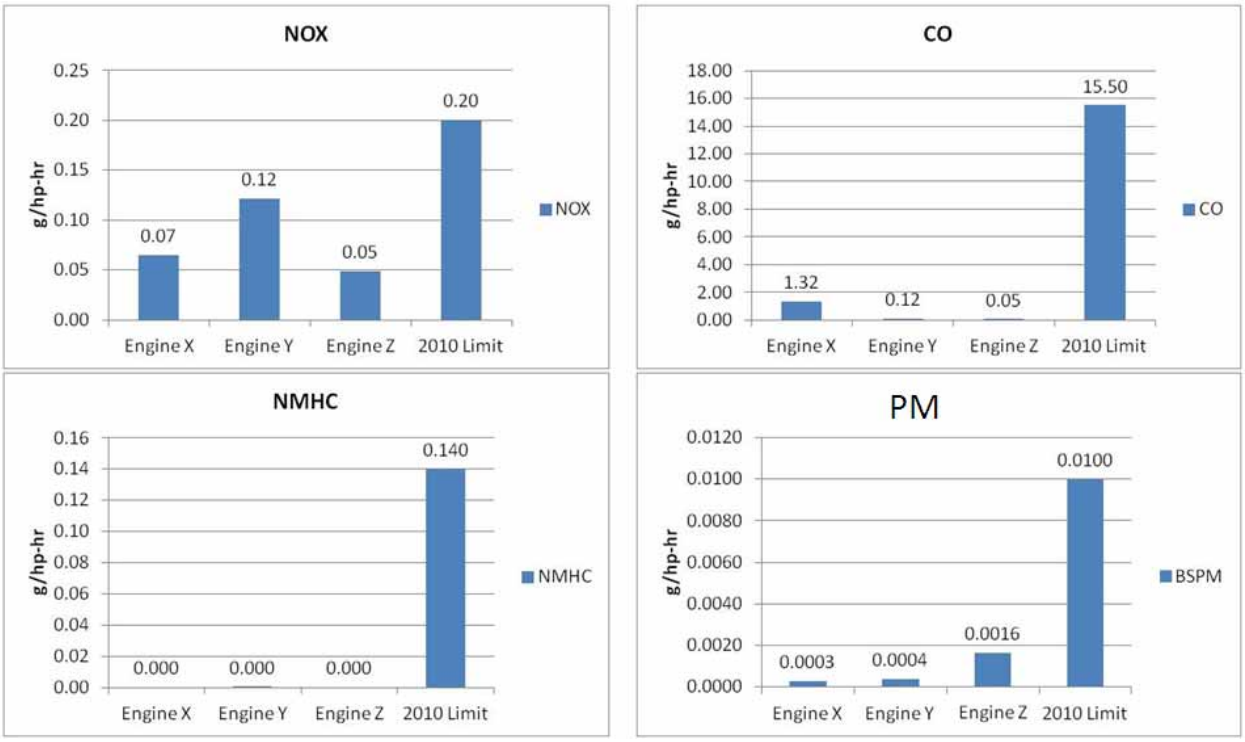

FIGURE 8. REGULATED EMISSIONS FOR FTP COLD- AND HOT-START COMPOSITE

6.1 Nitrogen Oxides (NO_X), Nitrogen Dioxide (NO_2), Nitrous Oxide (N_2O), and Ammonia (NH_3) Emissions

Figures 9 and 10 show a summary of the results for NO_X and NO_2 during the hot-start FTP and the 16-Hour. NO_X is a regulated emissions species that includes NO and NO_2. The 2010 emissions limit for NO_X is 0.20 g/hp-hr for the cold/hot start FTP composite. As can be seen from Figure 9, the NO_X emissions for the hot-start FTP were substantially below the 2010 standard, demonstrating the strong effectiveness of the SCR system in reducing NO_X under hot-start conditions. The 16-Hour resulted in higher NO_X emissions compared to the FTP, most likely due to the low temperature segments of the cycle (Idle and Creep) and the fact that the cycle had a cold-start portion, during which the SCR catalyst may not be very effective in reducing NO_X. As we saw with the 2007 technology engines, the majority of NO_X was in the form of NO_2 due to NO oxidation over the DOC. NO_2 is desirable downstream of the DOC since it acts as a low temperature EC oxidant in the DPF leading to passive DPF regeneration. NO_2 is also the desired species to have at the inlet of the SCR since SCR catalysts favor the reduction of NO_2 over NO. As can be seen from Figure 10, NO_2 was absent for Engine X and Engine Z for the FTP, while constituting a high percentage (60%) of the NO_X level for Engine Y during the FTP and for all engines during the 16-Hour ranging from 33% to 69%.

Another byproduct of SCR/AMOX NO_X control is N_2O emissions species (Figure 11), which is a strong greenhouse gas. Some of the NO_X reduction over the SCR or NH_3 reduction over the AMOX may lead to N_2O formation. N_2O as a percent of NO_X was higher than that of NO_2. N_2O will be regulated in 2014 with an emission limit of 0.1 g/hp-hr based on the FTP cold/hot start composite. The N_2O limit is a "cap" standard designed to prevent major increases in N_2O. It is also required for up to an EPA specified engine useful life[12]. It was set at approximately twice the level of N_2O emissions from 2008 heavy-duty diesel and gasoline engines. The Engine X and Engine Z N_2O emissions were well below the 2014 limit based on the hot-start FTP, and Engine Y was about 12 percent above the limit. The average emissions ranged from 0.052 g/hp-hr and 0.054 g/hp-hr for Engines X and Z to 0.11 g/hp-hr for Engine Y. Figure 12 shows the average N_2O emissions for ACES Phase 2 (2010 Technology) and ACES Phase 1 (2007 Technology) engines relative to the 2014 limit. It can be observed from Figure 12 that the 2010 technology engines on average had a much higher N_2O emissions than the 2007 technology engines, but the emissions are still 26% to 31% below the 2014 standard of 0.1 g/hp-hr.

NH_3 is another important byproduct of the urea-SCR NO_X control strategy. NH_3 is the ultimate required urea decomposition product needed to reduce NO_X. Without ammonia production, NO_X reduction will not take place. Some of the NH_3 that is produced slips past the SCR catalyst and makes it to engine exhaust. To reduce ammonia slip, an ammonia slip catalyst (AMOX) was used downstream of the SCR with all 2010 technology engines tested in ACES Phase 2. Figure 13 shows the NH_3 emissions on a brake-specific emissions basis during the hot-start FTP and the 16-Hour, although there is no regulation for ammonia comparison. In the EU and perhaps later in the US, there are discussions underway to limit average exhaust ammonia slip to no more than 10 ppm to 15 ppm. Table 10 summarizes the NH_3 concentration in engine exhaust. The average NH_3 concentration ranged from 0.124 ppm for Engine X to 0.465 ppm and 0.647 ppm for Engine Y and Z, respectively. Similar trends were observed for the 16-Hour but

[12] CFR 76, 179 page 57176, September 15, 2011

the level was higher in the range from 0.422 ppm to 1.369 ppm. Regardless of the cycle used, the NH_3 concentrations were well below a potential standard at 10 ppm or 15 ppm level.

Test Cycle		NOx, g/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	0.016	0.072	0.023
	2	0.014	0.073	0.019
	3	0.013	0.080	0.019
	Avg	0.014	0.075	0.020
	Stdev	0.002	0.004	0.002
	COV	12%	6%	11%
16-Hour	1	0.058	0.106	0.072
	2	0.062	0.131	0.063
	3	0.060	0.123	0.057
	Avg	0.060	0.120	0.064
	Stdev	0.002	0.013	0.008
	COV	4%	11%	12%

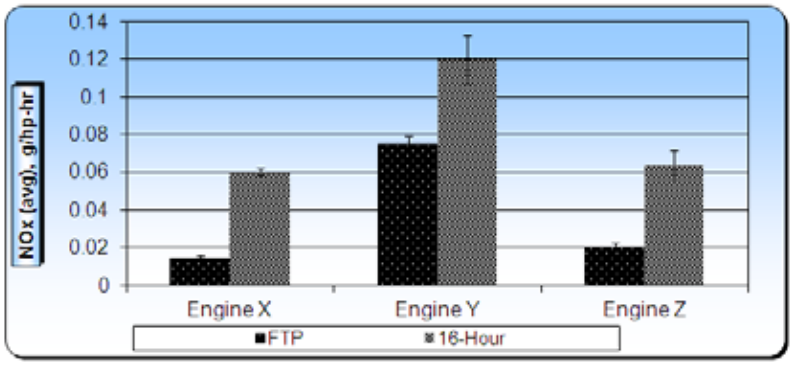

FIGURE 9. NO_X EMISSIONS FOR THE HOT-START FTP AND 16-HOUR

Test Cycle		NO2, g/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	0.000	0.046	0.000
	2	0.000	0.043	0.000
	3	0.000	0.047	0.000
	Avg	0.000	0.045	0.000
	Stdev	0.000	0.002	0.000
	COV	na	4%	na
16-Hour	1	0.019	0.072	0.040
	2	0.021	0.087	0.032
	3	0.021	0.091	0.031
	Avg	0.020	0.083	0.034
	Stdev	0.001	0.010	0.005
	COV	5%	12%	15%

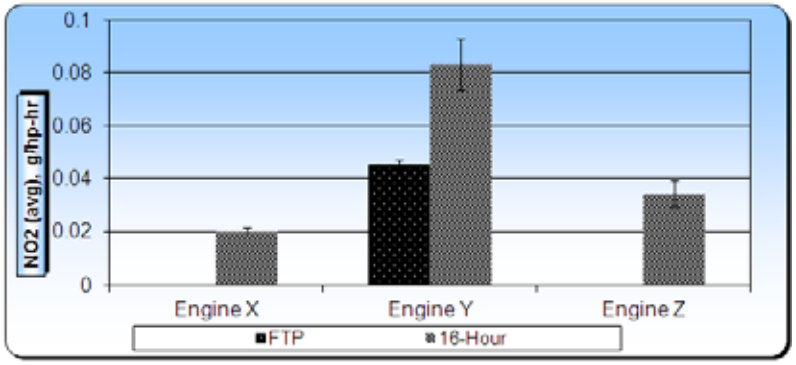

FIGURE 10. NO_2 EMISSIONS FOR THE HOT-START FTP AND 16-HOUR

Test Cycle		N2O, g/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	0.050	0.122	0.034
	2	0.054	0.114	0.038
	3	0.052	0.109	0.043
	Avg	0.052	0.115	0.038
	Stdev	0.002	0.007	0.004
	COV	4%	6%	11%
16-Hour	1	0.053	0.113	0.057
	2	0.054	0.110	0.049
	3	0.056	0.116	0.049
	Avg	0.054	0.113	0.052
	Stdev	0.002	0.003	0.005
	COV	3%	3%	9%

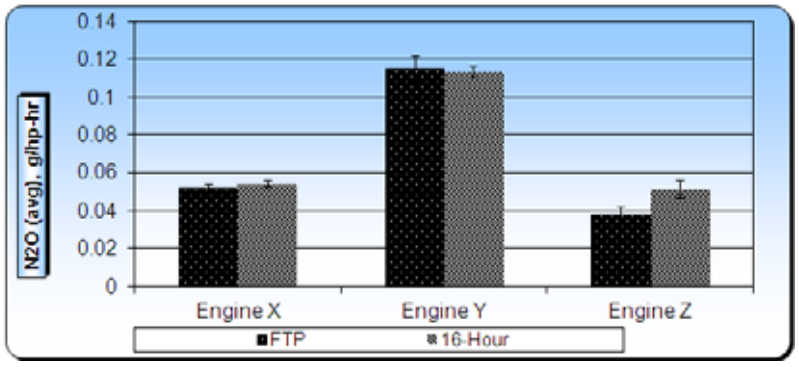

FIGURE 11. N_2O EMISSIONS FOR THE HOT-START FTP AND 16-HOUR

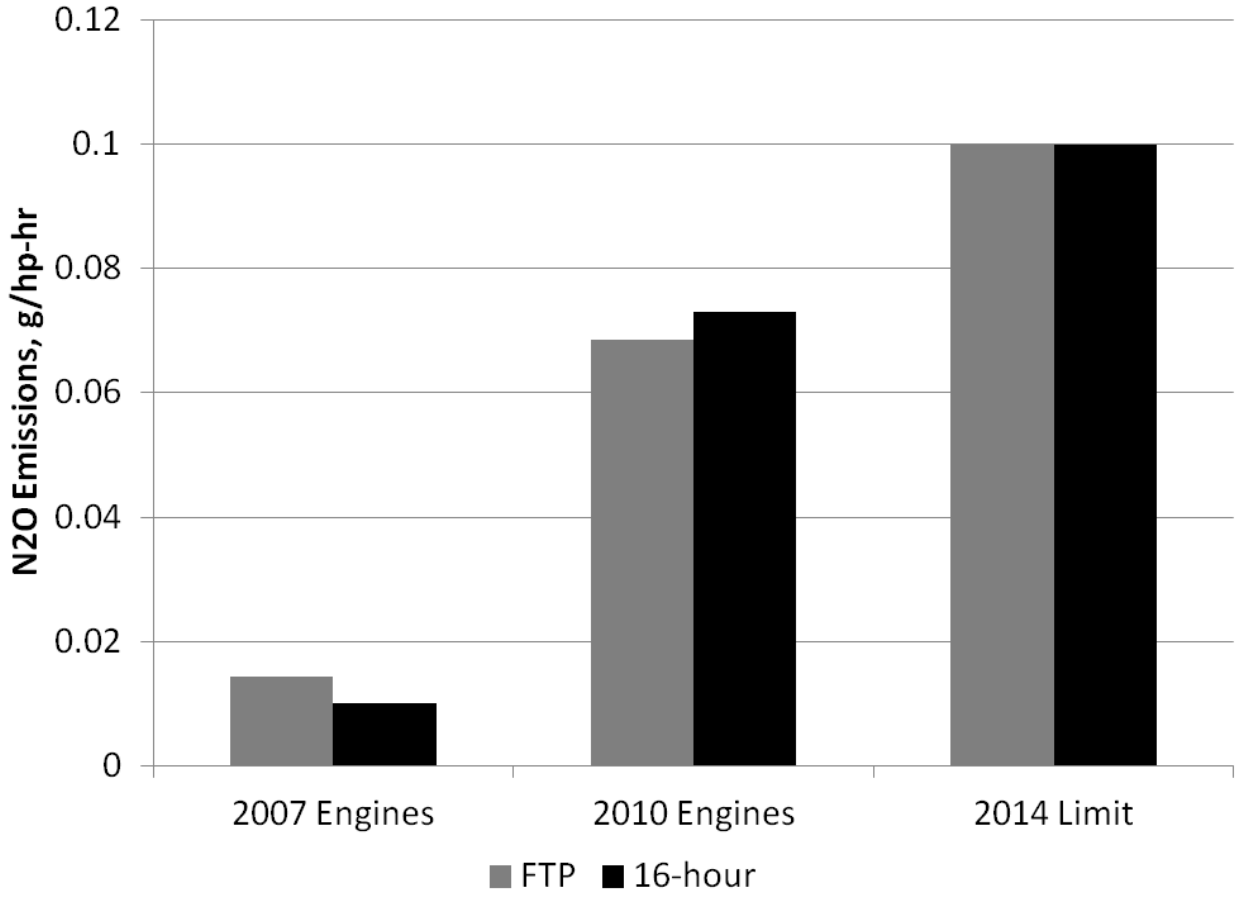

FIGURE 12. COMPARISON BETWEEN 2007 AND 2010 N_2O EMISSIONS AND THE 2014 LIMIT (LIMIT APPLIES ONLY TO COLD/HOT COMPOSITE OF THE FTP)

Test Cycle		NH3, g/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	0.000	0.004	0.003
	2	0.000	0.002	0.004
	3	0.001	0.002	0.004
	Avg	0.000	0.003	0.004
	Stdev	0.000	0.001	0.000
	COV	87%	39%	14%
16-Hour	1	0.001	0.002	0.004
	2	0.001	0.002	0.004
	3	0.001	0.003	0.004
	Avg	0.001	0.002	0.004
	Stdev	0.000	0.000	0.000
	COV	10%	22%	3%

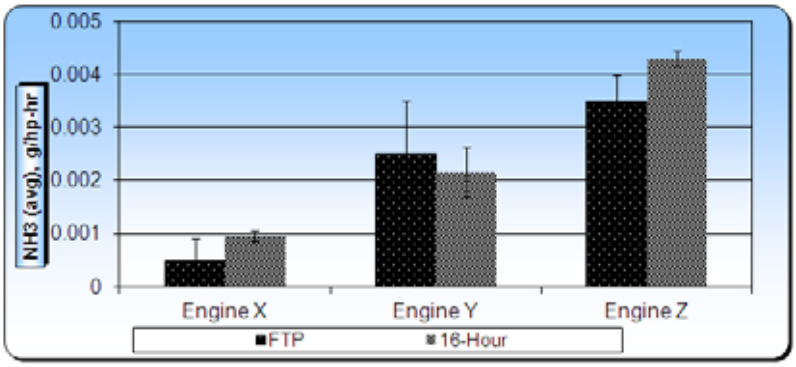

FIGURE 13. NH_3 EMISSIONS FOR THE HOT-START FTP AND 16-HOUR

TABLE 10. NH_3 CONCENTRATION IN ENGINE EXHAUST

Test Cycle		NH3, ppmv		
		Engine X	Engine Y	Engine Z
FTP	1	0.021	0.672	0.549
	2	0.116	0.398	0.668
	3	0.235	0.325	0.724
	Avg	**0.124**	**0.465**	**0.647**
	Stdev	**0.107**	**0.183**	**0.090**
	COV	**87%**	**39%**	**14%**
16-Hour	1	0.396	0.613	1.415
	2	0.396	0.588	1.368
	3	0.473	0.824	1.323
	Avg	**0.422**	**0.675**	**1.369**
	Stdev	**0.044**	**0.130**	**0.046**
	COV	**11%**	**19%**	**3%**

6.2 Carbon Monoxide (CO) Emissions

The 2010 CO emission standard is 15.5 g/hp-hr. Figure 14 shows the brake-specific CO emissions for all three engines. Overall, CO emissions were much lower than the standard for all engines under both cycles. In diesel engines, CO engine-out emissions are typically very low. The aftertreatment systems, especially the DOC and DPF, oxidize CO into CO_2 and bring it further down to a very low level. Although the emissions are low, there is still variation among the different engines tested.

Test Cycle		CO, g/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	0.069	0.032	0.026
	2	0.070	0.032	0.023
	3	0.073	0.033	0.020
	Avg	0.071	0.033	0.023
	Stdev	0.002	0.001	0.003
	COV	2%	2%	11%
16-Hour	1	0.091	0.046	0.020
	2	0.098	0.050	0.024
	3	0.098	0.049	0.024
	Avg	0.096	0.048	0.023
	Stdev	0.004	0.002	0.002
	COV	4%	4%	10%

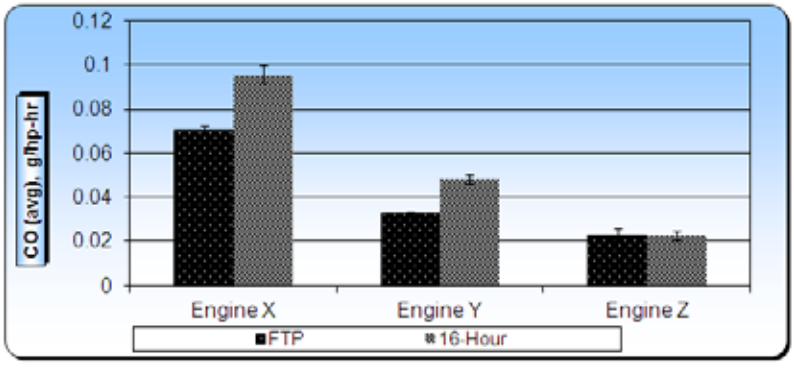

FIGURE 14. CO EMISSIONS FOR THE HOT-START FTP AND 16-HOUR

6.3 Total Hydrocarbon (THC), Methane (CH_4), and Non-Methane Hydrocarbon (NMHC) Emissions

The NMHC emission standard for 2010 is 0.14 g/hp-hr. NMHC was determined by taking the difference between the measurement of THC and CH_4. Table 11 shows the brake-specific emissions for THC, CH_4, and NMHC, respectively. Except for the very low emissions of THC and NMHC with Engine X for the FTP, hydrocarbon emissions measured in accordance with EPA CFR Part 1065 were effectively zero or less than the detection limit of 0.001 g/hp-hr.

TABLE 11. THC, CH_4, AND NMHC EMISSIONS

Test Cycle		THC, g/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	0.002	0.000	0.000
	2	0.002	0.000	0.000
	3	0.000	0.000	0.000
	Avg	0.001	0.000	0.000
	Stdev	0.001	0.000	0.000
	COV	76%	na	na
16-Hour	1	0.000	0.000	0.000
	2	0.000	0.000	0.000
	3	0.000	0.000	0.000
	Avg	0.000	0.000	0.000
	Stdev	0.000	0.000	0.000
	COV	na	na	na
Test Cycle		CH4, g/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	0.000	0.000	0.000
	2	0.000	0.000	0.000
	3	0.000	0.000	0.000
	Avg	0.000	0.000	0.000
	Stdev	0.000	0.000	0.000
	COV	na	na	na
16-Hour	1	0.000	0.000	0.000
	2	0.000	0.000	0.000
	3	0.000	0.000	0.000
	Avg	0.000	0.000	0.000
	Stdev	0.000	0.000	0.000
	COV	na	na	na
Test Cycle		NMHC, g/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	0.002	0.000	0.000
	2	0.002	0.000	0.000
	3	0.000	0.000	0.000
	Avg	0.001	0.000	0.000
	Stdev	0.001	0.000	0.000
	COV	76%	na	na
16-Hour	1	0.000	0.000	0.000
	2	0.000	0.000	0.000
	3	0.000	0.000	0.000
	Avg	0.000	0.000	0.000
	Stdev	0.000	0.000	0.000
	COV	na	na	na

6.4 Carbon Dioxide (CO_2) Emissions and BSFC

CO_2 emissions have become a very important emission species because CO_2 is major greenhouse gas. The first greenhouse gas regulation pertaining to heavy-duty on-highway diesel engines will take effect in 2014, when the CO_2 emissions limit (based on the FTP cold and hot-start composite) will be 567 g/hp-hr. Since CO_2 is a major byproduct of complete fuel combustion, CO_2 emissions will also be impacted by regulations requiring improved fuel economy. Figure 15 shows the CO_2 emissions for the FTP and 16-Hour for all three engines. Relative to the 2014 standard (not applicable but used as a reference only), Engine X met the standard on both the FTP and the 16-Hour while Engine Y was borderline with Engine Z exceeding the standard. As mentioned before, CO_2 emission is a major component of fuel economy, which is expressed in brake-specific fuel consumption (BSFC). BSFC is calculated in accordance to CFR Part 1065 for the diesel fuel using gaseous emissions species such as CH_4, NMHC, CO, and CO_2. Figure 16 shows the BSFC for all three engines. Similar trends were observed in BSFC to that of CO_2. BSFC calculation does not take into account urea consumption. Urea can be considered a fuel that adds to the overall fuel consumption. Based on our internal calculation, the urea consumption from all three engines was 2% to 3% of the diesel fuel consumed. Thus, urea consumptions should not impact the trends observed below in BSFC among the three engines.

Test Cycle		CO2, g/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	541	571	667
	2	535	573	665
	3	535	572	672
	Avg	537	572	668
	Stdev	3	1	3
	COV	1%	0%	1%
16-Hour	1	534	549	621
	2	534	558	626
	3	534	558	628
	Avg	534	555	625
	Stdev	0	5	3
	COV	0%	1%	1%

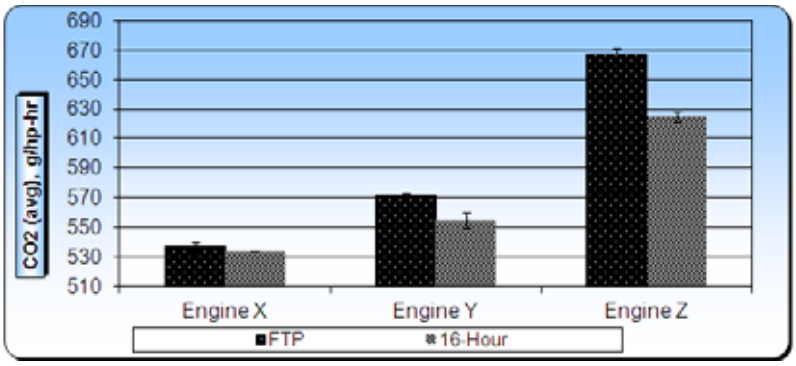

FIGURE 15. CO_2 EMISSIONS FOR THE HOT-START FTP AND 16-HOUR

Test Cycle		BSFC, lb/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	0.375	0.396	0.462
	2	0.371	0.397	0.461
	3	0.371	0.396	0.465
	Avg	0.372	0.396	0.463
	Stdev	0.002	0.001	0.002
	COV	1%	0%	1%
16-Hour	1	0.370	0.380	0.430
	2	0.370	0.386	0.434
	3	0.370	0.387	0.435
	Avg	0.370	0.384	0.433
	Stdev	0.000	0.004	0.002
	COV	0%	1%	1%

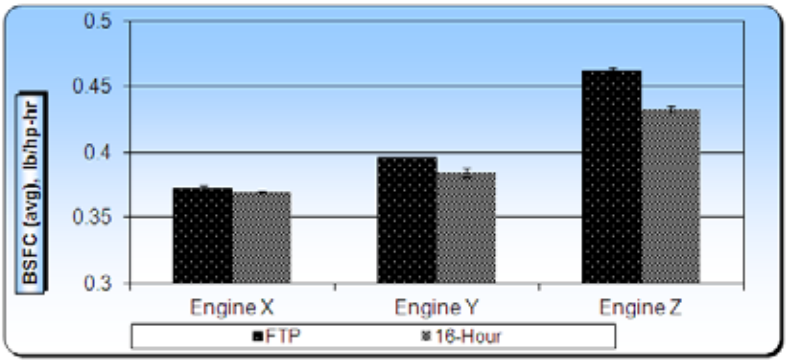

FIGURE 16. BSFC FOR THE HOT-START FTP AND 16-HOUR

6.4.1 Greenhouse Gas and Global Warming Potential

It is important to note that the greenhouse gas regulations do not apply to the 2010 technology engines that we test. Those regulations initially take effect in 2014. Nonetheless, in Figures 11, 12, Table 11 and Figure 15, we reported results on the three greenhouse gas emissions species (N_2O, CH_4, and CO_2) emitted from the tested engines, although CH_4 emissions were essentially zero. Using CO_2, N_2O, and CH_4 data as applicable, we compared the 100 year global warming potential (GWP), as defined by EPA greenhouse gas rulemaking for medium and heavy-duty engines[13], between the 2010 and 2007 technology engines. GWP is a relative measure of the amount of heat trapped from the instantaneous release of one kilogram of a trace substance relative to that of one kilogram of a reference gas. For the purpose of our calculation, we used CO_2 as the reference and we multiplied CH_4 by 25 and N_2O by 298 to get the 100 year GWP[14]. Based on our calculation, the 100 year GWP of the two engine technologies was very similar leading only to a 0.1% increase with the 2010 technology engines.

6.4.2 Sulfur Dioxide (SO_2) Emissions

SO_2 emissions are combustion byproducts of sulfur in the fuel and the lube oil. Figure 17 shows SO_2 emissions for FTP and 16-Hour using all three ACES engines. The 16-Hour data in this case are much more reliable because the levels measured are well above the detection limit of 0.03 mg/hp-hr for the 16-Hour. To give a better perspective on SO_2 emissions, we assumed that all sulfur in the fuel is converted to SO_2 to predict SO_2 emissions. We also assumed an oil sulfur contribution to SO_2 emissions using a measured oil sulfur content of 4,000 ppm and an oil consumption of 0.06% of fuel consumption. The oil to fuel consumption was derived from a 2007 medium duty technology vehicle with a DOC in the exhaust, using calcium as a tracer for oil consumption[15]. Table 12 shows the estimated SO_2 emissions calculation. The calculated SO_2 emissions were significantly higher than the measured SO_2 emissions, suggesting significant sulfur storage in the aftertreatment system, particularly the DPF due to the lack of DPF active regeneration, where internal surfaces of the DPF increase in temperature causing a release of the stored sulfur. To investigate this point further, we compared measured and calculated SO_2 emissions between 2010 (no occurrence of DPF active regeneration) and 2007 technology engines used in ACES Phase 1, where DPF active regeneration occurred one to three times during the 16-Hour. For the 2007 technology engines (Figure 18), the calculated SO_2 emissions based on the assumptions made above were a factor of 2 of the measured SO_2 emissions, while the calculated SO_2 emissions for the 2010 engines were nearly a factor of 10 higher. This storage of sulfur in the aftertreatment system is not permanent and will likely be cleared through an active DPF regeneration that we did not observe during ACES Phase 2 tests. So far, in the above analysis, we did not include the contribution of sulfur from the particle-phase sulfate for the overall sulfur mass balance. For the 2010 engines, the total sulfur mass in measured particle-phase sulfate (Figure 36) is insignificant, representing less than 1 percent of the sulfur mass in measured SO_2. So, it can be ignored in the sulfur mass balance. However, sulfur mass in particle-phase sulfate for the 2007 technology engines is equal to 70% of the sulfur mass in measured

[13] (http://www.epa.gov/otaq/climate/documents/420r11901.pdf)
[14] Intergovernmental Panel on Climate Change. Chapter 2. Changes in Atmospheric Constituents and in Radiative Forcing. September 2007. http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf Docket ID: EPA-HQ-OAR-2009-0472-0117
[15] Carroll J, I Khalek, L. Smith, E. Fujita, and B. Zielinska, "Collaborative Lubricating Oil Study on Emissions," http://www.nrel.gov/docs/fy12osti/52668.pdf

SO_2. For the 2007 engines, the sulfur level in sulfate combined with the sulfur level in SO_2 led to total sulfur mass that is similar to that calculated based on fuel and oil consumption.

Test Cycle		SO2, mg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	5.784	0.640	0.860
	2	3.025	0.535	1.352
	3	1.378	0.000	0.564
	Avg	3.396	0.392	0.925
	Stdev	2.226	0.343	0.398
	COV	66%	88%	43%
16-Hour	1	0.361	0.294	0.220
	2	0.475	0.267	0.145
	3	0.599	0.442	0.134
	Avg	0.479	0.334	0.166
	Stdev	0.119	0.094	0.047
	COV	25%	28%	28%

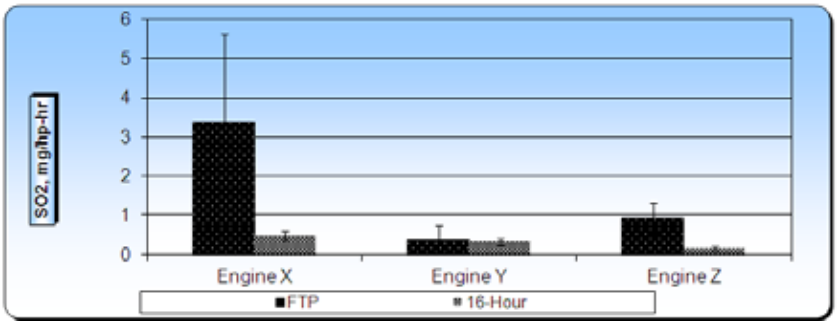

FIGURE 17. MEASURED SO_2 EMISSIONS FOR THE HOT-START FTP AND 16-HOUR

TABLE 12. 2010 ENGINES PREDICTED SO_2 EMISSIONS USING FUEL AND OIL SULFUR CONTRIBUTION

Test Cycle		SO2, mg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	3.03	3.20	3.74
	2	3.00	3.21	3.73
	3	3.00	3.20	3.77
	Avg	**3.01**	**3.21**	**3.75**
	Stdev	**0.019**	**0.005**	**0.019**
	COV	**1%**	**0%**	**1%**
16-Hour	1	2.99	3.08	3.48
	2	2.99	3.13	3.51
	3	3.00	3.13	3.52
	Avg	**2.99**	**3.11**	**3.51**
	Stdev	**0.001**	**0.030**	**0.019**
	COV	**0%**	**1%**	**1%**

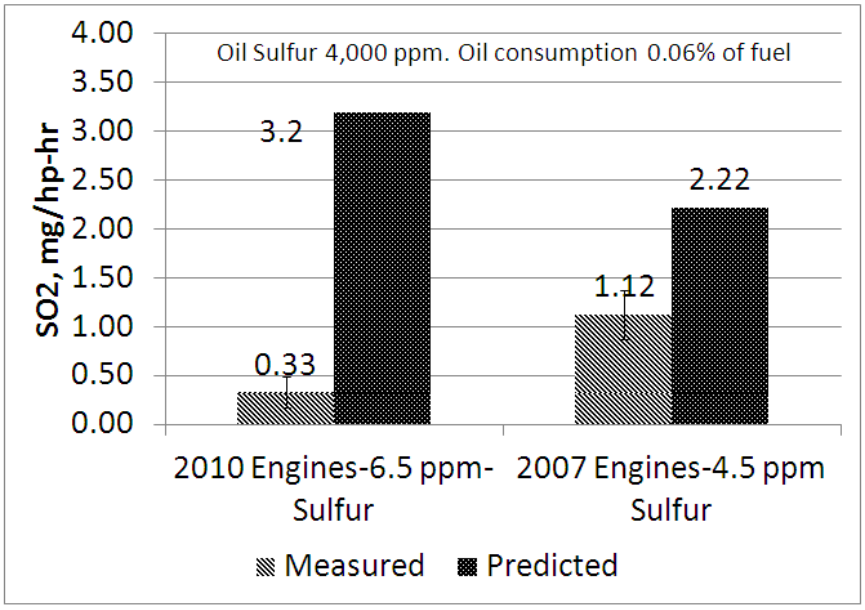

FIGURE 18. COMPARISON BETWEEN PREDICTED AND MEASURED SO_2 EMISSIONS FOR 2010 AND 2007 TECHNOLOGY ENGINES

6.5 Particulate Matter Emissions

Several metrics and methods were used to characterize PM. This section includes information on Teflon® membrane filter-based PM measurements, quartz filter-based OC/EC analysis, filter-based elemental EDXRF and ICPMS analysis, real time total PM using the DMM-230, real time soot using the MSS, and real time number and size distribution measurements using the EEPS.

6.5.1 Filter-Based PM Mass-CVS Tunnel and Exposure Chamber

Filter-based PM was collected from two locations. The first location was from the CVS tunnel sample zone, in accordance with CFR Part 1065, where the filter face temperature was maintained at 47°C ±5°C, and total residence time (CVS plus secondary tunnel) was on the order of 3 to 5 seconds. The second location was from the exposure chamber, where the dilution ratio from the CVS tunnel was about 2, the filter face temperature was about 28°C, and the residence time was on the order of 4 to 5 minutes to purge 90 percent of the volume entering the chamber. It takes an additional 15 minutes for the remaining 10 percent volume to be fully purged. The temperature of the exposure chamber filter was not actively controlled and was dictated by the temperature inside the exposure chamber. The total flow through each of the 47 mm filters was approximately 57 slpm, resulting in a filter face velocity near 100 cm/s.

Figures 19 and 20 show the brake-specific PM emissions from the CFR Part 1065 method and the exposure chamber, respectively. Generally, PM emissions were very low, more than 90% below the 2010 PM standard of 0.01 g/hp-hr. However, the PM reported based on exposure chamber collection was much higher, especially for the FTP. This observation is not surprising since the filter face temperature (47°C vs. 28°C) and residence time (3 seconds vs. 4 minutes) between the two sampling locations are different. Lower temperature and particle growth in the chamber are likely contributing to the higher emissions. Also note that the FTP PM emissions

based on the chamber collection were higher than those for the 16-Hour. During the short FTP, the PM is typically dominated by gas phase artifact collection by the filter at these low emissions levels. During the 16-Hour, due to the long duration of sampling, the filter saturates and minimizes the contribution of artifacts, thus leading to lower PM emissions that better reflects the true particle phase.

Test Cycle		PM (Part 1065), g/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	0.0002	0.0010	0.0008
	2	0.0007	0.0001	0.0010
	3	0.0005	0.0006	0.0010
	Avg	0.0005	0.0006	0.0010
	Stdev	0.0002	0.0005	0.0001
	COV	48%	80%	13%
16-Hour	1	0.0002	0.0000	0.0006
	2	0.0002	0.0002	0.0006
	3	0.0002	0.0002	0.0009
	Avg	0.0002	0.0001	0.0007
	Stdev	0.0000	0.0001	0.0002
	COV	20%	83%	22%

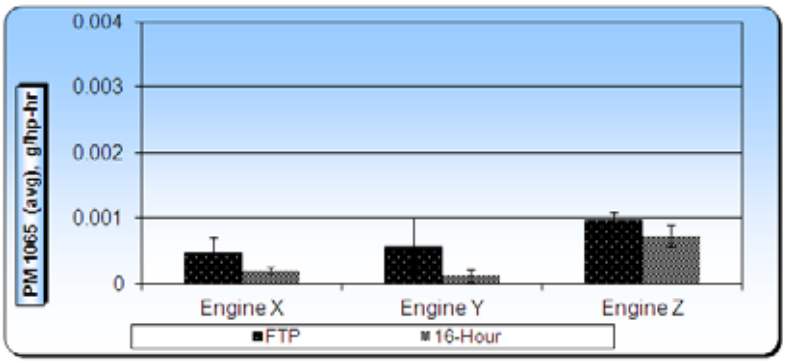

FIGURE 19. PM EMISSIONS FOR THE HOT-START FTP AND 16-HOUR BASED ON CVS TUNNEL CFR PART 1065 COLLECTION METHOD

Test Cycle		PM (Exp. Chamber), g/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	0.0014	0.0039	0.0009
	2	0.0022	0.0032	0.0018
	3	0.0012	0.0020	0.0019
	Avg	0.0016	0.0030	0.0015
	Stdev	0.0005	0.0009	0.0005
	COV	30%	32%	35%
16-Hour	1	0.0002	0.0005	0.0010
	2	0.0003	0.0007	0.0012
	3	0.0003	0.0009	0.0012
	Avg	0.0003	0.0007	0.0011
	Stdev	0.0000	0.0002	0.0001
	COV	9%	34%	9%

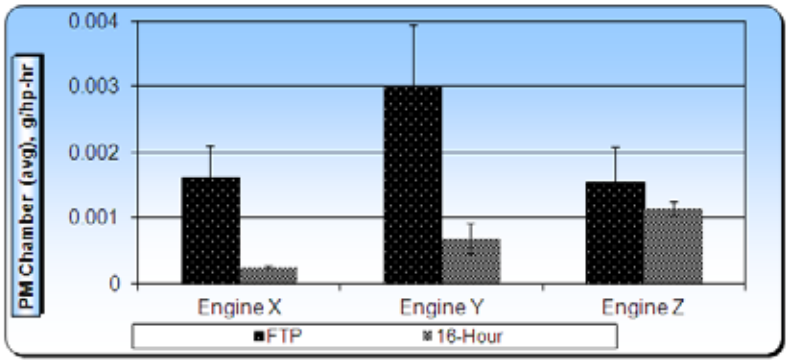

FIGURE 20. PM EMISSIONS FOR THE HOT-START FTP AND 16-HOUR BASED ON EXPOSURE CHAMBER COLLECTION

Figure 21 shows the average ratio of exposure chamber-based PM and CVS-based PM for all engines. The PM emissions based on exposure chamber filter collection were a factor of three higher for the FTP and a factor of 2 higher for the 16-Hour than those using CFR Part 1065 method. The reason for the higher PM in the chamber relative to the PM measured in accordance with CFR Part 1065 can be attributed to temperature and residence time. The filter face temperature in the chamber was at 28°C, compared to a temperature of 47°C using the CFR Part 1065 method. The residence time in the chamber was on the order of 5 minutes compared to the 5 seconds in CVS and secondary dilution system for the CFR Part 1065 PM collection method. The lower temperature and the longer residence time in the chamber may have enhanced gas phase adsorption onto existing particles and promote particle nucleation and growth resulting in higher PM emissions, compared to those based on the CFR Part 1065 method.

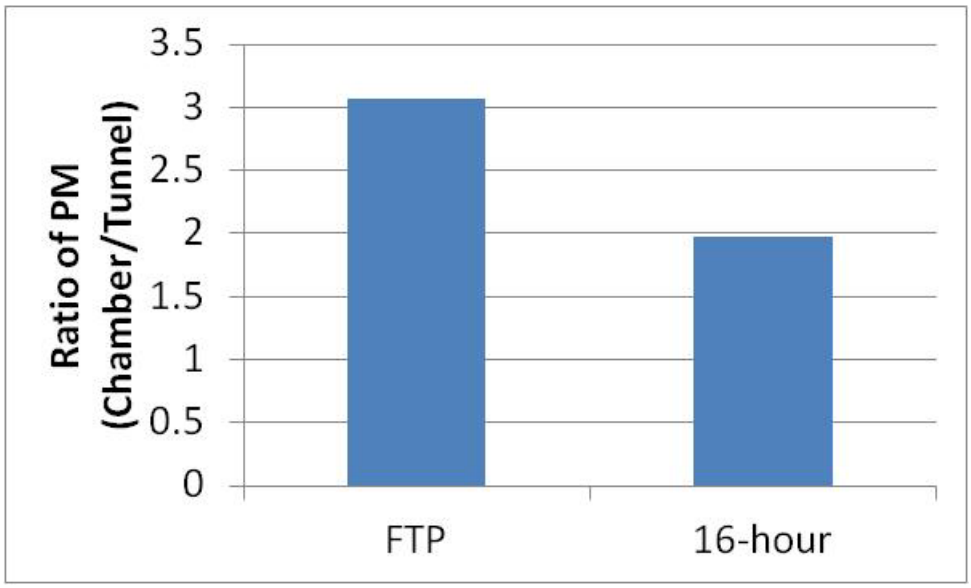

FIGURE 21. RATIO OF PM BASED ON EXPOSURE CHAMBER OVER PM BASED ON CVS USING CFR PART 1065

6.5.2 Quartz Filter-Based OC and EC-Exposure Chamber

PM was collected on quartz filters from the exposure chamber, and the filters were analyzed using the OC/EC reflectance method by DRI. Similar to what was done in ACES Phase 1, we report OC based on the primary filter used for PM collection with no subtraction of the back-up filter. For the 16-Hour, due to the long sampling time, it is not clear whether the back-up filter should be subtracted or added to the primary filter. So, we used the primary filter only as measured. Figures 22 and 23 show the brake-specific OC and EC emissions for the FTP and 16-Hour. OC emissions were substantially higher for the short FTP, compared to the 16-Hour. This observation is consistent with the PM filter measurement shown in Figure 20. Essentially, for the short cycle, the filter was likely dominated by gas phase artifact collection, compared to the 16-Hour filter. By sampling for a longer time with the 16-Hour, the filter saturates and the artifact contribution to filter measurement is minimized. The EC emissions were extremely low, to the point where they were not detected during the FTP that has an EC detection limit of 90 µg/hp-hr. For the 16-Hour, the EC levels were also extremely low between 59 and 170 µg/hp-hr, but well above the detection limit of 2 µg/hp-hr. The highest EC emission levels represent only 2% of the 2010 PM standard. The highest average EC emissions represent an EC chamber concentration of 3.5 µg/m³.

Figures 24 and 25 show the average reduction in OC and EC for the 16-Hour relative to the 2007 technology engines. The OC reduction was 36%, while the EC was 53%. The OC reduction was likely due to the lack of active DPF regeneration and some probable additional oxidation and/or adsorption of heavy-molecular hydrocarbon by the SCR catalyst. The reduction in EC is likely due to a higher efficiency DPF operation due to the lack of active regeneration. We know from our previous work that a partially loaded DPF has a higher efficiency than a clean DPF.

Test Cycle		Organic Carbon, µg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	1111.5	2070.1	2118.4
	2	1551.0	2113.0	1996.3
	3	1062.1	2088.1	1803.9
	Avg	1241.5	2090.4	1972.9
	Stdev	269.2	21.5	158.6
	COV	22%	1%	8%
16-Hour	1	220.9	250.1	754.3
	2	275.8	291.3	793.2
	3	263.7	278.5	988.5
	Avg	253.5	273.3	845.3
	Stdev	28.8	21.1	125.5
	COV	11%	8%	15%

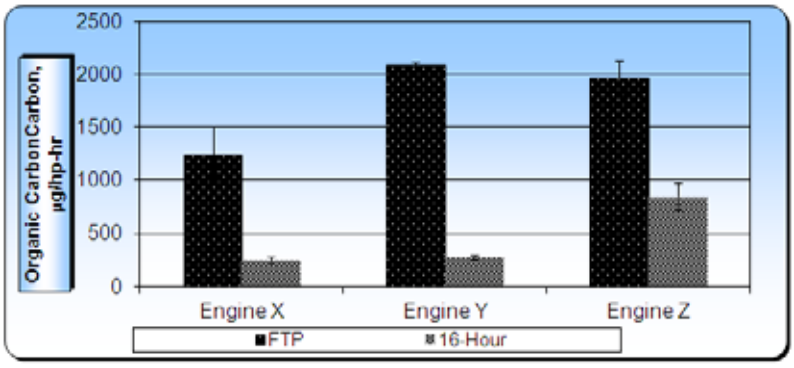

FIGURE 22. ORGANIC CARBON EMISSIONS FOR THE HOT-START FTP AND 16-HOUR

Test Cycle		Elemental Carbon, µg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	nd	nd	121.5
	2	nd	nd	nd
	3	nd	nd	nd
	Avg	na	na	na
	Stdev	na	na	na
	COV	na	na	na
16-Hour	1	61.6	30.4	134.5
	2	122.3	78.6	141.8
	3	122.2	67.2	231.4
	Avg	102.0	58.7	169.2
	Stdev	35.0	25.2	53.9
	COV	34%	43%	32%

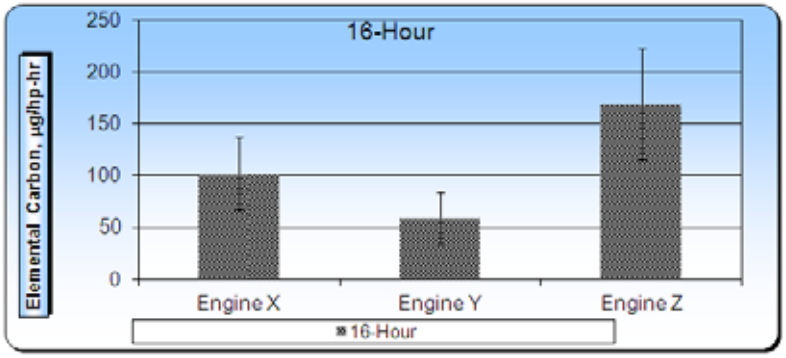

FIGURE 23. ELEMENTAL CARBON EMISSIONS FOR THE HOT-START FTP AND 16-HOUR

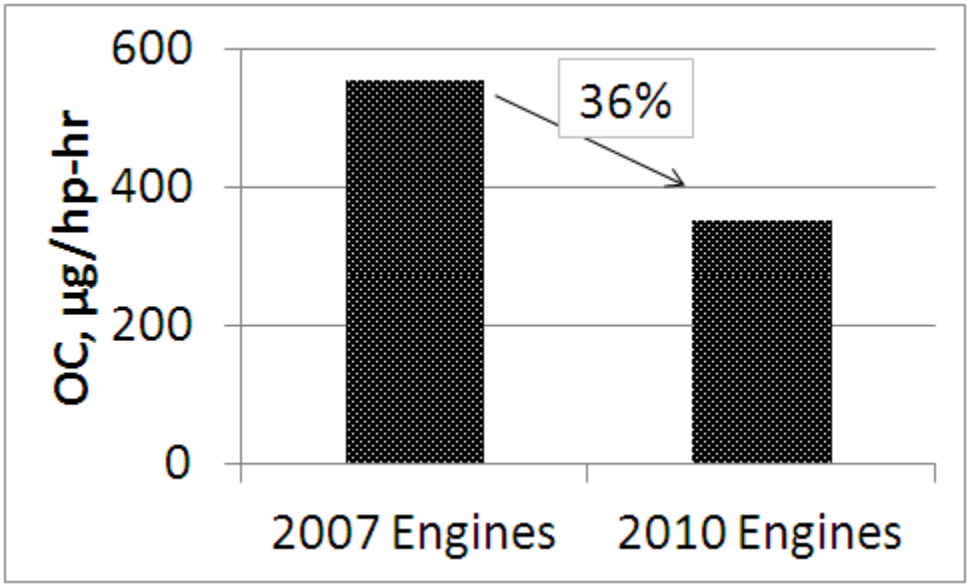

FIGURE 24. ORGANIC CARBON REDUCTION WITH 2010 VS. 2007 TECHNOLOGY ENGINES (16-HOUR)

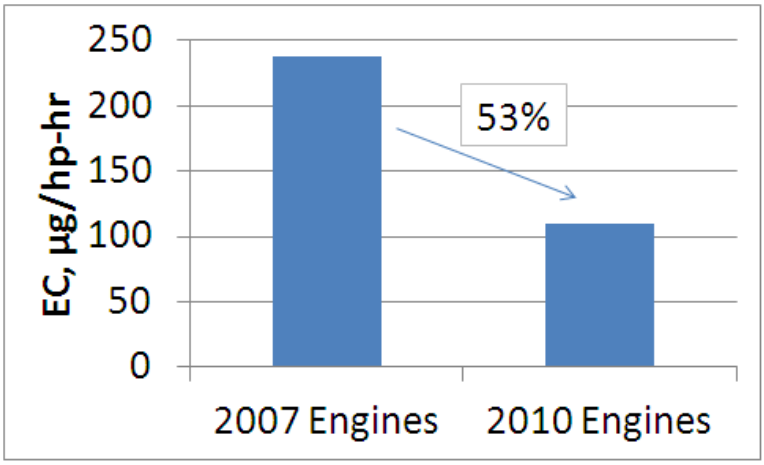

FIGURE 25. ELEMENTAL CARBON REDUCTION WITH 2010 VS. 2007 TECHNOLOGY ENGINES (16-HOUR)

6.5.3 MSS-Based Soot Mass-Exposure Chamber

Overall, the soot measurement from the exposure chamber was below the detection limit of the instrument at 5 µg/m³. At this very low level of PM, the instrument showed sensitivity to exhaust gas composition where negative values were observed. For example, the reading went slightly negative when switching from HEPA-filtered zero air reading to sampling from the chamber. There was not enough soot in the chamber to overcome the negative readings, so some of the average emission levels were negative. The EC reported in Figure 25 and 23 for the 16-Hour gives a more representative reading of the soot or elemental carbon emitted.

6.5.4 DMM-Based Total PM Mass-Exposure Chamber

Figure 26 summarizes the DMM-based PM emissions for the FTP and 16-Hours. Overall, the DMM gave a relatively similar PM emissions trend to that reported by the PM collection from the exposure chamber (Figure 20). At this low level of PM, and due to the virtual absence of EC particles in the exhaust, this instrument can only be used to give qualitative information on PM.

Test Cycle		DMM-PM, g/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	0.00004	0.00345	0.00076
	2	0.00005	0.00284	0.00090
	3	0.00004	0.00240	0.00096
	Avg	0.00004	0.00290	0.00087
	Stdev	0.0000	0.0005	0.0001
	COV	9%	18%	11%
16-Hour	1	0.00027	0.00250	0.00120
	2	0.00040	0.00235	0.00166
	3	0.00041	0.00284	0.00231
	Avg	0.00036	0.00256	0.00173
	Stdev	0.0001	0.0002	0.0006
	COV	21%	10%	32%

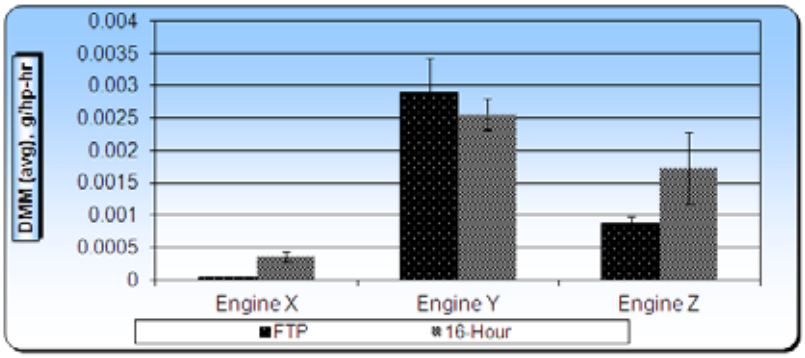

FIGURE 26. PM EMISSIONS FOR THE HOT-START FTP AND 16-HOUR BASED ON DMM MEASUREMENT FROM THE EXPOSURE CHAMBER

6.5.5 Metals and Other Elements

Figure 27 shows the sum of the elements emitted over the FTP and the 16-Hour using the XRF detection method. These elements were dominated by a non-metallic element such as sulfur and metallic elements such as Ca, Zn, Fe, and Al. The total elements collected on a sample filter over the FTP were similar in levels to those detected in a filter blank. As a result, we have some negative data for the FTP due to sample filter correction with the filter blank. The mass of total elements collected on a sample filter over the 16-Hour was much higher than that measured for a filter blank. Thus, we should only use the emissions data for the 16-Hour. Still, the elements mass emitted over the 16-Hour was extremely low, representing only about 2% of the very low PM. The emissions vary among engines with a range between 6 µg/hp-hr and 23 µg/hp-hr. The dominant non-metallic element in the particle phase is sulfur. Sulfur represents 23% (1.91 µg/hp-hr ± 0.24) of the total elements emitted for Engine X, 23% (1.34 µg/hp-hr ± 0.31) for Engine Y and 41% (4.38 µg/hp-hr ± 1.96) for Engine Z. Figure 28 shows a substantial reduction in emissions from elements relative to the 2007 technology engines used in ACES Phase 1. The reduction in the emissions from elements may be partially attributed to the lack of DPF regeneration. When active regeneration occurs, sulfur is expected to be released and the DPF is expected to become less efficient after the EC is burned. Both factors may elevate the emissions of sulfur as well as metallic ash.

Figure 29 shows the total metallic elements emissions using the ICPMS method. Metallic elements detected during the FTP are on the same order of those detected in a filter blank. Thus, negative values are reported for the FTP due to filter blank subtraction. Similar to the conclusion we made with the XRF method, only data for the 16-Hour should be used. The emissions for the 16-Hour vary among engines with a range between 3.2 to 4.0 µg/hp-hr for Engine X and Y to 11.6 µg/hp-hr for Engine Z. A linear regression between the XRF method and the ICPMS is shown in Figure 30 using the exact same species. A reasonable agreement between the two methods was obtained, where the ICPMS method reported about 20% lower metallic emissions than those reported by the XRF. In principle, the ICPMS method has a lower detection limit and can be considered more accurate. Figure 31 shows individual metal elements detected using the ICPMS method (A) and the XRF method (B). Figure 31 includes all the metal elements that we analyzed using the XRF and ICPMS methods. Both methods showed a similar trend. The emissions were dominated by calcium and zinc (oil additives) followed by engine wear elements such as iron and aluminum. Other traces of engine wear elements such as chromium, nickel and copper were observed. This is in addition to traces of lube oil elements such as magnesium and manganese.

Test Cycle		Metals and Elements (XRF), µg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	-34.0	-6.9	-32.7
	2	116.3	-17.8	-45.9
	3	28.1	-6.7	-43.0
	Avg	36.8	-10.5	-40.5
	Stdev	75.5	6.4	6.9
	COV	205%	-61%	-17%
16-Hour	1	6.9	5.3	17.7
	2	11.1	7.2	18.3
	3	6.7	5.3	32.4
	Avg	8.2	5.9	22.8
	Stdev	2.5	1.1	8.4
	COV	30%	18%	37%

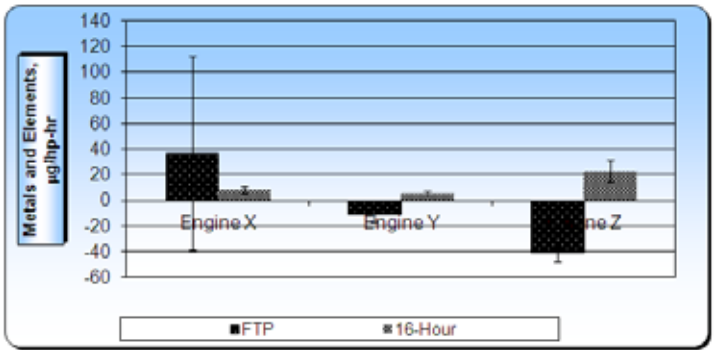

FIGURE 27. TOTAL ELEMENTS EMISSIONS USING THE XRF METHOD

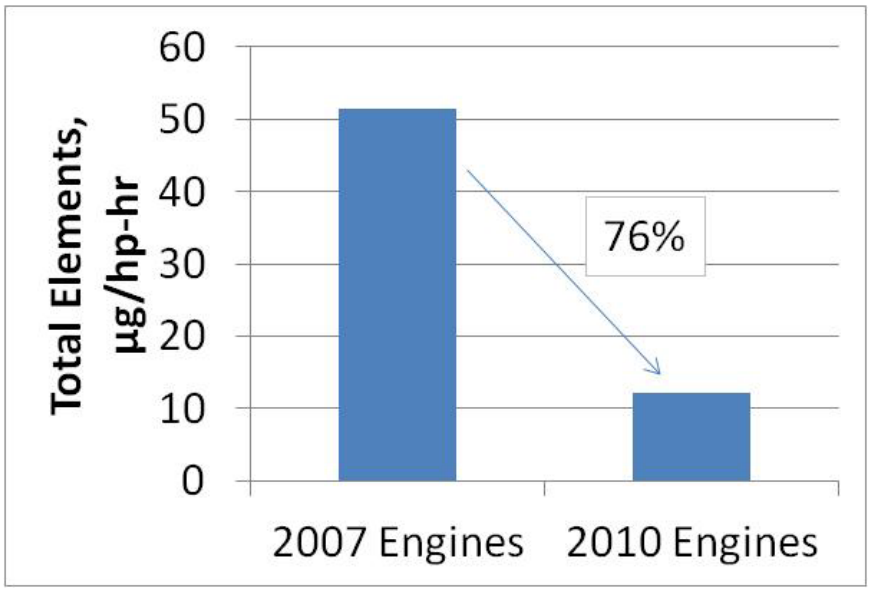

FIGURE 28. TOTAL ELEMENTS EMISSIONS COMPARISON bETWEEN 2010 AND 2007 TECHNOLOGY ENGINES

Test Cycle		Metals (ICP), µg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	-12.7	47.1	5.9
	2	37.1	-15.8	-9.2
	3	40.5	-6.6	-18.6
	Avg	21.6	8.2	-7.3
	Stdev	29.8	33.9	12.4
	COV	138%	412%	-169%
16-Hour	1	2.9	2.9	8.9
	2	3.2	5.5	12.8
	3	3.4	3.6	13.1
	Avg	3.2	4.0	11.6
	Stdev	0.3	1.3	2.3
	COV	9%	33%	20%

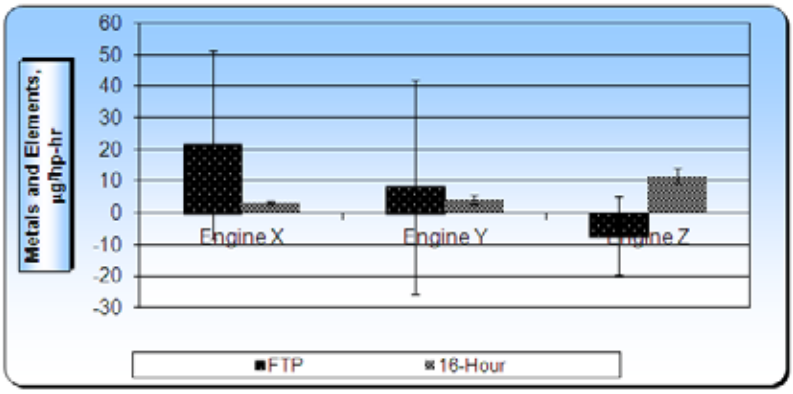

FIGURE 29. METALLIC ELEMENTS EMISSIONS USING THE ICPMS METHOD

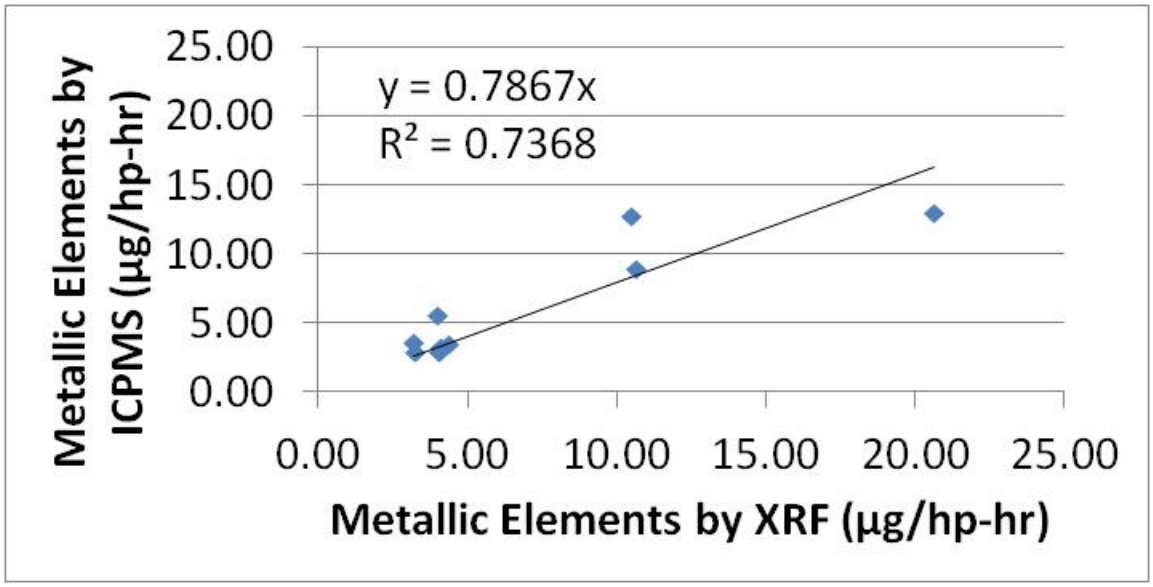

FIGURE 30. CORRELATION FOR METALLIC ELEMENTS USING XRF AND ICPMS (16-HOUR)

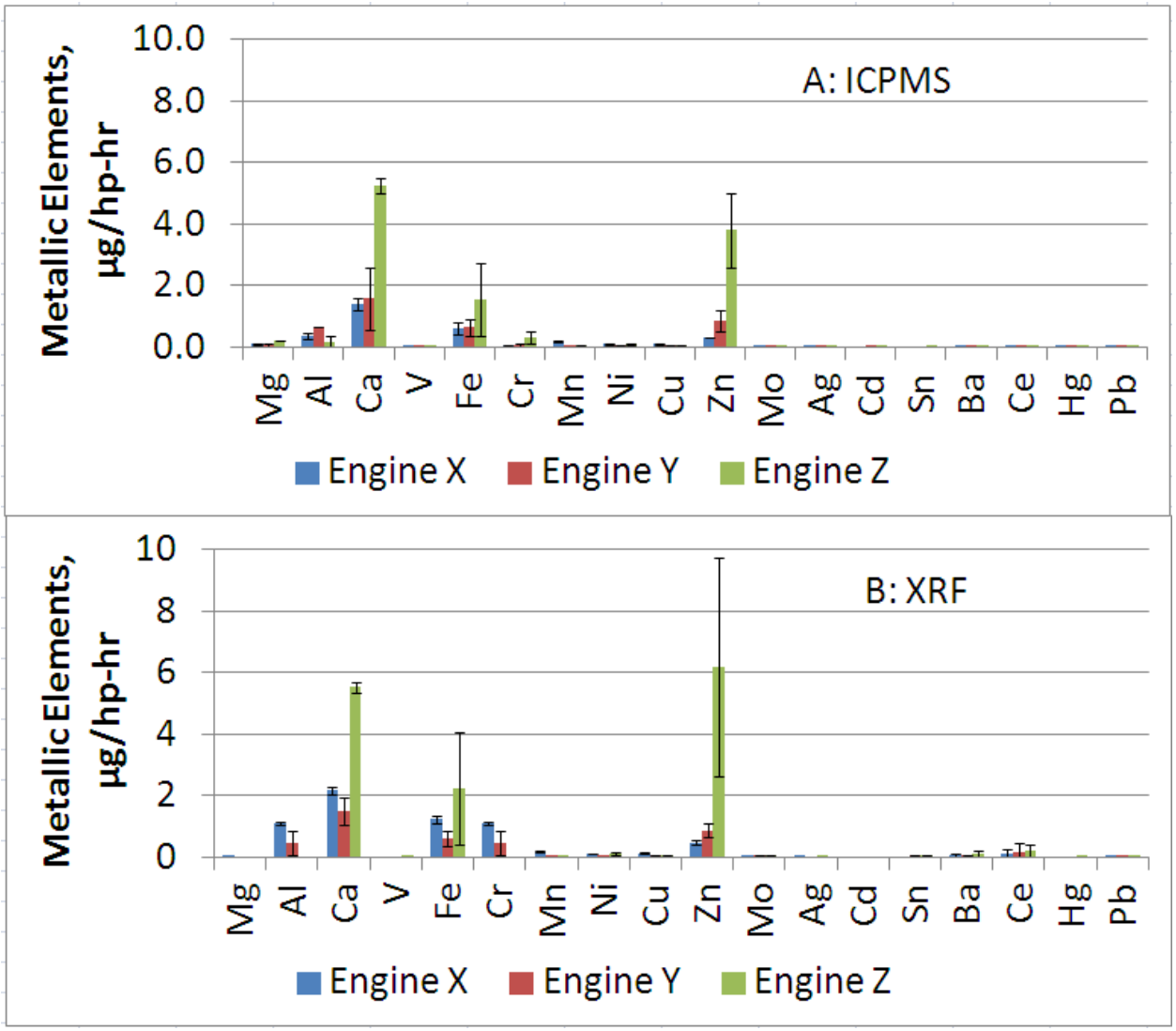

FIGURE 31. METALLIC ELEMENTS EMISSIONS USING ICPMS AND XRF (16-HOUR)

6.6 Inorganic Ions Emissions

Figures 32 through 35 show sulfate, ammonium, and nitrate emissions for the FTP and 16-Hour. Sulfate is typically derived from sulfur in the fuel and lube oil. We did not observe ammonium and nitrate emissions with the 2007 technology engines. They are likely present here because of the urea-SCR system interaction. Although the emissions data are above the detection limit for both the FTP and the 16-Hour, unless otherwise noted, the ion detection for the 16-Hour is more reliable. For example, the average emissions for the FTP were 2 to 4 times higher than the detection limit, while they were 30 times higher for the 16-Hour. Also, some of the nitrate emissions for the FTP exceeded the total PM emissions, suggesting unreliable measurements for nitrate during the FTP. Thus, the focus will be on the 16-Hour. Sulfate emissions represent a very small fraction of total PM on the order of 1%, followed by 2% for ammonium, and 14% for nitrate. Also, sulfate emissions were substantially lower than those observed with 2007 technology engines in ACES Phase 1, as shown in Figure 35. The reduced level of sulfate is likely due to sulfur adsorption by the aftertreatment system. This is also consistent with the

reduced level of SO_2 emissions (Figure 18) observed with the 2010 engine technology. As discussed before, the lack of active regeneration was one of the key differences between the two engine technologies that suppressed the release of sulfate. Another reason for the continued adsorption of sulfate could be the fact that the DPF did not have sufficiently long hours of engine operation to be saturated with sulfur. At some point in the engine operation, the aftertreatment system will be saturated with sulfur and stop adsorbing. We hypothesize that this phenomenon occurred with Engine Z during the 3rd 16-Hour. We noted that sulfate emissions went up between the 1st and 2nd 16-Hour and drastically increased for the 3rd 16-Hour, as shown in the table in Figure 32. Furthermore, we will show in the next section on particle number and size that the number emissions of nuclei mode nanoparticles increased drastically during the 3rd 16-Hour with Engine Z.

Test Cycle		Sulfate PM, µg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	24.3	43.2	37.0
	2	100.4	31.6	1.6
	3	14.0	34.6	26.7
	Avg	46.2	36.5	21.8
	Stdev	47.2	6.0	18.2
	COV	102%	17%	84%
16-Hour	1	4.9	4.5	2.2
	2	6.1	6.1	3.9
	3	5.9	7.5	11.6
	Avg	5.6	6.0	5.9
	Stdev	0.6	1.5	5.0
	COV	11%	25%	85%

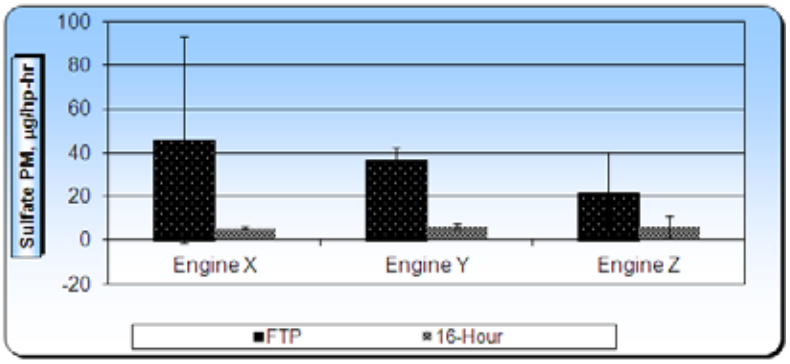

FIGURE 32. SULFATE EMISSIONS FOR THE HOT-START FTP AND 16-HOUR

Test Cycle		Ammonium PM, µg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	Nd	Nd	Nd
	2	Nd	Nd	Nd
	3	Nd	Nd	Nd
	Avg	Nd	Nd	Nd
	Stdev	Nd	Nd	Nd
	COV	na	na	na
16-Hour	1	0.0	22.3	4.5
	2	0.0	31.4	3.3
	3	0.0	14.0	5.7
	Avg	0.0	22.5	4.5
	Stdev	0.0	8.7	1.2
	COV	na	39%	26%

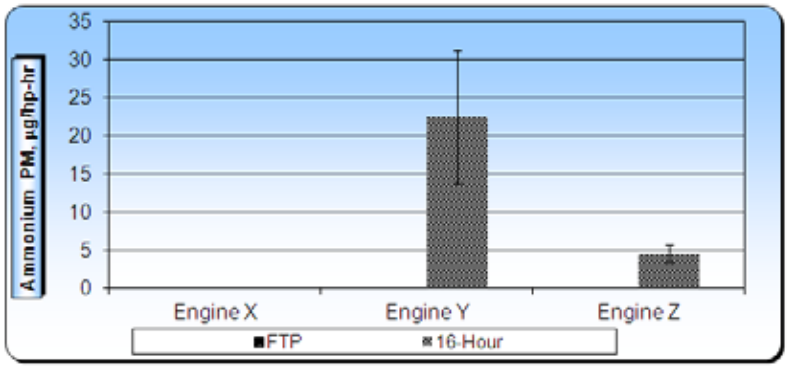

FIGURE 33. AMMONIUM EMISSIONS FOR THE HOT-START FTP AND 16-HOUR

Test Cycle		Nitrate PM, µg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	42.3	2057.2	751.9
	2	43.4	1392.4	623.0
	3	21.6	2167.1	474.4
	Avg	35.8	1872.2	616.4
	Stdev	12.3	419.1	138.9
	COV	34%	22%	23%
16-Hour	1	39.0	193.7	80.1
	2	53.5	285.9	46.1
	3	56.1	174.1	60.7
	Avg	49.2	217.9	62.3
	Stdev	8.8	59.7	17.0
	COV	18%	27%	27%

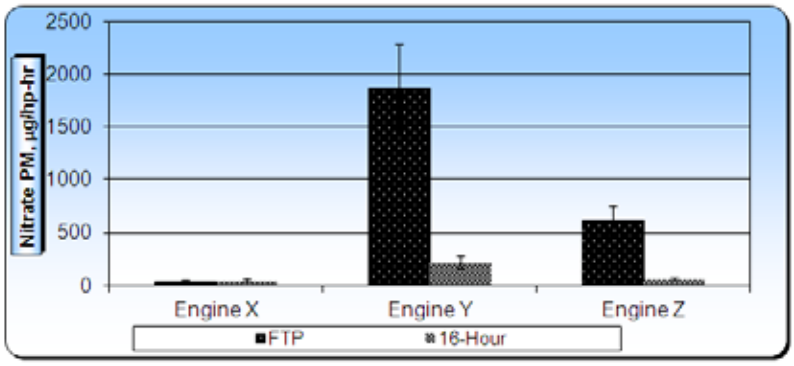

FIGURE 34. NITRATE EMISSIONS FOR THE HOT-START FTP AND 16-HOUR

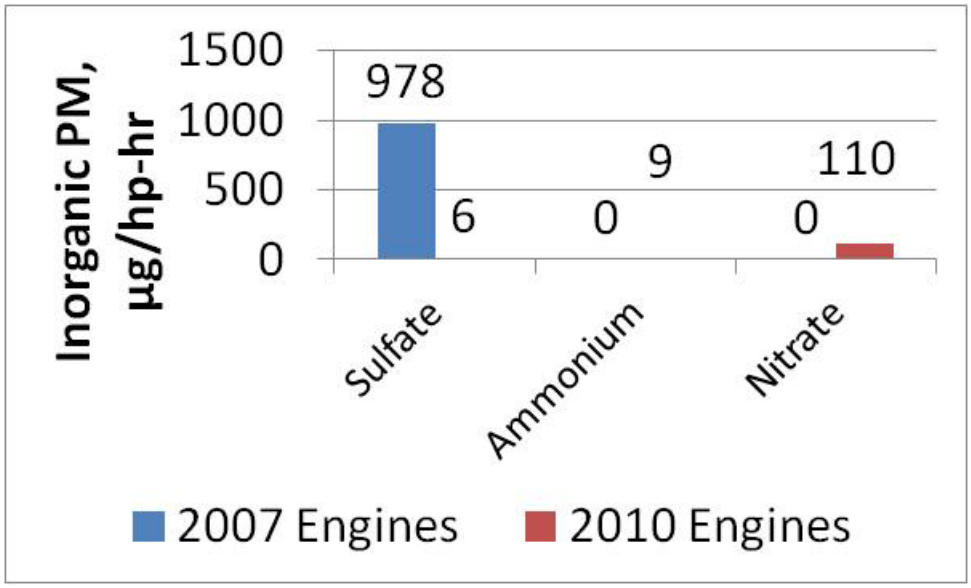

FIGURE 35. INORGANIC ION EMISSIONS COMPARISON BETWEEN 2010 AND 2007 ENGINES (16-HOUR)

6.7 EEPS-Based Particle Number and Size-Exposure Chamber

It is important to note here that we measured total (solid + volatile) particle number in the size range from 5.6 nm to 560 nm. Thus, our measurements cannot be directly compared with the EU regulations. However, since volatile particle formation dominates the range below 23 nm, one can determine the number emissions for particles larger than 23 nm to give an indication of particle emissions relative to the EU standard at 0.45 x 10^{12} part./hp-hr (6 x10^{11} part./kW-hr), based on the World Harmonized Transient Cycle (WHTC), a different cycle than those used in ACES Phase 2.

Figure 36 shows the particle number emissions for particles in the size range from 5.6 nm to 560 nm. The number emissions for the FTP were lower than that observed for the 16-Hour. For the FTP, the number ranged from 1.8×10^{12} part./hp-hr for Engine X to 3 $\times10^{12}$ part./hp-hr for Engine Y. Engine Z was in between at 2.3×10^{12}part./hp-hr. For the 16-Hour, the number ranged from 5×10^{12} part./hp-hr for Engine X to 7×10^{12} part./hp-hr for Engine Y and 1.6×10^{13}

part./hp-hr for Engine Z. Note that although the average number emissions were on the same order for the FTP, the size distribution characteristics were different among the three engines. For example, Figure 37 shows that Engine X and Y number emissions were dominated by nuclei mode nanoparticles with a mean diameter of 10 nm to 14 nm, while Engine Z emissions were dominated by particles with a mean diameter of 41 nm with no nuclei mode particles. We determined that Engine Z had 80% of the particles emitted larger than 23 nm while they constituted only 22% for Engine X and Y.

For the 16-Hour, the geometric number mean diameter (GNMD) of the size distribution for Engine X and Y was similar to that of the FTP, as shown in Figure 38, but that was not the case for Engine Z. For Engine Z, more nuclei mode particles were produced during the 16-Hour, resulting in a GNMD shift from 41 nm for the FTP to 21 nm for the 16-Hour. Furthermore, Engine Z average number emissions data had a large standard deviation, suggesting a difference in number emissions among the three 16-Hour runs. To look further into this issue, Figure 39 shows the average size distribution for each of the three 16-Hour tested with Engine Z. The average and standard deviation were based on the four 4-hour repeated segments that make up each 16-Hour. As shown in Figure 39, there was a progressive shift in the GNMD toward smaller particles among the 16-Hour runs. The GNMD shifted from 39 nm for the first 16-Hour run to 31 nm for the second run to an 18 nm for the third run. This was accompanied by a large increase in particle number. The reason for the increase in particle number with Engine Z is not known, but we have seen some evidence (Figures 22 and 23) of increased OC and especially EC as we progressed from the first 16-Hour to the third one for Engine Z. Based on our recent work with OC[16], it is very difficult to have any nucleation of OC at these low levels. Also, the increase in EC cannot account for the strong rise in nuclei mode particles observed for Engine Z in Figure 40. The most likely cause for the rise in nanoparticle emissions with Engine Z is sulfuric acid nucleation and growth. This can be corroborated by the large increase observed in Engine Z sulfate emissions (Figure 32) between the second 16-Hour run (3.9 µg/hp-hr) and the third (11.6 µg/hp-hr) 16-Hour run.

Test Cycle		Particle Number, part./hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	2.38E+11	1.75E+12	2.03E+12
	2	1.94E+12	2.61E+12	2.37E+12
	3	3.10E+12	4.51E+12	2.37E+12
	Avg	1.76E+12	2.96E+12	2.26E+12
	Stdev	1.44E+12	1.42E+12	1.98E+11
	COV	82%	48%	9%
16-Hour	1	5.63E+12	7.08E+12	3.40E+12
	2	5.52E+12	5.09E+12	6.25E+12
	3	3.56E+12	9.47E+12	3.77E+13
	Avg	4.91E+12	7.21E+12	1.58E+13
	Stdev	1.16E+12	2.19E+12	1.90E+13
	COV	24%	30%	121%

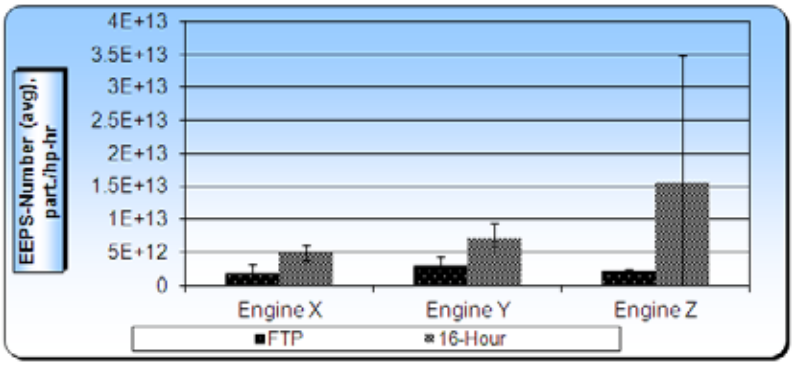

FIGURE 36. PARTICLE NUMBER EMISSIONS FOR THE HOT-START FTP AND 16-HOUR

[16] Khalek, I., A. Mamakos, V. Premnath, R. Mechler, D. Preece, R. Giannelli, and M. Spears, "Particle Generator For Engine Exhaust Simulation: 2012-2013 Progress, 23rd CRC Real World Emissions Workshop, April, 2013

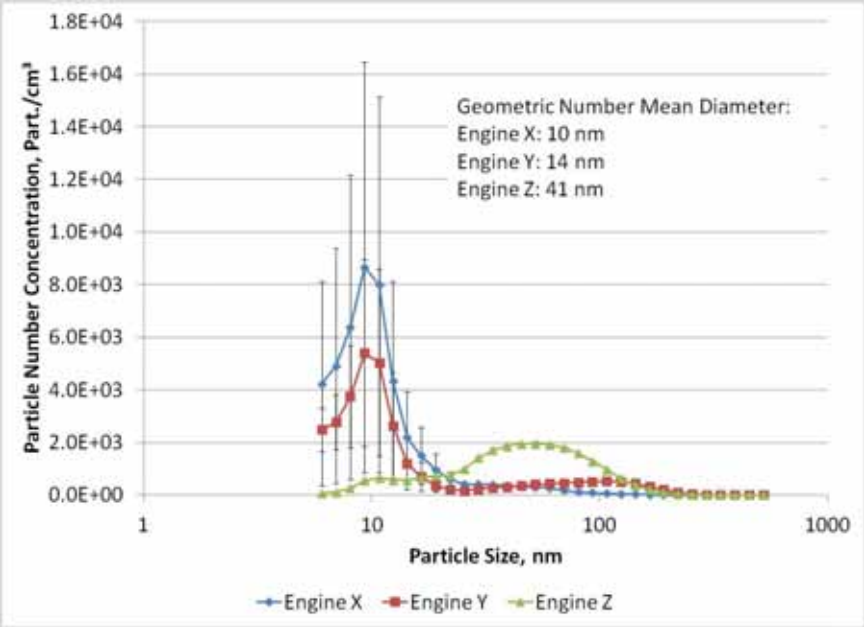

FIGURE 37. AVERAGE PARTICLE NUMBER-WEIGHTED SIZE DISTRIBUTION FOR THE FTP CYCLE (EXPOSURE CHAMBER, STANDARD DEVIATION BASED ON THREE REPEATS OF THE FTP)

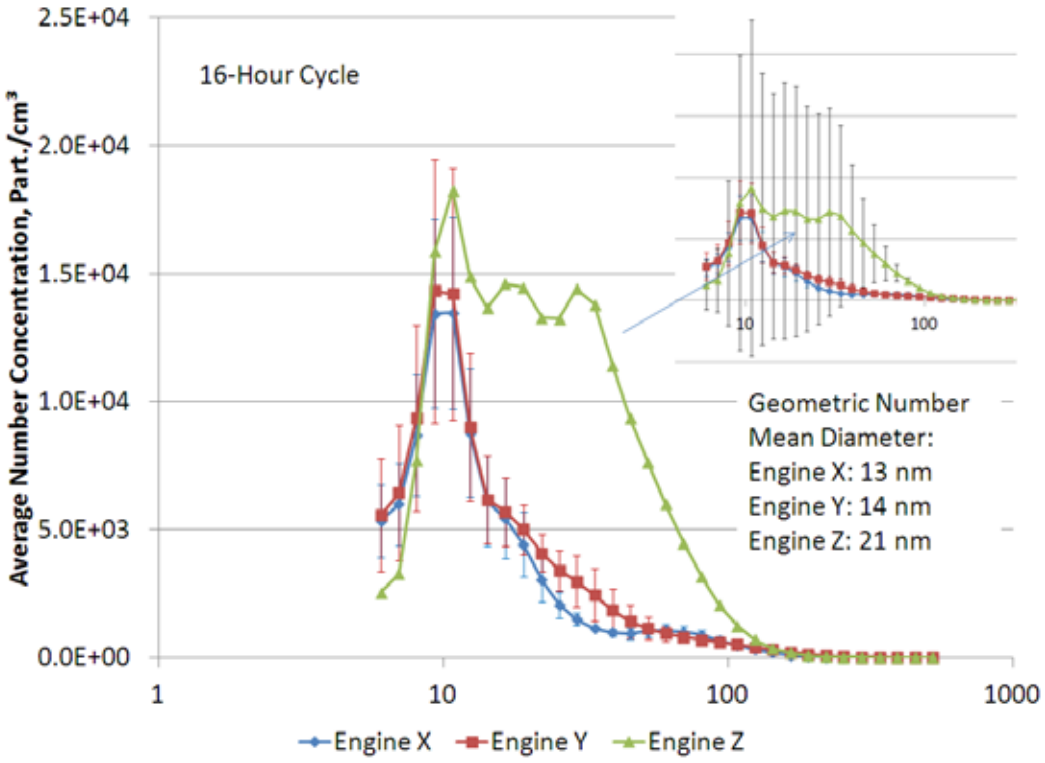

FIGURE 38. AVERAGE PARTICLE NUMBER-WEIGHTED SIZE DISTRIBUTION FOR THE 16-HOUR (EXPOSURE CHAMBER, STANDARD DEVIATION BASED ON THREE REPEATS OF 16-HOUR)

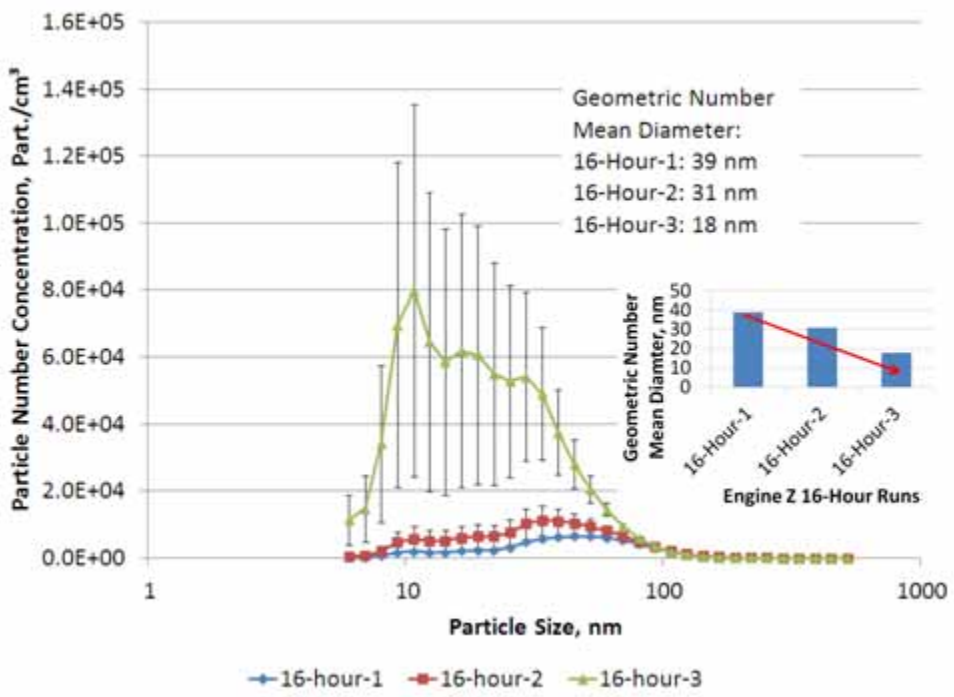

FIGURE 39. AVERAGE PARTICLE NUMBER-WEIGHTED SIZE DISTRIBUTION FOR THE 16-HOUR USING ENGINE Z (EXPOSURE CHAMBER, STANDARD DEVIATION BASED ON FOUR 4-HOUR SEGMENTS OF EACH 16-HOUR)

Figure 40 shows the average (based on three repeats) particle number concentration in exposure chamber for the FTP. Based on a dilution ratio of 16 between the exhaust and the chamber, the average number concentration was between 20,000 part./cm³ and 40,000 part./cm³. That is a very low concentration (close to the ambient background concentration), considering that the dilution ratio was only 16. Figure 41 summarizes the average particle number concentration expected in the exposure chamber during the 16-Hour operation. The average concentration ranged from about a 100,000 part./cm³ for Engine X and Engine Y to 200,000 part./cm³ for Engine Z.

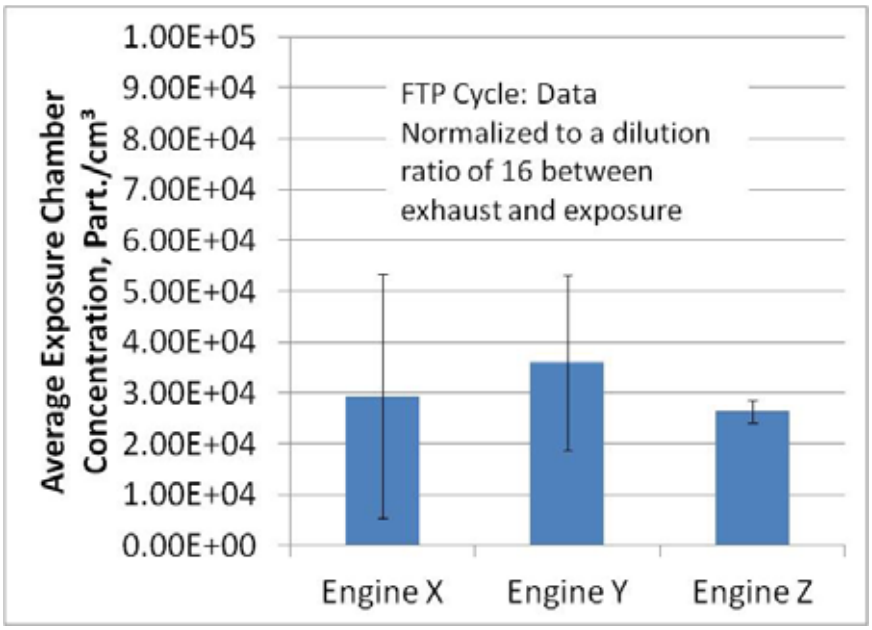

FIGURE 40. AVERAGE PARTICLE NUMBER CONCENTRATION IN EXPOSURE CHAMBER (FTP)

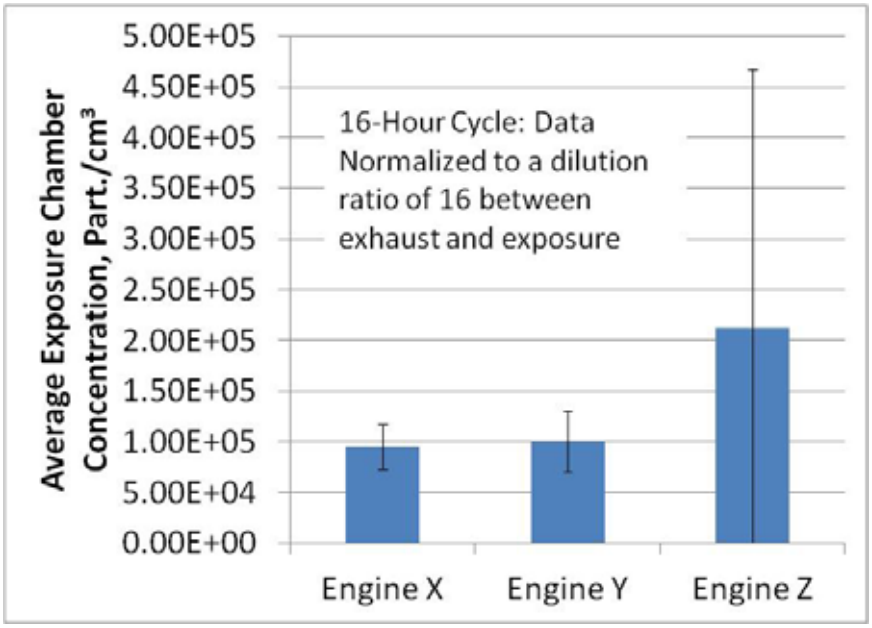

FIGURE 41. AVERAGE PARTICLE NUMBER CONCENTRATION IN EXPOSURE CHAMBER (16-HOUR)

6.8 Carbonyl Emissions

Figure 42 shows the carbonyl emissions species for the 16-Hour. Carbonyl emissions were dominated by formaldehyde and acetaldehyde. Figure 43 summarizes the emissions of total carbonyl emissions for all engines and cycles. We also compared (Figure 44) the emissions of carbonyls with those emitted from 2007 technology engines. We observed an 80% reduction

with the 2010 technology engines, compared to the 2007 technology engines used in ACES Phase 1.

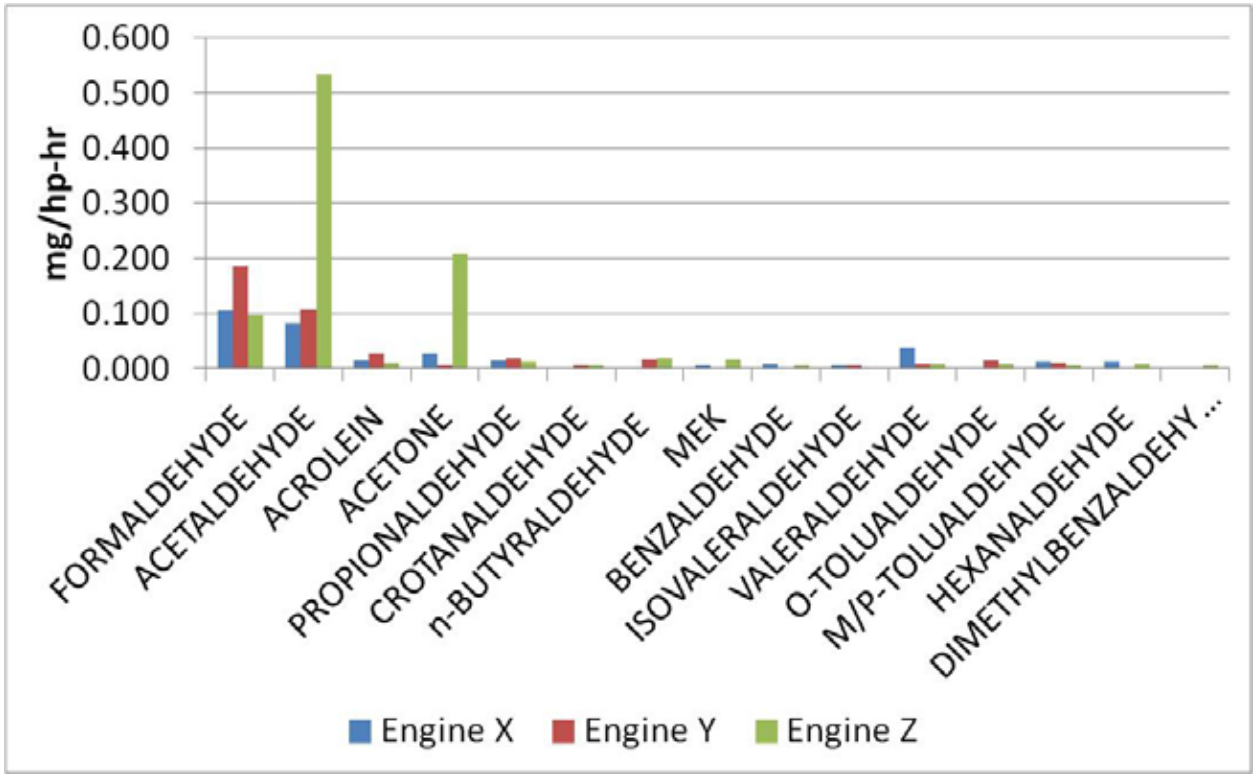

FIGURE 42. CARBONYLS SPECIES EMISSIONS FOR THE 16-HOUR

Test Cycle		Total Aldehydes, mg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	0.544	1.453	1.835
	2	0.929	0.410	1.419
	3	0.463	0.273	0.748
	Avg	0.646	0.712	1.334
	Stdev	0.249	0.645	0.549
	COV	39%	91%	41%
16-Hour	1	0.364	0.235	0.518
	2	0.146	0.447	2.022
	3	0.278	0.437	0.228
	Avg	0.262	0.373	0.922
	Stdev	0.110	0.119	0.963
	COV	42%	32%	104%

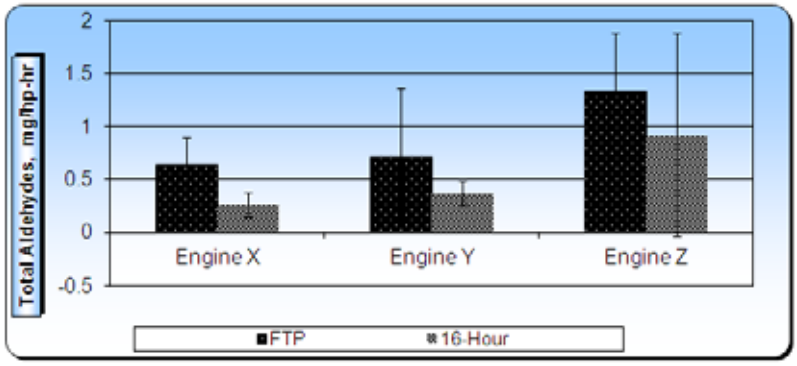

FIGURE 43. CARBONYLS EMISSIONS FOR THE FTP AND 16-HOUR

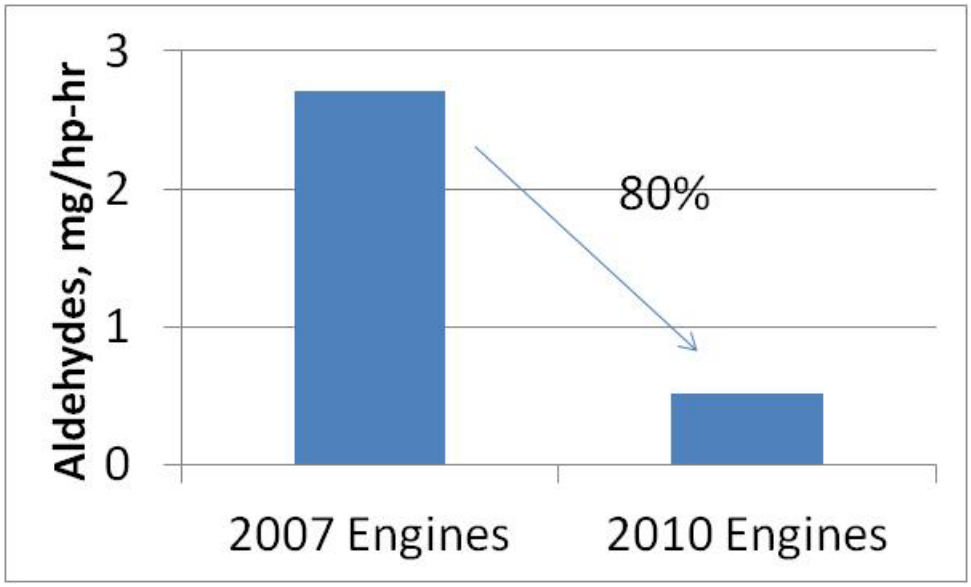

FIGURE 44. CARBONYLS EMISSIONS REDUCTION BETWEEN 2007 AND 2010 TECHNOLOGY ENGINES (16-HOUR)

6.9 Volatile Organic Compounds (VOC) Speciation-C_1-C_{12}

Figure 45 summarizes the emissions of benzene, toluene, ethylbenzene, and mixed xylenes (BTEX) for the different engines using the 16-Hour. The rise in ethylbenzene and mixed xylenes with Engine Z occurred only during the third 16-Hour run, where we observed the rise of in other emissions such as OC and sulfate. It is worth noting here that BTEX was below detection for the FTP. Figure 46 summarizes the BTEX emissions, and Figure 47 shows that the BTEX emissions for the 2010 technology engines were 50% lower than those emitted from 2007 technology engines.

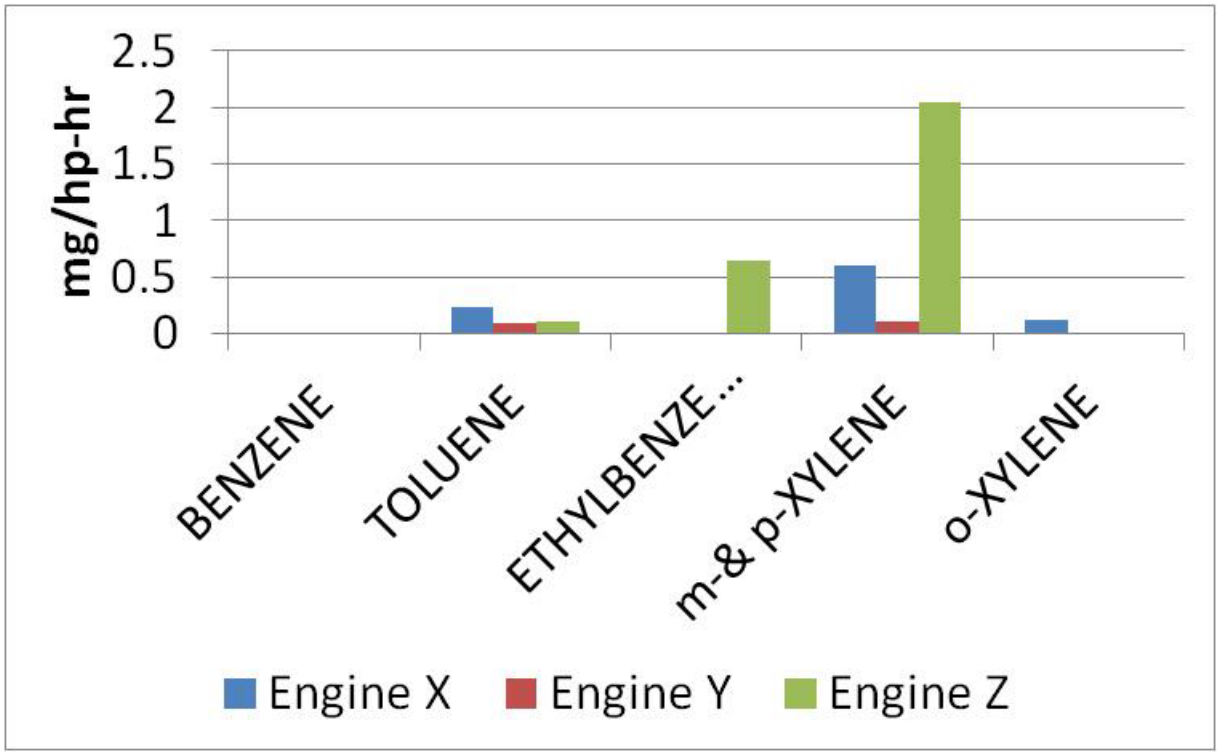

FIGURE 45. BTEX SPECIES EMISSIONS FOR THE 16-HOUR

Test Cycle		BTEX, mg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	ND	ND	ND
	2	ND	ND	ND
	3	ND	ND	ND
	Avg	ND	ND	ND
	Stdev	na	na	na
	COV	na	na	na
16-Hour	1	1.000	0.091	0.109
	2	0.933	0.076	ND
	3	0.733	0.231	2.685
	Avg	0.889	0.133	1.397
	Stdev	0.139	0.085	1.822
	COV	16%	64%	130%

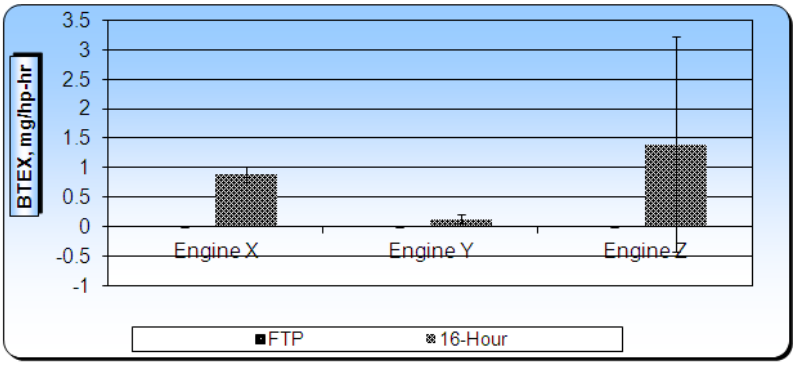

FIGURE 46. BTEX EMISSIONS FOR THE 16-HOUR

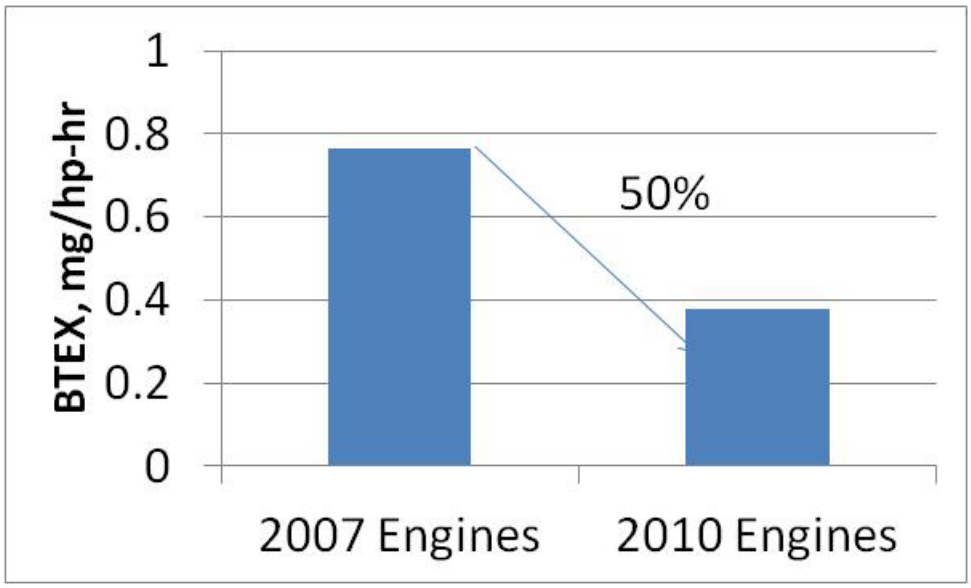

FIGURE 47. BTEX EMISSIONS REDUCTION BETWEEN 2007 AND 2010 TECHNOLOGY ENGINES (16-HOUR)

6.10 Alkanes

As shown in Figure 48, alkanes are mainly found in the fuel at a much higher percentage than in the lube oil. Figure 49 shows total alkane emissions. The emissions were comparable between the FTP and 16-Hour ranging from 76 to 137 µg/hp-hr. Substantial emission reductions of alkanes (92% reductions) was observed when the emissions were compared to those emitted from 2007 technology engines, as shown in Figure 50.

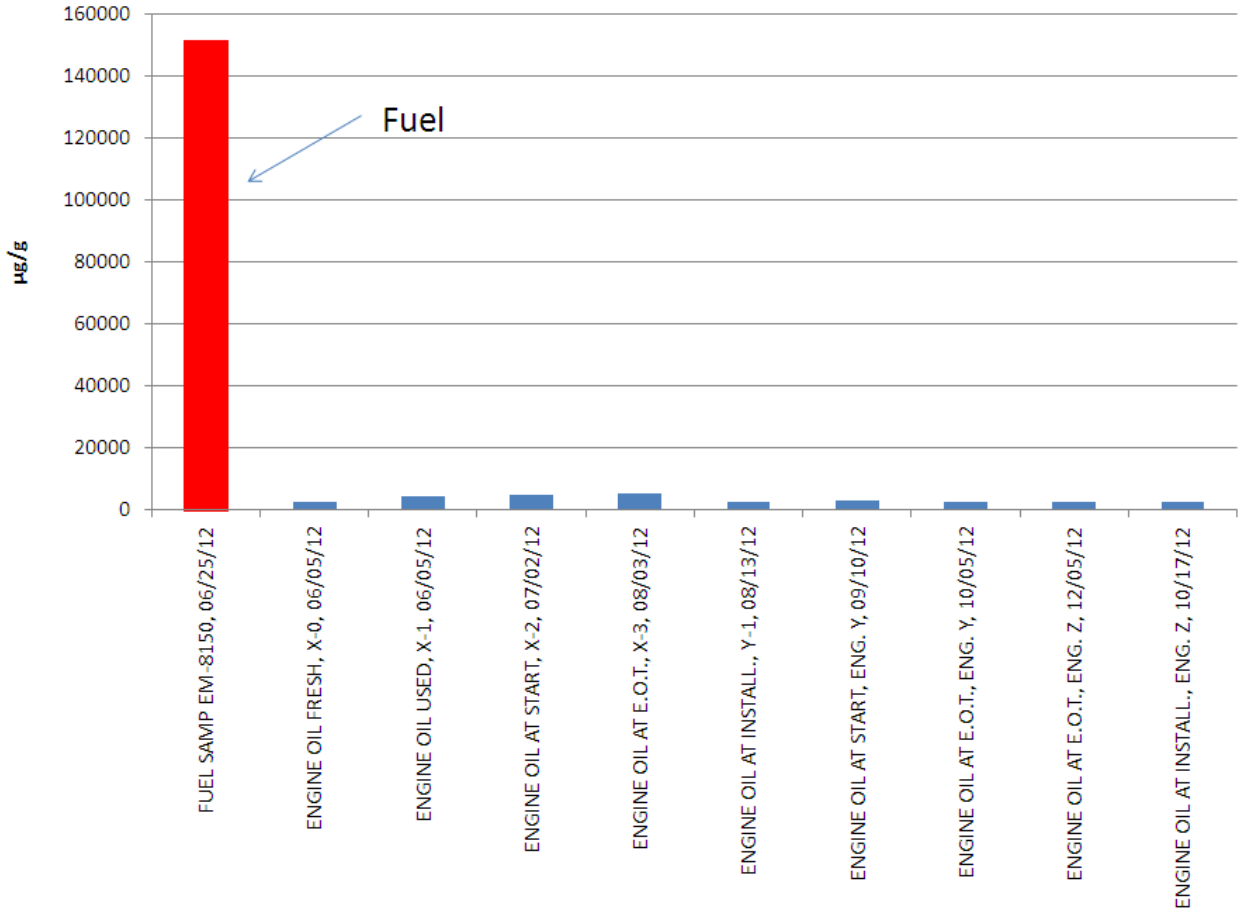

FIGURE 48. TOTAL ALKANES IN DIESEL FUEL AND LUBE OIL

Test Cycle		Total Alkanes, µg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	59.6	169.2	94.5
	2	80.1	133.0	135.7
	3	105.5	109.2	77.4
	Avg	81.7	137.1	102.5
	Stdev	23.0	30.2	29.9
	COV	28%	22%	29%
16-Hour	1	8.3	83.5	101.6
	2	98.2	199.1	131.5
	3	124.3	92.1	132.1
	Avg	76.9	124.9	121.7
	Stdev	60.9	64.4	17.4
	COV	79%	52%	14%

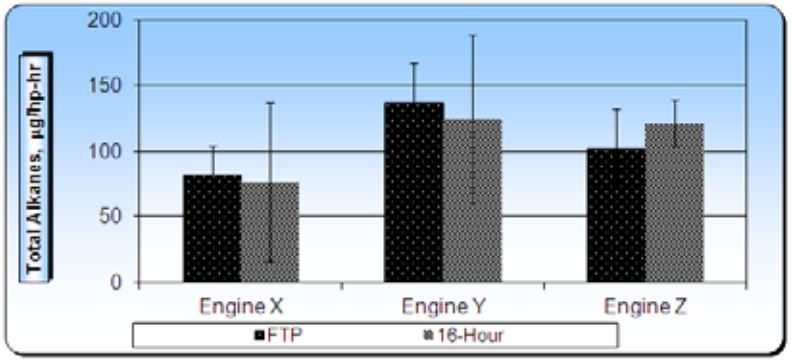

FIGURE 49. ALKANES EMISSIONS FOR THE FTP AND 16-HOUR

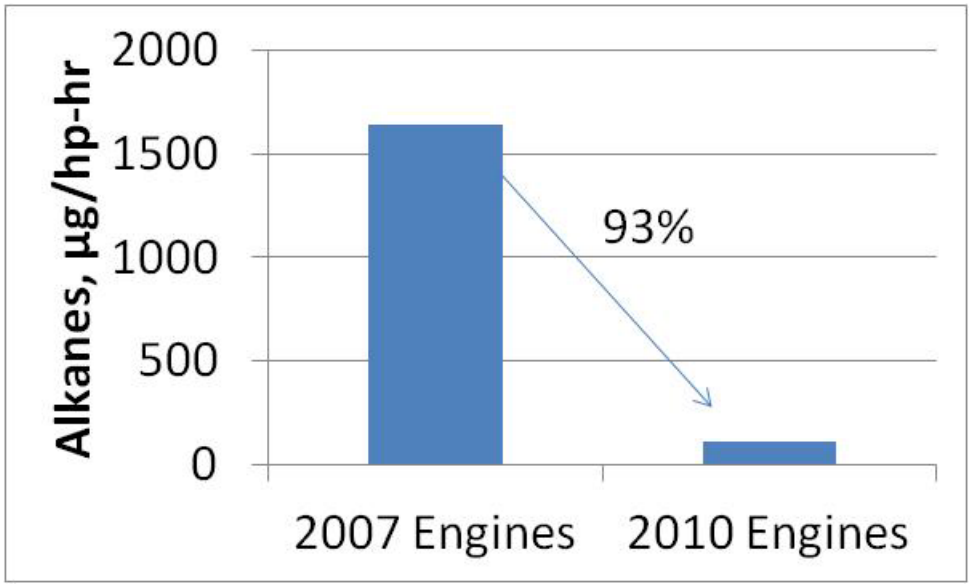

FIGURE 50. ALKANES EMISSIONS REDUCTION BETWEEN 2007 AND 2010 TECHNOLOGY ENGINES (16-HOUR)

6.11 Alcohol and Organic Acid

Figure 51 shows a summary of the alcohol and organic acid compounds reported as brake-specific emissions. The emissions ranged between 26 and 58 µg/hp-hr for the 16-Hour, and were higher for the FTP. The same trend was observed with 2007 technology engines. However, 2010 technology engines reduced the emissions as shown in Figure 52. 2010 technology engines reduced the emissions of alcohols and organic acid by 96% relative to 2007 technology engines.

Test Cycle		Polar Compounds, µg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	178.8	835.9	43.7
	2	300.1	421.0	518.8
	3	620.3	949.3	385.3
	Avg	366.4	735.4	315.9
	Stdev	228.1	278.1	245.0
	COV	62%	38%	78%
16-Hour	1	8.9	62.6	56.2
	2	22.4	35.0	48.2
	3	48.9	24.5	69.9
	Avg	26.7	40.7	58.1
	Stdev	20.3	19.7	11.0
	COV	76%	48%	19%

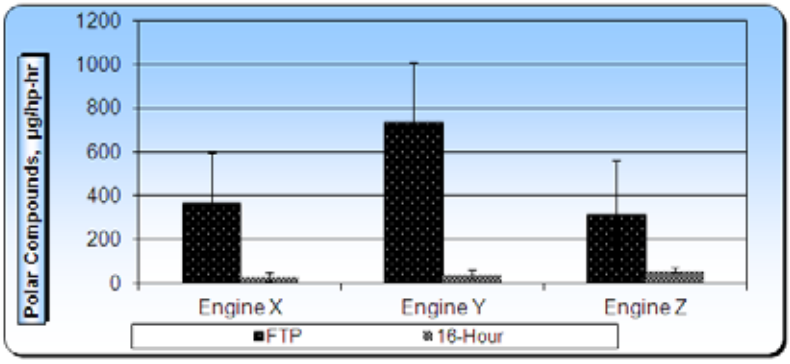

FIGURE 51. ALCOHOLS AND ORGANIC ACID EMISSIONS FOR THE FTP AND 16-HOUR

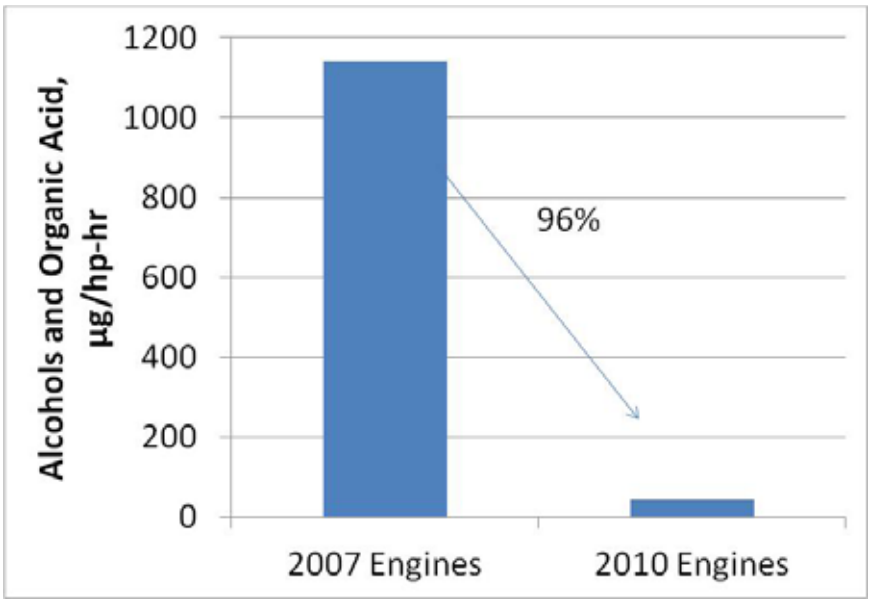

FIGURE 52. ALCOHOLS AND ORGANIC ACID EMISSIONS REDUCTION BETWEEN 2007 AND 2010 TECHNOLOGY ENGINES (16-HOUR)

6.12 Polynuclear Aromatic Hydrocarbon (PAH) Compounds

As shown in Figure 53, PAH compounds are mainly found in the fuel at a much higher percentage than in lube oil. Summaries of the emissions of PAH, nitro-PAH and oxy-PAH for the 16-Hour are shown in Figures 54, 55, and 56, respectively. Figure 57 shows the reduction of those compounds compared to 2007 technology engines. The reductions were 96% for total PAH, 97% for oxyPAH and 99% for nitroPAH.

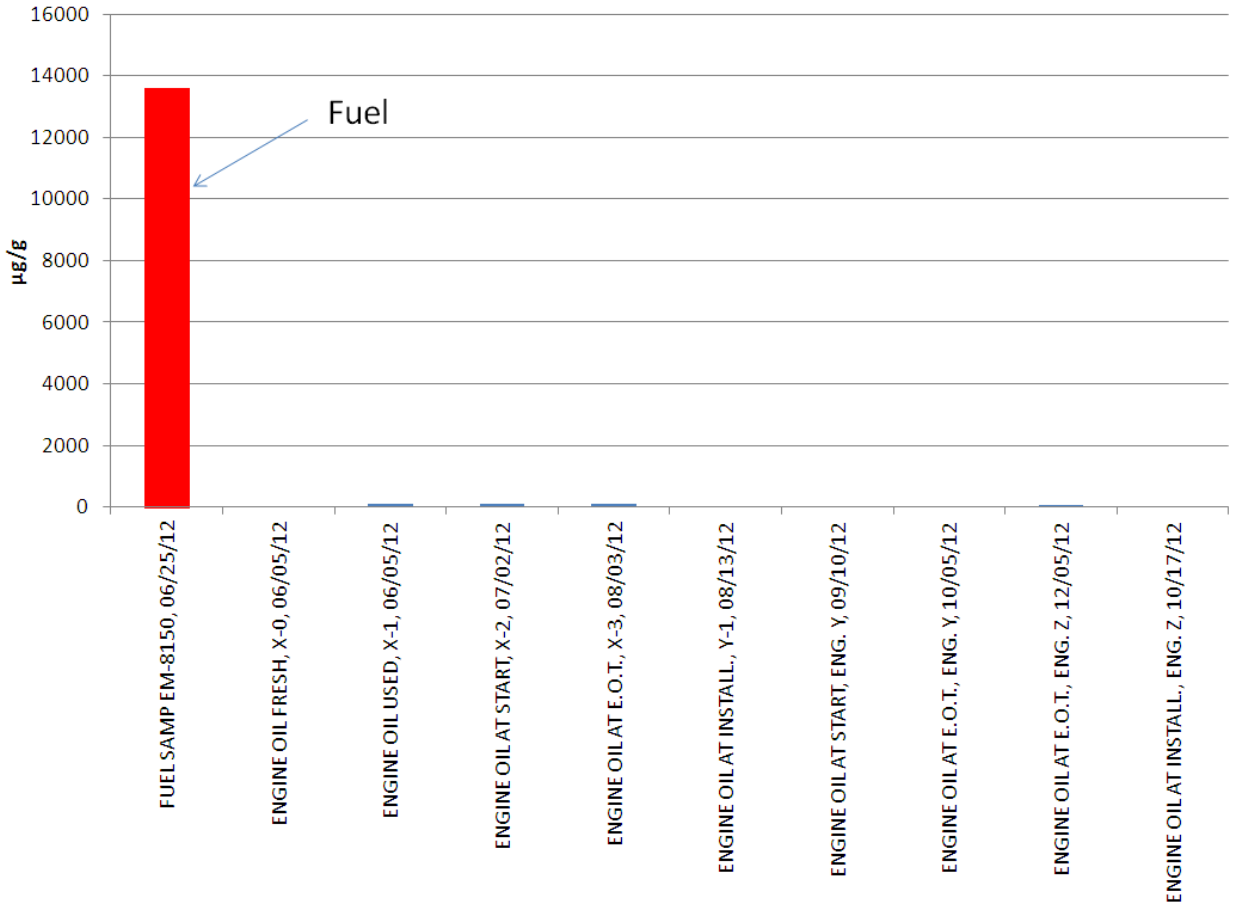

FIGURE 53. TOTAL PAH COMPOUNDS IN DIESEL FUEL AND LUBE OIL

Test Cycle		Total PAH, µg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	15.78	32.96	19.97
	2	34.21	44.39	26.75
	3	46.82	65.71	14.34
	Avg	32.270	47.686	20.356
	Stdev	15.609	16.620	6.215
	COV	48%	35%	31%
16-Hour	1	2.77	11.13	25.23
	2	19.66	19.35	32.82
	3	31.63	14.54	36.27
	Avg	18.020	15.008	31.438
	Stdev	14.497	4.130	5.645
	COV	80%	28%	18%

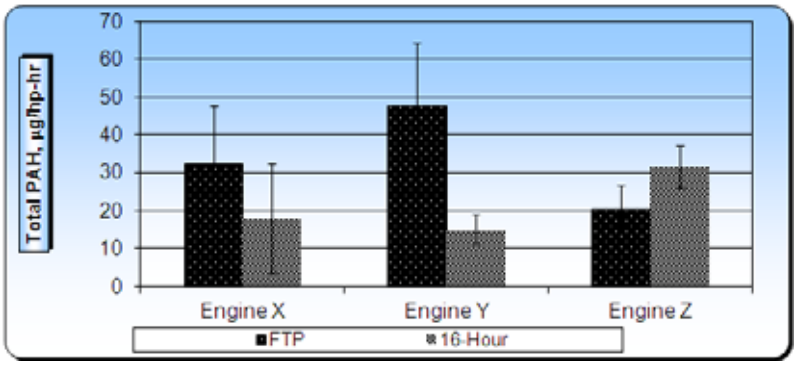

FIGURE 54. PAH EMISSIONS FOR THE FTP AND 16-HOUR

Test Cycle		Nitro PAH, µg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	0.18	0.02	0.03
	2	0.12	0.07	0.05
	3	0.33	0.19	0.01
	Avg	0.209	0.095	0.029
	Stdev	0.111	0.083	0.016
	COV	53%	88%	54%
16-Hour	1	0.00	0.01	0.01
	2	0.01	0.02	0.01
	3	0.01	0.02	0.01
	Avg	0.005	0.015	0.010
	Stdev	0.003	0.005	0.001
	COV	56%	31%	14%

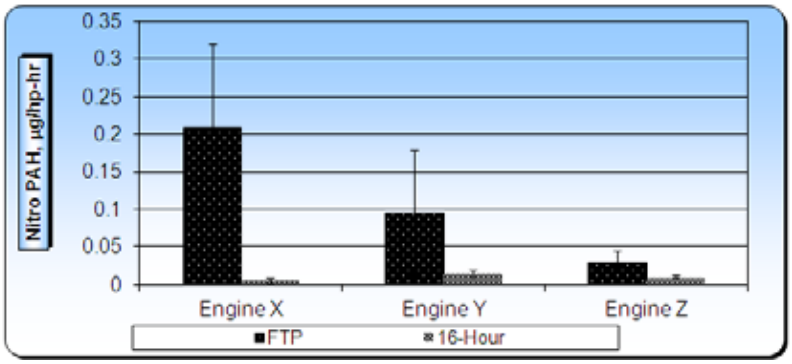

FIGURE 55. NITRO-PAH EMISSIONS FOR THE FTP AND 16-HOUR

Test Cycle		Oxy PAH, µg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	0.05	0.06	0.04
	2	0.50	0.14	0.07
	3	0.95	0.31	0.01
	Avg	0.498	0.171	0.040
	Stdev	0.451	0.127	0.032
	COV	91%	75%	80%
16-Hour	1	0.01	0.11	0.11
	2	0.09	0.19	0.14
	3	0.14	0.16	0.14
	Avg	0.081	0.152	0.130
	Stdev	0.068	0.041	0.014
	COV	83%	27%	11%

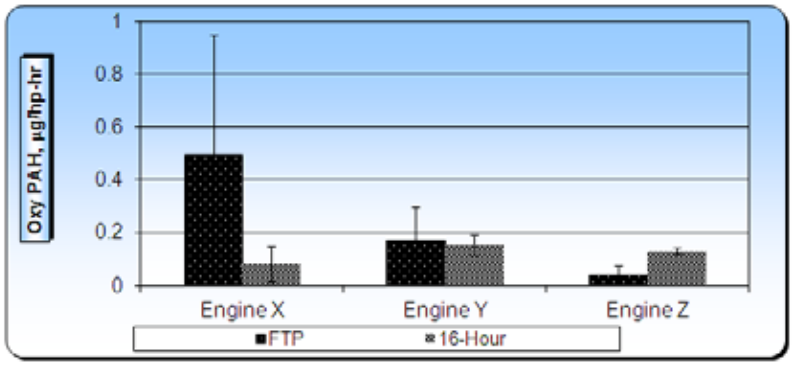

FIGURE 56. OXY-PAH EMISSIONS FOR THE FTP AND 16-HOUR

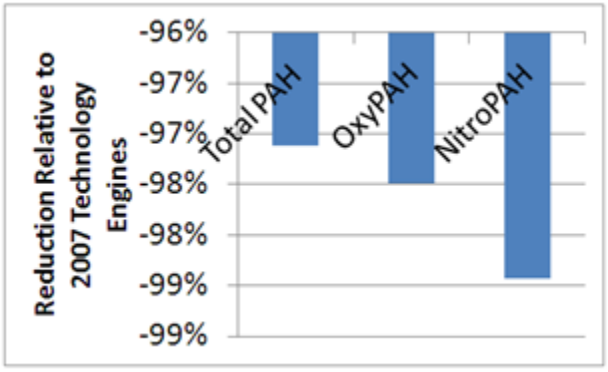

FIGURE 57. PAH EMISSIONS REDUCTION BETWEEN 2007 AND 2010 TECHNOLOGY ENGINES (16-HOUR)

6.13 Hopanes and Steranes

As shown in Figure 58, hopanes and steranes are mainly lube oil components with virtually no detection in the fuel. Figure 59 and 60 summarize the results for hopanes and steranes for the FTP and 16-Hour. Figure 61 shows the substantial reduction observed in hopanes

(83%) and steranes (95%) with the 2010 technology engines, compared to the 2007 technology engines used in ACES Phase 1.

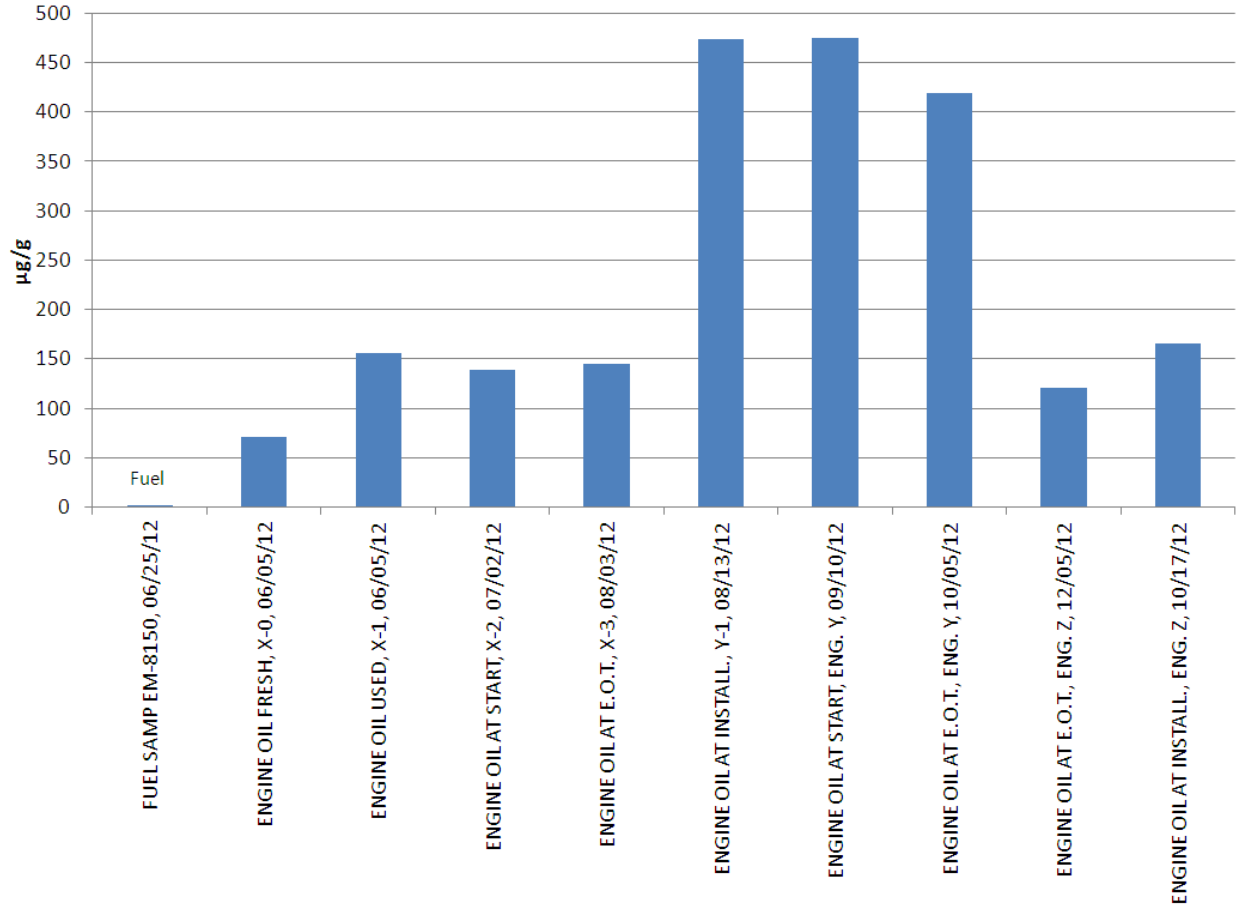

FIGURE 58. TOTAL HOPANES AND STERANES IN DIESEL FUEL AND LUBE OIL

Test Cycle		Hopanes, µg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	0.10	0.07	0.17
	2	0.08	0.03	0.25
	3	0.11	0.05	0.13
	Avg	0.095	0.050	0.181
	Stdev	0.017	0.020	0.061
	COV	17%	41%	34%
16-Hour	1	0.02	0.02	0.22
	2	0.03	0.07	0.10
	3	0.03	0.06	0.12
	Avg	0.024	0.050	0.146
	Stdev	0.008	0.022	0.062
	COV	31%	45%	42%

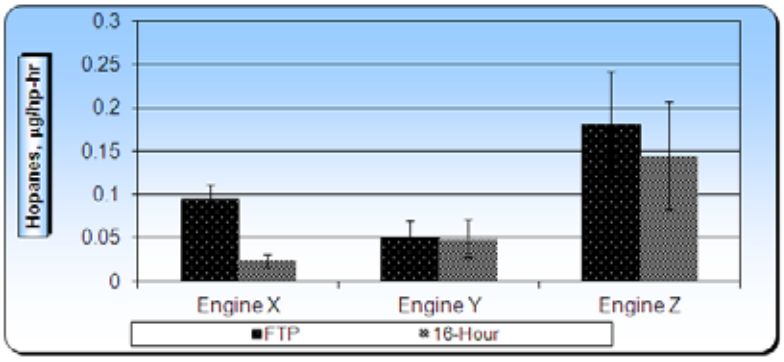

FIGURE 59. HOPANES EMISSIONS FOR THE FTP AND 16-HOUR

Test Cycle		Steranes, µg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	0.03	0.03	0.05
	2	0.05	0.03	0.07
	3	0.10	0.09	0.03
	Avg	0.059	0.048	0.049
	Stdev	0.033	0.036	0.019
	COV	56%	75%	39%
16-Hour	1	0.01	0.01	0.06
	2	0.01	0.02	0.03
	3	0.01	0.02	0.04
	Avg	0.007	0.014	0.043
	Stdev	0.002	0.005	0.016
	COV	22%	34%	38%

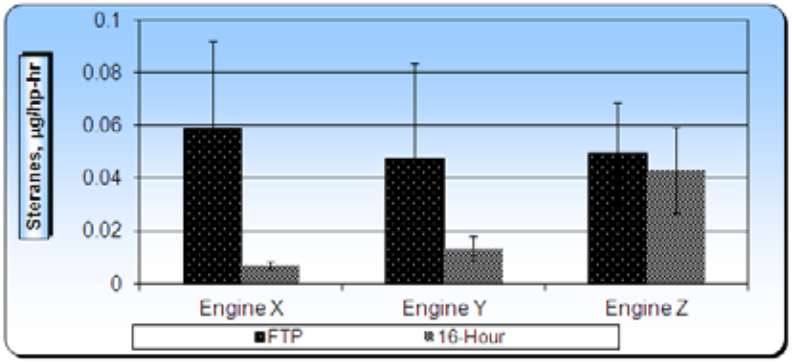

FIGURE 60. STERANES EMISSIONS FOR THE FTP AND 16-HOUR

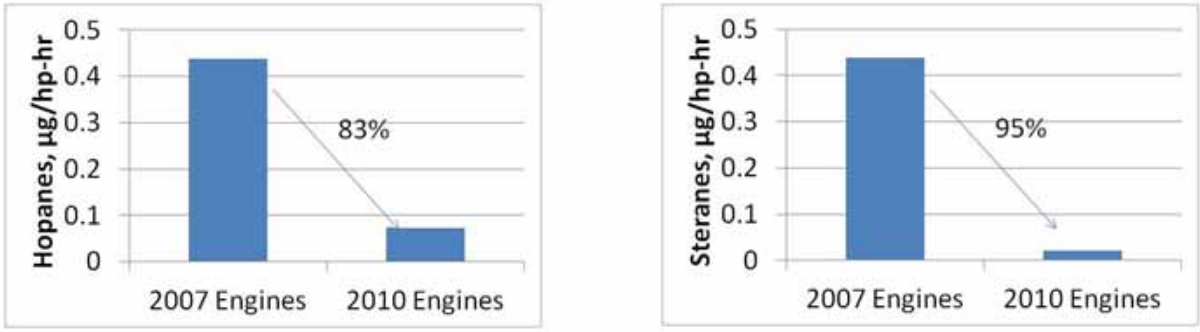

FIGURE 61. HOPANES AND STERANES EMISSIONS REDUCTION BETWEEN 2007 AND 2010 TECHNOLOGY ENGINES (16-HOUR)

6.14 Dioxins and Furans

Figure 62 shows the toxic equivalent (TEQ) brake-specific emissions of 17 dioxin and furan compounds, for Engines X, Y, and Z, respectively. Out of the 17 compounds, 14 were detected with Engine Z, 8 with Engine Y, and 4 with Engine X. The majority of the species detected were in the gas phase rather than in the particle phase. Figure 63 shows the total brake-specific emissions that ranged from 0.004 pg/hp-hr for Engine X, to 0.032 pg/hp-hr for Engine Y, and 0.196 pg/hp-hr for Engine Z. The emissions were extremely low, representing an 88% reduction relative to 2007 technology engines, as shown in Figure 64. In ACES Phase 1, we already showed that dioxins and furans emissions were substantially lower than 1998 technology engines. The 2010 technology engines showed even more reduction, thus minimizing any potential concerns associated with SCR catalyst promotion of dioxins and furans.

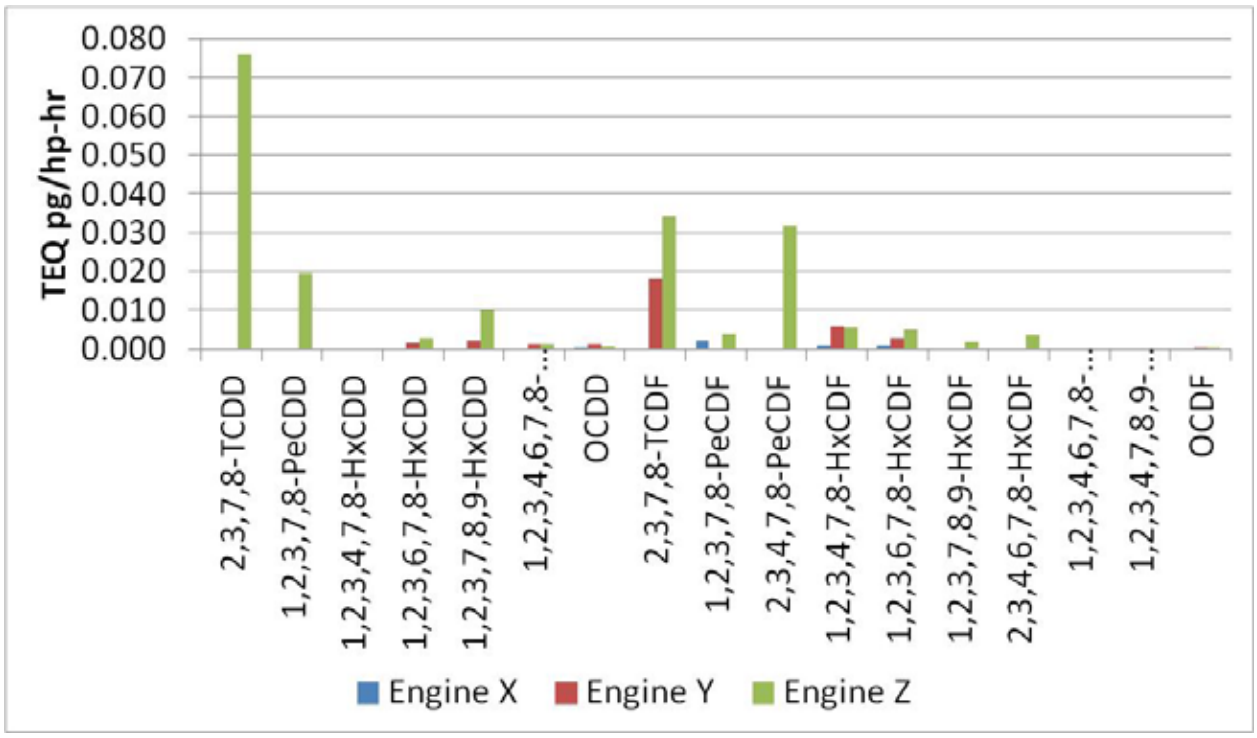

FIGURE 62. DIOXINS AND FURANS EMISSIONS SPECIES (16-HOUR)

Test Cycle		Dioxins and Furans, pg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	-	-	-
	2	-	-	-
	3	-	-	-
	Avg	ND	ND	ND
	Stdev	na	na	na
	COV	na	na	na
16-Hour	1	0.004	0.032	0.196
	2	-	-	-
	3	-	-	-
	Avg	0.004	0.032	0.196
	Stdev	na	na	na
	COV	na	na	na

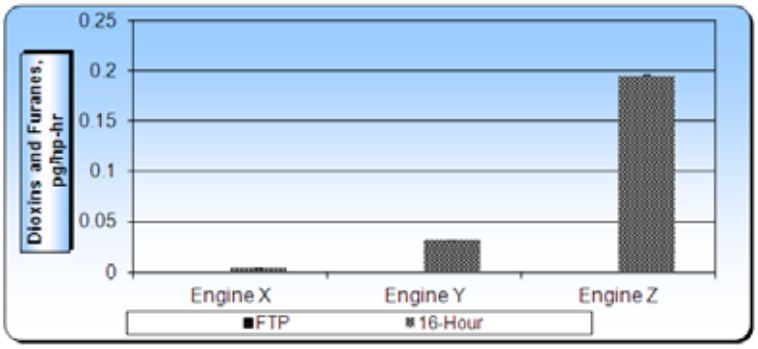

FIGURE 63. DIOXINS AND FURANS EMISSIONS FOR THE 16-HOUR

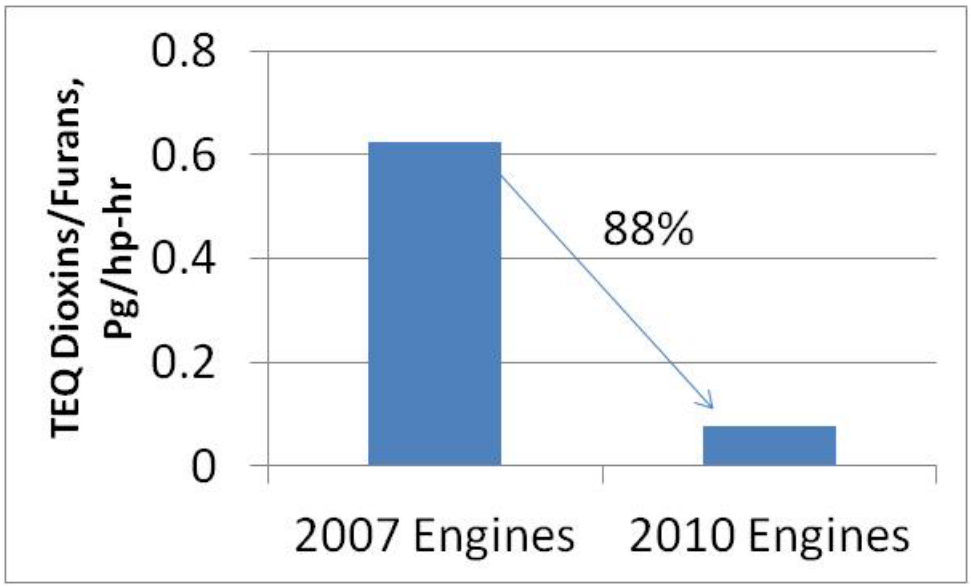

FIGURE 64. DIOXINS AND FURANS EMISSIONS REDUCTION BETWEEN 2007 AND 2010 TECHNOLOGY ENGINES (16-HOUR)

6.15 Cyanide, Sulfide, and Hexavalent Chromium

The emissions for cyanide, sulfide, and hexavalent chromium were all below the lowest detection limits, which were about 45, 90, and 9 µg/hp-hr, respectively, for the 16-Hour.

6.16 Nitrosamines

Figure 65 shows a summary of total nitrosamines and Figure 66 shows that nitrosamines are emitted at much lower levels than those emitted from 2007 technology engines. 2010 technology engines reduced nitrosamines by more than 99%, relative to 2007 technology engines.

Test Cycle		Nitrosamines, µg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	5.29	4.20	1.49
	2	4.22	2.70	2.42
	3	3.58	2.79	2.31
	Avg	4.361	3.230	2.073
	Stdev	0.866	0.839	0.511
	COV	20%	26%	25%
16-Hour	1	0.09	0.02	0.05
	2	0.06	0.04	0.04
	3	0.07	0.08	0.05
	Avg	0.073	0.049	0.046
	Stdev	0.014	0.030	0.008
	COV	19%	61%	18%

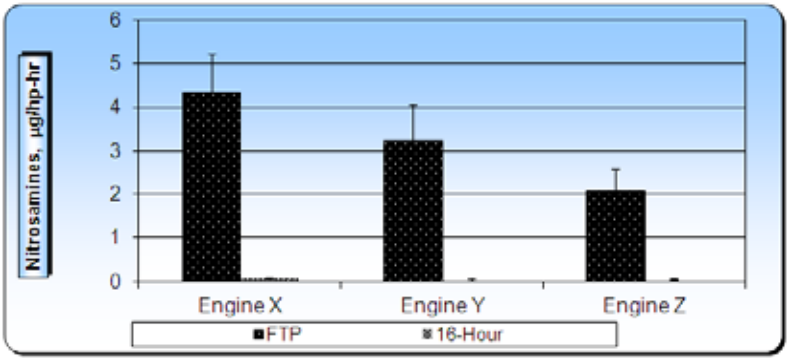

FIGURE 65. NITROSAMINES EMISSIONS FOR THE 16-HOUR

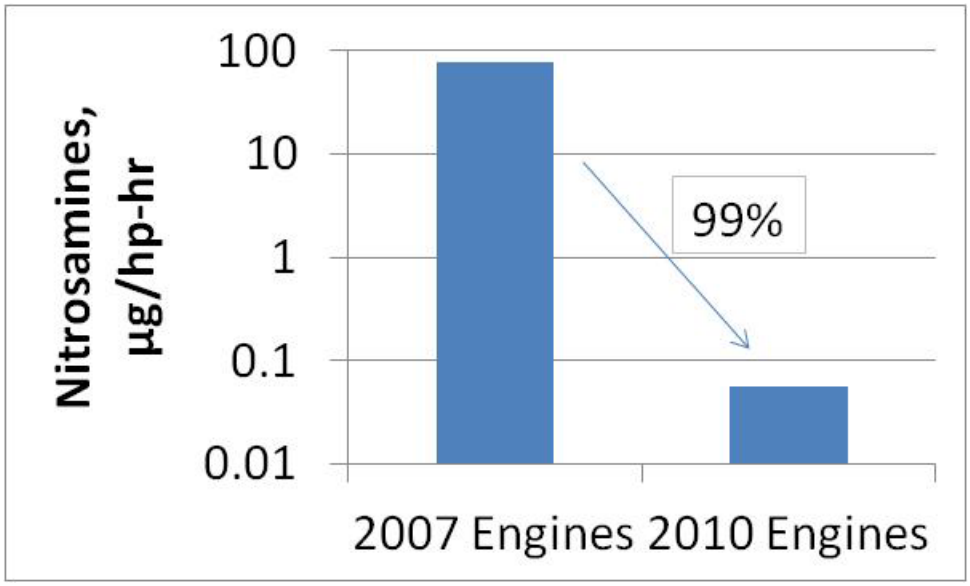

FIGURE 66. NITROSAMINES EMISSIONS REDUCTION BETWEEN 2007 AND 2010 TECHNOLOGY ENGINES (16-HOUR)

6.17 Selected Volatile Organic Compounds

Figure 67 shows the brake-specific emissions of selected VOCs. These included carbonyl sulfide (COS), nitromethane, nitroethane, 2-nitropropane, and 1-nitropropane. In general these compounds were below the limit of detection of 1 to 4 ppb.

Test Cycle		SUMMA VOCs, mg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	ND	ND	2.18
	2	ND	6.67	ND
	3	ND	ND	ND
	Avg	ND	6.67	2.18
	Stdev	na	na	na
	COV	na	na	na
16-Hour	1	ND	ND	ND
	2	ND	ND	ND
	3	ND	5.82	ND
	Avg	ND	5.82	ND
	Stdev	na	na	na
	COV	na	na	na

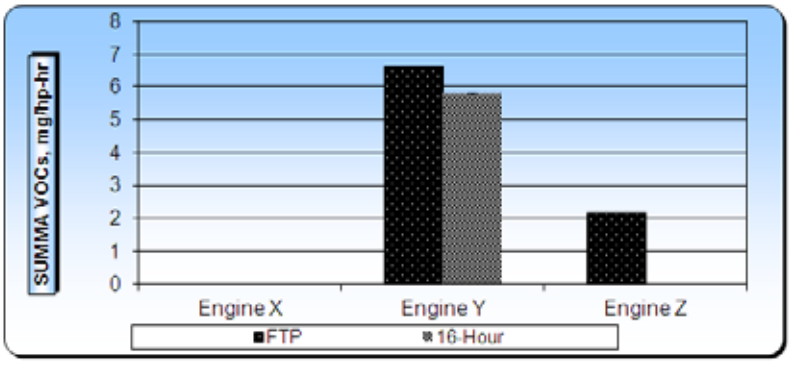

FIGURE 67. SELECTED VOC EMISSIONS

6.18 Particle Phase Urea-Related Compounds

Particle phase urea compounds were analyzed by ORNL. Those compounds were not analyzed in ACES Phase 1 because they are derived from 2010 technology engines equipped with SCR. Out of the six urea-related compounds that included urea, melamine, cyanuric acid, ammelide, ammeline, and biuret, only urea and cyanuric acid were detected for the 16-Hour, but the emissions were very low. As shown in Figures 68 and 69, urea emissions ranged from 0.04 µg/hp-hr for Engine Z to 1.49 µg/hp-hr for Engine X. Engine Y emissions were 1.09 µg/hp-hr. Cyanuric acid emissions ranged from 4.8 µg/hp-hr with Engine X to 15.5 µg/hp-hr for Engine Z.

Engine Y emissions were 6.4 µg/hp-hr. The highest exhaust concentration of cyanuric acid calculated based on this work is about 18 ppb by mass.

Test Cycle		Urea, µg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	N/A	N/A	N/A
	2	N/A	N/A	N/A
	3	N/A	N/A	N/A
	Avg	N/A	N/A	N/A
	Stdev	N/A	N/A	N/A
	COV	N/A	N/A	N/A
16-Hour	1	2.01	3.28	0.00
	2	0.77	0.00	0.12
	3	1.69	0.00	0.00
	Avg	1.49	1.09	0.04
	Stdev	0.64	1.89	0.07
	COV	43%	173%	173%

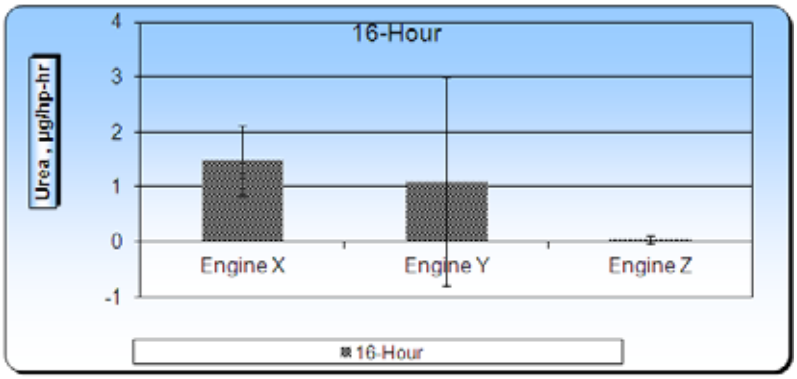

FIGURE 68. UREA EMISSIONS FOR (16-HOUR)

Test Cycle		Cyanauric Acid, µg/hp-hr		
		Engine X	Engine Y	Engine Z
FTP	1	N/A	N/A	N/A
	2	N/A	N/A	N/A
	3	N/A	N/A	N/A
	Avg	N/A	N/A	N/A
	Stdev	N/A	N/A	N/A
	COV	N/A	N/A	N/A
16-Hour	1	0.0	14.1	26.2
	2	4.1	1.1	2.0
	3	10.4	4.1	18.3
	Avg	4.8	6.4	15.5
	Stdev	5.2	6.8	12.3
	COV	108%	106%	80%

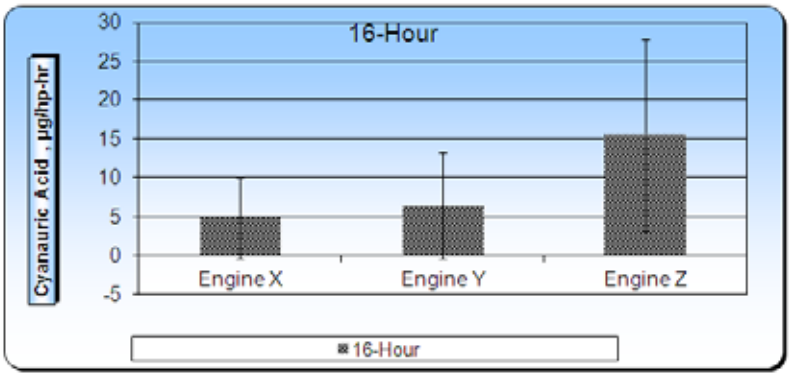

FIGURE 69. CYANURIC ACID EMISSIONS (16-HOUR)

7.0 SUMMARY

ACES Phase 2 engine testing started in March, 2012. Three model year 2011 heavy-duty on-highway diesel engines were characterized for regulated and unregulated emissions using the FTP and the 16-Hour. Each of the engines complied with EPA 2010 standards, and was equipped with a DOC+DPF+SCR+AMOX in the exhaust system. One batch of refinery ULSD fuel (6.5 ppm sulfur content) was used throughout this program along with one batch of CJ-4 15W40 lube oil provided by Lubrizol. Also, one batch of commercial grade urea was used for urea injection upstream of the SCR catalysts. In general, 2010 technology engines showed substantial reductions in regulated and unregulated emissions species versus the emission standards, 2007-compliant engines, and pre-2007 technology engines. Below is a summary of the key results:

- Regulated emissions of NO_X, NMHC, CO, and PM were 61%, 100%, 97%, and 92% below the 2010 emission standards, respectively.
- Greenhouse gas emissions resulted in no increase in global warming potential, when compared to 2007 technology engines. The improved fuel economy and lower average CO_2 emission with the 2010 technology engines were offset by a rise in N_2O emissions. However, N_2O remained 30% below the EPA 2014 emissions limit.
- Unregulated emissions that included single ring aromatics, PAH, oxyPAH, nitroPAH, alkanes, alcohol and organic acids, hopanes/steranes, carbonyls, metals and elements, organic carbon, elemental carbon, dioxins and furans were 50% to 99% percent lower than those emitted from 2007 technology engines tested in ACES Phase 1.
- In contrast to 2007 technology engines, no active DPF regenerations were encountered throughout this work, including the 16-Hour. This resulted in a PM composition that is virtually sulfate-free, with some levels of elemental carbon, organic carbon, nitrate and ammonium, with the latter two compounds being urea-SCR derived species.
- Average particle number emissions were 41% to 72% lower than those observed with the 2007 technology engines used in ACES Phase 1, and one to two orders of magnitude lower than those emitted from typical 2004 technology engines.
- Only two out of six particle-phase urea-related compounds were detected. But, even the ones that were detected such as urea and cyanuric acid had an extremely low emissions level.

The observed reductions in PM (total mass, soot, and number) and unregulated emissions from 2007 to 2010 engines are likely due to differences in active DPF regeneration operation. The 2007 engines triggered multiple regeneration events during the 16-hour cycles, while the 2010 engines did not trigger any events. The improvement/reduction in regeneration was achieved through some combination of lower engine-out PM, increased passive regeneration and improved control strategies. PM emissions during regeneration events have been observed to be higher than normal operation for the 2007 engines used in ACES Phase 1. Unregulated emissions are believed to be higher during regeneration events. Thus, the results from the 2007 engines include emissions measured over both normal (no active regeneration) and regeneration operation, while the results from the 2010 engines only include emissions measured over normal operation. DPF active regeneration would have occurred had the 2010 engines been run for a much longer period of time (100 or more hours). The 2010 engines did not trigger a regeneration event even after three back-to-back 16-hour cycles (48 hours of operation).

According to the engine manufacturers, the process and length of time for DPF active regeneration is expected to be similar for 2010 and 2007 engines. Therefore, the emissions during regeneration events are expected to be similar except for any differences due to increased loading of certain species like sulfur and heavy molecular weight hydrocarbons that are not oxidized by the aftertreatment system. Since 2010 engines have fewer regeneration events, the PM and unregulated emissions averaged over both normal and active regeneration operation are expected to be lower than 2007 engines. While it is not known how much the average PM and unregulated emissions on the 2010 engines may have increased if the test were continued to include regeneration events, the consensus of this study's principal investigator and its sponsors is that the 2010 engines' PM and unregulated emissions averaged over both normal and active regeneration operation are somewhere between the results measured during normal operation and the results measured on the 2007 engines over both normal and active regeneration operation.

Finally, all analyzed species including second-by-second data will be posted on the publically accessible CRC website at http://www.crcao.org.

FEBRUARY 2012

HEI Communication 17

HEALTH EFFECTS INSTITUTE

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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Health Effects Institute
Boston, Massachusetts

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ABOUT HEI

The Health Effects Institute is a nonprofit corporation chartered in 1980 as an independent research organization to provide high-quality, impartial, and relevant science on the effects of air pollution on health. To accomplish its mission, the institute

- 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.

HEI's independent Board of Directors consists of leaders in science and policy who are committed to fostering the public–private partnership that is central to the organization. The Health Research Committee solicits input from HEI sponsors and other stakeholders and works with scientific staff to develop a Five-Year Strategic Plan, select research projects for funding, and oversee their conduct. The Health Review Committee, which has no role in selecting or overseeing studies, works with staff to evaluate and interpret the results of funded studies and related research.

All project results and accompanying comments by the Health Review Committee are widely disseminated through HEI's Web site (*www.healtheffects.org*), printed reports, newsletters and other publications, annual conferences, and presentations to legislative bodies and public agencies.

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PREFACE

HEI's Advanced Collaborative Emissions Study

BACKGROUND

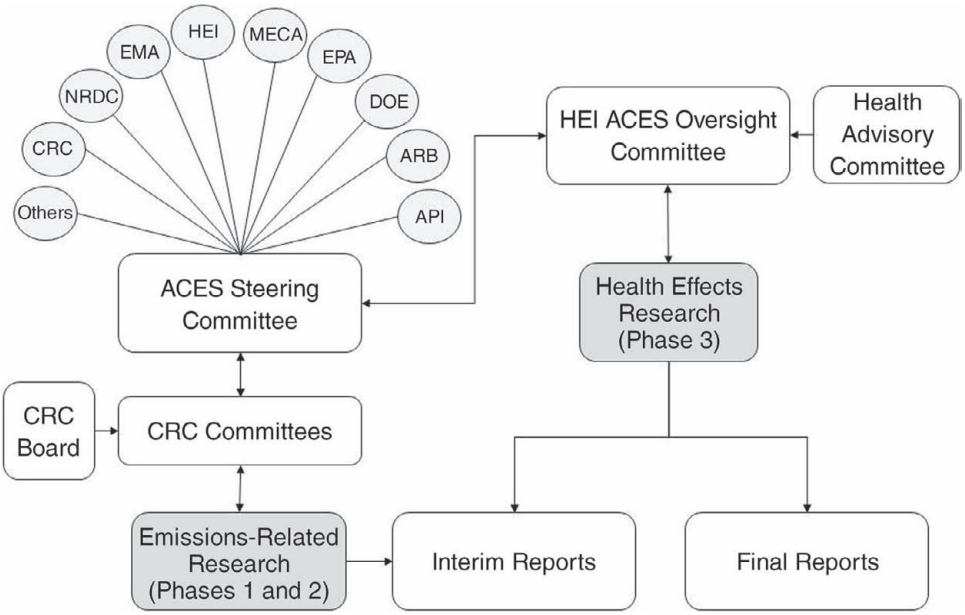
Because of health concerns related to exposure to diesel exhaust emissions, the U.S. Environmental Protection Agency (EPA*) and the California Air Resources Board (CARB) in 2001 adopted stringent new standards for diesel fuel and for heavy-duty diesel engine emissions. In 2007, engines were required 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).

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.

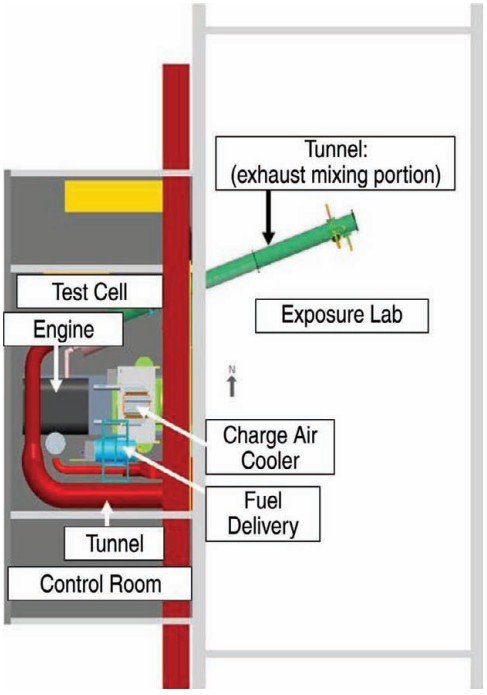

Figure 1. Overhead view of the engine laboratory and dilution tunnel. The tunnel portions shown in red are upstream from the engine exhaust mixing. The exhaust mixing portion is green, and the extraction point for the exposure chamber distribution system is at the end of the dilution tunnel (the remainder 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.

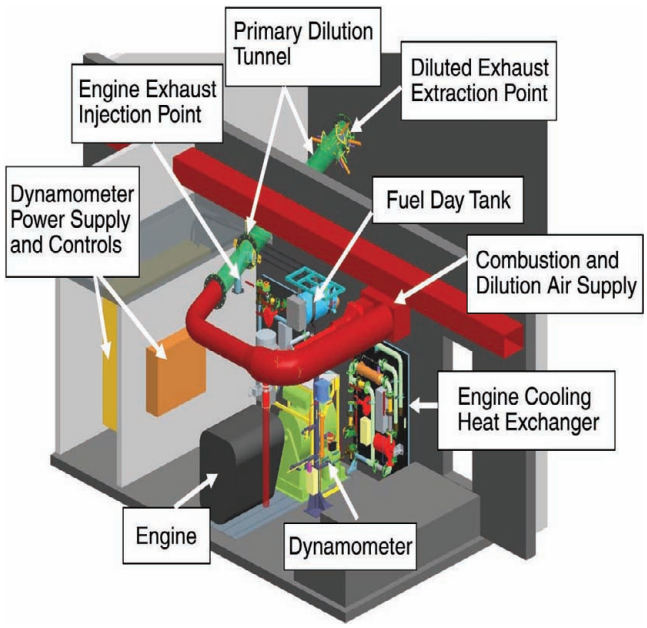

Figure 2. Front quarter view of engine laboratory and dilution tunnel. The tunnel portions shown in red come before the mixing of the engine exhaust. The green area shows the exhaust mixing section and the extraction point for the exposure chamber distribution system. The engine is shown in black, and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

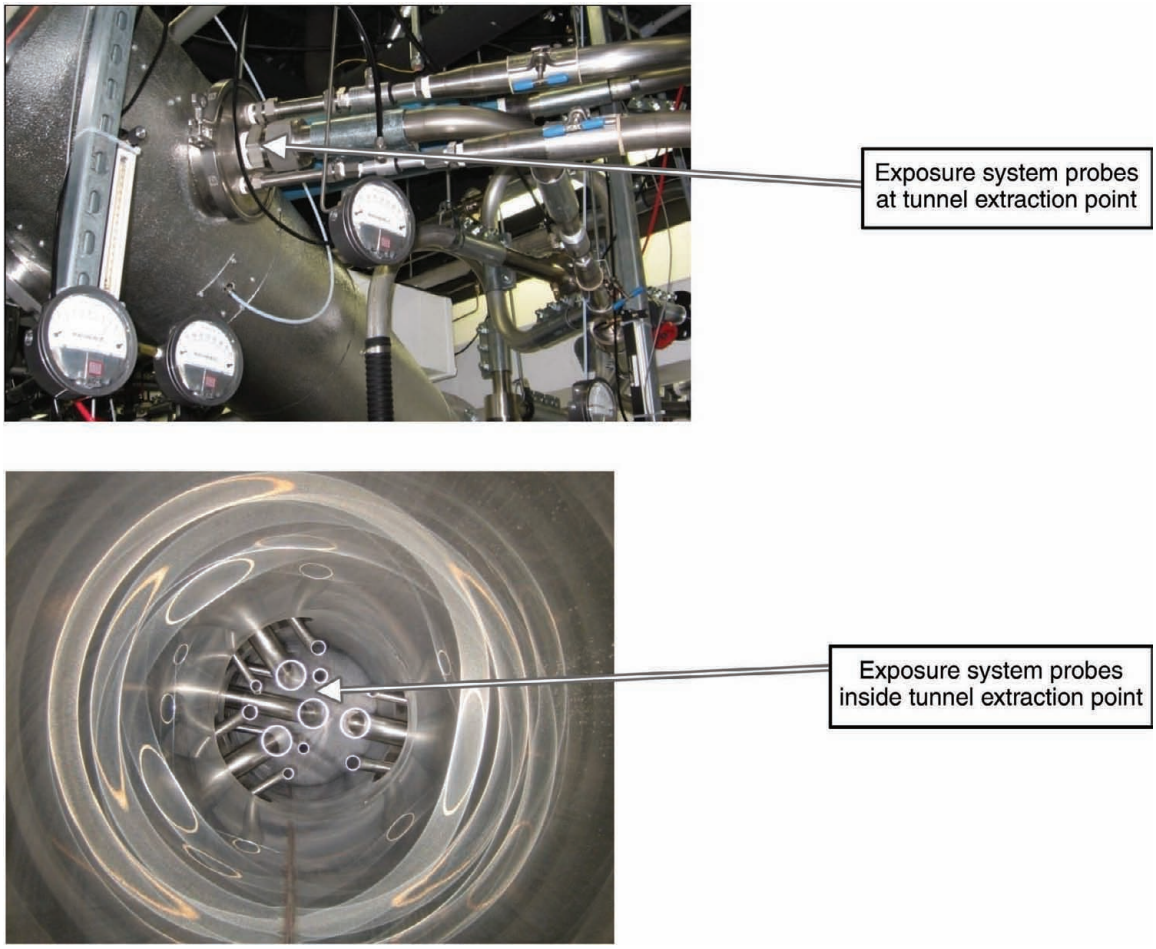

Figure 3. Photographs of sample probes on the outside and inside of the dilution tunnel at the exposure system aerosol extraction point.

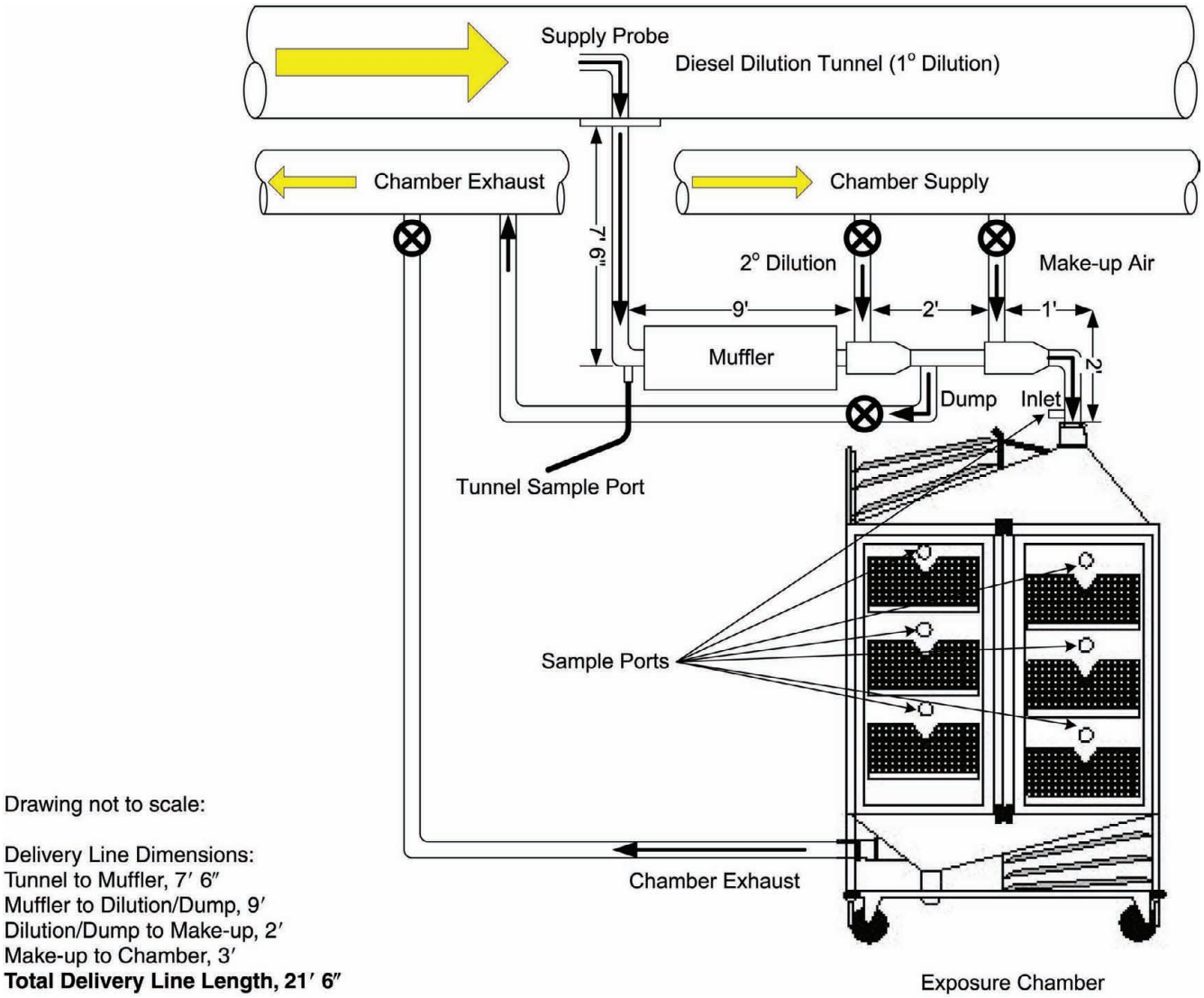

Figure 4. Schematic (not to scale) of secondary (2°) and tertiary (make-up air) dilution system before the inhalation exposure chamber. Diluted exhaust is extracted through a sampling probe. The probe size ranges from 0.95 to 5 cm, with the smallest size extraction for the lowest exposure level and the 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]

	SEE		Regression Slope (m)		Y-Intercept (b)		r^2	
Run	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]

	SEE		Regression Slope (m)		Y-Intercept (b)		r^2	
Run	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]

	SEE		Regression Slope (m)		Y-Intercept (b)		r^2	
Run	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

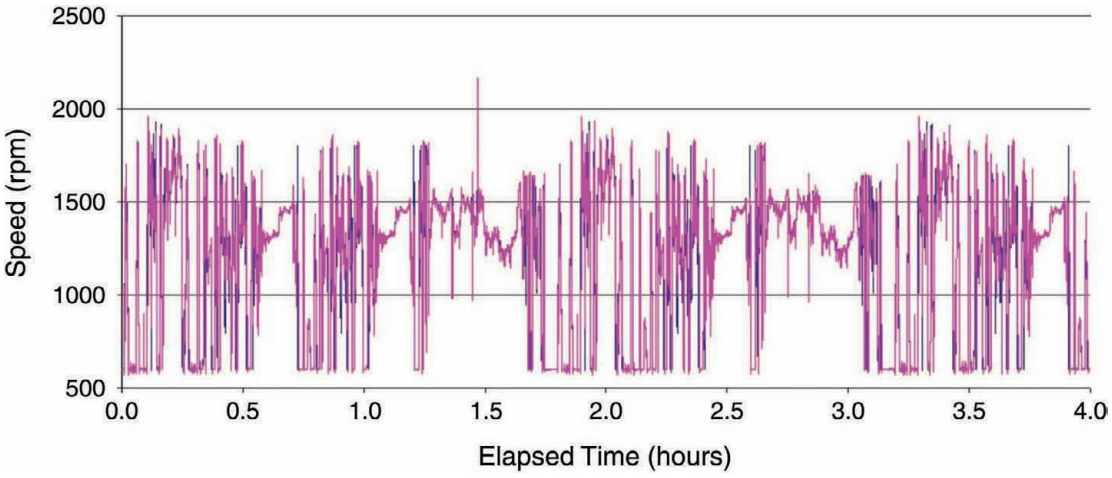

Figure 5. Target (blue) vs. actual speed (pink) during a representative 4-hour segment of the ACES transient cycle.

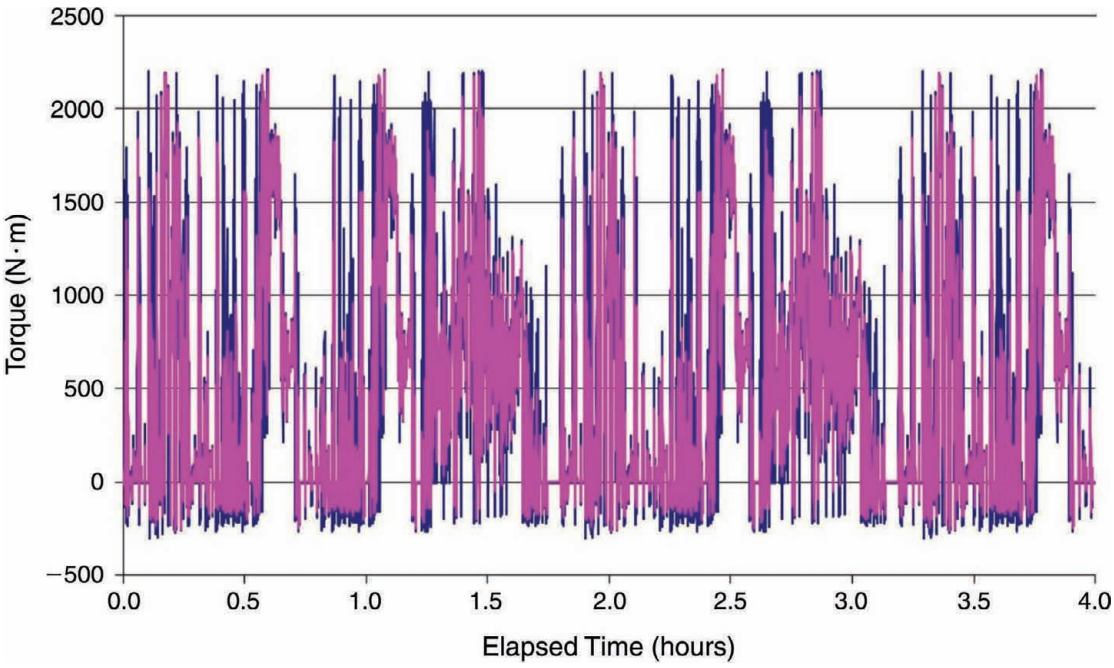

Figure 6. Target (blue) vs. actual torque (pink) during a representative 4-hour segment of the ACES transient cycle.

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

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

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 nondispersive 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.

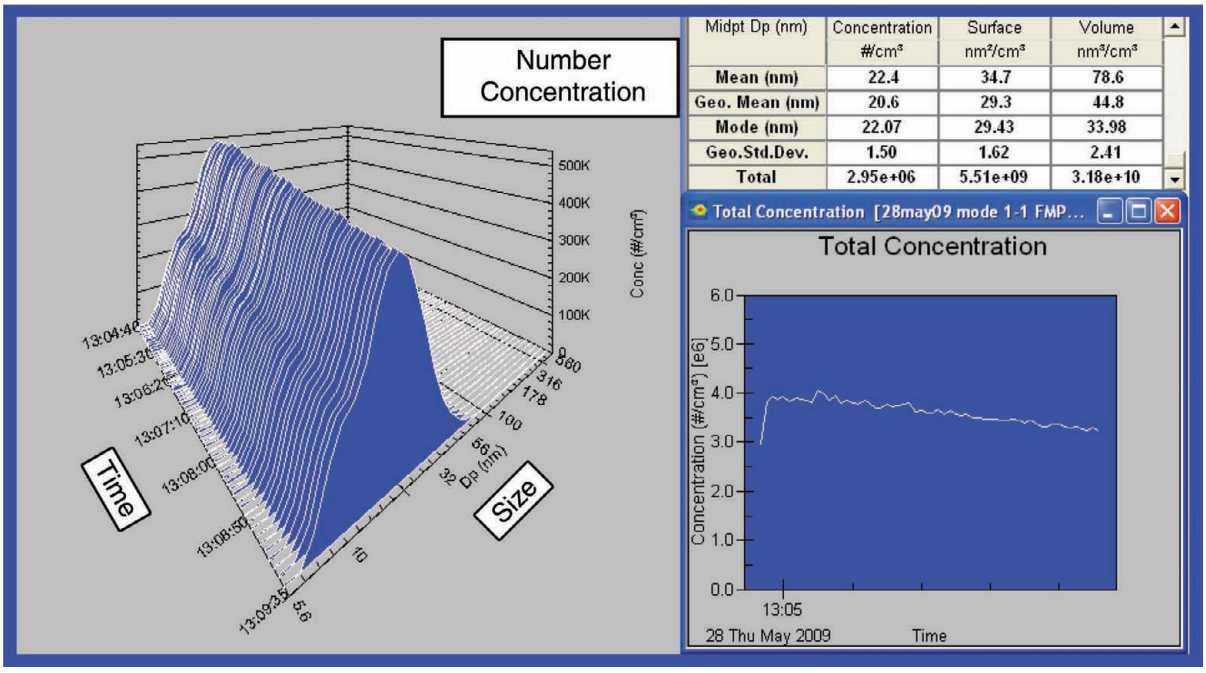

Figure 7. Sample particle size distribution for steady-state Mode 1 obtained from engine B.

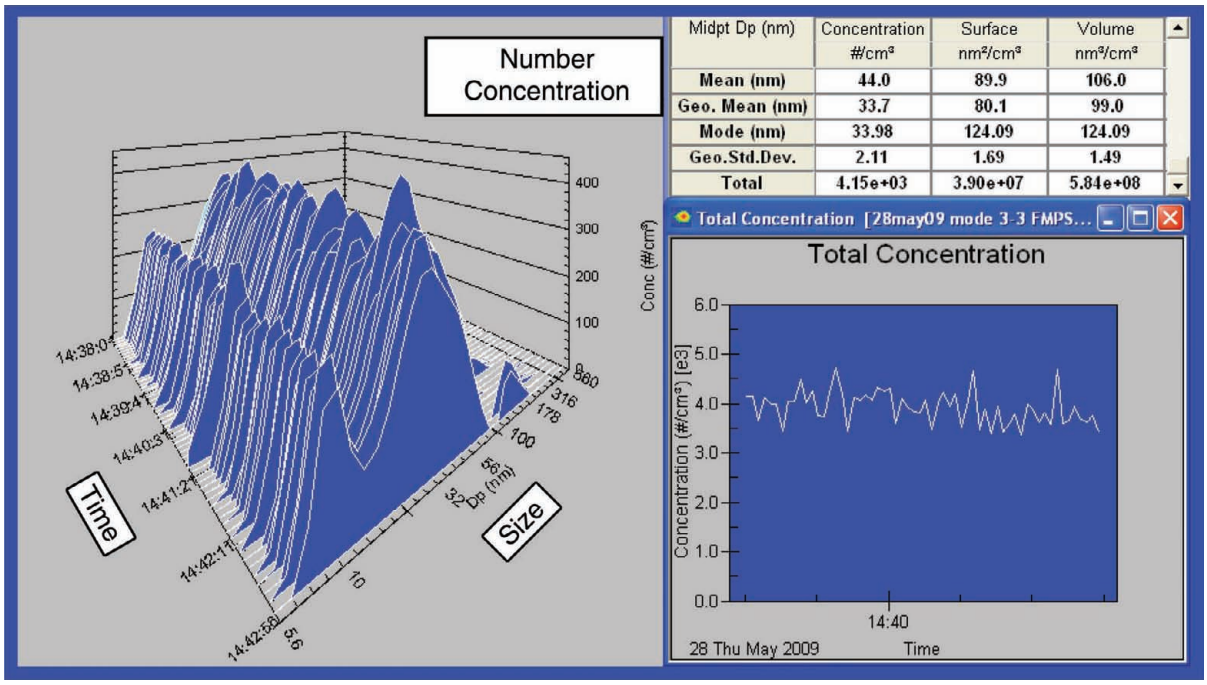

Figure 8. Sample particle size distribution for steady-state Mode 3 obtained from engine B.

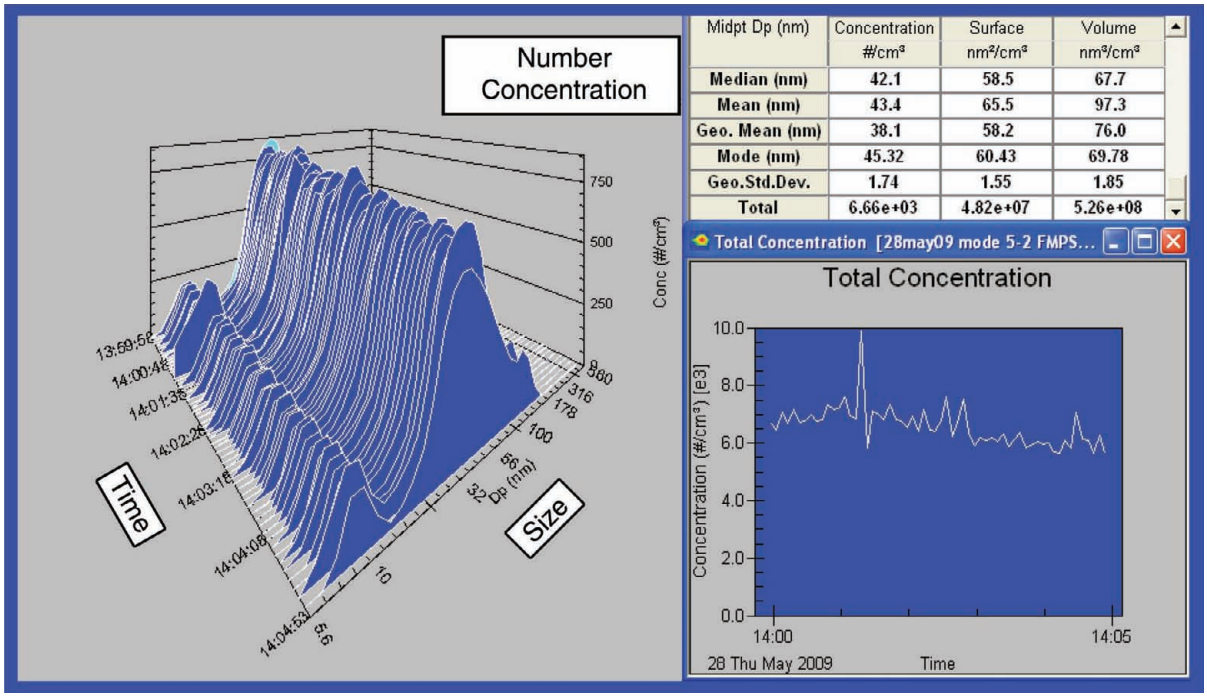

Figure 9. Sample particle size distribution for steady-state Mode 5 obtained from engine B.

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.

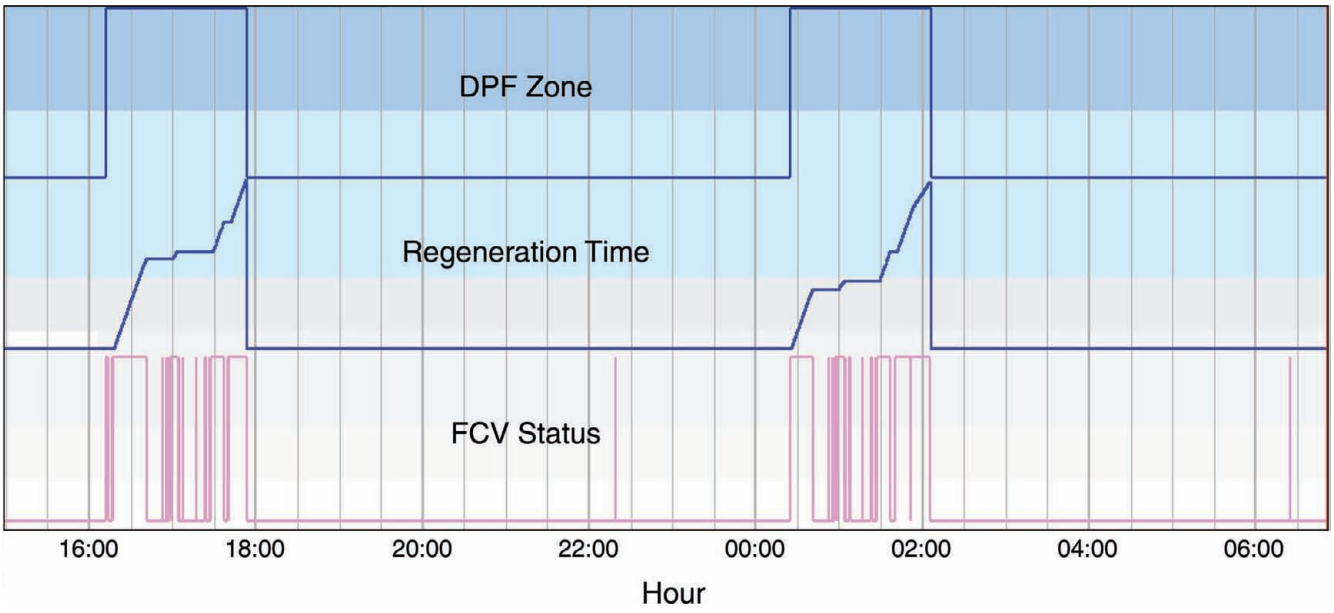

Figure 10. Indication of the DPF regeneration status during a representative 16-hour ACES cycle. During the cycle, two 90- to 120-minute regenerations occurred. This figure indicates DPF regeneration status (top), the regeneration time (middle), and the FCV status (bottom) during the cycle.

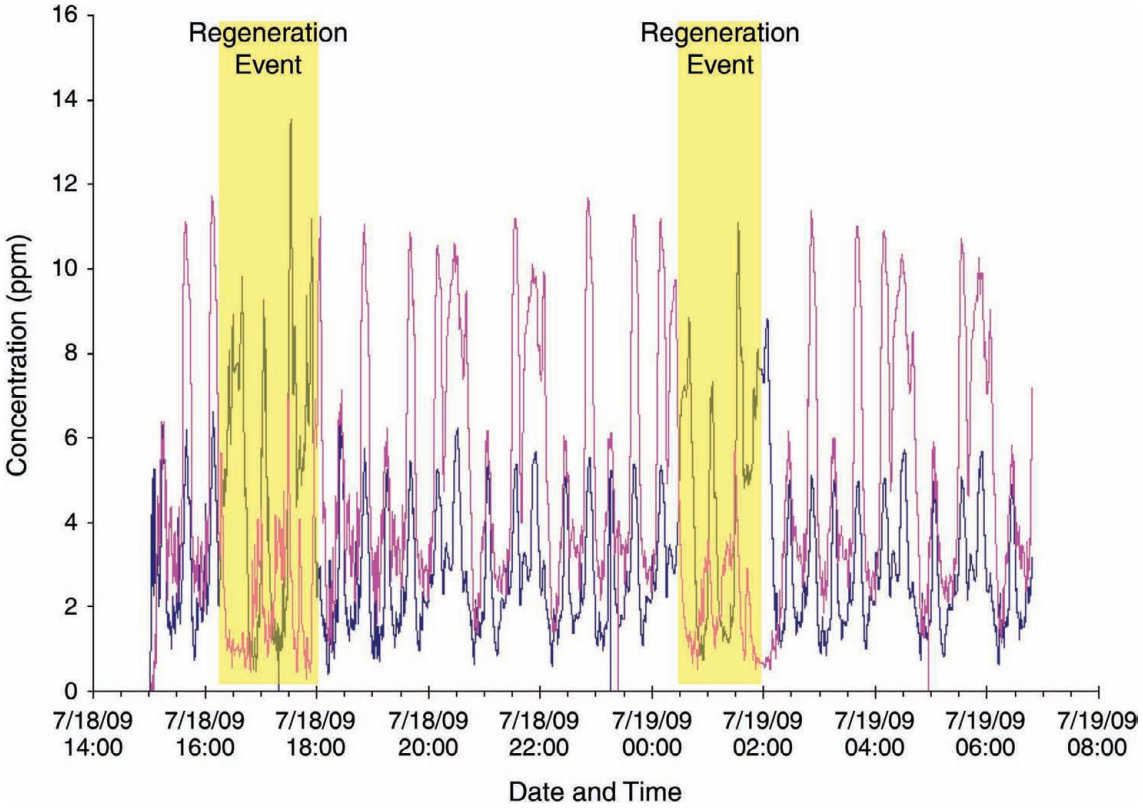

Figure 11. Representative real-time concentrations of NO (blue) and NO_2 (pink) during a 16-hour ACES transient cycle (with two regeneration events) at the high exposure level. The average concentrations of NO and NO_2 were 3.2 and 4.6 ppm.

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.

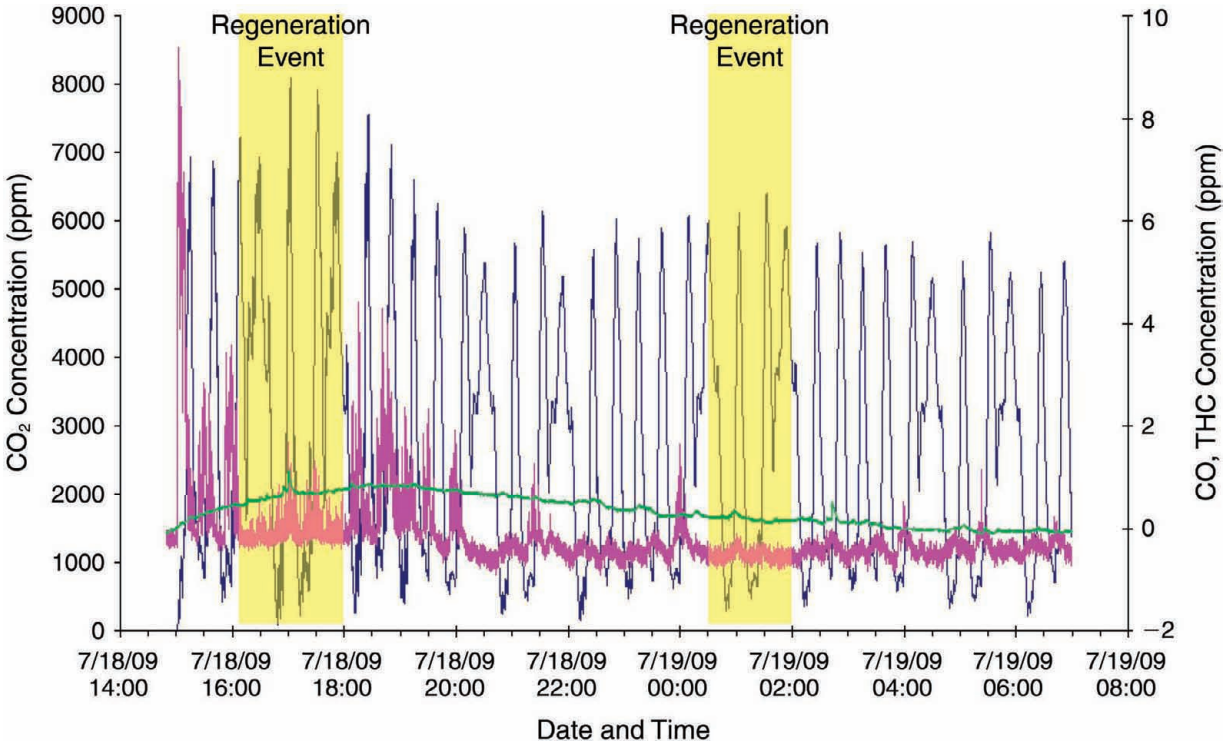

Figure 12. Representative real-time concentrations of CO_2 (blue), CO (pink), and THC (green) during a 16-hour ACES transient cycle (with two regeneration events) at the high exposure level. The average concentrations were 2714, −0.280, and 0.35 ppm.

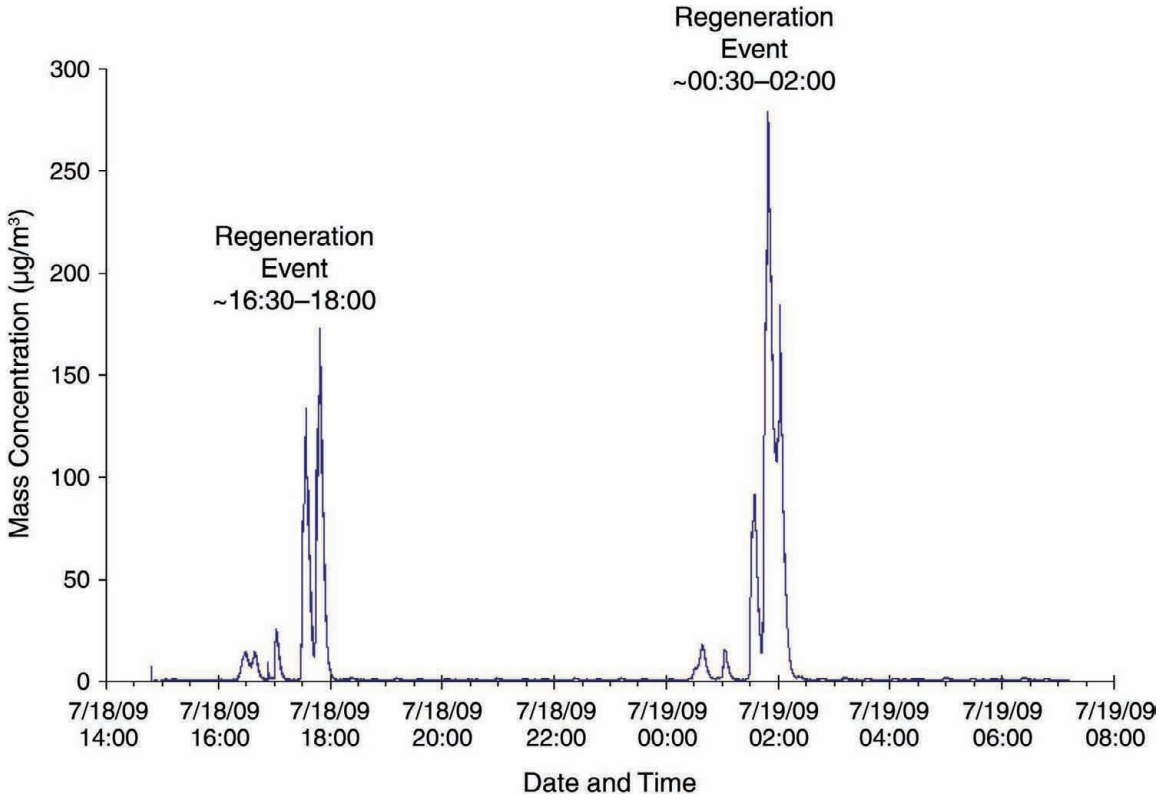

Figure 13. Representative real-time particle mass concentration measured by the DMM in the high-level chamber during the 16-hour ACES cycle. Particle concentrations peaked during the DPF regenerations. The approximate average concentrations during regenerations were 50 µg/m^3, and concentrations peaked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

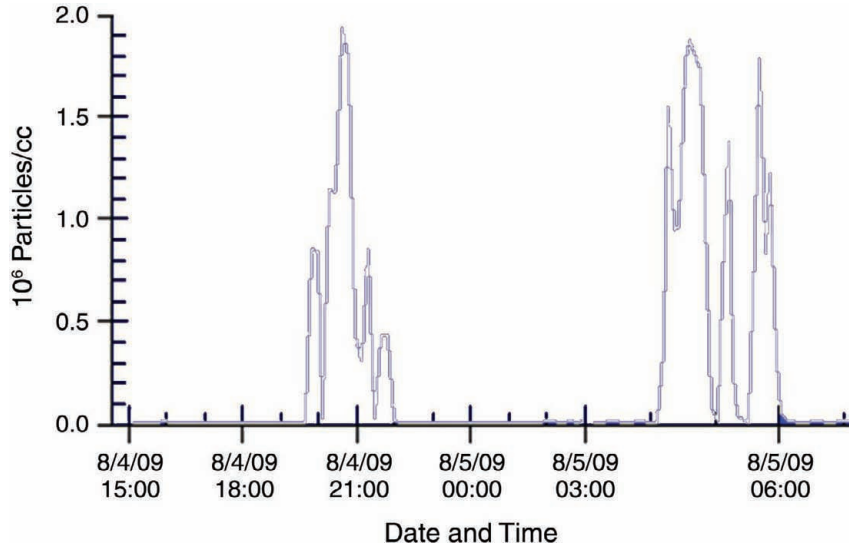

Figure 14. Representative real-time particle number concentration during a 16-hour ACES transient cycle. Particle number concentrations peaked during two trap regenerations.

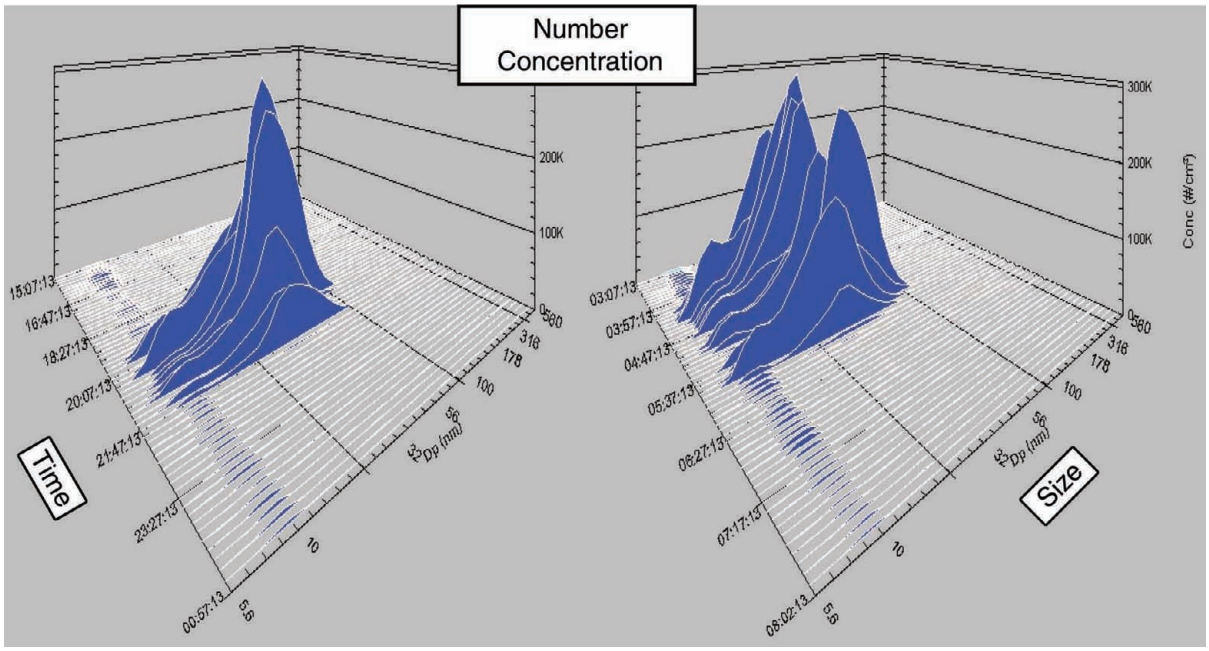

Figure 15. Representative real-time particle size distribution during a 16-hour ACES transient cycle with two regenerations (shown on the left and right). Particle concentrations were highest during DPF regeneration.

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

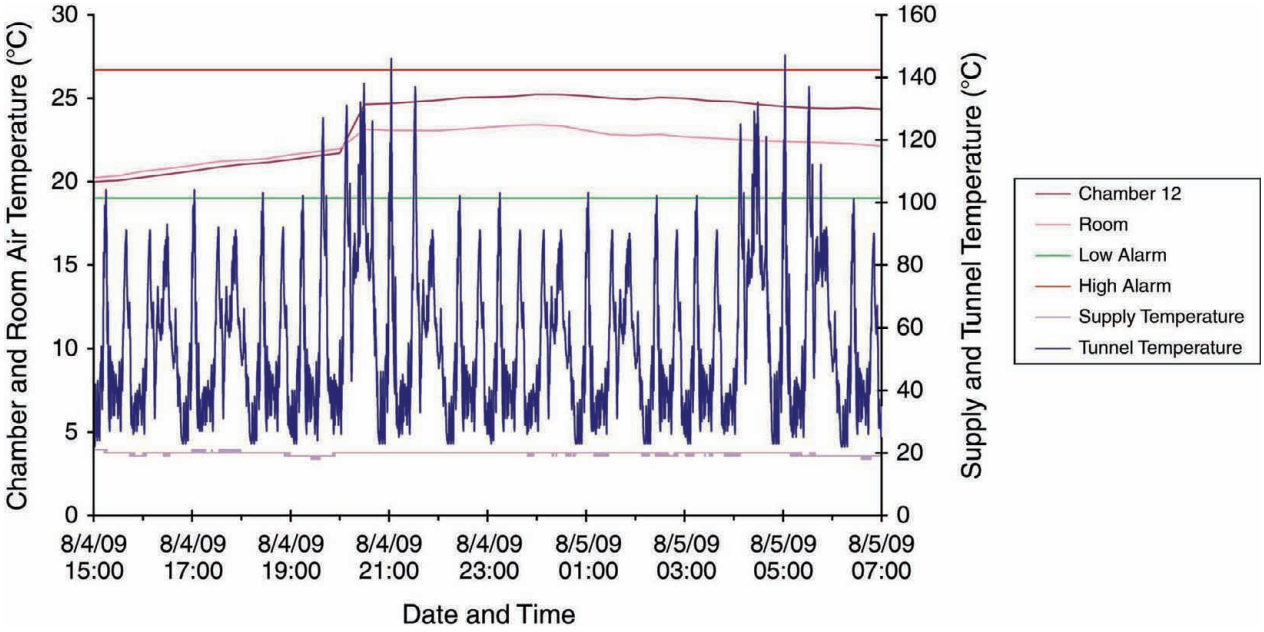

Figure 16. Temperature alarm limits, room temperature, and high-level exposure chamber temperature during a typical 16-hour transient cycle. Measurements were taken from exposure chamber 12, the room, the building supply air, and the dilution tunnel. Temperature alarms were set at 19.0°C (low) and 26.7°C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

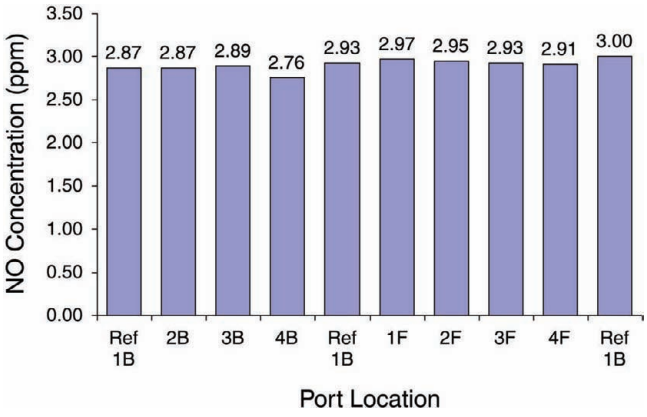

Figure 17. Chamber distribution of NO in the whole-body exposure chamber. "Ref" are reference ports to which the other exposure ports are compared. The labels 1B–4B indicate sampling locations in the back of the chamber. The labels 1F–4F indicate four different chamber sampling locations in the front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

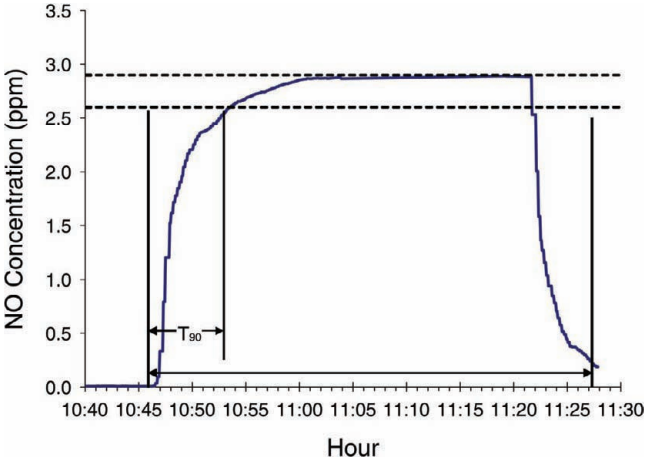

Figure 18. Time-to-chamber equilibrium for NO concentration. Chamber equilibrium was achieved 7 minutes after engine start.

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.

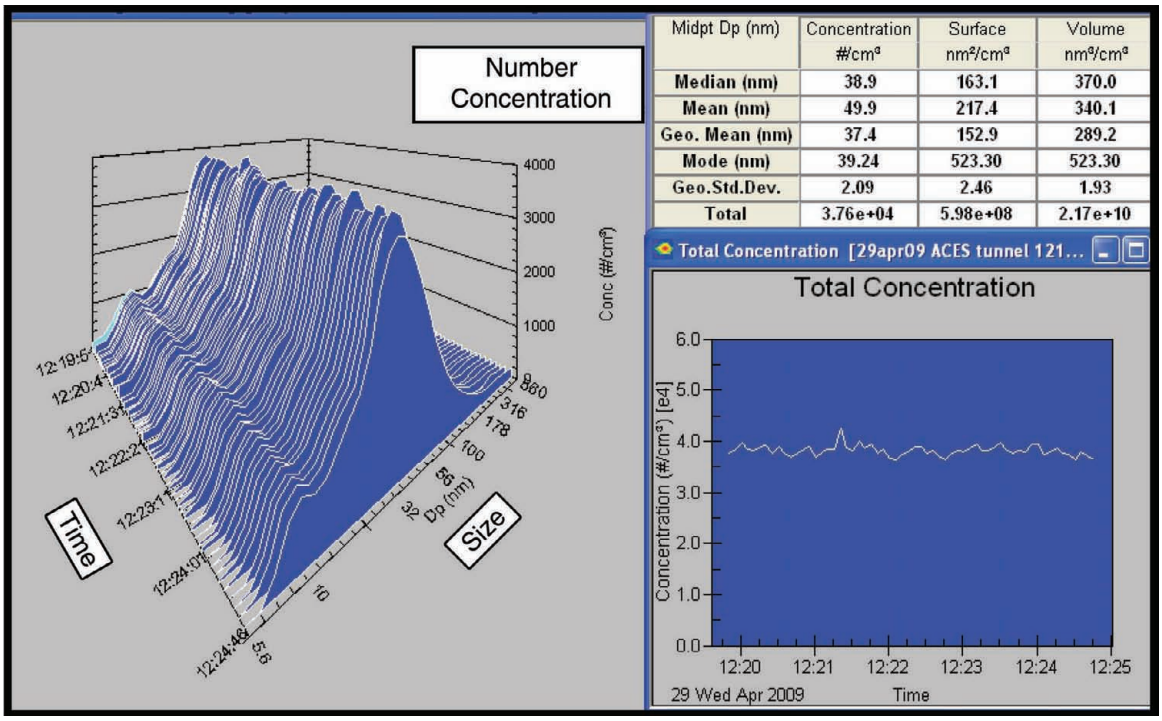

Figure 19. An example of particle size distribution at the tunnel extraction point during steady-state engine operation. Particle characteristics reported are particle number, surface area, and volume-weighted distributions.

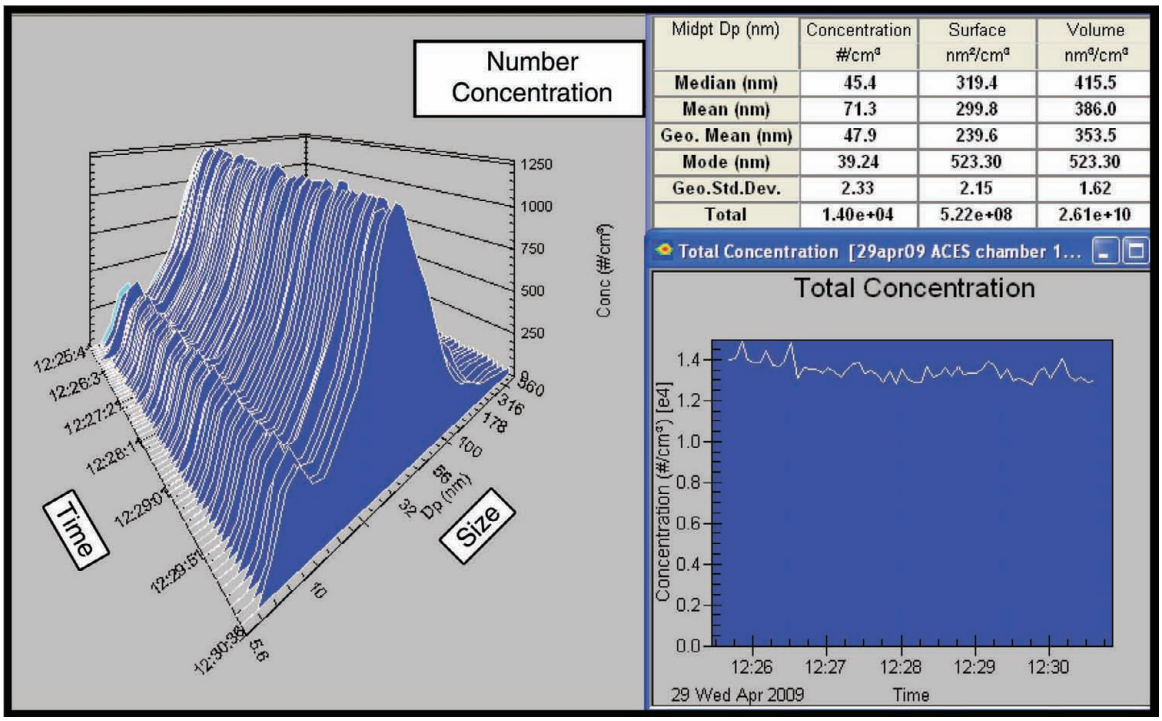

Figure 20. An example of particle size distribution from the exposure chamber during steady-state operating conditions. Particle characteristics reported are particle number, surface area, and volume-weighted distributions.

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:

$$\text{kg of } CO_2\text{/kg of Exhaust} = \frac{CO_2 \text{ Rate in Exhaust}}{1^\circ \text{ Dilution Factor} \times \text{Exhaust Rate}} \times \frac{MW_{CO_2}}{MW_{EXH}}$$

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 ($\mu g/m^3$)	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 ($\mu g/m^3$)	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

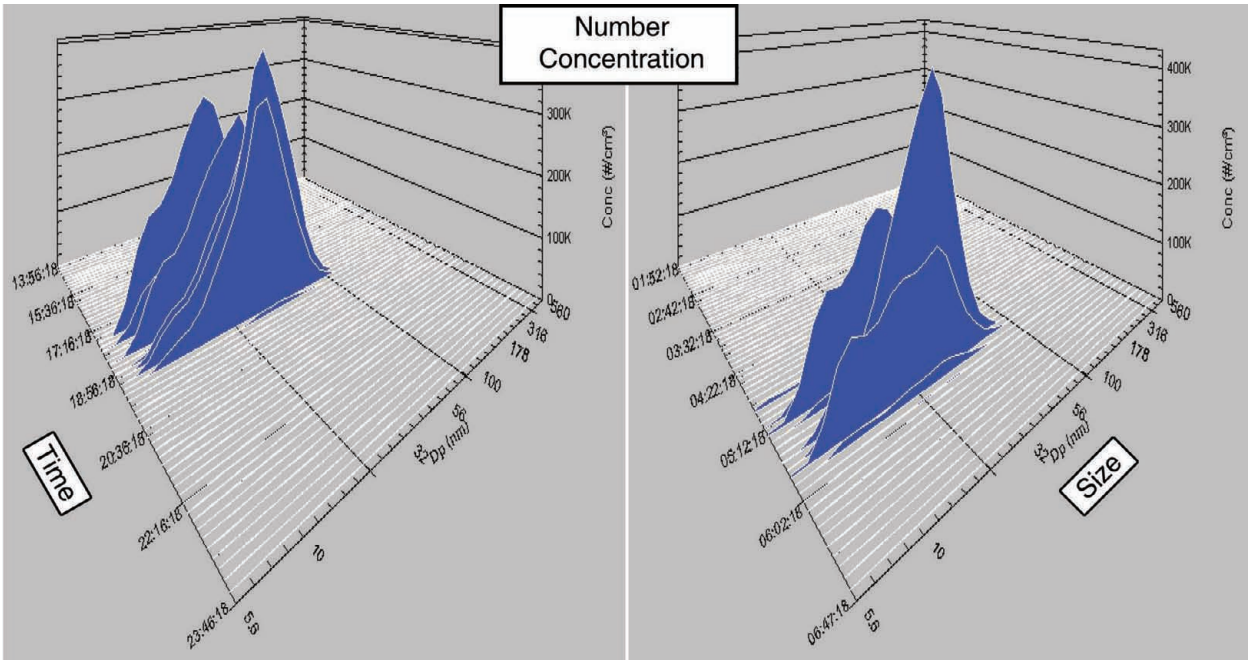

Figure 21. Real-time particle size distribution at the high-exposure level throughout the 16-hour cycle (September 28, 2009), which included two DPF regenerations (shown on the left and right).

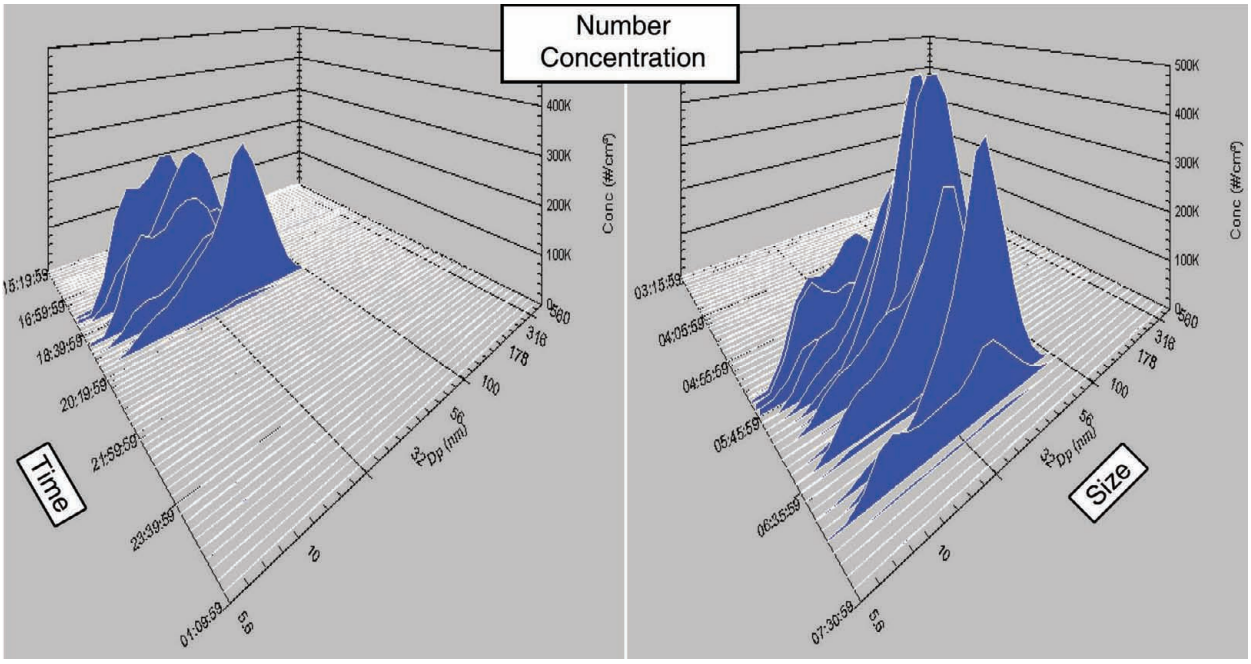

Figure 22. Another example of a real-time particle size distribution at the high-exposure level throughout the 16-hour cycle (October 1, 2009), which included two DPF regenerations (shown on the left and right).

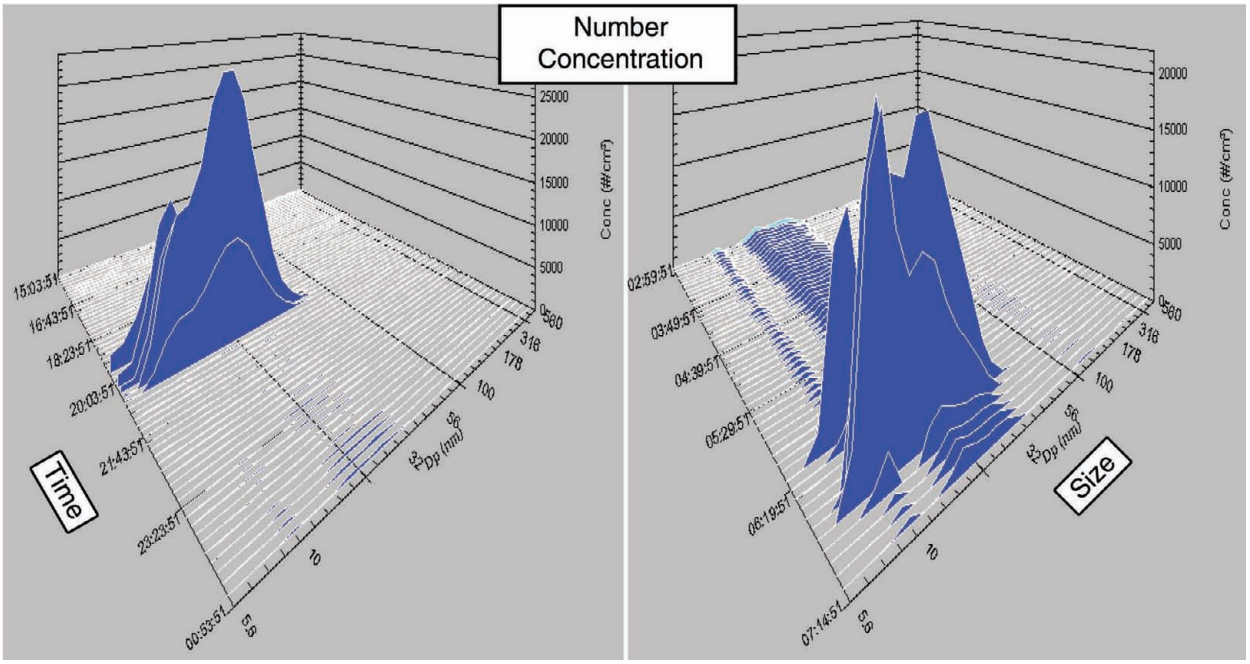

Figure 23. Real-time particle size distribution at the mid-exposure level throughout the 16-hour cycle (October 6, 2009), which included two DPF regenerations (shown on the left and right).

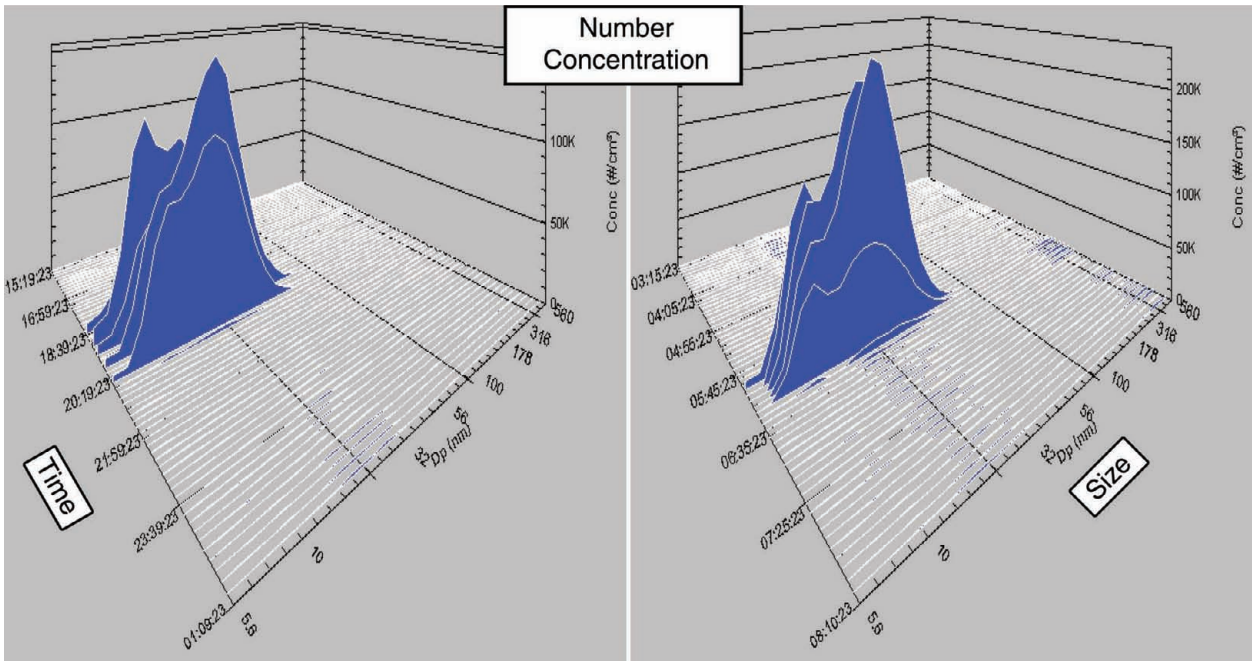

Figure 24. Another example of real-time particle size distribution at the mid-exposure level throughout the 16-hour cycle (October 12, 2009), which included two DPF regenerations (shown on the left and right).

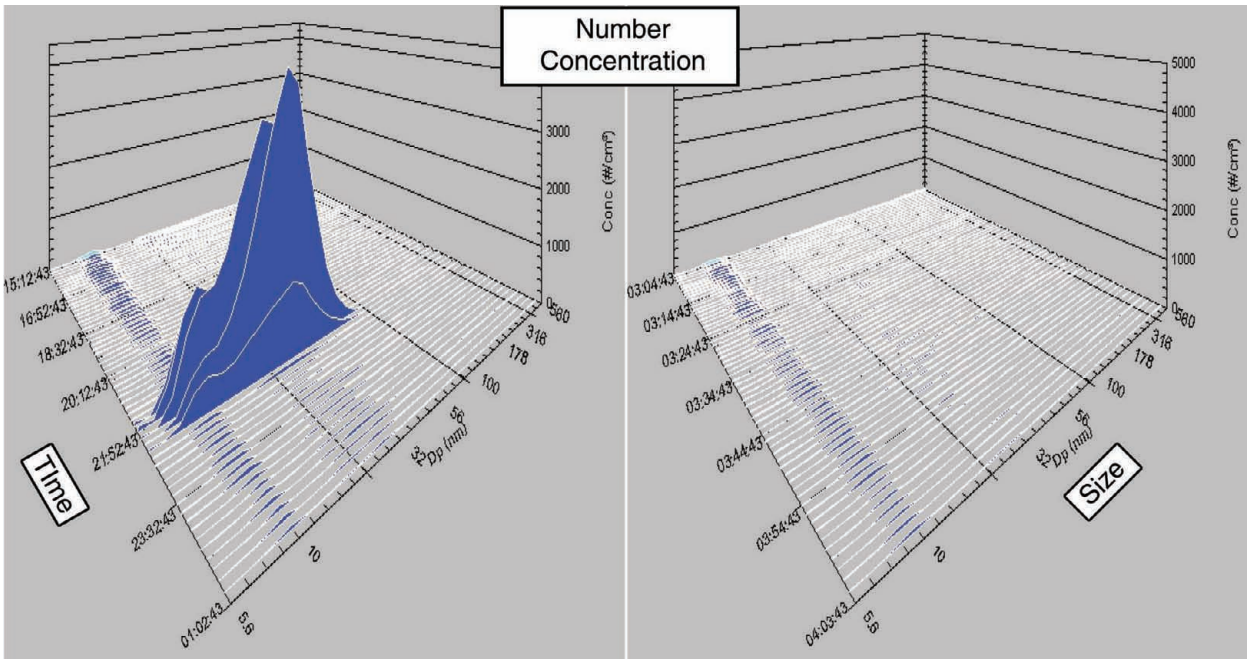

Figure 25. Real-time particle size distribution at the low-exposure level throughout the 16-hour cycle (September 24, 2009), which included one DPF regeneration (shown on the left).

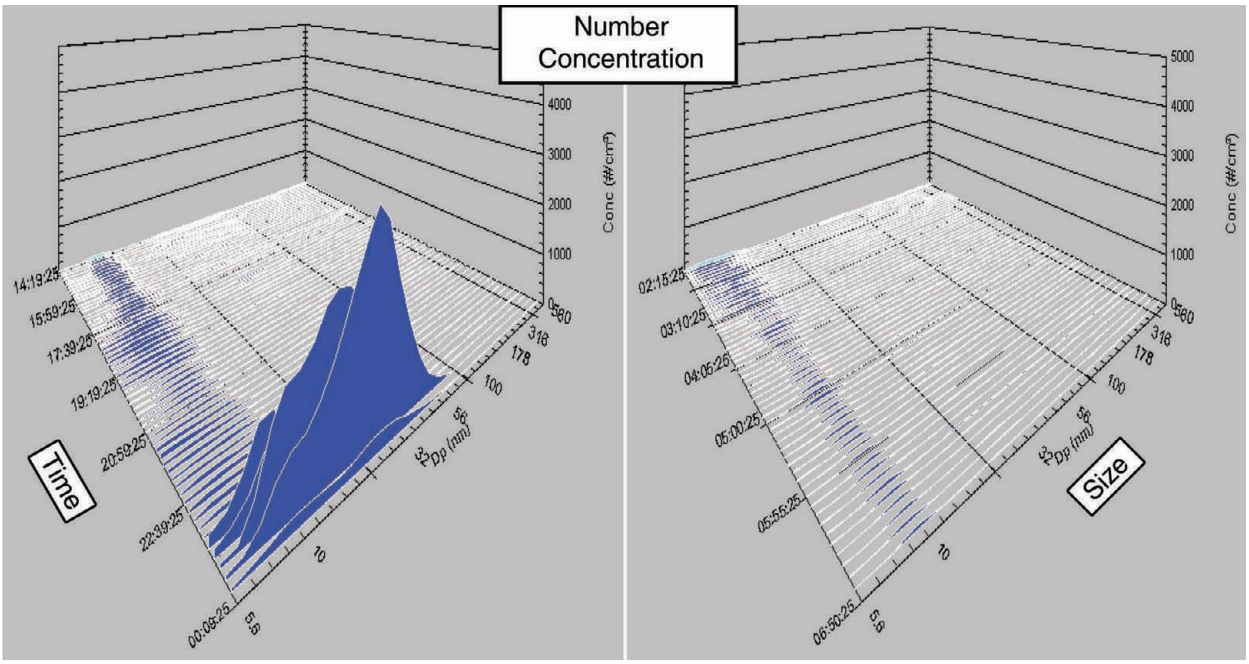

Figure 26. Another example of a real-time particle size distribution at the low-exposure level throughout the 16-hour cycle (September 25, 2009), which included one DPF regeneration (shown on the left).

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/m³; DMM)	PM Number (#/cm³)	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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DRAFT FINAL REPORT

Health Effects Institute Advanced Collaborative Emissions Study (ACES): Phase 3B: Characterization of Exposure Atmospheres

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EXECUTIVE SUMMARY

A characterization protocol was implemented to define rodent exposures during the Phase 3 chronic bioassay of the Advanced Collaborative Emissions Study (ACES) inhalation exposure study. Previous HEI reports defined the system operations and characterizations conducted both during system commissioning and as part of the initial reports of the biological response after 3 months (Mauderly and McDonald, 2012; McDonald et al., 2012). The composition of the exposure chamber was characterized in detail and the final dilution targets set to concentrations of 4.2, 0.8, and 0.1 ppm nitrogen dioxide (NO_2). This included measurement of gases, particle mass, size distribution, real-time mass, and detailed chemical composition. At an average of 4.2 ppm NO_2 in the high exposure level, the nitrogen monoxide (NO) concentration ranged from 7.5 ppm, CO_2 was 4794 ppm, carbon monoxide (CO) was 6.4 ppm, total hydrocarbons (HCs) were 0.45 ppm, and particle mass concentrations were ~12 $\mu g/m^3$ on average. The ratio of NO:NO_2 changed throughout the study from approximately 1:1 and the beginning of study to ~2:1 towards the end, presumably due to expected degradation of the catalyst on the diesel particulate filter (DPF) that occurred with time. When measured in real-time, it was shown that the majority of the particle mass was observed during the 1–2 DPF regenerations that occurred during each 16-hours 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 number diameter. The concentrations of these components, in general, scaled with dilution to the lower exposure levels. There were some exceptions to this scaling for some of the components that were revealed during the detailed characterizations of the test atmospheres.

The detailed composition of the test atmospheres is provided in an Appendix to this report. The detailed assessments were conducted at 4 times throughout the studies, April 2010, September 2010, April 2011 and April 2012. An analyte list was prescribed that included

approximately 200 analytes. These analytes included gases, semivolatile organic compounds (SVOC), metals and detailed particle assessments. The major classes of gas-phase SVOCs that were measured included the aliphatic (straight chain and cyclic), acids, and lower molecular weight polycyclic aromatic hydrocarbons (PAH). For the volatile organic compounds (VOCs), the majority were observed in the light (< C5) fraction and were mostly acetylene and the alkanes/alkenes. Some aromatics were observed (e.g., toluene), but the benzene concentration was low. For the particle characterization, there was reasonable agreement (~ 15%) between weighed mass and the sum of measured species considering the uncertainty in each of the measurements. Depending on the atmosphere, carbon accounted for approximately one-third to one-half of the mass, and the carbon was primarily organic. There was a likely bias in the measurement of organic carbon due to adsorption artifacts and contributions from the animals that made the organic measurements higher than actual. The inorganic ions (mostly sulfate and ammonium) made up about half of the mass as well. The remaining mass was made up of the elements. The composition of the test atmospheres, in general, showed only modest changes with time.

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ACRONYMS AND ABBREVIATIONS

ACES	Advanced Collaborative Emissions Study
Av	Average
BHP	Brake Horse Power
CFM	Cubic Feet per Minute
CFR	Code of Federal Regulations
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CRC	Coordinating Research Council
CPC	Condensation Particle Counter
CV	Coefficient of Variation
CVS	Constant Volume Sampler
DE	Diesel Exhaust
DMM	Dekati Mass Monitor
DNPH	Dinitrophenylhydrazine
DPF	Diesel Particulate Filter
EC	Elemental Carbon
EPA	Environmental Protection Agency
FMPS	Fast-Mobility Particle Sizer
ft-lb	Foot Pounds
g/hp-hr	Grams per Horsepower-Hour
FCV	Fuel Cut-off Valve
FTP	Federal Test Procedure
GC/MS	Gas Chromatography/Mass Spectroscopy

GLP	Good Laboratory Practice
GPM	Gallons per Minute
HCD	Hydrocarbon Doser
HCs	Hydrocarbons
HEI	Health Effects Institute
hr	Hour
i.d.	Internal diameter
ISO	International Organization for Standards
LC/UV	Liquid Chromatography/Ultraviolet
LRRI	Lovelace Respiratory Research Institute
NA	Not Applicable
NO	Nitric Oxide
NO	Nitrogen Monoxide
NO_2	Nitrogen Dioxide
NO_x	Oxides of Nitrogen
OC	Organic Carbon
PAH	Polycyclic Aromatic Hydrocarbon
PM	Particulate Matter
QC	Quality Control
Regen	Regeneration Time
RPM	Revolutions per Minute
SEE	Standard Error of Estimate
St. Dev.	Standard Deviation
SCFM	Standard Cubic Feet per Minute

SVOC	Semi-Volatile Organic Compounds
T_{90}	Time to reach 90% of target concentration
THC	Total Hydrocarbon
TOR	Thermal/Optical Reflectance
VOC	Volatile Organic Compounds
XAD	Polyaromatic Adsorbing Resins
XRF	X-Ray Fluorescence

INTRODUCTION

The Advanced Collaborative Emissions Study is a multidisciplinary program that is being carried out by the Health Effects Institute (HEI) and Coordinating Research Council to better characterize the composition and potential toxicity of advanced technology compression ignition, after treatment, and reformulated fuels that have been developed to meet 2007 and 2010 U.S. Environmental Protection Agency (EPA) emissions standards. The program consisted of several phases that were designed to characterize 2007 compliant emissions (Phase 1; Khalek et al., 2011), characterize 2010 compliant emissions (Phase 2), and assess the toxicity of exhaust from 2007 technology (Phase 3) (McDonald et al., 2012). This report describes the results of the exposure atmosphere characterizations that occurred during the Phase 3 chronic bioassay. Previous HEI reports defined the system operations and characterizations conducted both during system commissioning and as part of the initial reports of the biological response after 3 months (Mauderly and McDonald, 2012; McDonald et al., 2012). The composition of the exposure chamber was characterized in detail and the final dilution targets set to concentrations of 4.2, 0.8, and 0.1 ppm nitrogen dioxide (NO_2). This included measurement of gases, particle mass, size distribution, real-time mass, and detailed chemical composition. The routine monitoring and detailed characterization results are reported here.

SPECIFIC AIMS

The overall aims of the research reported here was to characterize the composition of test atmospheres used for a chronic bioassay of 2007 compliant diesel emissions. The goal was to define exposure in detail as a means of ultimately interpreting the results of the bioassay and the stability of the test atmospheres over the duration of the study. Specifically, the report defines 1) results of daily measurements and control of exposure atmosphere concentrations/dilutions; and 2) description of the composition of test atmospheres during four ‘intensive’ measurement

periods taken in April 2010, September 2010, April 2011 and April 2012; 3) and a description of the engine and test facility performance.

METHODS AND STUDY DESIGN

ENGINE AND EXPOSURE FACILITY

A 2007 Series 60 14.0L on-highway certified heavy-duty diesel engine and its stock after treatment system was used to generate test atmospheres for the ACES Phase 3 bioassay. The engine manufacturer provided two engines, termed B and B´. Prestudy testing put 1200 hours of operation on each of these engines. During the study, engine B' was used from February 2010-September, 2011. The engine was replaced with engine B, and engine B continued in operation until May 2012. Engine B' was installed in June 2012 and operated until the end of the study in December 2012. Engine exchanges occurred because of engine maintenance requirements. At the end of the study, engine B' was used for 10,090 hours and engine B was used for 4031 hours. At each oil change or in the event of an engine change-out the engine was 'mapped' as required by the 40 CFR Part 86. Speed torque, and power measurements were compared to the speed, torque, and power cycle demand values using the "least squares" method. All engine maps met the criteria for performance.

The system was mated to a Dyne Systems, 550-hp, 660-A, alternating-current dynamometer and controlled remotely using a Dyne Systems, Inter-Loc V, Digital Multi-Loop Controller interfaced to a personal computer. The engine test cycle was controlled with the Dyne Systems Cell Assistant for Windows software. The engine was operated on a 16-hours duty cycle developed specifically for the ACES program (Clark et al. 2007). Diesel fuel meeting current on-road specifications was delivered to LRRI from a local commercial source (Chevron-branded D-2 [legal for on-road use], Ever-Ready Oil Co., Albuquerque, NM). The engine and associated systems were maintained as recommended by the engine manufacturer. Crankcase lubricating oil

was changed every 250 hours. The oil was a proprietary blend approved by HEI and the Coordinating Research Council (CRC), provided by Lubrizol Corp., and also used in Phase 1 of the ACES Program. The manufacturer-recommended oil filter was changed with each change of lubrication oil. Fuel and oil analysis was conducted at each change. Analytical data from the fuel and oil analyses are included in Appendices A and B. Note that all fuel was within specification and that several of the oil analyses revealed increased (and sometimes excessive) levels of soot in the oil. The increase in soot in the oil was likely a sign of the extremely tough conditions that the engine was operated under for the ACES cycle. The other major components of the oil were phosphorous, calcium, zinc and sodium.

Exhaust was passed through a stock after treatment system before injection into a 35.6 cm internal diameter dilution tunnel. Figure 1 shows a diagram of the engine test cell and its coupling to the dilution tunnel. The crankcase ventilation effluent joined the exhaust stream downstream of the after treatment system. The exhaust was diluted with filtered air under turbulent conditions at the point of injection. The dilution tunnel supply-air flow was approximately 3000 cubic feet per minute. The primary dilution tunnel was a constant–pressure tunnel, rather than constant volume. When exhaust flow increased, the increased pressure caused the dilution air to be dumped into a bypass leg in the test cell. At a distance of 5.5 m from the injection point (in the exposure room), a portion of the diluted exhaust was drawn through an in-line extraction probe. The exhaust mixture was withdrawn from the primary dilution plenum through individual probes and transit lines for each exposure chamber. A schematic of this chamber and each exposure chamber had its own extraction probe and dilution system. Subsequent to this extraction, the exhaust was diluted with filtered compressed air provided through a rotary dilution/dilution bypass system. Diluting flows were adjusted as needed to reach the final dilution and concentration targets. The residence time of diesel exhaust (DE) in the

dilution tunnel and transit lines was less than 5 seconds. After the exhaust reached the exposure chamber, the residence time was approximately 4 minutes. All dilution and transit lines were constructed of stainless steel, and were of near equal lengths for each of the exposure levels. Exhaust was diluted to achieve pre-selected target exposure concentrations of 4.2, 0.8, and 0.1 ppm NO_2. This required dilution ratios of approximately 25:1, 115:1, and 840:1. The dilution rate in the primary dilution tunnel was approximately 5:1. The residence time of DE in the dilution tunnel and transit lines was less than 5 seconds. After the exhaust reached the exposure chamber, the residence time was approximately 4 minutes. The control chamber consisted of filtered air.

Exposures were conducted 16 hours/day, 5 day/wk from approximately 1600 to 0800 hours Sunday through Thursday. Exposures were conducted for 16 hours plus the time to reach 90% of the target atmosphere (T90). The environmental conditions within the system was operated without continuous operator presence between 1800 and 0800 hours, although surveillance personnel were always available and checked the system periodically during the night. Several control-alarm systems were in place to automatically shut down the engine and notify personnel in case of malfunction. The system was programmed to automatically terminate the engine cycle and switch the exposure chambers to clean dilution air at 0800 hours.

ATMOSPHERE CHARACTERIZATION METHODS

The measurements, sample conditions and analytical techniques applied to the chamber characterization are summarized in Table 1. Continuous concentrations of nitrogen oxides (NO_x), made up of nitric oxide (NO) and nitrogen dioxide NO_2, were measured daily at each exposure level throughout each exposure day. NO_x concentrations were also measured from the primary dilution tunnel for the purpose of calculating the dilution ratio between the primary tunnel and the chambers. Continuous concentrations of CO, CO_2, nonmethane HCs, particle

mass using a Dekati Mass Monitor (DMM) and size distribution (using an aerodynamic particle sizer) and black carbon (using a photoacoustic spectrometer) were measured daily in the high-DE exposure chamber. Note that all real-time measurements were recorded once per second. Exposure atmosphere measurements were collected throughout the 16-hours exposure period. During periodic intensive characterizations, these measurements were taken at the other exposure levels, and on those days, the measurements were not made at the high-DE exposure level. During periodic intensive characterizations, these measurements were taken at the other exposure levels, and on those days the measurements were not made at the high level. Particle size was measured as part of the DMM analysis. A more detailed measurement of particle size was conducted once per week at each exposure level by the Fast Mobility Particle Sizer (TSI, St. Paul, MN). A periodic measurement of size in the chamber was conducted with an Aerodynamic Particle Sizer (TSI, St Paul, MN). Particle mass concentration by gravimetric analysis of Teflon-membrane filters at the inlet of the chamber and inside the exposure chamber was measured once a week at each exposure level.

A more detailed characterization of particle mass and size was conducted once per week at each exposure level. Integrated particulate matter (PM) mass concentration was measured by gravimetric analysis of Teflon-membrane filters at both the inlet of the chamber and inside the exposure chamber. These two measurements allowed determination of how much PM the animals in the exposure chamber contributed to the total PM in the chamber. A fast-mobility particle sizer (FMPS) was used to measure particle volume (mass), number, and number-based particle size distribution for particles between 5 and 500 nm in diameter, and an aerodynamic particle sizer was used to measure the mass-based size distribution

Sample Collection

PM measurements collected on filters (as described below) were collected both at the inlet to the exposure chamber just prior to entry or in the exposure chamber. This approach was taken because of the significant contribution of the animals to the PM concentration made within the chamber (including at smaller particle sizes). Pre-study characterizations showed that the chamber inlet was predictive of the contribution and composition of DE PM present in the exposure chamber. For the detailed characterization efforts with the exception of the Teflon membrane filter for metals and the filter/XAD-4 cartridge for semi-volatile organics (see below), all chamber samples were collected from the breathing zone through sample ports. Samples were obtained through ~ 12″ long ¼″-diameter stainless steel probes.

Particulate Matter Mass

PM concentration was measured gravimetrically by sampling for 16 hours intervals on 47-mm Teflon membrane filters (TEFLO, Pall-Gelman, East Hills, NY) connected to the exposure chamber with a 0.6 cm internal diameter (i.d.) probe connected to an aluminum in-line filter holder (In-Tox Products, Inc., Albuquerque, NM). Pre- and post-sample filter weights were measured using a Mettler MT5 microbalance. A static discharger was used prior to weighing filters to avoid any interference from electrical charge on the filters.

Real-Time Mass and Size Distribution

Real-time PM was measured using a Dekati Mass Monitor (DMM-230, Dekati, Finland) directly from the exposure chamber. The instrument was factory calibrated and operated/maintained according to manufacturer recommendations. 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, Inc., St. Paul, MN) also was

used to measure particle number size distribution (in real-time) with enhanced resolution for particle size (resolution 1 second).

Chemical Characteristics of PM

Elemental and Organic Carbon Mass

Elemental carbon (EC) and organic carbon (OC) masses were determined at the Desert Research Institute using pre-baked quartz fiber filters by the IMPROVE (Interagency Monitoring of Protected Visual Environments) temperature/oxygen cycle (IMPROVE TOR), as described previously (Chow et al., 1993;2001).

. A section of the filter sample is placed in the carbon analyzer oven such that the optical reflectance or transmittance of He-Ne laser light (632.8 nm) can be monitored during the analysis process. The filter is first heated under oxygen-free helium purge gas. The volatilized or pyrolyzed carbonaceous gases are carried by the purge gas to the oxidizer catalyst where all carbon compounds are converted to carbon dioxide. The CO_2 is then reduced to methane, which is quantified by a flame ionization detector (FID). The carbon evolved during the oxygen-free heating stage is defined as “organic carbon”. The sample is then heated in the presence of helium gas containing 2 percent of oxygen and the carbon evolved during this stage is defined as “elemental carbon”. Some organic compounds pyrolyze when heated during the oxygen-free stage of the analysis and produce additional EC, which is defined as pyrolyzed carbon (PC). The formation of PC is monitored during the analysis by the sample reflectance or transmittance. EC and OC are thus distinguished based upon the refractory properties of EC using a thermal evolution carbon analyzer with optical (reflectance or transmittance) correction to compensate for the pyrolysis (charring) of OC. Carbon fractions in the IMPROVE method correspond to temperature steps of 120oC (OC1), 250oC (OC2), 450oC (OC3), and 550oC (OC4) in a

nonoxidizing helium atmosphere, and at 550oC (EC1), 700oC (EC2), and 850oC (EC3) in an oxidizing atmosphere.

Organic Carbon Class and Species

Particulate and semi-volatile organic carbon compounds (SVOCs) were collected using Teflon impregnated glass fiber (TIGF) 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 Desert Research Institute (Fujita et al., 2007).

Prior to extraction, the following deuterated internal standards were added to each filter and cartridge pair: naphthalene-d8, acenaphthylene-d8, phenanthrene-d10, anthracene-d10, chrysene-d12, pyrene-d10, benz[a]anthracene-d12, benzo[a]pyrene-d12, benzo[e]pyrene-d12, benzo[k]fluoranthene-d-12, benzo[g,h,i]perylene-d12, coronene-d12, cholestane-d50, and tetrocosane-d50. Filters and XAD-4 were extracted with dichloromethane, followed by acetone, using the Dionex ASE. The extracts were then combined and concentrated by rotary evaporation at 20 °C under gentle vacuum to ~1 ml and filtered through 0.45 mm Acrodiscs (Gelman Scientific). The extract was concentrated to 1 ml and split into two fractions: (1) the first fraction was precleaned by the solid-phase extraction technique (Wang et al., 1994A,B) using Superclean LC-SI SPE cartridges (Supelco) with sequential elution with hexane, and hexane/benzene (1:1). The hexane fraction contained the non-polar aliphatic hydrocarbons, and hopanes and steranes, and the hexane/benzene fraction contained the PAH. These two fractions were combined and concentrated to ~100 µL and analyzed by GC/MS technique for hydrocarbons, hopanes, steranes, PAH and oxy-PAH.

The second fraction was utilized for the polar compound analysis without precleaning. It was derivatized using a mixture of bis(trimethylsilyl)trifluoroacetamide and pyridine to convert

the polar compounds into their trimethylsilyl derivatives. The second fraction was evaporated to 100 ml under moisture filtered ultra high purity nitrogen and transferred to 300 ml silanized glass inserts (National Scientific Company, Inc.). Samples were further evaporated to 50 ml, and 25 ml of pyridine (Pierce), 25 ml of internal standard mixture (succinic acid d-4, myristic acid -d27, and 1,2,4-butanetriol), and 150 ml of BSTFA with 1 % TMCS [N, O-bis (trimethylsilyl) trifluoroacetamide with 1% trimethylchlorosilane (Pierce)] were added. The glass insert containing the sample was put into a 2 ml vial and sealed. The sample was then placed into a thermal plate (custom made) containing individual vial wells at 70 ºC for 3 hours. The calibration solutions were freshly prepared and derivatized just prior to the analysis of each sample set, and then all samples were analyzed by GC/MS within 18 hours to avoid degradation. Analysis of the polar organic compounds and the internal standards added are described elsewhere (Mazzoleni et al., 2007).

The extracts were analyzed for PAH, alkanes and polar compounds by gas chromatography/mass spectrometry (GC/MS), using Varian CP-3800 GC equipped with a CP8400 autosampler and interfaced to a Varian 4000 Ion Trap with electron impact (EI) ionization mode. The hopanes and steranes were analyzed using the Varian 1200 triple quadrupole gas chromatograph/mass spectrometer (GC/MS/MS) system with CP-8400 autosampler. Injections (1 μL) were made in the splitless mode onto a 30m 5% phenylmethylsilicone fused-silica capillary column (DB-5ms, J&W Scientific or equivalent). Quantification of the individual compounds was obtained by selective ion storage (SIS) technique, monitoring the molecular (or the most characteristic) ion of each compound of interest and the corresponding deuterated internal standard. Calibration curves for the GC/MS quantification were made for the most abundant and characteristic ion peaks of the compounds of interest using the deuterated species most closely matched in volatility and retention

characteristics as internal standards. National Institute of Standards and Technology (NIST) Standard Reference Material (SRM) 1647 (certified PAH) with the addition of deuterated internal standards and of those compounds not present in the SRM (i.e., oxy-PAH, nitro-PAH, hopane, sterenes, carpanes, hydrocarbons, cycloalkanes) was used to make calibration solutions. A six- to eight-level calibration was performed for each compound of interest and the calibration check (using median calibration standards) was run every 10 samples to check for accuracy of analyses. If the relative accuracy of measurement (defined as a percentage difference from the standard value) was less than 20%, the instrument was recalibrated.

The nitro-PAH were analyzed using the Varian 1200 triple quadrupole gas chromatograph/mass spectrometer (GC/MS/MS) system with CP-8400 autosampler. The tandem MS/MS system allows for structural elucidation of unknown compounds with precursor, product and neutral loss scan. The GC interface allows for sensitive analyses of complex mixtures in electron impact (EI) as well as positive and negative chemical ionization (CI) mode. Negative CI offers a superior sensitivity for the analysis of nitro-PAH (approximately 100 times higher than EI or positive CI) that could be emitted from combustion sources, including motor vehicle engines. The sensitivity of this instrument in full scan EI/MS mode is approximately 1 pg/µl with 20:1 signal-to-noise ratio (S/N). In EI/MS SIM mode it reaches 50 fg/ul with 10:1 S/N. For negative CI, 10 fg/ul of octafluoronaphthalene gives S/N of 20:1. This superior sensitivity offers the advantage of analyzing small samples collected during a short sampling time.

Total Metals and Associated Elements

Samples for metal analysis were collected on clean Teflon membrane filters and analyzed at the Desert Research Institute by energy dispersive XRF. Energy Dispersive X-ray Fluorescence (EDXRF) analysis will be performed on Teflon-membrane filters. XRF analyses was performed on a PANalytical Epsilon 5 EDXRF analyzer. After EDXRF analysis, the Teflon-membrane

filters are returned to their Petri slides and stored under refrigeration until the XRF data validation is completed and indicates that the runs were acceptable.

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

One-half of the quartz filters (and blanks) that were collected for the carbon analysis were extracted and analyzed at the DRI for water-soluble chloride, nitrite, nitrate, sulfate, and formic and acetic acid by ion chromatography. This extract was also analyzed for NH_4^+ by the indolphenol colorimetric method.

Gases and Vapors

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

Oxides of nitrogen (NO_x) were measured using chemiluminescent analysis (Teledyne Model 200 series; Ecophysics 700 series). CO and CO_2 concentrations were determined using a nondispersive infrared gas analyzer (California Analytical Model 600 series). HCs were measured using a real-time flame ionization detector (Model 300H, California Analytical Instruments) calibrated against a certified propane standard. SO_2 was measured with a pulsed fluorescence analyzer (Thermo Electron Model 43i). Analyzers were zeroed daily using ultra-zero air and calibrated with National Institute of Standards and Technology-traceable span gases.

Gas Phase Hydrocarbon Speciation

VOCs (except acids and carbonyls, which are too polar for collection and analysis from canister) were collected using a custom-designed canister sampler (L. Sheetz Enterprises, Reno, NV). Samples were collected downstream of a NO_x denuder in a pre-cleaned 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 led to false low concentrations of reactive compounds such

as 1,3-butadiene and styrene. Analysis was conducted at the Desert Research Institute by GC/MS.

Canister samples were analyzed for VOC species using gas chromatography/mass spectrometry according to EPA Method TO-15. The GC-FID/MS system includes a Lotus Consulting Ultra-Trace Toxics sample preconcentration system built into a Varian 3800 gas chromatograph with flame ionization detector (FID) coupled to a Varian Saturn 2000 ion trap mass spectrometer. The Lotus preconcentration system consists of three traps. Mid- and heavier weight hydrocarbons are trapped on the front trap consisting of 1/8" nickel tubing packed with multiple adsorbents. Trapping is performed at 55 ºC and eluting is performed at 200 ºC. The rear traps consist of two traps: empty 0.040" ID nickel tubing for trapping light hydrocarbons and a cryo-focusing trap for mid and higher weight hydrocarbons isolated in the front trap. The cryo-focusing trap is built from 6' x 1/8" nickel tubing filled with glass beads. Trapping of both rear traps occurs at -180 ºC and eluting at 200 ºC. Light hydrocarbons are deposited to a Varian CP-Sil5 column (15m x 0.32mm x 1µm) plumbed to a column-switching valve in the GC oven, then to a Chrompack Al2O3/KCl column (25m x 0.53mm x 10µm) leading to the flame ionization detector for quantitation of light hydrocarbons. The mid-range and heavier hydrocarbons cryo-focused in the rear trap are deposited to a J&W DB-1 column (60m x 0.32mm x 1µm) connected to the ion trap mass spectrometer. The GC initial temperature is 5 ºC held for approximately 9.5 minutes, then ramps at 3 ºC/min to 200 ºC for a total run time of 80 minutes.

Calibration of the system is conducted with a mixture that contained commonly found hydrocarbons (75 compounds from ethane to n-undecane, purchased from Air Environmental) in the range of 0.2 to 10 ppbv. Three point external calibrations are run prior to analysis, and one calibration check is run every 24 hours. If the response of an individual compound is more then

10% off, the system is recalibrated. Replicate analysis is conducted at least 24 hours after the initial analysis to allow re-equilibration of the compounds within the canister.

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 pre-filter to remove PM. To assess the trapping efficiency of the DNPH cartridge, two cartridges were used in series, and the back-up cartridge was analyzed to ensure that all carbonyls were trapped on the first cartridge. Analysis was to be conducted at the Desert Research Institute by liquid chromatography/ultraviolet (LC/UV) (photo-diode-array). The hydrazones are separated and quantified per EPA Method TO-11A using a high performance liquid chromatograph (Waters 2690 Alliance HPLC System with 996 Photodiode Array Detector). After sampling, the cartridges are eluted with acetonitrile. An aliquot of the eluent is transferred into a 2-ml septum vial and injected with an autosampler into a Polaris C18-A 3μm 100 x 2.0 mm HPLC column. Since our HPLC system is equipped with the photodiode array detector, the identification of carbonyl compounds is much more accurate than with standard UV/VIS detector. Also, the sensitivity of the analysis is enhanced by using the photodiode array detector (Zielinska and Fujita, 2003).

QUALITY ASSURANCE

This research was conducted in a manner that is consistent with many of the standards developed for Good Laboratory Practice (GLP), although full compliance with GLP requirements was not a requirement of the protocol. Quality control (QC) consisted of the conduct of all work according to approved protocols and standard operation procedures, the inclusion of verified QC standards for the calibration of the certification of system performance, and third-party verification of all data before submission to the statistician for analysis. These

QC processes applied to all aspects of the study, including the test and evaluation of engine performance, the verification of fuel and oil composition, and the analysis of test atmospheres. For each of the analytical tools, calibration or "span" checks were conducted each time of use. The Quality Assurance Unit duties for the study protocol included evaluating study-start parameters, auditing exposure system functions, auditing the processes of scientific data collection, and determining if data were recorded and stored according to LRRI Policy 602. The data were stored in a secure electronic database.

RESULTS

Table 2 provides the mean of the major atmospheric components that were measured throughout the study. These are study averages from the initiation of the study to completion for each of the exposure levels. Table 3 provides the detailed composition of the high exposure level test atmospheres during each of the intensive monitoring events in April, 2010, September 2010, April 2011 and April 2012. The detailed exposure atmosphere compositions for each exposure level are provided in the Appendix. The composition of the test atmospheres, including commentary on the observed composition over time throughout the study, are described below.

GAS MONITORING

Gases that were routinely monitored included NO, NO_2, CO_2, CO, SO_2, and HC. NO_2 concentrations, which were used as the dilution indicator, were within 10% of the target at the mid level and within 5 % at the high and low. The corresponding average concentrations of NO_2 were 4.2, 0.88 and 0.1 ppm, and NO was 7.5, 1.7 and 0.4 ppm. Of interest is that the NO:NO_2 ratio changed throughout the study. Table 3 illustrates the NO and NO_2 concentrations at the four different 'intensive' characterizations. In April, 2010, the NO:NO_2 ratio was approximately 53:46 per cent NO:NO_2. There no significant change in this ratio in September 2010. However, in April 2011 the ratio of NO:NO_2 was 62:38 followed by 67:33 in April 2012. The change in

this ratio likely occurred because degradation of the catalyst on the DPF with extended operation. The catalyst is intended to oxidize NO:NO_2 to help facilitate trap regeneration. It is expected that the catalyst will have some degradation with time. By 2011, when the major change was observed, there was approximately 7500 operating hours on the DPF. The impact of the change in the NO:NO_2 ratio is that over the duration of the study it required a decreased in dilution to achieve the same amount of NO_2 in the chambers. The outcome is an increase in NO from approximately 4.8 to 9.8 ppm over the course of the study. There was a corresponding increase in CO_2 (Table 3) that reflected the difference in dilution with time. The change in NO_x was higher than CO_2; however, this was due to the contribution of CO_2 from animal respiration. The impact on other atmosphere components is described when appropriate. Overall, the approximate 35-40% decrease in dilution had only a modest impact on other atmosphere constituents because of the relatively variable emissions and low concentrations.

Figures 3 and 4 indicate the real-time traces of the gases at each of the intensive monitoring periods during the 16-hours ACES cycle. The plots show that with the exception of HCs all of the gases varied throughout the cycle as a function of duty cycle and DPF status. As described above, NO_x concentrations increased over the duration of the study, and by the end of the study NO maximum concentrations exceeded 20 ppm at some points during the cycle. NO_2 concentrations did not exceed 12 ppm at any point during the cycle. During trap regeneration, the NO_x became almost completely NO because the conditions during that period do not favor conversion of NO to NO_2. The rate of conversion was not as efficient as time when on throughout the study. 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-hours cycle and decreased later, presumably due to improved conversion efficiency of the after-treatment system with increasing temperature during warm-up. HC stayed reasonably

constant throughout the cycle. The concentrations of HC and CO were relatively low and variable throughout the study.

PARTICULATE MATTER

PM was also low in concentration, as expected. The composition of the PM resulted from a combination of DPM and PM derived from animals in the chamber. The animal contribution undoubtedly included both dander and fine food dust. In addition, some PM likely formed in the chamber as a result of reactions between exhaust gases and ammonia, as previously shown (e.g., McDonald et al. 2004). Real-time particle mass and particle number/particle size distribution were also monitored routinely, and representative illustrations of both are shown in Figures 5 and 6. The results were from samples from the breathing zone of the rodents in the high-level exposure chamber during the intensive characterizations (2010 and 2012 shown for number/size). Each plot represents measurements obtained during a representative 16-hours transient cycle. As indicated, particles were measurable primarily during the two, 90minute regeneration periods. On most exposure days there were two trap regenerations. A minority of the days (i.e. 2-3/month) showed only one regeneration per cycle. The particle mass concentration throughout the study did not show significant increases. A typical average concentration of PM during a trap regeneration was approximately 50 $\mu g/m^3$, with peaks ranging from approximately 70 to over 250 $\mu g/m^3$. The particle number traces (Figure 6 followed the same pattern as the PM in real time. For the regeneration events shown, the particle number size distributions were both approximately 15-20 nm with a 1.5-2 nm geometric standard deviation. There were small changes in median number size that occurred over the duration of the study, but the changes were within 5 nm.

The PM mass concentrations were measured at the inlet to the chamber and in the chamber to allow the contribution from animals to be distinguished from the DE contribution. As

expected, the concentration in the chamber (average 17-27 $\mu g/m^3$ range between clean air control and high level atmosphere) was much higher than that in the chamber inlet, showing that the major portion of PM mass was due to contributions from animals in the chamber. Of interest was that the difference between the measured PM (via filter) in the high exposure level was approximately the difference between the total measured PM in the chamber minus the amount in the inlet. In other words, it is estimated that in the high exposure level the PM consisted of approximately 8 $\mu g/m^3$ diesel PM and 19-20 $\mu g/m^3$ background PM from the animals. As a result, particle mass concentration within the chambers was not closely dilution dependent. In contrast, there was a dilution-dependent difference in mass at the inlet. In addition, there was a dilution-dependent difference in particle number count, with the highest particle number observed in the high level chamber. The particle number–based size distribution had a median size of approximately 20 nm, and the particle mass size distribution had a median size of 40 nm at the mid and high levels. This size and transient nature of the particles associated with the trap regenerations was consistent with what was reported in Phase 1 of the ACES program (Khalek et al. 2011). The low and control levels had much larger sizes, but the mass concentrations were very low. Particle mass size distribution was measured with the FMPS (Table 2) and an APS, which spans the larger size range of 0.5-20 microns. The APS detected very few particles (i.e. 1 particle/cm^3) that did not change in character or amount between the control and high exposure chamber. These few of particles can not be reliably measured by this technique, so the data are not presented. Although with caveat, we note that the particle size was approximately 3.5-4 microns, with a geometric standard deviation of 2. Those particles are the dander present from the animals.

The PM did not change over the course of the study. Any changes that are observed are likely within the measurement uncertainties of the assays. PM concentration was measured by

both the DMM and filter. Of interest is that the DMM, which was measured inside the chamber, was consistent with the measured values by filters at the inlet. The concentrations measured by the DMM should 'filter' out the dander measurements because it only measures submicron sized particles.

Particle counts in the exposure chambers were variable throughout the study, and likely depended on the number of regenerations, the performance e of the trap and to a lesser extent to background. The particle count in the exposure chamber ranged from approximately 215,000 particles/cm^3 in the low exposure (average) to 828,000 particles/cm3 at the high exposure level on average. The concentrations fluctuated at different times throughout the study, and reached a maximum of approximately 2 million particles/cm^3 at one sampling. The overall high particle number count was similar to what was reported for a previous study that used 2000 diesel technology (McDonald et al., 2004). In that study at a dilution of 10:1 the NO_2 concentration was approximately 5 ppm and the particle count was approximately 1 million particles/cm^3.

CHEMICAL COMPOSITION OF ATMOSPHERE

Figure 7 summarizes the composition of the atmospheres (at the rodent breathing zone) as the percentage of total measured mass for each chemical class. The composition details and the standard deviations for the measurements of the atmospheres shown in Figure 3 shown in Figure 7 with detailed analytical results for each exposure level and time in the Appendices. As Figure 7 indicates, NO, NO_2 and CO accounted for most of the mass of the measured components of the exposure atmospheres. The contribution of NO and NO_2 as a fraction of total mass increased proportionally with exposure level, as expected. CO accounted for more proportional mass in the low level, mostly because of background CO relative to the low concentration of NO_2. In general, the VOCs accounted for a small proportion of the mass, but because of the low concentrations of CO and NO_x, the VOCs accounted for up to 10% of the

mass at the low and control exposure levels. It is noteworthy that this result indicates the animals contributed a significant portion of the measured VOCs. Sulfur dioxide was low at all exposure levels.

The VOC concentrations in general showed dilution proportionality, with the highest concentration at the high exposure level when measuring total mass. However, concentrations at the lower exposure levels were not significantly higher than the control background. The VOCs that could be attributed to DE were primarily the alkanes (straight chain), alkenes, and aromatics. Of particular interest are the VOCs listed by the EPA as mobile source air toxics: benzene, toluene, ethyl benzene, and xylene (the four together are referred to as BTEX) and 1,3-butadiene. The concentrations of BTEX early in the study were very low and showed a trend toward increasing with the DE exposure level, especially benzene and toluene. In the 2012 measurement campaign, the concentrations of the BTEX compounds showed an increase relative to earlier measurements by about a factor of 5. For example, the concentration of benzene in April 2012 was 11.2 $\mu g/m^3$ compared with approximately 2 $\mu g/m^3$ in previous measurements.

The carbonyls showed no concentration proportionality with dilution, and in fact were lower in concentration at the higher exposure levels. While animals do contribute to a background carbonyls concentration, the dilution-dependent decrease suggested that reactions occurred with NO_x at the time samples were being taken. Further investigation into the chromatograms (data not shown) from the carbonyl analysis suggested that, indeed, the NO_x–carbonyl reactions occurred at the high level. A cobalt oxide denuder was used to attempt to remove NO_x before sampling, but because it was rapidly saturated it was not effective.

PM composition was slightly different at each of the exposure levels. This was shown by a change in the proportional amount of inorganic PM that occurred through these reactions in the chamber. The proportions of organic carbon also varied at different levels. Because the sum of

organic carbon and additional species exceeded the total measured mass, the organic carbon measurements are considered to be biased by a sampling artifact (organic vapor adsorption). Furthermore, some of the organic carbon measured in the chamber may have come from the animals, including dander and SVOC emissions from respiration. The high-exposure level had the largest contribution of PM that was derived from the engine. At that level, carbon accounted for about 50% of the mass, and the remainder was a combination of the inorganic ions and elements. The EC/OC ratio in Phase 3B was approximately 0.5 at the high exposure level during the first two intensive measurement periods, compared with 1.1 for engine B in Phase 1 (Khalek et al. 2009;2011), suggesting a higher proportion of organic material in the particles collected in the chambers with the animals present. Figure 8 shows the measured EC and OC values from each of the sampling campaigns. The OC concentrations were variable and higher than expected based on the likely actual concentration, with excess concentration likely due to adsorption of vapor organic to the quartz filters during sampling. The OC was primarily found in the second fraction of the thermal analysis, suggesting it was primarily composed of moderate volatility compounds. The EC concentrations also showed some variance, but overall decreased over the course of the study, suggesting that the DPF efficiency improved with time. In the last two measurement campaigns the organic carbon measurement artifact was substantially higher, resulting in an EC/OC ratio of approximately 0.05-0.1.

The elements were primarily composed of zinc, manganese, copper, and iron. Potassium and calcium were also present. The metal concentrations were small and not substantially different from background in most cases. Figure 9 shows the concentrations of total elements, iron, calcium and zinc during each of the intensive measurement campaigns. As indicated, the total sum of measured elements did not change substantially over the course of the study, especially considering their relatively low levels. If anything, there was a notable decrease in September

2010 and April 2011, followed by an increase to 2010 level in April 2012. The values for calcium and zinc mostly should reflect fuel/lubricant additives. Their concentrations followed the general trend described above for total elements. Iron, which may reflect engine and component wear, showed a modest increase over the course of the study at the high exposure level. At the lower levels there appeared to be a decrease in iron concentration because of a high concentration measured in April 2010.

Among the measured SVOCs, the alkanes and polars contributed the highest contributions to the test atmospheres, followed by PAHs. The polars were primarily benzoic acid derivatives, and the alkanes were higher molecular weight compounds derived mostly from non combusted fuel. The PAH were dominated by lower molecular weight compounds that would primarily be in the gas phase. Hopanes and steranes, as well as nitro-PAHs, were substantially lower, as expected. The nitro-PAH were observed, however. They were mostly lower molecular weight nitro-PAH. The hopanes and steranes are indicators of oil in the emissions. Of note is that early on in these compounds increased slightly at later time points in the study, suggesting that the aging of the system led to increased oil blow-by. Figure 10 shows the concentrations of these classes of compounds at each exposure level during each of the intensive measurement campaigns. Of note is that these compounds, perhaps better than many of the measured atmospheric constituents, showed good dilutional linearity with changing exposure level (suggesting the diesel exhaust was the major contributor). Overall, the concentrations were consistent at each exposure level over the course of the study. There was some variance, but it considered to be within the measurement variability. The exception may be hopanes and steranes. These indicators of oil/fuel showed very low concentrations early in the study that increased towards the end of the study.

COMPARISON OF RESULTS WITH PREVIOUS STUDIES

Several major diesel studies set the stage for the ACES study. It is worth mentioning the major contrasts in the test atmospheres here benchmarked against those studies. These studies were conducted with older technology, including a 1988 6.2 L light-duty diesel engine (Mauderly et al., 1994)); a 1.6L light-duty diesel engine (Heinrich et al., 1995), and a model 2000 5.9L diesel engine (McDonald et al., 2004). The PM in the current study showed very low to negligible contribution from EC, which is typically defined as soot. The atmosphere also contained low concentrations of VOC and SVOC, especially compared with previous studies of DE. Of interest is that the

The older technologies consisted of high concentration of soot laden PM, NO_x, CO and HCs. The HCs and SVOCs contained high proportional concentrations (relative to 2007 technology) of aromatics and polycyclic aromatic hydrocarbons. In the 2000 engine exhaust characterized by McDonald et al. (2004), the EC/OC ratio was around 2.3 at the mid-exposure concentration versus 0.23 in the ACES Phase 3B study (with comparable NO_2 concentrations), indicating a much larger amount of soot from the older engine technology. NO_x for the older technology had a ratio of approximately 90:10 NO:NO_2 as compared to the current technology that ranged from 50:50 to 70:30. The composition of the ACES test atmospheres revealed very low PM, SVOC, VOC and CO, as expected. The concentrations of PM at the highest exposure levels reported by Mauderly et al. (1995) were approximately 1000 times higher than the ACES test atmosphere. Further, the lowest PM concentration that resulted in statistical increases in tumors during those studies was 300 $\mu g/m^3$ in the Mauderly et al. (1994) report, compared with 8 $\mu g/m^3$ in the current study.

Despite significantdecreases in many of the atmosphere components based on mass, there was not a significant decrease in particle number in the current study compared model year 2000

technology diesel exhaust reported earlier (McDonald et al., 2004). The particle number concentration reported in that study was $1x10^6$ particles/cm3 at the high exposure level, which was conducted at a dilution of 10:1 and a NOx concentration of 45.3 ppm (NO_2 was 4.0 ppm) and a PM concentration of 1000 $\mu g/m^3$. In the current study the high exposure level showed a particle number concentration of $0.8x10^6$ particles/cm^3 at a dilution of 25:1, PM of 7.8 $\mu g/m^3$ and NOx of 11.7 ppm (NO_2 = 4.2 ppm). The particle number concentration was transient in both studies, corresponding in McDonald et al. 2004 to changes in emissions during the engine test cycle and in the current study corresponding primarily to periods of DPF regenerataion. As described elsewhere (Khalek et al.,2000; Swanson et al, 2009; Khalek et al., 2011), the composition of the particles that contribute to the particle number from two different technologies are different in composition, mostly related to the differences in how they are formed. In the 2007 technology diesel the DPF regeneration corresponds with a significant increase in exhaust temperature, which leads to release of organic particles and sulfuric acid that serves as the nucleation source during dilution. As described by Khalek et al., 2011, the dilution conditions can lead to enhanced growth and formation of nanoparticles, and it is likely that atmospheres in the animal exposure chambers have higher particle numbers because of the long residence time in the chambers (4 minutes).

The emissions and composition of the exhaust from the engine used in this study was characterized in Phase 1 of ACES and reported previously (Khalek et al., 2011). As expected, that study showed similar overall composition of emissions to those developed for the test atmospheres here. They reported increased NO_2, low CO and HC, and low PM. The PM composition in that report (average of 4 technologies) was 53 % sulfate, 30 % OC, 13 % EC and 4 % metals. In the current study, benchmarked against total measured PM we show similar percentages of EC (~15 %) and a lower contribution to sulfate directly. However, the total

inorganic ions, which included nitrate, sulfate and ammonium, accounted for greater than 50 % of the mass at the high exposure level. The higher percentage in the current study was due to the reaction of ammonia with the gases to convert nitric acid to ammonium nitrate. Of interest was that Khalek et al. (2011) did not detect nitrate in the Phase 1 characterization of this engine, affirming that the presence of the nitrate is due to the reaction with ammonia (from the animals) to form ammonium nitrate salts.

The contribution from the elements was slightly higher (compared to the Phase 1 work) in the current studies, at about 10 % of PM. The majority of this mass was sodium, however, similar to the current study. The other elements were primarily calcium, zinc and phosphorous (matched composition of oil). Regarding the speciated organics, Khalek et al. (2011) showed similar trends of high proportions of alkanes, single ring aromatics, and lower molecular weight PAH's as the dominant measured organics (based on concentration), with low levels of the hopanes/steranes and nitro-PAH. They also reported high concentrations of carbonyls, which were likely present in the current study but the results were not accurate at the high exposure levels due to sampling problems.

Overall, the test atmospheres in the current study were so low for many of the analytes observed in the previous reports that they were difficult to measure against the background measured in the chamber. Only NO_x, particle number and CO were present at a similar magnitude of concentrations to the components tested in the previous studies with older technology engines. The overall composition of the test atmospheres in this study was different from prior studies of DE (using older technology) both in terms of quantity and type of components present. The current study showed substantial decreases in soot and both volatile and nonvolatile organics, most notably.

SUMMARY

Diesel exhaust from a 2007-compliant heavy-duty diesel engine equipped with emission controls was selected from four candidate engines in Phase 1 of the ACES Program (see Khalek et al. 2009; 2011) and used to generate test atmospheres for a chronic rodent bioassay. The engine was operated on a dynamometer and fueled with ultra low-sulfur diesel fuel that met current on-road specifications. The engine and associated systems were maintained as recommended by the engine manufacturer. The crankcase lubricating oil, which was changed every 250 hours, was a proprietary blend provided by Lubrizol that had also been used in Phase 1 of the ACES program. The engine was operated on a 16-hours cycle that was specifically designed for the ACES study (as described in the Preface) to represent a combination of highway and urban driving conditions.

The concentrations of PM, SVOC and VOCs were generally very low. This confirms the original expectations during the planning of ACES and the results in Phase 1 (Khalek et al., 2011). The most abundant pollutants were CO_2, CO, NO, and NO_2. In comparison to earlier DE inhalation studies, the ratio of PM to NO_2 was at least 3 times lower. The NO:NO2 ratio shifted over the course of the study due to aging of the oxidation catalyst on the DPF. The result was less NO2 in the exhaust. Because NO2 was the primary dilution indicator, the level of dilution decreased over the duration of the study. This led to an approximate 35-40% decrease in dilution by the end of the study. This change had only a modest impact on other atmosphere constituents because of the relatively variable emissions and low concentrations.

The overall composition of the test atmospheres revealed that animals contributed to the composition of the test atmosphere, both by contributing dander and volatile organics, but also because of reactions that occur with animal ‘emissions’ and components from the exhaust. Measurements at the chamber inlet compared with the chamber allowed the assessment of the

differential amount of PM from the animals or the engine exhaust. Data from the intensive characterization also showed that the animals contributed particle-bound organic compounds, led to the formation of nitrate particles and VOCs. The particle mass and number-based size distributions (determined with the FMPS, which measures particles up to only 500 nm) confirm the presence in the chamber of very small particles with a median diameter of 20 to 40 nm, which were considered to be derived almost exclusively from the engine. Of note is that the particle number was similar in concentration to older technology, but differed markedly in composition.

IMPLICATIONS OF FINDINGS

The ACES Phase 3 studies are the first of their kind to investigate the biological response in animals exposed to exhaust from 2007 compliant diesel technology. The results reported here define the test atmospheres from that study. As expected, the test atmospheres showed marked contrasts to previous studies of pre-2007 diesel technology. The most notable differences were the significant decrease in the total VOC, SVOC and PM relative to the concentration of the exhaust in the chamber. In addition to being lower in concentration than older technology diesel, the composition of the exhaust was markedly different. There was an absence of soot, relatively high proportions of inorganic ions, and an increase in the relative proportion of NO_2 compared to NO. There were also low concentrations of CO. Because of the low concentrations of VOC and PM, the implication of the animals on the test atmospheres was significant. The animals contributed the majority of the mass of PM in the exposure chambers through dander. They also contributed to the VOC and to the composition of the exhaust PM through reaction of ammonia with inorganic ions/gases to form inorganic salts. The study atmospheres were employed for the successful conduct of up to 30 months (11,721 operating hours) of exposure to rodents. The findings of this study will provide a major step forward in our understanding of the potential

health benefit of the emissions reductions that have been implemented in modern diesel powered vehicles.

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Table 1. Description of Methodology for Sampling and Analysis of Exposure Atmospheres

Analysis	Collection Device	Collection Media	Collection Point	Sample Flow Rate (L/m)	Analytical Instrument	Analytical Laboratory	Sampling Frequency
gravimetric mass	aluminum in-line filter holder	Teflon filter	Chamber/ Chamber Inlet	10	MB	LRRI	weekly
continuous mass/ black carbon	Dekati Mass Monitor/ Photoacoustic	NA	Chamber	2	NA	LRRI	daily
Number size distribution (5-500 nm)	Fast Mobility Particle Sizer	NA	Chamber	10	FMPS	LRRI	daily
Size distribution (0.5-20 μm)	Aerodynamic Particle Sizer	NA	Chamber	5	APS	LRRI	detailed
nitric oxides	chemiluminescence analyzer	NA	Chamber	0.4	NA	LRRI	daily
CO/CO_2/THC	Infrared	NA	Chamber	1	NA	LRRI	daily
THC	flame ionization detector	NA	Chamber	1	NA	LRRI	daily
organic/black carbon	aluminum in-line filter holder	quartz filter (1)	Plenum	10–50	TOR	DRI	detailed
ions (sulfate/nitrate/ ammonium)	aluminum in-line filter holder	quartz filter (2)	Plenum	10–50	IC, AC	DRI	detailed
SO_2	UV fluorescence analyzer	NA	Chamber	1	NA	LRRI	daily
metals and other elements	Teflon in-line filter holder	Teflon filter (2)	Plenum	20–50	ICPMS	DRI	detailed
volatile hydrocarbons (C_1-C_{12})	volatile organic sampler	electropolished canister	Chamber	0.1	GCMS/GCFID	DRI	detailed
volatile carbonyls	volatile organic sampler	DNPH cartridge	Chamber	0.3	LC/MS	DRI	detailed
semivolatile/ fine particle organics	Tisch environmental sampler	quartz filter/ XAD-4	Plenum	80	GCMS	DRI	detailed

List of Abbreviations

Chemical Species: CO = carbon monoxide; CO_2 = carbon dioxide; SO_2 = sulfur dioxide; NH_3 = ammonia; THC = total hydrocarbons

Instruments/Collection Devices: MB = microbalance; NA = not applicable; TOR = thermal/optical reflectance; IC = ion chromatography; ICPMS = inductively coupled plasma mass spectrometry; GCMS = gas chromatography mass spectrometry; GCFID = gas chromatography flame ionization detector; DNPH = dinitrophenylhydrazine; LC/DMS = liquid chromatography/diode array/mass spectrometry; GCMS/LCMS = gas chromatography mass spectrometry/liquid chromatography mass spectrometry; FMPS = fast mobility particle sizer; CPC = condensation particle counter. TIGF = Teflon impregnated glass fiber filter. AC= automated colorimetry

Table 2. Average Exposure Atmosphere Composition during ACES 3B

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Dekati Particle Mass-Chamber Inlet	µg/m³	NA	NA	NA	NA
Dekati Particle Mass-Inside Chamber	µg/m³	0.3 ± 0.2	0.2 ± 0.2	0.9 ± 0.6	6.3 ± 4
Filter Sample - Chamber Inlet	µg/m³	NA	2.5 ± 1.6	2.7 ± 1.2	7.8 ± 2.8
Filter Sample - Inside Chamber	µg/m³	16.9 ± 6.7	23.3 ± 11.4	20 ± 5.4	27.3 ± 6.2
Particle Mass-FMPS	µg/m³	0.2 ± 0.2	1.1 ± 0.9	2 ± 1.7	5.3 ± 2.9
Particle Count -FMPS	Particle/cm³	17136 ± 23420.5	215225.5 ± 412548.9	678184 ± 1247908.6	828814.3 ± 1041924.8
NMAD (GSD) - FMPS	nm	23 (1.8) ± 8.8 (0.5)	16.6 (1.5) ± 6.3 (0.2)	15.4 (1.5) ± 5.5 (0.2)	18.6 (1.6) ± 4.4 (0.1)
MMAD (GSD) - FMPS	nm	196.8 (1.7) ± 149 (0.2)	181.8 (2.7) ± 113.4 (0.6)	81.2 (2.9) ± 32 (0.8)	41.6 (2.2) ± 4.1 (0.5)
Nitrogen Oxide (NO)	µg/m³ (ppm)	2 ± 3 (0.001 ± 0.002)	274.3 ± 186.3 (0.3 ± 0.2)	1376.6 ± 390.4 (1.3 ± 0.4)	6878.6 ± 2591.8 (6.6 ± 2.4)
Nitrogen Dioxide (NO_2)	µg/m³ (ppm)	2.6 ± 5.2 (0.002 ± 0.004)	159.5 ± 16.6 (0.1 ± 0.01)	1421.5 ± 83.7 (0.9 ± 0.05)	6873.2 ± 489.4 (4.4 ± 0.3)
Carbon Monoxide (CO)	µg/m³ (ppm)	895.8 ± 883.2 (0.9 ± 0.9)	1042.2 ± 510.1 (1.1 ± 0.5)	1787.1 ± 444 (1.9 ± 0.5)	6167.6 ± 2445.4 (6.4 ± 2.6)
Carbon Dioxide (CO_2)	mg/m³ (ppm)	2110.6 ± 800.1 (1402.2 ± 531.7)	2695.7 ± 1175.2 (1790.9 ± 780.9)	3599.1 ± 497.8 (2391.2 ± 330.8)	7215.6 ± 1456.4 (4794.1 ± 967.5)
Sulfur Dioxide (SO_2)	µg/m³ (ppb)	4.9 ± 1 (2.2 ± 0.4)	6.6 ± 1.5 (2.9 ± 0.7)	20.5 ± 6.2 (9.1 ± 2.7)	69.6 ± 28.6 (30.8 ± 12.6)
Elemental Carbon	µg/m³	0.4 ± 0.4	1.2 ± 1.2	0.4 ± 0.4	1.2 ± 1
Organic Carbon	µg/m³	4.5 ± 1.4	6.6 ± 1.4	4.8 ± 1.9	5.7 ± 2.4
Ammonium	ng/m³	31.3 ± 31.3	57.2 ± 29	203.2 ± 150.6	1312.2 ± 450.2
Sulfate	ng/m³	101.6 ± 26	193.1 ± 153.1	644.8 ± 405.5	2121.1 ± 968.2
Nitrate	ng/m³	18.6 ± 16.7	181.2 ± 195.9	220.2 ± 73.9	2087.3 ± 747
Elements (Metals)	ng/m³	461.3 ± 208.5	567.9 ± 224	661 ± 302.1	811.5 ± 336.3
Alkanes	µg/m³	2.8 ± 0.5	4.7 ± 1.9	8.6 ± 2.8	26.6 ± 9.3
Carbonyl	µg/m³	53.8 ± 12.1	71.2 ± 40.2	21.4 ± 5.1	1 ± 1.5
Polyaromatic Hydrocarbon (PAH)	µg/m³	0.8 ± 0.5	1.1 ± 0.4	1.9 ± 0.7	4.7 ± 1.6
Nitro-PAH	ng/m³	0.4 ± 0.2	0.8 ± 0.4	1.6 ± 0.5	8 ± 2.5
Polars (Acids)	µg/m³	3.2 ± 1.2	4.1 ± 1.6	6.9 ± 2.9	16 ± 6
Hopane and Steranes	ng/m³	2 ± 0.7	5.1 ± 3.5	2.5 ± 1.6	3.7 ± 3.9
Volatile Organic Compounds (VOC)	µg/m³	33.5 ± 21.3	50.3 ± 31.3	44.2 ± 15.3	148.9 ± 96.9

Table 3. Temporal Comparison of Exposure Atmosphere Composition (High Exposure Level)

		April 2010	September 2010	April 2011	April 2012
	Units	**High**	**High**	**High**	**High**
Dekati Particle Mass-Chamber Inlet	µg/m³	NA	NA	NA	NA
Dekati Particle Mass-Inside Chamber	µg/m³	10.3 ± 5.2	9.04 ± 11.8	2 ± 0.8	3.8 ± 2.8
Filter Sample - Chamber Inlet	µg/m³	8.3 ± 2.1	8.0 ± 3.0	4 ± 1	10.7 ± 0.5
Filter Sample - Inside Chamber	µg/m³	28.3 ± 23.0	20.0 ± 2.0	35 ± 44	26.0 ± 9.3
Particle Mass-FMPS	µg/m³	2.93 ± 0.84	6.23 ± 3.89	3.1 ± 1.4	9.12 ± 0.47
Particle Count -FMPS	Particle/cm³	9.68e+04 ± 1.66e+04	2.37E06 ± 1.16E+06	5.2E05 ± 1.6E+05	328457 ± 121864
NMAD (GSD) - FMPS	nm	20.17 (1.55) ± 6.40 (0.05)	12.1 (1.7) ± 0.5 (0.1)	14.5 (1.5) ± 1.0 (0.03)	21.1 (1.6) ± 2.1 (0.02)
MMAD (GSD) - FMPS	nm	44.17 (2.53) ± 1.72 (0.71)	35.5 (1.8) ± 3.1 (0.1)	29.6 (1.8) ± 3.7 (0.2)	43.3 (2.8) ± 2.0 (0.4)
Nitrogen Oxide (NO)	µg/m³ (ppm)	4875 ± 728 (4.75 ± 0.71)	4936.1 ± 738.9 (4.8 ± 0.7)	7338.5 ± 142.1 (7.2 ± 0.1)	10364.7 ± 1949.8 (9.8 ± 1.9)
Nitrogen Dioxide (NO_2)	µg/m³ (ppm)	6389 ± 1448 (4.06 ± 0.92)	6813.3 ± 1148.7 (4.3 ± 0.7)	6737.5 ± 204.0 (4.3 ± 0.1)	7552.9 ± 1416.2 (4.8 ± 0.9)
Carbon Monoxide (CO)	µg/m³ (ppm)	5977 ± 785 (6.24 ± 0.82)	9453.4 ± 1724.0 (9.9 ± 1.8)	5696.3 ± 518.9 (5.9 ± 0.5)	3543.8 ± 383.1 (3.7 ± 0.4)
Carbon Dioxide (CO_2)	mg/m³ (ppm)	5388 ± 343 (3580 ± 228)	8950.9 ± 681.9 (5947.0 ± 453.1)	7322.3 ± 59.1 (4865 ± 39.3)	7201.0 ± 185.0 (4784.4 ± 122.9)
Sulfur Dioxide (SO_2)	µg/m³(ppb)	53.2 ± 9 (23.6 ± 3.88)	43.8 ± 11.7 (19.4 ± 5.2)	73.0 ± 2.2 (32.3 ± 1.0)	108.4 ± 3.61 (48 ± 1.6)
Elemental Carbon	µg/m³	2.7 ± 0.15	1.0	0.7 ± 0.02	0.4 ± 0.1
Organic Carbon	µg/m³	6.1 ± 0.20	2.6 ± 0.04	5.5 ± 0.3	8.5 ± 0.4
Ammonium	ng/m³	1740.4 ± 0.3	1374.3 ± 27.3	679.4 ± 112.4	1454.8 ± 5.4
Sulfate	ng/m³	1740.4 ± 0.9	2863.7 ± 4.0	927.5 ± 0.1	2952.6 ± 3.8
Nitrate	ng/m³	1193.3 ± 0.4	2975 ± 0.5	2298.4 ± 1.9	1882.3 ± 50.9
Elements (Metals)	ng/m³	823.8 ± 240.8	712.0 ± 226.2	451.7 ± 6.7	1258.5 ± 29.2
Alkanes	ng/m³	26.7 ± 1.5	16 ± 0.9	24.9 ± 1.3	38.6 ± 2
Carbonyl	µg/m³	0.3 ± 1.0	3.3 ± 0.5	0.4 ± 0.4	0 ± 0.3
Polyaromatic Hydrocarbon (PAH)	µg/m³	6.2 ± 0.3	3.8 ± 0.3	6 ± 0.33	2.89 ± 0.18
Nitro-PAH	ng/m³	6.5 ± 0.4	5.5 ± 0.3	8.6 ± 0.46	11.2 ± 1
Polars (Acids)	ng/m³	24.8 ± 2.2	12.1 ± 1	15 ± 0.8	12.1 ± 1
Hopane and Steranes	ng/m³	0.9 ± 0.1	1.3 ± 0.2	3.1 ± 0.2	9.3 ± 0.7
Volatile Organic Compounds (VOC)	µg/m³	74.9 ± 12.8	73.6 ± 10	169.1 ± 17.3	277.8 ± 16.3

Table 3. Temporal Comparison of Exposure Atmosphere Composition (High Exposure Level)

Carbon:

		April 2010	September 2010	April 2011	April 2012
Exposure Atmosphere Composition	**Units**	**High**	**High**	**High**	**High**
Organic Carbon Fraction 1	µg/m³	0.5 ± 0.13	0.2 ± 0.01	0.5 ± 0.11	1.5 ± 0.1
Organic Carbon Fraction 2	µg/m³	2.1 ± 0.02	1.2 ± 0.09	2.1 ± 0.14	4.8 ± 1.3
Organic Carbon Fraction 3	µg/m³	2.6 ± 0.26	0.9 ± 0.06	2.2 ± 0.05	1.3 ± 0.1
Organic Carbon Fraction 4	µg/m³	0.9 ± 0.18	0.2 ± 0.01	0.6 ± 0.03	0.6
Pyrolyzed Organic Carbon Reflectance	µg/m³	0.0	0.1	0.1	0.6 ± 0.2
Pyrolyzed Organic Carbon Transmittance	µg/m³	1.1 ± 0.41	0.1 ± 0.01	0.3	0.3
Organic Carbon	µg/m³	6.1 ± 0.2	2.6 ± 0.04	5.5 ± 0.27	8.5 ± 0.4
Elemental Carbon Fraction 1	µg/m³	1.0	0.1	0.2 ± 0.02	0.3
Elemental Carbon Fraction 2	µg/m³	1.5 ± 0.11	0.9 ± 0.05	0.5 ± 0.01	0.4 ± 0.1
Elemental Carbon Fraction 3	µg/m³	0.1 ± 0.03	0.0	0.0	0.0
Elemental Carbon	µg/m³	2.7 ± 0.15	1.0	0.7 ± 0.02	0.4 ± 0.1
Total Carbon	µg/m³	8.7 ± 0.36	3.6 ± 0.01	6.2 ± 0.27	8.9 ± 0.4

Table 3. Temporal Comparison of Exposure Atmosphere Composition (High Exposure Level)

Elements (Metals):

Exposure Atmosphere Composition	Units	April 2010 High	September 2010 High	April 2011 High	April 2012 High
Sodium	ng/m³	228.5 ± 63.4	278.3 ± 62	153 ± 5.76	819.8 ± 28.3
Magnesium	ng/m³	9.6 ± 19.2	19.2 ± 17.8	7.4 ± 0.08	22.3 ± 0.2
Aluminum	ng/m³	19.2 ± 3.8	19.1 ± 3.5	0.4	36.3 ± 0.1
Silicon	ng/m³	14.2 ± 2.4	0.9 ± 2.1	13.8 ± 0.07	12.7
Phosphorous	ng/m³	106.2 ± 1	10.2 ± 0.6	1.9 ± 0.01	20.8
Sulfur	ng/m³	806.9 ± 3.3	1060.8 ± 4.1	481 ± 1.44	1251 ± 3
Chlorine	ng/m³	93.1 ± 0.9	64.3 ± 0.8	49.1 ± 0.09	28.2
Potassium	ng/m³	186.9 ± 1.1	216.2 ± 1.1	126 ± 0.15	72.9
Calcium	ng/m³	122.2 ± 2.8	52.9 ± 2.5	33.5 ± 0.08	77.2 ± 0.1
Scandium	ng/m³	0 ± 11.5	0 ± 10.7	1 ± 0.01	0.0
Titanium	ng/m³	1.8 ± 0.9	0.6 ± 0.9	0.1	1.0
Vanadium	ng/m³	0 ± 0.6	0 ± 0.6	0.0	0.1
Chromium	ng/m³	1.1 ± 0.6	1 ± 0.6	0.9	0.1
Manganese	ng/m³	2.4 ± 1.9	0.7 ± 1.8	3.1 ± 0.02	3.5
Iron	ng/m³	15 ± 0.7	8.8 ± 0.6	36.1 ± 0.07	52.9
Cobalt	ng/m³	0.1 ± 0.6	0 ± 0.6	0.0	0.2
Nickel	ng/m³	0.6 ± 1.8	0.2 ± 1.7	0.6	0.3
Copper	ng/m³	5.4 ± 2.3	9.1 ± 2.1	9.7 ± 0.02	37.1
Zinc	ng/m³	7.1 ± 0.6	10 ± 0.6	10.2 ± 0.03	29.5
Gallium	ng/m³	0 ± 3.1	1 ± 2.8	0.0	0.1
Arsenic	ng/m³	0 ± 0.6	0 ± 0.6	0.1	0.0
Selenium	ng/m³	0 ± 0.6	0 ± 0.6	0.0	0.0
Bromine	ng/m³	0.2 ± 0.6	0.4 ± 0.6	0.2	0.2
Rubidium	ng/m³	0 ± 0.6	0.2 ± 0.6	0.3	0.1
Strontium	ng/m³	0.4 ± 0.6	0.4 ± 0.6	0.1	0.4
Yttrium	ng/m³	0.4 ± 0.6	0.4 ± 0.6	0.0	0.2

Table 3. Temporal Comparison of Exposure Atmosphere Composition (High Exposure Level)

Elements (Metals):

Exposure Atmosphere Composition	Units	April 2010 High	September 2010 High	April 2011 High	April 2012 High
Zirconium	ng/m³	0 ± 1	0.5 ± 0.9	0.0	1.4
Niobium	ng/m³	0.2 ± 0.9	0 ± 0.8	0.0	0.0
Molybdenum	ng/m³	0.5 ± 1.3	0.1 ± 1.2	0.0	0.0
Palladium	ng/m³	0 ± 1.5	0.5 ± 1.4	0.0	0.8
Silver	ng/m³	0.1 ± 1.4	0 ± 1.3	0.1	0.1
Cadmium	ng/m³	0 ± 1.8	0 ± 1.7	0.0	0.0
Indium	ng/m³	0.9 ± 1.9	0 ± 1.8	0.1	0.5
Tin	ng/m³	0.1 ± 1.9	0.1 ± 1.8	0 ± 0.03	0.9
Antimony	ng/m³	0 ± 3.1	0.2 ± 2.8	0.0	1.1
Cesium	ng/m³	0 ± 6.2	0 ± 5.8	0.0	1.8
Barium	ng/m³	1.8 ± 7.2	0 ± 6.7	0.0	0.7
Lanthanum	ng/m³	2.8 ± 9	1.8 ± 8.4	0.0	4.0
Cerium	ng/m³	0 ± 8.5	2.8 ± 7.8	0 ± 0.04	0.0
Samarium	ng/m³	0 ± 15	3.9 ± 13.9	0.5 ± 0.04	4.3
Europium	ng/m³	2 ± 21.5	5 ± 19.9	1.3 ± 0.1	0.0
Terbium	ng/m³	0 ± 16.2	0 ± 15.3	0 ± 0.09	25 ± 0.1
Hafnium	ng/m³	0.3 ± 4.5	0 ± 4.2	0.0	0.0
Tantalum	ng/m³	0 ± 2.5	0.6 ± 2.3	1 ± 0.01	0.0
Wolfram	ng/m³	0 ± 7.2	1.1 ± 6.6	0.0	0.0
Iridium	ng/m³	0.3 ± 1.1	0 ± 1.1	0.3	0.0
Gold	ng/m³	0 ± 1.1	0 ± 1	0.0	0.0
Mercury	ng/m³	0.1 ± 0.6	0 ± 0.6	0.0	0.1
Thallium	ng/m³	0.4 ± 0.8	0 ± 0.7	0.1	0.0
Lead	ng/m³	0.1 ± 0.7	1.3 ± 0.6	0.6	1.8
Uranium	ng/m³	0 ± 1	0 ± 0.8	0.1	0.0

Table 3. Temporal Comparison of Exposure Atmosphere Composition (High Exposure Level)

Alkanes:

		April 2010	September 2010	April 2011	April 2012
Exposure Atmosphere Composition	**Units**	**High**	**High**	**High**	**High**
Dodecane	ng/m³	2660.8 ± 219.6	1906.5 ± 95.3	3336.8 ± 166.8	6102.9 ± 305.1
Norfarnesane	ng/m³	2172.1 ± 108.7	1857.1 ± 108.6	1166.1 ± 58.4	1740.5 ± 87.2
Tridecane	ng/m³	5360.8 ± 268.1	3585.3 ± 179.4	5368.5 ± 268.4	7752.7 ± 387.6
Heptylcyclohexane	ng/m³	527.3 ± 35.8	402.3 ± 50.4	569.6 ± 30.2	561.1 ± 45.7
Farnesane	ng/m³	1294.6 ± 78.3	1165.8 ± 62	1418.9 ± 71.1	1277.2 ± 64
Tetradecane	ng/m³	3828.6 ± 191.5	2302 ± 115.1	3919.3 ± 196	6042.5 ± 302.1
Octylcyclohexane	ng/m³	361 ± 18.1	232.5 ± 16.8	356.6 ± 17.8	437 ± 46.6
Pentadecane	ng/m³	3456.0 ± 172.9	1558.7 ± 78	3016.8 ± 150.9	3826.4 ± 191.4
Nonylcyclohexane	ng/m³	275.5 ± 24.1	140.7 ± 7.2	240.8 ± 15.5	356.6 ± 17.9
Hexadecane	ng/m³	2247.3 ± 112.4	880.9 ± 44	1909.9 ± 95.5	2720.8 ± 136
Norpristane	ng/m³	972.5 ± 48.7	413.7 ± 20.8	744.2 ± 37.3	1258.9 ± 63
Decylcyclohexane	ng/m³	106.3 ± 11.9	67.3 ± 7.3	124.7 ± 6.3	237.3 ± 13.3
Heptadecane	ng/m³	1131.4 ± 63.7	446.5 ± 22.5	940.7 ± 51.9	2215.1 ± 110.8
Heptadecane	ng/m³	663 ± 35.2	296.4 ± 15	591.7 ± 29.6	1067.1 ± 53.5
Undecylcyclohexane	ng/m³	96.9 ± 7.8	34.3 ± 4.8	52.5 ± 2.7	132.9 ± 6.7
Octadecane	ng/m³	640.2667 ± 32.1	250.4 ± 12.5	489.8 ± 24.5	1227.3 ± 61.4
Phytane	ng/m³	435.9 ± 30.5	142 ± 8.2	255.4 ± 24.6	834.8 ± 41.8
Dodecylcyclohexane	ng/m³	39 ± 2.7	14.1 ± 2.6	26.3 ± 1.7	73.7 ± 4.1
Nonadecane	ng/m³	184.9 ± 19.2	62.6 ± 3.2	91.2 ± 4.6	339.2 ± 29.2
Tridecylcyclohexane	ng/m³	18.6667 ± 1.1	6.3 ± 0.4	6.6 ± 1.5	20.5 ± 3
Eicosane	ng/m³	85.7 ± 18.7	64.5 ± 3.3	96.2 ± 4.8	181.9 ± 9.5
Tetradecylcyclohexane	ng/m³	7.1 ± 0.4	1.4 ± 0.3	3.9 ± 0.3	9.5 ± 1.1
Heneicosane	ng/m³	34.1 ± 2.6	16.1 ± 1.1	17.1 ± 0.9	71.6 ± 3.6
Pentadecylcyclohexane	ng/m³	4.6 ± 0.6	2.8 ± 0.4	2.1 ± 0.3	8.8 ± 0.6
Docosane	ng/m³	16.5 ± 2.1	36.7 ± 2	40.5 ± 2	49.3 ± 2.5

Table 3. Temporal Comparison of Exposure Atmosphere Composition (High Exposure Level)

Alkanes:

		April 2010	September 2010	April 2011	April 2012
Exposure Atmosphere Composition	**Units**	**High**	**High**	**High**	**High**
Hexadecylcyclohexane	ng/m³	1.3 ± 0.3	1.2 ± 0.3	1.2 ± 0.3	2.1 ± 0.3
Tricosane	ng/m³	7.8 ± 1.5	8.4 ± 1	5.8 ± 0.7	21.9 ± 1.2
Heptadecylcyclohexane	ng/m³	1.0± 0.2	2.7 ± 0.3	1.5 ± 0.3	4.5 ± 0.5
Tetracosane	ng/m³	4.4 ± 0.3	24.1 ± 1.4	25.9 ± 1.3	17.3 ± 0.9
Octadecylcyclohexane	ng/m³	1.4 ± 0.4	0.4 ± 0.3	1.3 ± 0.3	1.5 ± 0.3
Pentacosane	ng/m³	6.5 ± 0.6	3.6 ± 0.4	5.2 ± 0.4	5.2 ± 0.7
Hexacosane	ng/m³	3.7 ± 0.3	9.2 ± 0.6	13.8 ± 0.7	8.7 ± 0.5
Nonadecylcyclohexane	ng/m³	0.8 ± 0.2	3.4 ± 0.4	1.7 ± 0.3	2 ± 0.3
Heptacosane	ng/m³	1.9 ± 0.4	1.7 ± 0.4	4.6 ± 0.4	4.5 ± 0.5
Eicosylcyclohexane	ng/m³	0.2 ± 0.2	0.1 ± 0.3	0.1 ± 0.3	0.8 ± 0.3
Octacosane	ng/m³	1.5 ± 0.3	6.8 ± 0.6	11 ± 0.7	7.4 ± 0.8
Nonacosane	ng/m³	0.9 ± 0.2	1.2 ± 0.3	3.4 ± 0.4	2.7 ± 0.3
Heneicosylcyclohexane	ng/m³	0.1 ± 0.2	0.5 ± 0.3	0.2 ± 0.3	0.8 ± 0.3
Triacontane	ng/m³	0.8 ± 0.2	3.5 ± 0.4	7.2 ± 0.4	7.2 ± 0.6
Hentriacontane	ng/m³	0.7 ± 0.2	2.5 ± 0.4	5.2 ± 0.8	3.6 ± 0.3
Dotriacontane	ng/m³	0.4 ± 0.2	1.9 ± 0.3	6.1 ± 0.8	2.7 ± 0.3
Tritriacontane	ng/m³	0.3 ± 0.2	2.3 ± 0.4	3.1 ± 0.4	0.6 ± 0.3
Tetratriacontane	ng/m³	0.5 ± 0.2	2.7 ± 0.4	7.1 ± 1	1.1 ± 0.3
Pentatriacontane	ng/m³	0.3 ± 0.2	1.3 ± 0.4	1.1 ± 0.3	0.3 ± 0.3
Hexatriacontane	ng/m³	0.3 ± 0.2	0.7 ± 0.3	2.6 ± 0.4	0.6 ± 0.3
Heptatriacontane	ng/m³	0 ± 0.2	0.5 ± 0.3	0.4 ± 0.3	0.2 ± 0.3
Octatriacontane	ng/m³	0 ± 0.2	1 ± 0.3	2.2 ± 0.5	1.3 ± 0.4
Nonatriacontane	ng/m³	0 ± 0.2	0 ± 0.3	0.2 ± 0.3	0.1 ± 0.3
Tetracontane	ng/m³	0 ± 0.2	0 ± 0.3	1.2 ± 0.3	0.7 ± 0.3

Table 3. Temporal Comparison of Exposure Atmosphere Composition (High Exposure Level)

Carbonyl:

		April 2010	September 2010	April 2011	April 2012
Exposure Atmosphere Composition	**Units**	**High**	**High**	**High**	**High**
Formaldehyde	µg/m³	0 ± 0.07	0 ± 0.02	0 ± 0.03	0.0
Acetaldehyde	µg/m³	0 ± 0.07	0 ± 0.02	0 ± 0.03	0.0
Acrolein	µg/m³	0 ± 0.07	2.3 ± 0.15	0 ± 0.03	0.0
Glyoxal	µg/m³	0.1 ± 0.07	0 ± 0.02	0 ± 0.03	0.0
Acetone	µg/m³	0 ± 0.07	0.7 ± 0.05	0 ± 0.03	0.0
Propionaldehyde	µg/m³	0 ± 0.07	0 ± 0.02	0 ± 0.03	0.0
Crotonaldehyde	µg/m³	0 ± 0.07	0 ± 0.02	0 ± 0.03	0.0
Methacrolein	µg/m³	0 ± 0.07	0 ± 0.02	0 ± 0.03	0.0
n-butyraldehyde	µg/m³	0 ± 0.07	0 ± 0.02	0 ± 0.03	0.0
2-Butanone (MEK)	µg/m³	0 ± 0.07	0 ± 0.02	0 ± 0.03	0.0
Valeraldehyde	µg/m³	0 ± 0.07	0.1 ± 0.02	0 ± 0.03	0.0
Hexaldehyde	µg/m³	0.2 ± 0.07	0.1 ± 0.03	0.4 ± 0.03	0.0
Benzaldehyde	µg/m³	0 ± 0.07	0.1 ± 0.02	0 ± 0.03	0.0
m-Tolualdehyde	µg/m³	0 ± 0.07	0 ± 0.02	0 ± 0.03	0.0

Table 3. Temporal Comparison of Exposure Atmosphere Composition (High Exposure Level)

PolyAromatic HydroCarbon (PAH):

Exposure Atmosphere Composition	Units	April 2010 High	September 2010 High	April 2011 High	April 2012 High
1+2ethylnaphthalene	ng/m³	81.6 ± 5.38	55.4 ± 3.5		
Naphthalene	ng/m³	682.7 ± 34.14	696.7 ± 60.1	1006.5 ± 50.3	807 ± 40.4
Quinoline	ng/m³	2.4 ± 0.76	10.9 ± 1.2	17.8 ± 1	10.8 ± 1.0
2-methylnaphthalene	ng/m³	335 ± 16.75	242.2 ± 12.7	450.5 ± 22.5	225.8 ± 11.3
1-methylnaphthalene	ng/m³	246.4 ± 12.32	185.3 ± 11.4	322.2 ± 16.1	165.4 ± 8.3
Nicotine				0 ± 0.1	
Biphenyl	ng/m³	166 ± 8.3	109.3 ± 5.5	182.4 ± 9.1	104.2 ± 5.2
2-methylbiphenyl	ng/m³	468 ± 25.83	410.2 ± 29.9	522.6 ± 26.1	488 ± 24.4
2,6+2,7-dimethylnaphthalene	ng/m³	246.2 ± 12.31	132.3 ± 9.6	274.6 ± 13.7	109.4 ± 5.5
1,3+1,6+1,7dimethylnaphth	ng/m³	465.8 ± 23.29	234.5 ± 15.2	506 ± 25.3	228.4 ± 11.4
1,4+1,5+2,3-dimethylnaphth	ng/m³	147.8 ± 7.39	66.7 ± 3.7	150.6 ± 7.5	74.9 ± 3.8
Acenaphthylene	ng/m³	18 ± 2.4	2.1 ± 0.2	39.3 ± 4.2	8.7 ± 0.4
1,2-dimethylnaphthalene	ng/m³	33.7 ± 2.58	14.6 ± 1.2	35 ± 2.9	21.2 ± 1.1
1+2ethylnaphthalene				102.3 ± 5.1	44.4 ± 2.2
1,8-dimethylnaphthalene	ng/m³	0 ± 0.12	0 ± 0.1	0 ± 0.1	0.2 ± 0.1
Acenaphthene	ng/m³	19.7 ± 5.21	3.1 ± 0.2	10.7 ± 1.3	8.1 ± 1.4
3-methylbiphenyl	ng/m³	1874.8 ± 93.74	807.4 ± 42.7	1097.4 ± 54.9	
4-methylbiphenyl	ng/m³	719.2 ± 35.96	384.3 ± 26.6	412.7 ± 20.6	169.4 ± 14.7
Dibenzofuran	ng/m³	13 ± 1.3	11.7 ± 0.9	18.5 ± 1.1	12.6 ± 8.5
Bibenzyl				78.1 ± 3.9	4.9 ± 0.8
1-ethyl-2-methylnaphthalene	ng/m³	27.4 ± 4.31	11.1 ± 0.7	25.6 ± 2.6	9.1 ± 0.2
2,3,5+I-trimethylnaphthalene	ng/m³	60.7 ± 3.76	37 ± 5.5	51 ± 4.4	29.7 ± 1.1
B-trimethylnaphthalene	ng/m³	92.7 ± 4.63	54.9 ± 2.7	121.7 ± 6.1	41.6 ± 1.6
A-trimethylnaphthalene	ng/m³	112 ± 5.6	64 ± 3.2	136.7 ± 6.8	49.4 ± 2.1
C-trimethylnaphthalene	ng/m³	83.8 ± 4.19	47.8 ± 2.8	104.4 ± 7.2	39.1 ± 2.5
2-ethyl-1-methylnaphthalene	ng/m³	3.8 ± 0.23	1.5 ± 0.1	2.9 ± 0.4	1.5 ± 2.0

Table 3. Temporal Comparison of Exposure Atmosphere Composition (High Exposure Level)

PolyAromatic HydroCarbon (PAH):

		April 2010	September 2010	April 2011	April 2012
Exposure Atmosphere Composition	**Units**	**High**	**High**	**High**	**High**
E-trimethylnaphthalene	ng/m³	56.8 ± 2.97	33 ± 2.7	73.3 ± 3.7	25.4 ± 0.2
2,4,5-trimethylnaphthalene	ng/m³	7.6 ± 1.09	5.6 ± 0.7	13.2 ± 1.1	7.2 ± 1.3
F-trimethylnaphthalene	ng/m³	45.5 ± 4.74	26.2 ± 1.9	56.8 ± 4.2	19.3 ± 0.8
Fluorene	ng/m³	19.4 ± 1	11.1 ± 1.2	39.5 ± 5.3	30.9 ± 1.0
1,4,5-trimethylnaphthalene	ng/m³	4.1 ± 0.23	2.4 ± 0.1	7 ± 0.9	6.1 ± 3.6
J-trimethylnaphthalene	ng/m³	29 ± 1.72	9.1 ± 0.6	36.1 ± 2.3	14.4 ± 0.6
A-Methylfluorene	ng/m³	11 ± 0.73	3.8 ± 0.5	8.1 ± 0.8	5 ± 1.4
B-Methylfluorene	ng/m³	1.7 ± 0.16	0.2 ± 0.1	1.4 ± 0.2	1.8 ± 0.4
1-Methylfluorene	ng/m³	6.6 ± 1.08	1.5 ± 0.2	8.5 ± 0.5	5.7 ± 0.4
9-fluorenone	ng/m³	10.3 ± 1.06	3.9 ± 0.3	10 ± 1.6	5.9 ± 0.4
Dibenzothiophene	ng/m³	0.3 ± 0.12	0.2 ± 0.1	0.2 ± 0.1	0.1 ± 0.6
Phenanthrene	ng/m³	42.2 ± 4.26	23.4 ± 1.8	63.4 ± 3.2	36.7 ± 0.1
Anthracene	ng/m³	3.4 ± 0.57	56.3 ± 7.4	3.6 ± 0.5	2.3 ± 1.8
Xanthone	ng/m³	1.3 ± 0.22	0.9 ± 0.2	2.8 ± 0.4	1 ± 0.1
Acenaphthenequinone	ng/m³	0 ± 0.12	0 ± 0.1	0 ± 0.1	0 ± 0.2
3-methylphenanthrene	ng/m³	4.1 ± 0.23	1.2 ± 0.2	3.6 ± 0.3	2.4 ± 0.1
2-methylphenanthrene	ng/m³	4 ± 0.31	1.1 ± 0.1	4.2 ± 0.7	2.7 ± 0.3
Perinaphthenone	ng/m³	1.3 ± 0.41	0.5 ± 0.1	1 ± 0.1	1 ± 0.2
2-methylanthracene	ng/m³	2.1 ± 0.27	36.7 ± 9	0.6 ± 0.1	1.1 ± 0.2
4,5-methylenephenanthrene	ng/m³	1.2 ± 0.13	1.7 ± 0.3	4.5 ± 0.2	2.9 ± 0.1
9-methylphenanthrene	ng/m³	3.9 ± 0.56	0.3 ± 0.1	2.4 ± 0.2	2.4 ± 0.4
1-methylphenanthrene	ng/m³	2.3 ± 0.36	0.2 ± 0.1	1.6 ± 0.3	1.4 ± 0.1
Dibutyl phthalate					44.2 ± 0.3
Anthrone	ng/m³	4.7 ± 0.24	0.6 ± 0.1	0.8 ± 0.1	1.3 ± 2.2
9-methylanthracene	ng/m³	0.6 ± 0.12	0.2 ± 0.1	0.3 ± 0.1	0.2 ± 0.1
2-phenylnaphthalene	ng/m³	1.3 ± 0.14	0.4 ± 0.1	1.2 ± 0.1	0.4 ± 0.1

Table 3. Temporal Comparison of Exposure Atmosphere Composition (High Exposure Level)

PolyAromatic HydroCarbon (PAH):

		April 2010	September 2010	April 2011	April 2012
Exposure Atmosphere Composition	**Units**	**High**	**High**	**High**	**High**
Anthraquinone	ng/m³	0.9 ± 0.13	1.9 ± 0.3	1.8 ± 0.3	1.8 ± 0.1
A-dimethylphenanthrene	ng/m³	0.9 ± 0.15	0.4 ± 0.1	0.7 ± 0.1	0.9 ± 0.1
B-dimethylphenanthrene	ng/m³	0.4 ± 0.12	0.5 ± 0.1	0.7 ± 0.1	0.5 ± 0.2
1,7-dimethylphenanthrene	ng/m³	0.6 ± 0.12	0.5 ± 0.2	0.5 ± 0.1	0.8 ± 0.1
3,6-dimethylphenanthrene	ng/m³	0.5 ± 0.12	0.3 ± 0.1	0.5 ± 0.1	0.9 ± 0.1
D-dimethylphenanthrene	ng/m³	0.4 ± 0.12	0.2 ± 0.1	0.4 ± 0.1	0.4 ± 0.2
E-dimethylphenanthrene	ng/m³	0.3 ± 0.12	0.4 ± 0.2	0.2 ± 0.1	0.1 ± 0.1
C-dimethylphenanthrene	ng/m³	1.2 ± 0.18	0.3 ± 0.1	1.2 ± 0.2	1.7 ± 0.1
Fluoranthene	ng/m³	2.6 ± 0.32	11.4 ± 1.7	5.3 ± 0.5	2.6 ± 0.1
Pyrene	ng/m³	2.6 ± 0.25	10 ± 0.7	4.8 ± 0.7	1.5 ± 0.2
9-Anthraaldehyde	ng/m³	0.3 ± 0.12	0.4 ± 0.1	0.6 ± 0.1	0.3 ± 0.1
Retene	ng/m³	0 ± 0.12	0 ± 0.1	0 ± 0.1	0 ± 0.1
Benzo(a)fluorene	ng/m³	0.2 ± 0.12	0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
Benzo(b)fluorene	ng/m³	0.1 ± 0.12	0 ± 0.1	0 ± 0.1	0 ± 0.1
B-MePy/MeFl	ng/m³	0.2 ± 0.12	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
1-MeFl+C-MeFl/Py	ng/m³	0.2 ± 0.12	0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
1+3-methylfluoranthene	ng/m³	0.1 ± 0.12	0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
4-methylpyrene	ng/m³	0.2 ± 0.12	0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
C-MePy/MeFl	ng/m³	0.1 ± 0.12	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
D-MePy/MeFl	ng/m³	0.2 ± 0.12	0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
1-methylpyrene	ng/m³	0.1 ± 0.12	0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
Benzonaphthothiophene	ng/m³	0 ± 0.12	0 ± 0.1	0 ± 0.1	0 ± 0.1
Benzo(c)phenanthrene	ng/m³	0 ± 0.12	0 ± 0.1	0 ± 0.1	0 ± 0.1
Benzo(ghi)fluoranthene	ng/m³	0.4 ± 0.13	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1
9-phenylanthracene	ng/m³	0 ± 0.12	0 ± 0.1	0 ± 0.1	0 ± 0.1
Cyclopenta(c,d)pyrene	ng/m³	0.1 ± 0.12	0 ± 0.1	0.2 ± 0.1	0 ± 0.1

Table 3. Temporal Comparison of Exposure Atmosphere Composition (High Exposure Level)

PolyAromatic HydroCarbon (PAH):

		April 2010	September 2010	April 2011	April 2012
Exposure Atmosphere Composition	**Units**	**High**	**High**	**High**	**High**
Benz(a)anthracene	ng/m³	0 ± 0.12	0.2 ± 0.1	0.1 ± 0.1	0 ± 0.1
Chrysene-Triphenylene	ng/m³	0 ± 0.24	0.1 ± 0.1		0 ± 0.1
Chrysene				0 ± 0.1	
Benzanthrone	ng/m³	0 ± 0.12	0.1 ± 0.1	0.1 ± 0.1	0 ± 0.1
Bis[2-ethylhexyl]phthalate					0 ± 0.1
Benz(a)anthracene-7,12-dione	ng/m³	0 ± 0.12	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
3-methylchrysene	ng/m³	0 ± 0.12	0 ± 0.1	0 ± 0.1	0 ± 0.1
Chry56m	ng/m³	0 ± 0.12	0 ± 0.1		
5+6-methylchrysene				0 ± 0.1	0 ± 0.1
7-methylbenz(a)anthracene	ng/m³	0 ± 0.12	0.2 ± 0.2	0 ± 0.1	0 ± 0.1
7,12-dimethylbenz(a)anthracene	ng/m³	0.2 ± 0.13	0.1 ± 0.1	0.3 ± 0.2	0.2 ± 0.1
Benzo(b+j+k)fluoranthene	ng/m³	0 ± 0.12	0 ± 0.1	0.1 ± 0.1	0 ± 0.1
Benzo(a)fluoranthene	ng/m³	0 ± 0.12	0 ± 0.1	0 ± 0.1	0 ± 0.1
Benzo(j)fluoranthene				0 ± 0.1	0.1 ± 0.1
BeP	ng/m³	0.1 ± 0.12	0 ± 0.1	0 ± 0.1	0 ± 0.1
BaP	ng/m³	0 ± 0.12	0 ± 0.1	0.1 ± 0.1	0 ± 0.1
Perylene	ng/m³	0.2 ± 0.12	0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
3-methylcholanthrene				0.3 ± 0.1	0.5 ± 0.1
Dibenz(a,j)acridine	ng/m³	0.3 ± 0.12	0 ± 0.1	0 ± 0.1	0.2 ± 0.1
7-methylbenzo(a)pyrene	ng/m³	0 ± 0.12	0 ± 0.1	1.3 ± 0.2	0.1 ± 0.1
Bpy910dih	ng/m³	0 ± 0.12	0 ± 0.1		
Indeno[123-cd]fluoranthene	ng/m³	0 ± 0.12	0 ± 0.1	1 ± 0.3	0.1 ± 0.1
Dibenz(a,h)acridine	ng/m³	0 ± 0.12	0 ± 0.1	0 ± 0.1	0.2 ± 0.1
Dbajacr	ng/m³	0 ± 0.12	0 ± 0.1		
Indeno[123-cd]pyrene	ng/m³	0 ± 0.12	0 ± 0.1	0 ± 0.1	0 ± 0.1
9,10-dihydrobenzo(a)pyrene-7(8H)-one				0 ± 0.1	0 ± 0.1

Table 3. Temporal Comparison of Exposure Atmosphere Composition (High Exposure Level)

PolyAromatic HydroCarbon (PAH):

		April 2010	September 2010	April 2011	April 2012
Exposure Atmosphere Composition	**Units**	**High**	**High**	**High**	**High**
Dibenzo(ah+ac)anthracene	ng/m³	0 ± 0.12	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(a,j)anthracene	ng/m³	0 ± 0.12	0.2 ± 0.1	0 ± 0.1	0 ± 0.1
Benzo(b)chrysene	ng/m³	0 ± 0.12	0.1 ± 0.1	0 ± 0.1	0 ± 0.1
Picene	ng/m³	0.1 ± 0.12	0.1 ± 0.1	0 ± 0.1	0 ± 0.1
7H-dibenzo[c,g]carbazole				0.1 ± 0.1	0.1 ± 0.1
Benzo(ghi)perylene	ng/m³	0.1 ± 0.12	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
Anthanthrene	ng/m³	0 ± 0.12	0 ± 0.1	0 ± 0.1	0 ± 0.1
Triphenylene				0 ± 0.1	
Dibenzo(a,l)pyrene	ng/m³	0 ± 0.12	0 ± 0.1	0 ± 0.1	0 ± 0.1
Coronene	ng/m³	0 ± 0.12	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(a,e)pyrene	ng/m³	0 ± 0.12	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(a,i)pyrene	ng/m³	0 ± 0.12	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(a,h)pyrene	ng/m³	0 ± 0.12	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(b,k)fluoranthene	ng/m³	0 ± 0.12	0 ± 0.1	0 ± 0.1	0 ± 0.1
Benzo(b)fluoranthene					0 ± 0.1

Table 3. Temporal Comparison of Exposure Atmosphere Composition (High Exposure Level)

Nitro-PAH:

		April 2010	September 2010	April 2011	April 2012
Exposure Atmosphere Composition	**Units**	**High**	**High**	**High**	**High**
1-nitronaphthalene	ng/m³	0.0	0.0	2.31 ± 0.12	1.6 ± 0.1
1-methyl-5-nitronaphthalene	ng/m³	1.7 ± 0.08	1.4 ± 0.07	0.54 ± 0.03	0.9 ± 0.1
2-nitronaphthalene	ng/m³	0.5 ± 0.03	0.3 ± 0.01	3.23 ± 0.16	4.3 ± 0.3
2-nitrobiphenyl	ng/m³	2.8 ± 0.14	1.8 ± 0.09	0.06	0.0
2-methyl-4-nitronaphthalene	ng/m³	0.1 ± 0.01	0.1 ± 0.01	0.92 ± 0.05	1.1 ± 0.4
1-methyl-4-nitronaphthalene	ng/m³	0.6 ± 0.03	0.5 ± 0.03	0.97 ± 0.05	2.7 ± 0.2
1-methyl-6-nitronaphthalene	ng/m³	0.4 ± 0.1	0.2 ± 0.02	0.07 ± 0.01	0.0
3-nitrobiphenyl	ng/m³	0.1 ± 0.01	0.3 ± 0.02	0.1 ± 0.01	0.1
4-nitrobiphenyl	ng/m³	0.1	0.0	0.14 ± 0.01	0.0
1,3-dinitronaphthalene	ng/m³	0.0	0.1 ± 0.01	0.04	0.0
1,5-dinitronaphthalene	ng/m³	0.0	0.0	0.00	0.0
5-nitroacenaphthene	ng/m³	0.0	0.0	0.02	0.0
2-nitrofluorene	ng/m³	0.0	0.4 ± 0.04	0.00	0.0
4-nitrophenanthrene	ng/m³	0.0	0.0	0.00	0.0
9-nitroanthracene	ng/m³	0.0	0.0	0.1 ± 0.01	0.2
9-nitrophenanthrene	ng/m³	0.1 ± 0.01	0.1 ± 0.01	0.04	0.0
1,8-dinitronaphthalene	ng/m³	0.0	0.0	0.01	0.0
3-nitrophenanthrene	ng/m³	0.0	0.0	0.01	0.1
2-nitrophenanthrene	ng/m³	0.0	0.0	0.01	0.0
2-nitroanthracene	ng/m³	0.0	0.1 ± 0.01	0.02	0.0
2-nitrofluoranthene	ng/m³	0.0	0.0	0.00	0.0
3-nitrofluoranthene	ng/m³	0.0	0.0	0.00	0.0
4-nitropyrene	ng/m³	0.0	0.0	0.00	0.0

Table 3. Temporal Comparison of Exposure Atmosphere Composition (High Exposure Level)

Nitro-PAH:

		April 2010	September 2010	April 2011	April 2012
Exposure Atmosphere Composition	**Units**	**High**	**High**	**High**	**High**
1-nitropyrene	ng/m³	0.0	0.0	0.07 ± 0.01	0.1
2-nitropyrene	ng/m³	0.0	0.1 ± 0.01	0.00	0.0
2,7-dinitrofluorene	ng/m³	0.0	0.0	0.00	0.0
2,7-dinitrofluoren-9-one	ng/m³	0.0	0.0	0.00	0.0
7-nitrobenz(a)anthracene	ng/m³	0.0	0.0	0.00	0.00
6-nitrochrysene	ng/m³	0.0	0.0	0.00	0.00
3-nitrobenzanthrone	ng/m³	0.0	0.0	0.00	0.00
1,3-dinitropyrene	ng/m³	0.0	0.0	0.00	0.00
1,6-dinitropyrene	ng/m³	0.0	0.0	0.00	0.00
1,8-dinitropyrene	ng/m³	0.0	0.0	0.00	0.00
3-nitrobenzo[e]pryene	ng/m³	0.0	0.0	0.00	0.00
6a+1e-nitrobenzpyrene	ng/m³	0.0	0.0	0.00	0.00

Table 3. Temporal Comparison of Exposure Atmosphere Composition (High Exposure Level)

Polars:

Exposure Atmosphere Composition	Units	April 2010 High	September 2010 High	April 2011 High	April 2012 High
8,15-Pimaradien-18-oic acid	ng/m³	2.3 ± 0.3	2.9 ± 0.3	1.1 ± 0.3	0.8 ± 0.3
Maleic acid	ng/m³	775.4 ± 85.1	825.7 ± 127.4	521 ± 34.2	132.9 ± 12.8
Guaiacol	ng/m³	11.6 ± 3.6	24 ± 2.8	10.6 ± 0.7	3 ± 0.3
Salicylic acid	ng/m³	133.3 ± 7.9	136.1 ± 7	101 ± 5.2	143.8 ± 7.3
4-me-guaiacol	ng/m³	5.6 ± 0.6	0 ± 0.3	1.8 ± 0.3	1.1 ± 0.3
2,3- and 3,5- dimethylbenzoic acid	ng/m³	0 ± 0.2	0 ± 0.3	0 ± 0.3	0 ± 0.3
2,4-dimethylbenzoic acid	ng/m³	1697.9 ± 91.9	864.8 ± 49.4	1549.3 ± 94.3	2961 ± 148.2
2,5-dimethylbenzoic acid	ng/m³	120.2 ± 7	71.7 ± 6.6	81.6 ± 6.2	99.2 ± 5.1
2,6-dimethylbenzoic acid	ng/m³	59.5 ± 3.2	23.4 ± 2.5	8.5 ± 0.6	17.8 ± 2.4
3,4-dimethylbenzoic acid	ng/m³	166.9 ± 9.5	172.4 ± 8.9	163.1 ± 8.3	221.2 ± 25.6
4-formyl-guaiacol (vanillin)	ng/m³	92 ± 9.5	129.6 ± 6.6	42.7 ± 2.3	73.6 ± 3.8
4-ethyl-guaiacol	ng/m³	8 ± 0.7	2.5 ± 0.6	1.7 ± 0.4	1.8 ± 0.4
Syringol	ng/m³	283.6 ± 15.2	1673.2 ± 83.8	595.3 ± 29.9	358.6 ± 72.5
Levoglucosan	ng/m³	7.8 ± 1	20 ± 2	23.2 ± 1.2	13.2 ± 0.8
4-allyl-guaiacol (eugenol)	ng/m³	3.3 ± 0.6	0 ± 0.3	2.7 ± 0.5	1.6 ± 0.4
Isoeugenol	ng/m³	7.3 ± 1.3	8.7 ± 1.5	7.3 ± 1.5	6.7 ± 0.7
Isophthalic acid	ng/m³	2011.2 ± 136.2	538.1 ± 30.6	1681 ± 87.8	872.9 ± 43.8
Phthalic acid	ng/m³	38.8 ± 2.2	15.2 ± 1.7	7.2 ± 0.7	1.1 ± 0.3
Acetovanillone	ng/m³	198.2 ± 18.8	0 ± 0.3	9.8 ± 0.6	5.8 ± 1.0
Vanillic acid	ng/m³	47.7 ± 2.6	41.7 ± 3.5	15.2 ± 1.7	28 ± 4.1
4-methyl-syringol	ng/m³	23.7 ± 7.3	100.4 ± 5.1	2 ± 0.3	81.5 ± 19.2
2,3-dimethoxybenzoic acid	ng/m³	440.3 ± 38.7	183.4 ± 9.3	21.6 ± 1.2	343.3 ± 36.9
2,4-dimethoxybenzoic acid	ng/m³	14.1 ± 1	5.4 ± 0.4	10.2 ± 0.7	18 ± 1.4
2,5-dimethoxybenzoic acid	ng/m³	64.9 ± 10.1	112.2 ± 10.5	1.1 ± 0.3	219.2 ± 28.9

Table 3. Temporal Comparison of Exposure Atmosphere Composition (High Exposure Level)

Polars:

		April 2010	September 2010	April 2011	April 2012
Exposure Atmosphere Composition	**Units**	**High**	**High**	**High**	**High**
2,6-dimethoxybenzoic acid	ng/m³	26 ± 5.7	0 ± 0.3	7.5 ± 0.7	3.9 ± 0.5
3,4-dimethoxybenzoic acid	ng/m³	2.5 ± 0.4	2.9 ± 0.4	3 ± 0.6	3.5 ± 0.8
3,5-dimethoxybenzoic acid	ng/m³	23 ± 3.6	20.7 ± 2.6	8.8 ± 1.4	20 ± 1.1
Docosanoic acid (c22)	ng/m³	0.6 ± 0.2	22.6 ± 2.9	9.2 ± 0.8	3 ± 0.3
Homovanillic acid	ng/m³	5.4 ± 0.4	6.1 ± 0.6	4.7 ± 0.5	2.7 ± 0.3
Syringaldehyde	ng/m³	31 ± 1.8	12.3 ± 2.6	4.9 ± 0.8	1 ± 0.3
cis-pinonic acid	ng/m³	62.9 ± 6.2	77.8 ± 4.5	149.6 ± 12.2	49.7 ± 3.6
Syringic acid	ng/m³	2.9 ± 0.4	0 ± 0.3	0 ± 0.3	0 ± 0.3
Myristoleic acid	ng/m³	38.6 ± 11.1	36.1 ± 4.5	9.4 ± 0.6	6.3 ± 2.0
Traumatic acid	ng/m³	44.3 ± 0.9	52.2 ± 10.2	4.7 ± 0.8	2.1 ± 0.4
1,11-undecanedicarboxylic acid	ng/m³	6.2 ± 1.9	2.3 ± 0.4	5.9 ± 0.4	6.3 ± 0.5
Palmitoleic acid	ng/m³	39.1 ± 2	27.1 ± 1.7	14.8 ± 0.9	12.2 ± 1.3
1,12-dodecanedicarboxylic acid	ng/m³	0.6 ± 0.2	1 ± 0.3	0.8 ± 0.3	1 ± 0.3
Elaidic acid	ng/m³	7.7 ± 0.2	12 ± 3.2	6.1 ± 1.9	6.4 ± 0.8
Isostearic acid	ng/m³	14.4 ± 0.8	1 ± 0.3	10.2 ± 2.4	66.4 ± 25.3
Dehydroabietic acid	ng/m³	42.6 ± 0.2	2.2 ± 0.6	1 ± 0.3	0.9 ± 0.3
Pimaric acid	ng/m³	26.2 ± 1.5	13.4 ± 1.7	10.8 ± 1	6.4 ± 0.4
Sandaracopimaric acid	ng/m³	7.4 ± 0.5	5.3 ± 0.4	4.2 ± 0.5	1.8 ± 0.3
Abietic acid	ng/m³	1.2 ± 0.2	2.1 ± 0.4	1 ± 0.3	1 ± 0.3
Isopimaric acid	ng/m³	5.5 ± 0.5	2 ± 0.4	1.4 ± 0.3	1.7 ± 0.3
7-oxodehydroabietic acid	ng/m³	1.9 ± 0.2	0.2 ± 0.3	1.4 ± 0.3	1.1 ± 0.3
Heneicosanoic acid (c21)	ng/m³	9.6 ± 0.6	3.1 ± 0.8	2.1 ± 0.3	1.3 ± 0.3
Tricosanoic acid	ng/m³	0.2 ± 0.2	1.7 ± 0.7	1.8 ± 0.4	0.7 ± 0.3
Tetracosanoic acid (c24)	ng/m³	2.4 ± 0.5	8.9 ± 1.4	7.9 ± 0.9	7.1 ± 1.8

Table 3. Temporal Comparison of Exposure Atmosphere Composition (High Exposure Level)

Polars:

Exposure Atmosphere Composition	Units	April 2010 High	September 2010 High	April 2011 High	April 2012 High
Cholesterol	ng/m³	11.7 ± 0.2	18.7 ± 5	8.4 ± 0.5	5.1 ± 0.4
b-sitosterol	ng/m³	2 ± 0.2	1.5 ± 0.3	0.4 ± 0.3	1 ± 0.3
Hexanoic acid (c6)	ng/m³	6155.9 ± 784.9	1223.8 ± 159.7	1556.1 ± 77.8	698.5 ± 171.1
Heptanoic acid (c7)	ng/m³	6465.2 ± 383.6	1306.7 ± 130.8	1771.8 ± 88.8	469.1 ± 62.0
Benzoic acid	ng/m³	2416.6 ± 164.3	2633.6 ± 133.4	3376.5 ± 169	3393.3 ± 169.7
Octanoic acid (c8)	ng/m³	976.4 ± 103.7	457.5 ± 37.7	745.3 ± 37.3	165.6 ± 14.8
o-toluic	ng/m³	211.4 ± 16.1	96.4 ± 4.9	212.6 ± 10.8	251.5 ± 12.7
m-toluic	ng/m³	317.5 ± 18.2	254.8 ± 12.9	258 ± 13	437.7 ± 34.2
Nonanoic acid (c9)	ng/m³	238.2 ± 70.9	0 ± 0.3	369.7 ± 22.2	314.2 ± 21.5
p-toluic	ng/m³	154.6 ± 13.5	108 ± 6.1	132.5 ± 14.5	219.7 ± 11.1
Decanoic acid (c10)	ng/m³	199.5 ± 72.1	56.7 ± 3.7	184.5 ± 9.2	55.3 ± 3.7
Undecanoic acid (c11)	ng/m³	36 ± 6.7	4.2 ± 0.4	77.4 ± 4	53.7 ± 3.1
Dodecanoic (lauric) acid (c12)	ng/m³	8.1 ± 3.1	12.6 ± 1	105.5 ± 5.6	0 ± 0.3
Tridecanoic acid (c13)	ng/m³	90.1 ± 7.9	65.9 ± 7.2	37.3 ± 2	36.9 ± 3.4
Myristic acid (c14)	ng/m³	100.2 ± 8.6	65.5 ± 3.4	71.1 ± 3.6	7.5 ± 0.5
Pentadecanoic acid (c15)	ng/m³	184.9 ± 19.5	156.6 ± 23.5	20.6 ± 2.1	18.4 ± 1.8
Palmitic acid (c16)	ng/m³	346.9 ± 7	183.4 ± 9.3	151.6 ± 7.6	112.5 ± 6.3
Heptadecanoic acid (c17)	ng/m³	58.2 ± 0.6	57.6 ± 9.8	2.1 ± 0.4	2.9 ± 0.4
Oleic acid	ng/m³	73.4 ± 0.2	1.2 ± 0.3	11.2 ± 2.3	17.1 ± 1.1
Stearic acid (c18)	ng/m³	80.8 ± 0.2	64.5 ± 3.4	47.3 ± 2.4	65.6 ± 3.4
Nonadecanoic acid (c19)	ng/m³	0 ± 0.2	20.1 ± 8.1	8.7 ± 2.5	0.4 ± 0.3
Eicosanoic acid (c20)	ng/m³	13.3 ± 4.1	7.3 ± 1.3	2.1 ± 0.4	5.7 ± 0.5

Table 3. Temporal Comparison of Exposure Atmosphere Composition (High Exposure Level)

Hopane and Steranes:

		April 2010	September 2010	April 2011	April 2012
Exposure Atmosphere Composition	**Units**	**High**	**High**	**High**	**High**
17A(H),21B(H)-22,29,30-Trisnorhopane	ng/m³	0.1 ± 0.01	0.0	0.17 ± 0.01	0.7
17A(H),21B(H)-30-Norhopane	ng/m³	0.2 ± 0.02	0.1 ± 0.01	0.44 ± 0.02	2.2 ± 0.1
17A(H),21B(H)-Hopane	ng/m³	0.2 ± 0.01	0.1	0.41 ± 0.02	1.3 ± 0.1
17B(H),21A(H)-hopane	ng/m³	0.0	0.0	0.01	0.0
22S-17A(H),21B(H)-30-Homohopane	ng/m³	0.0	0.4 ± 0.02	0.17 ± 0.01	0.6
22R-17A(H),21B(H)-30-Homohopane	ng/m³	0.0	0.1 ± 0.01	0.22 ± 0.01	0.8 ± 0.1
17B(H),21B(H)-Hopane	ng/m³	0.0	0.0	0.07 ± 0.01	0.0
22S-17A(H),21B(H)-30,31-Bishomohopane	ng/m³	0.0	0.1 ± 0.01	0.24 ± 0.05	0.7 ± 0.1
22R-17A(H),21B(H)-30,31-Bishomohopane	ng/m³	0.0	0.0	0.00	0.3
22S-17A(H),21B(H)-30,31,32-Trisomohopane	ng/m³	0.0	0.0	0.05 ± 0.01	0.2
22R-17A(H),21B(H)-30,31,32-Trishomohopane	ng/m³	0.0	0.1	0.04 ± 0.01	0.1
C27-20S5A(H),14A(H)-cholestane	ng/m³	0.0	0.0	0.12 ± 0.01	0.0
C27-20R5A(H),14B(H)-cholestane	ng/m³	0.0	0.0	0.11 ± 0.01	0.2
C27-20S5A(H),14B(H),17B(H)-cholestane	ng/m³	0.2 ± 0.01	0.0	0.19 ± 0.01	0.4
C27-20R5A(H),14A(H),17A(H)-cholestane & C29 -20S13B(H),17A(H)-dia	ng/m³	0.1	0.1	0.29 ± 0.01	0.4
C28-20S5A(H),14A(H),17A(H)-ergostane	ng/m³	0.0	0.0	0.03	0.0
C28-20R5A(H),14B(H),17B(H)-ergostane	ng/m³	0.0	0.0	0.12 ± 0.01	0.2
C28-20S5A(H),14B(H),17B(H)-ergostane	ng/m³	0.1 ± 0.01	0.1 ± 0.02	0.11 ± 0.01	0.2
C28-20R5A(H),14A(H),17A(H)-ergostane	ng/m³	0.1	0.0	0.03	0.2
C29-20S5A(H),14A(H),17A(H)-stigmastane	ng/m³	0.0	0.0	0.13 ± 0.02	0.2
C29-20R5A(H),14B(H),17B(H)-stigmastane	ng/m³	0.0	0 ± 0.01	0.1 ± 0.01	0.2
C29-20S5A(H),14B(H),17B(H)-stigmastane	ng/m³	0.0	0.1 ± 0.05	0.05	0.2
C29-20R5A(H),14A(H),17A(H)-stigmastane	ng/m³	0.1 ± 0.01	0.0	0.06	0.1

Table 3. Temporal Comparison of Exposure Atmosphere Composition (High Exposure Level)

Volatile Organic Compounds (VOC):

Exposure Atmosphere Composition	Units	April 2010	September 2010	April 2011	April 2012
		High	High	High	High
Acetylene	µg/m³	2.9 ± 0.49	5.4 ± 0.3	13.3 ± 3.68	9.3 ± 0.5
Ethene	µg/m³	0.2 ± 0.17	0.7 ± 0.1	15.3 ± 1.91	54.1 ± 2.7
Ethane	µg/m³	6.4 ± 0.32	2.8 ± 0.3	12.4 ± 0.62	9.3 ± 0.5
Propene	µg/m³	3.5 ± 2.51	3.2 ± 0.3	18.7 ± 1.69	20 ± 1
Propane	µg/m³	1.1 ± 0.07	0.0	2 ± 0.1	3.8 ± 0.2
1,3-butadiene	µg/m³	0 ± 0.02	0.1	0 ± 0.02	0.0
1-butene	µg/m³	0.9 ± 0.05	0.7	4.9 ± 0.44	7 ± 0.4
c-2-butene	µg/m³	6.1 ± 0.31	2.4 ± 0.1	1.2 ± 0.32	1 ± 0.1
Isobutylene	µg/m³	0.3 ± 0.03	0.4	7.2 ± 0.36	9.8 ± 1.2
t-2-butene	µg/m³	0.5 ± 0.33	0.6	2.1 ± 0.13	1.9 ± 0.1
n-butane	µg/m³	1.3 ± 0.07	0.9 ± 0.1	1.2 ± 0.06	1.3 ± 0.1
Iso-butane	µg/m³	0.5 ± 0.08	0.8 ± 0.1	1 ± 0.05	1.5 ± 0.1
Iso-pentane	µg/m³	0.9 ± 0.18	0.8	0.9 ± 0.04	4.7 ± 0.2
n-pentane	µg/m³	0.8 ± 0.09	0.7 ± 0.1	1 ± 0.11	6.5 ± 0.7
1,2-butadiene	µg/m³	0.2 ± 0.08	0.2	1.1 ± 0.06	0.0
1-pentene	µg/m³	0.1 ± 0.03	0.1	0.3 ± 0.03	2.7 ± 0.1
2-methyl-1-butene	µg/m³	0 ± 0.03	0.0	0 ± 0.03	0.6
Isoprene	µg/m³	0.1 ± 0.03	0.1	0.6 ± 0.06	0.0
t-2-pentene	µg/m³	0.1 ± 0.03	0.1	0.3 ± 0.08	0.8
c-2-pentene	µg/m³	0.1 ± 0.03	0.1	0.3 ± 0.03	0.4
2-methyl-2-butene	µg/m³	0 ± 0.04	0.0	0 ± 0.04	0.5
2,2-dimethylbutane	µg/m³	0.1 ± 0.04	0.1	0.4 ± 0.04	0.1
Cyclopentene	µg/m³	0.1 ± 0.04	0.1	0.1 ± 0.03	0.8
Cyclopentane	µg/m³	0.1 ± 0.04	0.2	0.1 ± 0.04	0.3

Table 3. Temporal Comparison of Exposure Atmosphere Composition (High Exposure Level)

Volatile Organic Compounds (VOC):

Exposure Atmosphere Composition	Units	April 2010	September 2010	April 2011	April 2012
		High	High	High	High
2,3-dimethylbutane	µg/m³	0.4 ± 0.04	0.9 ± 0.1	0.4 ± 0.04	0.6 ± 0.1
2-methylpentane	µg/m³	0.3 ± 0.04	1.1 ± 0.1	0.4 ± 0.04	0.9 ± 0.4
3-methylpentane	µg/m³	0.2 ± 0.22	0.3	0.7 ± 0.05	1.3 ± 0.1
2-methyl-1-pentene	µg/m³	0.4 ± 0.04	2.5 ± 0.8	0.5 ± 0.04	2.5 ± 0.1
n-hexane	µg/m³	0.1 ± 0.04	0.1	0.2 ± 0.04	1.5 ± 0.1
t-2-hexene	µg/m³	0 ± 0.04	0.0	0.1 ± 0.04	0.4
c-2-hexene	µg/m³	0 ± 0.04	0.0	0 ± 0.04	0.2
1,3-hexadiene (trans)	µg/m³	0.5 ± 0.04	1.5 ± 0.1	0.9 ± 0.1	0.0
Methylcyclopentane	µg/m³	0.2 ± 0.04	0.4	0.1 ± 0.04	1.3 ± 0.1
2,4-dimethylpentane	µg/m³	4.1 ± 0.21	4.2 ± 0.8	5.6 ± 0.28	0.2
Benzene	µg/m³	1.5 ± 0.08	2.2 ± 0.1	2.6 ± 0.13	11.2 ± 0.6
Cyclohexane	µg/m³	0.2 ± 0.04	0.6	0.4 ± 0.04	3.4 ± 0.2
2-methylhexane	µg/m³	0.6 ± 0.05	0.8 ± 0.1	0.7 ± 0.05	0.0
2,3-dimethylpentane	µg/m³	0.2 ± 0.04	0.1	0.3 ± 0.04	0.0
Cyclohexene	µg/m³	0.3 ± 0.04	0.6	0.6 ± 0.04	1.3 ± 0.1
3-methylhexane	µg/m³	0.1 ± 0.04	0.2	0.3 ± 0.04	0.8
1,3-dimethylcyclopentane (cis)	µg/m³	0.6 ± 0.04	0.8 ± 0.1	1.1 ± 0.06	0.3
1-heptene	µg/m³	0.7 ± 0.05	0.2 ± 0.1	0.2 ± 0.05	2.6 ± 0.1
2,2,4-trimethylpentane	µg/m³	0.6 ± 0.06	0.7	1 ± 0.06	1.7 ± 0.1
n-heptane	µg/m³	0 ± 0.04	0.0	0 ± 0.04	1.4 ± 0.1
2,3-dimethyl-2-pentene	µg/m³	3.5 ± 0.81	4.1 ± 0.9	5.7 ± 0.37	0.0
Methylcyclohexane	µg/m³	0.1 ± 0.05	0 ± 0.1	0.1 ± 0.05	6.3 ± 0.3
2,3,4-trimethylpentane	µg/m³	2.1 ± 0.11	4.5 ± 0.6	3.7 ± 0.18	0 ± 0.1
Toluene	µg/m³	0.5 ± 0.05	0.7 ± 0.1	0.9 ± 0.17	8.9 ± 0.4

Table 3. Temporal Comparison of Exposure Atmosphere Composition (High Exposure Level)

Volatile Organic Compounds (VOC):

Exposure Atmosphere Composition	Units	April 2010	September 2010	April 2011	April 2012
		High	High	High	High
2-methylheptane	µg/m³	0.2 ± 0.05	0.2 ± 0.1	0.3 ± 0.05	1.4 ± 0.1
4-methylheptane	µg/m³	0.4 ± 0.14	0.4 ± 0.1	0.8 ± 0.14	0.5 ± 0.1
3-methylheptane	µg/m³	1.5 ± 0.07	1.7 ± 0.4	2.6 ± 0.27	0.8 ± 0.1
n-octane	µg/m³	1 ± 0.05	1.2 ± 0.3	2 ± 0.13	4.2 ± 0.2
Ethylbenzene	µg/m³	1.7 ± 0.08	2.2 ± 0.5	4.2 ± 0.21	4.3 ± 0.2
m&p-xylene	µg/m³	0 ± 0.05	0.1	0 ± 0.05	7.1 ± 0.4
Styrene	µg/m³	0.6 ± 0.05	0.9	1.6 ± 0.08	0.2
o-xylene	µg/m³	2.4 ± 0.12	3 ± 0.3	4.8 ± 0.24	3.3 ± 0.2
n-nonane	µg/m³	0.3 ± 0.05	0.3 ± 0.1	0.5 ± 0.05	8.8 ± 0.4
Isopropylbenzene	µg/m³	0.6 ± 0.05	0.7 ± 0.1	1.2 ± 0.14	1.2 ± 0.1
n-propylbenzene	µg/m³	0 ± 0.06	0 ± 0.1	0 ± 0.06	3.1 ± 0.2
Alpha-pinene	µg/m³	1.3 ± 0.07	1.5 ± 0.2	2.9 ± 0.34	0.1 ± 0.1
3-ethyltoluene	µg/m³	0.7 ± 0.05	0.8 ± 0.1	1.9 ± 0.2	8 ± 0.4
4-ethyltoluene	µg/m³	0.6 ± 0.18	0.8 ± 0.2	1.9 ± 0.17	3.3 ± 0.2
1,3,5-trimethylbenzene	µg/m³	0.5 ± 0.05	0.6 ± 0.1	1.2 ± 0.06	3.1 ± 0.2
o-ethyltoluene	µg/m³	0 ± 0.05	NA	0 ± 0.05	2.7 ± 0.1
n-decane	µg/m³	8.1 ± 2.72	4.3 ± 0.6	14.4 ± 1.56	29.3 ± 1.5
1,2,3-trimethylbenzene	µg/m³	1 ± 0.33	0.9 ± 0.1	2.2 ± 0.22	4.2 ± 0.2
Indan	µg/m³	0.2 ± 0.05	0.3 ± 0.1	0.4 ± 0.05	1 ± 0.1
1,3-diethylbenzene	µg/m³	0.7 ± 0.06	0.5 ± 0.1	1 ± 0.06	1.9 ± 0.1
1,4-diethylbenzene	µg/m³	0.7 ± 0.27	0.6 ± 0.1	1 ± 0.14	2.1 ± 0.1
n-butylbenzene	µg/m³	0 ± 0.06	NA		3.6 ± 0.4
n-undecane	µg/m³	8.6 ± 0.81	5.5 ± 0.5	12.9 ± 1.03	0 ± 0.1

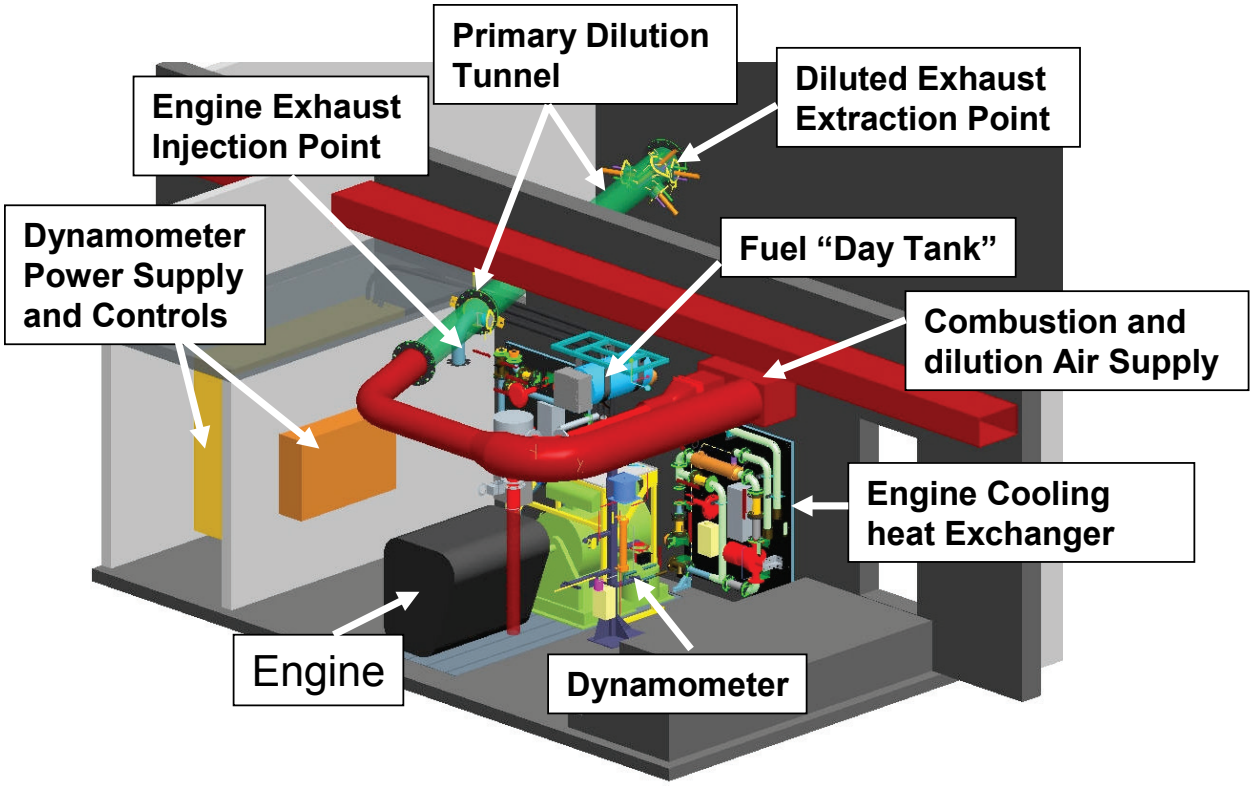
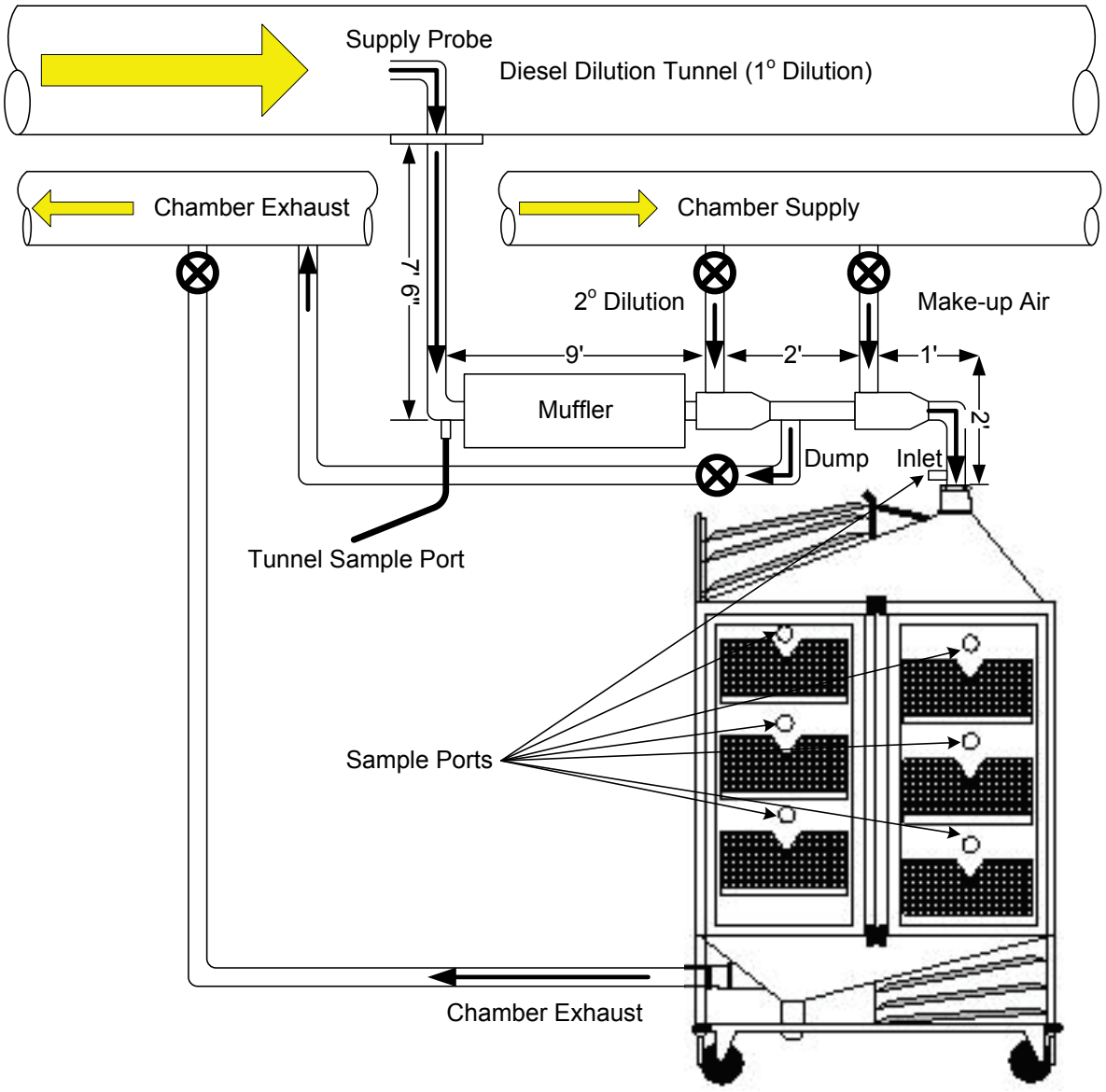


Figure 1. Front quarter view of engine laboratory and dilution tunnel. The tunnel portions shown in red are prior to mixing of the engine exhaust. The green area shows the exhaust mixing section and the take-off point for the exposure chamber distribution system. The engine is shown in black, and the fuel delivery system in blue. The dynamometer is shown in light green.



Drawing not to scale:

Delivery Line Dimensions:
Tunnel to Muffler - 7' 6"
Muffler to Dilution/Dump - 9'
Dilution/Dump to Make-up - 2'
Make-up to Chamber - 3'
Total Delivery Line Length - 21' 6"

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

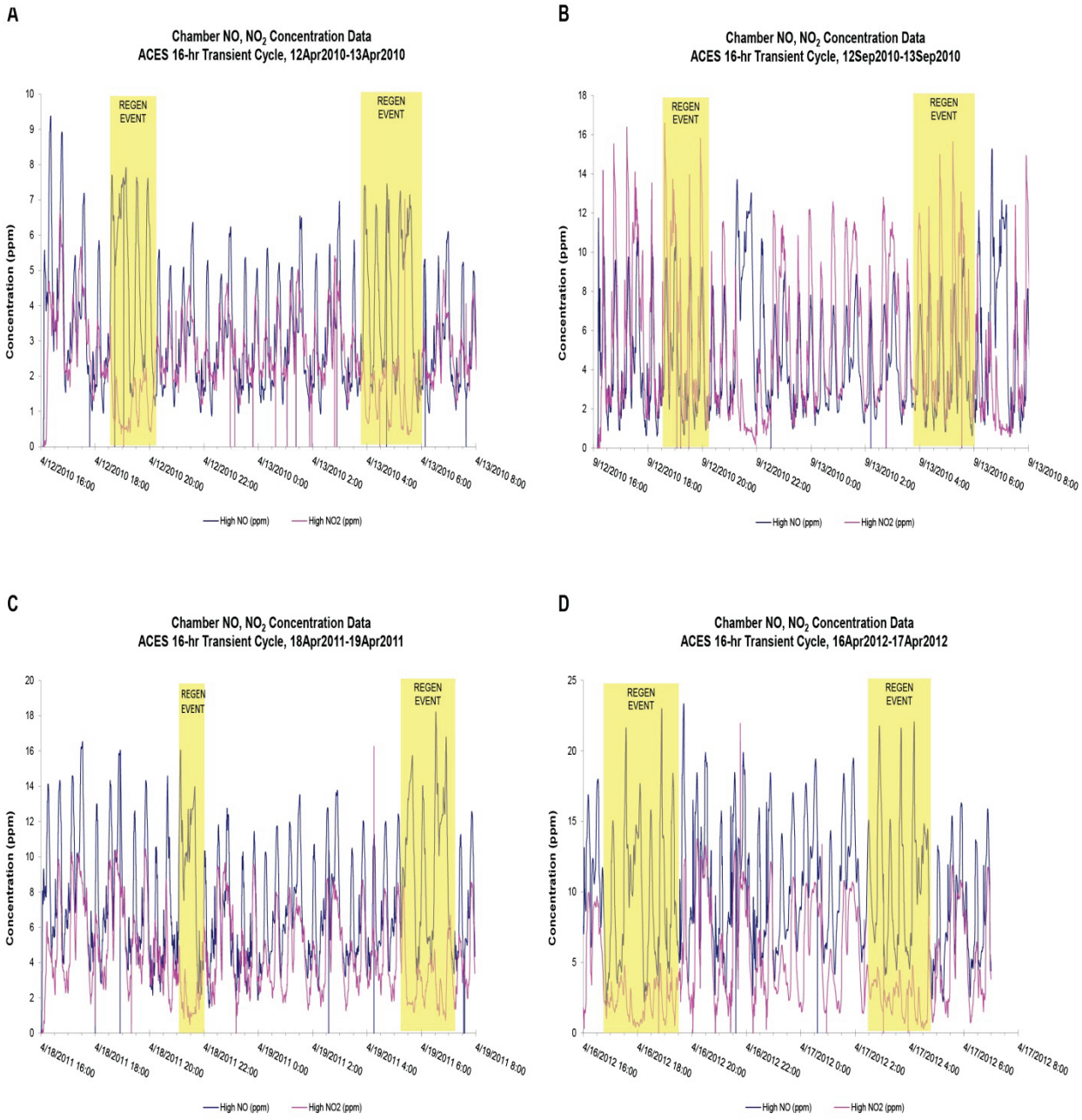


Figure 3. Representative real-time concentrations of NO and NO_2 during a 16-hr ACES transient cycle. The average concentrations of NO and NO2 were 3.2 and 4.6 ppm (A). . Data were otbained from the high exposure level (4.2 ppm average NO_2 target) during parallel 'intensive' measurements of test atmospheres made in April 2010, September 2010, April 2011 and April 2012.

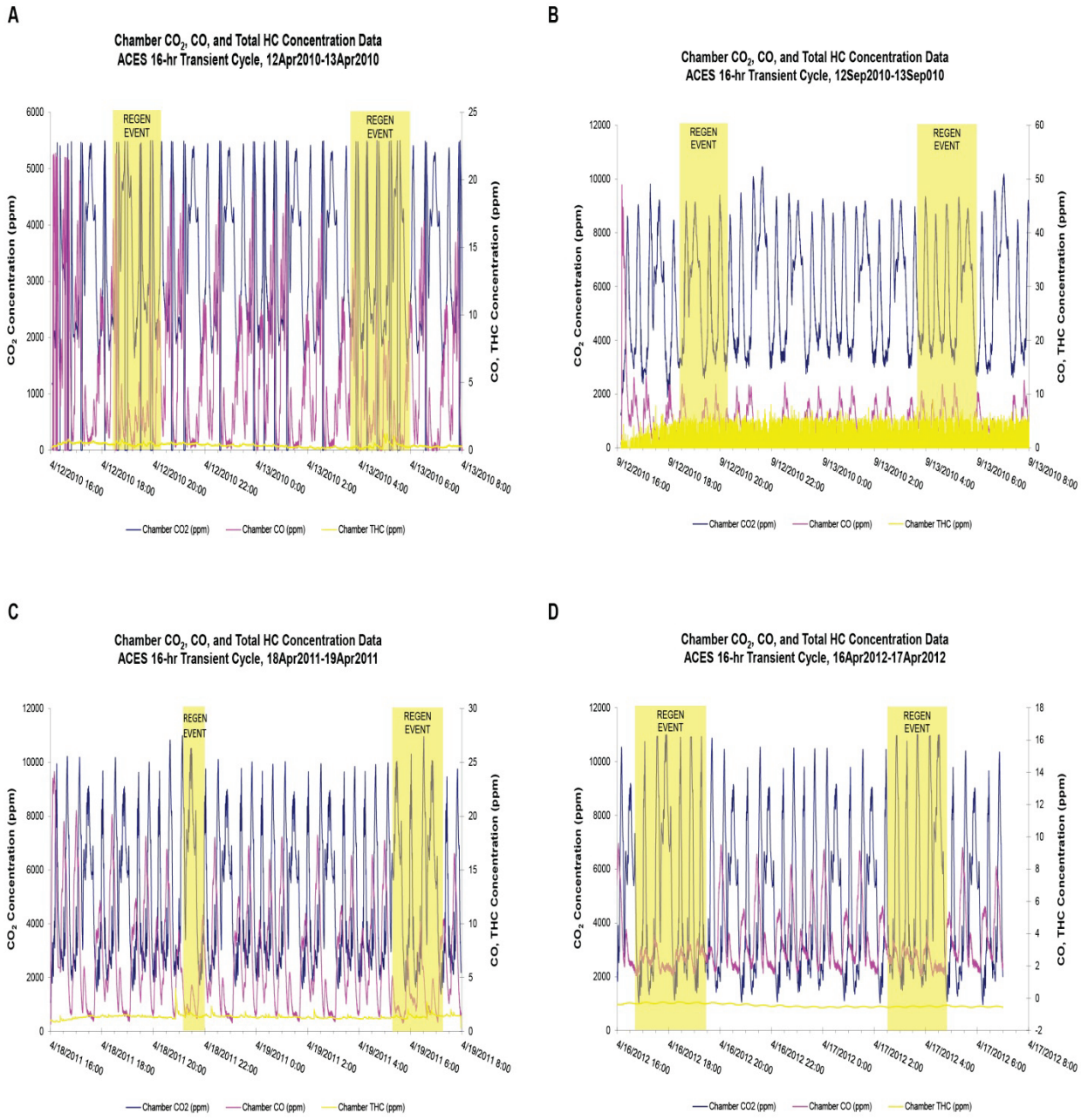


Figure 4. Representative real-time concentrations of CO_2, CO, and HC (indicated as HC) during a 16-hr ACES transient cycle. Data were obtained from high exposure level measurements made in April 2010, September 2010, April 2011 and April 2012.

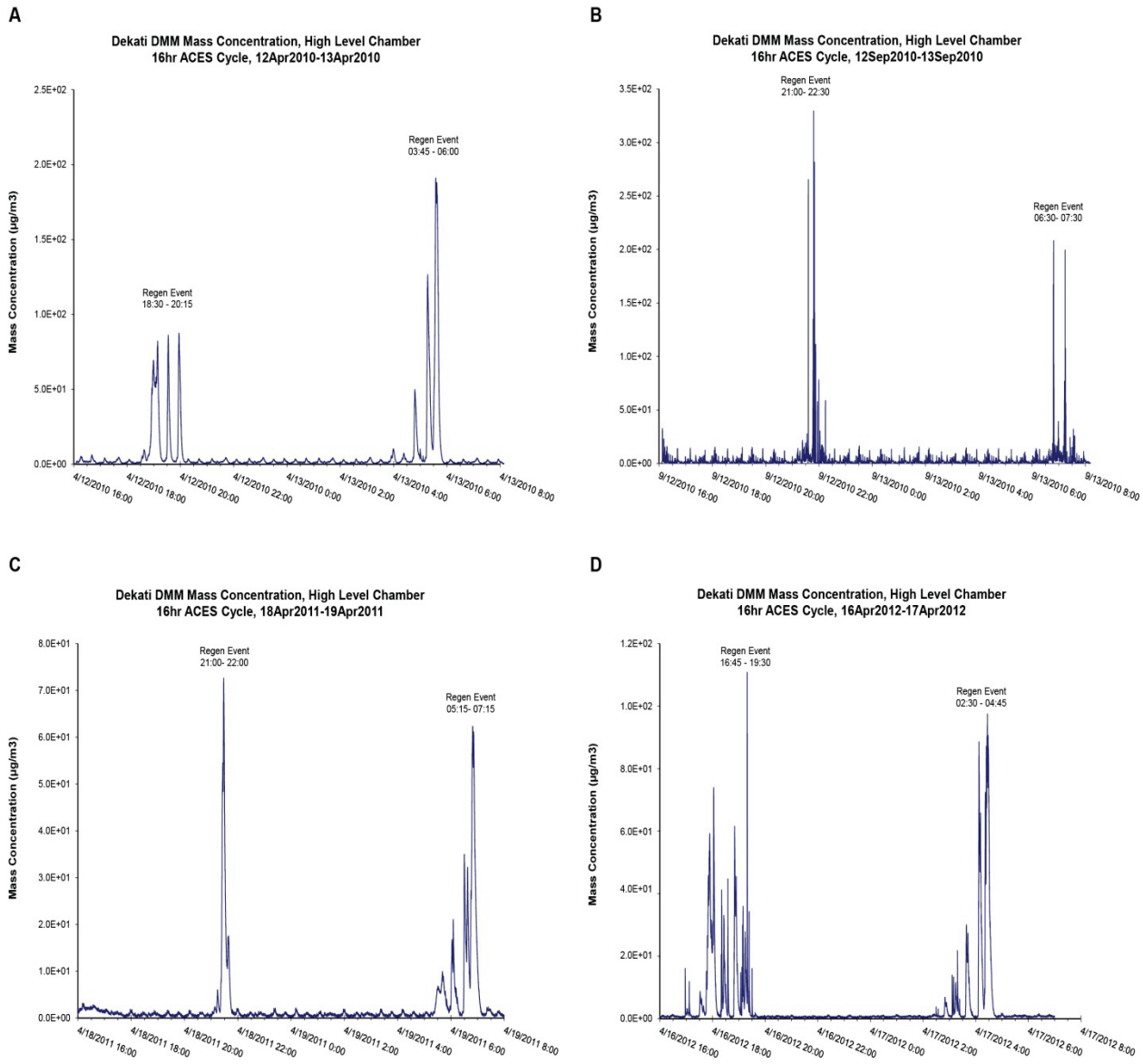
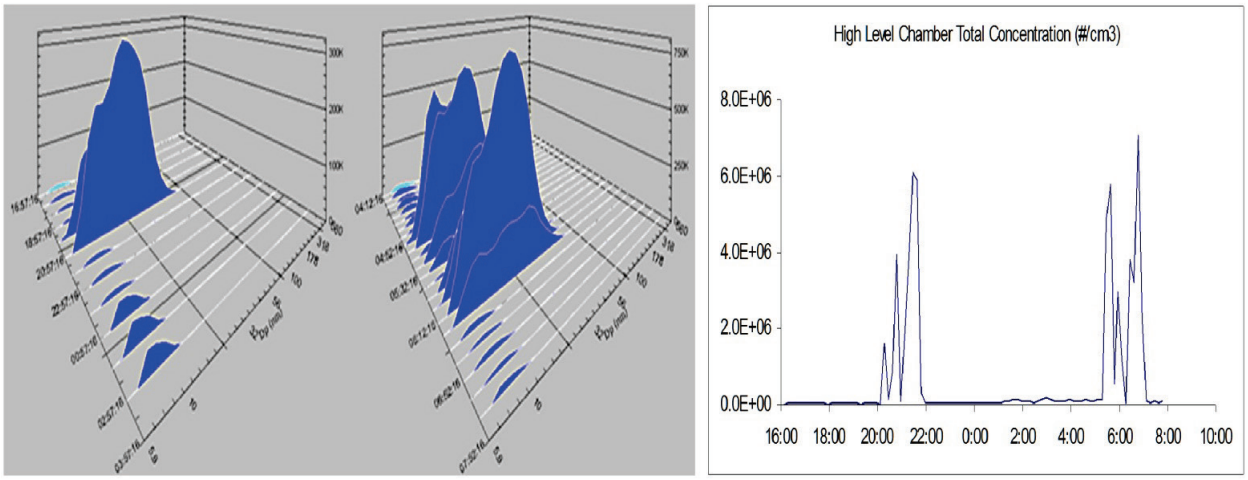


Figure 5. Representative real-time particle mass concentrations measured by the DMM. Particle concentrations peaked during the DPF regenerations. Data are from measurements made in April 2010, September 2010, April 2011 and April 2012.

September 2010



April 2012

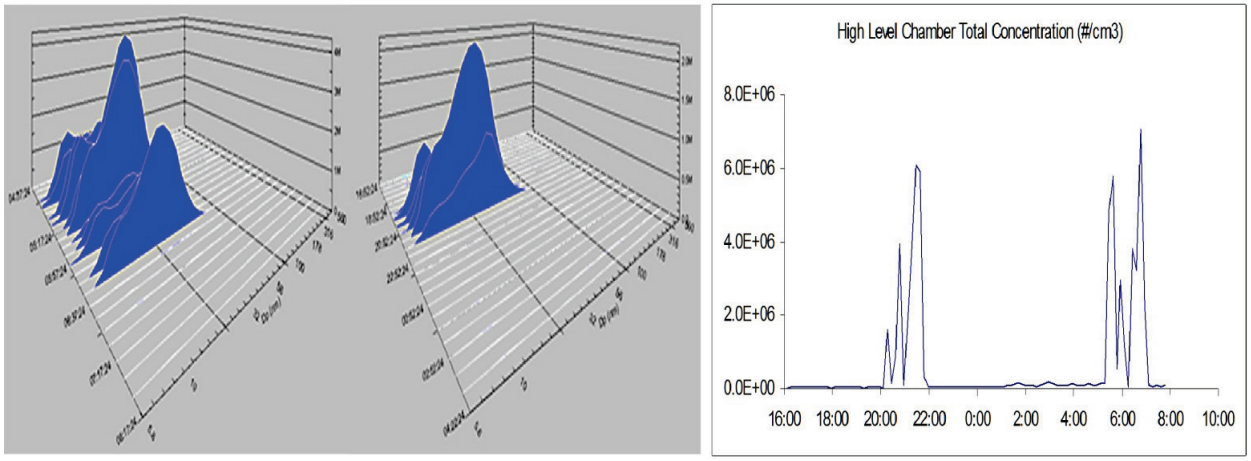


Figure 6. Representative real-time particle size and number concentrations measured by the FMPS. Particle concentrations peaked during the DPF regenerations. Data are measurements made in September 2010 and April 2012.

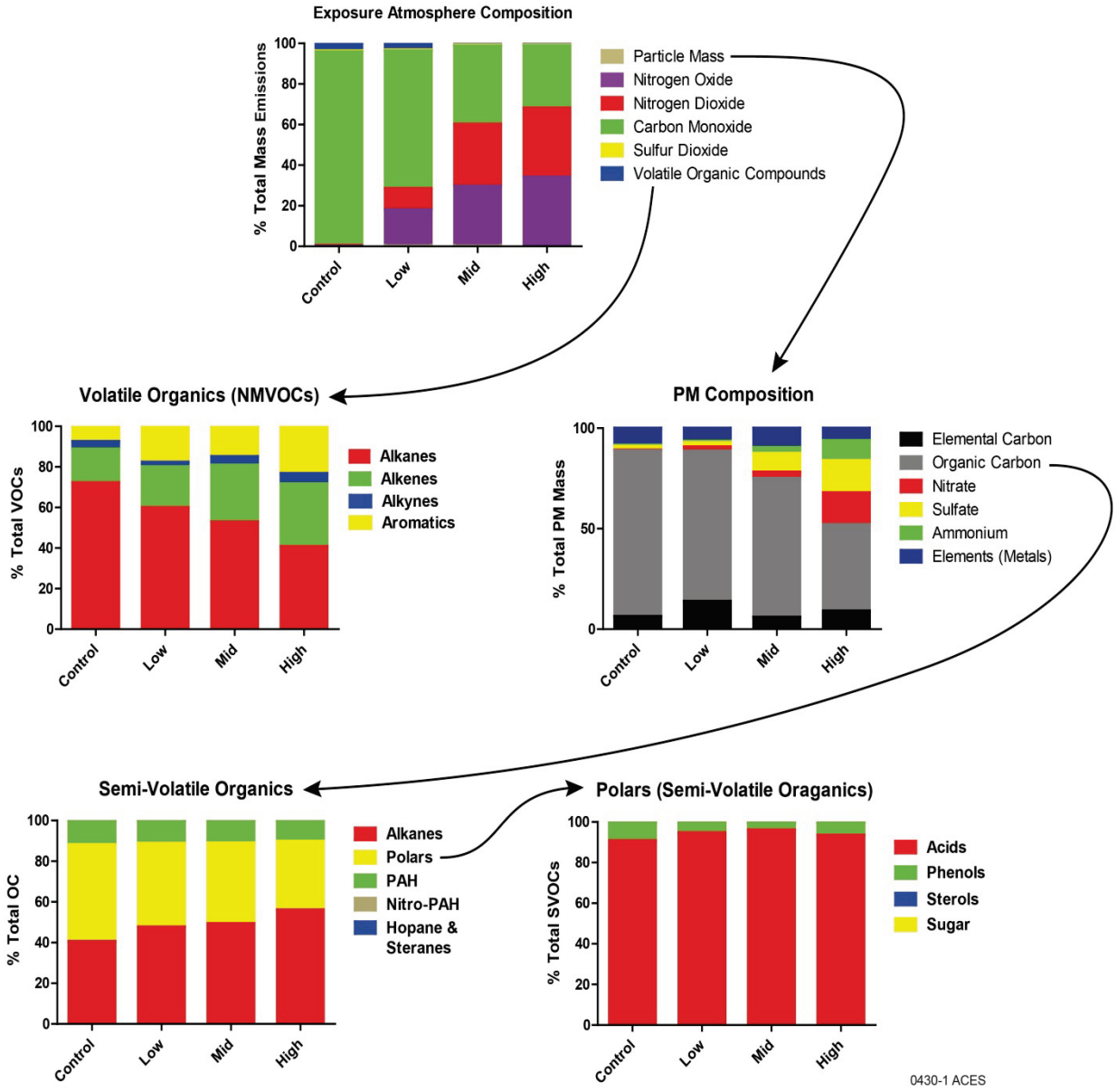


Figure 7. Average exposure atmosphere composition during the ACES Chronic Bioassay. Percent contribution for each chemical class are shown. Data are averages of measurements made in April 2010, September 2010, April 2011 and April 2012.

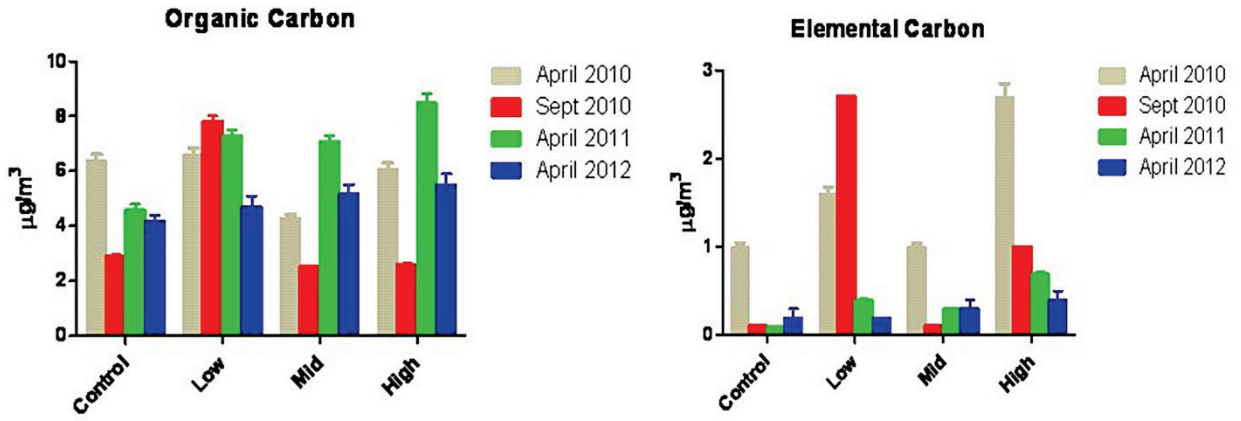


Figure 8. Concentrations of organic carbon and elemental carbon at each exposure level in April 2010, September 2010, April 2011 and April 2012.

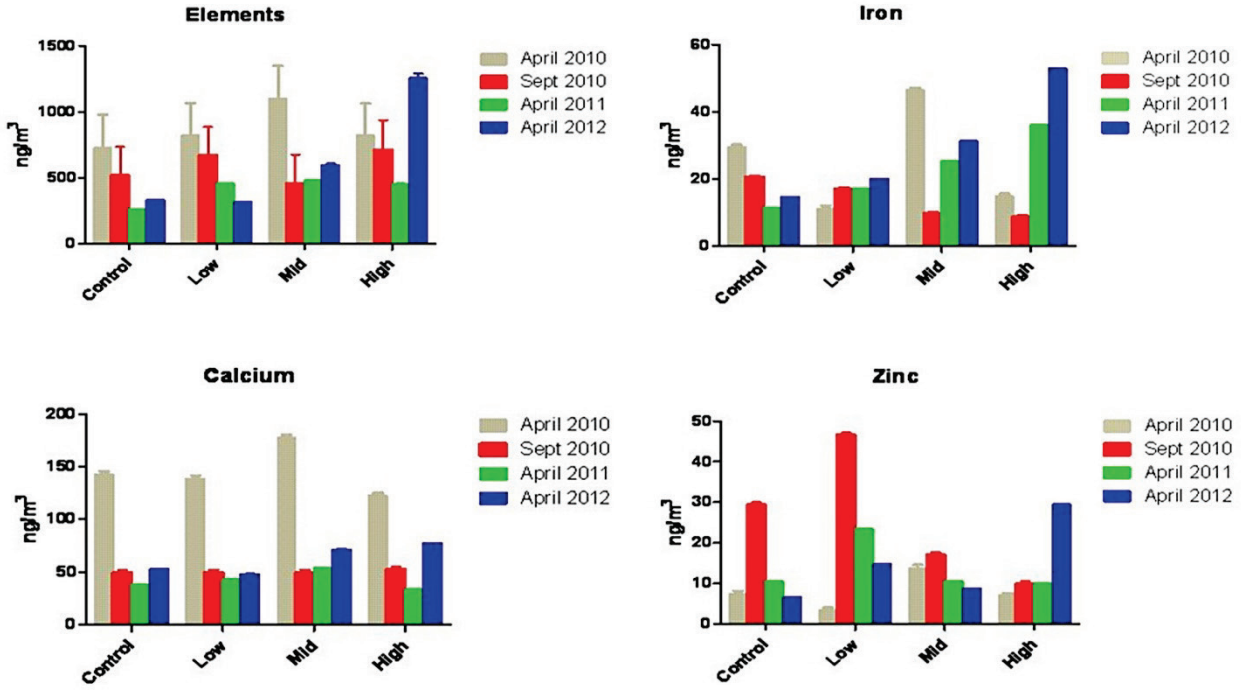


Figure 9. Concentrations of total sum of elements, iron, calcum and zinc in April 2010, September 2010, April 2011 and April 2012.

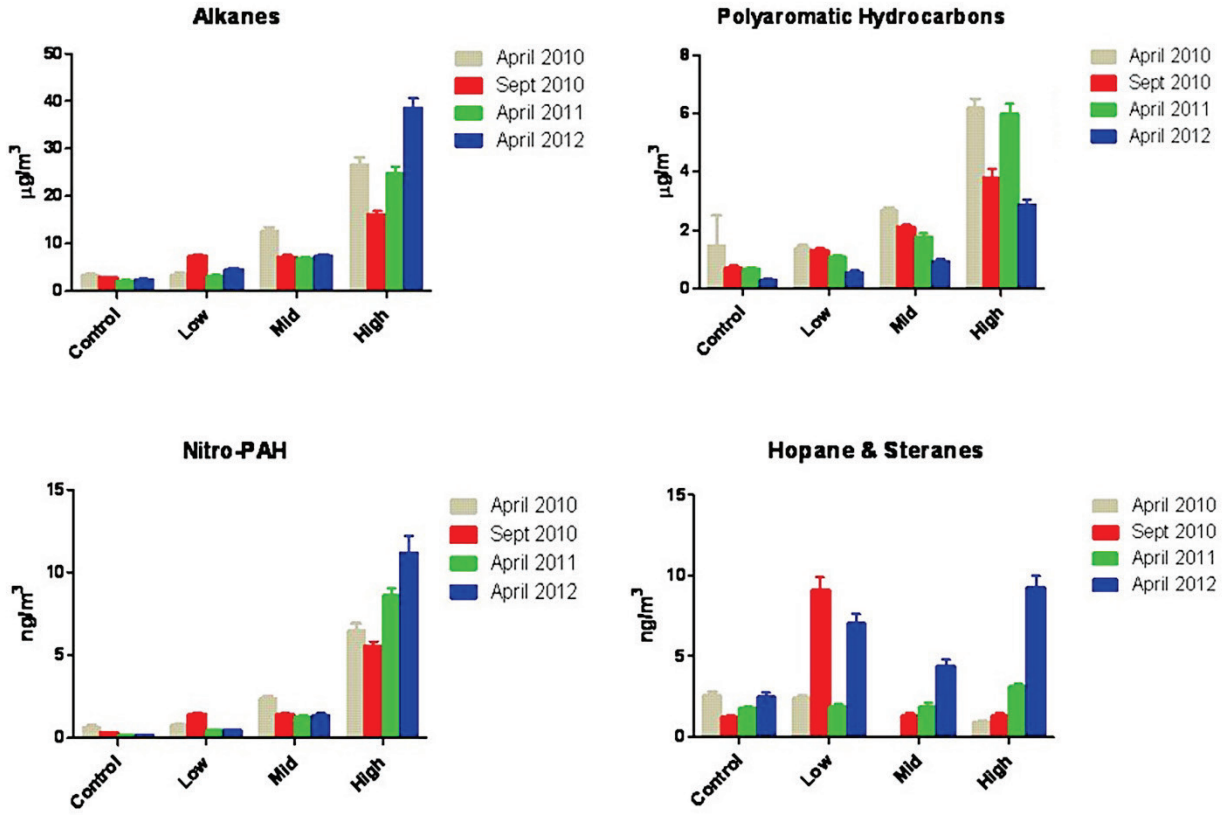


Figure 10. Concentrations of semivolatile alkanes, PAH, nitro-PAH and hopanes/steranes in April 2010, September 2010, April 2011 and April 2012.

Appendix A.

Fuel Analysis

Herguth Laboratories, Inc.
People and Data You Can Count On!

Certificate of Analysis

Lab Number V7000244A

Michael Clearwater
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE
Albuquerque NM 87108

03/11/10

Page 1

Client Code : LOVEMC Sample Date : 02/19/10 P.O. Number : JLMAMS
Herguth ID : LABV7000244
Description : Sample ID: 19FEB10-F409-111, Diesel Fuel
Serial#: 1802741 09744
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		757	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		315	Deg. F
5%		369	Deg. F
10%		388	Deg. F
15%		402	Deg. F
20%		414	Deg. F
30%		434	Deg. F
40%		458	Deg. F
50%		483	Deg. F
60%		509	Deg. F
70%		538	Deg. F
80%		571	Deg. F
85%		590	Deg. F
90%		614	Deg. F
95%		648	Deg. F
End Point		660	Deg. F
Recovery		97.0	% vol.
Sulfur, X-Ray Fluorescence ASTM D4294	4294-2.8	<0.0020	% Wt
Cetane Index ASTM D976	0976-1.3	49.0	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	38.2	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		25.2	% vol
Olefins		2.0	% vol
Saturates		72.8	% vol

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Albuquerque NM 87108

03/11/10

Page 2

Client Code : LOVEMC Sample Date : 02/19/10 P.O. Number : JLMAMS
Herguth ID :
Description : Sample ID: 19FEB10-F409-111, Diesel Fuel
Serial#: 1802741 09744
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result
Sulfur by Microcoulometry ASTM D3120	3120-3.0	5 mg/kg

REVISED REPORT supersedes lab # V7000244 and includes sulfur by D3120 result.
Result(s) meet the specifications of ASTM D975 for S15 No. 2 Diesel Fuel for the test(s) performed.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Michael Clearwater

Bobby R Licu, Senior Evaluator

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Page 1

Client Code : LOVEMC Sample Date : 02/19/10 P.O. Number : JLMAMS
Herguth ID : LABV7000244
Description : Sample ID: 19FEB10-F409-111, Diesel Fuel
Serial#: 1802741 09744
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		757	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		315	Deg. F
5%		369	Deg. F
10%		388	Deg. F
15%		402	Deg. F
20%		414	Deg. F
30%		434	Deg. F
40%		458	Deg. F
50%		483	Deg. F
60%		509	Deg. F
70%		538	Deg. F
80%		571	Deg. F
85%		590	Deg. F
90%		614	Deg. F
95%		648	Deg. F
End Point		660	Deg. F
Recovery		97.0	% vol.
Sulfur, X-Ray Fluorescence ASTM D4294	4294-2.8	<0.0020	% Wt
Cetane Index ASTM D976	0976-1.3	49.0	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	38.2	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		25.2	% vol
Olefins		2.0	% vol
Saturates		72.8	% vol

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Page 2

Client Code : LOVEMC Sample Date : 02/19/10 P.O. Number : JLMAMS
Herguth ID :
Description : Sample ID: 19FEB10-F409-111, Diesel Fuel
Serial#: 1802741 09744
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result
Sulfur by Microcoulometry ASTM D3120	3120-3.0	5 mg/kg

REVISED REPORT supersedes lab # V7000244 and includes sulfur by D3120 result.
Result(s) meet the specifications of ASTM D975 for S15 No. 2 Diesel Fuel for the test(s) performed.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Michael Clearwater

Bobby R Licu, Senior Evaluator

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04/26/10

Page 1

Client Code : LOVEMC Sample Date : 04/14/10 P.O. Number : JLMDEM
Herguth ID : LABV7000633
Description : Serial# F409-111-14APR10, Clear Diesel
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		754	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		343	Deg. F
5%		381	Deg. F
10%		398	Deg. F
15%		413	Deg. F
20%		427	Deg. F
30%		452	Deg. F
40%		478	Deg. F
50%		504	Deg. F
60%		530	Deg. F
70%		559	Deg. F
80%		593	Deg. F
85%		614	Deg. F
90%		639	Deg. F
95%		680	Deg. F
End Point		689	Deg. F
Recovery		96.9	% vol.
Cetane Index ASTM D976	0976-1.3	51.0	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	37.0	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		28.1	% vol
Olefins		1.1	% vol
Saturates		70.8	% vol
Sulfur, X-Ray Fluorescence ASTM D4294	4294-2.8	<0.0020	% Wt

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04/26/10

Page 2

Client Code : LOVEMC Sample Date : 04/14/10 P.O. Number : JLMDEM
Herguth ID :
Description : Serial# F409-111-14APR10, Clear Diesel

Test Performed	Proc-Rev	Result

Result(s) meet the specifications of ASTM D975 for No. 2 Diesel Fuel for the test(s) performed.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Tom Holmes

Bobby R Licu, Senior Evaluator

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04/30/10

Page 1

Client Code : LOVEMC Sample Date : 04/14/10 P.O. Number : JLMDEM
Herguth ID : LABV7000633
Description : Serial# F409-111-14APR10, Clear Diesel
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result
Distillation of Petroleum ASTM D86	0086-2.6	
Observed Barometric Pressure		754 mm Hg
All results are corrected to 760 mm Hg		
Initial Boiling Point		343 Deg. F
5%		381 Deg. F
10%		398 Deg. F
15%		413 Deg. F
20%		427 Deg. F
30%		452 Deg. F
40%		478 Deg. F
50%		504 Deg. F
60%		530 Deg. F
70%		559 Deg. F
80%		593 Deg. F
85%		614 Deg. F
90%		639 Deg. F
95%		680 Deg. F
End Point		689 Deg. F
Recovery		96.9 % vol.
Cetane Index ASTM D976	0976-1.3	51.0
API Gravity @ 60 Deg F ASTM D287	0287-2.1	37.0 Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0	
Aromatics		28.1 % vol
Olefins		1.1 % vol
Saturates		70.8 % vol
Sulfur by Microcoulometry ASTM D3120	3120-3.0	5 ppm

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04/30/10

Page 2

Client Code : LOVEMC Sample Date : 04/14/10 P.O. Number : JLMDEM
Herguth ID :
Description : Serial# F409-111-14APR10, Clear Diesel

Test Performed	Proc-Rev	Result

REVISED REPORT supersedes lab # V7000633 and includes updated sulfur test.
Result(s) meet the specifications of ASTM D975 for S15 No. 2 Diesel Fuel for the test(s) performed.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Tom Holmes

Bobby R Licu, Senior Evaluator

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06/22/10

Page 1

Client Code : LOVEMC Sample Date : 06/08/10 P.O. Number : JK101621
Herguth ID : LABV7001241
Description : Sample ID: FY09-111-08JUN10-Fuel, Chevron #2 Clear Diesel
Label States: Total Engine Hours: 2586
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		760	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		336	Deg. F
5%		380	Deg. F
10%		396	Deg. F
15%		411	Deg. F
20%		424	Deg. F
30%		448	Deg. F
40%		473	Deg. F
50%		496	Deg. F
60%		522	Deg. F
70%		550	Deg. F
80%		583	Deg. F
85%		604	Deg. F
90%		629	Deg. F
95%		668	Deg. F
End Point		676	Deg. F
Recovery		97.2	% vol.
Cetane Index ASTM D976	0976-1.3	49.5	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	37.6	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		26.5	% vol
Olefins		1.1	% vol
Saturates		72.4	% vol
Sulfur by Microcoulometry ASTM D3120	3120-3.0	3	ppm

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06/22/10

Page 2

Client Code : LOVEMC Sample Date : 06/08/10 P.O. Number : JK101621
Herguth ID :
Description : Sample ID: FY09-111-08JUN10-Fuel, Chevron #2 Clear Diesel
Label States: Total Engine Hours: 2586

Test Performed	Proc-Rev	Result

Result(s) meet the specifications of ASTM D975 for S15 No. 2 Diesel Fuel for the test(s) performed.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Tom Holmes

Bobby R Licu, Senior Evaluator

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08/16/10

Page 1

Client Code : LOVEMC Sample Date : 07/29/10 P.O. Number : JK101657
Herguth ID : LABV7001845
Description : Sample ID: FY09-111-30JUL10-Fuel, Chevron #2 Clear Diesel
Project# FY09-111 ACES, Acct/Org/Project: JLMEPR
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		761	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		336	Deg. F
5%		380	Deg. F
10%		402	Deg. F
15%		420	Deg. F
20%		434	Deg. F
30%		460	Deg. F
40%		486	Deg. F
50%		510	Deg. F
60%		534	Deg. F
70%		560	Deg. F
80%		590	Deg. F
85%		609	Deg. F
90%		632	Deg. F
95%		671	Deg. F
End Point		676	Deg. F
Recovery		96.8	% vol.
Cetane Index ASTM D976	0976-1.3	49.5	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	36.5	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		28.6	% vol
Olefins		1.2	% vol
Saturates		70.2	% vol
Sulfur by Microcoulometry ASTM D3120	3120-3.0	5	ppm

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08/16/10

Page 2

Client Code : LOVEMC Sample Date : 07/29/10 P.O. Number : JK101657
Herguth ID :
Description : Sample ID: FY09-111-30JUL10-Fuel, Chevron #2 Clear Diesel
Project# FY09-111 ACES, Acct/Org/Project: JLMEPR

Test Performed	Proc-Rev	Result

Result(s) meet the specifications of ASTM D975 for S15 No. 2 Diesel Fuel for the test(s) performed.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Tom Holmes

Bobby R Licu, Senior Evaluator

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10/14/10

Page 1

Client Code : LOVEMC Sample Date : 10/01/10 P.O. Number : FY09-111 ACES
Herguth ID : LABV7002326
Description : Sample ID: FY09-111-01OCT10, Chevron #2 Clear Diesel Fuel
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		762	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		340	Deg. F
5%		379	Deg. F
10%		398	Deg. F
15%		411	Deg. F
20%		422	Deg. F
30%		445	Deg. F
40%		468	Deg. F
50%		492	Deg. F
60%		518	Deg. F
70%		550	Deg. F
80%		588	Deg. F
85%		611	Deg. F
90%		641	Deg. F
95%		DNR	Deg. F
End Point		686	Deg. F
Recovery		95.8	% vol.
Cetane Index ASTM D976	0976-1.3	48.5	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	37.3	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		33.6	% vol
Olefins		1.1	% vol
Saturates		65.3	% vol
Sulfur by Microcoulometry ASTM D3120	3120-3.1	3	ppm

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10/14/10

Page 2

Client Code : LOVEMC Sample Date : 10/01/10 P.O. Number : FY09-111 ACES
Herguth ID :
Description : Sample ID: FY09-111-01OCT10, Chevron #2 Clear Diesel Fuel

Test Performed	Proc-Rev	Result

Result does not meet the specifications of ASTM D975 for S15 No. 2 Diesel Fuel for the test(s) performed.
Distillation at 90% exceeds maximum (640°F). Testing could not be completed due to sample condition.
Value(s) have been rechecked and verified.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Tom Holmes

Bobby R Licu, Senior Evaluator

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12/09/10

Page 1

Client Code : LOVEMC Sample Date : 11/24/10 P.O. Number : FY09-111 ACES
Herguth ID : LABV7003059
Description : Sample: FY09-111-24nov10-fuel, Chevon #2 Clear Diesel Fuel
Label States: Total Engine Hours: 4505
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		765	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		336	Deg. F
5%		367	Deg. F
10%		381	Deg. F
15%		395	Deg. F
20%		406	Deg. F
30%		429	Deg. F
40%		454	Deg. F
50%		479	Deg. F
60%		507	Deg. F
70%		537	Deg. F
80%		570	Deg. F
85%		590	Deg. F
90%		615	Deg. F
95%		654	Deg. F
End Point		660	Deg. F
Recovery		96.9	% vol.
Cetane Index ASTM D976	0976-1.3	47.5	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	37.7	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		27.1	% vol
Olefins		0.9	% vol
Saturates		72.0	% vol
Sulfur by Microcoulometry ASTM D3120	3120-3.1	4	ppm

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12/09/10

Page 2

Client Code : LOVEMC Sample Date : 11/24/10 P.O. Number : FY09-111 ACES
Herguth ID :
Description : Sample: FY09-111-24nov10-fuel, Chevon #2 Clear Diesel Fuel
Label States: Total Engine Hours: 4505

Test Performed	Proc-Rev	Result

Result(s) meet the specifications of ASTM D975 for S15 No. 2 Diesel Fuel for the test(s) performed.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Tom Holmes

Bobby R Licu, Senior Evaluator

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Lab Number V7003451

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE
Albuquerque NM 87108

01/28/11

Page 1

Client Code : LOVEMC Sample Date : 01/17/11 P.O. Number : JK110737
Herguth ID : LABV7003451
Description : Sample ID: FY09-111-17Jan11-Fuel
Total Engine Hours: 5082, Paperwork States: Sample Description: Chevron #2 Clear Diesel Fuel, Project/PO#: FY09-111 ACES
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		764	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		331	Deg. F
5%		361	Deg. F
10%		375	Deg. F
15%		386	Deg. F
20%		399	Deg. F
30%		422	Deg. F
40%		445	Deg. F
50%		471	Deg. F
60%		500	Deg. F
70%		530	Deg. F
80%		566	Deg. F
85%		586	Deg. F
90%		610	Deg. F
95%		646	Deg. F
End Point		659	Deg. F
Recovery		97.5	% vol.
Cetane Index ASTM D976	0976-1.3	46.5	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	38.4	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		28.0	% vol
Olefins		2.3	% vol
Saturates		69.7	% vol

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Certificate of Analysis
Lab Number V7003451

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01/28/11

Page 2

Client Code : LOVEMC Sample Date : 01/17/11 P.O. Number : JK110737
Herguth ID :
Description : Sample ID: FY09-111-17Jan11-Fuel
Total Engine Hours: 5082, Paperwork States: Sample Description: Chevron #2 Clear Diesel Fuel,
Project/PO#: FY09-111 ACES
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result
Sulfur, X-Ray Fluorescence ASTM D4294	4294-2.8	<0.0020 % Wt

Result(s) meet the specifications of ASTM D975 for No. 2 Diesel Fuel for the test(s) performed.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Tom Holmes

Bobby R Licu, Senior Evaluator

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02/10/11

Page 1

Client Code : LOVEMC Sample Date : 01/17/11 P.O. Number : JK110737
Herguth ID : LABV7003451
Description : Sample ID: FY09-111-17Jan11-Fuel
Total Engine Hours: 5082, Paperwork States: Sample Description: Chevron #2 Clear Diesel Fuel, Project/PO#: FY09-111 ACES
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		764	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		331	Deg. F
5%		361	Deg. F
10%		375	Deg. F
15%		386	Deg. F
20%		399	Deg. F
30%		422	Deg. F
40%		445	Deg. F
50%		471	Deg. F
60%		500	Deg. F
70%		530	Deg. F
80%		566	Deg. F
85%		586	Deg. F
90%		610	Deg. F
95%		646	Deg. F
End Point		659	Deg. F
Recovery		97.5	% vol.
Cetane Index ASTM D976	0976-1.3	46.5	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	38.4	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		28.0	% vol
Olefins		2.3	% vol
Saturates		69.7	% vol

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02/10/11

Page 2

Client Code : LOVEMC Sample Date : 01/17/11 P.O. Number : JK110737
Herguth ID :
Description : Sample ID: FY09-111-17Jan11-Fuel
Total Engine Hours: 5082, Paperwork States: Sample Description: Chevron #2 Clear Diesel Fuel,
Project/PO#: FY09-111 ACES
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result
Sulfur by Microcoulometry ASTM D3120	3120-3.1	3 ppm

REVISED REPORT supersedes lab # V7003451 and includes updated sulfur result.
Result(s) meet the specifications of ASTM D975 for No. 2 Diesel Fuel for the test(s) performed.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Tom Holmes

Bobby R Licu, Senior Evaluator

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Quotation No. 204887 (LOVEMC)
Quotation Date: February 1, 2011

QUOTATION

Item	Qty	Description/Analysis	Methodology	Fee	Extend
1	***1***	***Fuels***		***353.85***	***353.85***
		Volume of sample required: 631 ml			
		Distillation of Petroleum Product (FUELS)	ASTM D86		
		Cetane Index (Calculation Only) (FUELS)	ASTM D976		
		Gravity, API (Hydrometer Method) (FUELS)	ASTM D287		
		*Hydrocarbon Types by Fluorescent (FUELS)	ASTM D1319		
		Sulfur by Microcoul. (FUELS)	ASTM D3120		

Turnaround time is 7-10 working day(s) from receipt of sample.

QUOTATION TOTAL 353.85 each

*Test are subcontracted to another facility and should be completed between 7-10 working days

Thank you for the opportunity to provide you with the above quotation for your samples. The above quotation is based on your requested scope of work and/or our recommended analytical methods for your sample type. However, prices are subject to change based on the actual sample type as determined upon receipt. Reference oils are required for baseline data.

Our standard turn around time is four (4) working days. Rush charges are double above prices for 48-hour turn around and triple for 24-hour. Any analysis that is subcontracted to another facility (lab) will be processed within 7-10 working days depending on the test. Samples arriving in large batches may have longer turn around times based on testing and oil types. This quotation is valid for 90 days. Please refer to quotation number when submitting samples. All ASTM methods will be performed at the latest published revision.

Reports can be transmitted via email upon completion at no additional charge. We also have Internet access-iLAMP available for an additional $300/ year that will allow you to retrieve your data, view and print reports, set up units and route list, print labels, etc. Please contact Customer Service to order iLAMP.

A credit application or payment is required with all new accounts. Please fax one to 707-554-0109. Credit will be extended based on the reference verification. The sample turn around time may be longer based on credit reference responses.

Laboratory Pricing Policy

1. Hours of Operation And Normal Availability

Regular laboratory hours are 8:00 AM to 5:00 PM Monday through Friday. For condition monitoring analyses, our normal turnaround is 48 hours (two working days). For all other analyses, our normal turnaround is 96 hours (four working days). Any analysis that is subcontracted to another facility

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(lab) will be processed within 7-10 working days depending on the test. Please note there may be delays in turn around times based on account setup and credit references.

2. Minimum Invoice Charges, Rush Analyses and Overtime Rates

A minimum fee of $25.00 may be charged for any analysis invoice. For Condition Monitoring analyses, "RUSH" samples results are available within 24 hours (or less) and are charged at three times the normal analyses rate. For other analyses there are two "RUSH" provisions for work performed during our regular laboratory hours:

a) 48 hour (2 working day) analysis time is charged at twice the normal analysis fee.

b) 24 hour (one working day) turnaround, or less, is charged at three times the normal analysis fee.

There are some analyses that cannot be completed in less than 24 hours; however, they can be moved ahead of the scheduled samples waiting for that analysis. These analyses will be charged at the 24 hour rush rate. Laboratory work performed during other hours, including Saturday, Sunday or recognized Holidays may be charged at triple our normal analyses rates, an hourly rate with a four (4) hour minimum charge, or $1,500, whichever is greater. Nuclear Quality Assured (10 CFR 50 Appendix B) or radioactive samples analyzed during periods other than normal hours will be charged a minimum of $2,500.

3. Quality Assurance Program And Surveillance

Analyses performed under the Safety Related Part 21 Program are charged at 1.35 times the applicable fee. Surveillance of work performed at Herguth Laboratories, Inc. by client representatives may be charged at three times the applicable fee. All ASTM methods are performed at the latest published revision.

4. Radioactive Materials

Analyses on radioactive samples will be assessed a surcharge of 1.5 times the analysis fee or a fee of $125 per sample (Condition Monitoring Rads), as specifically quoted to the customer. Radioactive lubricant samples are properly disposed of by Herguth provided the sample meets our disposal criteria. This service is not applicable for non-liquid lubricant samples, which must be returned to the client.

5. Sample Pick-Up And Delivery

Sample pick-up and delivery during normal working hours may be charged at a minimum of $25 within a 25 mile radius. The fee will be $50 within a radius of 50 miles. Sample pick-up during non-working hours may be charged a minimum of $100 plus expenses. This applies to the nine (9) San Francisco Bay Area counties. Special arrangements must be made for custody transfers and pick-ups outside of this area.

6. Sample Retention and Disposal

Samples will be held for a minimum of 30 days. Long term retention services are available by special request. Non-hydrocarbon samples, "unknown" samples, and samples containing elements or constituents which cannot be accommodated by our normal waste streams will either be returned, or if requested, disposed of properly. Handling and disposal surcharges may be assessed. Samples can be returned to the client if requested.

Terms, Conditions, and Limitations

All services rendered by Herguth Laboratories, Inc. are undertaken, and all rates are based upon the following terms:

(a) Neither Herguth Laboratories, Inc., nor any of its employees, agents or sub-contractors shall be liable for any loss or damage arising out of Herguth Laboratories, Inc.'s. performance or non-performance, whether by way of negligence or breach of contract, or otherwise, in any amount greater than twice the amount billed to the customer for the work leading to the claim of the customer. Said remedy shall be the sole and exclusive remedy against Herguth Laboratories, Inc. arising out of its work.

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(b) All claims must be in writing within forty-five (45) days after delivery of the Herguth Laboratories, Inc. report regarding said work, or such claim shall be deemed as irrevocably waived.

(c) Herguth Laboratories, Inc. reports are submitted in writing and are for our customers only. Our customers are considered to be only those entities being billed for our services. Acquisition of a Herguth Laboratories, Inc. report by other than our customer does not constitute a representation of Herguth Laboratories, Inc. as to the accuracy of the contents thereof.

(d) In no event shall Herguth Laboratories, Inc., its employees, agents or sub-contractors be responsible for consequential or special damages of any kind or in any amount.

(e) No deviation from the terms set forth herein shall bind Herguth Laboratories, Inc. unless explicitly agreed upon and accepted contractually, or unless explicitly expressed in writing and signed by a Corporate Officer of Herguth Laboratories, Inc.

(f) Depending on specific customer requirements and/or changes in operations, Herguth Laboratories, Inc. reserves the right to change the pricing and availability of analyses as published in price list(s).

(g) All ASTM methods are performed at the latest published revision.

Should you have any questions regarding this quote, please contact myself at 800-645-5227 ext. 3012. We look forward to working with you on this and future projects. Please refer to this quotation number when submitting samples.

Please visit our website for additional services and capabilities www.herguth.com.

Linda J. Perry

_____

Linda Perry
Sales & Marketing

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Lab Number V7004199

Tom Holmes
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2425 Ridgecrest Drive, SE
Albuquerque NM 87108

03/28/11

Page 1

Client Code : LOVEMC Sample Date : 03/15/11 P.O. Number : JK110737
Herguth ID : LABV7004199
Description : Sample: FY09-111-15mar11-fuel, Chevron #2 Clear Diesel Fuel
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		755	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		337	Deg. F
5%		366	Deg. F
10%		382	Deg. F
15%		394	Deg. F
20%		405	Deg. F
30%		427	Deg. F
40%		452	Deg. F
50%		478	Deg. F
60%		505	Deg. F
70%		535	Deg. F
80%		570	Deg. F
85%		590	Deg. F
90%		615	Deg. F
95%		651	Deg. F
End Point		664	Deg. F
Recovery		97.1	% vol.
Cetane Index ASTM D976	0976-1.3	47.0	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	37.6	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		27.9	% vol
Olefins		3.0	% vol
Saturates		69.1	% vol
Sulfur by Microcoulometry ASTM D3120	3120-3.1	5	mg/kg

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03/28/11

Page 2

Client Code : LOVEMC Sample Date : 03/15/11 P.O. Number : JK110737
Herguth ID :
Description : Sample: FY09-111-15mar11-fuel, Chevron #2 Clear Diesel Fuel

Test Performed	Proc-Rev	Result

Result(s) meet the specifications of ASTM D975 for S15 No. 2 Diesel Fuel for the test(s) performed.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Tom Holmes

Bobby R Licu, Senior Evaluator

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Albuquerque NM 87108

05/20/11

Page 1

Client Code : LOVEMC Sample Date : 05/10/11 P.O. Number : JK110737
Herguth ID : LABV7004725
Description : Sample ID: FY09-111-10may-11fuel, Diesel Fuel
Chevron #2 Clear Diesel Fuel, Label States: Total Engine Hours: 6351
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		758	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		342	Deg. F
5%		377	Deg. F
10%		393	Deg. F
15%		409	Deg. F
20%		424	Deg. F
30%		451	Deg. F
40%		479	Deg. F
50%		504	Deg. F
60%		530	Deg. F
70%		556	Deg. F
80%		585	Deg. F
85%		603	Deg. F
90%		626	Deg. F
95%		661	Deg. F
End Point		671	Deg. F
Recovery		97.1	% vol.
Cetane Index ASTM D976	0976-1.3	47.5	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	35.9	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		29.7	% vol
Olefins		1.6	% vol
Saturates		68.7	% vol
Sulfur by Microcoulometry ASTM D3120	3120-3.1	3	mg/kg

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Albuquerque NM 87108

05/20/11

Page 2

Client Code : LOVEMC Sample Date : 05/10/11 P.O. Number : JK110737
Herguth ID : LABV7004725
Description : Sample ID: FY09-111-10may-11fuel, Diesel Fuel
Chevron #2 Clear Diesel Fuel, Label States: Total Engine Hours: 6351

Test Performed	Proc-Rev	Result

Result(s) meet the specifications of ASTM D975 for S15 No. 2 Diesel Fuel for the test(s) performed.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Tom Holmes

Bobby R Licu, Senior Evaluator

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Albuquerque NM 87108

07/21/11

Page 1

Client Code : LOVEMC Sample Date : 07/07/11 P.O. Number : JK110737
Herguth ID : LABV7005385
Description : Sample ID: FY09-111-07Jul11-Fuel, Diesel Fuel
Chevron #2 Clear Diesel Fuel
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		760	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		353	Deg. F
5%		383	Deg. F
10%		401	Deg. F
15%		416	Deg. F
20%		428	Deg. F
30%		454	Deg. F
40%		480	Deg. F
50%		506	Deg. F
60%		532	Deg. F
70%		560	Deg. F
80%		591	Deg. F
85%		610	Deg. F
90%		635	Deg. F
95%		674	Deg. F
End Point		680	Deg. F
Recovery		97.0	% vol.
Cetane Index ASTM D976	0976-1.3	50.0	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	37.2	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		31.0	% vol
Olefins		1.9	% vol
Saturates		67.1	% vol
Sulfur by Microcoulometry ASTM D3120	3120-3.1	10	mg/kg

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07/21/11

Page 2

Client Code : LOVEMC Sample Date : 07/07/11 P.O. Number : JK110737
Herguth ID : LABV7005385
Description : Sample ID: FY09-111-07Jul11-Fuel, Diesel Fuel
Chevron #2 Clear Diesel Fuel

Test Performed	Proc-Rev	Result

Result(s) meet the specifications of ASTM D975 for S15 No. 2 Diesel Fuel for the test(s) performed.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Tom Holmes

Bobby R Licu, Senior Evaluator

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09/21/11

Page 1

Client Code : LOVEMC Sample Date : 09/06/11 P.O. Number : JK110737
Herguth ID : LABV7006238
Description : Sample: FY09-111-06SEP11-Fuel, Chevron #2 Clear Diesel Fuel
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		761	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		339	Deg. F
5%		369	Deg. F
10%		382	Deg. F
15%		396	Deg. F
20%		406	Deg. F
30%		430	Deg. F
40%		455	Deg. F
50%		482	Deg. F
60%		509	Deg. F
70%		540	Deg. F
80%		572	Deg. F
85%		591	Deg. F
90%		615	Deg. F
95%		654	Deg. F
End Point		656	Deg. F
Recovery		96.7	% vol.
Cetane Index ASTM D976	0976-1.3	48.0	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	37.9	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		26.5	% vol
Olefins		1.3	% vol
Saturates		72.2	% vol
Sulfur by Microcoulometry ASTM D3120	3120-3.1	10	mg/kg

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09/21/11

Page 2

Client Code : LOVEMC Sample Date : 09/06/11 P.O. Number : JK110737
Herguth ID : LABV7006238
Description : Sample: FY09-111-06SEP11-Fuel, Chevron #2 Clear Diesel Fuel

Test Performed	Proc-Rev	Result

Result(s) meet the specifications of ASTM D975 for S15 No. 2 Diesel Fuel for the test(s) performed, noting visible debris was present in sample.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Tom Holmes

Bobby R Licu, Senior Evaluator

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Lab Number V7006931

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE
Albuquerque NM 87108

11/22/11

Page 1

Client Code : LOVEMC Sample Date : 11/07/11 P.O. Number : JK120015
Herguth ID : LABV7006931
Description : FY09-111-07NOV11-Fuel, Chevron #2 Clear Diesel Fuel
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		762	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		358	Deg. F
5%		382	Deg. F
10%		403	Deg. F
15%		414	Deg. F
20%		425	Deg. F
30%		447	Deg. F
40%		469	Deg. F
50%		489	Deg. F
60%		508	Deg. F
70%		530	Deg. F
80%		555	Deg. F
85%		571	Deg. F
90%		592	Deg. F
95%		624	Deg. F
End Point		642	Deg. F
Recovery		97.2	% vol.
Cetane Index ASTM D976	0976-1.3	51.5	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	39.3	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		20.7	% vol
Olefins		2.8	% vol
Saturates		76.5	% vol
Sulfur by Microcoulometry ASTM D3120	3120-3.1	7	mg/kg

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11/22/11

Page 2

Client Code : LOVEMC Sample Date : 11/07/11 P.O. Number : JK120015
Herguth ID : LABV7006931
Description : FY09-111-07NOV11-Fuel, Chevron #2 Clear Diesel Fuel

Test Performed	Proc-Rev	Result

Result(s) meet the specifications of ASTM D975 for S15 No. 2 Diesel Fuel for the test(s) performed.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Tom Holmes

Bobby R Licu, Senior Evaluator

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Albuquerque NM 87108

12/29/11

Page 1

Client Code : LOVEMC Sample Date : 12/13/11 P.O. Number : JK120015
Herguth ID : LABV7007282
Description : FY09-111-13DEC11-FUEL, Chevron #2 Clear Diesel Fuel
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		762	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		343	Deg. F
5%		373	Deg. F
10%		387	Deg. F
15%		402	Deg. F
20%		413	Deg. F
30%		437	Deg. F
40%		460	Deg. F
50%		482	Deg. F
60%		505	Deg. F
70%		529	Deg. F
80%		559	Deg. F
85%		577	Deg. F
90%		600	Deg. F
95%		632	Deg. F
End Point		650	Deg. F
Recovery		98.0	% vol.
Cetane Index ASTM D976	0976-1.3	49.5	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	38.8	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		24.7	% vol
Olefins		3.6	% vol
Saturates		71.7	% vol
Sulfur by Microcoulometry ASTM D3120	3120-3.1	4	mg/kg

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12/29/11

Page 2

Client Code : LOVEMC Sample Date : 12/13/11 P.O. Number : JK120015
Herguth ID : LABV7007282
Description : FY09-111-13DEC11-FUEL, Chevron #2 Clear Diesel Fuel

Test Performed	Proc-Rev	Result

Result(s) meet the specifications of ASTM D975 for S15 No. 2 Diesel Fuel for the test(s) performed.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Tom Holmes

Bobby R Licu, Senior Evaluator

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Albuquerque NM 87108

02/13/12

Page 1

Client Code : LOVEMC Sample Date : 01/31/12 P.O. Number : JK120015
Herguth ID : LABV7007704
Description : FY09-111-30JAN2012-Fuel, Chevron #2 Clear Diesel Fuel
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		764	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		326	Deg. F
5%		370	Deg. F
10%		385	Deg. F
15%		400	Deg. F
20%		411	Deg. F
30%		435	Deg. F
40%		458	Deg. F
50%		484	Deg. F
60%		511	Deg. F
70%		540	Deg. F
80%		573	Deg. F
85%		592	Deg. F
90%		614	Deg. F
95%		647	Deg. F
End Point		664	Deg. F
Recovery		97.5	% vol.
Cetane Index ASTM D976	0976-1.3	47.0	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	37.2	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		32.3	% vol
Olefins		3.8	% vol
Saturates		63.9	% vol
Sulfur by Microcoulometry ASTM D3120	3120-3.1	4	mg/kg

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02/13/12

Page 2

Client Code : LOVEMC Sample Date : 01/31/12 P.O. Number : JK120015
Herguth ID : LABV7007704
Description : FY09-111-30JAN2012-Fuel, Chevron #2 Clear Diesel Fuel

Test Performed	Proc-Rev	Result

Result(s) meet the specifications of ASTM D975 for S15 No. 2 Diesel Fuel for the test(s) performed.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Tom Holmes

Bobby R Licu, Senior Evaluator

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04/12/12

Page 1

Client Code : LOVEMC Sample Date : 03/29/12 P.O. Number : JK120015
Herguth ID : LABV7008264
Description : Sample ID: FY09-111-29MAR2012, Chevron #2 Clear Diesel Fuel
Label States: Total Engine Hours: 3312
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		765	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		334	Deg. F
5%		370	Deg. F
10%		386	Deg. F
15%		399	Deg. F
20%		414	Deg. F
30%		434	Deg. F
40%		458	Deg. F
50%		484	Deg. F
60%		510	Deg. F
70%		538	Deg. F
80%		568	Deg. F
85%		585	Deg. F
90%		605	Deg. F
95%		632	Deg. F
End Point		654	Deg. F
Recovery		97.9	% vol.
Cetane Index ASTM D976	0976-1.3	48.0	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	37.8	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		27.9	% vol
Olefins		2.1	% vol
Saturates		70.0	% vol
Sulfur by Microcoulometry ASTM D3120	3120-3.1	6	mg/kg

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04/12/12

Client Code : LOVEMC Sample Date : 03/29/12 P.O. Number : JK120015
Herguth ID : LABV7008264
Description : Sample ID: FY09-111-29MAR2012, Chevron #2 Clear Diesel Fuel
Label States: Total Engine Hours: 3312

Test Performed	Proc-Rev	Result

Result(s) meet the specifications of ASTM D975 for S15 No. 2 Diesel Fuel for the test(s) performed.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Tom Holmes

Bobby R Licu, Senior Evaluator

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06/15/12

Page 1

Client Code : LOVEMC Sample Date : 05/29/12 P.O. Number : JK120015
Herguth ID : LABV7008917
Description : Sample ID: FY09-111-29MAY2012, Chevron #2 Clear Diesel Fuel
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		758	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		348	Deg. F
5%		386	Deg. F
10%		402	Deg. F
15%		414	Deg. F
20%		425	Deg. F
30%		447	Deg. F
40%		467	Deg. F
50%		486	Deg. F
60%		507	Deg. F
70%		528	Deg. F
80%		553	Deg. F
85%		567	Deg. F
90%		585	Deg. F
95%		610	Deg. F
End Point		633	Deg. F
Recovery		98.3	% vol.
Cetane Index ASTM D976	0976-1.3	52.5	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	40.0	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		21.2	% vol
Olefins		4.8	% vol
Saturates		74.0	% vol
Sulfur by Microcoulometry ASTM D3120	3120-3.1	6	mg/kg

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Albuquerque NM 87108

06/15/12

Page 2

Client Code : LOVEMC Sample Date : 05/29/12 P.O. Number : JK120015
Herguth ID : LABV7008917
Description : Sample ID: FY09-111-29MAY2012, Chevron #2 Clear Diesel Fuel

Test Performed	Proc-Rev	Result

Result(s) meet the specifications of ASTM D975 for No. 2 Diesel Fuel for the test(s) performed.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

Mindy L. Villalba, Project Manager

cc: Tom Holmes

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08/23/12

Page 1

Client Code : LOVEMC Sample Date : 08/02/12 P.O. Number : JK120015
Herguth ID : LABV7010055
Description : Sample ID: FY09-111-02Aug2012, Chevron #2 Clear Diesel Fuel
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		758	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		332	Deg. F
5%		377	Deg. F
10%		390	Deg. F
15%		405	Deg. F
20%		417	Deg. F
30%		440	Deg. F
40%		466	Deg. F
50%		490	Deg. F
60%		518	Deg. F
70%		549	Deg. F
80%		584	Deg. F
85%		606	Deg. F
90%		632	Deg. F
95%		670	Deg. F
End Point		685	Deg. F
Recovery		97.4	% vol.
Cetane Index ASTM D976	0976-1.3	48.0	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	37.1	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		30.0	% vol
Olefins		2.3	% vol
Saturates		67.7	% vol
Sulfur by Microcoulometry ASTM D3120	3120-3.1	7	mg/kg

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08/23/12

Page 2

Client Code : LOVEMC Sample Date : 08/02/12 P.O. Number : JK120015
Herguth ID : LABV7010055
Description : Sample ID: FY09-111-02Aug2012, Chevron #2 Clear Diesel Fuel

Test Performed	Proc-Rev	Result

Result(s) meet the specifications of ASTM D975 for S15 No. 2 Diesel Fuel for the test(s) performed.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Tom Holmes

Bobby R Licu, Senior Evaluator

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10/11/12

Page 1

Client Code : LOVEMC Sample Date : 09/25/12 P.O. Number : JK120015
Herguth ID : LABV7010749
Description : Sample ID: FY09-111-25Sep2012, Chevron #2 Clear Diesel Fuel
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001) UnitTime : 1262

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		757	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		357	Deg. F
5%		394	Deg. F
10%		408	Deg. F
15%		422	Deg. F
20%		434	Deg. F
30%		458	Deg. F
40%		479	Deg. F
50%		499	Deg. F
60%		520	Deg. F
70%		541	Deg. F
80%		568	Deg. F
85%		583	Deg. F
90%		602	Deg. F
95%		629	Deg. F
End Point		648	Deg. F
Recovery		98.1	% vol.
Cetane Index ASTM D976	0976-1.3	53.5	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	39.7	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		20.8	% vol
Olefins		3.1	% vol
Saturates		76.1	% vol
Sulfur by Microcoulometry ASTM D3120	3120-3.1	5	mg/kg

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10/11/12

Page 2

Client Code : LOVEMC Sample Date : 09/25/12 P.O. Number : JK120015
Herguth ID : LABV7010749
Description : Sample ID: FY09-111-25Sep2012, Chevron #2 Clear Diesel Fuel

Test Performed	Proc-Rev	Result

Result(s) meet the specifications of ASTM D975 for S15 No. 2 Diesel Fuel for the test(s) performed.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Tom Holmes

Bobby R Licu, Senior Evaluator

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01598 Folio 09/025

LOADING ORDER – TRUCK BILL OF LADING AND MANIFEST

NuStar Logistics, L.P.

THIS IS TO CERTIFY THAT THE BELOW NAMED MATERIALS ARE PROPERLY CLASSIFIED, DESCRIBED, PACKAGED, MARKED AND LABELED, AND ARE IN PROPER CONDITION FOR TRANSPORTATION, ACCORDING TO APPLICABLE REGULATIONS OF THE DEPARTMENT OF TRANSPORTATION.

SHIPPER CERTIFIES THAT THE GOODS COVERED BY THIS MANIFEST WERE PRODUCED IN COMPLIANCE WITH ALL REQUIREMENTS OF THE FAIR LABOR STANDARDS ACT, AS AMENDED.

IF SHIPMENT INCLUDES UNLEADED GASOLINE THE PRODUCT CONTAINS NO MORE THAN 0.05 GRAMS OF LEAD PER GALLON AND NO MORE THAN 0.005 GRAMS OF PHOSPHOROUS PER GALLON CONFORMING TO E.P.A. REGULATIONS - 40 CFR 80

THIS GASOLINE IS CERTIFIED TO HAVE A VAPOR PRESSURE OF NO MORE THAN STATED BELOW.

RECEIVED SUBJECT TO TARRIFFS OR CONTRACT IN EFFECT THIS DATE.

THE CARRIER CERTIFIES THAT THE CARGO TANK SUPPLIED FOR THIS SHIPMENT IS A PROPER CONTAINER FOR THE TRANSPORTATION OF THIS COMMODITY AS DESCRIBED BY THE SHIPPER.

ALBUQUERQUE, NM
6348 State Road 303
Albuquerque, NM 87105
Phone (505) 877-9210
Fax (505) 877-0680

FOR CHEMICAL EMERGENCY – SPILL, LEAK, FIRE, EXPOSURE OR ACCIDENT CALL CHEMTREC 800-424-9300 DAY OR NIGHT. NUSTAR CHEMTREC CRM # 00675631

THE DRIVER BY SIGNING THIS TICKET HEREBY CERTIFIES THAT TRANSPORT WAS LOADED AS SPECIFIED.

SIGN HERE 9-25-12 DATE

MATERIAL SAFETY DATA SHEET AVAILABLE ON REQUEST.
ORDER #
CUST ORDER #

BILL TO	SHIP TO
KENDRICK OIL CO. INC P.O. BOX 788 FRIONA, TX 79035 8062503991 Lovelace Health Effects	KENDRICK OIL CO NM CONT 554967 , NM

SHIP FROM ADDRESS	DATE SHIPPED	CUSTOMER/ACCOUNT NO	MANIFEST NO.	MANIFEST DATE
ALBUQUERQUE, NM Albuquerque, NM 87105	09/25/12	0124292 /0554967	0084755	09/25/12

FREIGHT TERMS PPD.	FREIGHT TERMS COLL	F.O.B.	SHIPPER	CUST ORDER NO.	FACILITY	LFCL NUMBER
X			VALERO MARKETING & SUPPLY			0000000

DRIVER NAME	SHIP VIA - CARRIER ID / NAME	TRUCK NO. LIC NO.	TRAILER NO. LIC NO.	LOADING START/STOP	LOAD POS.
ZAPATA, JOSEPH	HONSTEIN OIL COMPANY		2477	0632/0642	01

DIESEL FUEL, 3, NA1993, PGIII COMBUSTIBLE

1 Cargo Tank
Gross Gallons 4000

	OCTANE	GROSS	TEMP	GRAV	NET	MAX RVP
ULSD	.0	4000	70	40.1	3982	.0
ULSD		4000				

#2DMV15, #2ULSD, 15ppm SULFUR MAX. FOR USE IN ALL DIESEL VEHICLES AND ENGINES EPA FAC. 4010-81464 NOT TxLED COMPLIANT. FUTHER PROCESSING REQUIRED IF USED IN COUNTIES THAT REQUIRE TxLED.

B = 16 1/4"
A = 75"

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Certificate of Analysis
Lab Number V7011835

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE
Albuquerque NM 87108

12/05/12

Page 1

Client Code : LOVEMC Sample Date : 11/27/12 P.O. Number : JK120015
Herguth ID : LABV7011835
Description : FY09-111-14NOV2012-Fuel, Chevron #2 Clear Diesel Fuel
Oil Type : Diesel Fuel (GN_130)
Unit Type : Diesel Fuel (GN_DF001)

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		763	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		335	Deg. F
5%		378	Deg. F
10%		395	Deg. F
15%		408	Deg. F
20%		421	Deg. F
30%		445	Deg. F
40%		469	Deg. F
50%		491	Deg. F
60%		513	Deg. F
70%		537	Deg. F
80%		564	Deg. F
85%		581	Deg. F
90%		601	Deg. F
95%		631	Deg. F
End Point		654	Deg. F
Recovery		98.4	% vol.
Cetane Index ASTM D976	0976-1.3	51.0	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	38.9	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		45.9	% vol
Olefins		10.0	% vol
Saturates		44.1	% vol
Sulfur by Microcoulometry ASTM D3120	3120-3.1	3	mg/kg

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Certificate of Analysis
Lab Number V7011835

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE
Albuquerque NM 87108

12/05/12

Page 2

Client Code : LOVEMC Sample Date : 11/27/12 P.O. Number : JK120015
Herguth ID : LABV7011835
Description : FY09-111-14NOV2012-Fuel, Chevron #2 Clear Diesel Fuel

Test Performed	Proc-Rev	Result

Result(s) meet the specifications of ASTM D975 for S15 No. 2 Diesel Fuel for the test(s) performed. Noting, Aromatic level exceeds the maximum of 35 % vol. and Cetane Index is > 40.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Tom Holmes

Bobby R Licu, Senior Evaluator

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Certificate of Analysis

Lab Number V7011835A

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE
Albuquerque NM 87108

12/19/12

Page 1

Client Code : LOVEMC Sample Date : 11/27/12 P.O. Number : JK120015
Herguth ID : LABV7011835
Description : FY09-111-14NOV2012-Fuel, Chevron #2 Clear Diesel Fuel
Oil Type : Diesel Fuel (GN_130)

Test Performed	Proc-Rev	Result	
Distillation of Petroleum ASTM D86	0086-2.6		
Observed Barometric Pressure		763	mm Hg
All results are corrected to 760 mm Hg			
Initial Boiling Point		335	Deg. F
5%		378	Deg. F
10%		395	Deg. F
15%		408	Deg. F
20%		421	Deg. F
30%		445	Deg. F
40%		469	Deg. F
50%		491	Deg. F
60%		513	Deg. F
70%		537	Deg. F
80%		564	Deg. F
85%		581	Deg. F
90%		601	Deg. F
95%		631	Deg. F
End Point		654	Deg. F
Recovery		98.4	% vol.
Cetane Index ASTM D976	0976-1.3	51.0	
API Gravity @ 60 Deg F ASTM D287	0287-2.1	38.9	Deg. API
Hydrocarbon Types by FIA ASTM D1319	1319-1.0		
Aromatics		24.5	% vol
Olefins		2.9	% vol
Saturates		72.6	% vol
Sulfur by Microcoulometry ASTM D3120	3120-3.1	3	mg/kg

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Certificate of Analysis
Lab Number V7011835A

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE
Albuquerque NM 87108

12/19/12

Page 2

Client Code : LOVEMC Sample Date : 11/27/12 P.O. Number : JK120015
Herguth ID : LABV7011835
Description : FY09-111-14NOV2012-Fuel, Chevron #2 Clear Diesel Fuel

Test Performed	Proc-Rev	Result

REVISED REPORT supersedes lab # V7011835 and includes updated D1319 results.
Result(s) meet the specifications of ASTM D975 for S15 No. 2 Diesel Fuel for the test(s) performed.
Hydrocarbon Types by FIA was subbed out.

Respectfully Submitted,
Herguth Laboratories, Inc.

cc: Tom Holmes

Bobby R Licu, Senior Evaluator

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Appendix B.

Oil Analysis

Attachment 4

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Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE
Albuquerque, NM 87108
Phone: (505) 348-9600

Email: tholmes@lrri.org
Fax: (505) 348-4980

Quotation No. 204505 (LOVEMC)
Quotation Date: July 29, 2010

QUOTATION

Item	Qty	Description/Analysis	Methodology	Fee	Extend
1	***1***	***Diesel Engine Oils***		***21.63***	***21.63***
		Volume of sample required: 100 ml			
		Viscosity Measurements (SBD1)	ASTM D445		
		Neutralization Number (SBD1)	HL-1118		
		FTIR Nicolet (SBD1)	HL-1140		
		Metals by ICP AES (SBD1)	HL-1158		
		Turnaround time is 2 working day(s) from receipt of sample.			
			QUOTATION TOTAL		21.63 ea

Thank you for the opportunity to provide you with the above quotation for your samples. The above quotation is based on your requested scope of work and/or our recommended analytical methods for your sample type and package pricing. Tests selected on a one-on-one basis and not tested as a package may be subject to price adjustments. Prices are also subject to change based on the actual sample type as determined upon receipt. Reference oils are required for baseline information.

Our standard turn around time is two (2) working days. Rush analysis is triple for a 24 hour turn around time. Any analysis that is subcontracted to another facility (lab) will be processed within 7-10 working days depending on the test. Samples received in larger batches may have a longer turn around time depending on sample type and tests requested. This quotation is valid for 90 days. Please refer to this quotation number when submitting samples.

Sampling kits will be included in this program. Kits include a bottle, label, ID Form, and mailer. Sampling pumps and tubing will be charged at list price. Postage paid labels are also available for an additional fee. Please visit our website to view a current list of supplies

Reports can be transmitted via email upon completion at no additional charge. We also have Internet access-iLAMP available for an additional $300/ year that will allow you to retrieve your data, view and print reports, set up units and route list, print labels, etc. Please contact Customer Service to order iLAMP.

A credit application or payment is required with all new accounts. Please fax one to 707-554-0109. Credit will be extended based on the reference verification. The sample turn around time may be longer based on credit reference responses.

Laboratory Pricing Policy

1. Hours of Operation And Normal Availability

Regular laboratory hours are 8:00 AM to 5:00 PM Monday through Friday. For condition monitoring analyses, our normal turnaround is 48 hours (two working days). For all other analyses, our normal turnaround is 96 hours (four working days). Any analysis that is subcontracted to another facility

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(lab) will be processed within 7-10 working days depending on the test. Please note there may be delays in turn around times based on account setup and credit references.

2. Minimum Invoice Charges, Rush Analyses and Overtime Rates

A minimum fee of $25.00 may be charged for any analysis invoice. For Condition Monitoring analyses, "RUSH" samples results are available within 24 hours (or less) and are charged at three times the normal analyses rate. For other analyses there are two "RUSH" provisions for work performed during our regular laboratory hours:

a) 48 hour (2 working day) analysis time is charged at twice the normal analysis fee.

b) 24 hour (one working day) turnaround, or less, is charged at three times the normal analysis fee.

There are some analyses that cannot be completed in less than 24 hours; however, they can be moved ahead of the scheduled samples waiting for that analysis. These analyses will be charged at the 24 hour rush rate. Laboratory work performed during other hours, including Saturday, Sunday or recognized Holidays may be charged at triple our normal analyses rates, an hourly rate with a four (4) hour minimum charge, or $1,500, whichever is greater. Nuclear Quality Assured (10 CFR 50 Appendix B) or radioactive samples analyzed during periods other than normal hours will be charged a minimum of $2,500.

3. Quality Assurance Program And Surveillance

Analyses performed under the Safety Related Part 21 Program are charged at 1.35 times the applicable fee. Surveillance of work performed at Herguth Laboratories, Inc. by client representatives may be charged at three times the applicable fee. All ASTM methods are performed at the latest published revision.

4. Radioactive Materials

Analyses on radioactive samples will be assessed a surcharge of 1.5 times the analysis fee or a fee of $125 per sample (Condition Monitoring Rads), as specifically quoted to the customer. Radioactive lubricant samples are properly disposed of by Herguth provided the sample meets our disposal criteria. This service is not applicable for non-liquid lubricant samples, which must be returned to the client.

5. Sample Pick-Up And Delivery

Sample pick-up and delivery during normal working hours may be charged at a minimum of $25 within a 25 mile radius. The fee will be $50 within a radius of 50 miles. Sample pick-up during non-working hours may be charged a minimum of $100 plus expenses. This applies to the nine (9) San Francisco Bay Area counties. Special arrangements must be made for custody transfers and pick-ups outside of this area.

6. Sample Retention and Disposal

Samples will be held for a minimum of 30 days. Long term retention services are available by special request. Non-hydrocarbon samples, "unknown" samples, and samples containing elements or constituents which cannot be accommodated by our normal waste streams will either be returned, or if requested, disposed of properly. Handling and disposal surcharges may be assessed. Samples can be returned to the client if requested.

Terms, Conditions, and Limitations

All services rendered by Herguth Laboratories, Inc. are undertaken, and all rates are based upon the following terms:

(a) Neither Herguth Laboratories, Inc., nor any of its employees, agents or sub-contractors shall be liable for any loss or damage arising out of Herguth Laboratories, Inc.'s. performance or non-performance, whether by way of negligence or breach of contract, or otherwise, in any amount greater than twice the amount billed to the customer for the work leading to the claim of the customer. Said remedy shall be the sole and exclusive remedy against Herguth Laboratories, Inc. arising out of its work.

Attachment 4

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(b) All claims must be in writing within forty-five (45) days after delivery of the Herguth Laboratories, Inc. report regarding said work, or such claim shall be deemed as irrevocably waived.

(c) Herguth Laboratories, Inc. reports are submitted in writing and are for our customers only. Our customers are considered to be only those entities being billed for our services. Acquisition of a Herguth Laboratories, Inc. report by other than our customer does not constitute a representation of Herguth Laboratories, Inc. as to the accuracy of the contents thereof.

(d) In no event shall Herguth Laboratories, Inc., its employees, agents or sub-contractors be responsible for consequential or special damages of any kind or in any amount.

(e) No deviation from the terms set forth herein shall bind Herguth Laboratories, Inc. unless explicitly agreed upon and accepted contractually, or unless explicitly expressed in writing and signed by a Corporate Officer of Herguth Laboratories, Inc.

(f) Depending on specific customer requirements and/or changes in operations, Herguth Laboratories, Inc. reserves the right to change the pricing and availability of analyses as published in price list(s).

(g) All ASTM methods are performed at the latest published revision.

Should you have any questions regarding this quote, please contact myself at 800-645-5227 ext. 3012. We look forward to working with you on this and future projects. Please refer to this quotation number when submitting samples.

Please visit our website for additional services and capabilities www.herguth.com.

Linda J. Perry

_____

Linda Perry
Sales & Marketing

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NORMAL

Normal
MACHINE CONDITION
FLUID CONDITION

Lab Number : V1056619

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-28 - Lubrizol Motor Oil O5222049B, Diesel Engine Page 1
Acct/Org/Project: JLMEPR 08/12/10
Unit Type : Engine, Diesel (GN_DE001) 14:09:28
Oil Type : SAE 40 (GN_032) P.O. : JK101657
Sampled : 07/28/10 Shipped : 08/09/10 Received: 08/10/10 Printed: 08/12/10

NORMAL: Sample data is satisfactory. No action is required at this time.
Please provide equipment make and model. Additional sample is needed to help establish trend. Resample at half normal interval. Please send a new fluid reference sample for analysis. Mark the sample 'REFERENCE' and indicate the FULL NAME and GRADE of the lubricant.

Attachment 4

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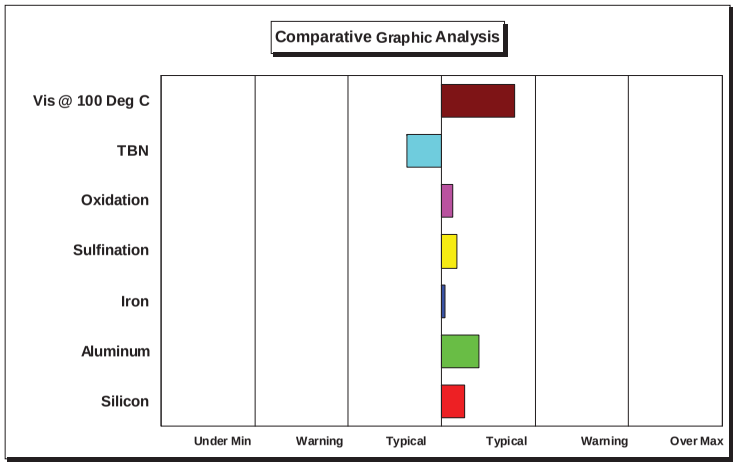
* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number Sample Date	Minimum	Maximum	V1056619 07/28/10
Unit Time ()			0
Oil Time ()			0
Vis @ 100 Deg C	12.00	16.80	15.88
TBN mg KOH/g	2.00		8.09
FTIR			
Soot % wt.		3.0	<0.1
Oxidation Abs/cm		30	3
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	4
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		75	2
Aluminum ppm		7	2
Chromium ppm		4	<1
Copper ppm		32	<1
Lead ppm		8	<1
Tin ppm		4	<1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			1
Silicon ppm		20	3
Sodium ppm			2
Boron ppm			<1
Zinc ppm			1365
Phosphorus ppm			1224
Calcium ppm			2579
Magnesium ppm			7
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm			<3

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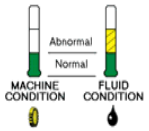
ABNORMAL



Lab Number : V1061066

ID: KU09-111-19AUG10 - KU09-111-19AUG10, Diesel Engine	Page 1
	08/28/10
Unit Type : Engine, Diesel (GN_DE001)	09:30:02
Oil Type : SAE 40 (GN_032) P.O. : KU09-111	
Sampled : 08/19/10 Shipped : 08/24/10 Received: 08/25/10 Printed: 08/28/10	

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. Please provide equipment make and model as well as the full name and grade of the lubricant in service. Drain oil and change filter(s). Check for proper combustion properties (exhaust back pressure, operating temperatures, worn/broken rings, excessive idling, hung valves, improper fuel settings, air intake restrictions). Resample at half normal interval.

Attachment 4

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

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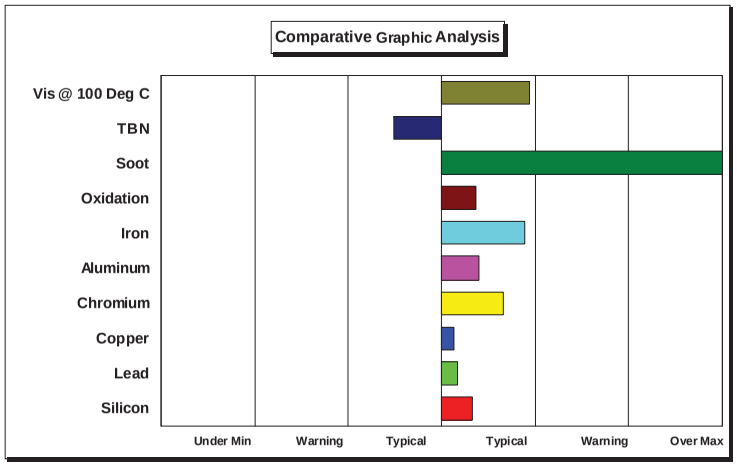

Lab Number Sample Date	Minimum	Maximum	V1061066 08/19/10
Unit Time (HR)			3367
Oil Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	16.18
TBN mg KOH/g	2.00		5.81
FTIR			
Soot % wt.		3.0	**4.0
Oxidation Abs/cm		30	9
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	<2
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		76	54
Aluminum ppm		7	2
Chromium ppm		4	2
Copper ppm		32	3
Lead ppm		8	1
Tin ppm		4	<1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	4
Sodium ppm			2
Boron ppm			2
Zinc ppm			1189
Phosphorus ppm			1075
Calcium ppm			2431
Magnesium ppm			6
Barium ppm			<1
Molybdenum ppm			2
Potassium ppm			<3

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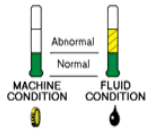
ABNORMAL



ID: FY09-111-09SEPT10 - FY09-111-09SEPT10, Diesel Engine

09/20/10

18:24:43

Unit Type : Engine, Diesel (GN_DE001)

Oil Type : Appears to be SAE 40 P.O. : SG100350

Sampled : 09/09/10 Shipped : 09/12/10 Received: 09/13/10 Printed: 09/20/10

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. Please provide equipment make and model as well as the full name and grade of the lubricant in service. Drain oil and change filter(s). Check for proper combustion properties (exhaust back pressure, operating temperatures, worn/broken rings, excessive idling, hung valves, improper fuel settings, air intake restrictions). Resample at half normal interval.

Attachment 4

Lab Number : V1066282

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

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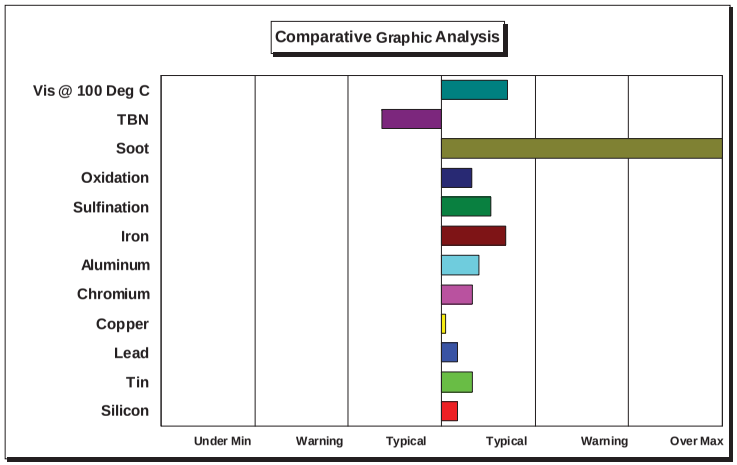

Lab Number Sample Date	Minimum	Maximum	V1066282 09/09/10
Unit Time (HR)			3617
Oil Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.73
TBN mg KOH/g	2.00		4.68
FTIR			
Soot % wt.		3.0	**3.7
Oxidation Abs/cm		30	8
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	13
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		76	42
Aluminum ppm		7	2
Chromium ppm		4	1
Copper ppm		32	1
Lead ppm		8	1
Tin ppm		4	1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			1
Silicon ppm		20	2
Sodium ppm			4
Boron ppm			<1
Zinc ppm			1041
Phosphorus ppm			928
Calcium ppm			2011
Magnesium ppm			5
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm			<3

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ABNORMAL

Abnormal / Normal
MACHINE CONDITION FLUID CONDITION

Lab Number : V1072491

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-30SEP10-OIL - FY09-111-30SEP10-OIL, Diesel Engine

12/07/10
08:51:20

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : FY09-111 ACES
Sampled : 09/30/10 Shipped : 10/06/10 Received: 10/07/10 Printed: 10/11/10

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. Other test results are acceptable. Drain oil and change filter(s). Additional sample is needed to help establish trend. Resample at half normal interval. Please provide equipment make and model as well as the full name and grade of the lubricant in service.

Attachment 4

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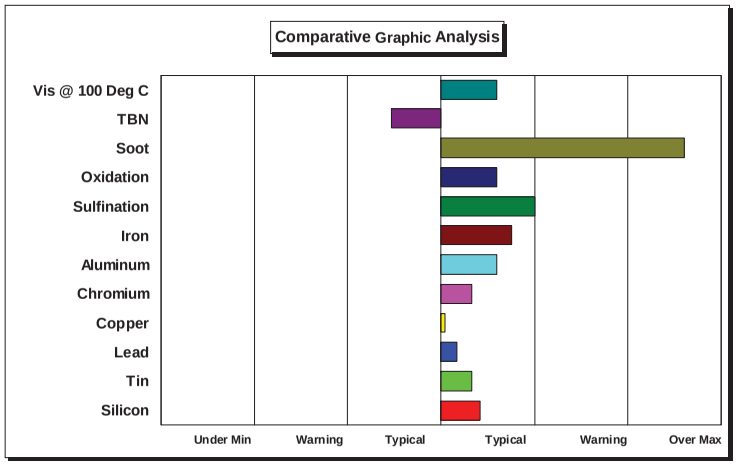
* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number Sample Date	Minimum	Maximum	V1072491 09/30/10
Unit Time (HR)			5063
Oil Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.53
TBN mg KOH/g	2.00		5.62
FTIR			
Soot % wt.		3.0	**3.3
Oxidation Abs/cm		30	15
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	25
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		76	46
Aluminum ppm		7	3
Chromium ppm		4	1
Copper ppm		32	1
Lead ppm		8	1
Tin ppm		4	1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	5
Sodium ppm			3
Boron ppm			3
Zinc ppm			1325
Phosphorus ppm			1060
Calcium ppm			2567
Magnesium ppm			8
Barium ppm			<1
Molybdenum ppm			3
Potassium ppm			<3

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ABNORMAL

Abnormal / Normal
MACHINE CONDITION | FLUID CONDITION

Lab Number : V1077577

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-25OCT10-OIL - FY09-111-25OCT10-OIL, Diesel Engine

11/01/10
16:10:19

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : FY09-111 ACES
Sampled : 10/25/10 Shipped : 10/25/10 Received: 10/28/10 Printed: 11/01/10

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. Please provide equipment make and model as well as the full name and grade of the lubricant in service. Drain oil and change filter(s). Check for proper combustion properties (exhaust back pressure, operating temperatures, worn/broken rings, excessive idling, hung valves, improper fuel settings, air intake restrictions). Resample at half normal interval.

Attachment 4

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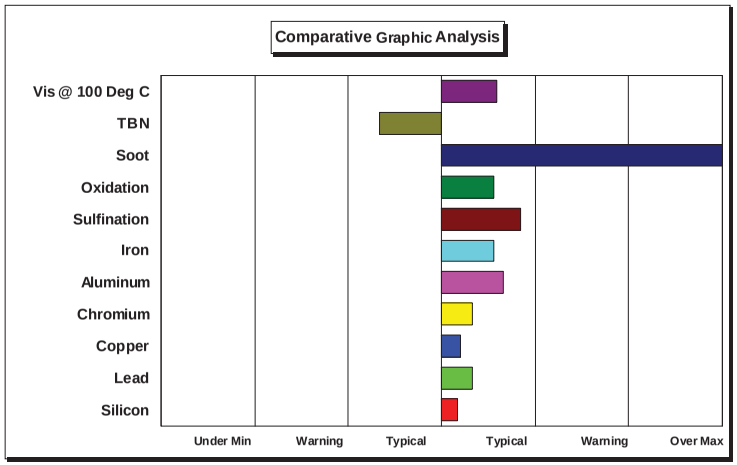
* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number Sample Date	Minimum	Maximum	V1077577 10/25/10
Unit Time (HR)			4136
Oil Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.51
TBN mg KOH/g	2.00		4.56
FTIR			
Soot % wt.		3.0	**3.5
Oxidation Abs/cm		30	14
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	21
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		74	33
Aluminum ppm		4	2
Chromium ppm		4	1
Copper ppm		7	1
Lead ppm		4	1
Tin ppm		4	<1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	2
Sodium ppm			<2
Boron ppm			1
Zinc ppm			919
Phosphorus ppm			815
Calcium ppm			1826
Magnesium ppm			5
Barium ppm			<1
Molybdenum ppm			1
Potassium ppm			<3

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ABNORMAL

Abnormal / Normal
MACHINE CONDITION FLUID CONDITION

Lab Number : V1084887

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-15NOV10-E - FY09-111-15NOV10, Diesel Engine

12/06/10
18:22:03

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 15W-40 (GN_045) P.O. : FY09-111 ACES
Sampled : 11/15/10 Shipped : 12/01/10 Received: 12/02/10 Printed: 12/06/10

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. Levels may be due to oil service time (not provided). Drain oil and change filter(s). Additional sample is needed to help establish trend. Resample at half normal interval. Please provide equipment make and model as well as the full name and grade of the lubricant in service.

Attachment 4

ISO 9001:2008 and ISO/IEC 17025:2005 Certified

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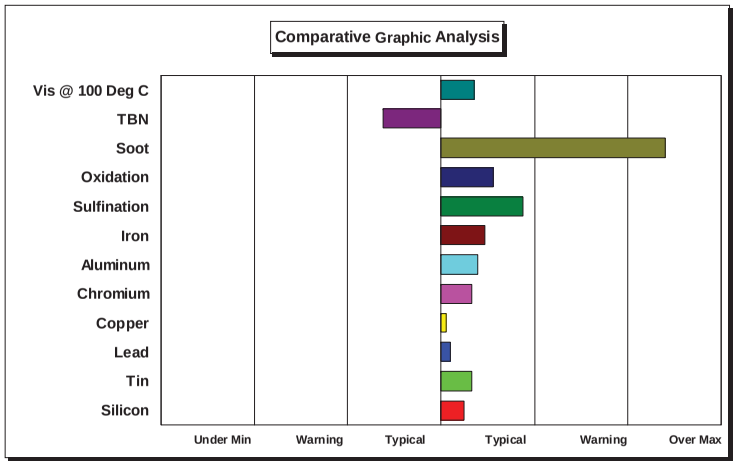

Lab Number / Sample Date	Minimum	Maximum	V1084887 11/15/10
Unit Time (HR)			0
Oil Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.07
TBN mg KOH/g	2.00		4.83
FTIR			
Soot % wt.		3.0	**3.2
Oxidation Abs/cm		30	14
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	22
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		93	35
Aluminum ppm		7	2
Chromium ppm		4	1
Copper ppm		26	1
Lead ppm		15	1
Tin ppm		4	1
Nickel ppm		4	<1
Silver ppm		3.1	<0.1
Antimony ppm			<1
Silicon ppm		20	3
Sodium ppm			<2
Boron ppm			3
Zinc ppm			940
Phosphorus ppm			962
Calcium ppm			2092
Magnesium ppm			8
Barium ppm			<1
Molybdenum ppm			1
Potassium ppm			<3

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ABNORMAL

Abnormal / Normal
MACHINE CONDITION FLUID CONDITION

Lab Number : V1086580

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-10DEC10-OIL - FY09-111--10DEC10-Diesel Engine

12/16/10
17:33:16

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : FY09-111 ACES
Sampled : 12/06/10 Shipped : 12/13/10 Received: 12/14/10 Printed: 12/16/10

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. Please provide equipment make and model as well as the full name and grade of the lubricant in service. Drain oil and change filter(s). Check for proper combustion properties. Additional sample is needed to help establish trend. Resample at half normal interval.

Attachment 4

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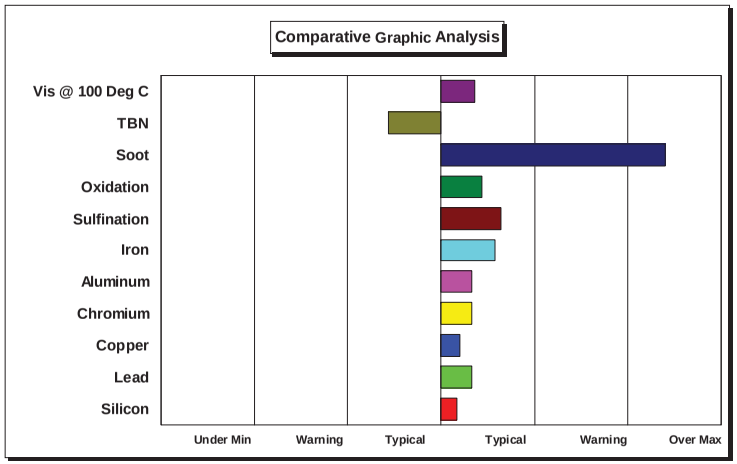

Lab Number Sample Date	Minimum	Maximum	V1086580 12/06/10
Unit Time (HR)			4627
Oil Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.09
TBN mg KOH/g	2.00		5.32
FTIR			
Soot % wt.		3.0	**3.2
Oxidation Abs/cm		30	11
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	16
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		66	34
Aluminum ppm		4	1
Chromium ppm		4	1
Copper ppm		7	1
Lead ppm		4	1
Tin ppm		4	<1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	2
Sodium ppm			<2
Boron ppm			<1
Zinc ppm			920
Phosphorus ppm			865
Calcium ppm			2016
Magnesium ppm			10
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm			<3

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ABNORMAL

Abnormal / Normal
MACHINE CONDITION FLUID CONDITION

Lab Number : V1089771

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-03JAN11-OIL - FY09-111-03JAN11-OIL, Diesel Engine

01/10/11
15:52:38

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : JK110737
Sampled : 01/03/11 Shipped : 01/05/11 Received: 01/06/11 Printed: 01/10/11

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. Levels may be due to oil service time (not provided). Drain oil and change filter(s). Additional sample is needed to help establish trend. Resample at half normal interval. Please provide equipment make and model as well as the full name and grade of the lubricant in service.

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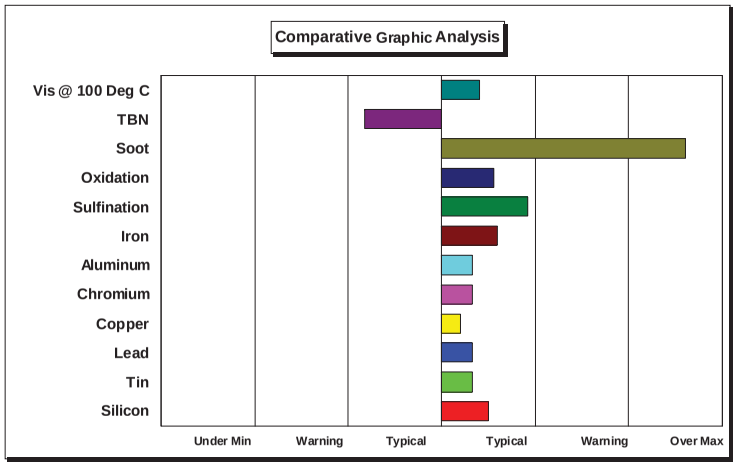

Lab Number / Sample Date	Minimum	Maximum	V1089771 01/03/11
Unit Time (HR)			4877
Oil Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.17
TBN mg KOH/g	2.00		3.63
FTIR			
Soot % wt.		3.0	**3.3
Oxidation Abs/cm		30	14
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	23
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		65	34
Aluminum ppm		4	1
Chromium ppm		4	1
Copper ppm		7	1
Lead ppm		4	1
Tin ppm		4	1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	6
Sodium ppm			10
Boron ppm			<1
Zinc ppm			1100
Phosphorus ppm			871
Calcium ppm			2117
Magnesium ppm			6
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm			<3

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ABNORMAL

Abnormal / Normal
MACHINE CONDITION FLUID CONDITION

Lab Number : V1093635

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-24JAN11-OIL - FY09-111-24JAN11-OIL, Diesel Engine

02/02/11
14:13:01

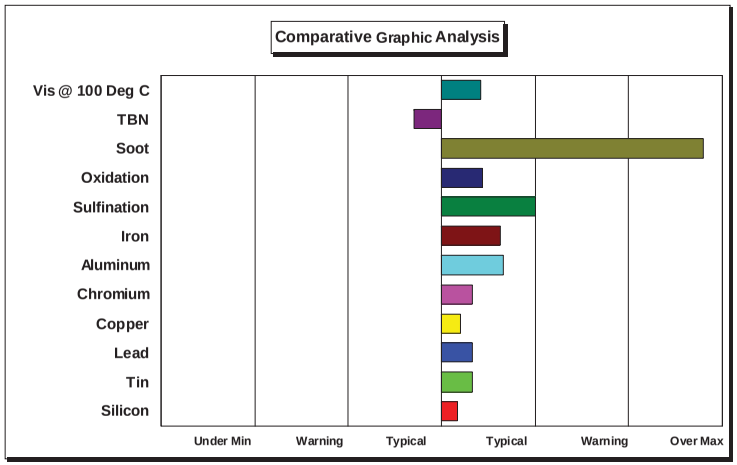
Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : JK110737
Sampled : 01/24/11 Shipped : 01/27/11 Received: 01/28/11 Printed: 02/02/11

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. Please provide equipment make and model as well as the full name and grade of the lubricant in service. Drain oil and change filter(s). Check for proper combustion properties (exhaust back pressure, operating temperatures, worn/broken rings, excessive idling, hung valves, improper fuel settings, air intake restrictions). Resample at half normal interval.

Attachment 4

ISO 9001:2008 and ISO/IEC 17025:2005 Certified

* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number / Sample Date	Minimum	Maximum	V1093635 01/24/11
Unit Time (HR)			5146
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.19
TBN mg KOH/g	2.00		10.10
FTIR			
Soot % wt.		3.0	**3.4
Oxidation Abs/cm		30	11
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	25
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		64	35
Aluminum ppm		4	2
Chromium ppm		4	1
Copper ppm		7	1
Lead ppm		4	1
Tin ppm		4	1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			1
Silicon ppm		20	2
Sodium ppm			3
Boron ppm			<1
Zinc ppm			983
Phosphorus ppm			812
Calcium ppm			2017
Magnesium ppm			6
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm			<3

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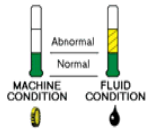
ABNORMAL



Lab Number : V1099127

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-22FEB11-OIL - FY09-111-22FEB11-OIL, Diesel Engine Page 1
03/01/11
Unit Type : Engine, Diesel (GN_DE001) 15:28:59
Oil Type : SAE 15W-40 (GN_045) P.O. : JK110737
Sampled : 02/22/11 Shipped : 02/24/11 Received: 02/25/11 Printed: 03/01/11

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. Other test results are acceptable. Drain oil and change filter(s). Additional sample is needed to help establish trend. Resample at half normal interval. Please provide equipment make and model as well as the full name and grade of the lubricant in service.

Attachment 4

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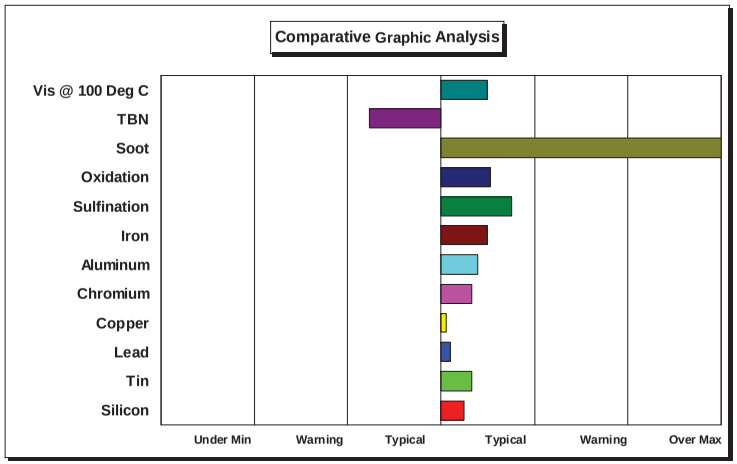

Lab Number Sample Date	Minimum	Maximum	V1099127 02/22/11
Unit Time (HR)			5437
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.34
TBN mg KOH/g	2.00		3.92
FTIR			
Soot % wt.		3.0	**3.8
Oxidation Abs/cm		30	13
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	19
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		89	35
Aluminum ppm		7	2
Chromium ppm		4	1
Copper ppm		24	1
Lead ppm		15	1
Tin ppm		4	1
Nickel ppm		4	<1
Silver ppm		3.1	<0.1
Antimony ppm			<1
Silicon ppm		20	3
Sodium ppm			5
Boron ppm			<1
Zinc ppm			1010
Phosphorus ppm			902
Calcium ppm			1723
Magnesium ppm			7
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm			<3

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ABNORMAL

Abnormal / Normal
MACHINE CONDITION FLUID CONDITION

Lab Number : V1102645

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-14MAR11-OIL - FY09-111-14MAR11-OIL, Diesel Engine

03/21/11
13:31:46

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : JK110737
Sampled : 03/14/11 Shipped : 03/16/11 Received: 03/17/11 Printed: 03/21/11

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. Please provide equipment make and model as well as the full name and grade of the lubricant in service. Drain oil and change filter(s). Check for proper combustion properties (exhaust back pressure, operating temperatures, worn/broken rings, excessive idling, hung valves, improper fuel settings, air intake restrictions). Resample at half normal interval.

Attachment 4

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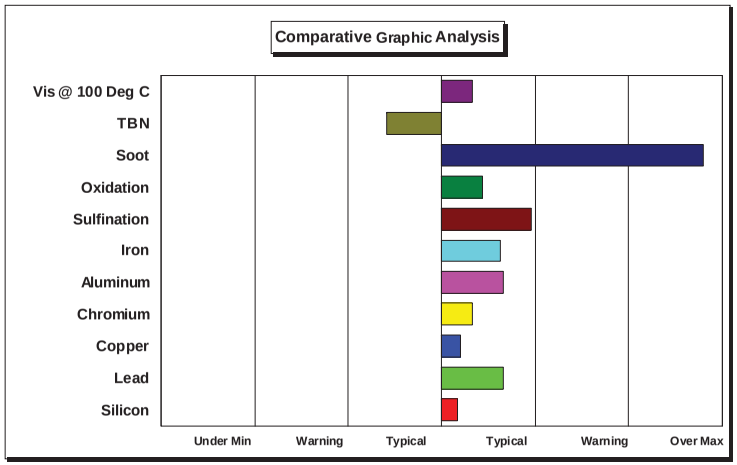

Lab Number / Sample Date	Minimum	Maximum	V1102645 03/14/11
Unit Time (HR)			5693
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.02
TBN mg KOH/g	2.00		5.07
FTIR			
Soot % wt.		3.0	**3.4
Oxidation Abs/cm		30	11
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	24
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		62	34
Aluminum ppm		4	2
Chromium ppm		4	1
Copper ppm		7	1
Lead ppm		4	2
Tin ppm		4	<1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	2
Sodium ppm			2
Boron ppm			<1
Zinc ppm			1064
Phosphorus ppm			931
Calcium ppm			2182
Magnesium ppm			5
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm			<3

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ABNORMAL

Abnormal / Normal
MACHINE CONDITION FLUID CONDITION

Lab Number : V1106274

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-05APR11-OIL - FY09-111-05APR11-OIL, Diesel Engine

04/12/11
17:41:32

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : JK110737
Sampled : 04/01/11 Shipped : 04/07/11 Received: 04/08/11 Printed: 04/12/11

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. Other test results are acceptable. Drain oil and change filter(s). Additional sample is needed to help establish trend. Resample at half normal interval. Please provide equipment make and model as well as the full name and grade of the lubricant in service.

Attachment 4

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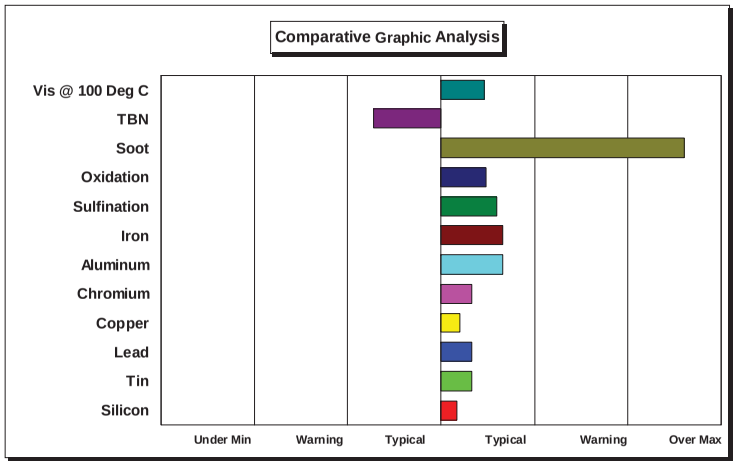
* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number Sample Date	Minimum	Maximum	V1106274 04/01/11
Unit Time (HR)			5950
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.28
TBN mg KOH/g	2.00		4.15
FTIR			
Soot % wt.		3.0	**3.3
Oxidation Abs/cm		30	12
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	15
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		60	35
Aluminum ppm		4	2
Chromium ppm		4	1
Copper ppm		7	1
Lead ppm		4	1
Tin ppm		4	1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	2
Sodium ppm			<2
Boron ppm			<1
Zinc ppm			987
Phosphorus ppm			899
Calcium ppm			2103
Magnesium ppm			7
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm			<3

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NORMAL

Normal
MACHINE CONDITION
FLUID CONDITION

Lab Number : V1109344

ID: FY09-111-26APR11-NEW - New Motor Oil: FY09-111-26APR11-OS222049C

05/02/11
13:36:18

Unit Type : New Oil (GN_NO001)
Oil Type : SAE 40 (GN_032) P.O. : JK110737
Sampled : 04/26/11 Shipped : 04/27/11 Received: 04/28/11 Printed: 05/02/11

This is a baseline reference sample. Result(s) appear acceptable, noting the full name and grade of the lubricant in unavailable.

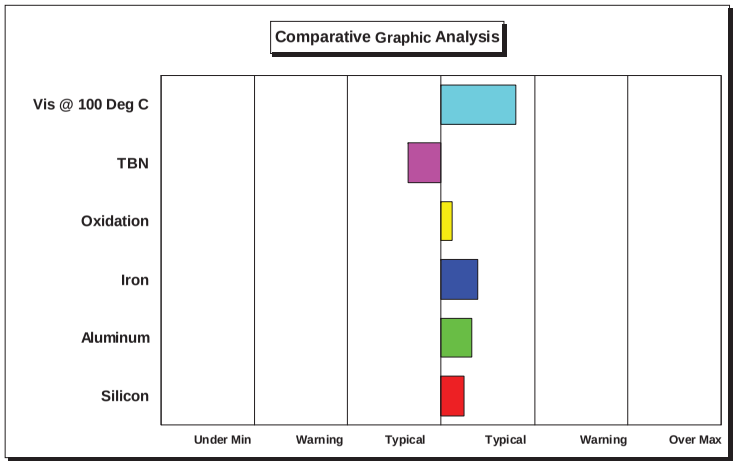
Attachment 4

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ISO 9001:2008 and ISO/IEC 17025:2005 Certified

* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number Sample Date	Minimum	Maximum	V1109344 04/26/11
Unit Time (HR)			0
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.93
TBN mg KOH/g	2.00		8.43
FTIR			
Soot % wt.		3.0	<0.1
Oxidation Abs/cm		30	3
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	<2
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		6	2
Aluminum ppm		4	1
Chromium ppm		4	<1
Copper ppm		7	<1
Lead ppm		4	<1
Tin ppm		4	<1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	3
Sodium ppm			16
Boron ppm			1
Zinc ppm			1339
Phosphorus ppm			1161
Calcium ppm			2558
Magnesium ppm			8
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm			<3

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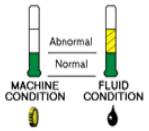
ABNORMAL



Lab Number : V1109345

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-26APR11-OIL - FY09-111-26APR11-OIL, Diesel Engine

Page 1
05/02/11
13:36:20

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : JK110737
Sampled : 04/26/11 Shipped : 04/27/11 Received: 04/28/11 Printed: 05/02/11

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. The Total Base Number (reserve alkalinity) is approaching minimum acceptable level. Levels may be due to oil service time (not provided). Drain oil and change filter(s). Additional sample is needed to help establish trend. Resample at half normal interval. Please provide equipment make and model as well as the full name and grade of the lubricant in service.

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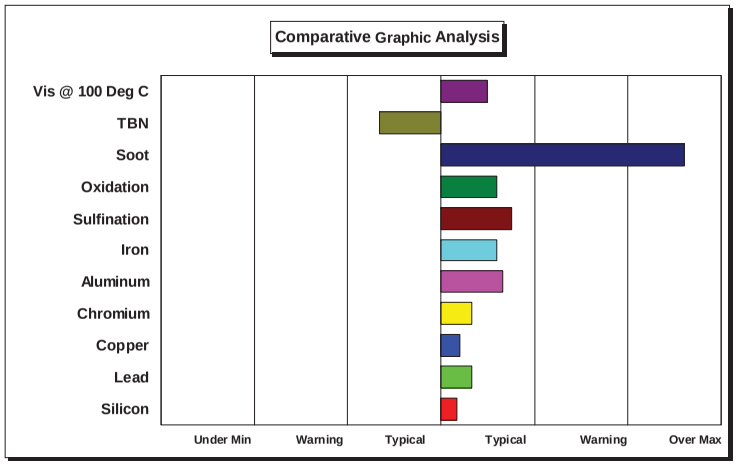
* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number Sample Date	Minimum	Maximum	V1109345 04/26/11
Unit Time (HR)			6191
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.34
TBN mg KOH/g	2.00		*4.52
FTIR			
Soot % wt.		3.0	**3.3
Oxidation Abs/cm		30	15
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	19
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		59	31
Aluminum ppm		4	2
Chromium ppm		4	1
Copper ppm		7	1
Lead ppm		4	1
Tin ppm		4	<1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	2
Sodium ppm			<2
Boron ppm			<1
Zinc ppm			1024
Phosphorus ppm			894
Calcium ppm			2082
Magnesium ppm			6
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm			<3

Attachment 4

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ID: FY09-111-26APR11-OIL - FY09-111-26APR11-OIL, Diesel Engine Page 1
05/02/11
Unit Type : Engine, Diesel (GN_DE001) 13:36:20
Oil Type : SAE 40 (GN_032) P.O. : JK110737
04/26/11Sampled : 04/27/11Shipped : 04/28/11Received: 05/02/11Printed:

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory.

Lab Number : V1109345 Soot content is high. The Total Base Number (reserve alkalinity) is approaching minimum acceptable level. Levels may be due to oil service time (not provided). Drain oil and change filter(s).

Tom Holmes

Additional sample is needed to help establish trend. Resample at half normal interval. Please

Lovelace Respiratory Research Institute

provide equipment make and model as well as the full name and grade of the lubricant in service.

2425 Ridgecrest Drive, SE

Albuquerque, NM 87108 ISO 9001:2008 and ISO/IEC 17025:2005 Certified * = exceeds Caution limit ** = exceeds Alarm limit

Comparative Graphic Analysis
Silicon
Lead
Copper
Chromium
Aluminum
Iron
Sulfination
Oxidation
Soot
TBN
Vis @ 100 Deg C
Under Min Warning Typical Typical Warning Over Max
Lab Number
Sample Date
Minimum Maximum V1109345
04/26/11
Unit Time (HR)
Fluid Time (HR)
6191
0
Vis @ 100 Deg C 12.00 16.80 15.34
TBN mg KOH/g
FTIR
2.00 *4.52

_____
Soot % wt. 3.0 **3.3
Oxidation Abs/cm 30 15
Water FTIR % Vol 0.20 <0.10
Sulfination Abs/ 30 19
Fuel % Vol 5.0 <2.0
Glycol % Vol
Metals
0.20 <0.10

_____
Iron ppm 59 31
Aluminum ppm 4 2
Chromium ppm 4 1
Copper ppm 7 1
Lead ppm 4 1
Tin ppm 4 <1
Nickel ppm 4 <1
Silver ppm
Antimony ppm
4.5 <0.1
<1
Silicon ppm
Sodium ppm
Boron ppm
Zinc ppm
Phosphorus ppm
Calcium ppm
Magnesium ppm
Barium ppm
Molybdenum ppm
Potassium ppm
20 2
<2
<1
1024
894
2082
6
<1
<1
<3

Evaluated By: David F. Frycki, CLS - For questions about this report, please call 888-437-4884. Code :LOVEMC
Lovelace Respiratory Research Institute Phone :(505) 348-9600 Fax :(505) 348-4980

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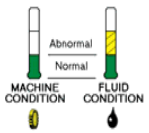
ABNORMAL



Lab Number : V1112739

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-18MAY11-OIL - FY09-111-18MAR11-OIL, Diesel Engine

Page 1
05/24/11
17:09:56

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : JK110737
Sampled : 05/18/11 Shipped : 05/19/11 Received: 05/20/11 Printed: 05/24/11

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. Drain oil and change filter(s). Check for proper combustion properties (exhaust back pressure, operating temperatures, worn/broken rings, excessive idling, hung valves, improper fuel settings, air intake restrictions). Additional sample is needed to help establish trend. Resample at half normal interval.

Attachment 4

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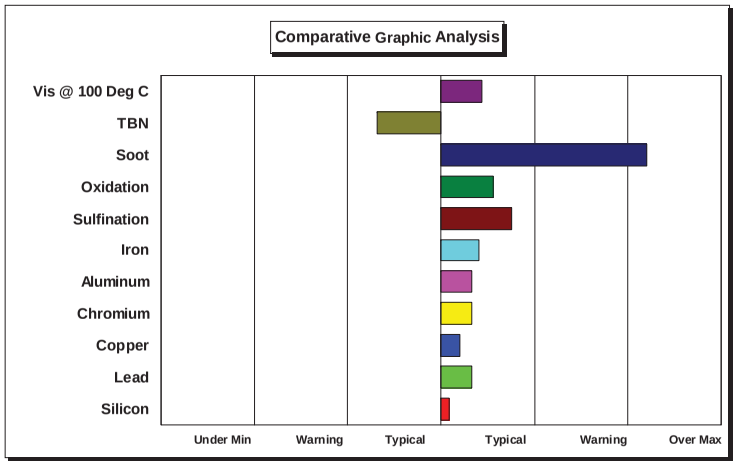
* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number Sample Date	Minimum	Maximum	V1112739 05/18/11
Unit Time (HR)			6438
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.24
TBN mg KOH/g	2.00		4.37
FTIR			
Soot % wt.		3.0	**3.1
Oxidation Abs/cm		30	14
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	19
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		58	21
Aluminum ppm		4	1
Chromium ppm		4	1
Copper ppm		7	1
Lead ppm		4	1
Tin ppm		4	<1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	1
Sodium ppm			5
Boron ppm			<1
Zinc ppm			827
Phosphorus ppm			705
Calcium ppm			1622
Magnesium ppm			4
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm			<3

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ABNORMAL

Abnormal / Normal
MACHINE CONDITION FLUID CONDITION

Lab Number : V1116193

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-09JUN11-OIL - FY09-111-09JUN11-OIL, Diesel Engine

06/21/11
09:08:18

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 15W-40 (GN_045) P.O. : JK110737
Sampled : 06/09/11 Shipped : 06/13/11 Received: 06/14/11 Printed: 06/21/11

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. Levels may be due to oil service time (not provided). Drain oil and change filter(s). Additional sample is needed to help establish trend. Resample at half normal interval. Please provide equipment make and model as well as the full name and grade of the lubricant in service.

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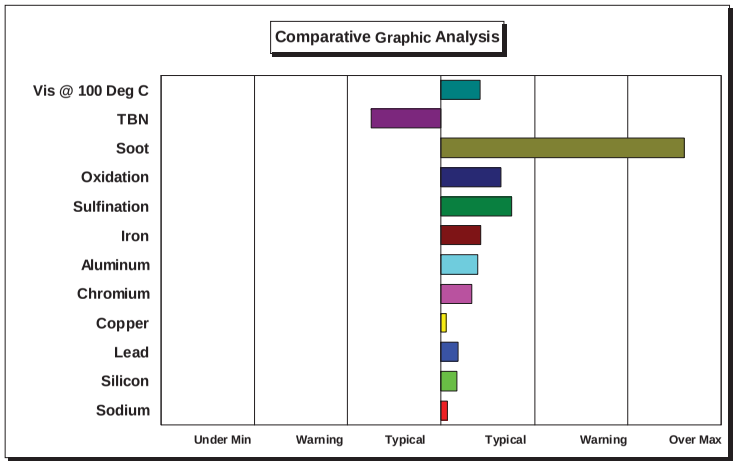
* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number / Sample Date	Minimum	Maximum	V1116193 06/09/11
Unit Time (HR)			6694
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.20
TBN mg KOH/g	3.00		5.37
FTIR			
Soot % wt.		3.0	**3.3
Oxidation Abs/cm		30	16
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	19
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		89	30
Aluminum ppm		7	2
Chromium ppm		4	1
Copper ppm		24	1
Lead ppm		15	2
Tin ppm		4	<1
Nickel ppm		4	<1
Silver ppm		3.1	<0.1
Antimony ppm			<1
Silicon ppm		20	2
Sodium ppm		50	2
Boron ppm			<1
Zinc ppm			1119
Phosphorus ppm			1045
Calcium ppm			2332
Magnesium ppm			11
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm		50	<3

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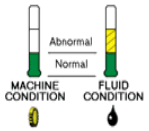
ABNORMAL



Lab Number : V1120804

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-04JUL11-OIL - FY09-111-04JUL11-OIL, Diesel Engine

Page 1
07/14/11
15:03:16

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 15W-40 (GN_045) P.O. : JK110737
Sampled : 07/04/11 Shipped : 07/11/11 Received: 07/12/11 Printed: 07/14/11

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory.
The Total Base Number (reserve alkalinity) is approaching minimum acceptable level. Soot content is high. Drain oil and change filter(s). Check for proper combustion properties (exhaust back pressure, operating temperatures, worn/broken rings, excessive idling, hung valves, improper fuel settings, air intake restrictions). Additional sample is needed to help establish trend. Resample at half normal interval. Please provide equipment make and model as well as the full name and grade

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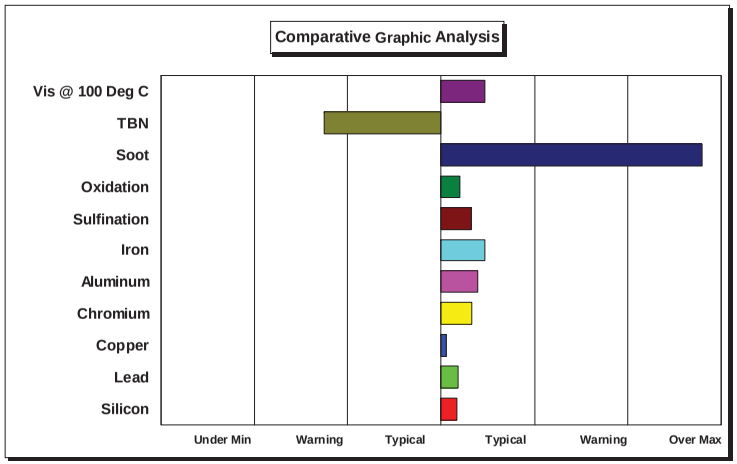
* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number Sample Date	Minimum	Maximum	V1120804 07/04/11
Unit Time (HR)			6966
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.29
TBN mg KOH/g	3.00		*3.75
FTIR			
Soot % wt.		3.0	**3.4
Oxidation Abs/cm		30	5
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	8
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		89	33
Aluminum ppm		7	2
Chromium ppm		4	1
Copper ppm		24	1
Lead ppm		15	2
Tin ppm		4	<1
Nickel ppm		4	<1
Silver ppm		3.1	<0.1
Antimony ppm			<1
Silicon ppm		20	2
Sodium ppm		50	<2
Boron ppm			1
Zinc ppm			1312
Phosphorus ppm			1029
Calcium ppm			2572
Magnesium ppm			6
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm		50	<3

Attachment 4

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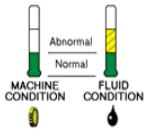
ABNORMAL



ID: FY09-111-21JUL11-OIL - FY09-111-21Jul11-Oil, Diesel Engine

10/04/11
13:02:17

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : JK110737
Sampled : 07/21/11 Shipped : 09/29/11 Received: 09/30/11 Printed: 10/04/11

Attachment 4

Lab Number : V1132899

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. Please provide equipment make and model as well as the full name and grade of the lubricant in service. Drain oil and change filter(s). Check for proper combustion properties (exhaust back pressure, operating temperatures, worn/broken rings, excessive idling, hung valves, improper fuel settings, air intake restrictions). Resample at half normal interval.

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2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

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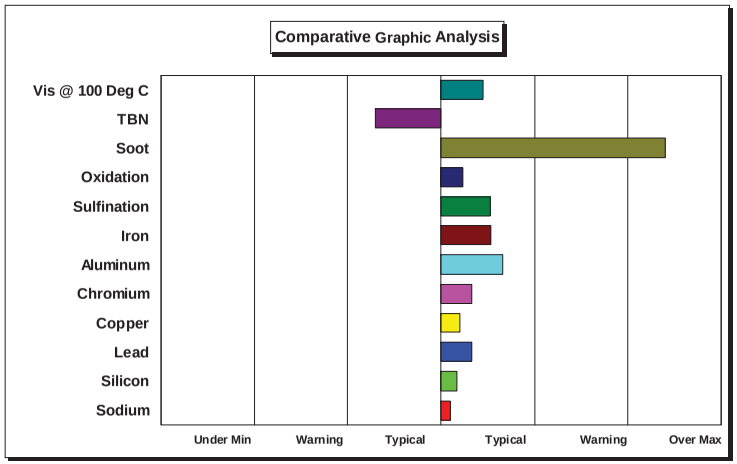

Lab Number Sample Date	Minimum	Maximum	V1132899 07/21/11
Unit Time (HR)			7191
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.26
TBN mg KOH/g	3.00		5.65
FTIR			
Soot % wt.		3.0	**3.2
Oxidation Abs/cm		30	6
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	13
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		60	28
Aluminum ppm		4	2
Chromium ppm		4	1
Copper ppm		7	1
Lead ppm		4	1
Tin ppm		4	<1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	2
Sodium ppm		50	3
Boron ppm			1
Zinc ppm			1108
Phosphorus ppm			1001
Calcium ppm			2235
Magnesium ppm			6
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm		50	<3

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ABNORMAL

Abnormal / Normal
MACHINE CONDITION FLUID CONDITION

Lab Number : V1125618

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-14AUG11-OIL - FY09-111-14aug11, Diesel Engine

08/18/11
13:02:11

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : JK110737
Sampled : 08/14/11 Shipped : 08/15/11 Received: 08/16/11 Printed: 08/18/11

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. FTIR indicates oil is sulfinated. Drain oil and change filter(s). Check for proper combustion properties (exhaust back pressure, operating temperatures, worn/broken rings, excessive idling, hung valves, improper fuel settings, air intake restrictions). Additional sample is needed to help establish trend. Resample at half normal interval.

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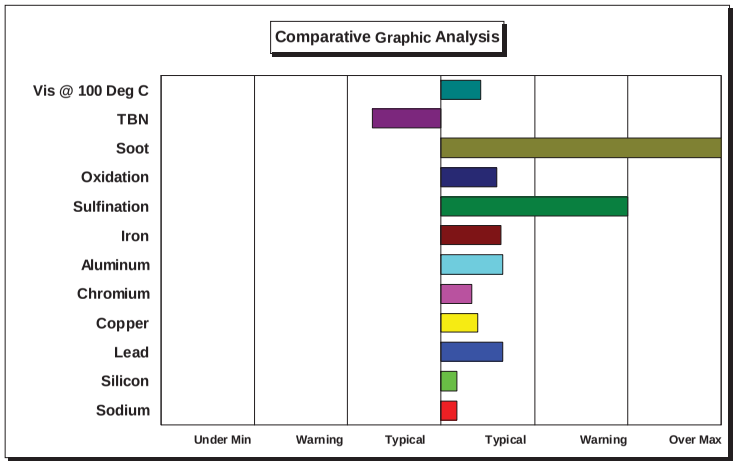
* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number / Sample Date	Minimum	Maximum	V1125618 08/14/11
Unit Time (HR)			7445
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.21
TBN mg KOH/g	3.00		5.45
FTIR			
Soot % wt.		3.0	**3.5
Oxidation Abs/cm		30	15
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	*30
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		61	34
Aluminum ppm		4	2
Chromium ppm		4	1
Copper ppm		7	2
Lead ppm		4	2
Tin ppm		4	<1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	2
Sodium ppm		50	5
Boron ppm			<1
Zinc ppm			1236
Phosphorus ppm			1115
Calcium ppm			2497
Magnesium ppm			10
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm		50	<3

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ABNORMAL

Abnormal / Normal
MACHINE CONDITION FLUID CONDITION

Lab Number : V1129682

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-07SEP11-OIL - FY09-111-07SEP11-OIL, Diesel Engine

09/15/11
16:19:59

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 15W-40 (GN_045) P.O. : JK110737
Sampled : 09/07/11 Shipped : 09/12/11 Received: 09/13/11 Printed: 09/15/11

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. Levels may be due to oil service time (not provided). Drain oil and change filter(s). Additional sample is needed to help establish trend. Resample at half normal interval. Please provide equipment make and model as well as the full name and grade of the lubricant in service.

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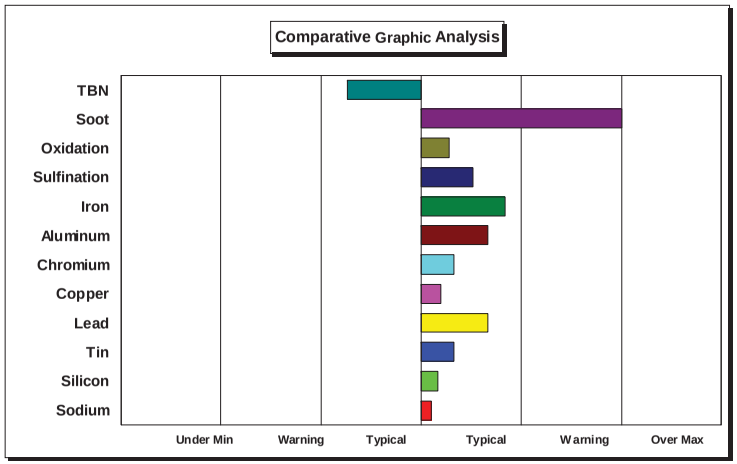

Lab Number / Sample Date	Minimum	Maximum	V1129682 09/07/11
Unit Time (HR)			0
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.04
TBN mg KOH/g	3.00		5.43
FTIR			
Soot % wt.		3.0	*3.0
Oxidation Abs/cm		30	7
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	13
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		39	31
Aluminum ppm		4	2
Chromium ppm		4	1
Copper ppm		7	1
Lead ppm		4	2
Tin ppm		4	1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	2
Sodium ppm		50	3
Boron ppm			3
Zinc ppm			1322
Phosphorus ppm			1122
Calcium ppm			2557
Magnesium ppm			9
Barium ppm			<1
Molybdenum ppm			1
Potassium ppm		50	<3

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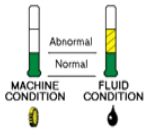
ABNORMAL



ID: FY09-111-26SEP11-OIL - FY09-111-26Sep11-Oil, Diesel Engine

10/04/11

13:02:14

Unit Type : Engine, Diesel (GN_DE001)

Oil Type : SAE 40 (GN_032) P.O. : JK110737

Sampled : 09/26/11 Shipped : 09/29/11 Received: 09/30/11 Printed: 10/04/11

Lab Number : V1132898

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. Glycol and sodium indicate coolant inhibitors; check for source. Drain oil and change filter(s). Check for proper combustion properties (exhaust back pressure, operating temperatures, worn/broken rings, excessive idling, hung valves, improper fuel settings, air intake restrictions). Monitor cooling system for level changes and/or additions. Resample at half normal interval.

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

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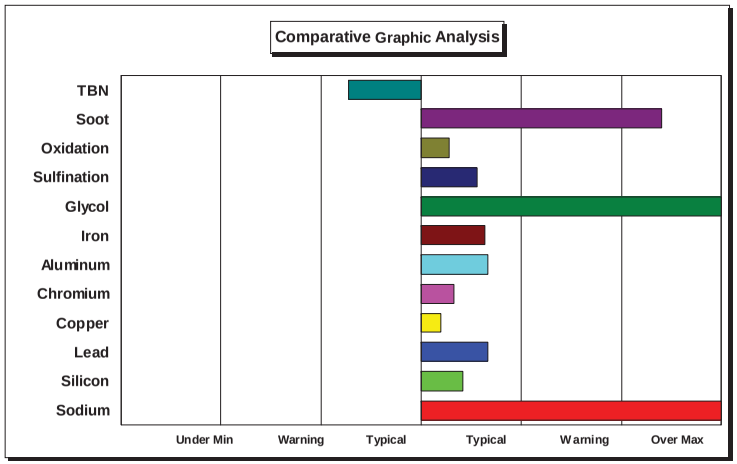
* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number Sample Date	Minimum	Maximum	V1132898 09/26/11
Unit Time (HR)			7937
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	14.90
TBN mg KOH/g	3.00		5.53
FTIR			
Soot % wt.		3.0	**3.2
Oxidation Abs/cm		30	7
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	14
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	**0.42
Metals			
Iron ppm		60	33
Aluminum ppm		4	2
Chromium ppm		4	1
Copper ppm		7	1
Lead ppm		4	2
Tin ppm		4	<1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			1
Silicon ppm		20	5
Sodium ppm		50	**150
Boron ppm			12
Zinc ppm			969
Phosphorus ppm			875
Calcium ppm			1982
Magnesium ppm			8
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm		50	<3

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NORMAL

Normal
MACHINE CONDITION
FLUID CONDITION

Lab Number : V1137700

ID: FY09-111-20OCT11-OIL - FY09-111-20OCT11-OIL, Diesel Engine	Page 1
	11/01/11
Unit Type : Engine, Diesel (GN_DE001)	17:05:20
Oil Type : SAE 40 (GN_032) P.O. : JK110737	
Sampled : 10/20/11 Shipped : 10/27/11 Received: 10/28/11 Printed: 11/01/11	

NORMAL: Sample data is satisfactory. No action is required at this time. Additional sample is needed to help establish trend. Resample at half normal interval. Please provide equipment make and model as well as the full name and grade of the lubricant in service.

Attachment 4

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

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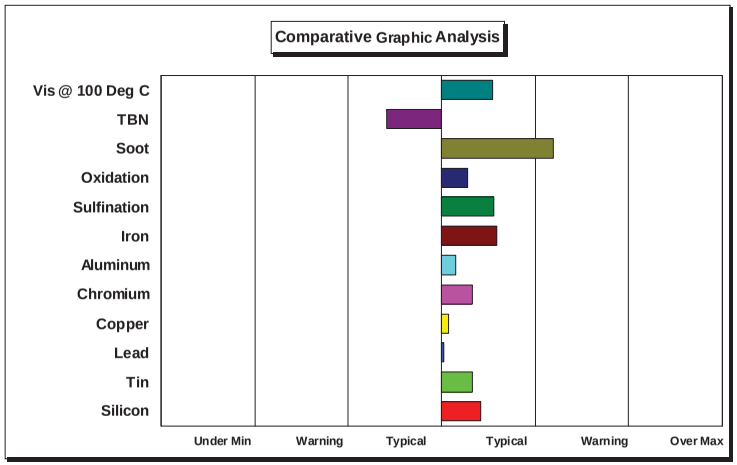
* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number Sample Date	Minimum	Maximum	V1137700 10/20/11
Unit Time (HR)			1487
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.44
TBN mg KOH/g	2.00		5.11
FTIR			
Soot % wt.		3.0	2.6
Oxidation Abs/cm		30	7
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	14
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		99	46
Aluminum ppm		16	2
Chromium ppm		4	1
Copper ppm		36	2
Lead ppm		50	1
Tin ppm		4	1
Nickel ppm		4	<1
Silver ppm		3.1	<0.1
Antimony ppm			<1
Silicon ppm		20	5
Sodium ppm			4
Boron ppm			1
Zinc ppm			1150
Phosphorus ppm			1063
Calcium ppm			2392
Magnesium ppm			6
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm			<3

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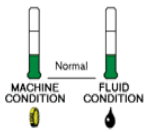
NORMAL



Lab Number : V1140205

ID: FY09-111-09NOV11-OIL - FY09-111-09NOV11-OIL, Diesel Engine	Page 1
	11/15/11
Unit Type : Engine, Diesel (GN_DE001)	12:57:03
Oil Type : SAE 40 (GN_032) P.O. : JK120015	
Sampled : 11/09/11 Shipped : 11/10/11 Received: 11/11/11 Printed: 11/15/11	

NORMAL: Sample data is satisfactory. No action is required at this time.
Please provide equipment make and model as well as the full name and grade of the lubricant in service. Additional sample is needed to help establish trend. Resample at half normal interval.

Attachment 4

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

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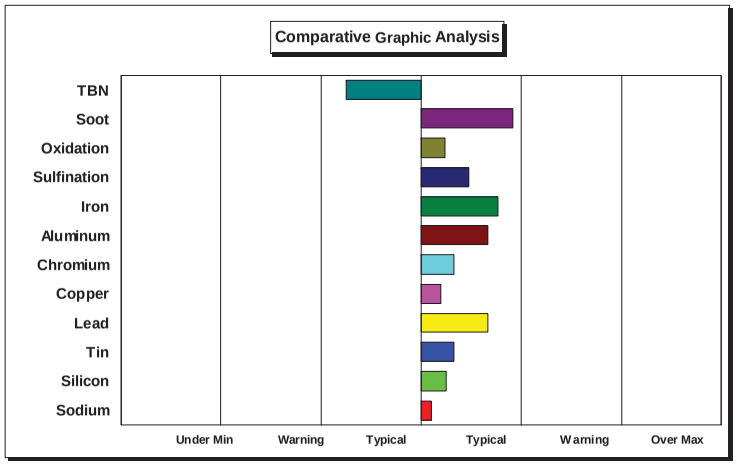

Lab Number Sample Date	Minimum	Maximum	V1140205 11/09/11
Unit Time (HR)			1697
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.23
TBN mg KOH/g	3.00		5.32
FTIR			
Soot % wt.		3.0	2.3
Oxidation Abs/cm		30	6
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	12
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		59	40
Aluminum ppm		4	2
Chromium ppm		4	1
Copper ppm		7	1
Lead ppm		4	2
Tin ppm		4	1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	3
Sodium ppm		50	3
Boron ppm			<1
Zinc ppm			1301
Phosphorus ppm			1100
Calcium ppm			2476
Magnesium ppm			6
Barium ppm			<1
Molybdenum ppm			1
Potassium ppm		50	<3

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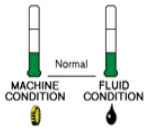

Lab Number : V1143041

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-01DEC11-OIL - FY09-111-01dec11-oil, Diesel Engine

12/06/11
12:50:52

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : JK110737
Sampled : 12/01/11 Shipped : 12/01/11 Received: 12/02/11 Printed: 12/06/11

MONITOR: Data for machine and/or fluid condition should be noted and monitored. Soot content is high. Levels may be due to oil service time (not provided). Drain oil and change filter(s). Additional sample is needed to help establish trend. Resample at half normal interval. Please provide equipment make and model as well as the full name and grade of the lubricant in service.

Attachment 4

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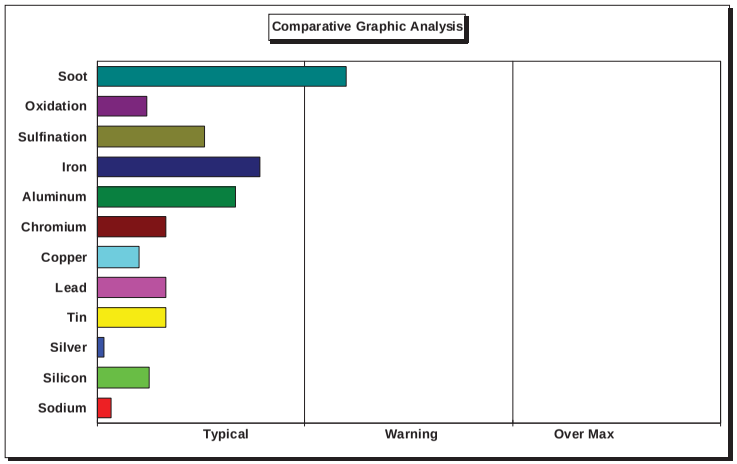
* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number Sample Date	Minimum	Maximum	V1143041 12/01/11
Unit Time (HR)			1949
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.45
TBN mg KOH/g	3.00		4.67
FTIR			
Soot % wt.		3.0	*2.6
Oxidation Abs/cm		30	6
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	13
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		59	40
Aluminum ppm		4	2
Chromium ppm		4	1
Copper ppm		7	1
Lead ppm		4	1
Tin ppm		4	1
Nickel ppm		4	<1
Silver ppm		4.5	0.1
Antimony ppm			<1
Silicon ppm		20	3
Sodium ppm		50	2
Boron ppm			1
Zinc ppm			1115
Phosphorus ppm			1017
Calcium ppm			2253
Magnesium ppm			6
Barium ppm			<1
Molybdenum ppm			1
Potassium ppm		50	<3

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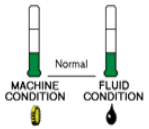
MONITOR



Lab Number : V1143041

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-01DEC11-OIL - FY09-111-01dec11-oil, Diesel Engine

12/06/11
12:50:52

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : JK110737
Sampled : 12/01/11 Shipped : 12/01/11 Received: 12/02/11 Printed: 12/06/11

MONITOR: Data for machine and/or fluid condition should be noted and monitored. Soot content is high. Levels may be due to oil service time (not provided). Drain oil and change filter(s). Additional sample is needed to help establish trend. Resample at half normal interval. Please provide equipment make and model as well as the full name and grade of the lubricant in service.

Attachment 4

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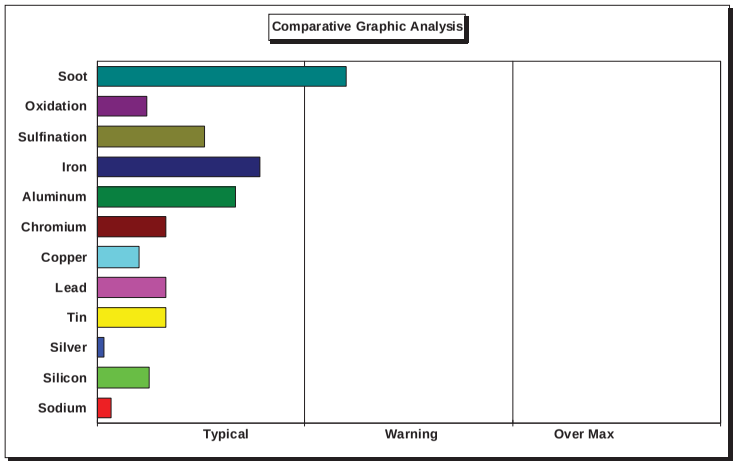

Lab Number Sample Date	Minimum	Maximum	V1143041 12/01/11
Unit Time (HR)			1949
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.45
TBN mg KOH/g	3.00		4.67
FTIR			
Soot % wt.		3.0	*2.6
Oxidation Abs/cm		30	6
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	13
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		59	40
Aluminum ppm		4	2
Chromium ppm		4	1
Copper ppm		7	1
Lead ppm		4	1
Tin ppm		4	1
Nickel ppm		4	<1
Silver ppm		4.5	0.1
Antimony ppm			<1
Silicon ppm		20	3
Sodium ppm		50	2
Boron ppm			1
Zinc ppm			1115
Phosphorus ppm			1017
Calcium ppm			2253
Magnesium ppm			6
Barium ppm			<1
Molybdenum ppm			1
Potassium ppm		50	<3

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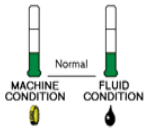
NORMAL



Lab Number : V1145938

ID: FY09-111-19DEC11-OIL - FY09-111-19dec11-oil, Diesel Engine	Page 1
	12/27/11
Unit Type : Engine, Diesel (GN_DE001)	15:52:45
Oil Type : SAE 40 (GN_032) P.O. : JK-110737	
Sampled : 12/19/11 Shipped : 12/20/11 Received: 12/21/11 Printed: 12/27/11	

NORMAL: Sample data is satisfactory. No action is required at this time.
Please provide equipment make and model as well as the full name and grade of the lubricant in service. Additional sample is needed to help establish trend. Resample at half normal interval.

Attachment 4

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

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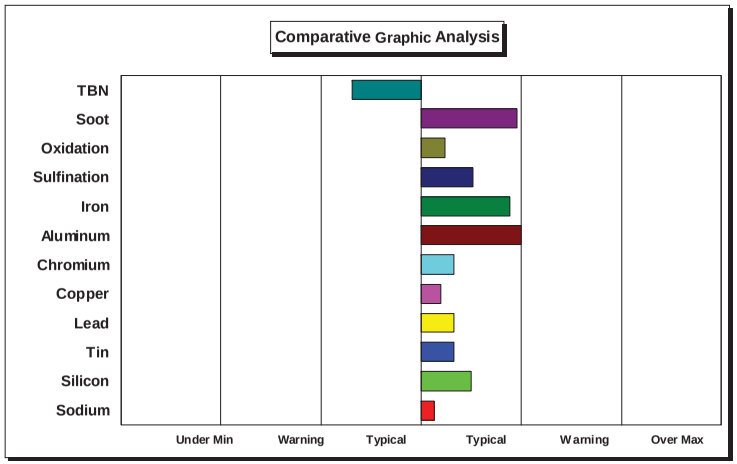

Lab Number Sample Date	Minimum	Maximum	V1145938 12/19/11
Unit Time (HR)			2181
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.29
TBN mg KOH/g	3.00		5.84
FTIR			
Soot % wt.		3.0	2.4
Oxidation Abs/cm		30	6
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	13
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		59	45
Aluminum ppm		4	3
Chromium ppm		4	1
Copper ppm		7	1
Lead ppm		4	1
Tin ppm		4	1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			1
Silicon ppm		20	6
Sodium ppm		50	4
Boron ppm			<1
Zinc ppm			1503
Phosphorus ppm			1274
Calcium ppm			2879
Magnesium ppm			7
Barium ppm			<1
Molybdenum ppm			1
Potassium ppm		50	<3

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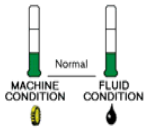
MONITOR



ID: FY09-111-16JAN12-OIL - FY09-111-16JAN2012-OIL, Diesel Engine

01/18/12

17:24:11

Unit Type : Engine, Diesel (GN_DE001)

Oil Type : SAE 40 (GN_032) P.O. : JK120015

Sampled : 01/16/12 Shipped : 01/16/12 Received: 01/17/12 Printed: 01/18/12

Attachment 4

Lab Number : V1149543

MONITOR: Data for machine and/or fluid condition should be noted and monitored. Soot content is high. Please provide equipment make and model as well as the full name and grade of the lubricant in service. Additional sample is needed to help establish trend. Resample at half normal interval.

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

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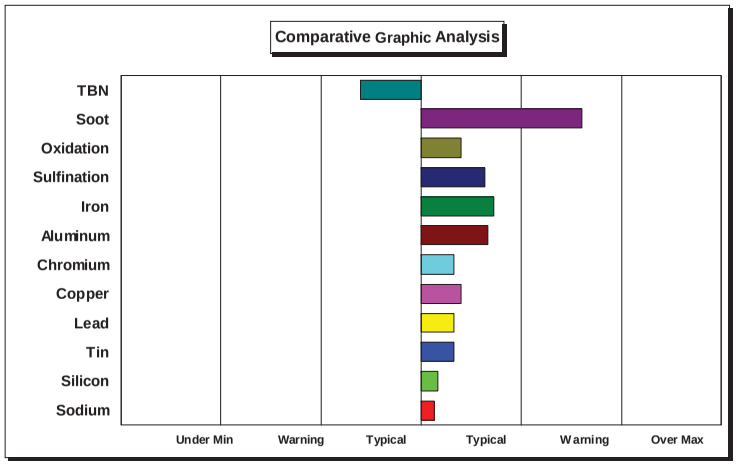

Lab Number Sample Date	Minimum	Maximum	V1149543 01/16/12
Unit Time (HR)			2411
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.25
TBN mg KOH/g	3.00		6.58
FTIR			
Soot % wt.		3.0	*2.8
Oxidation Abs/cm		30	10
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	16
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		59	38
Aluminum ppm		4	2
Chromium ppm		4	1
Copper ppm		7	2
Lead ppm		4	1
Tin ppm		4	1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	2
Sodium ppm		50	4
Boron ppm			5
Zinc ppm			897
Phosphorus ppm			856
Calcium ppm			1982
Magnesium ppm			11
Barium ppm			<1
Molybdenum ppm			1
Potassium ppm		50	<3

Evaluated By: Bobby R Licu, Senior Evaluator - For questions about this report, please call 888-437-4884. **Code :LOVEMC Lovelace Respiratory Research Institute** **Phone :(505) 348-9600 Fax :(505) 348-4980**

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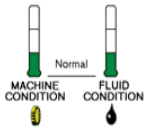
MONITOR



Lab Number : V1152780

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-06FEB12-OIL - FY09-111-06FEB2012-OIL, Diesel Engine

02/13/12
15:08:49

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : JK120015
Sampled : 02/06/12 Shipped : 02/07/12 Received: 02/08/12 Printed: 02/13/12

MONITOR: Data for machine and/or fluid condition should be noted and monitored. Soot content is high. Please provide equipment make and model as well as the full name and grade of the lubricant in service. Drain oil and change filter(s). Additional sample is needed to help establish trend. Resample at half normal interval.

Attachment 4

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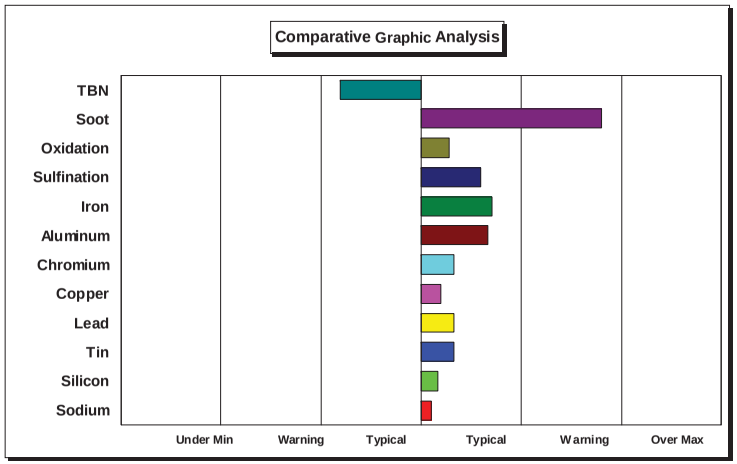
* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number Sample Date	Minimum	Maximum	V1152780 02/06/12
Unit Time (HR)			2683
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.53
TBN mg KOH/g	3.00		4.94
FTIR			
Soot % wt.		3.0	*2.9
Oxidation Abs/cm		30	7
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	15
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		59	37
Aluminum ppm		4	2
Chromium ppm		4	1
Copper ppm		7	1
Lead ppm		4	1
Tin ppm		4	1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	2
Sodium ppm		50	3
Boron ppm			<1
Zinc ppm			1105
Phosphorus ppm			923
Calcium ppm			2190
Magnesium ppm			6
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm		50	<3

Evaluated By: Bobby R Licu, Senior Evaluator - For questions about this report, please call 888-437-4884. **Code :LOVEMC Lovelace Respiratory Research Institute** **Phone :(505) 348-9600 Fax :(505) 348-4980**

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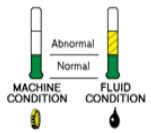
ABNORMAL



ID: FY09-111-01MAR12-OIL - FY09-111-01Mar12-Oil, Diesel Engine

03/09/12

15:53:55

Unit Type : Engine, Diesel (GN_DE001)

Oil Type : SAE 40 (GN_032) P.O. : JK120015

Sampled : 03/06/12 Shipped : 03/06/12 Received: 03/07/12 Printed: 03/09/12

Attachment 4

Lab Number : V1157136

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. FTIR indicates oil is sulfinated. Drain oil and change filter(s). Check for proper combustion properties (exhaust back pressure, operating temperatures, worn/broken rings, excessive idling, hung valves, improper fuel settings, air intake restrictions). Additional sample is needed to help establish trend. Resample at half normal interval.

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

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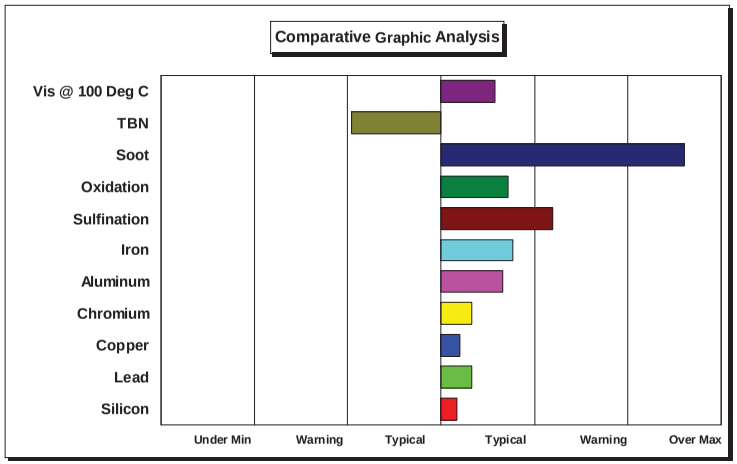

Lab Number Sample Date	Minimum	Maximum	V1157136 03/06/12
Unit Time (HR)			2998
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.49
TBN mg KOH/g	3.00		4.18
FTIR			
Soot % wt.		3.0	**3.3
Oxidation Abs/cm		30	18
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	*26
Fuel % Vol		5.0	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		58	39
Aluminum ppm		4	2
Chromium ppm		4	1
Copper ppm		7	1
Lead ppm		4	1
Tin ppm		4	<1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	2
Sodium ppm		50	<2
Boron ppm			1
Zinc ppm			955
Phosphorus ppm			815
Calcium ppm			1950
Magnesium ppm			5
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm		50	<3

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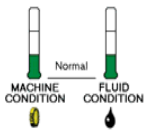
NORMAL



Lab Number : V1159000

ID: FY09-111-19MAR12-OIL - FY09-111-19MAR12-OIL, Diesel Engine Page 1

03/23/12

Unit Type : Engine, Diesel (GN_DE001) 16:24:25

Oil Type : SAE 40 (GN_032) P.O. : JK120015

Sampled : 03/20/12 Shipped : 03/20/12 Received: 03/21/12 Printed: 03/23/12

NORMAL: Sample data is satisfactory. No action is required at this time. Please provide equipment make and model as well as the full name and grade of the lubricant in service. Additional sample is needed to help establish trend. Resample at half normal interval.

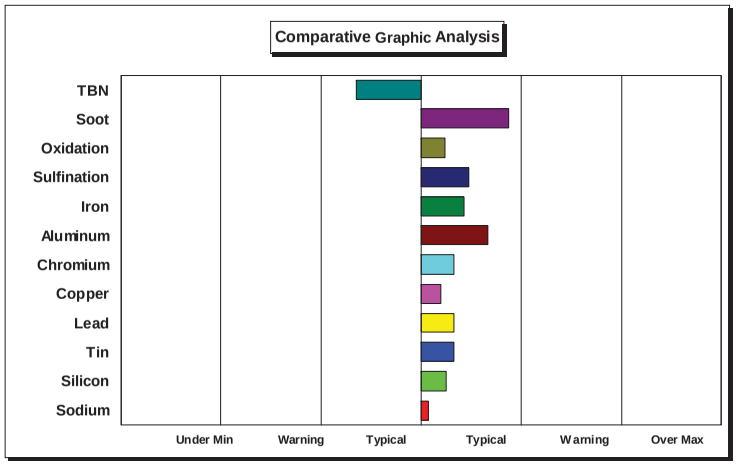
Attachment 4

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ISO 9001:2008 and ISO/IEC 17025:2005 Certified

* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number Sample Date	Minimum	Maximum	V1159000 03/20/12
Unit Time (HR)			3189
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	14.76
TBN mg KOH/g	3.00		6.22
FTIR			
Soot % wt.		3.0	2.2
Oxidation Abs/cm		30	6
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	12
Fuel % Vol		2.5	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		58	22
Aluminum ppm		4	2
Chromium ppm		4	1
Copper ppm		7	1
Lead ppm		4	1
Tin ppm		4	1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	3
Sodium ppm		50	2
Boron ppm			1
Zinc ppm			979
Phosphorus ppm			879
Calcium ppm			2123
Magnesium ppm			6
Barium ppm			<1
Molybdenum ppm			27
Potassium ppm		50	<3

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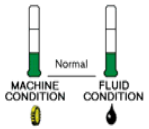
MONITOR



Lab Number : V1161935

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-10APR2012-O - FY09-111-10apr2012-oil, Diesel Engine

04/16/12
12:51:09

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : JK120015
Sampled : 04/10/12 Shipped : 04/11/12 Received: 04/12/12 Printed: 04/16/12

MONITOR: Data for machine and/or fluid condition should be noted and monitored. Please provide equipment make and model as well as the full name and grade of the lubricant in service. Other test results are acceptable. Additional sample is needed to help establish trend. Resample at half normal interval.

Attachment 4

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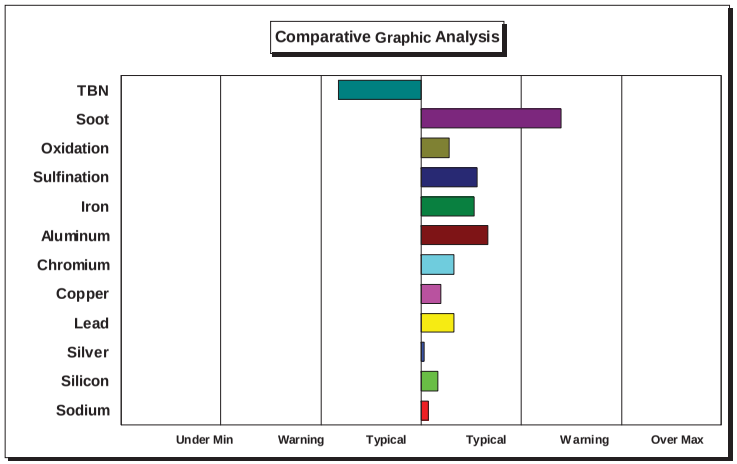
* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number Sample Date	Minimum	Maximum	V1161935 04/10/12
Unit Time (HR)			0
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.03
TBN mg KOH/g	3.00		4.83
FTIR			
Soot % wt.		3.0	*2.7
Oxidation Abs/cm		30	7
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	14
Fuel % Vol		2.5	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		59	27
Aluminum ppm		4	2
Chromium ppm		4	1
Copper ppm		7	1
Lead ppm		4	1
Tin ppm		4	<1
Nickel ppm		4	<1
Silver ppm		4.5	0.1
Antimony ppm			1
Silicon ppm		20	2
Sodium ppm		50	2
Boron ppm			<1
Zinc ppm			941
Phosphorus ppm			822
Calcium ppm			1877
Magnesium ppm			4
Barium ppm			<1
Molybdenum ppm			1
Potassium ppm		50	<3

Evaluated By: Bobby R Licu, Senior Evaluator - For questions about this report, please call 888-437-4884. **Code :LOVEMC Lovelace Respiratory Research Institute** **Phone :(505) 348-9600 Fax :(505) 348-4980**

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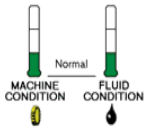
MONITOR



Lab Number : V1161935

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-10APR2012-O - FY09-111-10apr2012-oil, Diesel Engine

04/16/12
12:51:09

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : JK120015
Sampled : 04/10/12 Shipped : 04/11/12 Received: 04/12/12 Printed: 04/16/12

MONITOR: Data for machine and/or fluid condition should be noted and monitored. Please provide equipment make and model as well as the full name and grade of the lubricant in service. Other test results are acceptable. Additional sample is needed to help establish trend. Resample at half normal interval.

Attachment 4

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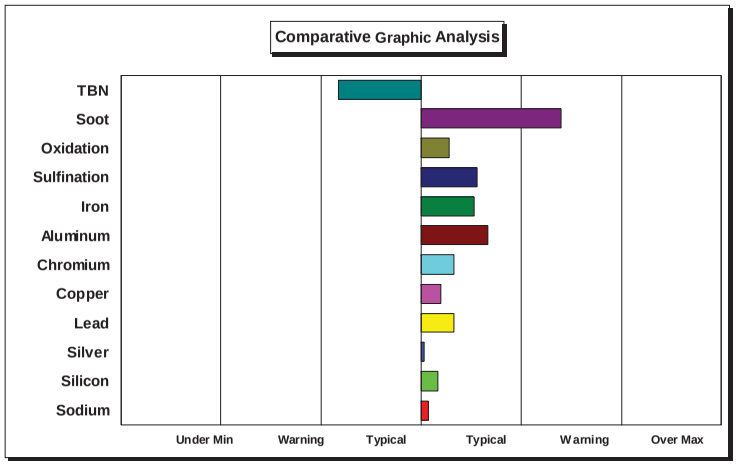
* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number Sample Date	Minimum	Maximum	V1161935 04/10/12
Unit Time (HR)			0
Fluid Time (HR)			0
Vis @ 100 Deg C	12.00	16.80	15.03
TBN mg KOH/g	3.00		4.83
FTIR			
Soot % wt.		3.0	*2.7
Oxidation Abs/cm		30	7
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	14
Fuel % Vol		2.5	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		59	27
Aluminum ppm		4	2
Chromium ppm		4	1
Copper ppm		7	1
Lead ppm		4	1
Tin ppm		4	<1
Nickel ppm		4	<1
Silver ppm		4.5	0.1
Antimony ppm			1
Silicon ppm		20	2
Sodium ppm		50	2
Boron ppm			<1
Zinc ppm			941
Phosphorus ppm			822
Calcium ppm			1877
Magnesium ppm			4
Barium ppm			<1
Molybdenum ppm			1
Potassium ppm		50	<3

Evaluated By: Bobby R Licu, Senior Evaluator - For questions about this report, please call 888-437-4884. **Code :LOVEMC Lovelace Respiratory Research Institute** **Phone :(505) 348-9600 Fax :(505) 348-4980**

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ABNORMAL

Abnormal / Normal
MACHINE CONDITION FLUID CONDITION

Lab Number : V1165160

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-03MAY12-OIL - FY09-111-03MAY2012 OIL, Diesel Engine

05/09/12
13:51:52

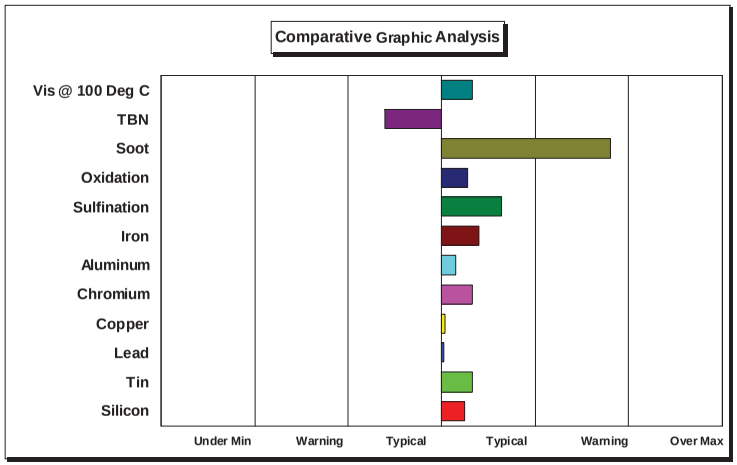
Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : JK120015
Sampled : 05/03/12 Shipped : 05/06/12 Received: 05/07/12 Printed: 05/09/12

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. Drain oil and change filter(s). Check for proper combustion properties (exhaust back pressure, operating temperatures, worn/broken rings, excessive idling, hung valves, improper fuel settings, air intake restrictions). Please provide equipment make and model as well as the full name and grade of the lubricant in service. Resample at half normal interval.

Attachment 4

ISO 9001:2008 and ISO/IEC 17025:2005 Certified

* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number / Sample Date	Minimum	Maximum	V1165160 05/03/12
Unit Time (HR)			3910
Fluid Time (HR)			0
Vis @ 100 Deg C	12.50	16.80	15.13
TBN mg KOH/g	2.00		4.94
FTIR			
Soot % wt.		3.0	*2.9
Oxidation Abs/cm		30	7
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	16
Fuel % Vol		2.5	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		99	31
Aluminum ppm		16	2
Chromium ppm		4	1
Copper ppm		36	1
Lead ppm		50	1
Tin ppm		4	1
Nickel ppm		4	<1
Silver ppm		3.1	<0.1
Antimony ppm			<1
Silicon ppm		20	3
Sodium ppm			2
Boron ppm			1
Zinc ppm			1151
Phosphorus ppm			983
Calcium ppm			2404
Magnesium ppm			5
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm			<3

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ABNORMAL

Abnormal / Normal
MACHINE CONDITION FLUID CONDITION

Lab Number : V1173601

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-02JUL2012 - FY09-111-02jul2012-oil

07/10/12
17:22:05

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : JK110737
Sampled : 07/02/12 Shipped : 07/08/12 Received: 07/09/12 Printed: 07/10/12

ABNORMAL: Abnormal test results are present.
Soot content is high. Chromium may indicate ring wear. Tin is an indicator of bearing/bushing alloys, brass and/or solder. Drain oil and change filter(s). Additional sample is needed to help establish trend. Resample at half normal interval. Please provide equipment make and model as well as the full name and grade of the lubricant in service.

Attachment 4

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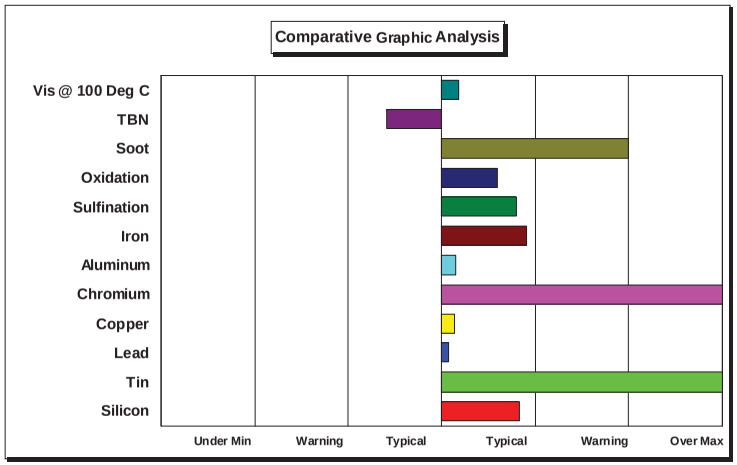
* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number Sample Date	Minimum	Maximum	V1173601 07/02/12
Unit Time (HR)			274
Fluid Time (HR)			0
Vis @ 100 Deg C	12.50	16.80	14.87
TBN mg KOH/g	2.00		5.09
FTIR			
Soot % wt.		3.0	*3.0
Oxidation Abs/cm		30	15
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	20
Fuel % Vol		2.5	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		99	72
Aluminum ppm		16	2
Chromium ppm		4	**7
Copper ppm		36	4
Lead ppm		50	3
Tin ppm		4	**6
Nickel ppm		4	<1
Silver ppm		3.1	<0.1
Antimony ppm			<1
Silicon ppm		20	10
Sodium ppm			16
Boron ppm			1
Zinc ppm			1493
Phosphorus ppm			1158
Calcium ppm			2939
Magnesium ppm			10
Barium ppm			<1
Molybdenum ppm			1
Potassium ppm			<3

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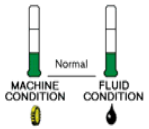
MONITOR



ID: FY09-111-30JUL12-OI - FY09-111-30JUL2012 OIL, Diesel Engine

Page 1
08/09/12
14:25:23

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : JK120015
Sampled : 07/30/12 Shipped : 08/06/12 Received: 08/07/12 Printed: 08/09/12

Attachment 4

Lab Number : V1177939

MONITOR: Data for machine and/or fluid condition should be noted and monitored. Soot content is high. Please provide equipment make and model as well as the full name and grade of the lubricant in service. Drain oil and change filter(s). Additional sample is needed to help establish trend. Resample at half normal interval.

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

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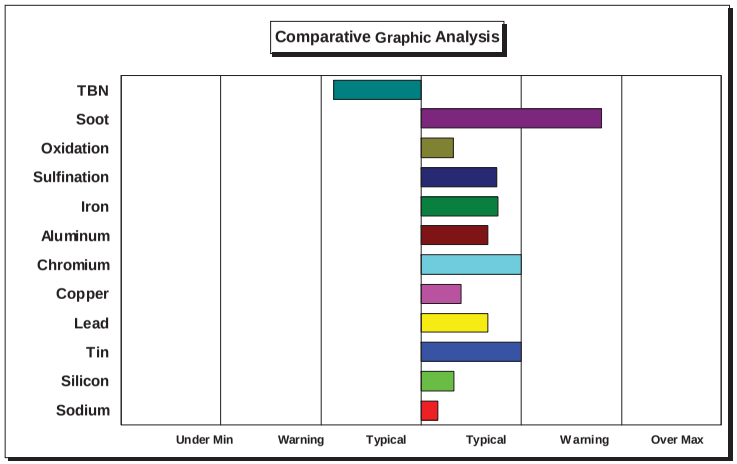

Lab Number Sample Date	Minimum	Maximum	V1177939 07/30/12
Unit Time (HR)			540
Fluid Time (HR)			0
Vis @ 100 Deg C	12.50	16.80	14.44
TBN mg KOH/g	3.00		4.55
FTIR			
Soot % wt.		3.0	*2.9
Oxidation Abs/cm		30	8
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	19
Fuel % Vol		2.5	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		67	44
Aluminum ppm		4	2
Chromium ppm		4	3
Copper ppm		6	2
Lead ppm		4	2
Tin ppm		4	3
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	4
Sodium ppm		50	5
Boron ppm			1
Zinc ppm			1196
Phosphorus ppm			979
Calcium ppm			2255
Magnesium ppm			6
Barium ppm			<1
Molybdenum ppm			1
Potassium ppm		50	<3

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ABNORMAL

Abnormal / Normal
MACHINE CONDITION FLUID CONDITION

Lab Number : V1180056

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-21AUG2012 - FY09-111-21aug2012-oil

08/27/12
18:12:18

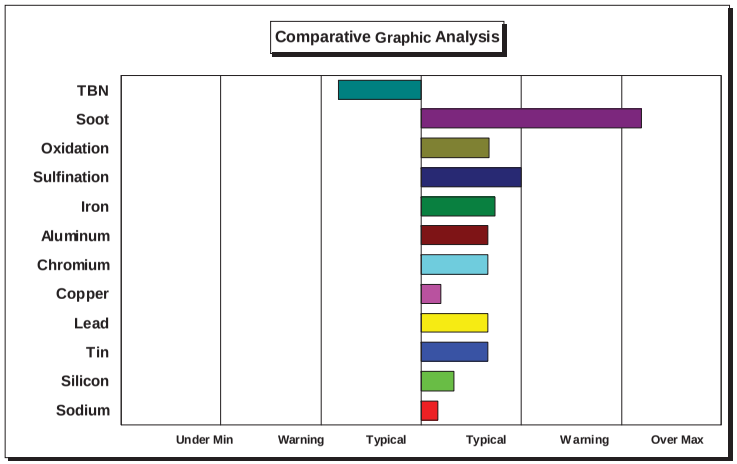
Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : JK110737
Sampled : 08/21/12 Shipped : 08/22/12 Received: 08/23/12 Printed: 08/27/12

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. Please provide equipment make and model as well as the full name and grade of the lubricant in service. Drain oil and change filter(s). Check for proper combustion properties (exhaust back pressure, operating temperatures, worn/broken rings, excessive idling, hung valves, improper fuel settings, air intake restrictions). Resample at half normal interval.

Attachment 4

ISO 9001:2008 and ISO/IEC 17025:2005 Certified

* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number / Sample Date	Minimum	Maximum	V1180056 08/21/12
Unit Time (HR)			780
Fluid Time (HR)			0
Vis @ 100 Deg C	12.50	16.80	14.78
TBN mg KOH/g	3.00		4.81
FTIR			
Soot % wt.		3.0	**3.1
Oxidation Abs/cm		30	17
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	25
Fuel % Vol		2.5	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		67	42
Aluminum ppm		4	2
Chromium ppm		4	2
Copper ppm		6	1
Lead ppm		4	2
Tin ppm		4	2
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	4
Sodium ppm		50	5
Boron ppm			1
Zinc ppm			1248
Phosphorus ppm			1056
Calcium ppm			2543
Magnesium ppm			8
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm		50	<3

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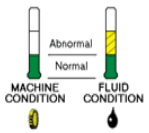
ABNORMAL



Lab Number : V1183634

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-11SEP2012 - FY09-111-11sep2012-oil, Diesel Engine

Page 1
09/20/12
13:33:52

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : JK110737
Sampled : 09/11/12 Shipped : 09/17/12 Received: 09/18/12 Printed: 09/20/12

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Sodium may indicate coolant inhibitors; check for source. Drain oil and change filter(s). Check for proper combustion properties (exhaust back pressure, operating temperatures, worn/broken rings, excessive idling, hung valves, improper fuel settings, air intake restrictions). Additional sample is needed to help establish trend. Resample at half normal interval. Please provide equipment make and model as well as the full name and grade of the lubricant in service.

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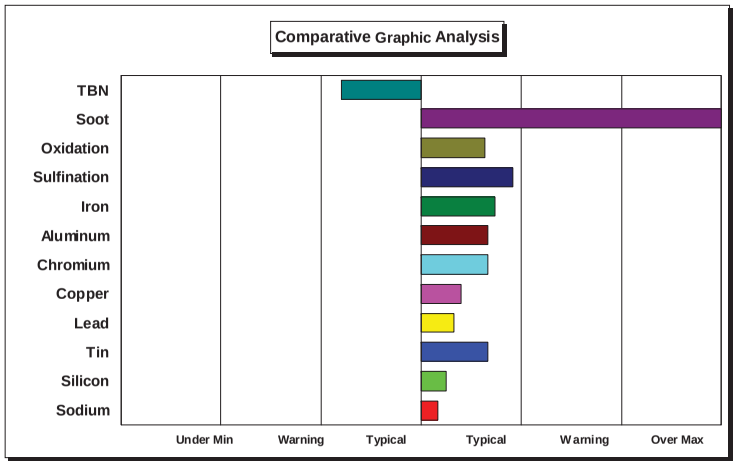
* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number Sample Date	Minimum	Maximum	V1183634 09/11/12
Unit Time (HR)			1069
Fluid Time (HR)			0
Vis @ 100 Deg C	12.50	16.80	15.01
TBN mg KOH/g	3.00		5.02
FTIR			
Soot % wt.		3.0	**3.6
Oxidation Abs/cm		30	16
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	23
Fuel % Vol		2.5	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		67	42
Aluminum ppm		4	2
Chromium ppm		4	2
Copper ppm		6	2
Lead ppm		4	1
Tin ppm		4	2
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	3
Sodium ppm		50	5
Boron ppm			2
Zinc ppm			1222
Phosphorus ppm			1059
Calcium ppm			2291
Magnesium ppm			61
Barium ppm			<1
Molybdenum ppm			3
Potassium ppm		50	<3

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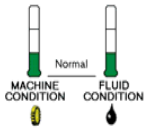
MONITOR



Lab Number : V1190418

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-22OCT2012 - FY09-111-22oct2012-oil, Diesel Engine

11/02/12
11:01:43

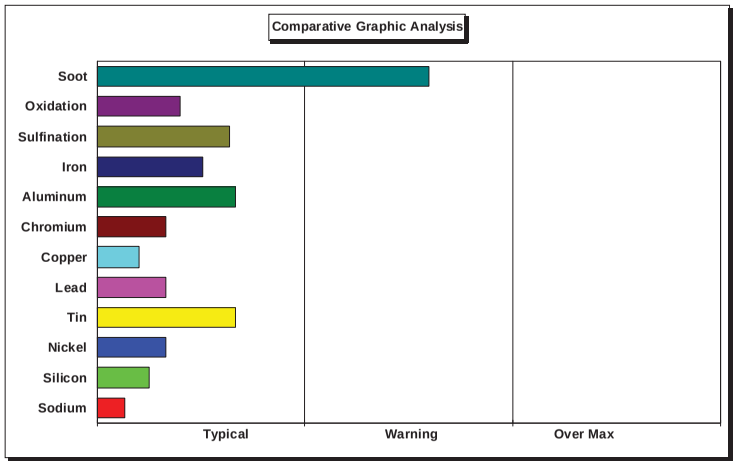
Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : JK110737
Sampled : 10/22/12 Shipped : 10/29/12 Received: 10/30/12 Printed: 11/02/12

MONITOR: Data for machine and/or fluid condition should be noted and monitored. Soot content is high. Please provide equipment make and model as well as the full name and grade of the lubricant in service. Additional sample is needed to help establish trend. Resample at half normal interval.

Attachment 4

ISO 9001:2008 and ISO/IEC 17025:2005 Certified

* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number Sample Date	Minimum	Maximum	V1190418 10/22/12
Unit Time (HR)			1625
Fluid Time (HR)			0
Vis @ 100 Deg C	12.50	16.80	14.43
TBN mg KOH/g	3.00		4.67
FTIR			
Soot % wt.		3.0	*2.8
Oxidation Abs/cm		30	10
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	16
Fuel % Vol		2.5	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		66	29
Aluminum ppm		4	2
Chromium ppm		4	1
Copper ppm		6	1
Lead ppm		4	1
Tin ppm		4	2
Nickel ppm		4	1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	3
Sodium ppm		50	4
Boron ppm			2
Zinc ppm			1199
Phosphorus ppm			1008
Calcium ppm			2296
Magnesium ppm			7
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm		50	<3

Evaluated By: Bobby R Licu, Senior Evaluator - For questions about this report, please call 888-437-4884. **Code :LOVEMC Lovelace Respiratory Research Institute** **Phone :(505) 348-9600 Fax :(505) 348-4980**

These results are submitted pursuant to our current Terms, Conditions and Limitations and Laboratory Pricing Policy. No responsibility or liability is assumed for the manner in which these results are used or interpreted.

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ABNORMAL

Abnormal / Normal
MACHINE CONDITION FLUID CONDITION

Lab Number : V1186752

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-03OCT12-OIL - FY09-111-03OCT2012-OIL, Diesel Engine

10/09/12
12:18:10

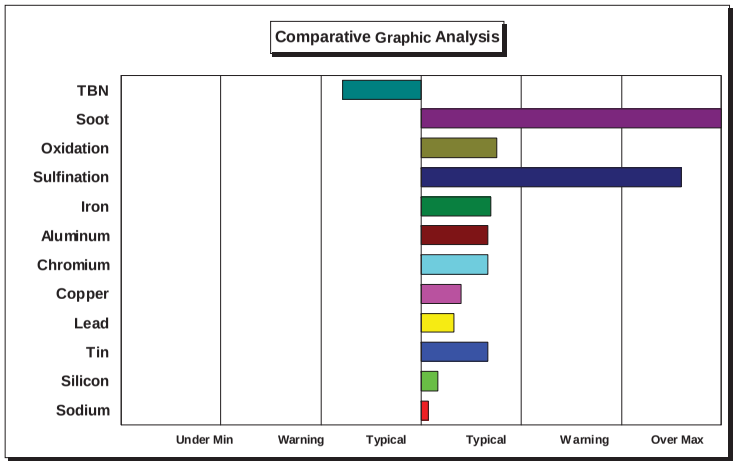
Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : JK120015
Sampled : 10/03/12 Shipped : 10/04/12 Received: 10/05/12 Printed: 10/09/12

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. FTIR indicates oil is sulfinated. Drain oil and change filter(s). Check for proper combustion properties (exhaust back pressure, operating temperatures, worn/broken rings, excessive idling, hung valves, improper fuel settings, air intake restrictions). Additional sample is needed to help establish trend. Resample at half normal interval.

Attachment 4

ISO 9001:2008 and ISO/IEC 17025:2005 Certified

* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number Sample Date	Minimum	Maximum	V1186752 10/03/12
Unit Time (HR)			1376
Fluid Time (HR)			0
Vis @ 100 Deg C	12.50	16.80	14.95
TBN mg KOH/g	3.00		5.08
FTIR			
Soot % wt.		3.0	**3.7
Oxidation Abs/cm		30	19
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	**33
Fuel % Vol		2.5	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		67	40
Aluminum ppm		4	2
Chromium ppm		4	2
Copper ppm		6	2
Lead ppm		4	1
Tin ppm		4	2
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			1
Silicon ppm		20	2
Sodium ppm		50	2
Boron ppm			1
Zinc ppm			1155
Phosphorus ppm			995
Calcium ppm			2407
Magnesium ppm			7
Barium ppm			<1
Molybdenum ppm			1
Potassium ppm		50	<3

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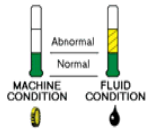
ABNORMAL



Lab Number : V1192703

Tom Holmes
Lovelace Respiratory Research Institute
2425 Ridgecrest Drive, SE

Albuquerque, NM 87108

ID: FY09-111-12NOV12-OIL - FY09-111-12Nov2012-Oil, Diesel Engine

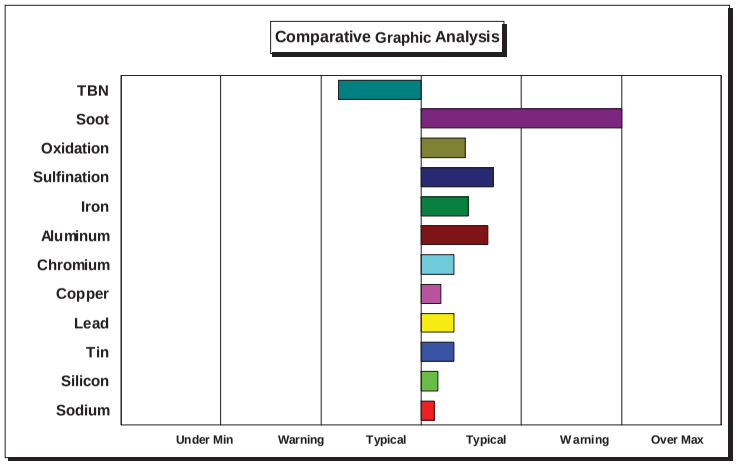
Page 1
11/16/12
10:46:39

Unit Type : Engine, Diesel (GN_DE001)
Oil Type : SAE 40 (GN_032) P.O. : JK120015
Sampled : 11/12/12 Shipped : 11/13/12 Received: 11/14/12 Printed: 11/16/12

ABNORMAL: Abnormal results for fluid are present. Equipment appears satisfactory. Soot content is high. Levels may be due to oil service time (not provided). Drain oil and change filter(s). Additional sample is needed to help establish trend. Resample at half normal interval. Please provide equipment make and model as well as the full name and grade of the lubricant in service.

ISO 9001:2008 and ISO/IEC 17025:2005 Certified

* = exceeds Caution limit ** = exceeds Alarm limit



Lab Number Sample Date	Minimum	Maximum	V1192703 11/12/12
Unit Time (HR)			1889
Fluid Time (HR)			0
Vis @ 100 Deg C	12.50	16.80	14.40
TBN mg KOH/g	3.00		4.83
FTIR			
Soot % wt.		3.0	*3.0
Oxidation Abs/cm		30	11
Water FTIR % Vol		0.20	<0.10
Sulfination Abs/		30	18
Fuel % Vol		2.5	<2.0
Glycol % Vol		0.20	<0.10
Metals			
Iron ppm		66	26
Aluminum ppm		4	2
Chromium ppm		4	1
Copper ppm		6	1
Lead ppm		4	1
Tin ppm		4	1
Nickel ppm		4	<1
Silver ppm		4.5	<0.1
Antimony ppm			<1
Silicon ppm		20	2
Sodium ppm		50	4
Boron ppm			<1
Zinc ppm			1185
Phosphorus ppm			923
Calcium ppm			2264
Magnesium ppm			6
Barium ppm			<1
Molybdenum ppm			<1
Potassium ppm		50	<3

These results are submitted pursuant to our current Terms, Conditions and Limitations and Laboratory Pricing Policy. No responsibility or liability is assumed for the manner in which these results are used or interpreted.

Appendix C.

Exposure Summary for Routine Monitoring of Exposure Atmospheres

Exposure Summary for Routine Monitoring of Exposure Atmospheres (Total)

	Tunnel	High Level Chamber									Filter	
Date	NO_x (ppm)	NO (ppm)	NO_x (ppm)	NO_2 (ppm)	CO_2 (ppm)	CO (ppm)	HC (ppm)	SO_2 (ppb)	DMM ($\mu g/m^3$)	PASS ($\mu g/m^3$)	Inlet ($\mu g/m^3$)	Chamber ($\mu g/m^3$)
May-10	28.97	4.76	8.32	3.56	4710	7.5	0.2	23	21.4	0.7	13	43
	29.90	5.21	10.19	4.98	4902	6.8	0.0	24	*	*	*	45
Jun-10	27.96	4.80	8.88	4.08	4670	8.1	0.3	17	*	*	*	15
	28.50	4.07	7.06	2.99	4563	7.6	0.2	18	8.3	0.7	11	38
	28.76	4.73	7.12	3.14	4563	7.4	0.2	18	3.5	0.5	*	32
Jul-10	26.73	5.83	10.18	4.36	4859	10.4	0.6	22	32.1	1.5	*	31
	26.42	4.08	6.57	2.49	4948	10.1	0.5	22	*	*	11	32
	26.40	4.72	7.81	3.08	4962	10.5	0.6	21	8.2	0.8	*	19
Aug-10	22.57	5.27	9.24	3.97	5768	13.7	0.1	22	59.5	1.6	16	42
	22.53	5.61	9.81	4.20	5888	13.4	0.2	22	*	*	19	28
	22.47	6.43	10.41	3.98	5526	12.9	0.2	22	*	*	*	*
Sep-10	22.82	4.33	8.28	3.95	5862	8.4	*	18	35.4	0.9	*	*
	22.76	4.74	9.19	4.45	5717	8.6	*	18	9.0	0.5	8	20
	22.77	5.33	9.99	4.66	5749	8.6	*	18	*	*	*	*
Oct-10	21.04	4.65	8.77	4.12	5928	9.7	*	19	*	*	*	*
	26.53	5.30	10.12	4.82	5087	3.7	0.6	24	4.1	0.1	6	25
	21.19	4.79	9.02	4.24	5955	9.8	*	19	*	*	*	*
Nov-10	25.75	5.78	10.35	4.58	5071	3.8	0.6	22	*	*	*	*
	26.53	5.30	10.12	4.82	5087	3.7	0.6	24	4.1	0.1	6	25
	25.67	5.03	9.50	4.48	5092	3.8	0.6	23	*	*	*	*
Dec-10	28.41	6.26	10.31	4.06	4668	4.1	-0.1	22	*	*	*	*
	28.39	4.81	8.63	3.82	4760	4.1	0.0	22	3.3	0.1	5	12
	29.09	5.41	9.82	4.41	4800	4.0	-0.1	22	*	*	*	*
Jan-11	29.67	7.02	11.32	4.30	4702	4.2	1.1	26	*	*	*	*
	29.95	5.65	10.01	4.36	4702	4.3	1.3	26	2.2	0.1	4	18
	29.84	5.82	9.79	3.97	4695	4.2	1.1	26	*	*	*	*

NO_x = oxides of nitrogen, NO= Nitrogen monoxide. NO_2 = nitrogen dioxide. CO_2 = carbon dioxide, CO = carbon monoxide, HC= hydrocarbon, SO_2 = sulfur dioxide; DMM = Dekati mass monitor, PASS = photoacoustic soot monitor.
*No data were collected during that period due to study design or instrument failure.

Exposure Summary for Routine Monitoring of Exposure Atmospheres (Total)

	Tunnel	High Level Chamber									Filter	
Date	NO_x (ppm)	NO (ppm)	NO_x (ppm)	NO_2 (ppm)	CO_2 (ppm)	CO (ppm)	HC (ppm)	SO_2 (ppb)	DMM ($\mu g/m^3$)	PASS ($\mu g/m^3$)	Inlet ($\mu g/m^3$)	Chamber ($\mu g/m^3$)
Feb-11	38.22	6.90	11.25	4.35	5534	5.1	0.9	32	*	*	*	*
	38.05	6.97	11.94	4.97	5502	5.1	0.9	32	3.3	0.1	5	21
	37.85	5.99	10.18	4.18	5504	5.1	0.9	33	*	*	*	*
Mar-11	41.20	7.00	11.13	4.14	5165	5.1	0.4	29	*	*	*	*
	40.83	6.26	10.60	4.34	5180	5.1	0.4	30	1.7	0.0	5	16
	41.14	6.64	11.02	4.38	5198	5.0	0.4	30	*	*	*	*
Apr-11	41.80	8.10	12.69	4.60	5346	5.7	1.2	32	*	*	*	*
	41.75	6.82	11.25	4.44	5308	5.9	1.2	34	2.0	0.1	4	35
	42.04	6.78	10.91	4.13	5355	5.8	1.0	34	*	*	*	*
May-11	40.38	8.31	12.66	4.35	5260	7.1	1.1	28	*	*	*	*
	39.76	7.03	11.44	4.42	5234	7.1	1.1	28	3.7	0.1	8	20
	40.30	7.01	11.16	4.16	5309	7.1	1.0	28	*	*	*	*
Jun-11	28.29	8.16	12.22	4.06	5228	7.3	1.1	33	*	*	*	*
	28.24	7.65	11.97	4.32	5219	7.7	1.1	34	5.7	0.2	7	21
	28.48	7.57	11.77	4.20	5262	7.4	1.2	33	*	*	*	*
Jul-11	24.05	9.80	13.69	3.89	5969	10.9	1.4	31	*	*	*	*
	24.08	8.17	12.16	4.00	5945	11.0	1.4	31	15.6	0.7	12	22
	24.13	8.86	13.14	4.28	5929	11.8	1.1	30	*	*	*	*
Aug-11	28.52	8.82	12.86	4.04	5797	7.3	1.5	34	*	*	*	*
	28.88	8.92	13.49	4.58	5792	7.1	1.5	34	36.3	0.5	15	23
	29.10	7.64	11.68	4.04	5805	7.3	1.5	34	*	*	*	*
Sep-11	29.56	9.01	13.36	4.36	5416	5.2	0.6	31	*	*	*	*
	30.13	7.75	12.16	4.42	5495	5.5	0.6	32	35.8	0.4	16	49
	29.94	7.83	12.21	4.39	5452	5.2	0.6	32	*	*	*	*

NO_x = oxides of nitrogen, NO= Nitrogen monoxide. NO_2 = nitrogen dioxide. CO_2 = carbon dioxide, CO = carbon monoxide, HC= hydrocarbon, SO_2 = sulfur dioxide; DMM = Dekati mass monitor, PASS = photoacoustic soot monitor.
*No data were collected during that period due to study design or instrument failure.

Exposure Summary for Routine Monitoring of Exposure Atmospheres (Total)

	Tunnel	High Level Chamber									Filter	
Date	NO_x (ppm)	NO (ppm)	NO_x (ppm)	NO_2 (ppm)	CO_2 (ppm)	CO (ppm)	HC (ppm)	SO_2 (ppb)	DMM ($\mu g/m^3$)	PASS ($\mu g/m^3$)	Inlet ($\mu g/m^3$)	Chamber ($\mu g/m^3$)
Oct-11	31.09	8.06	12.00	3.95	5110	2.3	0.3	33	*	*	*	*
	31.52	7.04	11.30	4.26	5008	2.5	0.3	32	20.3	0.4	22	39
	31.72	7.27	11.53	4.26	5077	2.5	0.3	33	*	*	*	*
Nov-11	34.24	8.97	13.02	4.05	5189	2.0	0.0	39	*	*	*	*
	34.24	7.66	11.72	4.05	5154	2.1	-0.4	38	5.8	0.2	9	32
	33.97	7.60	11.61	4.01	5171	2.1	-0.2	38	*	*	*	*
Dec-11	31.68	2.91	4.32	4.06	5484	3.4	0.1	38	*	*	*	*
	31.83	8.59	12.72	4.13	5406	3.2	0.0	39	6.5	0.2	15	27
	30.76	8.81	12.61	3.80	5418	2.9	0.0	40	*	*	*	*
Jan-12	32.68	9.04	13.44	4.41	4712	3.0	0.0	39	*	*	*	*
	32.35	8.44	12.59	4.15	4722	2.9	0.1	40	4.7	0.1	10	29
	32.53	9.16	13.39	4.24	4734	3.0	0.0	40	*	*	*	*
Feb-12	33.93	9.99	14.32	4.33	5540	3.6	0.3	47	*	*	*	*
	34.00	9.99	14.42	4.43	5373	3.6	0.3	46	6.5	0.1	11	46
	33.52	11.01	15.34	4.33	5492	3.5	0.4	47	*	*	*	*
Mar-12	35.20	10.19	14.54	4.36	5065	3.9	0.0	47	*	*	*	*
	35.19	9.74	14.11	4.38	5097	3.9	0.0	47	4.0	0.1	16	25
	35.13	10.24	14.58	4.35	5015	3.9	0.0	47	*	*	*	*
Apr-12	33.33	8.84	12.88	4.04	4706	4.0	0.0	39	*	*	*	*
	33.23	8.68	12.77	4.33	4720	4.0	0.0	36	3.8	0.1	11	26
	33.02	9.63	13.81	4.18	4737	3.8	0.0	36	*	*	*	*
May-12	31.33	9.32	13.29	3.97	4577	4.2	0.1	7	*	*	*	*
	31.38	9.11	13.39	4.29	4510	4.0	0.0	7	5.9	0.1	13	19
	31.14	10.11	14.51	4.41	4668	4.0	0.0	7	*	*	*	*

NO_x = oxides of nitrogen, NO= Nitrogen monoxide. NO_2 = nitrogen dioxide. CO_2 = carbon dioxide, CO = carbon monoxide, HC= hydrocarbon, SO_2 = sulfur dioxide; DMM = Dekati mass monitor, PASS = photoacoustic soot monitor.
*No data were collected during that period due to study design or instrument failure.

Exposure Summary for Routine Monitoring of Exposure Atmospheres (Total)

	Tunnel	High Level Chamber									Filter	
Date	NO_x (ppm)	NO (ppm)	NO_x (ppm)	NO_2 (ppm)	CO_2 (ppm)	CO (ppm)	HC (ppm)	SO_2 (ppb)	DMM ($\mu g/m^3$)	PASS ($\mu g/m^3$)	Inlet ($\mu g/m^3$)	Chamber ($\mu g/m^3$)
Jun-12	29.17	9.14	13.42	4.28	5208	9.0	*	38	*	*	*	*
	29.09	8.88	13.29	4.42	5123	9.0	*	38	5.0	0.1	11	21
	28.91	9.12	13.52	4.40	5162	9.1	*	41	*	*	*	*
Jul-12	24.04	8.83	12.85	4.02	5241	8.3	*	32	*	*	*	*
	24.11	8.73	13.13	4.40	5310	8.3	*	32	34.0	0.2	15	24
	24.24	8.78	12.94	4.17	5356	8.1	*	32	*	*	*	*
Aug-12	27.95	10.48	14.87	4.39	5038	6.3	0.2	35	*	*	*	*
	28.21	9.20	13.62	4.42	5083	6.8	0.2	35	9.4	0.2	13	26
	28.07	9.99	14.69	4.71	5009	6.4	0.2	34	*	*	*	*
Sep-12	30.15	*	*	*	5162	6.4	0.2	38	*	*	*	*
	30.85	8.24	12.58	4.35	4263	4.7	0.3	36	10.5	0.2	16	24
	30.67	8.94	13.45	4.51	4271	4.6	0.3	36	*	*	*	*
Oct-12	30.10	8.53	13.08	4.56	4244	4.6	0.2	39	7.6	0.2	34	42
	30.11	9.45	14.13	4.68	4214	4.7	0.2	40	*	*	*	*
Nov-12	26.35	8.62	12.90	4.29	4009	4.6	0.1	39	6.5	0.2	23	104
	26.57	9.75	14.23	4.49	3960	5.1	0.1	38	*	*	*	*
Dec-12	24.96	9.17	13.91	4.75	4321	5.6	0.1	46	4.1	0.2	6	44
	25.14	9.81	14.12	4.31	4370	5.5	0.1	50	*	*	*	*
average	30.28	7.54	11.72	4.23	5114	6.0	0.45	31	12.3	0.4	12	31
stdev	5.17	1.88	2.14	0.38	468	2.7	0.48	9	13.6	0.4	6	16
%cv	17.1%	25.0%	18.3%	9.0%	9.2%	45.2%	104.6%	29.8%	110.8%	108.9%	53.1%	51.0%
min	21.04	2.91	4.32	2.49	3960	2.0	-0.38	7	1.7	0.0	4	12
max	42.04	11.01	15.34	4.98	5969	13.7	1.48	50	59.5	1.6	34	104
%target				**101%**								

NO_x = oxides of nitrogen, NO= Nitrogen monoxide. NO_2 = nitrogen dioxide. CO_2 = carbon dioxide, CO = carbon monoxide, HC= hydrocarbon, SO_2 = sulfur dioxide; DMM = Dekati mass monitor, PASS = photoacoustic soot monitor.
*No data were collected during that period due to study design or instrument failure.

Exposure Summary for Routine Monitoring of Exposure Atmospheres (Total)

	Tunnel	Mid Level Chamber					Filter	
Date	NO_x (ppm)	NO (ppm)	NO_x (ppm)	NO_2 (ppm)	DMM ($\mu g/m^3$)	PASS ($\mu g/m^3$)	Inlet ($\mu g/m^3$)	Chamber ($\mu g/m^3$)
May-10	28.97	0.96	1.82	0.86	*	*	4	55
	29.90	1.41	2.57	1.17	*	*	*	47
Jun-10	27.96	1.00	1.89	0.89	*	*	*	20
	28.50	1.14	2.14	0.99	*	*	3	34
	28.76	1.57	2.53	1.05	*	*	*	24
Jul-10	26.73	1.43	2.51	1.08	*	*	*	27
	26.42	1.08	1.80	0.72	*	*	3	37
	26.40	1.48	2.26	0.77	*	*	*	26
Aug-10	22.57	2.13	3.37	1.24	*	*	*	*
	22.53	1.44	2.39	0.95	*	*	10	11
	22.47	1.75	2.62	0.86	*	*	*	*
Sep-10	22.82	1.32	2.24	0.91	*	*	*	*
	22.76	1.17	2.17	1.00	1.6	*	3	16
	22.77	1.18	2.10	0.92	*	*	*	*
Oct-10	21.04	1.13	1.95	0.83	*	*	*	*
	26.53	1.21	2.18	0.98	*	*	5	75
	21.19	1.22	2.06	0.84	*	*	*	*
Nov-10	25.75	1.34	2.25	0.91	*	*	*	*
	26.53	1.21	2.18	0.98	*	*	5	75
	25.67	1.32	2.16	0.84	*	*	*	*
Dec-10	28.41	1.38	2.21	0.83	*	*	*	*
	28.39	1.25	2.16	0.91	*	*	5	18
	29.09	1.25	2.08	0.84	*	*	*	*
Jan-11	29.67	1.43	2.28	0.85	*	*	*	*
	29.95	1.29	2.13	0.84	*	*	2	17
	29.84	1.59	2.53	0.93	*	*	*	*

NO_x = oxides of nitrogen, NO= Nitrogen monoxide. NO_2 = nitrogen dioxide. CO_2 = carbon dioxide, CO = carbon monoxide, HC= hydrocarbon, SO_2 = sulfur dioxide; DMM = Dekati mass monitor, PASS = photoacoustic soot monitor.

*No data were collected during that period due to study design or instrument failure.

Exposure Summary for Routine Monitoring of Exposure Atmospheres (Total)

	Tunnel	Mid Level Chamber					Filter	
Date	NO_x (ppm)	NO (ppm)	NO_x (ppm)	NO_2 (ppm)	DMM ($\mu g/m^3$)	PASS ($\mu g/m^3$)	Inlet ($\mu g/m^3$)	Chamber ($\mu g/m^3$)
Feb-11	38.22	1.44	2.27	0.83	*	*	*	*
	38.05	1.46	2.40	0.95	*	*	2	26
	37.85	1.84	2.85	1.01	*	*	*	*
Mar-11	41.20	1.48	2.31	0.83	*	*	*	*
	40.83	1.46	2.29	0.83	*	*	2	22
	41.14	1.44	2.27	0.83	*	*	*	*
Apr-11	41.80	1.67	2.62	0.95	*	*	*	*
	41.75	1.57	2.42	0.85	0.5	0.0	1	11
	42.04	1.57	2.42	0.85	*	*	*	*
May-11	40.38	1.57	2.40	0.83	*	*	*	*
	39.76	1.50	2.32	0.83	*	*	2	26
	40.30	1.61	2.42	0.81	*	*	*	*
Jun-11	28.29	1.61	2.42	0.81	*	*	*	*
	28.24	1.61	2.43	0.83	*	*	2	19
	28.48	1.85	2.74	0.88	*	*	*	*
Jul-11	24.05	1.93	2.74	0.82	*	*	*	*
	24.08	1.79	2.57	0.80	*	*	3	19
	24.13	2.18	3.00	0.84	*	*	*	*
Aug-11	28.52	2.14	3.07	0.94	*	*	*	*
	28.88	1.82	2.60	0.78	*	*	2	10
	29.10	2.23	3.03	0.80	*	*	*	*
Sep-11	29.56	1.71	2.55	0.84	*	*	*	*
	30.13	1.78	2.62	0.84	*	*	6	13
	29.94	2.09	2.95	0.85	*	*	*	*
Oct-11	31.09	1.63	2.45	0.82	*	*	*	*
	31.52	1.61	2.50	0.89	*	*	4	28
	31.72	1.68	2.50	0.82	*	*	*	*

NO_x = oxides of nitrogen, NO= Nitrogen monoxide. NO_2 = nitrogen dioxide. CO_2 = carbon dioxide, CO = carbon monoxide, HC= hydrocarbon, SO_2 = sulfur dioxide; DMM = Dekati mass monitor, PASS = photoacoustic soot monitor.

*No data were collected during that period due to study design or instrument failure.

Exposure Summary for Routine Monitoring of Exposure Atmospheres (Total)

	Tunnel	Mid Level Chamber					Filter	
Date	NO_x (ppm)	NO (ppm)	NO_x (ppm)	NO_2 (ppm)	DMM ($\mu g/m^3$)	PASS ($\mu g/m^3$)	Inlet ($\mu g/m^3$)	Chamber ($\mu g/m^3$)
Nov-11	34.24	1.57	2.40	0.83	*	*	*	*
	34.24	1.50	2.32	0.82	*	*	2	16
	33.97	1.72	2.50	0.78	*	*	*	*
Dec-11	31.68	1.36	2.14	0.78	*	*	*	*
	31.83	1.61	2.43	0.82	*	*	10	98
	30.76	1.76	2.52	0.76	*	*	*	*
Jan-12	32.68	1.47	2.29	0.82	*	*	*	*
	32.35	1.65	2.47	0.82	*	*	2	20
	32.53	1.72	2.56	0.83	*	*	*	*
Feb-12	33.93	1.59	2.40	0.81	*	*	*	*
	34.00	1.67	2.48	0.81	*	*	6	25
	33.52	2.01	2.83	0.82	*	*	*	*
Mar-12	35.20	1.60	2.47	0.86	*	*	*	*
	35.19	1.75	2.55	0.81	*	*	6	36
	35.13	1.79	2.60	0.82	*	*	*	*
Apr-12	33.33	1.46	2.30	0.83	*	*	*	*
	33.23	1.58	2.40	0.82	*	*	4	26
	33.02	1.63	2.42	0.79	*	*	*	*
May-12	31.33	1.48	2.27	0.79	*	*	*	*
	31.38	1.72	2.54	0.83	*	*	7	41
	31.14	1.82	2.64	0.82	*	*	*	*
Jun-12	29.17	1.50	2.32	0.82	*	*	*	*
	29.09	1.69	2.55	0.86	*	*	3	21
	28.91	1.80	2.61	0.81	*	*	*	*
Jul-12	24.04	1.87	2.74	0.87	*	*	*	*
	24.11	2.00	2.85	0.85	*	*	4	24
	24.24	2.11	2.88	0.78	*	*	*	*

NO_x = oxides of nitrogen, NO= Nitrogen monoxide. NO_2 = nitrogen dioxide. CO_2 = carbon dioxide, CO = carbon monoxide, HC= hydrocarbon, SO_2 = sulfur dioxide; DMM = Dekati mass monitor, PASS = photoacoustic soot monitor.
*No data were collected during that period due to study design or instrument failure.

Exposure Summary for Routine Monitoring of Exposure Atmospheres (Total)

	Tunnel	Mid Level Chamber					Filter	
Date	NO_x (ppm)	NO (ppm)	NO_x (ppm)	NO_2 (ppm)	DMM ($\mu g/m^3$)	PASS ($\mu g/m^3$)	Inlet ($\mu g/m^3$)	Chamber ($\mu g/m^3$)
Aug-12	27.95	2.27	3.07	0.80	*	*	*	*
	28.21	2.29	3.16	0.86	*	*	4	23
	28.07	3.47	4.38	0.91	*	*	*	*
Sep-12	30.15	2.75	4.06	1.31	*	*	*	*
	30.85	2.80	3.81	1.01	*	*	6	24
	30.67	2.77	3.64	0.88	*	*	*	*
Oct-12	30.10	1.78	2.67	0.89	*	*	13	32
	30.11	1.88	2.85	0.97	*	*	*	*
Nov-12	26.35	1.83	2.79	0.96	*	*	12	38
	26.57	1.92	2.88	0.96	*	*	*	*
Dec-12	24.96	1.57	2.44	0.87	*	*	23	50
	25.14	2.64	3.82	1.19	*	*	*	*
average	30.28	1.68	2.55	0.88	1.1	0.0	5	30
stdev	5.17	0.41	0.45	0.10	0.7	*	4	19
%cv	17.1%	24.6%	17.5%	11.6%	69.1%	*	86.5%	63.0%
min	21.04	0.96	1.80	0.72	0.5	0.0	1	10
max	42.04	3.47	4.38	1.31	1.6	0.0	23	98
%target				**110%**				

NO_x = oxides of nitrogen, NO= Nitrogen monoxide. NO_2 = nitrogen dioxide. CO_2 = carbon dioxide, CO = carbon monoxide, HC= hydrocarbon, SO_2 = sulfur dioxide; DMM = Dekati mass monitor, PASS = photoacoustic soot monitor.
*No data were collected during that period due to study design or instrument failure.

Exposure Summary for Routine Monitoring of Exposure Atmospheres (Total)

Date	Tunnel	Low Level Chamber					Filter		Control Chamber					Filter
	NO_x (ppb)	NO (ppb)	NO_x (ppb)	NO_2 (ppb)	DMM ($\mu g/m^3$)	PASS ($\mu g/m^3$)	Inlet ($\mu g/m^3$)	Chamber ($\mu g/m^3$)	NO (ppb)	NO_x (ppb)	NO_2 (ppb)	DMM ($\mu g/m^3$)	PASS ($\mu g/m^3$)	Chamber ($\mu g/m^3$)
May-10	28.97	121	237	117	*	*	1	59	2	5	4	*	*	39
	29.90	284	414	131	*	*	*	*	1	-1	-2	*	*	77
Jun-10	27.96	79	180	101	*	*	*	12	1	2	1	*	*	10
	28.50	113	224	111	*	*	3	38	2	9	7	*	*	74
	28.76	134	252	118	*	*	*	29	2	9	7	*	*	30
Jul-10	26.73	142	283	141	*	*	*	14	1	-1	-2	*	*	21
	26.42	159	266	107	*	*	1	21	1	-2	-3	*	*	28
	26.40	205	336	131	*	*	*	18	1	1	0	*	*	23
Aug-10	22.57	130	206	76	*	*	*	*	15	55	39	*	*	*
	22.53	206	323	117	*	*	2	12	20	47	27	*	*	25
	22.47	140	240	99	*	*	*	*	18	46	28	*	*	*
Sep-10	22.82	219	347	126	*	*	*	*	0	0	0	*	*	*
	22.76	189	307	117	*	*	2	12	0	0	0	*	*	22
	22.77	152	259	106	*	*	*	*	0	0	0	*	*	*
Oct-10	21.04	212	306	94	*	*	*	*	1	-2	-4	*	*	*
	26.53	220	334	114	*	*	1	17	2	-13	-15	*	*	19
	21.19	167	267	103	*	*	*	*	1	-3	-4	*	*	*
Nov-10	25.75	225	327	102	*	*	*	*	2	-14	-16	*	*	*
	26.53	220	334	114	*	*	1	17	2	-13	-15	*	*	19
	25.67	233	362	129	*	*	*	*	2	-14	-16	*	*	*
Dec-10	28.41	429	532	103	*	*	*	*	0	-1	-1	*	*	*
	28.39	325	420	95	*	*	2	10	0	-1	-1	*	*	14
	29.09	343	463	119	*	*	*	*	0	-1	-1	*	*	*
Jan-11	29.67	401	498	97	*	*	*	*	3	-7	-10	*	*	*
	29.95	346	453	107	*	*	2	17	3	-7	-10	*	*	35
	29.84	299	401	102	*	*	*	*	3	-7	-10	*	*	*

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Exposure Summary for Routine Monitoring of Exposure Atmospheres (Total)

Date	Tunnel	Low Level Chamber					Filter		Control Chamber					Filter
	NO_x (ppb)	NO (ppb)	NO_x (ppb)	NO_2 (ppb)	DMM ($\mu g/m^3$)	PASS ($\mu g/m^3$)	Inlet ($\mu g/m^3$)	Chamber ($\mu g/m^3$)	NO (ppb)	NO_x (ppb)	NO_2 (ppb)	DMM ($\mu g/m^3$)	PASS ($\mu g/m^3$)	Chamber ($\mu g/m^3$)
Feb-11	38.22	467	583	117	*	*	*	*	1	-22	-24	*	*	*
	38.05	323	414	91	*	*	2	25	1	-23	-24	*	*	21
	37.85	423	528	105	*	*	*	*	1	-21	-23	*	*	*
Mar-11	41.20	466	564	98	*	*	*	*	2	-12	-13	*	*	*
	40.83	513	615	102	*	*	1	27	2	-12	-14	*	*	33
	41.14	732	837	105	*	*	*	*	2	-12	-13	*	*	*
Apr-11	41.80	507	617	110	*	*	*	*	2	-11	-13	*	*	*
	41.75	589	703	114	0.4	0.0	2	15	2	-11	-13	0.4	-0.1	8
	42.04	663	774	111	*	*	*	*	2	-11	-13	*	*	*
May-11	40.38	235	335	100	*	*	*	*	-3	-14	-11	*	*	*
	39.76	267	370	104	0.2	-0.1	2	14	-3	-14	-11	*	*	21
	40.30	260	362	102	*	*	*	*	-3	-14	-11	*	*	*
Jun-11	28.29	226	325	99	*	*	*	*	1	-7	-7	*	*	*
	28.24	253	352	99	*	*	2	16	1	-6	-7	*	*	14
	28.48	239	343	105	*	*	*	*	0	-7	-7	*	*	*
Jul-11	24.05	414	508	94	*	*	*	*	-1	-14	-14	*	*	*
	24.08	439	532	96	*	*	1	18	-2	-17	-14	*	*	11
	24.13	458	553	96	*	*	*	*	6	-6	-12	*	*	*
Aug-11	28.52	1166	1257	92	*	*	*	*	2	-45	-47	*	*	*
	28.88	968	1058	91	*	*	1	10	3	-43	-46	*	*	14
	29.10	1234	1329	97	*	*	*	*	2	-44	-47	*	*	*
Sep-11	29.56	718	830	119	*	*	*	*	3	5	1	*	*	*
	30.13	599	701	103	*	*	2	21	3	4	0	*	*	21
	29.94	861	963	108	*	*	*	*	4	3	0	*	*	*

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Exposure Summary for Routine Monitoring of Exposure Atmospheres (Total)

Date	Tunnel	Low Level Chamber					Filter		Control Chamber					Filter
	NO_x (ppb)	NO (ppb)	NO_x (ppb)	NO_2 (ppb)	DMM ($\mu g/m^3$)	PASS ($\mu g/m^3$)	Inlet ($\mu g/m^3$)	Chamber ($\mu g/m^3$)	NO (ppb)	NO_x (ppb)	NO_2 (ppb)	DMM ($\mu g/m^3$)	PASS ($\mu g/m^3$)	Chamber ($\mu g/m^3$)
Oct-11	31.09	293	399	106	*	*	*	*	2	1	-1	*	*	*
	31.52	262	363	101	*	*	2	23	2	1	-1	*	*	37
	31.72	298	400	103	*	*	*	*	2	1	-1	*	*	*
Nov-11	34.24	283	390	108	*	*	*	*	-1	-5	-4	*	*	*
	34.24	266	366	101	*	*	1	20	-1	-4	-3	*	*	23
	33.97	308	408	100	*	*	*	*	-1	-5	-4	*	*	*
Dec-11	31.68	227	318	92	*	*	*	*	-3	-7	-5	*	*	*
	31.83	264	366	102	*	*	1	25	-2	-5	-3	*	*	11
	30.76	344	445	101	*	*	*	*	-2	-6	-4	*	*	*
Jan-12	32.68	252	357	104	*	*	*	*	0	-1	-1	*	*	*
	32.35	305	407	103	*	*	1	13	0	-1	-1	*	*	17
	32.53	329	433	104	*	*	*	*	0	-1	-1	*	*	*
Feb-12	33.93	361	459	98	*	*	*	*	-2	-8	-6	*	*	*
	34.00	375	478	103	*	*	1	23	-2	-8	-6	*	*	26
	33.52	437	542	105	*	*	*	*	-3	-9	-7	*	*	*
Mar-12	35.20	484	589	106	*	*	*	*	0	-2	-1	*	*	*
	35.19	483	585	102	*	*	3	29	0	-1	-1	*	*	33
	35.13	516	617	101	*	*	*	*	0	-1	-1	*	*	*
Apr-12	33.33	479	601	122	*	*	*	*	-1	0	0	*	*	*
	33.23	451	545	94	*	*	5	32	-1	0	1	*	*	16
	33.02	506	602	97	*	*	*	*	0	0	0	*	*	*
May-12	31.33	326	427	101	*	*	*	*	0	0	0	*	*	*
	31.38	422	525	103	*	*	2	65	0	0	0	*	*	10
	31.14	479	583	104	*	*	*	*	1	1	0	*	*	*

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Exposure Summary for Routine Monitoring of Exposure Atmospheres (Total)

Date	Tunnel	Low Level Chamber					Filter		Control Chamber					Filter
	NO_x (ppb)	NO (ppb)	NO_x (ppb)	NO_2 (ppb)	DMM ($\mu g/m^3$)	PASS ($\mu g/m^3$)	Inlet ($\mu g/m^3$)	Chamber ($\mu g/m^3$)	NO (ppb)	NO_x (ppb)	NO_2 (ppb)	DMM ($\mu g/m^3$)	PASS ($\mu g/m^3$)	Chamber ($\mu g/m^3$)
Jun-12	29.17	353	451	98	*	*	*	*	0	0	0	*	*	*
	29.09	391	493	102	*	*	2	13	0	0	0	*	*	30
	28.91	461	566	105	*	*	*	*	0	0	0	*	*	*
Jul-12	24.04	647	721	74	*	*	*	*	0	0	0	*	*	*
	24.11	558	649	91	*	*	2	14	0	0	0	*	*	29
	24.24	624	687	74	*	*	*	*	0	0	0	*	*	*
Aug-12	27.95	1176	1184	67	*	*	*	*	0	0	0	*	*	*
	28.21	821	849	64	*	*	1	20	0	0	0	*	*	17
	28.07	1115	1125	100	*	*	*	*	0	0	0	*	*	*
Sep-12	30.15	*	*	*	*	*	*	*	0	0	0	*	*	*
	30.85	1054	1159	132	*	*	3	33	0	0	0	*	*	21
	30.67	1326	1416	90	*	*	*	*	0	0	0	*	*	*
Oct-12	30.10	750	842	110	*	*	10	50	0	0	0	*	*	64
	30.11	1105	1168	147	*	*	*	*	0	0	0	*	*	*
Nov-12	26.35	355	458	103	*	*	25	43	0	0	0	*	*	24
	26.57	708	830	143	*	*	*	*	0	0	0	*	*	*
Dec-12	24.96	484	627	143	*	*	20	74	0	0	0	*	*	51
	25.14	469	551	82	*	*	*	*	0	0	0	*	*	*
average	30.28	438	539	105	0.3	-0.1	3	25	1	-4	-5	0.4	-0.1	27
stdev	5.17	278	268	15	0.2	0.0	5	16	4	14	12	*	*	16
%cv	17.1%	63.5%	49.8%	14.2%	60.4%	-54.5%	160.4%	62.7%	330.3%	-383.8%	-255.2%	*	*	61.6%
min	21.04	79	180	64	0.2	-0.1	1	10	-3	-45	-47	0.4	-0.1	8
max	42.04	1326	1416	147	0.4	0.0	25	74	20	55	39	0.4	-0.1	77
%target				**105%**										

NO_x = oxides of nitrogen, NO= Nitrogen monoxide. NO_2 = nitrogen dioxide. CO_2 = carbon dioxide, CO = carbon monoxide, HC= hydrocarbon, SO_2 = sulfur dioxide; DMM = Dekati mass monitor, PASS = photoacoustic soot monitor.
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Appendix D.

April 2010 – Detailed Atmosphere Characterization

April 2010 – Detailed Atmosphere Characterization

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Dekati Particle Mass-Chamber Inlet	µg/m³	NA	NA	NA	NA
Dekati Particle Mass-Inside Chamber	µg/m³	0.12 ± 0.07	0.08	0.65	10.3 ± 5.2
Filter Sample - Chamber Inlet	µg/m³	NA	1.0	3.0	8.3 ± 2.1
Filter Sample - Inside Chamber	µg/m³	22.0	34.0	23.0	28.3 ± 23.0
Particle Mass-FMPS	µg/m³	0.25 ± 0.03	0.42	0.81	2.93 ± 0.84
Particle Count -FMPS	Particle/cm³	370 ± 83.4	2.47E+03	4.26E+04	9.68e+04 ± 1.66e+04
NMAD (GSD) - FMPS	nm	26.6 (2.0) ± 0.71 (0.08)	15.4 (1.59)	14.3 (1.50)	20.17 (1.55) ± 6.40 (0.05)
MMAD (GSD) - FMPS	nm	419.6 (1.64) ± 6.22 (0.06)	351.8 (2.89)	45.4 (3.31)	44.17 (2.53) ± 1.72 (0.71)
Nitrogen Oxide (NO)	µg/m³ (ppm)	0.5 (0.0005)	77.5 ± 35.3 (0.08 ± 0.03)	883 ± 226 (0.86 ± 0.22)	4875 ± 728 (4.75 ± 0.71)
Nitrogen Dioxide (NO_2)	µg/m³ (ppm)	0	143 ± 59 (0.091 ± 0.038)	1306 ± 378 (0.83 ± 0.24)	6389 ± 1448 (4.06 ± 0.92)
Carbon Monoxide (CO)	µg/m³ (ppm)	383 ± 287 (0.4 ± 0.3)	699 (0.73)	1839 (1.92)	5977 ± 785 (6.24 ± 0.82)
Carbon Dioxide (CO_2)	mg/m³ (ppm)	1817 ± 54 (1207 ± 36)	1969 (1308)	3051 (2027)	5388 ± 343 (3580 ± 228)
Sulfur Dioxide (SO_2)	µg/m³(ppb)	6.1 ± 1.8 (2.7 ± 0.8)	6.8 (3)	19.4 (8.59)	53.2 ± 9 (23.6 ± 3.88)
Elemental Carbon	µg/m³	1.0 ± 0.05	1.6 ± 0.08	1.0 ± 0.04	2.7 ± 0.15
Organic Carbon	µg/m³	6.4 ± 0.22	6.6 ± 0.23	4.3 ± 0.13	6.1 ± 0.20
Ammonium	ng/m³	21.3	24.2 ± 0.3	67.0	1740.4 ± 0.3
Sulfate	ng/m³	71.2	61.0 ± 1.2	253.1 ± 0.1	1740.4 ± 0.9
Nitrate	ng/m³	10.4	72.1 ± 0.2	131.5	1193.3 ± 0.4
Elements (Metals)	ng/m³	730.4 ± 249.0	824.6 ± 243.7	1104.7 ± 242.1	823.8 ± 240.8
Alkanes	ng/m³	3.4 ± 0.2	3.6 ± 0.2	12.7 ± 0.8	26.7 ± 1.5
Carbonyl	µg/m³	39.6 ± 2.6	129.0 ± 7.0	27.8 ± 2.0	0.3 ± 1.0
Polyaromatic Hydrocarbon (PAH)	µg/m³	1.5 ± 0.1	1.4 ± 0.1	2.7 ± 0.1	6.2 ± 0.3
Nitro-PAH	ng/m³	0.7 ± 0.05	0.8 ± 0.05	2.4 ± 0.1	6.5 ± 0.4
Polars (Acids)	µg/m³	4.2 ± 0.1	5.6 ± 0.1	6.4 ± 0.6	24.8 ± 2.2
Hopane and Steranes	ng/m³	2.6 ± 0.2	2.4 ± 0.2	NA	0.9 ± 0.1
Volatile Organic Compounds (VOC)	µg/m³	19.1 ± 4.3	92.5 ± 7.8	33.1 ± 6.6	74.9 ± 12.8

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Carbon:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Organic Carbon Fraction 1	µg/m³	0.5 ± 0.13	0.4 ± 0.11	0.3 ± 0.07	0.5 ± 0.13
Organic Carbon Fraction 2	µg/m³	1.6 ± 0.02	1.9 ± 0.02	1.7 ± 0.02	2.1 ± 0.02
Organic Carbon Fraction 3	µg/m³	3.1 ± 0.33	2.9 ± 0.29	1.8 ± 0.16	2.6 ± 0.26
Organic Carbon Fraction 4	µg/m³	0.8 ± 0.16	1.1 ± 0.23	0.6 ± 0.11	0.9 ± 0.18
Pyrolyzed Organic Carbon Reflectance	µg/m³	0.4	0.4	0.0	0.0
Pyrolyzed Organic Carbon Transmittance	µg/m³	0.6 ± 0.24	0.0	0.4 ± 0.13	1.1 ± 0.41
Organic Carbon	µg/m³	6.4 ± 0.22	6.6 ± 0.23	4.3 ± 0.13	6.1 ± 0.2
Elemental Carbon Fraction 1	µg/m³	0.8	0.9	0.4	1.0
Elemental Carbon Fraction 2	µg/m³	0.5 ± 0.02	0.8 ± 0.04	0.6 ± 0.03	1.5 ± 0.11
Elemental Carbon Fraction 3	µg/m³	0.0	0.2 ± 0.07	0.0	0.1 ± 0.03
Elemental Carbon	µg/m³	1 ± 0.04	1.6 ± 0.08	1 ± 0.04	2.7 ± 0.15
Total Carbon	µg/m³	7.4 ± 0.29	8.3 ± 0.33	5.3 ± 0.18	8.7 ± 0.36

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Elements (Metals):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Sodium	ng/m³	0 ± 59.7	83.7 ± 61.1	185.7 ± 62.5	228.5 ± 63.4
Magnesium	ng/m³	7.3 ± 20.3	5.6 ± 19.7	18.5 ± 19.3	9.6 ± 19.2
Aluminum	ng/m³	14.3 ± 4	3.6 ± 3.8	34.7 ± 3.9	19.2 ± 3.8
Silicon	ng/m³	49.4 ± 2.6	8.9 ± 2.4	117.3 ± 2.7	14.2 ± 2.4
Phosphorous	ng/m³	125.4 ± 1.1	175.3 ± 1.3	107.4 ± 1	106.2 ± 1
Sulfur	ng/m³	70.7 ± 0.8	89.2 ± 0.9	158.4 ± 1.1	806.9 ± 3.3
Chlorine	ng/m³	103.9 ± 0.9	118.2 ± 0.9	109.3 ± 0.9	93.1 ± 0.9
Potassium	ng/m³	229.7 ± 1.2	267 ± 1.2	235.6 ± 1.2	186.9 ± 1.1
Calcium	ng/m³	142.5 ± 3	138.6 ± 2.9	177.1 ± 3	122.2 ± 2.8
Scandium	ng/m³	0 ± 12.3	0 ± 11.9	0 ± 11.6	0 ± 11.5
Titanium	ng/m³	3.2 ± 1	0 ± 1	9.4 ± 1	1.8 ± 0.9
Vanadium	ng/m³	0 ± 0.7	0 ± 0.6	0 ± 0.6	0 ± 0.6
Chromium	ng/m³	1 ± 0.7	0.4 ± 0.6	2.5 ± 0.6	1.1 ± 0.6
Manganese	ng/m³	1.4 ± 2.1	1.4 ± 2	3.8 ± 1.9	2.4 ± 1.9
Iron	ng/m³	29.5 ± 0.7	11.3 ± 0.7	46.5 ± 0.7	15 ± 0.7
Cobalt	ng/m³	0.1 ± 0.7	0 ± 0.6	0.6 ± 0.6	0.1 ± 0.6
Nickel	ng/m³	0.4 ± 1.9	0 ± 1.9	1.1 ± 1.8	0.6 ± 1.8
Copper	ng/m³	7.8 ± 2.4	3.4 ± 2.3	15.3 ± 2.3	5.4 ± 2.3
Zinc	ng/m³	7.5 ± 0.7	3.5 ± 0.6	13.9 ± 0.7	7.1 ± 0.6
Gallium	ng/m³	0 ± 3.3	0.2 ± 3.1	0 ± 3.1	0 ± 3.1
Arsenic	ng/m³	0 ± 0.7	0 ± 0.6	0 ± 0.6	0 ± 0.6
Selenium	ng/m³	0 ± 0.7	0 ± 0.6	0 ± 0.6	0 ± 0.6
Bromine	ng/m³	0.6 ± 0.7	0 ± 0.6	0.2 ± 0.6	0.2 ± 0.6
Rubidium	ng/m³	0 ± 0.7	0 ± 0.6	0 ± 0.6	0 ± 0.6
Strontium	ng/m³	0.6 ± 0.7	0 ± 0.6	2 ± 0.6	0.4 ± 0.6
Yttrium	ng/m³	0 ± 0.7	0.4 ± 0.6	0 ± 0.6	0.4 ± 0.6

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Elements (Metals):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Zirconium	ng/m³	0 ± 1.1	0 ± 1	0 ± 1	0 ± 1
Niobium	ng/m³	0.2 ± 0.9	0 ± 0.9	0 ± 0.9	0.2 ± 0.9
Molybdenum	ng/m³	0 ± 1.4	0 ± 1.3	0.7 ± 1.3	0.5 ± 1.3
Palladium	ng/m³	0 ± 1.6	0 ± 1.5	0 ± 1.5	0 ± 1.5
Silver	ng/m³	0.4 ± 1.5	0 ± 1.5	0 ± 1.4	0.1 ± 1.4
Cadmium	ng/m³	0.2 ± 1.9	0 ± 1.9	0 ± 1.8	0 ± 1.8
Indium	ng/m³	0.5 ± 2.1	0.4 ± 2	0 ± 1.9	0.9 ± 1.9
Tin	ng/m³	0.8 ± 2	0 ± 2	0 ± 1.9	0.1 ± 1.9
Antimony	ng/m³	0 ± 3.3	0 ± 3.1	0 ± 3.1	0 ± 3.1
Cesium	ng/m³	0 ± 6.6	0 ± 6.4	0 ± 6.3	0 ± 6.2
Barium	ng/m³	0 ± 7.6	2.2 ± 7.4	5.8 ± 7.2	1.8 ± 7.2
Lanthanum	ng/m³	1.1 ± 9.5	0 ± 9.2	1.7 ± 9	2.8 ± 9
Cerium	ng/m³	0 ± 9.1	0 ± 8.7	0 ± 8.6	0 ± 8.5
Samarium	ng/m³	0 ± 16.1	0 ± 15.5	0 ± 15.2	0 ± 15
Europium	ng/m³	0 ± 22.9	0 ± 22	0 ± 21.6	2 ± 21.5
Terbium	ng/m³	0 ± 17.4	0 ± 16.7	10.6 ± 16.6	0 ± 16.2
Hafnium	ng/m³	0 ± 4.8	0 ± 4.6	1 ± 4.5	0.3 ± 4.5
Tantalum	ng/m³	0.7 ± 2.7	0 ± 2.6	0 ± 2.5	0 ± 2.5
Wolfram	ng/m³	0 ± 7.7	0 ± 7.4	0 ± 7.2	0 ± 7.2
Iridium	ng/m³	0.6 ± 1.2	0.5 ± 1.2	0 ± 1.1	0.3 ± 1.1
Gold	ng/m³	0 ± 1.2	0 ± 1.2	0 ± 1.1	0 ± 1.1
Mercury	ng/m³	0 ± 0.7	0 ± 0.6	0 ± 0.6	0.1 ± 0.6
Thallium	ng/m³	0.7 ± 0.8	0 ± 0.8	0.4 ± 0.8	0.4 ± 0.8
Lead	ng/m³	0.4 ± 0.7	0 ± 0.7	3.7 ± 0.7	0.1 ± 0.7
Uranium	ng/m³	0.2 ± 1.1	0 ± 1	0 ± 1	0 ± 1

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Alkanes:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Dodecane	ng/m³	324.2 ± 26.9	496.7 ± 41.1	1798.2 ± 148.4	2660.8 ± 219.6
Norfarnesane	ng/m³	208.9 ± 10.6	256 ± 12.9	826.5 ± 41.4	2172.1 ± 108.7
Tridecane	ng/m³	498.2 ± 25	463.4 ± 23.3	2071.7 ± 103.7	5360.8 ± 268.1
Heptylcyclohexane	ng/m³	55.2 ± 3.9	59.3 ± 4.1	231 ± 15.7	527.3 ± 35.8
Farnesane	ng/m³	127 ± 7.8	140.5 ± 8.6	668.4 ± 40.5	1294.6 ± 78.3
Tetradecane	ng/m³	515.4 ± 25.9	472.8 ± 23.7	1770.9 ± 88.6	3828.6 ± 191.5
Octylcyclohexane	ng/m³	51.5 ± 2.7	54.6 ± 2.8	157.1 ± 8	361 ± 18.1
Pentadecane	ng/m³	318.6 ± 16.1	391.7 ± 19.7	1449.3 ± 72.6	3456.0 ± 172.9
Nonylcyclohexane	ng/m³	42.3 ± 3.8	50.5 ± 4.5	135 ± 11.9	275.5 ± 24.1
Hexadecane	ng/m³	258.7 ± 13.1	274.7 ± 13.8	1035.7 ± 51.9	2247.3 ± 112.4
Norpristane	ng/m³	154.2 ± 7.9	132.2 ± 6.7	511.1 ± 25.7	972.5 ± 48.7
Decylcyclohexane	ng/m³	15.35 ± 1.8	30.4 ± 3.5	74.8 ± 8.4	106.3 ± 11.9
Heptadecane	ng/m³	235.4 ± 13.3	169.8 ± 9.6	666.8 ± 37.6	1131.4 ± 63.7
Heptadecane	ng/m³	152.9 ± 8.2	118.2 ± 6.4	354.4 ± 18.9	663 ± 35.2
Undecylcyclohexane	ng/m³	26.5 ± 2.2	31.2 ± 2.6	46.5 ± 3.8	96.9 ± 7.8
Octadecane	ng/m³	176.5 ± 8.9	127.1 ± 6.5	354.7 ± 17.8	640.2667 ± 32.1
Phytane	ng/m³	122.1 ± 8.6	112.2 ± 7.9	213.6 ± 15	435.9 ± 30.5
Dodecylcyclohexane	ng/m³	9.6 ± 0.7	12.9 ± 1	28.9 ± 2	39 ± 2.7
Nonadecane	ng/m³	62.4 ± 6.6	63.9 ± 6.7	142.5 ± 14.9	184.9 ± 19.2
Tridecylcyclohexane	ng/m³	7.95 ± 0.55	10.1 ± 0.6	5.5 ± 0.4	18.6667 ± 1.1
Eicosane	ng/m³	21.4 ± 4.8	23.7 ± 5.2	68.8 ± 15.1	85.7 ± 18.7
Tetradecylcyclohexane	ng/m³	2.8 ± 0.25	1.8 ± 0.2	4.3 ± 0.3	7.1 ± 0.4
Heneicosane	ng/m³	5.5 ± 0.6	2.3 ± 0.3	23.8 ± 1.9	34.1 ± 2.6
Pentadecylcyclohexane	ng/m³	0.9 ± 0.3	1 ± 0.2	6 ± 0.7	4.6 ± 0.6
Docosane	ng/m³	1.7 ± 0.25	3.5 ± 0.6	6.6 ± 0.9	16.5 ± 2.1
Hexadecylcyclohexane	ng/m³	0.3 ± 0.2	0.1 ± 0.2	0.6 ± 0.2	1.3 ± 0.3

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Alkanes:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Tricosane	ng/m³	2.4 ± 0.4	2.4 ± 0.5	2.3 ± 0.6	7.8 ± 1.5
Heptadecylcyclohexane	ng/m³	0.1 ± 0.2	32.3 ± 1.7	0.3 ± 0.2	1.0± 0.2
Tetracosane	ng/m³	6.6 ± 0.5	7.5 ± 0.5	5.4 ± 0.3	4.4 ± 0.3
Octadecylcyclohexane	ng/m³	2.1 ± 0.4	0 ± 0.2	1.6 ± 0.3	1.4 ± 0.4
Pentacosane	ng/m³	11.8 ± 0.7	11.1 ± 0.6	9.7 ± 0.7	6.5 ± 0.6
Hexacosane	ng/m³	5.1 ± 0.4	5.2 ± 0.4	5 ± 0.3	3.7 ± 0.3
Nonadecylcyclohexane	ng/m³	1.1 ± 0.3	0 ± 0.2	0.6 ± 0.2	0.8 ± 0.2
Heptacosane	ng/m³	2.8 ± 0.6	2.5 ± 0.5	2.2 ± 0.5	1.9 ± 0.4
Eicosylcyclohexane	ng/m³	0 ± 0.2	0 ± 0.2	0 ± 0.2	0.2 ± 0.2
Octacosane	ng/m³	0.8 ± 0.3	0.3 ± 0.2	0.5 ± 0.2	1.5 ± 0.3
Nonacosane	ng/m³	0.2 ± 0.2	0.4 ± 0.2	0.5 ± 0.2	0.9 ± 0.2
Heneicosylcyclohexane	ng/m³	0 ± 0.2	0 ± 0.2	0 ± 0.2	0.1 ± 0.2
Triacontane	ng/m³	0.1 ± 0.2	0 ± 0.2	0.4 ± 0.2	0.8 ± 0.2
Hentriacontane	ng/m³	0.1 ± 0.2	0 ± 0.2	0 ± 0.2	0.7 ± 0.2
Dotriacontane	ng/m³	0.2 ± 0.2	0 ± 0.2	0 ± 0.2	0.4 ± 0.2
Tritriacontane	ng/m³	0.2 ± 0.2	0 ± 0.2	0 ± 0.2	0.3 ± 0.2
Tetratriacontane	ng/m³	0.5 ± 0.2	0 ± 0.2	0 ± 0.2	0.5 ± 0.2
Pentatriacontane	ng/m³	0.5 ± 0.3	0 ± 0.2	0 ± 0.2	0.3 ± 0.2
Hexatriacontane	ng/m³	0.1 ± 0.2	0 ± 0.2	0 ± 0.2	0.3 ± 0.2
Heptatriacontane	ng/m³	0.3 ± 0.2	0 ± 0.2	0 ± 0.2	0 ± 0.2
Octatriacontane	ng/m³	0.3 ± 0.2	0 ± 0.2	0 ± 0.2	0 ± 0.2
Nonatriacontane	ng/m³	0 ± 0.2	0 ± 0.2	0 ± 0.2	0 ± 0.2
Tetracontane	ng/m³	0 ± 0.2	0 ± 0.2	0 ± 0.2	0 ± 0.2

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Carbonyl:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Formaldehyde	µg/m³	2.7 ± 0.11	1.6 ± 0.11	0.9 ± 0.08	0 ± 0.07
Acetaldehyde	µg/m³	8.3 ± 0.3	17.3 ± 0.87	10.5 ± 0.54	0 ± 0.07
Acrolein	µg/m³	0.2 ± 0.06	0.1 ± 0.07	0.1 ± 0.07	0 ± 0.07
Glyoxal	µg/m³	0.1 ± 0.05	0 ± 0.07	0 ± 0.07	0.1 ± 0.07
Acetone	µg/m³	13.5 ± 0.45	10.1 ± 0.5	4.6 ± 0.27	0 ± 0.07
Propionaldehyde	µg/m³	1.5 ± 0.07	1.4 ± 0.1	1.6 ± 0.12	0 ± 0.07
Crotonaldehyde	µg/m³	0 ± 0.05	0 ± 0.07	0 ± 0.07	0 ± 0.07
Methacrolein	µg/m³	0 ± 0.05	0 ± 0.07	0 ± 0.07	0 ± 0.07
n-butyraldehyde	µg/m³	1 ± 0.06	0.8 ± 0.08	0.6 ± 0.07	0 ± 0.07
2-Butanone (MEK)	µg/m³	1.9 ± 0.09	92 ± 4.6	3.7 ± 0.22	0 ± 0.07
Valeraldehyde	µg/m³	1.3 ± 0.07	1 ± 0.08	1 ± 0.08	0 ± 0.07
Hexaldehyde	µg/m³	8.5 ± 0.31	5.3 ± 0.3	4.7 ± 0.24	0.2 ± 0.07
Benzaldehyde	µg/m³	0.5 ± 0.05	0.1 ± 0.07	0 ± 0.07	0 ± 0.07
m-Tolualdehyde	µg/m³	0 ± 0.05	0 ± 0.07	0 ± 0.07	0 ± 0.07

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PolyAromatic HydroCarbon (PAH):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
1+2ethylnaphthalene	ng/m³	7.6 ± 0.5	6.3 ± 0.41	43.1 ± 2.84	81.6 ± 5.38
Naphthalene	ng/m³	37 ± 1.85	46 ± 2.3	231 ± 11.55	682.7 ± 34.14
Quinoline	ng/m³	0.5 ± 0.21	0 ± 0.12	0 ± 0.12	2.4 ± 0.76
2-methylnaphthalene	ng/m³	29.6 ± 1.48	24 ± 1.2	109.7 ± 5.49	335 ± 16.75
1-methylnaphthalene	ng/m³	20.4 ± 1.02	15 ± 0.75	82.9 ± 4.14	246.4 ± 12.32
Biphenyl	ng/m³	15 ± 0.75	14.8 ± 0.74	56.9 ± 2.84	166 ± 8.3
2-methylbiphenyl	ng/m³	66.7 ± 3.68	86.9 ± 4.8	179.4 ± 9.9	468 ± 25.83
2,6+2,7-dimethylnaphthalene	ng/m³	16.5 ± 0.82	14 ± 0.7	77.1 ± 3.86	246.2 ± 12.31
1,3+1,6+1,7dimethylnaphth	ng/m³	29.9 ± 1.49	24.5 ± 1.23	129.1 ± 6.46	465.8 ± 23.29
1,4+1,5+2,3-dimethylnaphth	ng/m³	8.4 ± 0.42	5.8 ± 0.29	37.6 ± 1.88	147.8 ± 7.39
Acenaphthylene	ng/m³	0.4 ± 0.12	2.6 ± 0.34	15.5 ± 2.06	18 ± 2.4
1,2-dimethylnaphthalene	ng/m³	2.4 ± 0.2	2.8 ± 0.21	9.6 ± 0.74	33.7 ± 2.58
1,8-dimethylnaphthalene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
Acenaphthene	ng/m³	0.5 ± 0.16	0.3 ± 0.12	0.7 ± 0.2	19.7 ± 5.21
3-methylbiphenyl	ng/m³	827.8 ± 41.39	740.2 ± 37.01	1028.7 ± 51.43	1874.8 ± 93.74
4-methylbiphenyl	ng/m³	300.5 ± 15.03	258.8 ± 12.94	382.6 ± 19.13	719.2 ± 35.96
Dibenzofuran	ng/m³	2.1 ± 0.21	2.2 ± 0.22	2.9 ± 0.29	13 ± 1.3
1-ethyl-2-methylnaphthalene	ng/m³	5 ± 0.79	1.7 ± 0.26	11.5 ± 1.81	27.4 ± 4.31
2,3,5+I-trimethylnaphthalene	ng/m³	9.8 ± 0.61	10.2 ± 0.63	20 ± 1.24	60.7 ± 3.76
B-trimethylnaphthalene	ng/m³	11.6 ± 0.58	13.4 ± 0.67	45.5 ± 2.27	92.7 ± 4.63
A-trimethylnaphthalene	ng/m³	14.3 ± 0.71	16.5 ± 0.82	46.9 ± 2.34	112 ± 5.6
C-trimethylnaphthalene	ng/m³	11.6 ± 0.58	11.1 ± 0.56	38.9 ± 1.94	83.8 ± 4.19
2-ethyl-1-methylnaphthalene	ng/m³	0.7 ± 0.12	0.1 ± 0.12	0.7 ± 0.12	3.8 ± 0.23
E-trimethylnaphthalene	ng/m³	7.8 ± 0.41	7.7 ± 0.41	27.7 ± 1.45	56.8 ± 2.97
2,4,5-trimethylnaphthalene	ng/m³	1.2 ± 0.22	0.4 ± 0.12	1.1 ± 0.16	7.6 ± 1.09
F-trimethylnaphthalene	ng/m³	6 ± 0.63	6.9 ± 0.72	19.4 ± 2.02	45.5 ± 4.74

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PolyAromatic HydroCarbon (PAH):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Fluorene	ng/m³	7.2 ± 0.38	3.1 ± 0.16	3.1 ± 0.16	19.4 ± 1
1,4,5-trimethylnaphthalene	ng/m³	0.9 ± 0.12	0.7 ± 0.12	0.5 ± 0.12	4.1 ± 0.23
J-trimethylnaphthalene	ng/m³	4.1 ± 0.24	4.6 ± 0.27	13.3 ± 0.79	29 ± 1.72
A-Methylfluorene	ng/m³	2.9 ± 0.2	3.4 ± 0.22	5.9 ± 0.39	11 ± 0.73
B-Methylfluorene	ng/m³	0.5 ± 0.12	0.3 ± 0.12	0.6 ± 0.12	1.7 ± 0.16
1-Methylfluorene	ng/m³	1 ± 0.21	2.1 ± 0.35	1.5 ± 0.25	6.6 ± 1.08
9-fluorenone	ng/m³	7.6 ± 0.79	6.2 ± 0.65	9.9 ± 1.02	10.3 ± 1.06
Dibenzothiophene	ng/m³	0.3 ± 0.12	0.2 ± 0.12	0.1 ± 0.12	0.3 ± 0.12
Phenanthrene	ng/m³	8.6 ± 0.87	6.6 ± 0.67	16.6 ± 1.68	42.2 ± 4.26
Anthracene	ng/m³	1 ± 0.18	0.8 ± 0.13	0.8 ± 0.14	3.4 ± 0.57
Xanthone	ng/m³	0.3 ± 0.12	0.1 ± 0.12	0.1 ± 0.12	1.3 ± 0.22
Acenaphthenequinone	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
3-methylphenanthrene	ng/m³	2.7 ± 0.15	1.8 ± 0.12	1.8 ± 0.12	4.1 ± 0.23
2-methylphenanthrene	ng/m³	2 ± 0.16	1.6 ± 0.13	1 ± 0.12	4 ± 0.31
Perinaphthenone	ng/m³	0.6 ± 0.25	0.1 ± 0.12	0.9 ± 0.27	1.3 ± 0.41
2-methylanthracene	ng/m³	0.1 ± 0.12	0.3 ± 0.12	0.9 ± 0.12	2.1 ± 0.27
4,5-methylenephenanthrene	ng/m³	0.6 ± 0.12	1.1 ± 0.12	0.4 ± 0.12	1.2 ± 0.13
9-methylphenanthrene	ng/m³	2.2 ± 0.33	0.6 ± 0.12	1 ± 0.15	3.9 ± 0.56
1-methylphenanthrene	ng/m³	1.8 ± 0.27	0.3 ± 0.12	0.6 ± 0.12	2.3 ± 0.36
Anthrone	ng/m³	2.2 ± 0.17	0.9 ± 0.12	5.6 ± 0.28	4.7 ± 0.24
9-methylanthracene	ng/m³	0.1 ± 0.12	0.2 ± 0.12	0.1 ± 0.12	0.6 ± 0.12
2-phenylnaphthalene	ng/m³	0.2 ± 0.12	0.3 ± 0.12	0.3 ± 0.12	1.3 ± 0.14
Anthraquinone	ng/m³	0.4 ± 0.12	0.4 ± 0.12	0 ± 0.12	0.9 ± 0.13
A-dimethylphenanthrene	ng/m³	0.3 ± 0.12	0.1 ± 0.12	0.1 ± 0.12	0.9 ± 0.15

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PolyAromatic HydroCarbon (PAH):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
B-dimethylphenanthrene	ng/m³	0.2 ± 0.12	0 ± 0.12	0.1 ± 0.12	0.4 ± 0.12
1,7-dimethylphenanthrene	ng/m³	0.2 ± 0.12	0.1 ± 0.12	0.2 ± 0.12	0.6 ± 0.12
3,6-dimethylphenanthrene	ng/m³	0.2 ± 0.12	0 ± 0.12	0.1 ± 0.12	0.5 ± 0.12
D-dimethylphenanthrene	ng/m³	0.2 ± 0.12	0 ± 0.12	0.1 ± 0.12	0.4 ± 0.12
E-dimethylphenanthrene	ng/m³	0.1 ± 0.12	0.2 ± 0.12	0.1 ± 0.12	0.3 ± 0.12
C-dimethylphenanthrene	ng/m³	0.7 ± 0.12	0.2 ± 0.12	0.1 ± 0.12	1.2 ± 0.18
Fluoranthene	ng/m³	0.4 ± 0.12	0.4 ± 0.12	0.4 ± 0.12	2.6 ± 0.32
Pyrene	ng/m³	0.6 ± 0.12	0.4 ± 0.12	1.2 ± 0.13	2.6 ± 0.25
9-Anthraaldehyde	ng/m³	0.2 ± 0.12	0 ± 0.12	0 ± 0.12	0.3 ± 0.12
Retene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
Benzo(a)fluorene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0.2 ± 0.12
Benzo(b)fluorene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0.1 ± 0.12
B-MePy/MeFl	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0.2 ± 0.12
1-MeFl+C-MeFl/Py	ng/m³	0 ± 0.12	0 ± 0.12	0.2 ± 0.12	0.2 ± 0.12
1+3-methylfluoranthene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0.1 ± 0.12
4-methylpyrene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0.2 ± 0.12
C-MePy/MeFl	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0.1 ± 0.12
D-MePy/MeFl	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0.2 ± 0.12
1-methylpyrene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0.1 ± 0.12
Benzonaphthothiophene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
Benzo(c)phenanthrene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
Benzo(ghi)fluoranthene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0.4 ± 0.13
9-phenylanthracene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
Cyclopenta(c,d)pyrene	ng/m³	0 ± 0.12	0 ± 0.12	0.1 ± 0.12	0.1 ± 0.12

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PolyAromatic HydroCarbon (PAH):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Benz(a)anthracene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
Chrysene-Triphenylene	ng/m³	0 ± 0.24	0 ± 0.24	0 ± 0.24	0 ± 0.24
Benzanthrone	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
Benz(a)anthracene-7,12-dione	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
3-methylchrysene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
Chry56m	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
7-methylbenz(a)anthracene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
7,12-dimethylbenz(a)anthracene	ng/m³	0.1 ± 0.13	0.1 ± 0.13	0.1 ± 0.12	0.2 ± 0.13
Benzo(b+j+k)fluoranthene	ng/m³	0 ± 0.12	0.1 ± 0.12	0 ± 0.12	0 ± 0.12
Benzo(a)fluoranthene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
BeP	ng/m³	0 ± 0.12	0.1 ± 0.12	0 ± 0.12	0.1 ± 0.12
BaP	ng/m³	0 ± 0.12	0.2 ± 0.12	0.1 ± 0.12	0 ± 0.12
Perylene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0.2 ± 0.12
Dibenz(a,j)acridine	ng/m³	0 ± 0.12	0.1 ± 0.12	0 ± 0.12	0.3 ± 0.12
7-methylbenzo(a)pyrene	ng/m³	0 ± 0.12	0.2 ± 0.12	0.2 ± 0.12	0 ± 0.12
Bpy910dih	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
Indeno[123-cd]fluoranthene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
Dibenz(a,h)acridine	ng/m³	0 ± 0.12	0.1 ± 0.12	0 ± 0.12	0 ± 0.12
Dbajacr	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
Indeno[123-cd]pyrene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
Dibenzo(ah+ac)anthracene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
Dibenzo(a,j)anthracene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
Benzo(b)chrysene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
Picene	ng/m³	0 ± 0.12	0 ± 0.12	0.1 ± 0.12	0.1 ± 0.12

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PolyAromatic HydroCarbon (PAH):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Benzo(ghi)perylene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0.1 ± 0.12
Anthanthrene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
Dibenzo(a,l)pyrene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
Coronene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
Dibenzo(a,e)pyrene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
Dibenzo(a,i)pyrene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
Dibenzo(a,h)pyrene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12
Dibenzo(b,k)fluoranthene	ng/m³	0 ± 0.12	0 ± 0.12	0 ± 0.12	0 ± 0.12

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Nitro-PAH:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
3-nitrobenzo[e]pryene	ng/m³	0.0	0.0	0.0	0.0
1-nitronaphthalene	ng/m³	0.1	0.2 ± 0.01	0.6 ± 0.03	1.7 ± 0.08
1-methyl-5-nitronaphthalene	ng/m³	0.0	0.0	0.1 ± 0.01	0.5 ± 0.03
2-nitronaphthalene	ng/m³	0.1	0.0	0.5 ± 0.03	2.8 ± 0.14
2-nitrobiphenyl	ng/m³	0.0	0.0	0.0	0.1 ± 0.01
2-methyl-4-nitronaphthalene	ng/m³	0.0	0.0	0.2 ± 0.01	0.6 ± 0.03
1-methyl-4-nitronaphthalene	ng/m³	0.0	0.0	0.0	0.4 ± 0.1
1-methyl-6-nitronaphthalene	ng/m³	0.1	0.0	0.0	0.1 ± 0.01
3-nitrobiphenyl	ng/m³	0.0	0.0	0.0	0.1
4-nitrobiphenyl	ng/m³	0.0	0.0	0.0	0.0
1,3-dinitronaphthalene	ng/m³	0.0	0.0	0.0	0.0
1,5-dinitronaphthalene	ng/m³	0.0	0.0	0.0	0.0
5-nitroacenaphthene	ng/m³	0.0	0.0	0.0	0.0
2-nitrofluorene	ng/m³	0.0	0.0	0.0	0.0
4-nitrophenanthrene	ng/m³	0.0	0.0	0.0	0.0
9-nitroanthracene	ng/m³	0.0	0.0	0.0	0.1 ± 0.01
9-nitrophenanthrene	ng/m³	0.0	0.0	0.0	0.0
1,8-dinitronaphthalene	ng/m³	0.0	0.0	0.0	0.0
3-nitrophenanthrene	ng/m³	0.4 ± 0.01	0.5 ± 0.03	0.9 ± 0.04	0.0
2-nitrophenanthrene	ng/m³	0.0	0.0	0.0	0.0
2-nitroanthracene	ng/m³	0.0	0.0	0.0	0.0
2-nitrofluoranthene	ng/m³	0.0	0.0	0.0	0.0
3-nitrofluoranthene	ng/m³	0.0	0.0	0.0	0.0
4-nitropyrene	ng/m³	0.0	0.0	0.0	0.0

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Nitro-PAH:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
1-nitropyrene	ng/m³	0.0	0.0	0.0	0.0
2-nitropyrene	ng/m³	0.0	0.0	0.0	0.0
2,7-dinitrofluorene	ng/m³	0.0	0.0	0.0	0.0
2,7-dinitrofluoren-9-one	ng/m³	0.0	0.0	0.0	0.0
7-nitrobenz(a)anthracene	ng/m³	0.0	0.0	0.0	0.0
6-nitrochrysene	ng/m³	0.0	0.0	0.0	0.0
3-nitrobenzanthrone	ng/m³	0.0	0.0	0.0	0.0
1,3-dinitropyrene	ng/m³	0.0	0.0	0.0	0.0
1,6-dinitropyrene	ng/m³	0.0	0.0	0.0	0.0
1,8-dinitropyrene	ng/m³	0.0	0.0	0.0	0.0
6a+1e-nitrobenzpyrene	ng/m³	0.0	0.0	0.0	0.0

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Polars:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
8,15-Pimaradien-18-oic acid	ng/m³	0.1 ± 0.2	0 ± 0.2	1.3 ± 0.2	2.3 ± 0.3
Maleic acid	ng/m³	130.8 ± 0.8	385.4 ± 0.8	330.6 ± 32.1	775.4 ± 85.1
Guaiacol	ng/m³	6.9 ± 0.2	1.2 ± 0.2	2.2 ± 0.3	11.6 ± 3.6
Salicylic acid	ng/m³	11.8 ± 0.4	58.3 ± 0.2	40.8 ± 3	133.3 ± 7.9
4-me-guaiacol	ng/m³	1 ± 0.2	0.4 ± 0.2	1.4 ± 0.2	5.6 ± 0.6
2,3- and 3,5- dimethylbenzoic acid	ng/m³	0 ± 0.2	0 ± 0.2	0 ± 0.2	0 ± 0.2
2,4-dimethylbenzoic acid	ng/m³	0.4 ± 0.3	168.1 ± 0.2	413.2 ± 8.5	1697.9 ± 91.9
2,5-dimethylbenzoic acid	ng/m³	0 ± 0.2	5.4 ± 0.2	53.6 ± 0.4	120.2 ± 7
2,6-dimethylbenzoic acid	ng/m³	0.2 ± 0.2	6.8 ± 0.2	10.6 ± 0.5	59.5 ± 3.2
3,4-dimethylbenzoic acid	ng/m³	4.6 ± 0.2	13.8 ± 0.3	57.1 ± 0.8	166.9 ± 9.5
4-formyl-guaiacol (vanillin)	ng/m³	12.7 ± 0.2	16.3 ± 0.2	17.7 ± 1.5	92 ± 9.5
4-ethyl-guaiacol	ng/m³	0.2 ± 0.2	0 ± 0.2	10 ± 0.2	8 ± 0.7
Syringol	ng/m³	1.5 ± 0.2	21.2 ± 0.2	55.9 ± 1.2	283.6 ± 15.2
Levoglucosan	ng/m³	2 ± 0.3	1.7 ± 0.2	2.1 ± 0.7	7.8 ± 1
4-allyl-guaiacol (eugenol)	ng/m³	0 ± 0.2	0.1 ± 0.2	0.7 ± 0.2	3.3 ± 0.6
Isoeugenol	ng/m³	0.2 ± 0.2	0.7 ± 0.2	7.1 ± 0.2	7.3 ± 1.3
Isophthalic acid	ng/m³	16.7 ± 0.4	1.5 ± 0.3	1 ± 4.5	2011.2 ± 136.2
Phthalic acid	ng/m³	4.7 ± 0.2	0.3 ± 0.2	2.4 ± 0.2	38.8 ± 2.2
Acetovanillone	ng/m³	11.5 ± 0.2	11 ± 0.2	0.3 ± 1.1	198.2 ± 18.8
Vanillic acid	ng/m³	0.5 ± 0.2	4.6 ± 0.2	7.9 ± 0.4	47.7 ± 2.6
4-methyl-syringol	ng/m³	0.3 ± 0.2	0.4 ± 0.2	0.9 ± 0.2	23.7 ± 7.3
2,3-dimethoxybenzoic acid	ng/m³	123.5 ± 0.2	381 ± 0.2	631.1 ± 19.2	440.3 ± 38.7
2,4-dimethoxybenzoic acid	ng/m³	0.8 ± 0.2	0.4 ± 0.2	12 ± 0.2	14.1 ± 1
2,5-dimethoxybenzoic acid	ng/m³	0.6 ± 0.2	0.4 ± 0.2	1.2 ± 0.2	64.9 ± 10.1

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Polars:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
2,6-dimethoxybenzoic acid	ng/m³	1.3 ± 0.2	2.5 ± 0.2	0.4 ± 0.6	26 ± 5.7
3,4-dimethoxybenzoic acid	ng/m³	0.2 ± 0.2	0.2 ± 0.2	0.2 ± 0.2	2.5 ± 0.4
3,5-dimethoxybenzoic acid	ng/m³	7.8 ± 0.2	30.2 ± 0.2	19.7 ± 3.1	23 ± 3.6
Docosanoic acid (c22)	ng/m³	1.5 ± 1.1	5.9 ± 0.4	1.5 ± 0.2	0.6 ± 0.2
Homovanillic acid	ng/m³	0 ± 0.2	0 ± 0.2	0 ± 0.2	5.4 ± 0.4
Syringaldehyde	ng/m³	0.6 ± 0.2	7.2 ± 0.2	0.9 ± 0.5	31 ± 1.8
cis-pinonic acid	ng/m³	43.8 ± 0.4	100.6 ± 0.2	37.2 ± 5.4	62.9 ± 6.2
Syringic acid	ng/m³	0 ± 0.2	0.3 ± 0.2	6.3 ± 0.2	2.9 ± 0.4
Myristoleic acid	ng/m³	1 ± 0.4	4.3 ± 0.2	24 ± 1.2	38.6 ± 11.1
Traumatic acid	ng/m³	2.8 ± 0.6	1.8 ± 0.3	2.5 ± 12.8	44.3 ± 0.9
1,11-undecanedicarboxylic acid	ng/m³	0.4 ± 0.2	1 ± 0.2	1.4 ± 0.4	6.2 ± 1.9
Palmitoleic acid	ng/m³	0 ± 0.2	0 ± 0.2	3.9 ± 0.4	39.1 ± 2
1,12-dodecanedicarboxylic acid	ng/m³	0.9 ± 0.2	0 ± 0.2	0 ± 0.2	0.6 ± 0.2
Elaidic acid	ng/m³	0.5 ± 0.2	2.2 ± 0.4	2.4 ± 1	7.7 ± 0.2
Isostearic acid	ng/m³	0.2 ± 0.2	1.9 ± 0.2	2.9 ± 0.2	14.4 ± 0.8
Dehydroabietic acid	ng/m³	34.3 ± 14.5	0 ± 0.2	84.5 ± 19.2	42.6 ± 0.2
Pimaric acid	ng/m³	1.9 ± 0.2	3.9 ± 0.2	7.6 ± 0.3	26.2 ± 1.5
Sandaracopimaric acid	ng/m³	0.7 ± 0.2	1.5 ± 0.2	1.8 ± 0.2	7.4 ± 0.5
Abietic acid	ng/m³	0.2 ± 0.2	0.2 ± 0.2	1.2 ± 0.2	1.2 ± 0.2
Isopimaric acid	ng/m³	1.4 ± 0.2	1.4 ± 0.2	4.9 ± 0.5	5.5 ± 0.5
7-oxodehydroabietic acid	ng/m³	0 ± 0.2	0 ± 0.2	2 ± 0.2	1.9 ± 0.2
Heneicosanoic acid (c21)	ng/m³	1.7 ± 0.2	0 ± 0.2	0 ± 0.2	9.6 ± 0.6
Tricosanoic acid	ng/m³	0 ± 0.2	0.5 ± 0.2	0.8 ± 0.2	0.2 ± 0.2
Tetracosanoic acid (c24)	ng/m³	0 ± 0.2	0.6 ± 0.2	4.9 ± 0.2	2.4 ± 0.5

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Polars:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Cholesterol	ng/m³	11.8 ± 4.1	21.6 ± 2.6	18.2 ± 1.2	11.7 ± 0.2
b-sitosterol	ng/m³	1.4 ± 0.3	1.4 ± 0.3	0.8 ± 0.3	2 ± 0.2
Hexanoic acid (c6)	ng/m³	730.6 ± 0.2	1357.9 ± 0.2	983.3 ± 147.9	6155.9 ± 784.9
Heptanoic acid (c7)	ng/m³	398.8 ± 0.2	981.3 ± 0.2	956.4 ± 52.5	6465.2 ± 383.6
Benzoic acid	ng/m³	254.6 ± 0.4	368.7 ± 0.2	747.3 ± 20.6	2416.6 ± 164.3
Octanoic acid (c8)	ng/m³	203.6 ± 0.2	484.9 ± 0.2	551.9 ± 37	976.4 ± 103.7
o-toluic	ng/m³	4.6 ± 0.3	15.8 ± 0.2	71 ± 1.2	211.4 ± 16.1
m-toluic	ng/m³	5.8 ± 0.2	42.9 ± 0.5	123.1 ± 2.4	317.5 ± 18.2
Nonanoic acid (c9)	ng/m³	374 ± 1.2	331.7 ± 0.2	195.5 ± 35.1	238.2 ± 70.9
p-toluic	ng/m³	2.5 ± 0.2	28 ± 0.2	46 ± 2.3	154.6 ± 13.5
Decanoic acid (c10)	ng/m³	172.3 ± 5.8	366.5 ± 0.7	214.5 ± 57.9	199.5 ± 72.1
Undecanoic acid (c11)	ng/m³	32 ± 0.2	65.5 ± 0.2	56.3 ± 5.2	36 ± 6.7
Dodecanoic (lauric) acid (c12)	ng/m³	8.9 ± 1.9	26.6 ± 0.2	11.6 ± 4.8	8.1 ± 3.1
Tridecanoic acid (c13)	ng/m³	33.3 ± 0.2	113.4 ± 0.2	103.3 ± 5.8	90.1 ± 7.9
Myristic acid (c14)	ng/m³	3.7 ± 2.4	18.4 ± 0.2	45 ± 23.7	100.2 ± 8.6
Pentadecanoic acid (c15)	ng/m³	7.7 ± 0.9	6.8 ± 0.5	59.2 ± 19.3	184.9 ± 19.5
Palmitic acid (c16)	ng/m³	107.4 ± 16.5	95.9 ± 15.8	240.1 ± 31.5	346.9 ± 7
Heptadecanoic acid (c17)	ng/m³	3.8 ± 1.2	3.2 ± 0.4	4.1 ± 21.9	58.2 ± 0.6
Oleic acid	ng/m³	0 ± 5.1	0.7 ± 11.9	57.5 ± 25.9	73.4 ± 0.2
Stearic acid (c18)	ng/m³	28.1 ± 4.7	43.1 ± 3.6	60.4 ± 8.6	80.8 ± 0.2
Nonadecanoic acid (c19)	ng/m³	0 ± 0.2	0 ± 0.2	0 ± 0.2	0 ± 0.2
Eicosanoic acid (c20)	ng/m³	14.7 ± 0.4	5.9 ± 0.3	2.5 ± 0.9	13.3 ± 4.1

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Hopane and Steranes:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
17A(H),21B(H)-22,29,30-Trisnorhopane	ng/m³	0.1 ± 0.01	0.1 ± 0.01	NA	0.1 ± 0.01
17A(H),21B(H)-30-Norhopane	ng/m³	0.2 ± 0.01	0.3 ± 0.02	NA	0.2 ± 0.02
17A(H),21B(H)-Hopane	ng/m³	0.3 ± 0.02	0.3 ± 0.02	NA	0.2 ± 0.01
17B(H),21A(H)-hopane	ng/m³	0 ± 0.01	0 ± 0.01	NA	0.0
22S-17A(H),21B(H)-30-Homohopane	ng/m³	0.1	0.1	NA	0.0
22R-17A(H),21B(H)-30-Homohopane	ng/m³	0.1 ± 0.01	0.1 ± 0.01	NA	0.0
17B(H),21B(H)-Hopane	ng/m³	0.0	0.0	NA	0.0
22S-17A(H),21B(H)-30,31-Bishomohopane	ng/m³	0.0	0.0	NA	0.0
22R-17A(H),21B(H)-30,31-Bishomohopane	ng/m³	0.0	0.0	NA	0.0
22S-17A(H),21B(H)-30,31,32-Trisomohopane	ng/m³	0.0	0.0	NA	0.0
22R-17A(H),21B(H)-30,31,32-Trishomohopane	ng/m³	0.0	0.0	NA	0.0
C27-20S5A(H),14A(H)-cholestane	ng/m³	0.2 ± 0.01	0.2 ± 0.02	NA	0.0
C27-20R5A(H),14B(H)-cholestane	ng/m³	0.1 ± 0.01	0.1 ± 0.01	NA	0.0
C27-20S5A(H),14B(H),17B(H)-cholestane	ng/m³	0.5 ± 0.02	0.3 ± 0.02	NA	0.2 ± 0.01
C27-20R5A(H),14A(H),17A(H)-cholestane & C29 -20S13B(H),17A(H)-dia	ng/m³	0.2 ± 0.01	0.1 ± 0.01	NA	0.1
C28-20S5A(H),14A(H),17A(H)-ergostane	ng/m³	0.1	0.1 ± 0.01	NA	0.0
C28-20R5A(H),14B(H),17B(H)-ergostane	ng/m³	0.1 ± 0.01	0.1 ± 0.01	NA	0.0
C28-20S5A(H),14B(H),17B(H)-ergostane	ng/m³	0.1	0.1	NA	0.1 ± 0.01
C28-20R5A(H),14A(H),17A(H)-ergostane	ng/m³	0.1 ± 0.01	0.1	NA	0.1
C29-20S5A(H),14A(H),17A(H)-stigmastane	ng/m³	0.1	0.1	NA	0.0
C29-20R5A(H),14B(H),17B(H)-stigmastane	ng/m³	0.3 ± 0.02	0.2 ± 0.01	NA	0.0
C29-20S5A(H),14B(H),17B(H)-stigmastane	ng/m³	0.0	0.0	NA	0.0
C29-20R5A(H),14A(H),17A(H)-stigmastane	ng/m³	0.1 ± 0.01	0.1 ± 0.01	NA	0.1 ± 0.01

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Volatile Organic Compounds (VOC):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Acetylene	µg/m³	0.3 ± 0.05	0.3 ± 0.05	1.2 ± 0.21	2.9 ± 0.49
Ethene	µg/m³	0.3 ± 0.22	0.2 ± 0.12	0.8 ± 0.67	0.2 ± 0.17
Ethane	µg/m³	7.6 ± 0.38	5.9 ± 0.29	4.3 ± 0.22	6.4 ± 0.32
Propene	µg/m³	0.3 ± 0.22	0.2 ± 0.12	1 ± 0.69	3.5 ± 2.51
Propane	µg/m³	2.1 ± 0.14	2 ± 0.13	0.8 ± 0.05	1.1 ± 0.07
1,3-butadiene	µg/m³	0 ± 0.02	0 ± 0.02	0 ± 0.02	0 ± 0.02
1-butene	µg/m³	0.1 ± 0.03	0.1 ± 0.03	0.2 ± 0.03	0.9 ± 0.05
Isobutylene	µg/m³	1.2 ± 0.06	3.2 ± 0.16	5.6 ± 0.28	6.1 ± 0.31
c-2-butene	µg/m³	0.1 ± 0.03	0 ± 0.03	0 ± 0.03	0.3 ± 0.03
t-2-butene	µg/m³	0.5 ± 0.3	0.2 ± 0.14	0.4 ± 0.29	0.5 ± 0.33
n-butane	µg/m³	0.9 ± 0.05	0.8 ± 0.04	0.7 ± 0.04	1.3 ± 0.07
iso-butane	µg/m³	0.6 ± 0.09	0.5 ± 0.07	0.3 ± 0.05	0.5 ± 0.08
iso-pentane	µg/m³	0.4 ± 0.07	0.4 ± 0.07	0.5 ± 0.09	0.9 ± 0.18
n-pentane	µg/m³	0.2 ± 0.04	0.3 ± 0.03	0.3 ± 0.03	0.8 ± 0.09
1-pentene	µg/m³	0 ± 0.03	0 ± 0.03	0.1 ± 0.03	0.2 ± 0.08
2-methyl-1-butene	µg/m³	0 ± 0.03	0.1 ± 0.03	0.1 ± 0.03	0.1 ± 0.03
isoprene	µg/m³	0 ± 0.03	0 ± 0.03	0 ± 0.03	0 ± 0.03
t-2-pentene	µg/m³	0 ± 0.03	0 ± 0.03	0 ± 0.03	0.1 ± 0.03
c-2-pentene	µg/m³	0 ± 0.03	0 ± 0.03	0 ± 0.03	0.1 ± 0.03
2-methyl-2-butene	µg/m³	0 ± 0.03	0.1 ± 0.03	0.1 ± 0.03	0.1 ± 0.03
2,2-dimethylbutane	µg/m³	0 ± 0.04	0.1 ± 0.04	0 ± 0.04	0 ± 0.04
Cyclopentene	µg/m³	0 ± 0.04	0 ± 0.04	0 ± 0.04	0.1 ± 0.04
Cyclopentane	µg/m³	0 ± 0.03	0.1 ± 0.03	0 ± 0.03	0.1 ± 0.04
2,3-dimethylbutane	µg/m³	0 ± 0.04	1 ± 0.06	0 ± 0.04	0.1 ± 0.04

April 2010 – Detailed Atmosphere Characterization

Volatile Organic Compounds (VOC):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
2-methylpentane	µg/m³	0.1 ± 0.04	6.8 ± 0.59	0.1 ± 0.04	0.4 ± 0.04
3-methylpentane	µg/m³	0.1 ± 0.04	7.5 ± 0.39	0.2 ± 0.04	0.3 ± 0.04
2-methyl-1-pentene	µg/m³	0 ± 0.04	0 ± 0.04	0.1 ± 0.08	0.2 ± 0.22
n-hexane	µg/m³	0.1 ± 0.04	15.3 ± 0.96	0.2 ± 0.04	0.4 ± 0.04
t-2-hexene	µg/m³	0 ± 0.04	0.1 ± 0.04	0.1 ± 0.04	0.1 ± 0.04
c-2-hexene	µg/m³	0 ± 0.04	0 ± 0.04	0 ± 0.04	0 ± 0.04
1,3-hexadiene (trans)	µg/m³	0 ± 0.04	0 ± 0.04	0 ± 0.04	0 ± 0.04
Methylcyclopentane	µg/m³	0.1 ± 0.04	7.8 ± 0.44	0.2 ± 0.04	0.5 ± 0.04
2,4-dimethylpentane	µg/m³	0 ± 0.04	2.3 ± 0.17	0.1 ± 0.04	0.2 ± 0.04
Benzene	µg/m³	0.3 ± 0.03	0.5 ± 0.03	1.3 ± 0.06	4.1 ± 0.21
Cyclohexane	µg/m³	0.1 ± 0.04	1.8 ± 0.09	0.6 ± 0.04	1.5 ± 0.08
2-methylhexane	µg/m³	0 ± 0.04	4.4 ± 0.29	0.1 ± 0.04	0.2 ± 0.04
2,3-dimethylpentane	µg/m³	0.2 ± 0.04	2.4 ± 0.18	0.5 ± 0.04	0.6 ± 0.05
Cyclohexene	µg/m³	0 ± 0.04	0.1 ± 0.04	0.1 ± 0.04	0.2 ± 0.04
3-methylhexane	µg/m³	0 ± 0.04	3 ± 0.15	0.1 ± 0.04	0.3 ± 0.04
1,3-dimethylcyclopentane (cis)	µg/m³	0 ± 0.04	0.2 ± 0.04	0 ± 0.04	0.1 ± 0.04
1-heptene	µg/m³	0 ± 0.04	0.4 ± 0.04	0.2 ± 0.04	0.6 ± 0.04
2,2,4-trimethylpentane	µg/m³	0.1 ± 0.05	0.2 ± 0.05	0.2 ± 0.05	0.7 ± 0.05
n-heptane	µg/m³	0.1 ± 0.04	0.2 ± 0.04	0.2 ± 0.04	0.6 ± 0.06
2,3-dimethyl-2-pentene	µg/m³	0 ± 0.04	0 ± 0.04	0 ± 0.04	0 ± 0.04
Methylcyclohexane	µg/m³	0.1 ± 0.04	0.1 ± 0.04	1.1 ± 0.26	3.5 ± 0.81
2,3,4-trimethylpentane	µg/m³	0 ± 0.05	0 ± 0.05	0 ± 0.05	0.1 ± 0.05
Toluene	µg/m³	0.5 ± 0.04	21 ± 1.05	0.9 ± 0.04	2.1 ± 0.11
2-methylheptane	µg/m³	0 ± 0.05	0.1 ± 0.05	0.2 ± 0.05	0.5 ± 0.05

April 2010 – Detailed Atmosphere Characterization

Volatile Organic Compounds (VOC):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
4-methylheptane	µg/m³	0 ± 0.05	0 ± 0.05	0.1 ± 0.05	0.2 ± 0.05
3-methylheptane	µg/m³	0 ± 0.05	0 ± 0.05	0.1 ± 0.05	0.4 ± 0.14
n-octane	µg/m³	0 ± 0.05	0.1 ± 0.05	0.5 ± 0.05	1.5 ± 0.07
Ethylbenzene	µg/m³	0.4 ± 0.05	0.3 ± 0.05	0.3 ± 0.05	1 ± 0.05
m&p-xylene	µg/m³	1.1 ± 0.07	0.9 ± 0.05	0.6 ± 0.05	1.7 ± 0.08
Styrene	µg/m³	0 ± 0.05	0 ± 0.05	0 ± 0.05	0 ± 0.05
o-xylene	µg/m³	0.3 ± 0.05	0.3 ± 0.05	0.2 ± 0.05	0.6 ± 0.05
n-nonane	µg/m³	0.1 ± 0.06	0.2 ± 0.06	0.8 ± 0.06	2.4 ± 0.12
Isopropylbenzene	µg/m³	0 ± 0.05	0 ± 0.05	0.1 ± 0.05	0.3 ± 0.05
n-propylbenzene	µg/m³	0 ± 0.05	0 ± 0.05	0.2 ± 0.05	0.6 ± 0.05
alpha-pinene	µg/m³	0 ± 0.06	0.2 ± 0.06	0.1 ± 0.06	0 ± 0.06
3-ethyltoluene	µg/m³	0.1 ± 0.05	0.1 ± 0.05	0.5 ± 0.05	1.3 ± 0.07
4-ethyltoluene	µg/m³	0 ± 0.05	0 ± 0.05	0.2 ± 0.05	0.7 ± 0.05
1,3,5-trimethylbenzene	µg/m³	0 ± 0.05	0 ± 0.05	0.2 ± 0.06	0.6 ± 0.18
o-ethyltoluene	µg/m³	0 ± 0.05	0 ± 0.05	0.2 ± 0.05	0.5 ± 0.05
1,2,4-trimethylbenzene+t-butylbenzene	µg/m³	0 ± 0.05	0 ± 0.05	0 ± 0.05	0 ± 0.05
n-decane	µg/m³	0.1 ± 0.07	0.3 ± 0.1	2.5 ± 0.84	8.1 ± 2.72
1,2,3-trimethylbenzene	µg/m³	0 ± 0.05	0.1 ± 0.05	0.3 ± 0.11	1 ± 0.33
Indan	µg/m³	0 ± 0.05	0 ± 0.05	0.1 ± 0.05	0.2 ± 0.05
1,3-diethylbenzene	µg/m³	0 ± 0.06	0 ± 0.06	0.2 ± 0.06	0.7 ± 0.06
1,4-diethylbenzene	µg/m³	0 ± 0.06	0 ± 0.06	0.2 ± 0.09	0.7 ± 0.27
n-butylbenzene	µg/m³	0 ± 0.06	0 ± 0.06	0 ± 0.06	0 ± 0.06
n-undecane	µg/m³	0.2 ± 0.07	0.4 ± 0.07	2.6 ± 0.24	8.6 ± 0.81

Appendix E.

Sept 2010 – Detailed Atmosphere Characterization

Sep 2010 – Detailed Atmosphere Characterization

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Dekati Particle Mass-Chamber Inlet	µg/m³	NA	NA	NA	NA
Dekati Particle Mass-Inside Chamber	µg/m³	NA	NA	1.6	9.04 ± 11.8
Filter Sample - Chamber Inlet	µg/m³	NA	2.0 ± 1.0	3.0 ± 1.0	8.0 ± 3.0
Filter Sample - Inside Chamber	µg/m³	22.0 ± 14.0	12.0 ± 8.0	16.0 ± 5.0	20.0 ± 2.0
Particle Mass-FMPS	µg/m³	0.42 ± 0.07	1.50 ± 0.13	4.27 ± 3.17	6.23 ± 3.89
Particle Count -FMPS	Particle/cm³	5.01E+04 ± 2.57E+04	8.34E+05 ± 1.50E+05	2.55E+06 ± 1.93E+06	2.37E06 ± 1.16E+06
NMAD (GSD) - FMPS	nm	9.9 (1.4) ± 0.02 (0.03)	8.2 (1.2) ± 0.03 (0.01)	8.0 (1.2) ± 0.3 (0.01)	12.1 (1.7) ± 0.5 (0.1)
MMAD (GSD) - FMPS	nm	138.4 (1.9) ± 0.5 (0.04)	131.4 (3.5) ± 4.5 (0.3)	123.3 (3.8) ± 3.8 (0.5)	35.5 (1.8) ± 3.1 (0.1)
Nitrogen Oxide (NO)	µg/m³ (ppm)	0(0)	191.9 ± 110.5 (0.19 ± 0.11)	1251.9 ± 502.8 (1.22 ± 0.49)	4936.1 ± 738.9 (4.8 ± 0.7)
Nitrogen Dioxide (NO_2)	µg/m³ (ppm)	0 ± 0.9 (0 ± 0.6)	182.5 ± 120.5 (0.12 ± .08)	1494.8 ± 645.1 (0.95 ± .41)	6813.3 ± 1148.7 (4.3 ± 0.7)
Carbon Monoxide (CO)	µg/m³ (ppm)	NA	NA	NA	9453.4 ± 1724.0 (9.9 ± 1.8)
Carbon Dioxide (CO_2)	mg/m³ (ppm)	NA	NA	NA	8950.9 ± 681.9 (5947.0 ± 453.1)
Sulfur Dioxide (SO_2)	µg/m³(ppb)	NA	NA	NA	43.8 ± 11.7 (19.4 ± 5.2)
Elemental Carbon	µg/m³	0.1	2.7 ± 0.01	0.1	1.0
Organic Carbon	µg/m³	2.9 ± 0.05	7.8 ± 0.2	2.5 ± 0.03	2.6 ± 0.04
Ammonium	ng/m³	25.2 ± 0.05	58.1 ± 0.1	156.5 ± 0.6	1374.3 ± 27.3
Sulfate	ng/m³	134.8 ± 0.01	228.4	729.7 ± 0.3	2863.7 ± 4.0
Nitrate	ng/m³	0.0	474.6	246.5	2975 ± 0.5
Elements (Metals)	ng/m³	516.4 ± 217.9	670.4 ± 215.7	458.7 ± 217.2	712.0 ± 226.2
Alkanes	µg/m³	2.8 ± 0.2	7.4 ± 0.4	7.2 ± 0.4	16 ± 0.9
Carbonyl	µg/m³	67.4 ± 4.3	66.1 ± 4.2	16.2 ± 1.4	3.3 ± 0.5
Polyaromatic Hydrocarbon (PAH)	µg/m³	0.7 ± 0.1	1.3 ± 0.1	2.1 ± 0.1	3.8 ± 0.3
Nitro-PAH	ng/m³	0.3 ± 0.02	1.4 ± 0.1	1.4 ± 0.1	5.5 ± 0.3
Polars (Acids)	µg/m³	2.9 ± 0.3	2.2 ± 0.2	3.7 ± 0.4	12.1 ± 1
Hopane and Steranes	ng/m³	1.2 ± 0.1	9.1 ± 0.8	1.3 ± 0.2	1.3 ± 0.2
Volatile Organic Compounds (VOC)	µg/m³	24.6 ± 4.1	17 ± 3.5	33.1 ± 5.2	73.6 ± 10

Sep 2010 – Detailed Atmosphere Characterization

Carbon:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Organic Carbon Fraction 1	µg/m³	0.2 ± 0.01	0.0	0.1 ± 0.01	0.2 ± 0.01
Organic Carbon Fraction 2	µg/m³	1 ± 0.07	2.2 ± 0.2	1.2 ± 0.08	1.2 ± 0.09
Organic Carbon Fraction 3	µg/m³	1.3 ± 0.11	3.5 ± 0.43	1 ± 0.06	0.9 ± 0.06
Organic Carbon Fraction 4	µg/m³	0.3 ± 0.01	1.6 ± 0.15	0.2	0.2 ± 0.01
Pyrolyzed Organic Carbon Reflectance	µg/m³	0.0	0.6	0.0	0.1
Pyrolyzed Organic Carbon Transmittance	µg/m³	0.1	0.6 ± 0.08	0.0	0.1 ± 0.01
Organic Carbon	µg/m³	2.9 ± 0.05	7.8 ± 0.23	2.5 ± 0.03	2.6 ± 0.04
Elemental Carbon Fraction 1	µg/m³	0.0	1.2 ± 0.1	0.0	0.1
Elemental Carbon Fraction 2	µg/m³	0.1	2 ± 0.15	0.1	0.9 ± 0.05
Elemental Carbon Fraction 3	µg/m³	0.0	0.1	0.0	0.0
Elemental Carbon	µg/m³	0.1	2.7 ± 0.01	0.0	1.0
Total Carbon	µg/m³	3 ± 0.01	10.5 ± 0.06	2.5	3.6 ± 0.01

Sep 2010 – Detailed Atmosphere Characterization

Elements (Metals):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Sodium	ng/m³	41.6 ± 55	139 ± 56.5	9.3 ± 54.5	278.3 ± 62
Magnesium	ng/m³	1.5 ± 17.5	41.1 ± 17.4	0 ± 17.6	19.2 ± 17.8
Aluminum	ng/m³	11.9 ± 3.5	1 ± 3.4	8.9 ± 3.5	19.1 ± 3.5
Silicon	ng/m³	38 ± 2.3	8 ± 2.1	4.6 ± 2.2	0.9 ± 2.1
Phosphorous	ng/m³	18 ± 0.6	11.6 ± 0.6	19 ± 0.6	10.2 ± 0.6
Sulfur	ng/m³	53.6 ± 0.7	118.4 ± 0.9	230.2 ± 1.3	1060.8 ± 4.1
Chlorine	ng/m³	68.3 ± 0.7	83.1 ± 0.8	98.1 ± 0.8	64.3 ± 0.8
Potassium	ng/m³	180.5 ± 1	239.9 ± 1.1	193.9 ± 1	216.2 ± 1.1
Calcium	ng/m³	49.7 ± 2.5	49.8 ± 2.4	49.6 ± 2.4	52.9 ± 2.5
Scandium	ng/m³	3.4 ± 10.6	1 ± 10.4	4.4 ± 10.6	0 ± 10.7
Titanium	ng/m³	11.2 ± 0.9	1.1 ± 0.8	0.6 ± 0.9	0.6 ± 0.9
Vanadium	ng/m³	0.1 ± 0.6	0 ± 0.6	0 ± 0.6	0 ± 0.6
Chromium	ng/m³	0.4 ± 0.6	0 ± 0.6	0 ± 0.6	1 ± 0.6
Manganese	ng/m³	0.7 ± 1.8	0.2 ± 1.7	0 ± 1.8	0.7 ± 1.8
Iron	ng/m³	20.5 ± 0.6	17 ± 0.6	9.7 ± 0.6	8.8 ± 0.6
Cobalt	ng/m³	0.1 ± 0.6	0.3 ± 0.6	0 ± 0.6	0 ± 0.6
Nickel	ng/m³	0.4 ± 1.7	0.2 ± 1.6	0 ± 1.7	0.2 ± 1.7
Copper	ng/m³	26.5 ± 2.1	26.6 ± 2	23.2 ± 2.1	9.1 ± 2.1
Zinc	ng/m³	29.4 ± 0.6	46.6 ± 0.6	17.1 ± 0.6	10 ± 0.6
Gallium	ng/m³	0.3 ± 2.8	0 ± 2.7	2.3 ± 2.8	1 ± 2.8
Arsenic	ng/m³	0 ± 0.6	0 ± 0.6	0 ± 0.6	0 ± 0.6
Selenium	ng/m³	0.6 ± 0.6	0 ± 0.6	0 ± 0.6	0 ± 0.6
Bromine	ng/m³	0.3 ± 0.6	0.9 ± 0.6	0.8 ± 0.6	0.4 ± 0.6
Rubidium	ng/m³	0 ± 0.6	0.1 ± 0.6	0.2 ± 0.6	0.2 ± 0.6
Strontium	ng/m³	0.6 ± 0.6	0.2 ± 0.6	0.2 ± 0.6	0.4 ± 0.6
Yttrium	ng/m³	0.1 ± 0.6	0.2 ± 0.6	0 ± 0.6	0.4 ± 0.6

Sep 2010 – Detailed Atmosphere Characterization

Elements (Metals):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Zirconium	ng/m³	0.6 ± 0.9	0.5 ± 0.9	0 ± 0.9	0.5 ± 0.9
Niobium	ng/m³	0 ± 0.8	0 ± 0.8	0 ± 0.8	0 ± 0.8
Molybdenum	ng/m³	0 ± 1.2	0 ± 1.2	0 ± 1.2	0.1 ± 1.2
Palladium	ng/m³	0.3 ± 1.4	0 ± 1.4	0.3 ± 1.4	0.5 ± 1.4
Silver	ng/m³	0.2 ± 1.3	0 ± 1.3	0 ± 1.4	0 ± 1.3
Cadmium	ng/m³	0 ± 1.7	0 ± 1.7	0 ± 1.7	0 ± 1.7
Indium	ng/m³	0.4 ± 1.8	1.4 ± 1.7	0 ± 1.8	0 ± 1.8
Tin	ng/m³	0 ± 1.8	0.5 ± 1.7	0 ± 1.8	0.1 ± 1.8
Antimony	ng/m³	0 ± 2.8	0 ± 2.8	0.9 ± 2.8	0.2 ± 2.8
Cesium	ng/m³	0 ± 5.7	0 ± 5.6	0 ± 5.8	0 ± 5.8
Barium	ng/m³	0 ± 6.7	0 ± 6.4	2 ± 6.6	0 ± 6.7
Lanthanum	ng/m³	0 ± 8.2	0 ± 8	0 ± 8.2	1.8 ± 8.4
Cerium	ng/m³	0.8 ± 7.7	0 ± 7.6	0 ± 7.7	2.8 ± 7.8
Samarium	ng/m³	2.1 ± 13.9	0 ± 13.5	0 ± 13.7	3.9 ± 13.9
Europium	ng/m³	1.3 ± 19.7	0 ± 19.4	10 ± 19.8	5 ± 19.9
Terbium	ng/m³	2.3 ± 14.9	0 ± 14.5	0 ± 14.8	0 ± 15.3
Hafnium	ng/m³	0 ± 4.1	0 ± 4	2.5 ± 4.2	0 ± 4.2
Tantalum	ng/m³	0 ± 2.3	0 ± 2.3	0 ± 2.3	0.6 ± 2.3
Wolfram	ng/m³	1.8 ± 6.6	0 ± 6.4	0 ± 6.5	1.1 ± 6.6
Iridium	ng/m³	0 ± 1.1	0 ± 1.1	0 ± 1.1	0 ± 1.1
Gold	ng/m³	0 ± 1	0 ± 1	0 ± 1	0 ± 1
Mercury	ng/m³	0 ± 0.6	0 ± 0.6	0 ± 0.6	0 ± 0.6
Thallium	ng/m³	0 ± 0.7	0 ± 0.7	0 ± 0.7	0 ± 0.7
Lead	ng/m³	2.5 ± 0.6	0 ± 0.6	0.8 ± 0.6	1.3 ± 0.6
Uranium	ng/m³	0.1 ± 0.9	0 ± 0.9	0.2 ± 0.9	0 ± 0.8

Sep 2010 – Detailed Atmosphere Characterization

Alkanes:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Dodecane	ng/m³	292.2 ± 14.7	688.9 ± 34.4	922.5 ± 46.1	1906.5 ± 95.3
Norfarnesane	ng/m³	437 ± 25.6	485.1 ± 28.5	696.5 ± 40.8	1857.1 ± 108.6
Tridecane	ng/m³	379.7 ± 19.1	695.3 ± 36.2	1240.9 ± 62.1	3585.3 ± 179.4
Heptylcyclohexane	ng/m³	39.6 ± 5.1	76.4 ± 9.7	141.4 ± 17.8	402.3 ± 50.4
Farnesane	ng/m³	71.2 ± 3.9	183.3 ± 9.9	344.5 ± 18.4	1165.8 ± 62
Tetradecane	ng/m³	204.4 ± 10.3	800.9 ± 40	962.1 ± 48.1	2302 ± 115.1
Octylcyclohexane	ng/m³	18.9 ± 1.4	73 ± 5	96.5 ± 7	232.5 ± 16.8
Pentadecane	ng/m³	172.9 ± 8.8	378.6 ± 19.1	709.5 ± 35.6	1558.7 ± 78
Nonylcyclohexane	ng/m³	16.4 ± 0.9	39.9 ± 2.1	70.5 ± 3.7	140.7 ± 7.2
Hexadecane	ng/m³	172.3 ± 8.7	863.5 ± 43.2	440.4 ± 22	880.9 ± 44
Norpristane	ng/m³	86.5 ± 4.5	130.2 ± 6.6	204.8 ± 10.4	413.7 ± 20.8
Decylcyclohexane	ng/m³	11.2 ± 1.3	31.8 ± 3.5	32.5 ± 3.6	67.3 ± 7.3
Heptadecane	ng/m³	120.3 ± 6.1	345.3 ± 18.2	271.8 ± 13.7	446.5 ± 22.5
Heptadecane	ng/m³	97.9 ± 5.1	130.5 ± 8	150.4 ± 7.6	296.4 ± 15
Undecylcyclohexane	ng/m³	13.3 ± 1.9	17.3 ± 2.5	20.7 ± 2.9	34.3 ± 4.8
Octadecane	ng/m³	178.4 ± 9	763.4 ± 38.2	215.8 ± 10.9	250.4 ± 12.5
Phytane	ng/m³	90.8 ± 5.3	78.4 ± 5.5	85.9 ± 5	142 ± 8.2
Dodecylcyclohexane	ng/m³	9.9 ± 1.9	9.6 ± 1.9	10.3 ± 2	14.1 ± 2.6
Nonadecane	ng/m³	94.4 ± 4.8	38.6 ± 2.1	35 ± 1.9	62.6 ± 3.2
Tridecylcyclohexane	ng/m³	3.8 ± 0.3	3.6 ± 0.3	3.3 ± 0.3	6.3 ± 0.4
Eicosane	ng/m³	100.5 ± 5.1	455.8 ± 22.8	151.7 ± 7.7	64.5 ± 3.3
Tetradecylcyclohexane	ng/m³	2.5 ± 0.4	2.4 ± 0.4	1.2 ± 0.3	1.4 ± 0.3
Heneicosane	ng/m³	21.3 ± 1.4	29.2 ± 1.9	9.4 ± 0.7	16.1 ± 1.1
Pentadecylcyclohexane	ng/m³	1.4 ± 0.3	3.3 ± 0.4	0.8 ± 0.3	2.8 ± 0.4
Docosane	ng/m³	45.2 ± 2.4	293.2 ± 14.7	128 ± 6.5	36.7 ± 2
Hexadecylcyclohexane	ng/m³	1.1 ± 0.3	1.5 ± 0.3	0.1 ± 0.3	1.2 ± 0.3

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Alkanes:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Tricosane	ng/m³	7.3 ± 0.9	7.8 ± 1	5.4 ± 0.7	8.4 ± 1
Heptadecylcyclohexane	ng/m³	0.5 ± 0.3	5.3 ± 0.4	0.7 ± 0.3	2.7 ± 0.3
Tetracosane	ng/m³	28.8 ± 1.5	171.3 ± 8.6	87.4 ± 4.5	24.1 ± 1.4
Octadecylcyclohexane	ng/m³	0.8 ± 0.3	0.1 ± 0.3	0.8 ± 0.3	0.4 ± 0.3
Pentacosane	ng/m³	2.3 ± 0.3	4.2 ± 0.3	2.1 ± 0.3	3.6 ± 0.4
Hexacosane	ng/m³	10.3 ± 0.7	109.6 ± 5.9	45.1 ± 2.4	9.2 ± 0.6
Nonadecylcyclohexane	ng/m³	2.4 ± 0.3	21.5 ± 1.7	8.3 ± 0.8	3.4 ± 0.4
Heptacosane	ng/m³	0 ± 0.3	9.9 ± 1.2	0.5 ± 0.3	1.7 ± 0.4
Eicosylcyclohexane	ng/m³	0.1 ± 0.3	0.2 ± 0.3	0.1 ± 0.3	0.1 ± 0.3
Octacosane	ng/m³	4.7 ± 0.4	75.3 ± 4.2	25.8 ± 1.9	6.8 ± 0.6
Nonacosane	ng/m³	0.2 ± 0.3	15.7 ± 1.5	0 ± 0.3	1.2 ± 0.3
Heneicosylcyclohexane	ng/m³	0 ± 0.3	0.9 ± 0.3	0.2 ± 0.3	0.5 ± 0.3
Triacontane	ng/m³	2 ± 0.3	58.4 ± 3	16.3 ± 1.1	3.5 ± 0.4
Hentriacontane	ng/m³	1.1 ± 0.3	21 ± 2.3	1.9 ± 0.3	2.5 ± 0.4
Dotriacontane	ng/m³	1 ± 0.3	56.4 ± 5.7	10.7 ± 0.8	1.9 ± 0.3
Tritriacontane	ng/m³	1.2 ± 0.3	13.7 ± 2.1	2.4 ± 0.5	2.3 ± 0.4
Tetratriacontane	ng/m³	1.3 ± 0.3	49.4 ± 2.6	7.2 ± 0.8	2.7 ± 0.4
Pentatriacontane	ng/m³	0.8 ± 0.3	17.9 ± 1	1 ± 0.3	1.3 ± 0.4
Hexatriacontane	ng/m³	0.5 ± 0.3	43.5 ± 2.2	1.6 ± 0.3	0.7 ± 0.3
Heptatriacontane	ng/m³	0.7 ± 0.3	5.8 ± 0.8	1.5 ± 0.3	0.5 ± 0.3
Octatriacontane	ng/m³	1.1 ± 0.3	30.5 ± 3	4.7 ± 0.5	1 ± 0.3
Nonatriacontane	ng/m³	0.1 ± 0.3	1.9 ± 0.4	0 ± 0.3	0 ± 0.3
Tetracontane	ng/m³	0.3 ± 0.3	18.2 ± 1	0.9 ± 0.3	0 ± 0.3

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Carbonyl:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Formaldehyde	µg/m³	6.2 ± 0.31	3.9 ± 0.19	1.8 ± 0.1	0 ± 0.02
Acetaldehyde	µg/m³	20.4 ± 1.02	24.1 ± 1.21	0.6 ± 0.04	0 ± 0.02
Acrolein	µg/m³	0.4 ± 0.03	0.4 ± 0.03	0 ± 0.02	2.3 ± 0.15
Glyoxal	µg/m³	0.4 ± 0.04	0.2 ± 0.02	0 ± 0.02	0 ± 0.02
Acetone	µg/m³	6.5 ± 0.34	5.4 ± 0.28	0 ± 0.02	0.7 ± 0.05
Propionaldehyde	µg/m³	2.4 ± 0.12	2.4 ± 0.12	0.1 ± 0.02	0 ± 0.02
Crotonaldehyde	µg/m³	0.2 ± 0.03	0 ± 0.02	0 ± 0.02	0 ± 0.02
Methacrolein	µg/m³	0.1 ± 0.03	0 ± 0.02	0 ± 0.02	0 ± 0.02
n-butyraldehyde	µg/m³	1.4 ± 0.12	1.8 ± 0.15	0.4 ± 0.04	0 ± 0.02
2-Butanone (MEK)	µg/m³	1.6 ± 0.08	0.8 ± 0.05	0 ± 0.02	0 ± 0.02
Valeraldehyde	µg/m³	3.8 ± 0.35	3.6 ± 0.33	0.8 ± 0.07	0.1 ± 0.02
Hexaldehyde	µg/m³	21.8 ± 1.63	21.4 ± 1.6	12.2 ± 0.91	0.1 ± 0.03
Benzaldehyde	µg/m³	2.2 ± 0.12	2.2 ± 0.12	0.3 ± 0.03	0.1 ± 0.02
m-Tolualdehyde	µg/m³	0.2 ± 0.04	0 ± 0.02	0 ± 0.02	0 ± 0.02

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PolyAromatic HydroCarbon (PAH):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
1+2ethylnaphthalene	ng/m³	2.4 ± 0.2	10 ± 0.6	16.5 ± 1.1	55.4 ± 3.5
Naphthalene	ng/m³	104.7 ± 9	177.7 ± 15.3	255.1 ± 22	696.7 ± 60.1
Quinoline	ng/m³	0.2 ± 0.1	1.8 ± 0.2	3.5 ± 0.4	10.9 ± 1.2
2-methylnaphthalene	ng/m³	19.9 ± 1	40.1 ± 2.1	62 ± 3.3	242.2 ± 12.7
1-methylnaphthalene	ng/m³	11.8 ± 0.7	25.9 ± 1.6	42.5 ± 2.6	185.3 ± 11.4
Biphenyl	ng/m³	9.2 ± 0.5	22.7 ± 1.1	43.9 ± 2.2	109.3 ± 5.5
2-methylbiphenyl	ng/m³	0 ± 0.1	13.6 ± 1	152.2 ± 11.1	410.2 ± 29.9
2,6+2,7-dimethylnaphthalene	ng/m³	9.7 ± 0.7	24.7 ± 1.8	39.2 ± 2.8	132.3 ± 9.6
1,3+1,6+1,7dimethylnaphth	ng/m³	17.7 ± 1.1	42.8 ± 2.8	68.2 ± 4.4	234.5 ± 15.2
1,4+1,5+2,3-dimethylnaphth	ng/m³	6.2 ± 0.3	13.9 ± 0.8	23.1 ± 1.3	66.7 ± 3.7
Acenaphthylene	ng/m³	0.3 ± 0.1	7.6 ± 0.7	16.5 ± 1.5	2.1 ± 0.2
1,2-dimethylnaphthalene	ng/m³	1.7 ± 0.1	3.7 ± 0.3	4.3 ± 0.4	14.6 ± 1.2
1,8-dimethylnaphthalene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Acenaphthene	ng/m³	0.8 ± 0.1	0.6 ± 0.1	0.5 ± 0.1	3.1 ± 0.2
3-methylbiphenyl	ng/m³	288.6 ± 15.3	556.5 ± 29.4	902.4 ± 47.7	807.4 ± 42.7
4-methylbiphenyl	ng/m³	106 ± 7.3	208.1 ± 14.4	342.2 ± 23.7	384.3 ± 26.6
Dibenzofuran	ng/m³	2.4 ± 0.2	5.8 ± 0.5	6 ± 0.5	11.7 ± 0.9
1-ethyl-2-methylnaphthalene	ng/m³	1.6 ± 0.1	3.4 ± 0.2	4.7 ± 0.3	11.1 ± 0.7
2,3,5+I-trimethylnaphthalene	ng/m³	5.3 ± 0.8	11.9 ± 1.8	18 ± 2.7	37 ± 5.5
B-trimethylnaphthalene	ng/m³	8.9 ± 0.4	19.1 ± 1	24.1 ± 1.2	54.9 ± 2.7
A-trimethylnaphthalene	ng/m³	8.7 ± 0.4	19 ± 0.9	26.5 ± 1.3	64 ± 3.2
C-trimethylnaphthalene	ng/m³	7.8 ± 0.4	17.1 ± 1	20.7 ± 1.2	47.8 ± 2.8
2-ethyl-1-methylnaphthalene	ng/m³	0 ± 0.1	0.9 ± 0.1	0.4 ± 0.1	1.5 ± 0.1
E-trimethylnaphthalene	ng/m³	5.6 ± 0.5	13 ± 1.1	14.1 ± 1.2	33 ± 2.7
2,4,5-trimethylnaphthalene	ng/m³	0.9 ± 0.1	1.7 ± 0.2	0.1 ± 0.1	5.6 ± 0.7
F-trimethylnaphthalene	ng/m³	4 ± 0.3	9 ± 0.7	13 ± 1	26.2 ± 1.9

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PolyAromatic HydroCarbon (PAH):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Fluorene	ng/m³	3.1 ± 0.3	3.6 ± 0.4	4.4 ± 0.5	11.1 ± 1.2
1,4,5-trimethylnaphthalene	ng/m³	1.1 ± 0.1	2.4 ± 0.1	1.7 ± 0.1	2.4 ± 0.1
J-trimethylnaphthalene	ng/m³	2.5 ± 0.2	3.9 ± 0.3	5 ± 0.3	9.1 ± 0.6
A-Methylfluorene	ng/m³	1.1 ± 0.2	3.1 ± 0.4	0.5 ± 0.1	3.8 ± 0.5
B-Methylfluorene	ng/m³	0.2 ± 0.1	0.5 ± 0.1	0.1 ± 0.1	0.2 ± 0.1
1-Methylfluorene	ng/m³	0.1 ± 0.1	0.3 ± 0.2	0.1 ± 0.1	1.5 ± 0.2
9-fluorenone	ng/m³	2.4 ± 0.2	1 ± 0.1	1.6 ± 0.1	3.9 ± 0.3
Dibenzothiophene	ng/m³	0.3 ± 0.1	0.4 ± 0.1	0.1 ± 0.1	0.2 ± 0.1
Phenanthrene	ng/m³	5.7 ± 0.4	7.3 ± 0.6	10.4 ± 0.8	23.4 ± 1.8
Anthracene	ng/m³	0.4 ± 0.1	0.7 ± 0.2	0.2 ± 0.1	56.3 ± 7.4
Xanthone	ng/m³	0.1 ± 0.1	0 ± 0.1	0.3 ± 0.1	0.9 ± 0.2
Acenaphthenequinone	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
3-methylphenanthrene	ng/m³	1.5 ± 0.2	1.2 ± 0.1	0.8 ± 0.1	1.2 ± 0.2
2-methylphenanthrene	ng/m³	1.8 ± 0.2	1.4 ± 0.1	0.6 ± 0.1	1.1 ± 0.1
Perinaphthenone	ng/m³	0.1 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.5 ± 0.1
2-methylanthracene	ng/m³	1.2 ± 0.4	0 ± 0.1	0.1 ± 0.1	36.7 ± 9
4,5-methylenephenanthrene	ng/m³	0.3 ± 0.1	0.3 ± 0.2	0.2 ± 0.1	1.7 ± 0.3
9-methylphenanthrene	ng/m³	0.8 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.3 ± 0.1
1-methylphenanthrene	ng/m³	0.9 ± 0.1	0.1 ± 0.1	0.5 ± 0.1	0.2 ± 0.1
Anthrone	ng/m³	0.4 ± 0.1	0.4 ± 0.1	0.3 ± 0.1	0.6 ± 0.1
9-methylanthracene	ng/m³	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.2 ± 0.1
2-phenylnaphthalene	ng/m³	0.3 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.4 ± 0.1
Anthraquinone	ng/m³	0.5 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	1.9 ± 0.3
A-dimethylphenanthrene	ng/m³	0.3 ± 0.1	0.2 ± 0.1	0 ± 0.1	0.4 ± 0.1

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PolyAromatic HydroCarbon (PAH):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
B-dimethylphenanthrene	ng/m³	0.3 ± 0.1	0.1 ± 0.1	0 ± 0.1	0.5 ± 0.1
1,7-dimethylphenanthrene	ng/m³	0.3 ± 0.1	0.3 ± 0.1	0 ± 0.1	0.5 ± 0.2
3,6-dimethylphenanthrene	ng/m³	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.3 ± 0.1
D-dimethylphenanthrene	ng/m³	0.1 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.2 ± 0.1
E-dimethylphenanthrene	ng/m³	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.4 ± 0.2
C-dimethylphenanthrene	ng/m³	0.7 ± 0.1	0.4 ± 0.2	0.1 ± 0.1	0.3 ± 0.1
Fluoranthene	ng/m³	0.5 ± 0.1	0.3 ± 0.1	0.3 ± 0.1	11.4 ± 1.7
Pyrene	ng/m³	0.5 ± 0.1	0.1 ± 0.1	0 ± 0.1	10 ± 0.7
9-Anthraaldehyde	ng/m³	0.1 ± 0.1	0 ± 0.1	0 ± 0.1	0.4 ± 0.1
Retene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Benzo(a)fluorene	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0 ± 0.1
Benzo(b)fluorene	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0 ± 0.1
B-MePy/MeFl	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
1-MeFl+C-MeFl/Py	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
1+3-methylfluoranthene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
4-methylpyrene	ng/m³	0 ± 0.1	0.2 ± 0.1	0 ± 0.1	0 ± 0.1
C-MePy/MeFl	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
D-MePy/MeFl	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
1-methylpyrene	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0 ± 0.1
Benzonaphthothiophene	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0 ± 0.1
Benzo(c)phenanthrene	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0 ± 0.1
Benzo(ghi)fluoranthene	ng/m³	0 ± 0.1	0 ± 0.1	0.1 ± 0.1	0.2 ± 0.1
9-phenylanthracene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Cyclopenta(c,d)pyrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1

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PolyAromatic HydroCarbon (PAH):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Benz(a)anthracene	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0.2 ± 0.1
Chrysene-Triphenylene	ng/m³	0 ± 0.1	0.2 ± 0.2	0 ± 0.1	0.1 ± 0.1
Benzanthrone	ng/m³	0 ± 0.1	0.2 ± 0.2	0 ± 0.1	0.1 ± 0.1
Benz(a)anthracene-7,12-dione	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
3-methylchrysene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Chry56m	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0 ± 0.1
7-methylbenz(a)anthracene	ng/m³	0.2 ± 0.2	0.2 ± 0.2	0.2 ± 0.2	0.2 ± 0.2
7,12-dimethylbenz(a)anthracene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
Benzo(b+j+k)fluoranthene	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0 ± 0.1
Benzo(a)fluoranthene	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0 ± 0.1
BeP	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0 ± 0.1
BaP	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0 ± 0.1
Perylene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenz(a,j)acridine	ng/m³	0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0 ± 0.1
7-methylbenzo(a)pyrene	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0 ± 0.1
Bpy910dih	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Indeno[123-cd]fluoranthene	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenz(a,h)acridine	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dbajacr	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Indeno[123-cd]pyrene	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(ah+ac)anthracene	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(a,j)anthracene	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0.2 ± 0.1
Benzo(b)chrysene	ng/m³	0 ± 0.1	0.2 ± 0.2	0 ± 0.1	0.1 ± 0.1
Picene	ng/m³	0 ± 0.1	0.2 ± 0.2	0 ± 0.1	0.1 ± 0.1

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PolyAromatic HydroCarbon (PAH):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Benzo(ghi)perylene	ng/m³	0 ± 0.1	0.2 ± 0.2	0 ± 0.1	0.1 ± 0.1
Anthanthrene	ng/m³	0 ± 0.1	0.1 ± 0.2	0 ± 0.1	0 ± 0.1
Dibenzo(a,l)pyrene	ng/m³	0 ± 0.1	0.1 ± 0.3	0 ± 0.1	0 ± 0.1
Coronene	ng/m³	0 ± 0.1	0.2 ± 0.2	0 ± 0.1	0 ± 0.1
Dibenzo(a,e)pyrene	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(a,i)pyrene	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(a,h)pyrene	ng/m³	0 ± 0.1	0.1 ± 0.2	0 ± 0.1	0 ± 0.1
Dibenzo(b,k)fluoranthene	ng/m³	0.5 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1

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Nitro-PAH:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
3-nitrobenzo[e]pryene	ng/m³	0.0	0.0	0.0	0.0
1-nitronaphthalene	ng/m³	0.0	0.2 ± 0.01	0.5 ± 0.03	1.4 ± 0.07
1-methyl-5-nitronaphthalene	ng/m³	0.0	0.0	0.0	0.3 ± 0.01
2-nitronaphthalene	ng/m³	0.0	0.1	0.3 ± 0.02	1.8 ± 0.09
2-nitrobiphenyl	ng/m³	0.0	0.1	0.1 ± 0.01	0.1 ± 0.01
2-methyl-4-nitronaphthalene	ng/m³	0.0	0.1	0.1 ± 0.01	0.5 ± 0.03
1-methyl-4-nitronaphthalene	ng/m³	0.0	0.0	0.1 ± 0.01	0.2 ± 0.02
1-methyl-6-nitronaphthalene	ng/m³	0.0	0.0	0.0	0.3 ± 0.02
3-nitrobiphenyl	ng/m³	0.0	0.0	0.0	0.0
4-nitrobiphenyl	ng/m³	0.0	0.0	0.0	0.1 ± 0.01
1,3-dinitronaphthalene	ng/m³	0.0	0.0	0.0	0.0
1,5-dinitronaphthalene	ng/m³	0.0	0.0	0.0	0.0
5-nitroacenaphthene	ng/m³	0.0	0.0	0.0	0.4 ± 0.04
2-nitrofluorene	ng/m³	0.0	0.0	0.0	0.0
4-nitrophenanthrene	ng/m³	0.0	0.0	0.0	0.0
9-nitroanthracene	ng/m³	0.0	0.0	0.0	0.1 ± 0.01
9-nitrophenanthrene	ng/m³	0.0	0.0	0.0	0.0
1,8-dinitronaphthalene	ng/m³	0.0	0.0	0.0	0.0
3-nitrophenanthrene	ng/m³	0.0	0.7 ± 0.04	0.3 ± 0.01	0.0
2-nitrophenanthrene	ng/m³	0.0	0.0	0.0	0.1 ± 0.01
2-nitroanthracene	ng/m³	0.0	0.0	0.0	0.0
2-nitrofluoranthene	ng/m³	0.0	0.0	0.0	0.0
3-nitrofluoranthene	ng/m³	0.0	0.0	0.0	0.0
4-nitropyrene	ng/m³	0.0	0.0	0.0	0.0

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Nitro-PAH:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
1-nitropyrene	ng/m³	0.0	0.0	0.0	0.1 ± 0.01
2-nitropyrene	ng/m³	0.0	0.0	0.0	0.0
2,7-dinitrofluorene	ng/m³	0.0	0.0	0.0	0.0
2,7-dinitrofluoren-9-one	ng/m³	0.0	0.0	0.0	0.0
7-nitrobenz(a)anthracene	ng/m³	0.0	0.0	0.0	0.0
6-nitrochrysene	ng/m³	0.0	0.0	0.0	0.0
3-nitrobenzanthrone	ng/m³	0.0	0.0	0.0	0.0
1,3-dinitropyrene	ng/m³	0.0	0.0	0.0	0.0
1,6-dinitropyrene	ng/m³	0.0	0.0	0.0	0.0
1,8-dinitropyrene	ng/m³	0.0	0.0	0.0	0.0
6a+1e-nitrobenzpyrene	ng/m³	0.0	0.0	0.0	0.0

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Polars:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
8,15-Pimaradien-18-oic acid	ng/m³	0.5 ± 0.3	0 ± 0.3	0 ± 0.3	2.9 ± 0.3
Maleic acid	ng/m³	1.5 ± 0.3	0 ± 0.3	44.3 ± 7	825.7 ± 127.4
Guaiacol	ng/m³	327.8 ± 37.4	60.1 ± 7	6.5 ± 0.9	24 ± 2.8
Salicylic acid	ng/m³	1.3 ± 0.3	0 ± 0.3	0 ± 0.3	136.1 ± 7
4-me-guaiacol	ng/m³	97.1 ± 14.4	0.1 ± 0.3	0.2 ± 0.3	0 ± 0.3
2,3- and 3,5- dimethylbenzoic acid	ng/m³	0 ± 0.3	0 ± 0.3	0 ± 0.3	0 ± 0.3
2,4-dimethylbenzoic acid	ng/m³	6.8 ± 1.1	0 ± 0.3	0 ± 0.3	864.8 ± 49.4
2,5-dimethylbenzoic acid	ng/m³	2.4 ± 0.6	0 ± 0.3	8.4 ± 0.9	71.7 ± 6.6
2,6-dimethylbenzoic acid	ng/m³	0.8 ± 0.3	4 ± 0.5	3.9 ± 0.5	23.4 ± 2.5
3,4-dimethylbenzoic acid	ng/m³	2.2 ± 0.4	5.1 ± 0.7	10.3 ± 0.9	172.4 ± 8.9
4-formyl-guaiacol (vanillin)	ng/m³	83.1 ± 4.3	40.3 ± 2.1	20.7 ± 1.2	129.6 ± 6.6
4-ethyl-guaiacol	ng/m³	2.9 ± 0.7	0 ± 0.3	0 ± 0.3	2.5 ± 0.6
Syringol	ng/m³	8.2 ± 0.5	117.3 ± 6	294.6 ± 14.9	1673.2 ± 83.8
Levoglucosan	ng/m³	1 ± 0.3	0 ± 0.3	0.2 ± 0.3	20 ± 2
4-allyl-guaiacol (eugenol)	ng/m³	1.3 ± 0.3	0 ± 0.3	0 ± 0.3	0 ± 0.3
Isoeugenol	ng/m³	0.1 ± 0.3	0.4 ± 0.3	2.4 ± 0.5	8.7 ± 1.5
Isophthalic acid	ng/m³	0.2 ± 0.3	0 ± 0.3	0.1 ± 0.3	538.1 ± 30.6
Phthalic acid	ng/m³	4.5 ± 0.6	0 ± 0.3	2.5 ± 0.4	15.2 ± 1.7
Acetovanillone	ng/m³	4.4 ± 0.4	87.8 ± 4.5	0 ± 0.3	0 ± 0.3
Vanillic acid	ng/m³	0 ± 0.3	0 ± 0.3	10.4 ± 1	41.7 ± 3.5
4-methyl-syringol	ng/m³	0.8 ± 0.3	0 ± 0.3	14.2 ± 0.8	100.4 ± 5.1
2,3-dimethoxybenzoic acid	ng/m³	33.9 ± 1.8	113.9 ± 5.8	141.4 ± 7.2	183.4 ± 9.3
2,4-dimethoxybenzoic acid	ng/m³	8.7 ± 0.6	18.7 ± 1.1	3.8 ± 0.3	5.4 ± 0.4
2,5-dimethoxybenzoic acid	ng/m³	0.3 ± 0.3	0 ± 0.3	1.2 ± 0.3	112.2 ± 10.5

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Polars:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
2,6-dimethoxybenzoic acid	ng/m³	1.2 ± 0.3	2 ± 0.3	2.3 ± 0.3	0 ± 0.3
3,4-dimethoxybenzoic acid	ng/m³	0.8 ± 0.3	0.9 ± 0.3	0.4 ± 0.3	2.9 ± 0.4
3,5-dimethoxybenzoic acid	ng/m³	13.3 ± 1.7	18.2 ± 2.3	7 ± 1	20.7 ± 2.6
Docosanoic acid (c22)	ng/m³	8.5 ± 1.3	0 ± 0.3	0 ± 0.3	22.6 ± 2.9
Homovanillic acid	ng/m³	3.3 ± 0.4	3.4 ± 0.4	0 ± 0.3	6.1 ± 0.6
Syringaldehyde	ng/m³	0.4 ± 0.3	0 ± 0.3	1.1 ± 0.3	12.3 ± 2.6
cis-pinonic acid	ng/m³	5.7 ± 0.6	0 ± 0.3	10.9 ± 0.7	77.8 ± 4.5
Syringic acid	ng/m³	0 ± 0.3	0 ± 0.3	0 ± 0.3	0 ± 0.3
Myristoleic acid	ng/m³	5.1 ± 0.8	5.7 ± 0.8	9.9 ± 1.3	36.1 ± 4.5
Traumatic acid	ng/m³	4.9 ± 1.2	0 ± 0.3	4.2 ± 1	52.2 ± 10.2
1,11-undecanedicarboxylic acid	ng/m³	0 ± 0.3	0.1 ± 0.3	0.4 ± 0.3	2.3 ± 0.4
Palmitoleic acid	ng/m³	0.2 ± 0.3	0 ± 0.3	2.9 ± 0.3	27.1 ± 1.7
1,12-dodecanedicarboxylic acid	ng/m³	0.4 ± 0.3	0.7 ± 0.3	0.1 ± 0.3	1 ± 0.3
Elaidic acid	ng/m³	0 ± 0.3	1.4 ± 0.5	1.6 ± 0.3	12 ± 3.2
Isostearic acid	ng/m³	81.9 ± 4.2	0.3 ± 0.3	0 ± 0.3	1 ± 0.3
Dehydroabietic acid	ng/m³	14.8 ± 1.7	0 ± 0.3	34.2 ± 3.6	2.2 ± 0.6
Pimaric acid	ng/m³	10.6 ± 1.5	0 ± 0.3	18.4 ± 2.5	13.4 ± 1.7
Sandaracopimaric acid	ng/m³	10.2 ± 0.7	0 ± 0.3	16.3 ± 0.9	5.3 ± 0.4
Abietic acid	ng/m³	0.1 ± 0.3	1.4 ± 0.3	1.5 ± 0.3	2.1 ± 0.4
Isopimaric acid	ng/m³	1.5 ± 0.3	2.5 ± 0.4	1.3 ± 0.3	2 ± 0.4
7-oxodehydroabietic acid	ng/m³	0.3 ± 0.3	0.2 ± 0.3	2 ± 0.5	0.2 ± 0.3
Heneicosanoic acid (c21)	ng/m³	3 ± 0.8	16 ± 3.6	0.5 ± 0.3	3.1 ± 0.8
Tricosanoic acid	ng/m³	0 ± 0.3	0 ± 0.3	0.3 ± 0.3	1.7 ± 0.7
Tetracosanoic acid (c24)	ng/m³	0 ± 0.3	0 ± 0.3	0 ± 0.3	8.9 ± 1.4

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Polars:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Cholesterol	ng/m³	14.7 ± 3.9	3 ± 0.9	21 ± 5.6	18.7 ± 5
b-sitosterol	ng/m³	1.2 ± 0.3	0.1 ± 0.3	1.2 ± 0.3	1.5 ± 0.3
Hexanoic acid (c6)	ng/m³	778.3 ± 101.6	566 ± 73.9	750.4 ± 98	1223.8 ± 159.7
Heptanoic acid (c7)	ng/m³	683.6 ± 68.9	795.5 ± 79.7	1086.7 ± 108.8	1306.7 ± 130.8
Benzoic acid	ng/m³	14.6 ± 0.9	0 ± 0.3	0 ± 0.3	2633.6 ± 133.4
Octanoic acid (c8)	ng/m³	169.5 ± 14.2	249.9 ± 20.9	347.9 ± 29.1	457.5 ± 37.7
o-toluic	ng/m³	0.7 ± 0.3	0.5 ± 0.3	0 ± 0.3	96.4 ± 4.9
m-toluic	ng/m³	13.4 ± 1.8	1.7 ± 0.3	0.3 ± 0.3	254.8 ± 12.9
Nonanoic acid (c9)	ng/m³	19.9 ± 1.7	0 ± 0.3	0 ± 0.3	0 ± 0.3
p-toluic	ng/m³	4.8 ± 1	0.9 ± 0.3	0 ± 0.3	108 ± 6.1
Decanoic acid (c10)	ng/m³	119.8 ± 11.4	79.7 ± 5.1	56.4 ± 3.9	56.7 ± 3.7
Undecanoic acid (c11)	ng/m³	16.7 ± 4	0.9 ± 0.3	5.5 ± 0.9	4.2 ± 0.4
Dodecanoic (lauric) acid (c12)	ng/m³	52.7 ± 3.5	0 ± 0.3	29.8 ± 2	12.6 ± 1
Tridecanoic acid (c13)	ng/m³	17 ± 1.5	11.3 ± 1.4	61.2 ± 6.2	65.9 ± 7.2
Myristic acid (c14)	ng/m³	48 ± 2.5	0 ± 0.3	75.1 ± 3.9	65.5 ± 3.4
Pentadecanoic acid (c15)	ng/m³	25 ± 4.7	32.6 ± 2.8	55.3 ± 9.2	156.6 ± 23.5
Palmitic acid (c16)	ng/m³	105.2 ± 5.4	0 ± 0.3	219 ± 11.1	183.4 ± 9.3
Heptadecanoic acid (c17)	ng/m³	6.1 ± 1.1	0 ± 0.3	5.4 ± 1	57.6 ± 9.8
Oleic acid	ng/m³	0.2 ± 0.3	1.7 ± 0.4	0.6 ± 0.3	1.2 ± 0.3
Stearic acid (c18)	ng/m³	33.5 ± 1.8	0 ± 0.3	53.9 ± 2.8	64.5 ± 3.4
Nonadecanoic acid (c19)	ng/m³	12.6 ± 5.2	0 ± 0.3	218.4 ± 85.7	20.1 ± 8.1
Eicosanoic acid (c20)	ng/m³	1.8 ± 0.4	0 ± 0.3	0 ± 0.3	7.3 ± 1.3

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Hopane and Steranes:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
17A(H),21B(H)-22,29,30-Trisnorhopane	ng/m³	0.0	0.3 ± 0.02	0.1 ± 0.01	0.0
17A(H),21B(H)-30-Norhopane	ng/m³	0.0	1.6 ± 0.08	0.2 ± 0.01	0.1 ± 0.01
17A(H),21B(H)-Hopane	ng/m³	0.0	1.3 ± 0.07	0.2 ± 0.01	0.1
17B(H),21A(H)-hopane	ng/m³	0.0	0.0	0.0	0.0
22S-17A(H),21B(H)-30-Homohopane	ng/m³	0.8 ± 0.04	0.0	0.0	0.4 ± 0.02
22R-17A(H),21B(H)-30-Homohopane	ng/m³	0.1 ± 0.01	0.8 ± 0.04	0.1 ± 0.01	0.1 ± 0.01
17B(H),21B(H)-Hopane	ng/m³	0.0	0.1 ± 0.02	0.0	0.0
22S-17A(H),21B(H)-30,31-Bishomohopane	ng/m³	0 ± 0.01	0.6 ± 0.12	0.1 ± 0.03	0.1 ± 0.01
22R-17A(H),21B(H)-30,31-Bishomohopane	ng/m³	0.0	0.1 ± 0.01	0.0	0.0
22S-17A(H),21B(H)-30,31,32-Trisomohopane	ng/m³	0.0	0.4 ± 0.03	0 ± 0.01	0.0
22R-17A(H),21B(H)-30,31,32-Trishomohopane	ng/m³	0.0	0.3 ± 0.04	0.1 ± 0.01	0.1
C27-20S5A(H),14A(H)-cholestane	ng/m³	0.0	0.1 ± 0.01	0.0	0.0
C27-20R5A(H),14B(H)-cholestane	ng/m³	0.0	0.5 ± 0.02	0.0	0.0
C27-20S5A(H),14B(H),17B(H)-cholestane	ng/m³	0.0	0.3 ± 0.01	0.0	0.0
C27-20R5A(H),14A(H),17A(H)-cholestane & C29 -20S13B(H),17A(H)-dia	ng/m³	0.0	0.8 ± 0.05	0.0	0.1
C28-20S5A(H),14A(H),17A(H)-ergostane	ng/m³	0.0	0.1 ± 0.01	0.0	0.0
C28-20R5A(H),14B(H),17B(H)-ergostane	ng/m³	0.0	0.3 ± 0.02	0.0	0.0
C28-20S5A(H),14B(H),17B(H)-ergostane	ng/m³	0.0	0.3 ± 0.03	0 ± 0.01	0.1 ± 0.02
C28-20R5A(H),14A(H),17A(H)-ergostane	ng/m³	0.0	0.1 ± 0.02	0.1 ± 0.01	0.0
C29-20S5A(H),14A(H),17A(H)-stigmastane	ng/m³	0.0	0.2 ± 0.03	0.1 ± 0.01	0.0
C29-20R5A(H),14B(H),17B(H)-stigmastane	ng/m³	0.0	0.3 ± 0.07	0.1 ± 0.01	0 ± 0.01
C29-20S5A(H),14B(H),17B(H)-stigmastane	ng/m³	0.1 ± 0.03	0.4 ± 0.06	0.1 ± 0.05	0.1 ± 0.05
C29-20R5A(H),14A(H),17A(H)-stigmastane	ng/m³	0.0	0.2 ± 0.01	0.0	0.0

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Volatile Organic Compounds (VOC):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Acetylene	µg/m³	4.1 ± 0.2	0.5	1.6 ± 0.1	5.4 ± 0.3
Ethene	µg/m³	2.9 ± 0.4	0.2	0.9 ± 0.1	0.7 ± 0.1
Ethane	µg/m³	2.4 ± 0.3	0.4	7 ± 0.7	2.8 ± 0.3
Propene	µg/m³	0.9 ± 0.1	1.5 ± 0.2	1.9 ± 0.2	3.2 ± 0.3
Propane	µg/m³	1.1 ± 0.1	0.0	0.3	0.0
1,3-butadiene	µg/m³	0.1	0.1	0.1	0.1
1-butene	µg/m³	0.3	0.4	0.3	0.7
Isobutylene	µg/m³	0.8	1.6 ± 0.1	1.8 ± 0.1	2.4 ± 0.1
c-2-butene	µg/m³	0.0	0.1	0.2	0.4
t-2-butene	µg/m³	0.1	0.2	0.3	0.6
n-butane	µg/m³	0.6 ± 0.1	0.4	0.9 ± 0.1	0.9 ± 0.1
iso-butane	µg/m³	0.5	0.5	0.7 ± 0.1	0.8 ± 0.1
iso-pentane	µg/m³	0.7	0.5	0.7	0.8
n-pentane	µg/m³	0.3	0.6 ± 0.1	0.5 ± 0.1	0.7 ± 0.1
1-pentene	µg/m³	0.2	0.1	0.1	0.2
2-methyl-1-butene	µg/m³	0.1	0.1	0.1	0.1
isoprene	µg/m³	0.2	0.3	0.0	0.0
t-2-pentene	µg/m³	0.0	0.1	0.1	0.1
c-2-pentene	µg/m³	0.0	0.0	0.0	0.1
2-methyl-2-butene	µg/m³	0.0	0.0	0.0	0.1
2,2-dimethylbutane	µg/m³	0.1	0.0	0.0	0.0
Cyclopentene	µg/m³	0.0	0.0	0.0	0.1
Cyclopentane	µg/m³	0.0	0.0	0.0	0.1
2,3-dimethylbutane	µg/m³	0.1	0.1	0.0	0.2

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Volatile Organic Compounds (VOC):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
2-methylpentane	µg/m³	0.3	0.2	0.2	0.9 ± 0.1
3-methylpentane	µg/m³	0.3	0.3	0.2	1.1 ± 0.1
2-methyl-1-pentene	µg/m³	0.2	0.2	0.1	0.3
n-hexane	µg/m³	0.3 ± 0.1	0.2 ± 0.1	0.4 ± 0.1	2.5 ± 0.8
t-2-hexene	µg/m³	0.1	0.1	0.1	0.1
c-2-hexene	µg/m³	0.0	0.0	0.0	0.0
1,3-hexadiene (trans)	µg/m³	0.0	0.0	0.0	0.0
Methylcyclopentane	µg/m³	0.2	0.1	0.2	1.5 ± 0.1
2,4-dimethylpentane	µg/m³	0.2	0.2	0.1	0.4
Benzene	µg/m³	0.9 ± 0.2	0.8 ± 0.1	1.6 ± 0.3	4.2 ± 0.8
Cyclohexane	µg/m³	0.5	0.1	0.6	2.2 ± 0.1
2-methylhexane	µg/m³	0.1	0.1	0.1	0.6
2,3-dimethylpentane	µg/m³	0.8 ± 0.1	0.7 ± 0.1	0.8 ± 0.1	0.8 ± 0.1
Cyclohexene	µg/m³	0.0	0.0	0.0	0.1
3-methylhexane	µg/m³	0.1	0.1	0.1	0.6
1,3-dimethylcyclopentane (cis)	µg/m³	0.0	0.0	0.0	0.2
1-heptene	µg/m³	0.2 ± 0.1	0.2	0.2	0.8 ± 0.1
2,2,4-trimethylpentane	µg/m³	0 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.2 ± 0.1
n-heptane	µg/m³	0.2	0.2	0.2	0.7
2,3-dimethyl-2-pentene	µg/m³	0.0	0.0	0.0	0.0
Methylcyclohexane	µg/m³	0.1 ± 0.1	0.3 ± 0.1	1 ± 0.2	4.1 ± 0.9
2,3,4-trimethylpentane	µg/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Toluene	µg/m³	0.7 ± 0.1	1 ± 0.1	1 ± 0.1	4.5 ± 0.6
2-methylheptane	µg/m³	0.1 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.7 ± 0.1

Sep 2010 – Detailed Atmosphere Characterization

Volatile Organic Compounds (VOC):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
4-methylheptane	µg/m³	0 ± 0.1	0 ± 0.1	0.1 ± 0.1	0.2 ± 0.1
3-methylheptane	µg/m³	0 ± 0.1	0 ± 0.1	0.1 ± 0.1	0.4 ± 0.1
n-octane	µg/m³	0.2 ± 0.1	0.4 ± 0.1	0.6 ± 0.1	1.7 ± 0.4
Ethylbenzene	µg/m³	0.1	0.1	0.3 ± 0.1	1.2 ± 0.3
m&p-xylene	µg/m³	0.3 ± 0.1	0.3 ± 0.1	0.5 ± 0.1	2.2 ± 0.5
Styrene	µg/m³	0.1	0.1	0.1	0.1
o-xylene	µg/m³	0.2	0.2	0.3	0.9
n-nonane	µg/m³	0.3 ± 0.1	0.5 ± 0.1	1.2 ± 0.1	3 ± 0.3
Isopropylbenzene	µg/m³	0 ± 0.1	0 ± 0.1	0.1 ± 0.1	0.3 ± 0.1
n-propylbenzene	µg/m³	0 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.7 ± 0.1
alpha-pinene	µg/m³	0.2 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0 ± 0.1
3-ethyltoluene	µg/m³	0.1 ± 0.1	0.2 ± 0.1	0.3 ± 0.1	1.5 ± 0.2
4-ethyltoluene	µg/m³	0.1 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.8 ± 0.1
1,3,5-trimethylbenzene	µg/m³	0.1 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.8 ± 0.2
o-ethyltoluene	µg/m³	0.1 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.6 ± 0.1
1,2,4-trimethylbenzene+t-butylbenzene	µg/m³	NA	NA	NA	NA
n-decane	µg/m³	0.5 ± 0.1	0.8 ± 0.1	1.8 ± 0.2	4.3 ± 0.6
1,2,3-trimethylbenzene	µg/m³	0.2 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.9 ± 0.1
Indan	µg/m³	0.1 ± 0.1	0 ± 0.1	0.1 ± 0.1	0.3 ± 0.1
1,3-diethylbenzene	µg/m³	0.1 ± 0.1	0 ± 0.1	0.1 ± 0.1	0.5 ± 0.1
1,4-diethylbenzene	µg/m³	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.6 ± 0.1
n-butylbenzene	µg/m³	NA	NA	NA	NA
n-undecane	µg/m³	0.7 ± 0.1	0.8 ± 0.1	1.7 ± 0.2	5.5 ± 0.5

Appendix F.

April 2011 – Detailed Atmosphere Characterization

April 2011 – Detailed Atmosphere Characterization

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Dekati Particle Mass-Chamber Inlet	µg/m³	NA	NA	NA	NA
Dekati Particle Mass-Inside Chamber	µg/m³	0.4	0.4	0.4	2 ± 0.8
Filter Sample - Chamber Inlet	µg/m³	NA	2 ± 1	1 ± 1	4 ± 1
Filter Sample - Inside Chamber	µg/m³	8 ± 8	15 ± 8	15 ± 8	35 ± 44
Particle Mass-FMPS	µg/m³	0.06 ± 0.08	0.16 ± 0.04	0.6 ± 0.01	3.1 ± 1.4
Particle Count -FMPS	Particle/cm³	1.76E+04 ± 2.19E+04	9.28E+03 ± 2.48E+03	6.4E+04 ± 4.3E+04	5.2E05 ± 1.6E+05
NMAD (GSD) - FMPS	nm	9.9 (1.5) ± 0.3 (0.03)	18.2 (1.6) ± 1.0 (0.06)	13.4 (1.5) ± 1.0 (0.01)	14.5 (1.5) ± 1.0 (0.03)
MMAD (GSD) - FMPS	nm	63.0 (1.9) ± 53.3 (0.2)	46.8 (2.1) ± 2.9 (0.2)	32.9 (2.2) ± 9.6 (0.6)	29.6 (1.8) ± 3.7 (0.2)
Nitrogen Oxide (NO)	µg/m³ (ppm)	5.4 ± 1.1 (0.005 ± 0.001)	314.7 ± 135.1 (0.3 ± 0.1)	1626.8 ± 285.7 (1.6 ± 0.3)	7338.5 ± 142.1 (7.2 ± 0.1)
Nitrogen Dioxide (NO_2)	µg/m³ (ppm)	10.4 ± 4.7 (0.007 ± 0.003)	155.1 ± 38.1 (0.10 ± 0.02)	1469.1 ± 436.9 (0.9 ± 0.3)	6737.5 ± 204.0 (4.3 ± 0.1)
Carbon Monoxide (CO)	µg/m³ (ppm)	388.8 ± 133.5 (0.4 ± 0.1)	799.2 ± 228.3 (0.8 ± 0.2)	1319.5 ± 66.5 (1.4 ± 0.1)	5696.3 ± 518.9 (5.9 ± 0.5)
Carbon Dioxide (CO_2)	mg/m³ (ppm)	3016.1 ± 39.3 (2003.9 ± 26.1)	4051.5 ± 433.2 (2691.8 ± 287.8)	4023.1 ± 218.3 (2673 ± 145)	7322.3 ± 59.1 (4865 ± 39.3)
Sulfur Dioxide (SO_2)	µg/m³(ppb)	4.2 ± 0.3 (1.9 ± 0.1)	5.0 ± 2.5 (2.2 ± 1.1)	14.9 ± 1.0 (6.6 ± 0.4)	73.0 ± 2.2 (32.3 ± 1.0)
Elemental Carbon	µg/m³	0.1	0.4 ± 0.01	0.3	0.7 ± 0.02
Organic Carbon	µg/m³	4.2 ± 0.2	4.7 ± 0.2	5.2 ± 0.2	5.5 ± 0.3
Ammonium	ng/m³	75.9 ± 3.9	94.6 ± 5	170.90	679.4 ± 112.4
Sulfate	ng/m³	99.3	88.2	420.1	927.5 ± 0.1
Nitrate	ng/m³	37.7	98.5	197.0	2298.4 ± 1.9
Elements (Metals)	ng/m³	264.9 ± 1.4	457.6 ± 2.9	482.00	451.7 ± 6.7
Alkanes	µg/m³	2.3 ± 0.1	3.2 ± 0.2	6.9 ± 0.4	24.9 ± 1.3
Carbonyl	µg/m³	59.3 ± 3.2	51.8 ± 2.8	22.8 ± 1.3	0.4 ± 0.4
Polyaromatic Hydrocarbon (PAH)	µg/m³	0.7 ± 0.05	1.1 ± 0.07	1.8 ± 0.1	6 ± 0.33
Nitro-PAH	ng/m³	0.2 ± 0.02	0.5 ± 0.03	1.3 ± 0.07	8.6 ± 0.46
Polars (Acids)	µg/m³	4.1 ± 0.2	5.2 ± 0.3	10.7 ± 0.6	15 ± 0.8
Hopane and Steranes	ng/m³	1.8 ± 0.1	1.9 ± 0.1	1.9 ± 0.2	3.1 ± 0.2
Volatile Organic Compounds (VOC)	µg/m³	25.1 ± 4.1	43.8 ± 6	65.6 ± 6.7	169.1 ± 17.3

April 2011 – Detailed Atmosphere Characterization

Carbon:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Organic Carbon Fraction 1	µg/m³	0.5 ± 0.1	0.7 ± 0.15	1.4 ± 0.31	0.5 ± 0.11
Organic Carbon Fraction 2	µg/m³	1.7 ± 0.11	1.7 ± 0.11	1.9 ± 0.13	2.1 ± 0.14
Organic Carbon Fraction 3	µg/m³	1.7 ± 0.03	1.8 ± 0.03	1.5 ± 0.02	2.2 ± 0.05
Organic Carbon Fraction 4	µg/m³	0.3 ± 0.01	0.5 ± 0.02	0.4 ± 0.01	0.6 ± 0.03
Pyrolyzed Organic Carbon Reflectance	µg/m³	0.0	0.0	0.0	0.1
Pyrolyzed Organic Carbon Transmittance	µg/m³	0.1	0.2	0.1	0.3
Total Organic Carbon	µg/m³	4.2 ± 0.17	4.7 ± 0.2	5.2 ± 0.23	5.5 ± 0.27
Elemental Carbon Fraction 1	µg/m³	0.0	0.2 ± 0.01	0.1	0.2 ± 0.02
Elemental Carbon Fraction 2	µg/m³	0.1	0.2	0.2	0.5 ± 0.01
Elemental Carbon Fraction 3	µg/m³	0.0	0.0	0.0	0.0
Total Elemental Carbon	µg/m³	0.1	0.4 ± 0.01	0.3	0.7 ± 0.02
Total Carbon	µg/m³	4.3 ± 0.15	5 ± 0.19	5.5 ± 0.22	6.2 ± 0.27

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Elements (Metals):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Sodium	ng/m³	17 ± 0.72	51.2 ± 1.97	100.1	153 ± 5.76
Magnesium	ng/m³	0.0	1.3 ± 0.02	0.0	7.4 ± 0.08
Aluminum	ng/m³	0.0	1.0	0.0	0.4
Silicon	ng/m³	10.6 ± 0.04	12.9 ± 0.06	32.5	13.8 ± 0.07
Phosphorous	ng/m³	16 ± 0.05	16.1 ± 0.04	11.3	1.9 ± 0.01
Sulfur	ng/m³	24.8 ± 0.07	52.1 ± 0.14	182.2	481 ± 1.44
Chlorine	ng/m³	41.9 ± 0.07	76.4 ± 0.12	73.1	49.1 ± 0.09
Potassium	ng/m³	102.2 ± 0.12	172.2 ± 0.2	153.4	126 ± 0.15
Calcium	ng/m³	37.9 ± 0.09	43.4 ± 0.1	53.6	33.5 ± 0.08
Scandium	ng/m³	0.0	0 ± 0.01	0.0	1 ± 0.01
Titanium	ng/m³	0.3	0.1	1.4	0.1
Vanadium	ng/m³	0.0	0.0	0.0	0.0
Chromium	ng/m³	0.5	2.4	0.5	0.9
Manganese	ng/m³	0.0	0.3	1.4	3.1 ± 0.02
Iron	ng/m³	11.6 ± 0.03	17.3 ± 0.03	25.3	36.1 ± 0.07
Cobalt	ng/m³	0.0	0.0	0.0	0.0
Nickel	ng/m³	0.5	1.1	0.4	0.6
Copper	ng/m³	10.2 ± 0.02	26.2 ± 0.04	10.5	9.7 ± 0.02
Zinc	ng/m³	10.6 ± 0.03	23.6 ± 0.06	10.6	10.2 ± 0.03
Gallium	ng/m³	0.0	0.0	0.2	0.0
Arsenic	ng/m³	0.0	0.0	0.0	0.1
Selenium	ng/m³	0.0	0.5	0.0	0.0
Bromine	ng/m³	0.0	0.2	0.4	0.2
Rubidium	ng/m³	0.3	0.0	0.4	0.3
Strontium	ng/m³	0.3	0.0	0.4	0.1
Yttrium	ng/m³	0.0	0.0	0.1	0.0

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Elements (Metals):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Zirconium	ng/m³	0.2	0.0	0.0	0.0
Niobium	ng/m³	0.1	0.0	0.0	0.0
Molybdenum	ng/m³	0.0	0.1	0.4	0.0
Palladium	ng/m³	0.0	0.0	0.0	0.0
Silver	ng/m³	0.0	0.0	0.0	0.1
Cadmium	ng/m³	0.0	0.0	0.0	0.0
Indium	ng/m³	0.1	0.2	0.0	0.1
Tin	ng/m³	0.1 ± 0.02	0 ± 0.03	0.0	0 ± 0.03
Antimony	ng/m³	0.6	1.8 ± 0.01	0.0	0.0
Cesium	ng/m³	0.0	0.0	0.0	0.0
Barium	ng/m³	0.0	0.0	0.0	0.0
Lanthanum	ng/m³	0.0	3.5 ± 0.02	0.0	0.0
Cerium	ng/m³	0 ± 0.03	0 ± 0.1	0.0	0 ± 0.04
Samarium	ng/m³	0 ± 0.07	0.0	0.0	0.5 ± 0.04
Europium	ng/m³	2.3 ± 0.07	0 ± 0.11	4.3	1.3 ± 0.1
Terbium	ng/m³	0.0	0.0	0.6	0 ± 0.09
Hafnium	ng/m³	0.0	0 ± 0.01	0.0	0.0
Tantalum	ng/m³	0 ± 0.02	0.0	0.0	1 ± 0.01
Wolfram	ng/m³	0.0	0.0	0.0	0.0
Iridium	ng/m³	0.0	0.0	0.3	0.3
Gold	ng/m³	0.5	0.0	0.0	0.0
Mercury	ng/m³	0.0	0.0	0.0	0.0
Thallium	ng/m³	0.3	0.2	0.5	0.1
Lead	ng/m³	0.9	5.6 ± 0.01	0.5	0.6
Uranium	ng/m³	0.0	0.0	0.0	0.1

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Alkanes:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Dodecane	ng/m³	265 ± 13.2	534.9 ± 26.7	1276.1 ± 63.8	3336.8 ± 166.8
Norfarnesane	ng/m³	134.8 ± 6.9	222.3 ± 11.2	491.6 ± 24.7	1166.1 ± 58.4
Tridecane	ng/m³	314.3 ± 15.7	518.2 ± 25.9	1279.2 ± 64	5368.5 ± 268.4
Heptylcyclohexane	ng/m³	34.5 ± 2	55.5 ± 3.1	135.3 ± 7.3	569.6 ± 30.2
Farnesane	ng/m³	84.4 ± 4.4	110.9 ± 5.7	324.8 ± 16.4	1418.9 ± 71.1
Tetradecane	ng/m³	266.2 ± 13.3	347.8 ± 17.4	992.3 ± 49.6	3919.3 ± 196
Octylcyclohexane	ng/m³	24.3 ± 1.2	32.9 ± 1.6	95.3 ± 4.8	356.6 ± 17.8
Pentadecane	ng/m³	208.8 ± 10.5	254.2 ± 12.8	658.8 ± 33	3016.8 ± 150.9
Nonylcyclohexane	ng/m³	20 ± 1.4	26.9 ± 1.8	59.8 ± 3.9	240.8 ± 15.5
Hexadecane	ng/m³	255.5 ± 12.8	283.6 ± 14.2	498.6 ± 24.9	1909.9 ± 95.5
Norpristane	ng/m³	85.5 ± 4.4	120.6 ± 6.2	197 ± 10	744.2 ± 37.3
Decylcyclohexane	ng/m³	15.6 ± 0.8	18.6 ± 1	32.2 ± 1.7	124.7 ± 6.3
Heptadecane	ng/m³	140.3 ± 7.7	180.9 ± 9.9	264.5 ± 14.5	940.7 ± 51.9
Heptadecane	ng/m³	70.1 ± 3.6	85.9 ± 4.3	139.1 ± 7	591.7 ± 29.6
Undecylcyclohexane	ng/m³	9.9 ± 0.6	12.3 ± 0.7	17 ± 0.9	52.5 ± 2.7
Octadecane	ng/m³	145.3 ± 7.3	169.7 ± 8.5	201.8 ± 10.1	489.8 ± 24.5
Phytane	ng/m³	43 ± 4.2	56.7 ± 5.5	76.9 ± 7.4	255.4 ± 24.6
Dodecylcyclohexane	ng/m³	6.8 ± 0.5	9.2 ± 0.7	12 ± 0.8	26.3 ± 1.7
Nonadecane	ng/m³	21.7 ± 1.2	29 ± 1.5	32.7 ± 1.7	91.2 ± 4.6
Tridecylcyclohexane	ng/m³	2.1 ± 0.6	2.6 ± 0.7	3.6 ± 0.9	6.6 ± 1.5
Eicosane	ng/m³	36.6 ± 1.8	42 ± 2.2	43.9 ± 2.2	96.2 ± 4.8
Tetradecylcyclohexane	ng/m³	0.5 ± 0.3	1 ± 0.3	0.5 ± 0.3	3.9 ± 0.3
Heneicosane	ng/m³	7.5 ± 0.5	9.9 ± 0.6	8.7 ± 0.5	17.1 ± 0.9
Pentadecylcyclohexane	ng/m³	0.7 ± 0.3	1.2 ± 0.3	0.8 ± 0.3	2.1 ± 0.3
Docosane	ng/m³	20.1 ± 1	22.3 ± 1.2	20.3 ± 1	40.5 ± 2
Hexadecylcyclohexane	ng/m³	0.4 ± 0.3	0.1 ± 0.3	0 ± 0.3	1.2 ± 0.3

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Alkanes:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Tricosane	ng/m³	5.8 ± 0.5	5.5 ± 0.5	5 ± 0.6	5.8 ± 0.7
Heptadecylcyclohexane	ng/m³	1 ± 0.3	0.3 ± 0.3	1.4 ± 0.3	1.5 ± 0.3
Tetracosane	ng/m³	15.1 ± 0.9	16.7 ± 1	16.2 ± 0.8	25.9 ± 1.3
Octadecylcyclohexane	ng/m³	0.6 ± 0.3	1.2 ± 0.3	0.8 ± 0.3	1.3 ± 0.3
Pentacosane	ng/m³	3.6 ± 0.4	3.7 ± 0.4	5.4 ± 0.4	5.2 ± 0.4
Hexacosane	ng/m³	7.2 ± 0.5	8.1 ± 0.5	8.5 ± 0.6	13.8 ± 0.7
Nonadecylcyclohexane	ng/m³	1.2 ± 0.3	1.6 ± 0.3	1.3 ± 0.3	1.7 ± 0.3
Heptacosane	ng/m³	2.3 ± 0.3	3.4 ± 0.3	3.6 ± 0.3	4.6 ± 0.4
Eicosylcyclohexane	ng/m³	0.1 ± 0.3	0.1 ± 0.3	0.1 ± 0.3	0.1 ± 0.3
Octacosane	ng/m³	4.9 ± 0.4	5.7 ± 0.4	5.9 ± 0.4	11 ± 0.7
Nonacosane	ng/m³	1.6 ± 0.3	1.8 ± 0.3	1.8 ± 0.3	3.4 ± 0.4
Heneicosylcyclohexane	ng/m³	0.1 ± 0.3	0.1 ± 0.3	0.1 ± 0.3	0.2 ± 0.3
Triacontane	ng/m³	2.8 ± 0.3	3.5 ± 0.3	4.2 ± 0.3	7.2 ± 0.4
Hentriacontane	ng/m³	1.3 ± 0.3	1.3 ± 0.3	1.5 ± 0.3	5.2 ± 0.8
Dotriacontane	ng/m³	2 ± 0.3	2.5 ± 0.4	3.8 ± 0.5	6.1 ± 0.8
Tritriacontane	ng/m³	0.6 ± 0.3	0.7 ± 0.3	1.8 ± 0.3	3.1 ± 0.4
Tetratriacontane	ng/m³	1.5 ± 0.3	2.7 ± 0.4	3.4 ± 0.4	7.1 ± 1
Pentatriacontane	ng/m³	0 ± 0.3	0.3 ± 0.3	0.7 ± 0.3	1.1 ± 0.3
Hexatriacontane	ng/m³	0.8 ± 0.3	1.5 ± 0.3	2.1 ± 0.4	2.6 ± 0.4
Heptatriacontane	ng/m³	0.3 ± 0.3	0.1 ± 0.3	0.4 ± 0.3	0.4 ± 0.3
Octatriacontane	ng/m³	1.1 ± 0.4	1.9 ± 0.5	2.3 ± 0.6	2.2 ± 0.5
Nonatriacontane	ng/m³	0.1 ± 0.3	0.3 ± 0.3	0.1 ± 0.3	0.2 ± 0.3
Tetracontane	ng/m³	0.6 ± 0.3	1.9 ± 0.3	1.8 ± 0.3	1.2 ± 0.3

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Carbonyl:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Formaldehyde	µg/m³	1.6 ± 0.09	1 ± 0.06	1 ± 0.01	0 ± 0.03
Acetaldehyde	µg/m³	21.8 ± 1.09	20.7 ± 1.03	6.6 ± 0.01	0 ± 0.03
Acrolein	µg/m³	0.2 ± 0.03	0.1 ± 0.03	0.1 ± 0.01	0 ± 0.03
Glyoxal	µg/m³	0 ± 0.02	0 ± 0.02	0 ± 0.01	0 ± 0.03
Acetone	µg/m³	18.9 ± 0.94	16.2 ± 0.81	0.3 ± 0.01	0 ± 0.03
Propionaldehyde	µg/m³	1.6 ± 0.09	1.1 ± 0.06	1 ± 0.01	0 ± 0.03
Crotonaldehyde	µg/m³	0 ± 0.02	0 ± 0.02	0 ± 0.01	0 ± 0.03
Methacrolein	µg/m³	0 ± 0.02	0 ± 0.02	0 ± 0.01	0 ± 0.03
n-butyraldehyde	µg/m³	1 ± 0.06	0.8 ± 0.05	0.7 ± 0.01	0 ± 0.03
2-Butanone (MEK)	µg/m³	2.2 ± 0.11	1.5 ± 0.08	0.4 ± 0.01	0 ± 0.03
Valeraldehyde	µg/m³	2.1 ± 0.12	1.8 ± 0.1	1.7 ± 0.01	0 ± 0.03
Hexaldehyde	µg/m³	9.7 ± 0.5	8.3 ± 0.42	10.8 ± 0.01	0.4 ± 0.03
Benzaldehyde	µg/m³	0.3 ± 0.03	0.3 ± 0.03	0.5 ± 0.01	0 ± 0.03
m-Tolualdehyde	µg/m³	0 ± 0.02	0 ± 0.02	0 ± 0.01	0 ± 0.03

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PolyAromatic HydroCarbon (PAH):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Naphthalene	ng/m³	20.4 ± 1	62.1 ± 3.1	214.6 ± 10.7	1006.5 ± 50.3
Quinoline	ng/m³	1.1 ± 0.1	3.3 ± 0.2	3.2 ± 0.2	17.8 ± 1
2-methylnaphthalene	ng/m³	17.1 ± 0.9	29.6 ± 1.5	88.6 ± 4.4	450.5 ± 22.5
1-methylnaphthalene	ng/m³	11.5 ± 0.6	21.8 ± 1.1	63.6 ± 3.2	322.2 ± 16.1
Nicotine	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Biphenyl	ng/m³	14.3 ± 0.7	22.8 ± 1.1	44.7 ± 2.2	182.4 ± 9.1
2-methylbiphenyl	ng/m³	24.6 ± 1.2	63 ± 3.2	168.4 ± 8.4	522.6 ± 26.1
2,6+2,7-dimethylnaphthalene	ng/m³	10.3 ± 0.5	14.9 ± 0.7	48.2 ± 2.4	274.6 ± 13.7
1,3+1,6+1,7dimethylnaphth	ng/m³	18.9 ± 0.9	30.6 ± 1.5	83.2 ± 4.2	506 ± 25.3
1,4+1,5+2,3-dimethylnaphth	ng/m³	6.4 ± 0.3	10.4 ± 0.5	24.6 ± 1.2	150.6 ± 7.5
1+2ethylnaphthalene	ng/m³	5.4 ± 0.3	9.9 ± 0.5	24.1 ± 1.2	102.3 ± 5.1
Acenaphthylene	ng/m³	0.6 ± 0.1	3.5 ± 0.4	16.2 ± 1.7	39.3 ± 4.2
1,2-dimethylnaphthalene	ng/m³	1.5 ± 0.2	3 ± 0.3	6.8 ± 0.6	35 ± 2.9
1,8-dimethylnaphthalene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Acenaphthene	ng/m³	0.4 ± 0.1	1.7 ± 0.3	1 ± 0.1	10.7 ± 1.3
3-methylbiphenyl	ng/m³	363.4 ± 18.2	512.7 ± 25.6	563.3 ± 28.2	1097.4 ± 54.9
4-methylbiphenyl	ng/m³	134.4 ± 6.7	191.7 ± 9.6	217.8 ± 10.9	412.7 ± 20.6
Dibenzofuran	ng/m³	2.4 ± 0.2	3.1 ± 0.2	5.1 ± 0.3	18.5 ± 1.1
Bibenzyl	ng/m³	18.6 ± 0.9	21.4 ± 1.1	21.3 ± 1.1	78.1 ± 3.9
1-ethyl-2-methylnaphthalene	ng/m³	1.6 ± 0.2	3.1 ± 0.3	5 ± 0.5	25.6 ± 2.6
2,3,5+I-trimethylnaphthalene	ng/m³	4.5 ± 0.4	6 ± 0.5	12.3 ± 1.1	51 ± 4.4
B-trimethylnaphthalene	ng/m³	8.6 ± 0.4	11.9 ± 0.6	25.6 ± 1.3	121.7 ± 6.1
A-trimethylnaphthalene	ng/m³	8.8 ± 0.4	12.3 ± 0.6	28.2 ± 1.4	136.7 ± 6.8
C-trimethylnaphthalene	ng/m³	7.4 ± 0.5	10.4 ± 0.7	22.9 ± 1.6	104.4 ± 7.2

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PolyAromatic HydroCarbon (PAH):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
2-ethyl-1-methylnaphthalene	ng/m³	0.1 ± 0.1	0.5 ± 0.1	0.4 ± 0.1	2.9 ± 0.4
E-trimethylnaphthalene	ng/m³	5.6 ± 0.3	7.9 ± 0.4	15.2 ± 0.8	73.3 ± 3.7
2,4,5-trimethylnaphthalene	ng/m³	1.7 ± 0.2	2.6 ± 0.2	3.9 ± 0.3	13.2 ± 1.1
F-trimethylnaphthalene	ng/m³	4.3 ± 0.3	5.5 ± 0.4	12.6 ± 0.9	56.8 ± 4.2
Fluorene	ng/m³	2 ± 0.3	4.5 ± 0.6	4.8 ± 0.6	39.5 ± 5.3
1,4,5-trimethylnaphthalene	ng/m³	0.6 ± 0.1	1.2 ± 0.2	1.6 ± 0.2	7 ± 0.9
J-trimethylnaphthalene	ng/m³	3.1 ± 0.2	3.3 ± 0.2	7.9 ± 0.5	36.1 ± 2.3
A-Methylfluorene	ng/m³	1.6 ± 0.2	3.9 ± 0.4	2.9 ± 0.3	8.1 ± 0.8
B-Methylfluorene	ng/m³	0.3 ± 0.1	0.8 ± 0.1	0.5 ± 0.1	1.4 ± 0.2
1-Methylfluorene	ng/m³	1.1 ± 0.1	3 ± 0.2	2.1 ± 0.1	8.5 ± 0.5
9-fluorenone	ng/m³	1 ± 0.2	1.8 ± 0.3	3.1 ± 0.5	10 ± 1.6
Dibenzothiophene	ng/m³	0.3 ± 0.1	0.5 ± 0.1	0 ± 0.1	0.2 ± 0.1
Phenanthrene	ng/m³	4.2 ± 0.2	14.4 ± 0.7	10.2 ± 0.5	63.4 ± 3.2
Anthracene	ng/m³	0.2 ± 0.1	2 ± 0.3	0.9 ± 0.1	3.6 ± 0.5
Xanthone	ng/m³	0.2 ± 0.1	0.1 ± 0.1	0.5 ± 0.1	2.8 ± 0.4
Acenaphthenequinone	ng/m³	1.4 ± 0.2	0 ± 0.1	0 ± 0.1	0 ± 0.1
3-methylphenanthrene	ng/m³	0.7 ± 0.1	1.7 ± 0.2	1.1 ± 0.1	3.6 ± 0.3
2-methylphenanthrene	ng/m³	0.8 ± 0.1	1.7 ± 0.3	1.3 ± 0.2	4.2 ± 0.7
Perinaphthenone	ng/m³	0.1 ± 0.1	0.5 ± 0.1	0 ± 0.1	1 ± 0.1
2-methylanthracene	ng/m³	0.1 ± 0.1	0.3 ± 0.1	0.3 ± 0.1	0.6 ± 0.1
4,5-methylenephenanthrene	ng/m³	0.1 ± 0.1	0.7 ± 0.1	0 ± 0.1	4.5 ± 0.2
9-methylphenanthrene	ng/m³	0.4 ± 0.1	1.8 ± 0.2	0.5 ± 0.1	2.4 ± 0.2
1-methylphenanthrene	ng/m³	0.4 ± 0.1	1.5 ± 0.3	0.2 ± 0.1	1.6 ± 0.3
Anthrone	ng/m³	0.2 ± 0.1	0.4 ± 0.1	0 ± 0.1	0.8 ± 0.1

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PolyAromatic HydroCarbon (PAH):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
9-methylanthracene	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0.3 ± 0.1
2-phenylnaphthalene	ng/m³	0 ± 0.1	0.3 ± 0.1	0 ± 0.1	1.2 ± 0.1
Anthraquinone	ng/m³	0.1 ± 0.1	0.3 ± 0.1	1.3 ± 0.2	1.8 ± 0.3
A-dimethylphenanthrene	ng/m³	0 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.7 ± 0.1
B-dimethylphenanthrene	ng/m³	0.3 ± 0.1	0.3 ± 0.1	0.3 ± 0.1	0.7 ± 0.1
1,7-dimethylphenanthrene	ng/m³	0.1 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.5 ± 0.1
3,6-dimethylphenanthrene	ng/m³	0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.5 ± 0.1
D-dimethylphenanthrene	ng/m³	0 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.4 ± 0.1
E-dimethylphenanthrene	ng/m³	0 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.2 ± 0.1
C-dimethylphenanthrene	ng/m³	0.2 ± 0.1	0.5 ± 0.1	0.6 ± 0.1	1.2 ± 0.2
Fluoranthene	ng/m³	0.1 ± 0.1	0.6 ± 0.1	0.8 ± 0.1	5.3 ± 0.5
Pyrene	ng/m³	0.2 ± 0.1	0.8 ± 0.1	1 ± 0.1	4.8 ± 0.7
9-Anthraaldehyde	ng/m³	0 ± 0.1	0.3 ± 0.1	0.1 ± 0.1	0.6 ± 0.1
Retene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Benzo(a)fluorene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
Benzo(b)fluorene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
B-MePy/MeFl	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
1-MeFl+C-MeFl/Py	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
1+3-methylfluoranthene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
4-methylpyrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
C-MePy/MeFl	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
D-MePy/MeFl	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
1-methylpyrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
Benzonaphthothiophene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1

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PolyAromatic HydroCarbon (PAH):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Benzo(c)phenanthrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Benzo(ghi)fluoranthene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.2 ± 0.1
9-phenylanthracene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Cyclopenta(c,d)pyrene	ng/m³	0.2 ± 0.2	0.2 ± 0.1	0.2 ± 0.2	0.2 ± 0.1
Benz(a)anthracene	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0.1 ± 0.1
Chrysene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Benzanthrone	ng/m³	0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
Benz(a)anthracene-7,12-dione	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
3-methylchrysene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
5+6-methylchrysene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
7-methylbenz(a)anthracene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
7,12-dimethylbenz(a)anthracene	ng/m³	0.3 ± 0.2	0.3 ± 0.2	0.3 ± 0.2	0.3 ± 0.2
Benzo(b+j+k)fluoranthene	ng/m³	0.1 ± 0.1	0.1 ± 0.1	0 ± 0.1	0.1 ± 0.1
Benzo(j)fluoranthene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Benzo(a)fluoranthene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
BeP	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
BaP	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
Perylene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
3-methylcholanthrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.3 ± 0.1
7-methylbenzo(a)pyrene	ng/m³	0.4 ± 0.1	0.3 ± 0.1	0.5 ± 0.1	1.3 ± 0.2
9,10-dihydrobenzo(a)pyrene-7(8H)-one	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Indeno[123-cd]fluoranthene	ng/m³	1.1 ± 0.3	1 ± 0.3	1.1 ± 0.3	1 ± 0.3
Dibenz(a,h)acridine	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenz(a,j)acridine	ng/m³	0.8 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1

April 2011 – Detailed Atmosphere Characterization

PolyAromatic HydroCarbon (PAH):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Indeno[123-cd]pyrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(ah+ac)anthracene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(a,j)anthracene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Benzo(b)chrysene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Picene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
7H-dibenzo[c,g]carbazole	ng/m³	0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
Benzo(ghi)perylene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
Anthanthrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Triphenylene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(a,l)pyrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Coronene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(a,e)pyrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(a,i)pyrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(a,h)pyrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(b,k)fluoranthene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1

April 2011 – Detailed Atmosphere Characterization

Nitro-PAH:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
1-nitronaphthalene	ng/m³	0.07	0.29 ± 0.01	0.68 ± 0.03	2.31 ± 0.12
1-methyl-5-nitronaphthalene	ng/m³	0.00	0.01	0.05	0.54 ± 0.03
2-nitronaphthalene	ng/m³	0.02	0.04	0.26 ± 0.01	3.23 ± 0.16
2-nitrobiphenyl	ng/m³	0.04	0.05	0.06	0.06
2-methyl-4-nitronaphthalene	ng/m³	0.00	0.03	0.09	0.92 ± 0.05
1-methyl-4-nitronaphthalene	ng/m³	0.01	0.01	0.08	0.97 ± 0.05
1-methyl-6-nitronaphthalene	ng/m³	0.00	0.00	0.00	0.07 ± 0.01
3-nitrobiphenyl	ng/m³	0.00	0.00	0.01	0.1 ± 0.01
4-nitrobiphenyl	ng/m³	0.00	0.00	0.00	0.14 ± 0.01
1,3-dinitronaphthalene	ng/m³	0.01	0.00	0.04	0.04
1,5-dinitronaphthalene	ng/m³	0.00	0.00	0.00	0.00
5-nitroacenaphthene	ng/m³	0.00	0.00	0.00	0.02
2-nitrofluorene	ng/m³	0.01	0.00	0.00	0.00
4-nitrophenanthrene	ng/m³	0.00	0.00	0.00	0.00
9-nitroanthracene	ng/m³	0.00	0.01	0.01	0.1 ± 0.01
9-nitrophenanthrene	ng/m³	0.00	0.00	0.02	0.04
1,8-dinitronaphthalene	ng/m³	0.01	0.00	0.01	0.01
3-nitrophenanthrene	ng/m³	0.01	0.00	0.01	0.01
2-nitrophenanthrene	ng/m³	0.00	0.00	0.00	0.01
2-nitroanthracene	ng/m³	0.03	0.03	0.01	0.02
2-nitrofluoranthene	ng/m³	0.00	0.00	0.00	0.00
3-nitrofluoranthene	ng/m³	0.00	0.00	0.00	0.00
4-nitropyrene	ng/m³	0.00	0.00	0.00	0.00
1-nitropyrene	ng/m³	0.00	0.00	0.00	0.07 ± 0.01
2-nitropyrene	ng/m³	0.00	0.00	0.00	0.00
2,7-dinitrofluorene	ng/m³	0.00	0.00	0.00	0.00

April 2011 – Detailed Atmosphere Characterization

Nitro-PAH:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
2,7-dinitrofluoren-9-one	ng/m³	0.00	0.00	0.00	0.00
7-nitrobenz(a)anthracene	ng/m³	0.00	0.00	0.00	0.00
6-nitrochrysene	ng/m³	0.00	0.00	0.00	0.00
3-nitrobenzanthrone	ng/m³	0.00	0.00	0.00	0.00
1,3-dinitropyrene	ng/m³	0.00	0.00	0.00	0.00
1,6-dinitropyrene	ng/m³	0.00	0.00	0.00	0.00
1,8-dinitropyrene	ng/m³	0.00	0.00	0.00	0.00
6a+1e-nitrobenzpyrene	ng/m³	0.00	0.00	0.00	0.00
3-nitrobenzo[e]pryene	ng/m³	0.00	0.00	0.00	0.00

April 2011 - Individual Average Characterization Data Tables

Polars:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
8,15-Pimaradien-18-oic acid	ng/m³	0.3 ± 0.3	0.7 ± 0.3	0 ± 0.3	1.1 ± 0.3
Maleic acid	ng/m³	13.5 ± 1	95.6 ± 6.1	237.5 ± 15.3	521 ± 34.2
Guaiacol	ng/m³	208.6 ± 10.6	81.9 ± 4.2	27.8 ± 1.5	10.6 ± 0.7
Salicylic acid	ng/m³	1.7 ± 0.3	12.5 ± 0.7	43.6 ± 2.3	101 ± 5.2
4-me-guaiacol	ng/m³	45.3 ± 3.9	3.2 ± 0.4	0.8 ± 0.3	1.8 ± 0.3
2,3- and 3,5- dimethylbenzoic acid	ng/m³	0 ± 0.3	0 ± 0.3	0 ± 0.3	0 ± 0.3
2,4-dimethylbenzoic acid	ng/m³	0.4 ± 0.3	186.7 ± 11.5	1280 ± 78	1549.3 ± 94.3
2,5-dimethylbenzoic acid	ng/m³	9.3 ± 0.8	19.5 ± 1.5	50 ± 3.8	81.6 ± 6.2
2,6-dimethylbenzoic acid	ng/m³	1 ± 0.3	4.5 ± 0.3	3.7 ± 0.3	8.5 ± 0.6
3,4-dimethylbenzoic acid	ng/m³	0.6 ± 0.3	3.5 ± 0.3	20.7 ± 1.2	163.1 ± 8.3
4-formyl-guaiacol (vanillin)	ng/m³	75.8 ± 3.9	123.7 ± 6.3	116.7 ± 6	42.7 ± 2.3
4-ethyl-guaiacol	ng/m³	4.6 ± 0.7	0.7 ± 0.3	0 ± 0.3	1.7 ± 0.4
Syringol	ng/m³	3.5 ± 0.4	79.4 ± 4.1	189.5 ± 9.6	595.3 ± 29.9
Levoglucosan	ng/m³	11 ± 0.7	11.4 ± 0.7	11.6 ± 0.7	23.2 ± 1.2
4-allyl-guaiacol (eugenol)	ng/m³	1.2 ± 0.3	0.1 ± 0.3	0 ± 0.3	2.7 ± 0.5
Isoeugenol	ng/m³	0.4 ± 0.3	0.4 ± 0.3	0.5 ± 0.3	7.3 ± 1.5
Isophthalic acid	ng/m³	165.5 ± 8.4	300.3 ± 15.1	840.1 ± 43.5	1681 ± 87.8
Phthalic acid	ng/m³	0.1 ± 0.3	0.9 ± 0.3	3.4 ± 0.4	7.2 ± 0.7
Acetovanillone	ng/m³	0.5 ± 0.3	7.3 ± 0.5	0 ± 0.3	9.8 ± 0.6
Vanillic acid	ng/m³	5.3 ± 0.6	18.6 ± 2	14.7 ± 1.6	15.2 ± 1.7
4-methyl-syringol	ng/m³	0.9 ± 0.3	6 ± 0.6	11.4 ± 1	2 ± 0.3
2,3-dimethoxybenzoic acid	ng/m³	106.5 ± 5.5	51.7 ± 2.8	0 ± 0.3	21.6 ± 1.2
2,4-dimethoxybenzoic acid	ng/m³	10.8 ± 0.7	8.1 ± 0.6	15.1 ± 0.9	10.2 ± 0.7
2,5-dimethoxybenzoic acid	ng/m³	0 ± 0.3	0.3 ± 0.3	0 ± 0.3	1.1 ± 0.3

April 2011 - Individual Average Characterization Data Tables

Polars:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
2,6-dimethoxybenzoic acid	ng/m³	3.4 ± 0.4	5 ± 0.5	5.3 ± 0.5	7.5 ± 0.7
3,4-dimethoxybenzoic acid	ng/m³	0.9 ± 0.3	1.3 ± 0.4	0.8 ± 0.3	3 ± 0.6
3,5-dimethoxybenzoic acid	ng/m³	10.3 ± 1.6	14.2 ± 2.2	10.7 ± 1.7	8.8 ± 1.4
Docosanoic acid (c22)	ng/m³	6.8 ± 0.5	7.5 ± 0.6	9.8 ± 0.9	9.2 ± 0.8
Homovanillic acid	ng/m³	1.2 ± 0.3	0.2 ± 0.3	0.2 ± 0.3	4.7 ± 0.5
Syringaldehyde	ng/m³	0.3 ± 0.3	0.4 ± 0.3	0.4 ± 0.3	4.9 ± 0.8
cis-pinonic acid	ng/m³	89.2 ± 7.4	48.2 ± 4	108.8 ± 8.9	149.6 ± 12.2
Syringic acid	ng/m³	0 ± 0.3	0 ± 0.3	0 ± 0.3	0 ± 0.3
Myristoleic acid	ng/m³	2.1 ± 0.3	3.6 ± 0.3	1.2 ± 0.3	9.4 ± 0.6
Traumatic acid	ng/m³	0.9 ± 0.3	1.6 ± 0.3	1.4 ± 0.3	4.7 ± 0.8
1,11-undecanedicarboxylic acid	ng/m³	0.7 ± 0.3	0.6 ± 0.3	0.6 ± 0.3	5.9 ± 0.4
Palmitoleic acid	ng/m³	0.5 ± 0.3	2.8 ± 0.3	7.7 ± 0.5	14.8 ± 0.9
1,12-dodecanedicarboxylic acid	ng/m³	0.1 ± 0.3	0.2 ± 0.3	0 ± 0.3	0.8 ± 0.3
Elaidic acid	ng/m³	0.1 ± 0.3	0.6 ± 0.3	0.9 ± 0.3	6.1 ± 1.9
Isostearic acid	ng/m³	0 ± 0.3	1.4 ± 0.5	0.3 ± 0.3	10.2 ± 2.4
Dehydroabietic acid	ng/m³	0 ± 0.3	1.1 ± 0.3	0.8 ± 0.3	1 ± 0.3
Pimaric acid	ng/m³	1.2 ± 0.3	5.1 ± 0.5	4 ± 0.4	10.8 ± 1
Sandaracopimaric acid	ng/m³	1.4 ± 0.3	5.7 ± 0.8	1.6 ± 0.3	4.2 ± 0.5
Abietic acid	ng/m³	0.1 ± 0.3	0.3 ± 0.3	0.6 ± 0.3	1 ± 0.3
Isopimaric acid	ng/m³	0.1 ± 0.3	0.8 ± 0.3	3.6 ± 0.4	1.4 ± 0.3
7-oxodehydroabietic acid	ng/m³	0.2 ± 0.3	0.2 ± 0.3	0.1 ± 0.3	1.4 ± 0.3
Heneicosanoic acid (c21)	ng/m³	1.6 ± 0.3	2.5 ± 0.3	4.3 ± 0.4	2.1 ± 0.3
Tricosanoic acid	ng/m³	0.3 ± 0.3	0.3 ± 0.3	0.4 ± 0.3	1.8 ± 0.4
Tetracosanoic acid (c24)	ng/m³	5.4 ± 0.7	4.2 ± 0.6	4.8 ± 0.8	7.9 ± 0.9

April 2011 - Individual Average Characterization Data Tables

Polars:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Cholesterol	ng/m³	4.8 ± 0.4	13.7 ± 0.8	9.5 ± 0.6	8.4 ± 0.5
b-sitosterol	ng/m³	0 ± 0.3	10.2 ± 0.7	0 ± 0.3	0.4 ± 0.3
Hexanoic acid (c6)	ng/m³	1075 ± 53.8	961.6 ± 48.1	1126.7 ± 56.3	1556.1 ± 77.8
Heptanoic acid (c7)	ng/m³	1099.4 ± 57.1	854.3 ± 43.9	1323.9 ± 66.6	1771.8 ± 88.8
Benzoic acid	ng/m³	2.8 ± 0.3	671.2 ± 33.6	3023 ± 151.3	3376.5 ± 169
Octanoic acid (c8)	ng/m³	255.3 ± 12.8	399.8 ± 20	563 ± 28.2	745.3 ± 37.3
o-toluic	ng/m³	2.4 ± 0.3	6.9 ± 0.5	35.4 ± 1.9	212.6 ± 10.8
m-toluic	ng/m³	3.7 ± 0.3	9.3 ± 0.6	37.8 ± 2	258 ± 13
Nonanoic acid (c9)	ng/m³	454.2 ± 26.3	433 ± 25.5	339.6 ± 20.3	369.7 ± 22.2
p-toluic	ng/m³	1 ± 0.3	5.5 ± 0.7	21.7 ± 2.5	132.5 ± 14.5
Decanoic acid (c10)	ng/m³	129.5 ± 6.5	177.6 ± 8.9	201.4 ± 10.1	184.5 ± 9.2
Undecanoic acid (c11)	ng/m³	28 ± 1.4	38.7 ± 2	43 ± 2.2	77.4 ± 4
Dodecanoic (lauric) acid (c12)	ng/m³	23.1 ± 1.6	46.8 ± 3	74.9 ± 4.3	105.5 ± 5.6
Tridecanoic acid (c13)	ng/m³	23.5 ± 1.3	28.4 ± 1.5	39 ± 2.1	37.3 ± 2
Myristic acid (c14)	ng/m³	24.2 ± 1.2	44.3 ± 2.2	73.9 ± 3.7	71.1 ± 3.6
Pentadecanoic acid (c15)	ng/m³	12.3 ± 1.3	16.4 ± 1.7	25.7 ± 2.6	20.6 ± 2.1
Palmitic acid (c16)	ng/m³	44.9 ± 2.3	86.5 ± 4.3	94.3 ± 4.7	151.6 ± 7.6
Heptadecanoic acid (c17)	ng/m³	1.3 ± 0.3	1.9 ± 0.3	2.1 ± 0.4	2.1 ± 0.4
Oleic acid	ng/m³	1.1 ± 0.3	11 ± 2.5	7 ± 1.5	11.2 ± 2.3
Stearic acid (c18)	ng/m³	44.2 ± 2.2	39.7 ± 2	34.9 ± 1.7	47.3 ± 2.4
Nonadecanoic acid (c19)	ng/m³	16.4 ± 5.2	17.5 ± 5.6	21.6 ± 6.8	8.7 ± 2.5
Eicosanoic acid (c20)	ng/m³	3.2 ± 0.4	7.9 ± 0.9	13.4 ± 1.5	2.1 ± 0.4

April 2011 - Individual Average Characterization Data Tables

Hopane and Steranes:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
17A(H),21B(H)-22,29,30-Trisnorhopane	ng/m³	0.06	0.07	0.07	0.17 ± 0.01
17A(H),21B(H)-30-Norhopane	ng/m³	0.18 ± 0.01	0.21 ± 0.01	0.25 ± 0.01	0.44 ± 0.02
17A(H),21B(H)-Hopane	ng/m³	0.18 ± 0.01	0.23 ± 0.01	0.27 ± 0.01	0.41 ± 0.02
17B(H),21A(H)-hopane	ng/m³	0.01	0.01	0.01	0.01
22S-17A(H),21B(H)-30-Homohopane	ng/m³	0.1 ± 0.01	0.1 ± 0.01	0.11 ± 0.01	0.17 ± 0.01
22R-17A(H),21B(H)-30-Homohopane	ng/m³	0.09	0.11 ± 0.01	0.12 ± 0.01	0.22 ± 0.01
17B(H),21B(H)-Hopane	ng/m³	0.04	0.05	0.05	0.07 ± 0.01
22S-17A(H),21B(H)-30,31-Bishomohopane	ng/m³	0.06 ± 0.01	0.1 ± 0.02	0.21 ± 0.04	0.24 ± 0.05
22R-17A(H),21B(H)-30,31-Bishomohopane	ng/m³	0.00	0.00	0 ± 0.03	0.00
22S-17A(H),21B(H)-30,31,32-Trisomohopane	ng/m³	0.02	0.02	0.03	0.05 ± 0.01
22R-17A(H),21B(H)-30,31,32-Trishomohopane	ng/m³	0.01	0.02	0.02	0.04 ± 0.01
C27-20S5A(H),14A(H)-cholestane	ng/m³	0.07	0.15 ± 0.01	0.12 ± 0.01	0.12 ± 0.01
C27-20R5A(H),14B(H)-cholestane	ng/m³	0.06	0.1 ± 0.01	0.08	0.11 ± 0.01
C27-20S5A(H),14B(H),17B(H)-cholestane	ng/m³	0.2 ± 0.01	0.1 ± 0.01	0.1 ± 0.01	0.19 ± 0.01
C27-20R5A(H),14A(H),17A(H)-cholestane & C29 -20S13B(H),17A(H)-dia	ng/m³	0.14 ± 0.01	0.21 ± 0.01	0.13 ± 0.01	0.29 ± 0.01
C28-20S5A(H),14A(H),17A(H)-ergostane	ng/m³	0.01	0.02	0.01	0.03
C28-20R5A(H),14B(H),17B(H)-ergostane	ng/m³	0.05	0.06	0.06	0.12 ± 0.01
C28-20S5A(H),14B(H),17B(H)-ergostane	ng/m³	0.19 ± 0.01	0.05	0.05	0.11 ± 0.01
C28-20R5A(H),14A(H),17A(H)-ergostane	ng/m³	0.16 ± 0.01	0.04	0.02	0.03
C29-20S5A(H),14A(H),17A(H)-stigmastane	ng/m³	0.06 ± 0.01	0.08 ± 0.01	0.03 ± 0.01	0.13 ± 0.02
C29-20R5A(H),14B(H),17B(H)-stigmastane	ng/m³	0.03	0.05	0.05 ± 0.01	0.1 ± 0.01
C29-20S5A(H),14B(H),17B(H)-stigmastane	ng/m³	0.03	0.09	0.04	0.05
C29-20R5A(H),14A(H),17A(H)-stigmastane	ng/m³	0.03	0.04	0.05	0.06

April 2011 - Individual Average Characterization Data Tables

Volatile Organic Compounds (VOC):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Acetylene	µg/m³	0.4 ± 0.11	3 ± 0.83	2.9 ± 0.8	13.3 ± 3.68
Ethene	µg/m³	0.2 ± 0.02	3 ± 0.38	4.8 ± 0.6	15.3 ± 1.91
Ethane	µg/m³	7.3 ± 0.37	7.6 ± 0.38	8.3 ± 0.42	12.4 ± 0.62
Propene	µg/m³	3.4 ± 0.31	7.8 ± 0.71	6.6 ± 0.6	18.7 ± 1.69
Propane	µg/m³	1.9 ± 0.1	2.1 ± 0.1	1.8 ± 0.09	2 ± 0.1
1,3-butadiene	µg/m³	0 ± 0.02	0.1 ± 0.02	0.1 ± 0.02	0 ± 0.02
1-butene	µg/m³	0.1 ± 0.03	0.4 ± 0.03	1.1 ± 0.1	4.9 ± 0.44
Isobutylene	µg/m³	0.1 ± 0.03	0.7 ± 0.18	0.3 ± 0.08	1.2 ± 0.32
c-2-butene	µg/m³	2.1 ± 0.1	2.2 ± 0.11	2.8 ± 0.14	7.2 ± 0.36
t-2-butene	µg/m³	0.1 ± 0.03	2.5 ± 0.15	0.7 ± 0.04	2.1 ± 0.13
n-butane	µg/m³	0.7 ± 0.03	0.5 ± 0.03	0.7 ± 0.04	1.2 ± 0.06
iso-butane	µg/m³	1.2 ± 0.06	1.9 ± 0.09	0.8 ± 0.04	1 ± 0.05
iso-pentane	µg/m³	0.4 ± 0.03	0.7 ± 0.03	0.4 ± 0.03	0.9 ± 0.04
n-pentane	µg/m³	0.5 ± 0.06	1.1 ± 0.12	0.5 ± 0.05	1 ± 0.11
1-pentene	µg/m³	0 ± 0.03	0.1 ± 0.03	0.3 ± 0.03	1.1 ± 0.06
2-methyl-1-butene	µg/m³	0 ± 0.03	0 ± 0.03	0.1 ± 0.03	0.3 ± 0.03
isoprene	µg/m³	0.1 ± 0.03	0.1 ± 0.03	0.1 ± 0.03	0 ± 0.03
t-2-pentene	µg/m³	0 ± 0.03	0.1 ± 0.03	0.1 ± 0.03	0.6 ± 0.06
c-2-pentene	µg/m³	0 ± 0.03	0 ± 0.03	0.1 ± 0.03	0.3 ± 0.08
2-methyl-2-butene	µg/m³	0 ± 0.03	0.1 ± 0.03	0.1 ± 0.03	0.3 ± 0.03
2,2-dimethylbutane	µg/m³	0 ± 0.04	0 ± 0.04	0 ± 0.04	0 ± 0.04
Cyclopentene	µg/m³	0 ± 0.04	0 ± 0.04	0.1 ± 0.04	0.4 ± 0.04
Cyclopentane	µg/m³	0 ± 0.03	0 ± 0.03	0 ± 0.03	0.1 ± 0.03
2,3-dimethylbutane	µg/m³	0 ± 0.04	0 ± 0.04	0.2 ± 0.04	0.1 ± 0.04

April 2011 - Individual Average Characterization Data Tables

Volatile Organic Compounds (VOC):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
2-methylpentane	µg/m³	0.1 ± 0.04	0.1 ± 0.04	1.2 ± 0.07	0.4 ± 0.04
3-methylpentane	µg/m³	0.1 ± 0.04	0.1 ± 0.04	1.4 ± 0.07	0.4 ± 0.04
2-methyl-1-pentene	µg/m³	0 ± 0.04	0.1 ± 0.04	0.2 ± 0.04	0.7 ± 0.05
n-hexane	µg/m³	0.2 ± 0.04	0.3 ± 0.04	3 ± 0.15	0.5 ± 0.04
t-2-hexene	µg/m³	0 ± 0.04	0 ± 0.04	0.1 ± 0.04	0.2 ± 0.04
c-2-hexene	µg/m³	0 ± 0.04	0 ± 0.04	0 ± 0.04	0.1 ± 0.04
1,3-hexadiene (trans)	µg/m³	0 ± 0.04	0 ± 0.04	0 ± 0.04	0 ± 0.04
Methylcyclopentane	µg/m³	0.1 ± 0.04	0.1 ± 0.04	1.6 ± 0.18	0.9 ± 0.1
2,4-dimethylpentane	µg/m³	0 ± 0.04	0 ± 0.04	0.4 ± 0.04	0.1 ± 0.04
Benzene	µg/m³	0.3 ± 0.03	0.6 ± 0.03	1.5 ± 0.07	5.6 ± 0.28
Cyclohexane	µg/m³	0 ± 0.04	0.4 ± 0.04	1.1 ± 0.05	2.6 ± 0.13
2-methylhexane	µg/m³	0.1 ± 0.04	0.1 ± 0.04	0.7 ± 0.07	0.4 ± 0.04
2,3-dimethylpentane	µg/m³	0.4 ± 0.04	0 ± 0.04	0.7 ± 0.04	0.7 ± 0.05
Cyclohexene	µg/m³	0 ± 0.04	0 ± 0.04	0.1 ± 0.04	0.3 ± 0.04
3-methylhexane	µg/m³	0.1 ± 0.04	0.1 ± 0.04	0.6 ± 0.04	0.6 ± 0.04
1,3-dimethylcyclopentane (cis)	µg/m³	0 ± 0.04	0 ± 0.04	0.1 ± 0.04	0.3 ± 0.04
1-heptene	µg/m³	0 ± 0.04	0.1 ± 0.04	0.4 ± 0.04	1.1 ± 0.06
2,2,4-trimethylpentane	µg/m³	0 ± 0.05	0 ± 0.05	0.1 ± 0.05	0.2 ± 0.05
n-heptane	µg/m³	0.1 ± 0.04	0.1 ± 0.04	0.3 ± 0.04	1 ± 0.06
2,3-dimethyl-2-pentene	µg/m³	0 ± 0.04	0 ± 0.04	0 ± 0.04	0 ± 0.04
Methylcyclohexane	µg/m³	0.1 ± 0.04	0.4 ± 0.04	1.2 ± 0.08	5.7 ± 0.37
2,3,4-trimethylpentane	µg/m³	0 ± 0.05	0 ± 0.05	0 ± 0.05	0.1 ± 0.05
Toluene	µg/m³	0.8 ± 0.04	0.7 ± 0.04	4.5 ± 0.23	3.7 ± 0.18
2-methylheptane	µg/m³	0 ± 0.05	0.1 ± 0.05	0.2 ± 0.05	0.9 ± 0.17

April 2011 - Individual Average Characterization Data Tables

Volatile Organic Compounds (VOC):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
4-methylheptane	µg/m³	0 ± 0.05	0 ± 0.05	0.1 ± 0.05	0.3 ± 0.05
3-methylheptane	µg/m³	0 ± 0.05	0 ± 0.05	0.2 ± 0.05	0.8 ± 0.14
n-octane	µg/m³	0.1 ± 0.05	0.2 ± 0.05	0.6 ± 0.06	2.6 ± 0.27
Ethylbenzene	µg/m³	0 ± 0.05	0.1 ± 0.05	0.4 ± 0.05	2 ± 0.13
m&p-xylene	µg/m³	0.1 ± 0.05	0.2 ± 0.05	0.8 ± 0.05	4.2 ± 0.21
Styrene	µg/m³	0 ± 0.05	0 ± 0.05	0 ± 0.05	0 ± 0.05
o-xylene	µg/m³	0.1 ± 0.05	0.2 ± 0.05	0.4 ± 0.05	1.6 ± 0.08
n-nonane	µg/m³	0.2 ± 0.06	0.4 ± 0.06	1.2 ± 0.06	4.8 ± 0.24
Isopropylbenzene	µg/m³	0 ± 0.05	0 ± 0.05	0.1 ± 0.05	0.5 ± 0.05
n-propylbenzene	µg/m³	0 ± 0.05	0.1 ± 0.05	0.2 ± 0.05	1.2 ± 0.14
alpha-pinene	µg/m³	1.5 ± 0.26	1.6 ± 0.23	0.1 ± 0.06	0 ± 0.06
3-ethyltoluene	µg/m³	0.1 ± 0.05	0.2 ± 0.05	0.6 ± 0.07	2.9 ± 0.34
4-ethyltoluene	µg/m³	0 ± 0.05	0.1 ± 0.05	0.4 ± 0.05	1.9 ± 0.2
1,3,5-trimethylbenzene	µg/m³	0 ± 0.05	0.1 ± 0.05	0.4 ± 0.05	1.9 ± 0.17
o-ethyltoluene	µg/m³	0 ± 0.05	0.1 ± 0.05	0.3 ± 0.05	1.2 ± 0.06
1,2,4-trimethylbenzene+t-butylbenzene	µg/m³	0 ± 0.05	0 ± 0.05	0 ± 0.05	0 ± 0.05
n-decane	µg/m³	0.7 ± 0.09	1.8 ± 0.2	3.6 ± 0.39	14.4 ± 1.56
1,2,3-trimethylbenzene	µg/m³	0.1 ± 0.05	0.1 ± 0.05	0.5 ± 0.05	2.2 ± 0.22
Indan	µg/m³	0 ± 0.05	0 ± 0.05	0.1 ± 0.05	0.4 ± 0.05
1,3-diethylbenzene	µg/m³	0 ± 0.06	0.1 ± 0.06	0.2 ± 0.06	1 ± 0.06
1,4-diethylbenzene	µg/m³	0 ± 0.06	0.1 ± 0.06	0.2 ± 0.06	1 ± 0.14
n-undecane	µg/m³	0.6 ± 0.07	1.2 ± 0.1	3.2 ± 0.25	12.9 ± 1.03

Appendix G.

April 2012 – Detailed Atmosphere Characterization

April 2012 – Detailed Atmosphere Characterization

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Dekati Particle Mass-Chamber Inlet	µg/m³	NA	NA	NA	NA
Dekati Particle Mass-Inside Chamber	µg/m³	NA	NA	NA	3.8 ± 2.8
Filter Sample - Chamber Inlet	µg/m³	NA	4.8 ± 3.1	3.8 ± 1.0	10.7 ± 0.5
Filter Sample - Inside Chamber	µg/m³	15.5 ± 14.9	32.3 ± 20.0	26.0 ± 13.2	26.0 ± 9.3
Particle Mass-FMPS	µg/m³	0.13 ± 0.10	2.19 ± 0.65	2.36 ± 1.89	9.12 ± 0.47
Particle Count -FMPS	Particle/cm³	474 ± 312	15152 ± 6254	56136 ± 52030	328457 ± 121864
NMAD (GSD) - FMPS	nm	27.8 (2.4) ± 3.9 (0.4)	21.4 (1.6) ± 1.2 (0.06)	19.6 (1.7) ± 1.3 (0.01)	21.1 (1.6) ± 2.1 (0.02)
MMAD (GSD) - FMPS	nm	114.6 (1.4) ± 7.0 (0.2)	122.0 (2.5) ± 6.8 (0.2)	78.0 (2.4) ± 41.9 (0.6)	43.3 (2.8) ± 2.0 (0.4)
Nitrogen Oxide (NO)	µg/m³ (ppm)	0.0 (0.0)	513.1 ± 205.2 (0.5 ± 0.2)	1744.6 ± 410.5 (1.7 ± 0.4)	10364.7 ± 1949.8 (9.8 ± 1.9)
Nitrogen Dioxide (NO_2)	µg/m³ (ppm)	0.0 (0.0)	157.4 (0.1)	1416.2 ± 472.1 (0.9 ± 0.3)	7552.9 ± 1416.2 (4.8 ± 0.9)
Carbon Monoxide (CO)	µg/m³ (ppm)	1915.6 ± 95.8 (2 ± 0.1)	1628.3 ± 95.8 (1.7 ± 0.1)	2202.9 ± 191.6 (2.3 ± 0.2)	3543.8 ± 383.1 (3.7 ± 0.4)
Carbon Dioxide (CO_2)	mg/m³ (ppm)	1498.8 ± 82.8 (995.8 ± 55)	2066.5 ± 416.9 (1373.0 ± 277.0)	3723.2 ± 71.6 (2473.7 ± 47.6)	7201.0 ± 185.0 (4784.4 ± 122.9)
Sulfur Dioxide (SO_2)	µg/m³(ppb)	4.5 (2)	7.9 ± 1.13 (3.5 ± 0.5)	27.09 (12)	108.4 ± 3.61 (48 ± 1.6)
Elemental Carbon	µg/m³	0.2 ± 0.1	0.2	0.3 ± 0.1	0.4 ± 0.1
Organic Carbon	µg/m³	4.6 ± 0.2	7.3 ± 0.4	7.1 ± 0.3	8.5 ± 0.4
Ammonium	ng/m³	2.8	52.0	418.2 ± 0.6	1454.8 ± 5.4
Sulfate	ng/m³	101.0	394.7 ± 0.1	1176.1 ± 0.6	2952.6 ± 3.8
Nitrate	ng/m³	26.4 ± 0.1	79.5 ± 0.4	305.6 ± 3.1	1882.3 ± 50.9
Elements (Metals)	ng/m³	333.3 ± 3.8	319.1 ± 2.5	598.5 ± 9.0	1258.5 ± 29.2
Alkanes	µg/m³	2.5 ± 0.1	4.7 ± 0.2	7.4 ± 0.4	38.6 ± 2
Carbonyl	µg/m³	48.8 ± 2.6	37.9 ± 2.0	18.7 ± 1.1	0 ± 0.3
Polyaromatic Hydrocarbon (PAH)	µg/m³	0.31 ± 0.04	0.58 ± 0.06	0.96 ± 0.08	2.89 ± 0.18
Nitro-PAH	ng/m³	0.2	0.5	1.4 ± 0.1	11.2 ± 1
Polars (Acids)	µg/m³	1.7 ± 0.2	3.3 ± 0.3	6.6 ± 0.5	12.1 ± 1
Hopane and Steranes	ng/m³	2.5 ± 0.2	7.1 ± 0.5	4.4 ± 0.4	9.3 ± 0.7
Volatile Organic Compounds (VOC)	µg/m³	65.1 ± 5.9	47.9 ± 4.7	45.1 ± 4.8	277.8 ± 16.3

April 2012 – Detailed Atmosphere Characterization

Carbon:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Organic Carbon Fraction 1	µg/m³	0.7	1.8 ± 0.1	0.7	1.5 ± 0.1
Organic Carbon Fraction 2	µg/m³	2.2 ± 0.6	3.7 ± 1	4.1 ± 1.1	4.8 ± 1.3
Organic Carbon Fraction 3	µg/m³	1.1	1.4 ± 0.1	1.8 ± 0.1	1.3 ± 0.1
Organic Carbon Fraction 4	µg/m³	0.4	0.4	0.5	0.6
Pyrolyzed Organic Carbon Reflectance	µg/m³	0.3 ± 0.1	0.1	0.1	0.6 ± 0.2
Pyrolyzed Organic Carbon Transmittance	µg/m³	0.1	0.0	0.0	0.3
Organic Carbon	µg/m³	4.6 ± 0.2	7.3 ± 0.4	7.1 ± 0.3	8.5 ± 0.4
Elemental Carbon Fraction 1	µg/m³	0.1	0.1	0.1	0.3
Elemental Carbon Fraction 2	µg/m³	0.2	0.1	0.2	0.4 ± 0.1
Elemental Carbon Fraction 3	µg/m³	0.0	0.0	0.0	0.0
Elemental Carbon	µg/m³	0.2 ± 0.1	0.2	0.3 ± 0.1	0.4 ± 0.1
Total Carbon	µg/m³	4.8 ± 0.2	7.5 ± 0.3	7.3 ± 0.3	8.9 ± 0.4

April 2012 – Detailed Atmosphere Characterization

Elements (Metals):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Sodium	ng/m³	92.7 ± 3.4	57.5 ± 2.3	242.1 ± 8.6	819.8 ± 28.3
Magnesium	ng/m³	0.0	0.0	0.0	22.3 ± 0.2
Aluminum	ng/m³	0.9	4.4	5.4	36.3 ± 0.1
Silicon	ng/m³	20.5	17.7	13.3	12.7
Phosphorous	ng/m³	13.1	12.8	13.6	20.8
Sulfur	ng/m³	36.7 ± 0.1	158.1 ± 0.3	523.9 ± 1.2	1251 ± 3
Chlorine	ng/m³	32.2 ± 0.1	36.5 ± 0.1	54.1 ± 0.1	28.2
Potassium	ng/m³	76.6 ± 0.1	74.5	121.3 ± 0.1	72.9
Calcium	ng/m³	52.8 ± 0.1	48.3 ± 0.1	71.4 ± 0.1	77.2 ± 0.1
Scandium	ng/m³	0.0	0.0	0.5	0.0
Titanium	ng/m³	0.5	0.5	1.1	1.0
Vanadium	ng/m³	0.0	0.1	0.0	0.1
Chromium	ng/m³	0.5	3.1	0.9	0.1
Manganese	ng/m³	0.4	0.5	0.6	3.5
Iron	ng/m³	14.7	20.1	31.3	52.9
Cobalt	ng/m³	0.0	0.0	0.0	0.2
Nickel	ng/m³	0.3	0.4	0.2	0.3
Copper	ng/m³	7.8	20.5	8.7	37.1
Zinc	ng/m³	6.7	14.8	8.9	29.5
Gallium	ng/m³	0.0	0.0	0.0	0.1
Arsenic	ng/m³	0.0	0.0	0.0	0.0
Selenium	ng/m³	0.0	0.1	0.0	0.0
Bromine	ng/m³	0.0	0.1	0.5	0.2
Rubidium	ng/m³	0.2	0.0	0.0	0.1
Strontium	ng/m³	0.4	0.6	0.0	0.4
Yttrium	ng/m³	0.6	0.7	0.0	0.2

April 2012 – Detailed Atmosphere Characterization

Elements (Metals):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Zirconium	ng/m³	1.2	0.6	0.6	1.4
Niobium	ng/m³	0.0	0.0	0.0	0.0
Molybdenum	ng/m³	0.0	0.0	0.0	0.0
Palladium	ng/m³	0.2	0.6	0.6	0.8
Silver	ng/m³	0.7	0.0	0.0	0.1
Cadmium	ng/m³	0.1	0.0	0.0	0.0
Indium	ng/m³	0.0	0.5	0.0	0.5
Tin	ng/m³	0.5	0.0	1.1	0.9
Antimony	ng/m³	0.6	0.5	3.1	1.1
Cesium	ng/m³	0.1	0.0	1.8	1.8
Barium	ng/m³	0.0	0.2	0.0	0.7
Lanthanum	ng/m³	0.5	0.0	0.0	4.0
Cerium	ng/m³	0.9	0.0	0.0	0.0
Samarium	ng/m³	0.0	0.0	0.0	4.3
Europium	ng/m³	0.0	0.0	0.0	0.0
Terbium	ng/m³	6.9 ± 0.3	2.6	14.8 ± 0.1	25 ± 0.1
Hafnium	ng/m³	0.0	0.0	0.0	0.0
Tantalum	ng/m³	0.0	0.0	0.0	0.0
Wolfram	ng/m³	0.0	0.3	0.8	0.0
Iridium	ng/m³	0.0	0.0	0.0	0.0
Gold	ng/m³	0.0	0.0	0.2	0.0
Mercury	ng/m³	0.1	0.0	0.0	0.1
Thallium	ng/m³	0.0	0.0	0.0	0.0
Lead	ng/m³	0.4	0.2	1.6	1.8
Uranium	ng/m³	0.2	0.3	0.0	0.0

April 2012 – Detailed Atmosphere Characterization

Alkanes:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Dodecane	ng/m³	501.2 ± 25.1	761.2 ± 38.1	1289.6 ± 64.5	6102.9 ± 305.1
Norfarnesane	ng/m³	148.2 ± 7.5	306.5 ± 15.5	497.6 ± 25	1740.5 ± 87.2
Tridecane	ng/m³	573.6 ± 28.7	812.3 ± 40.6	1464.1 ± 73.2	7752.7 ± 387.6
Heptylcyclohexane	ng/m³	29.4 ± 2.5	67 ± 5.6	128 ± 10.5	561.1 ± 45.7
Farnesane	ng/m³	50.2 ± 2.6	183.3 ± 9.3	237.1 ± 12	1277.2 ± 64
Tetradecane	ng/m³	207.9 ± 10.4	522.5 ± 26.1	899.2 ± 45	6042.5 ± 302.1
Octylcyclohexane	ng/m³	17.4 ± 1.7	52.5 ± 5.4	78.2 ± 8.2	437 ± 46.6
Pentadecane	ng/m³	151.2 ± 7.6	390.9 ± 19.6	658.5 ± 33	3826.4 ± 191.4
Nonylcyclohexane	ng/m³	12.6 ± 0.7	40.4 ± 2.1	63.7 ± 3.3	356.6 ± 17.9
Hexadecane	ng/m³	186.9 ± 9.3	367.2 ± 18.4	508.4 ± 25.4	2720.8 ± 136
Norpristane	ng/m³	87 ± 4.5	147.5 ± 7.5	231.6 ± 11.7	1258.9 ± 63
Decylcyclohexane	ng/m³	14.6 ± 0.9	34.1 ± 1.9	50.2 ± 2.8	237.3 ± 13.3
Heptadecane	ng/m³	121 ± 6	264.1 ± 13.2	395.7 ± 19.8	2215.1 ± 110.8
Heptadecane	ng/m³	62.1 ± 3.2	112.6 ± 5.7	194.9 ± 9.9	1067.1 ± 53.5
Undecylcyclohexane	ng/m³	10.8 ± 0.7	20.8 ± 1.1	35.4 ± 1.9	132.9 ± 6.7
Octadecane	ng/m³	114.7 ± 5.7	222.8 ± 11.1	274 ± 13.7	1227.3 ± 61.4
Phytane	ng/m³	39.8 ± 2.1	107.7 ± 5.4	134.3 ± 6.8	834.8 ± 41.8
Dodecylcyclohexane	ng/m³	5.3 ± 0.4	9.6 ± 0.6	15.4 ± 0.9	73.7 ± 4.1
Nonadecane	ng/m³	19.2 ± 1.8	60.3 ± 5.3	57.3 ± 5	339.2 ± 29.2
Tridecylcyclohexane	ng/m³	1.6 ± 0.4	2.9 ± 0.5	5.1 ± 0.8	20.5 ± 3
Eicosane	ng/m³	36 ± 1.9	65 ± 3.3	63.8 ± 3.3	181.9 ± 9.5
Tetradecylcyclohexane	ng/m³	1.2 ± 0.3	1 ± 0.3	0.4 ± 0.3	9.5 ± 1.1
Heneicosane	ng/m³	6 ± 0.4	12.9 ± 0.8	16.8 ± 0.9	71.6 ± 3.6
Pentadecylcyclohexane	ng/m³	0.2 ± 0.3	0.7 ± 0.3	2 ± 0.3	8.8 ± 0.6
Docosane	ng/m³	17 ± 0.9	26.2 ± 1.3	27.7 ± 1.4	49.3 ± 2.5
Hexadecylcyclohexane	ng/m³	0.4 ± 0.3	0.6 ± 0.3	0.9 ± 0.3	2.1 ± 0.3

April 2012 – Detailed Atmosphere Characterization

Alkanes:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Tricosane	ng/m³	10 ± 0.6	11 ± 0.7	11.6 ± 0.7	21.9 ± 1.2
Heptadecylcyclohexane	ng/m³	6.1 ± 0.9	0.8 ± 0.3	6.6 ± 0.9	4.5 ± 0.5
Tetracosane	ng/m³	7.5 ± 0.4	12.2 ± 0.6	12.1 ± 0.6	17.3 ± 0.9
Octadecylcyclohexane	ng/m³	1.2 ± 0.3	3.8 ± 0.4	0.7 ± 0.3	1.5 ± 0.3
Pentacosane	ng/m³	3 ± 0.5	3.6 ± 0.6	4.8 ± 0.7	5.2 ± 0.7
Hexacosane	ng/m³	3.8 ± 0.3	7.9 ± 0.5	6.4 ± 0.4	8.7 ± 0.5
Nonadecylcyclohexane	ng/m³	1 ± 0.3	1.8 ± 0.3	1.3 ± 0.3	2 ± 0.3
Heptacosane	ng/m³	1.4 ± 0.3	3.3 ± 0.4	0.7 ± 0.3	4.5 ± 0.5
Eicosylcyclohexane	ng/m³	0.5 ± 0.3	1.1 ± 0.3	0.5 ± 0.3	0.8 ± 0.3
Octacosane	ng/m³	4.5 ± 0.6	5 ± 0.6	5.9 ± 0.7	7.4 ± 0.8
Nonacosane	ng/m³	1.8 ± 0.3	0.8 ± 0.3	1.9 ± 0.3	2.7 ± 0.3
Heneicosylcyclohexane	ng/m³	0.2 ± 0.3	1 ± 0.3	0.1 ± 0.3	0.8 ± 0.3
Triacontane	ng/m³	5.1 ± 0.4	7.6 ± 0.6	5.9 ± 0.5	7.2 ± 0.6
Hentriacontane	ng/m³	1.8 ± 0.3	2.2 ± 0.3	2 ± 0.3	3.6 ± 0.3
Dotriacontane	ng/m³	2.5 ± 0.3	3.9 ± 0.3	3.5 ± 0.3	2.7 ± 0.3
Tritriacontane	ng/m³	0.4 ± 0.3	1.5 ± 0.4	0.5 ± 0.3	0.6 ± 0.3
Tetratriacontane	ng/m³	1.9 ± 0.4	2.5 ± 0.5	2 ± 0.4	1.1 ± 0.3
Pentatriacontane	ng/m³	0.2 ± 0.3	0.3 ± 0.3	0.1 ± 0.3	0.3 ± 0.3
Hexatriacontane	ng/m³	0.7 ± 0.3	0.5 ± 0.3	0.2 ± 0.3	0.6 ± 0.3
Heptatriacontane	ng/m³	0.2 ± 0.3	0.3 ± 0.3	0.2 ± 0.3	0.2 ± 0.3
Octatriacontane	ng/m³	2.3 ± 0.5	1.7 ± 0.5	2.4 ± 0.6	1.3 ± 0.4
Nonatriacontane	ng/m³	0.2 ± 0.3	0.3 ± 0.3	0.2 ± 0.3	0.1 ± 0.3
Tetracontane	ng/m³	1 ± 0.3	0.9 ± 0.3	0.8 ± 0.3	0.7 ± 0.3

April 2012 – Detailed Atmosphere Characterization

Carbonyl:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Formaldehyde	µg/m³	3 ± 0.2	3.5 ± 0.2	3.7 ± 0.2	0.0
Acetaldehyde	µg/m³	10.2 ± 0.5	10 ± 0.5	2.6 ± 0.1	0.0
Acrolein	µg/m³	0.1	0.1	0.1	0.0
Glyoxal	µg/m³	0.2	0.1	0.1	0.0
Acetone	µg/m³	21.2 ± 1.1	11.1 ± 0.6	2 ± 0.1	0.0
Propionaldehyde	µg/m³	1.2 ± 0.1	1.1 ± 0.1	0.8	0.0
Crotonaldehyde	µg/m³	0.4	0.2	0.0	0.0
Methacrolein	µg/m³	0.0	0.0	0.0	0.0
n-butyraldehyde	µg/m³	0.8 ± 0.1	0.7	0.4	0.0
2-Butanone (MEK)	µg/m³	1.5 ± 0.1	1.4 ± 0.1	0.1	0.0
Valeraldehyde	µg/m³	2 ± 0.1	1.4 ± 0.1	1.3 ± 0.1	0.0
Hexaldehyde	µg/m³	7.7 ± 0.4	7.8 ± 0.4	7.4 ± 0.4	0.0
Benzaldehyde	µg/m³	0.5	0.5	0.2	0.0
m-Tolualdehyde	µg/m³	0.0	0.0	0.0	0.0

April 2012 – Detailed Atmosphere Characterization

PolyAromatic HydroCarbon (PAH):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Naphthalene	ng/m³	9.3 ± 0.5	71.1 ± 3.6	190.5 ± 9.5	807 ± 40.4
Quinoline	ng/m³	1.6 ± 0.2	4 ± 0.4	5.9 ± 0.5	10.8 ± 1.0
2-methylnaphthalene	ng/m³	10.6 ± 0.5	29.3 ± 1.5	54 ± 2.7	225.8 ± 11.3
1-methylnaphthalene	ng/m³	4.8 ± 0.2	16.7 ± 0.9	31.9 ± 1.6	165.4 ± 8.3
Biphenyl	ng/m³	9.5 ± 0.5	18.4 ± 0.9	29.6 ± 1.5	104.2 ± 5.2
2-methylbiphenyl	ng/m³	27.2 ± 1.4	62.1 ± 3.1	183.5 ± 9.2	488 ± 24.4
2,6+2,7-dimethylnaphthalene	ng/m³	4.6 ± 0.2	11.7 ± 0.6	20.5 ± 1	109.4 ± 5.5
1,3+1,6+1,7dimethylnaphth	ng/m³	7.8 ± 0.4	21 ± 1.1	37.1 ± 1.9	228.4 ± 11.4
1,4+1,5+2,3-dimethylnaphth	ng/m³	2.5 ± 0.1	7.4 ± 0.4	12.6 ± 0.6	74.9 ± 3.8
Acenaphthylene	ng/m³	0.1 ± 0.1	3 ± 0.2	10.2 ± 0.5	8.7 ± 0.4
1,2-dimethylnaphthalene	ng/m³	0.9 ± 0.1	2.1 ± 0.1	3.8 ± 0.2	21.2 ± 1.1
1,8-dimethylnaphthalene	ng/m³	0 ± 0.1	0 ± 0.1	0.1 ± 0.1	0.2 ± 0.1
1+2ethylnaphthalene	ng/m³	2.4 ± 0.1	6.6 ± 0.3	13.6 ± 0.7	44.4 ± 2.2
Acenaphthene	ng/m³	0.5 ± 0.1	0.7 ± 0.1	1 ± 0.2	8.1 ± 1.4
4-methylbiphenyl	ng/m³	107.2 ± 11.6	139.1 ± 15.7	169 ± 18	169.4 ± 14.7
Dibenzofuran	ng/m³	1.8 ± 5.4	3.1 ± 7	3.7 ± 8.5	12.6 ± 8.5
Bibenzyl	ng/m³	16.9 ± 0.1	18.1 ± 0.2	15.6 ± 0.2	4.9 ± 0.8
1-ethyl-2-methylnaphthalene	ng/m³	0.5 ± 0.8	1.6 ± 0.9	2.7 ± 0.8	9.1 ± 0.2
2,3,5+I-trimethylnaphthalene	ng/m³	3.2 ± 0.1	6.6 ± 0.2	9.3 ± 0.3	29.7 ± 1.1
B-trimethylnaphthalene	ng/m³	3.9 ± 0.2	8.3 ± 0.4	11.8 ± 0.5	41.6 ± 1.6
A-trimethylnaphthalene	ng/m³	3.9 ± 0.2	8.7 ± 0.4	13.3 ± 0.6	49.4 ± 2.1
C-trimethylnaphthalene	ng/m³	3.3 ± 0.2	7.9 ± 0.4	11.4 ± 0.7	39.1 ± 2.5
2-ethyl-1-methylnaphthalene	ng/m³	0.1 ± 0.2	0.4 ± 0.4	0.2 ± 0.6	1.5 ± 2.0
E-trimethylnaphthalene	ng/m³	2.6 ± 0.1	5.3 ± 0.1	7.4 ± 0.1	25.4 ± 0.2

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PolyAromatic HydroCarbon (PAH):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
2,4,5-trimethylnaphthalene	ng/m³	0.8 ± 0.1	1.8 ± 0.3	2.6 ± 0.4	7.2 ± 1.3
F-trimethylnaphthalene	ng/m³	2 ± 0.1	4 ± 0.2	6.1 ± 0.3	19.3 ± 0.8
Fluorene	ng/m³	8.2 ± 0.1	13.8 ± 0.2	21.5 ± 0.3	30.9 ± 1.0
1,4,5-trimethylnaphthalene	ng/m³	0.2 ± 1	0.9 ± 1.6	0.7 ± 2.5	6.1 ± 3.6
J-trimethylnaphthalene	ng/m³	1.1 ± 0.1	3.1 ± 0.1	3.8 ± 0.1	14.4 ± 0.6
A-Methylfluorene	ng/m³	4.6 ± 0.1	5 ± 0.3	5.7 ± 0.4	5 ± 1.4
B-Methylfluorene	ng/m³	0.2 ± 0.4	0.2 ± 0.4	0.3 ± 0.5	1.8 ± 0.4
1-Methylfluorene	ng/m³	2 ± 0.1	2.3 ± 0.1	1.9 ± 0.1	5.7 ± 0.4
9-fluorenone	ng/m³	0.4 ± 0.1	1.3 ± 0.2	1.7 ± 0.1	5.9 ± 0.4
Dibenzothiophene	ng/m³	0.1 ± 0.1	0.2 ± 0.1	0.1 ± 0.2	0.1 ± 0.6
Phenanthrene	ng/m³	3.1 ± 0.1	8.2 ± 0.1	7.8 ± 0.1	36.7 ± 0.1
Anthracene	ng/m³	0.1 ± 0.2	0.5 ± 0.4	0.4 ± 0.4	2.3 ± 1.8
Xanthone	ng/m³	0.1 ± 0.1	0.1 ± 0.1	0.4 ± 0.1	1 ± 0.1
Acenaphthenequinone	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.2
3-methylphenanthrene	ng/m³	0.2 ± 0.1	1.1 ± 0.1	0.9 ± 0.1	2.4 ± 0.1
2-methylphenanthrene	ng/m³	0.6 ± 0.1	1.2 ± 0.2	1.2 ± 0.1	2.7 ± 0.3
Perinaphthenone	ng/m³	0.2 ± 0.1	0.2 ± 0.1	0.5 ± 0.1	1 ± 0.2
2-methylanthracene	ng/m³	0.1 ± 0.1	0.2 ± 0.1	0.3 ± 0.1	1.1 ± 0.2
4,5-methylenephenanthrene	ng/m³	0.1 ± 0.1	0.7 ± 0.1	0.6 ± 0.1	2.9 ± 0.1
9-methylphenanthrene	ng/m³	0.5 ± 0.1	1.2 ± 0.1	0.8 ± 0.1	2.4 ± 0.4
1-methylphenanthrene	ng/m³	0.4 ± 0.1	1.1 ± 0.1	0.4 ± 0.1	1.4 ± 0.1
Dibutyl phthalate	ng/m³	53.7 ± 0.1	74.8 ± 0.3	56.2 ± 0.1	44.2 ± 0.3
Anthrone	ng/m³	0.2 ± 2.7	0.3 ± 3.7	0.7 ± 2.8	1.3 ± 2.2
9-methylanthracene	ng/m³	0 ± 0.1	0 ± 0.1	0.1 ± 0.1	0.2 ± 0.1

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PolyAromatic HydroCarbon (PAH):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
2-phenylnaphthalene	ng/m³	0.1 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.4 ± 0.1
Anthraquinone	ng/m³	0.5 ± 0.1	1 ± 0.1	0.9 ± 0.1	1.8 ± 0.1
A-dimethylphenanthrene	ng/m³	0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.9 ± 0.1
B-dimethylphenanthrene	ng/m³	0 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.5 ± 0.2
1,7-dimethylphenanthrene	ng/m³	0.1 ± 0.1	0.3 ± 0.1	0.3 ± 0.1	0.8 ± 0.1
3,6-dimethylphenanthrene	ng/m³	0 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.9 ± 0.1
D-dimethylphenanthrene	ng/m³	0 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.4 ± 0.2
E-dimethylphenanthrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
C-dimethylphenanthrene	ng/m³	0.2 ± 0.1	0.5 ± 0.1	0.5 ± 0.1	1.7 ± 0.1
Fluoranthene	ng/m³	0.1 ± 0.1	0.6 ± 0.1	0.7 ± 0.1	2.6 ± 0.1
Pyrene	ng/m³	0.2 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	1.5 ± 0.2
9-Anthraaldehyde	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.3 ± 0.1
Retene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Benzo(a)fluorene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
Benzo(b)fluorene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
B-MePy/MeFl	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
1-MeFl+C-MeFl/Py	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
1+3-methylfluoranthene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
4-methylpyrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
C-MePy/MeFl	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
D-MePy/MeFl	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
1-methylpyrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
Benzonaphthothiophene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Benzo(c)phenanthrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1

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PolyAromatic HydroCarbon (PAH):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Benzo(ghi)fluoranthene	ng/m³	0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.2 ± 0.1
9-phenylanthracene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Cyclopenta(c,d)pyrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Benz(a)anthracene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Chrysene/Triphenylene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Benzanthrone	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Bis[2-ethylhexyl]phthalate	ng/m³	0 ± 0.1	0 ± 0.1	0.3 ± 0.1	0 ± 0.1
Benz(a)anthracene-7,12-dione	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
3-methylchrysene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
5+6-methylchrysene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
7-methylbenz(a)anthracene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
7,12-dimethylbenz(a)anthracene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.2 ± 0.1
Benzo(b+j+k)fluoranthene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Benzo(j)fluoranthene	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0.1 ± 0.1
Benzo(a)fluoranthene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
BeP	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
BaP	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Perylene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
3-methylcholanthrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.5 ± 0.1
7-methylbenzo(a)pyrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
9,10-dihydrobenzo(a)pyrene-7(8H)-one	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Indeno[123-cd]fluoranthene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
Dibenz(a,h)acridine	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.2 ± 0.1
Dibenz(a,j)acridine	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.2 ± 0.1

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PolyAromatic HydroCarbon (PAH):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Indeno[123-cd]pyrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(ah+ac)anthracene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(a,j)anthracene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Benzo(b)chrysene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Picene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
7H-dibenzo[c,g]carbazole	ng/m³	0 ± 0.1	0.1 ± 0.1	0 ± 0.1	0.1 ± 0.1
Benzo(ghi)perylene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0.1 ± 0.1
Anthanthrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(a,l)pyrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Coronene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(a,e)pyrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(a,i)pyrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(a,h)pyrene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Dibenzo(b,k)fluoranthene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Benzo(b)fluoranthene	ng/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1

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Nitro-PAH:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
1-nitronaphthalene	ng/m³	0.0	0.2	0.4	1.6 ± 0.1
1-methyl-5-nitronaphthalene	ng/m³	0.0	0.0	0.1	0.9 ± 0.1
2-nitronaphthalene	ng/m³	0.0	0.2	0.4	4.3 ± 0.3
2-nitrobiphenyl	ng/m³	0.1	0.0	0.0	0.0
2-methyl-4-nitronaphthalene	ng/m³	0.0	0.0	0.0	1.1 ± 0.4
1-methyl-4-nitronaphthalene	ng/m³	0.0	0.1	0.2	2.7 ± 0.2
1-methyl-6-nitronaphthalene	ng/m³	0.0	0.0	0.1	0.0
3-nitrobiphenyl	ng/m³	0.0	0.0	0.0	0.1
4-nitrobiphenyl	ng/m³	0.0	0.0	0.0	0.0
1,3-dinitronaphthalene	ng/m³	0.0	0.0	0.0	0.0
1,5-dinitronaphthalene	ng/m³	0.0	0.0	0.0	0.0
5-nitroacenaphthene	ng/m³	0.0	0.0	0.0	0.0
2-nitrofluorene	ng/m³	0.0	0.0	0.0	0.0
4-nitrophenanthrene	ng/m³	0.0	0.0	0.0	0.0
9-nitroanthracene	ng/m³	0.0	0.0	0.0	0.2
9-nitrophenanthrene	ng/m³	0.0	0.0	0.0	0.0
1,8-dinitronaphthalene	ng/m³	0.0	0.0	0.0	0.0
3-nitrophenanthrene	ng/m³	0.1	0.0	0.1	0.1
2-nitrophenanthrene	ng/m³	0.0	0.0	0.0	0.0
2-nitroanthracene	ng/m³	0.0	0.0	0.0	0.0
2-nitrofluoranthene	ng/m³	0.0	0.0	0.0	0.0
3-nitrofluoranthene	ng/m³	0.0	0.0	0.0	0.0
4-nitropyrene	ng/m³	0.0	0.0	0.0	0.0
1-nitropyrene	ng/m³	0.0	0.0	0.0	0.1
2-nitropyrene	ng/m³	0.0	0.0	0.0	0.0
2,7-dinitrofluorene	ng/m³	0.0	0.0	0.0	0.0

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Nitro-PAH:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
2,7-dinitrofluoren-9-one	ng/m³	0.0	0.0	0.0	0.0
7-nitrobenz(a)anthracene	ng/m³	0.00	0.00	0.00	0.00
6-nitrochrysene	ng/m³	0.00	0.00	0.00	0.00
3-nitrobenzanthrone	ng/m³	0.00	0.00	0.00	0.00
1,3-dinitropyrene	ng/m³	0.00	0.00	0.00	0.00
1,6-dinitropyrene	ng/m³	0.00	0.00	0.00	0.00
1,8-dinitropyrene	ng/m³	0.00	0.00	0.00	0.00
3-nitrobenzo[e]pryene	ng/m³	0.00	0.00	0.00	0.00
6a+1e-nitrobenzpyrene	ng/m³	0.00	0.00	0.00	0.00

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Polars:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
8,15-Pimaradien-18-oic acid	ng/m³	0.3 ± 0.3	0.2 ± 0.3	0.9 ± 0.3	0.8 ± 0.3
Maleic acid	ng/m³	4.4 ± 0.6	67.9 ± 6.5	169.4 ± 16	132.9 ± 12.8
Guaiacol	ng/m³	39.8 ± 3	13.8 ± 1.1	5.3 ± 0.5	3 ± 0.3
Salicylic acid	ng/m³	0.1 ± 0.3	4 ± 0.3	35.1 ± 1.9	143.8 ± 7.3
4-me-guaiacol	ng/m³	11.7 ± 1.6	0.2 ± 0.3	0.2 ± 0.3	1.1 ± 0.3
2,3- and 3,5- dimethylbenzoic acid	ng/m³	0 ± 0.3	0 ± 0.3	0 ± 0.3	0 ± 0.3
2,4-dimethylbenzoic acid	ng/m³	0 ± 0.3	183.3 ± 9.3	1434 ± 71.8	2961 ± 148.2
2,5-dimethylbenzoic acid	ng/m³	0.8 ± 0.3	2.5 ± 0.3	17 ± 1.0	99.2 ± 5.1
2,6-dimethylbenzoic acid	ng/m³	0.3 ± 0.3	0 ± 0.3	0 ± 0.3	17.8 ± 2.4
3,4-dimethylbenzoic acid	ng/m³	0 ± 0.3	3.4 ± 0.5	18.1 ± 2.2	221.2 ± 25.6
4-formyl-guaiacol (vanillin)	ng/m³	19 ± 1.1	43.5 ± 2.3	71.9 ± 3.7	73.6 ± 3.8
4-ethyl-guaiacol	ng/m³	0.2 ± 0.3	0.4 ± 0.3	1 ± 0.3	1.8 ± 0.4
Syringol	ng/m³	0.1 ± 0.3	0.2 ± 0.3	0.2 ± 0.3	358.6 ± 72.5
Levoglucosan	ng/m³	3.7 ± 0.3	2.5 ± 0.3	5.7 ± 0.4	13.2 ± 0.8
4-allyl-guaiacol (eugenol)	ng/m³	1.5 ± 0.4	0.5 ± 0.3	2 ± 0.4	1.6 ± 0.4
Isoeugenol	ng/m³	0.7 ± 0.3	0.7 ± 0.3	1.9 ± 0.3	6.7 ± 0.7
Isophthalic acid	ng/m³	0 ± 0.3	8.6 ± 0.6	233.3 ± 11.8	872.9 ± 43.8
Phthalic acid	ng/m³	0 ± 0.3	13.2 ± 2	0 ± 0.3	1.1 ± 0.3
Acetovanillone	ng/m³	1.9 ± 0.4	1.1 ± 0.3	0.3 ± 0.3	5.8 ± 1.0
Vanillic acid	ng/m³	1.4 ± 0.3	9.9 ± 1.5	25.1 ± 3.7	28 ± 4.1
4-methyl-syringol	ng/m³	0.2 ± 0.3	1.8 ± 0.6	14.7 ± 3.6	81.5 ± 19.2
2,3-dimethoxybenzoic acid	ng/m³	2.1 ± 0.3	3 ± 0.4	6.5 ± 0.8	343.3 ± 36.9
2,4-dimethoxybenzoic acid	ng/m³	20.4 ± 1.6	15.7 ± 1.2	17.2 ± 1.4	18 ± 1.4
2,5-dimethoxybenzoic acid	ng/m³	0.2 ± 0.3	0.3 ± 0.3	23.2 ± 3.2	219.2 ± 28.9

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Polars:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
2,6-dimethoxybenzoic acid	ng/m³	0.6 ± 0.3	0.5 ± 0.3	0.2 ± 0.3	3.9 ± 0.5
3,4-dimethoxybenzoic acid	ng/m³	0.4 ± 0.3	0.7 ± 0.3	1.6 ± 0.4	3.5 ± 0.8
3,5-dimethoxybenzoic acid	ng/m³	7.8 ± 0.5	7.9 ± 0.5	6.9 ± 0.5	20 ± 1.1
Docosanoic acid (c22)	ng/m³	3.9 ± 0.3	3 ± 0.3	4.7 ± 0.4	3 ± 0.3
Homovanillic acid	ng/m³	0.2 ± 0.3	0 ± 0.3	0.9 ± 0.3	2.7 ± 0.3
Syringaldehyde	ng/m³	0.1 ± 0.3	0.2 ± 0.3	0.6 ± 0.3	1 ± 0.3
cis-pinonic acid	ng/m³	53.6 ± 3.9	36 ± 2.5	74.2 ± 5.3	49.7 ± 3.6
Syringic acid	ng/m³	0 ± 0.3	0 ± 0.3	0 ± 0.3	0 ± 0.3
Myristoleic acid	ng/m³	0.1 ± 0.3	0 ± 0.3	4.3 ± 1.5	6.3 ± 2.0
Traumatic acid	ng/m³	2.7 ± 0.5	1.7 ± 0.4	5 ± 0.8	2.1 ± 0.4
1,11-undecanedicarboxylic acid	ng/m³	0.2 ± 0.3	0.8 ± 0.3	1.2 ± 0.3	6.3 ± 0.5
Palmitoleic acid	ng/m³	0.2 ± 0.3	0.7 ± 0.3	4.2 ± 0.5	12.2 ± 1.3
1,12-dodecanedicarboxylic acid	ng/m³	0.2 ± 0.3	0.2 ± 0.3	0.2 ± 0.3	1 ± 0.3
Elaidic acid	ng/m³	0.4 ± 0.3	1.6 ± 0.4	3 ± 0.7	6.4 ± 0.8
Isostearic acid	ng/m³	0.7 ± 0.4	0.7 ± 0.4	2.6 ± 1.1	66.4 ± 25.3
Dehydroabietic acid	ng/m³	20.8 ± 1.2	0.8 ± 0.3	26.8 ± 1.4	0.9 ± 0.3
Pimaric acid	ng/m³	1.5 ± 0.3	3.4 ± 0.3	3.4 ± 0.3	6.4 ± 0.4
Sandaracopimaric acid	ng/m³	0.2 ± 0.3	0.2 ± 0.3	0.6 ± 0.3	1.8 ± 0.3
Abietic acid	ng/m³	0.2 ± 0.3	0.4 ± 0.3	1 ± 0.3	1 ± 0.3
Isopimaric acid	ng/m³	0 ± 0.3	1.3 ± 0.3	6.8 ± 0.6	1.7 ± 0.3
7-oxodehydroabietic acid	ng/m³	0.2 ± 0.3	0 ± 0.3	0.3 ± 0.3	1.1 ± 0.3
Heneicosanoic acid (c21)	ng/m³	0.3 ± 0.3	2.7 ± 0.3	3.9 ± 0.4	1.3 ± 0.3
Tricosanoic acid	ng/m³	0.7 ± 0.3	0.9 ± 0.3	0.5 ± 0.3	0.7 ± 0.3
Tetracosanoic acid (c24)	ng/m³	9.2 ± 2.4	5.7 ± 1.5	14.4 ± 3.6	7.1 ± 1.8

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Polars:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Cholesterol	ng/m³	4.5 ± 0.3	6 ± 0.4	12.5 ± 0.7	5.1 ± 0.4
b-sitosterol	ng/m³	0.4 ± 0.3	0.1 ± 0.3	0.2 ± 0.3	1 ± 0.3
Hexanoic acid (c6)	ng/m³	472.8 ± 115.9	612.7 ± 150.1	558 ± 136.7	698.5 ± 171.1
Heptanoic acid (c7)	ng/m³	393 ± 51.5	305.9 ± 40.3	315.3 ± 41.8	469.1 ± 62.0
Benzoic acid	ng/m³	92.3 ± 4.6	1310.8 ± 65.5	2749.6 ± 137.5	3393.3 ± 169.7
Octanoic acid (c8)	ng/m³	0 ± 0.3	28.4 ± 2.7	5.2 ± 0.6	165.6 ± 14.8
o-toluic	ng/m³	7 ± 0.5	7.6 ± 0.5	30.6 ± 1.7	251.5 ± 12.7
m-toluic	ng/m³	0 ± 0.3	4.1 ± 0.5	37.1 ± 3.0	437.7 ± 34.2
Nonanoic acid (c9)	ng/m³	200.6 ± 13.7	199.6 ± 13.7	190.1 ± 13.1	314.2 ± 21.5
p-toluic	ng/m³	0.1 ± 0.3	1.2 ± 0.3	16.4 ± 0.9	219.7 ± 11.1
Decanoic acid (c10)	ng/m³	73.3 ± 4.6	98.1 ± 6.3	56.3 ± 3.6	55.3 ± 3.7
Undecanoic acid (c11)	ng/m³	19.9 ± 1.1	33.6 ± 1.9	28.5 ± 1.7	53.7 ± 3.1
Dodecanoic (lauric) acid (c12)	ng/m³	8.4 ± 0.5	9.8 ± 0.6	0 ± 0.3	0 ± 0.3
Tridecanoic acid (c13)	ng/m³	22.9 ± 2.2	36.5 ± 3.5	36.3 ± 3.4	36.9 ± 3.4
Myristic acid (c14)	ng/m³	12 ± 0.7	9.5 ± 0.6	12.4 ± 0.7	7.5 ± 0.5
Pentadecanoic acid (c15)	ng/m³	10 ± 1.5	14.8 ± 1.6	26.9 ± 2.5	18.4 ± 1.8
Palmitic acid (c16)	ng/m³	89.1 ± 5	69.2 ± 3.9	133.7 ± 7.4	112.5 ± 6.3
Heptadecanoic acid (c17)	ng/m³	3.7 ± 0.5	2.5 ± 0.4	6.6 ± 0.7	2.9 ± 0.4
Oleic acid	ng/m³	6.8 ± 0.5	21.8 ± 1.2	54.5 ± 2.8	17.1 ± 1.1
Stearic acid (c18)	ng/m³	30.8 ± 1.7	42.5 ± 2.2	79.5 ± 4.1	65.6 ± 3.4
Nonadecanoic acid (c19)	ng/m³	7.1 ± 1.2	6.9 ± 1.2	0 ± 0.3	0.4 ± 0.3
Eicosanoic acid (c20)	ng/m³	1.6 ± 0.3	4.6 ± 0.4	4.9 ± 0.6	5.7 ± 0.5

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Hopane and Steranes:

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
17A(H),21B(H)-22,29,30-Trisnorhopane	ng/m³	0.1	0.6	0.3	0.7
17A(H),21B(H)-30-Norhopane	ng/m³	0.5	1.8 ± 0.1	1.1 ± 0.1	2.2 ± 0.1
17A(H),21B(H)-Hopane	ng/m³	0.4	1.1 ± 0.1	0.7	1.3 ± 0.1
17B(H),21A(H)-hopane	ng/m³	0.0	0.0	0.0	0.0
22S-17A(H),21B(H)-30-Homohopane	ng/m³	0.2	0.6	0.4	0.6
22R-17A(H),21B(H)-30-Homohopane	ng/m³	0.2	0.4 ± 0.1	0.3	0.8 ± 0.1
17B(H),21B(H)-Hopane	ng/m³	0.0	0.0	0.0	0.0
22S-17A(H),21B(H)-30,31-Bishomohopane	ng/m³	0.4 ± 0.1	0.5 ± 0.1	0.3 ± 0.1	0.7 ± 0.1
22R-17A(H),21B(H)-30,31-Bishomohopane	ng/m³	0.2	0.2	0.1	0.3
22S-17A(H),21B(H)-30,31,32-Trisomohopane	ng/m³	0.1	0.2	0.1	0.2
22R-17A(H),21B(H)-30,31,32-Trishomohopane	ng/m³	0.0	0.1	0.1	0.1
C27-20S5A(H),14A(H)-cholestane	ng/m³	0.0	0.0	0.1	0.0
C27-20R5A(H),14B(H)-cholestane	ng/m³	0.1	0.1	0.1	0.2
C27-20S5A(H),14B(H),17B(H)-cholestane	ng/m³	0.1	0.2	0.1	0.4
C27-20R5A(H),14A(H),17A(H)-cholestane & C29 -20S13B(H),17A(H)-dia	ng/m³	0.1	0.3	0.2	0.4
C28-20S5A(H),14A(H),17A(H)-ergostane	ng/m³	0.0	0.0	0.0	0.0
C28-20R5A(H),14B(H),17B(H)-ergostane	ng/m³	0.0	0.1	0.1	0.2
C28-20S5A(H),14B(H),17B(H)-ergostane	ng/m³	0.0	0.1	0.1	0.2
C28-20R5A(H),14A(H),17A(H)-ergostane	ng/m³	0.0	0.0	0.0	0.2
C29-20S5A(H),14A(H),17A(H)-stigmastane	ng/m³	0.0	0.2	0.1	0.2
C29-20R5A(H),14B(H),17B(H)-stigmastane	ng/m³	0.1	0.2	0.1	0.2
C29-20S5A(H),14B(H),17B(H)-stigmastane	ng/m³	0.0	0.1	0.1	0.2
C29-20R5A(H),14A(H),17A(H)-stigmastane	ng/m³	0.0	0.1	0.0	0.1

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Volatile Organic Compounds (VOC):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Acetylene	µg/m³	0.3	0.7	1.7 ± 0.1	9.3 ± 0.5
Ethene	µg/m³	0.4	4 ± 0.2	6.3 ± 0.3	54.1 ± 2.7
Ethane	µg/m³	31.4 ± 1.6	15.1 ± 0.8	10.9 ± 0.5	9.3 ± 0.5
Propene	µg/m³	0.2	2 ± 0.1	2.2 ± 0.1	20 ± 1
Propane	µg/m³	15.4 ± 0.8	4.8 ± 0.2	3.4 ± 0.2	3.8 ± 0.2
1,3-butadiene	µg/m³	0.1	0.2	0.1	0.0
1-butene	µg/m³	0.1	0.5	0.7	7 ± 0.4
c-2-butene	µg/m³	0.1	0.3	0.2	1 ± 0.1
Isobutylene	µg/m³	2.2 ± 0.3	2.2 ± 0.3	5.7 ± 0.7	9.8 ± 1.2
t-2-butene	µg/m³	0.2	1.1 ± 0.1	0.4	1.9 ± 0.1
n-butane	µg/m³	3.3 ± 0.2	1.7 ± 0.1	0.8	1.3 ± 0.1
Iso-butane	µg/m³	1.8 ± 0.2	0.7 ± 0.1	0.4	1.5 ± 0.1
Iso-pentane	µg/m³	1.1 ± 0.1	0.9	0.7	4.7 ± 0.2
n-pentane	µg/m³	1 ± 0.1	0.8 ± 0.1	0.6 ± 0.1	6.5 ± 0.7
1,2-butadiene	µg/m³	0.0	0.0	0.0	0.0
1-pentene	µg/m³	0.0	0.2	0.2	2.7 ± 0.1
2-methyl-1-butene	µg/m³	0.0	0.1	0.1	0.6
Isoprene	µg/m³	0.0	0.1	0.0	0.0
t-2-pentene	µg/m³	0.0	0.1	0.1	0.8
c-2-pentene	µg/m³	0.0	0.1	0.0	0.4
2-methyl-2-butene	µg/m³	0.0	0.1	0.1	0.5
2,2-dimethylbutane	µg/m³	0.0	0.0	0.0	0.1
Cyclopentene	µg/m³	0.0	0.1	0.1	0.8
Cyclopentane	µg/m³	0.0	0.0	0.0	0.3

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Volatile Organic Compounds (VOC):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
2,3-dimethylbutane	µg/m³	0.0	0.0	0.0	0.6 ± 0.1
2-methylpentane	µg/m³	0.3 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.9 ± 0.4
3-methylpentane	µg/m³	0.2	0.2	0.2	1.3 ± 0.1
2-methyl-1-pentene	µg/m³	0.0	0.2	0.1	2.5 ± 0.1
n-hexane	µg/m³	0.4	0.4	0.2	1.5 ± 0.1
t-2-hexene	µg/m³	0.0	0.1	0.0	0.4
c-2-hexene	µg/m³	0.0	0.0	0.0	0.2
1,3-hexadiene (trans)	µg/m³	0.0	0.0	0.0	0.0
Methylcyclopentane	µg/m³	0.2	0.3	0.1	1.3 ± 0.1
2,4-dimethylpentane	µg/m³	0.1	0.1	0.0	0.2
Benzene	µg/m³	0.5	1.1 ± 0.1	1.1 ± 0.1	11.2 ± 0.6
Cyclohexane	µg/m³	0.4	0.8	0.4	3.4 ± 0.2
2-methylhexane	µg/m³	0.0	0.0	0.0	0.0
2,3-dimethylpentane	µg/m³	0.0	0.1	0.0	0.0
Cyclohexene	µg/m³	0.1	0.1	0.1	1.3 ± 0.1
3-methylhexane	µg/m³	0.1	0.1	0.1	0.8
1,3-dimethylcyclopentane (cis)	µg/m³	0.0	0.0	0.1	0.3
1-heptene	µg/m³	0.1	0.2	0.1	2.6 ± 0.1
2,2,4-trimethylpentane	µg/m³	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	1.7 ± 0.1
n-heptane	µg/m³	0.1	0.1	0.2	1.4 ± 0.1
2,3-dimethyl-2-pentene	µg/m³	0.0	0.0	0.0	0.0
Methylcyclohexane	µg/m³	0.3	0.6	0.4	6.3 ± 0.3
2,3,4-trimethylpentane	µg/m³	0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1
Toluene	µg/m³	0.4	1.4 ± 0.1	0.8	8.9 ± 0.4

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Volatile Organic Compounds (VOC):

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
2-methylheptane	µg/m³	0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	1.4 ± 0.1
4-methylheptane	µg/m³	0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.5 ± 0.1
3-methylheptane	µg/m³	0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.8 ± 0.1
n-octane	µg/m³	0.2 ± 0.1	0.2 ± 0.1	0.4 ± 0.1	4.2 ± 0.2
Ethylbenzene	µg/m³	0.1	0.3	0.3	4.3 ± 0.2
m&p-xylene	µg/m³	0.2	0.5	0.4	7.1 ± 0.4
Styrene	µg/m³	0.0	0.1	0.0	0.2
o-xylene	µg/m³	0.1	0.3	0.2	3.3 ± 0.2
n-nonane	µg/m³	0.2 ± 0.1	0.5 ± 0.1	0.6 ± 0.1	8.8 ± 0.4
Isopropylbenzene	µg/m³	0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	1.2 ± 0.1
n-propylbenzene	µg/m³	0.1 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	3.1 ± 0.2
Alpha-pinene	µg/m³	1.8 ± 0.1	0.1 ± 0.1	0 ± 0.1	0.1 ± 0.1
3-ethyltoluene	µg/m³	0.1 ± 0.1	0.4 ± 0.1	0.4 ± 0.1	8 ± 0.4
4-ethyltoluene	µg/m³	0.1 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	3.3 ± 0.2
1,3,5-trimethylbenzene	µg/m³	0.1 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	3.1 ± 0.2
o-ethyltoluene	µg/m³	0.1 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	2.7 ± 0.1
n-decane	µg/m³	0.4 ± 0.1	1.5 ± 0.1	2.1 ± 0.1	29.3 ± 1.5
1,2,3-trimethylbenzene	µg/m³	0.1 ± 0.1	0.3 ± 0.1	0.2 ± 0.1	4.2 ± 0.2
Indan	µg/m³	0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	1 ± 0.1
1,3-diethylbenzene	µg/m³	0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	1.9 ± 0.1
1,4-diethylbenzene	µg/m³	0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	2.1 ± 0.1
n-butylbenzene	µg/m³	0.2 ± 0.1	0.4 ± 0.1	0.3 ± 0.1	3.6 ± 0.4
n-undecane		0 ± 0.1	0 ± 0.1	0 ± 0.1	0 ± 0.1

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Overall Average - Individual Average Characterization Data Tables

Exposure Atmosphere Composition	Units	Control	Low	Mid	High
Dekati Particle Mass-Chamber Inlet	µg/m³	NA	NA	NA	NA
Dekati Particle Mass-Inside Chamber	µg/m³	0.3 ± 0.2	0.2 ± 0.2	0.9 ± 0.6	6.3 ± 4
Filter Sample - Chamber Inlet	µg/m³	NA	2.5 ± 1.6	2.7 ± 1.2	7.8 ± 2.8
Filter Sample - Inside Chamber	µg/m³	16.9 ± 6.7	23.3 ± 11.4	20 ± 5.4	27.3 ± 6.2
Particle Mass-FMPS	µg/m³	0.2 ± 0.2	1.1 ± 0.9	2 ± 1.7	5.3 ± 2.9
Particle Count -FMPS	Particle/cm³	17136 ± 23420.5	215225.5 ± 412548.9	678184 ± 1247908.6	828814.3 ± 1041924.8
NMAD (GSD) - FMPS	nm	23 (1.8) ± 8.8 (0.5)	16.6 (1.5) ± 6.3 (0.2)	15.4 (1.5) ± 5.5 (0.2)	18.6 (1.6) ± 4.4 (0.1)
MMAD (GSD) - FMPS	nm	196.8 (1.7) ± 149 (0.2)	181.8 (2.7) ± 113.4 (0.6)	81.2 (2.9) ± 32 (0.8)	41.6 (2.2) ± 4.1 (0.5)
Nitrogen Oxide (NO)	µg/m³ (ppm)	2 ± 3 (0.001 ± 0.002)	274.3 ± 186.3 (0.3 ± 0.2)	1376.6 ± 390.4 (1.3 ± 0.4)	6878.6 ± 2591.8 (6.6 ± 2.4)
Nitrogen Dioxide (NO_2)	µg/m³ (ppm)	2.6 ± 5.2 (0.002 ± 0.004)	159.5 ± 16.6 (0.1 ± 0.01)	1421.5 ± 83.7 (0.9 ± 0.05)	6873.2 ± 489.4 (4.4 ± 0.3)
Carbon Monoxide (CO)	µg/m³ (ppm)	895.8 ± 883.2 (0.9 ± 0.9)	1042.2 ± 510.1 (1.1 ± 0.5)	1787.1 ± 444 (1.9 ± 0.5)	6167.6 ± 2445.4 (6.4 ± 2.6)
Carbon Dioxide (CO_2)	mg/m³ (ppm)	2110.6 ± 800.1 (1402.2 ± 531.7)	2695.7 ± 1175.2 (1790.9 ± 780.9)	3599.1 ± 497.8 (2391.2 ± 330.8)	7215.6 ± 1456.4 (4794.1 ± 967.5)
Sulfur Dioxide (SO_2)	µg/m³(ppb)	4.9 ± 1 (2.2 ± 0.4)	6.6 ± 1.5 (2.9 ± 0.7)	20.5 ± 6.2 (9.1 ± 2.7)	69.6 ± 28.6 (30.8 ± 12.6)
Elemental Carbon	µg/m³	0.4 ± 0.4	1.2 ± 1.2	0.4 ± 0.4	1.2 ± 1
Organic Carbon	µg/m³	4.5 ± 1.4	6.6 ± 1.4	4.8 ± 1.9	5.7 ± 2.4
Ammonium	ng/m³	31.3 ± 31.3	57.2 ± 29	203.2 ± 150.6	1312.2 ± 450.2
Sulfate	ng/m³	101.6 ± 26	193.1 ± 153.1	644.8 ± 405.5	2121.1 ± 968.2
Nitrate	ng/m³	18.6 ± 16.7	181.2 ± 195.9	220.2 ± 73.9	2087.3 ± 747
Elements (Metals)	ng/m³	461.3 ± 208.5	567.9 ± 224	661 ± 302.1	811.5 ± 336.3
Alkanes	µg/m³	2.8 ± 0.5	4.7 ± 1.9	8.6 ± 2.8	26.6 ± 9.3
Carbonyl	µg/m³	53.8 ± 12.1	71.2 ± 40.2	21.4 ± 5.1	1 ± 1.5
Polyaromatic Hydrocarbon (PAH)	µg/m³	0.8 ± 0.5	1.1 ± 0.4	1.9 ± 0.7	4.7 ± 1.6
Nitro-PAH	ng/m³	0.4 ± 0.2	0.8 ± 0.4	1.6 ± 0.5	8 ± 2.5
Polars (Acids)	µg/m³	3.2 ± 1.2	4.1 ± 1.6	6.9 ± 2.9	16 ± 6
Hopane and Steranes	ng/m³	2 ± 0.7	5.1 ± 3.5	2.5 ± 1.6	3.7 ± 3.9
Volatile Organic Compounds (VOC)	µg/m³	33.5 ± 21.3	50.3 ± 31.3	44.2 ± 15.3	148.9 ± 96.9