Characterization of Off-Road Diesel Emissions of Criteria Pollutants
CY2005 Annual Report, WP-1336

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EXECUTIVE SUMMARY

The main goal of this project is to identify and fill knowledge gaps concerning emissions and activities of non-road military diesel engines. This requires the development of new measurement methods that quantify a larger number of chemical compounds and particle sizes for fuels and operating cycles that are not well represented by engine certification tests.

Specific project objectives are: 1) Develop, test, and apply new methods for quantifying non-road emissions that more efficiently and realistically represent actual operations than engine dynamometer certification tests do; 2) develop source-, activity-, and fuel-specific emission rate estimates for representative Department of Defense (DoD) mobile and stationary diesel equipment, most of which is not used on public roadways. Emitted pollutants include carbon monoxide (CO), oxides of nitrogen (NOx), volatile organic compounds (VOC), particulate matter (PM), sulfur dioxide, (SO2), and ammonia (NH3). Chemical source profiles for total PM and VOC are also quantified; and 3) integrate results into emissions modeling databases and software that permit quick and efficient total diesel emissions for a typical military base and provide the results to appropriate agencies in Consolidated Emission Reporting (CER) formats.

These objectives are accomplished by applying four different measurement methods to obtain emissions and chemical composition: 1) mobile emissions laboratory that emulates certification methods specified by the Code of Federal Regulations; 2) cross-plume sensor that measures infrared absorption and ultraviolet backscatter across exhaust plumes; 3) in-plume sensor that extracts small quantities of exhaust for analysis by several real-time and off-line instruments; and 4) compact and portable on-board monitors that measure exhaust from a single in-use vehicle. Methods 2 through 4 lend themselves to quantifying real-world emissions that often differ substantially from those of certification tests.

The project began on May 1, 2003, and is scheduled to continue for four years. CY2005 saw the following accomplishments:

- The literature survey and review continued, with more than 500 reports and publications identified and surveyed during 2004. These related to diesel exhaust emissions tests, test methods, diesel fuels and their effects on emissions, mobile laboratories, remote sensors, and on-board monitors. Only 60 new references were identified for 2005, down from the 150 obtained in 2004. This indicates a maturing of research in this area. Research interest in diesel emissions is possibly declining owing to the onset of U.S. standards for on-road and non-road diesel emissions. Ultra-fine particle emissions continue to be of great interest.

- Mobile emissions laboratory measured emissions from stationary diesel engines at military facilities. Tests focused on comparing emissions from a variety of fuels including JP-8, Ultra-low sulfur diesel, biodiesel, and ethanol-diesel.

- The cross-plume PM monitoring system was improved the addition of infrared sensing for e. This lowered the PM detection limit be an order of magnitude. A more accurate calibration method was perfected using a flexible duct from which extraneous gases can be purged. Software for data acquisition, visualization, and data analysis was improved to more efficiently and accurately the large amount of data. The cross-plume system was tested on gasoline vehicles and more than 200 diesel buses using regular diesel and biodiesel fuels for hot stabilized operation and cold...
starts. Results showed that biodiesel did not improve, and sometimes degraded, emission rates for PM and NO\textsubscript{x}. In addition to providing emission factor distributions for vehicle operation in real-world conditions, these tests allowed for testing and improvement of the cross-plume system.

- The in-plume monitoring system was further upgraded and procedures were perfected. The system was deployed at Camp Pendleton to measure emissions from a variety of 10 kW, 30 kW, 60 kW, and 100 kW generators.

- Four commercially available portable emission measurement systems were evaluated against the Federal Reference Method for emissions testing at CE-CERT. Comparisons were made for instrument flow, CO\textsubscript{2}, CO, NO\textsubscript{x}, PM, and THC concentrations. Good agreement was generally observed for CO\textsubscript{2} and NO\textsubscript{x}. When measured by a PEM, PM was generally biased lower and THC was biased higher than the FRM.
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1. INTRODUCTION

1.1 Background

Compression ignition (CI) diesel engines are in widespread use for non-road applications. Non-road refers to vehicle and engine use beyond normal operation on public, paved roads. Typical non-road mobile sources include construction equipment, aggregate haulers, farm implements, locomotives, and marine vessels. Typical non-mobile diesel engine uses include back-up generators (BUGs), pumps, and materials and cargo handling equipment. The U.S. military uses diesel vehicles and engines for all of these purposes and others related to base maintenance and troop training. Most non-road applications are exempt from highway fuel taxes, on-road fuel formulation requirements, and after-engine exhaust treatment, although regulations have been promulgated (U.S. EPA, 2003a, 2003b) to bring non-road diesel emissions into harmony with on-road diesel requirements (U.S. EPA, 2001).

Most non-road diesel emission rates and inventories are extrapolated from limited tests on similar engines by simulating on-road driving conditions and fuels. Test methods and cycles are intended to certify emissions from different engine designs on a common basis. These tests do not represent real-world emissions for on-road, let alone non-road engine use. Better information is needed to estimate emissions from stationary and mobile non-road diesel engines used on military bases.

1.2 Project Goals and Objectives

The main goal of this project is to identify and fill knowledge gaps concerning emissions and activities of non-road military diesel engines. This requires the development of new measurement methods that quantify a larger number of chemical compounds and particle sizes for fuels and operating cycles that are not well represented by engine certification tests.

Specific project objectives are:

- Develop, test, and apply new methods for quantifying non-road emissions that more efficiently and realistically represent actual operations than engine dynamometer certification tests do.
- Develop source-, activity-, and fuel-specific emission rate estimates for representative Department of Defense (DoD) mobile and stationary diesel equipment, most of which is not used on public roadways. Emitted pollutants include carbon monoxide (CO), oxides of nitrogen (NO\textsubscript{X}), volatile organic compounds (VOC), particulate matter (PM), sulfur dioxide, (SO\textsubscript{2}), and ammonia (NH\textsubscript{3}). Chemical source profiles for total PM and VOC are also quantified.
- Integrate results into emissions modeling databases and software that permit quick and efficient total diesel emissions for a typical military base and provide the results to appropriate agencies in Consolidated Emission Reporting (CER) formats.

This is the third annual report for this project. Its objectives are to:

- Summarize and update work performed in previous years (Watson et al., 2003, 2004).
- Consolidate and share information among project investigators, stakeholders, and sponsors.
• Document progress on project tasks.
• Identify potential problems and solutions.

1.3 Overview of Annual Report

Section 2 describes updates to the literature survey. Section 3 summarizes the activities, fuel, and emissions data base. Section 4 discusses progress on the testing methods. Section 5 describes tests performed on diesel emissions in CY2005. Section 6 presents how the emission factors collected in this study will be integrated into EPA emission factor models. Section 7 summarizes accomplishments and management tasks performed during CY2004. Bibliographic references are provided in Section 8.
2. LITERATURE REVIEW

More than 1360 citations relating to diesel engine emissions, diesel fuels and biofuels, and emissions testing methods have been identified and surveyed. Only sixty of these were added during 2005, further indicating the maturation of diesel emissions research. Several useful findings are noted here.

Conaway et al. (2005) tested gasoline and diesel samples from San Francisco Bay area refineries and service stations for mercury (Hg), finding Hg concentrations ranging from 0.05-0.34 ng/g in 19 diesel tests. There was little evidence for mercury enrichment or contamination into these fuels from the refining process. This was the first study to test Hg for real-world use, and it is important owing to impending Hg emissions regulations for coal-fired power stations and other sources. Ambient Hg levels are not considered hazardous to human health through inhalation, but these deposit to waterways and accumulate in fish through which they can become a health hazard through human ingestion. This study confirms that Hg was not an important variable to be measured in this study.

Johnson et al. (2005) applied their Mobile Emissions Laboratory as a chase vehicle on interstate highways in the Minneapolis metropolitan area. Using the difference between relative volumes of heavy duty diesel and light duty gasoline vehicles on weekdays and weekends, they estimated contributions from each type of emitter. Contributions to ultra fine particles emissions were $1.34 \pm 0.2 \times 10^{16}$ particles/kg of fuel for diesel exhaust and $7.1 \pm 1.6 \times 10^{15}$ particles/kg for gasoline engines. Heavy duty diesel engines produced much higher absolute emissions owing to their higher fuel consumption per distance traveled. This work represented on-road summer conditions, and it is believed that gasoline emissions of ultra fine particles might be higher for cold start and colder ambient conditions.

Lu et al. (2005) reported some of the few emissions measurements on backup generators similar to those being tested in this project. They applied a stationary source stack test, EPA method 5, and the NIOSH Method 5040 to measure organic carbon (OC) and elemental carbon (EC). OC and EC are operationally defined by the method, and the NIOSH workplace method differs from the methods commonly used for ambient air (Watson et al., 2005). The EC fraction of total PM emissions increased with increasing load from 21% at no load to 84% at 75 kW for low sulfur fuel, while the OC fraction decreased from 62% to 9%. OC ranged from 77% to 19% for the high sulfur fuel. Non-carbonaceous materials ranged from 27% to 18% for high sulfur fuel and 17% to 7% for low sulfur fuel.

Mohr et al. (2005) compared sixteen particle mass measurement systems for emissions from a diesel engine with a particle filter to investigate their feasibility for particle characterization for the low emission levels expected from new technology engines, fuels, and after-engine treatments. Instruments tested included filters, laser-induced incandescence, photoacoustic detection, photoelectric charging, combined inertial and mobility sizing, opacity, condensation particle counters, a diffusion battery, a diffusion charger, ELPI, and light scattering. Several of these same techniques are used with the in-plume monitor and showed good performance and gave comparable results. For all time-resolved advanced methods, poor correlation with the regulated filter method was observed, but most of them showed good correlation with the EC concentration.

Shah et al. (2005) applied the CE-CERT MEL to quantify emission rates of polycyclic aromatic hydrocarbon (PAH) and n-alkane compounds from on-road emissions of nine heavy-
duty diesels following the ARB’s Four Phase Cycle. Large differences were seen in emission rates over the different phases of the cycle. Creep phase fleet average emission rates (mg/mi) of PAHs and n-alkanes were approximately an order of magnitude higher than those for the Cruise phase. PAH and n-alkane source profiles remained relatively constant for the different modes of operation. Variability of source profiles within the vehicle fleet exceeded the variability due to different operating modes.
3. EMISSIONS DATA BASES AND MODELS

Kemme et al. (2004) completed a data base and documentation for engines, uses, and fuels used by the Army and Marines as part of this project, and this was summarized by Watson et al. (2004). A brief overview is presented here for completeness, with reference to the detailed reports for greater detail. It was found that data was insufficient to include information from the Navy and Air Force. The Microsoft Access data base contains information about fuels, equipment, engines, inventories, usage, and fuel consumption that was obtained from many disparate sources. The database includes an interface that allows users to view data in onscreen forms or analyze data using built in reports. Data analysis has shown that the top ten fuel consuming engines account for over 90% of fuel usage for the U.S. Army and over 80% for the U.S. Marine Corps (USMC).

DOD non-road diesel powered equipment includes combat, tactical, and ground support equipment found in the Army, Marine Corps, Air Force, and Navy, including: 1) wheeled vehicles, 2) tracked vehicles, 3) generator sets, 4) power plants, 6) construction equipment, and 6) material handling equipment. The EPA definition of off-road diesel powered equipment excludes equipment that will only be used in a single location. Equipment used in a single location is categorized as a stationary source. This excludes power plants, which are of fixed location. All of the other equipment is movable, even though it does not necessarily move while it is operating.

Wheeled vehicles, tracked vehicles, and generators make up most of the equipment found in the database. Engine displacement and horsepower data were collected for each engine with a unique manufacturer and model number.

The top five ranked engines account for over 50% of the fuel usage, the top ten almost 75%, and the top 20 almost 89%. HMMWs; tanks (M1A1, M1A2); trucks (HEMTT, 5 ton, family of medium tactical vehicles (FMTV, 10 ton), the amphibious assault vehicle (AAV), the logistics vehicle system (LVS), and the Bradley fighting vehicle (M2A2, M3A2) used almost 80% of the fuel.

The order of the top six engines remained the same from CY2001 through CY2003, and the total fuel consumption for these six engines accounted for almost the same percentage of consumption. The engine that showed the largest increase in fuel consumption was the Caterpillar 3126B. This increase is due to the increased deployment and usage of the Stryker vehicle between FY2001 and FY2003. Engines employed in generators also showed increases over this time period as the engines powering 10 kW, 30 kW, and 60 kW generators all had larger inventories and fuel consumptions. Engines showing decreases included the Cummins Engine VT 400 which powers the USMC AAV, the Cummins Engine NTC 400 which powers Army 10 ton trucks, and the John Deere 6466 6.8L which powers a USMC tractor/loader.

A similarity between the services is that the top ten engines account for a large percentage of the overall fuel usage with overall percentages of 92.9% and 84.5% for the Army and USMC respectively. The M1 tank, powered by the Allied Signal AGT 1500 turbine engine, accounts for the 2nd most percentage of fuel usage for both services. One difference between the services is the larger amount of overall fuel usage by the Army. Emissions Data Base

Emissions data from tests performed by different measurement methods used in this and other projects must be compiled on a common basis and added to the data base structure. This
presents some difficulty because the test methods used in this project are so different. For this reason, a basic emissions data set is needed that provides the quantities measured for specific operating modes or test cycles in terms of the total amount emitted. Each test result must also include the duration over which the sample was averaged for normalization between different tests. By including the CO$_2$ emission rate along with the other emissions, a fuel-based emission factor can be established.
4. PROJECT TEST METHODS AND PROCEDURES

Advances were made in each of the emissions measurement methods developed for this project: 1) the mobile emissions laboratory (MEL), 2) the In-Plume Emissions Testing System (IPETS), 3) the Cross-Plume Vehicle Remote Sensor System (VERSS); and 4) the on-board emissions monitors. Comparisons among the emissions rates derived from several of these were undertaken.

4.1 Mobile Emissions Laboratory (MEL) System

The UCR mobile emissions laboratory (MEL) is complete and operational (Cocker et al., 2004, Shah et al., 2004) with few modifications from the 2004 Annual Report (Watson et al., 2004). A schematic is shown in Figure 4-1 with monitoring equipment detailed in Table 4.1-1. The MEL samples all of the exhaust from an engine and dilutes it under constant volume sampling (CVS) conditions prior to sampling the emissions stream.

Figure 4-1. Schematic of the UCR Mobile Emissions Laboratory (MEL).
Table 4-1. Mobile laboratory test methods and analysis of exhaust emissions.

<table>
<thead>
<tr>
<th>Instrument/Method</th>
<th>Measurement</th>
<th>Sample Duration</th>
<th>Lower Quantifiable Limit (expressed in terms of fundamental measurement)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pierburg NDIR</td>
<td>CO₂, CO</td>
<td>1 s</td>
<td>50 - 500 ppm</td>
</tr>
<tr>
<td>California Analytical Instruments/Flame Ionization Detection</td>
<td>THC, CH₄</td>
<td>1 s</td>
<td>10 - 30 ppm</td>
</tr>
<tr>
<td>California Analytical Instruments/Chemiluminescence</td>
<td>NO, NO₂</td>
<td>1 s</td>
<td>10 ppm</td>
</tr>
<tr>
<td>Various/Filter*</td>
<td>PM₂.₅ Mass and Chemistry</td>
<td>0.25 - 2 hrs</td>
<td>Various</td>
</tr>
<tr>
<td>Tedlar Bag/GC-FID</td>
<td>VOC's (C₂ – C₁₂)</td>
<td>0.25 - 2 hrs</td>
<td>10 ppb C</td>
</tr>
<tr>
<td>DNPH Cartridges/Shimadzu HPLC/UV</td>
<td>Aldehydes and Ketones</td>
<td>0.25 - 2 hrs</td>
<td>0.02 µg/mL</td>
</tr>
</tbody>
</table>

*Includes Teflon and quartz media for mass, metals, ions, elemental/organic carbon and PAHs by GC/MS on extracts from filters.

4.2 In-Plume Emissions Testing System (IPETS)

The IPETS system is a combination of gaseous and particle measurement instruments that are configured to measure the composition of engine exhaust mixed with ambient air. A single inlet is held close to the exhaust source while the engine is operating. Emission factors are calculated from the ratio of the pollutant of interest to the carbon dioxide concentration (above ambient background) in the plume. This is related to the carbon content of the fuel to obtain the emission factor (e.g., mg pollutant/kg fuel).

Standard Operating Procedures (SOPs) for all instrumentation and the overall operation of the In-Plume system have been prepared and are included in the appendix of this report. These SOPs were evaluated with new operators at Camp Pendleton during the November generator set experiments.

Figure 4-2 presents a schematic diagram for the in-plume system with an updated specification of measurements in Table 4-2. The system is installed onto carts and mounted inside a cargo van. This versatile configuration permits sampling from sources that can be accessed by a vehicle (i.e. generators and mobile sources) as well as sources with more restricted access (i.e. roof top vents and stacks).
Figure 4-2. Schematic diagram of the in-plume monitoring system.
Table 4-2. Instrumentation for the in-plume monitoring system.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Measurement</th>
<th>Method</th>
<th>Response Time(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Midac I-Series FTIR</td>
<td>Molecular gas species concentration</td>
<td>Dispersive IR</td>
<td>1.5</td>
</tr>
<tr>
<td>Dekati Electronic Low Pressure Impactor (10 L/min)</td>
<td>Aerodynamic number size distribution of particles</td>
<td>Current dissipation arising from deposition of charged particles to impactor substrates</td>
<td>5</td>
</tr>
<tr>
<td>TSI DustTrak</td>
<td>Particle mass</td>
<td>780 nm laser light scattering of particle stream at 90 degrees</td>
<td>1</td>
</tr>
<tr>
<td>Nuclepore filter sampler</td>
<td>Mass and chemical composition of particles and gases</td>
<td>Collection and analysis of exposed filters</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>TSI 4043 Mass Flow Meters</td>
<td>Mass flow through filter</td>
<td>Hot wire anemometer</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Photoacoustic Instrument</td>
<td>Light absorbing carbon</td>
<td></td>
<td>&lt;1</td>
</tr>
<tr>
<td>GRIMM fine aerosol spectrometer</td>
<td>Particle size distribution</td>
<td>Light scattering</td>
<td>6</td>
</tr>
<tr>
<td>GRIMM coarse aerosol spectrometer</td>
<td>Particle size distribution</td>
<td>Light scattering</td>
<td>6</td>
</tr>
<tr>
<td>Li-Cor 840 CO₂/H₂O gas spectrometer</td>
<td>CO₂ (parts per million) and H₂O (parts per thousand)</td>
<td>NDIR (non-disperse infrared)</td>
<td>1</td>
</tr>
</tbody>
</table>

4.3 Cross-Plume Vehicle Remote Sensing System (VERSS)

The main work on the cross-plume sensor during the reporting period involved development of an infrared gaseous remote sensor for integration with the particulate matter remote sensor as described below. The cross-plume system is a vehicle remote sensing system (VERSS) that initially consisted of a commercial infrared cross-plume sensor for the measurement of gaseous emission factors (RSD 3000) and the DRI ultraviolet lidar and transmissometer (Moosmüller et al., 2003) for the measurement of PM emission factors. Due to complications with integrating the mechanical, optical, electrical, and software components of these two systems, an infrared (IR) system for the cross-plume sensing of CO₂, CO, and HC concentrations is integrated with the UV PM backscatter sensor.

The integrated system is based on a miniature broadband blackbody IR emitter (Cal Source SA1037-5M2) operating at a temperature of 1170 K. This emitter is enclosed in a TO-5 semiconductor can with internal parabolic reflector to provide near collimated and uniform IR output. The blackbody IR emitter is heated to its operating temperature of 1170 K with 2.1 W of electrical power. The emitted IR radiation is time and wavelength modulated with a wavelength-selective chopper (filter wheel) rotating at 50 Hz (i.e., 3000 rpm). The chopper wheel includes twenty 0.5” diameter wavelength selective filters. There are five sequences of four filters each, with each sequence consisting of one filter at a wavelength of 4.3 μm for the measurement of CO₂, one filter at 4.6 μm for the measurement of CO, one filter at 3.3 μm for the measurement of...
HC, and one reference filter (Ref) at 3.9 μm to normalize for wavelength independent IR extinction (Figure 4-3). As the chopper wheel rotates at 50 Hz, five transmissions of the wavelength sequence CO₂, CO, HC, and Ref occur per revolution, allowing repetitive measurements of gaseous concentrations at 250 Hz. The wavelength modulated IR radiation is transmitted through a beam splitter, further collimated with a 2” diameter, off-axis, parabolic mirror and transmitted through an internal calibration cell followed by transmission through the measurement volume extending across the vehicle path (Figure 4-3). On the opposite side of the vehicle path, the IR radiation is reflected back towards the transmitter with a 2.5” diameter corner cube used as retro-reflector. The retro-reflected light is focused by the off-axis, parabolic mirror onto a Peltier-cooled, lead-selenide (PbSe) detector (Cal Sensors BXT1-28T) (Figure 4-3). This detector produces a voltage signal proportional to the incident IR power that is shown in Figure 4-4 for one filter sequence. The average gaseous concentrations across the measurement path are derived from the detector signals as described below:

4.3.1 Measuring Gas Concentrations with the IR Cross-Plume System

Extinction and absorption processes can be described by Beer’s law if the absorption coefficient α is constant within the time, wavelength, and area that the measurement integrates over. In this case the transmission is integrated over relatively large wavelength intervals. While, the extinction due to particles stays fairly constant over these intervals, those of gases may not. Therefore, gaseous extinction coefficients are not necessarily proportional to gaseous concentrations and absorption path lengths. Nevertheless, the change of optical power due to extinction can still be written to look like Beer’s law

\[ P_i = P_{0,i} \exp\left[-\alpha_{p,i}x\right]\exp\left[-\alpha_{g,i}x\right], \]  

where \( P_i \) is the optical power measured by the detector after the measurement path, \( P_{0,i} \) the generally unknown optical power before the measurement path, \( \alpha_{p,i} \) and \( \alpha_{g,i} \) the particle and gaseous extinction coefficient (dimension of inverse distance) over the wavelength range \( i \) averaged over the absorption path length \( x \).

For the reference channel, gaseous absorption is negligible simplifying the equation to

\[ P_{ref} = P_{0,ref} \exp\left[-\alpha_{p,ref}x\right], \]  

where the subscript \( \text{ref} \) indicates the wavelength band of the reference channel. To measure the concentration of a gas \( i \), the ratio of eq. 1a and 1b may be written as

\[ \frac{P_{ref}}{P_i} = \frac{P_{0,ref}}{P_{0,i}} \frac{\exp\left[-\alpha_{p,\text{ref}}x\right]}{\exp\left[-\alpha_{p,i}x\right]} \exp\left[\alpha_{g,i}x\right]. \]  

The ratio \( \frac{P_{0,ref}}{P_{0,i}} \) is constant but unknown and can be replaced by a constant \( k \).

\[ k = \frac{P_{0,ref}}{P_{0,i}} \]  

Under the assumption that the particulate extinction \( \alpha_p \) is wavelength independent, and eq. 2a simplifies to

\[ \frac{P_{ref}}{P_i} = k \exp\left[\alpha_{g,i}x\right]. \]
The gaseous absorption coefficient $\alpha_{g_i}$ can be replaced with the product of absorption mass efficiency $E_{g_i}$ and mass concentration $c_{g_i}$ as

$$\alpha_{g_i} = E_{g_i} c_{g_i}. \quad (4-6)$$

If Beer’s law doesn’t apply, the absorption mass efficiency $E_{g_i}$ is not a constant but a function of the concentration depth $c_{g_i} x$. In any case the ratio $P_{ref}/P_i$ can be written as

$$\frac{P_{ref}}{P_i} = k \exp[E_{g_i} c_{g_i} x]. \quad (4-7)$$

Taking the natural logarithm of this equation, the concentration $c_{g_i}$ of gas $i$ can be obtained as

$$c_{g_i} = \frac{1}{E_{g_i} x} \ln \left[ \frac{1}{k} \frac{P_{ref}}{P_i} \right]. \quad (4-8)$$

### 4.3.2 Calibration of the IR Cross-Plume System

To obtain the concentration $c_{g_i}$ of gas $i$ from a measurement of $P_{ref}/P_i$ and eq. 4-8, knowledge of the constants $x$ and $k$ and of the function (or constant) $E_{g_i}$ is required. The absorption path length $x$ can be directly measured and the other unknowns can be obtained through calibration of the instrument as described below.

Taking the natural logarithm of eq. 4-8 yields

$$\ln \left[ \frac{P_{ref}}{P_i} \right] = \ln[k] + E_{g_i} c_{g_i} x, \quad (4.3-3)$$

which makes it possible to calibrate the measurement. For this calibration, the gaseous concentration depth, that is the product of concentration $c_{g_i}$ of gas $i$ and of the absorption path length $x$, is varied by introducing different concentrations of gas $i$ into the calibration cell. Figure 4.3-3 shows a hypothetical example of the measured $\ln[P_{ref}/P_i]$ as function of $c_{g_i} x$. If Beer’s law applies (i.e., $E_{g_i} =$ const), $\ln[P_{ref}/P_i]$ is a linear function of $c_{g_i} x$ with a zero offset of $\ln[k]$ and a slope of $E_{g_i}$ (see fig. 1). In this case (i.e., $E_{g_i} =$ const), the previously unknown constants can be determined by linear regression. In the more common case that the gaseous absorption is inhomogeneous over the broadband wavelength range used for the measurement, Beer’s law does not apply, and the function $E_{g_i}$ must be determined by fitting an empirical function to the experimental data. Once the constants and potentially the function $E_{g_i}$ have been determined through the calibration process, the average gas concentrations over the absorption path can be calculated from the measurements of $P_{ref}/P_i$ using eq. 3.3-2f.
Figure 4-3. Schematic diagram of the cross-plume system.

Figure 4-4. Detector signal for one filter sequence.
From a regulatory perspective, portable emission measurement systems (PEMS) can be used to determine if in-use emissions comply with regulations and to carry out emission measurements for inventory models. Hence there is widespread interest and importance in quantifying both the accuracy and precision of commercially available PEMS. During 2005, we compared the emissions measured with four commercially available PEMS to the emissions measured with federal reference methods (FRM) that are incorporated into the University of California at Riverside’s (UCR’s) heavy-duty mobile emissions laboratory (MEL). The four systems were:

1) Clean Air Technologies, Inc.'s (CATI) Montana system that measures gaseous pollutants (NO\textsubscript{x}, THC, CO and CO\textsubscript{2}) and infers PM mass emissions by laser light scattering.
2) Engine, Fuels and Emissions Engineering's, RAVEM system which measures gaseous pollutants (NO\textsubscript{x}, THC, CO and CO\textsubscript{2}) and quantifies PM using conventional filter-media.
3) Horiba's OBS-2000 series system that measures gaseous pollutants (THC, CO, NO\textsubscript{x}, and CO\textsubscript{2} emissions).
4) Sensors, Inc.'s Semtech D system that measures gaseous pollutants (NO, NO\textsubscript{2}, THC, CO and CO\textsubscript{2}).

During the testing all PEMS were simultaneously attached to the exhaust of a CAT 3406C engine that powered a backup generator (BUG). This size engine is similar to that used in Class 8 vehicles. Simultaneous connections allowed all PEMS to sample the same exhaust as the FRM so errors due to sample variation were eliminated. Exhaust emissions were measured seven times at 5%, 25%, 65%, and 100% load to provide the best estimate of accuracy and precision.
The selected range of loads allowed a comparison of concentrations representative of levels found over a wide operating range of a diesel engine.

Results for the basic measurements, concentration and flow rate were reported as a percentage of the FRM. Other figures in the executive summary compare the calculated grams per hour for the PEMS with the FRM. Note that results for the emissions in grams per hour use the independent measurements of mass flow and concentration so errors in either flow or concentration will carry through into the calculated mass emission rate. Further information on the results on a gram per horsepower-hour basis is also provided in the main body of the report. Figure 4-6 shows comparative emission rates for CO\textsubscript{2} and NO\textsubscript{x} for the PEMS and the FRM. Negative (positive) values indicate the PEMS under (over) reported relative to the FRM.

The agreement for CO\textsubscript{2} was relatively good for PEMS1, 2, and 4, with PEMS4 having the highest overall difference, about 10%. The agreement of PEMS3 was good at the highest load and flow rates, but the difference was about 50% at the lowest load. The PEMS3 manufacturer found a failed component that caused the errors at the low flow rates.

NO\textsubscript{x} values showed agreement within ~10% or better for PEMS2 and 4 with the FRM. PEMS3 values showed good agreement at high loads, with larger errors at the lowest load. For PEMS3, the NO\textsubscript{x}/CO\textsubscript{2} ratios, which eliminate the effects of flow measurement, were within 10% of those measured by the FRM for all load points. PEMS1 values were 12% to 30% higher with PEMS1. Some of the differences in NO\textsubscript{x} emissions for the PEMS1 are related to the omitted humidity correction (~10%) and a bias of about the same magnitude observed with the calibration gases, since the flow rates show good correlation with the FRM.

Three manufacturers - PEMS1, PEMS2, and PEMS4 - reported the total hydrocarbons (THC) and resultant values were significantly different relative to the FRM, as shown in Figure ES-2. It should be noted that the absolute THC values overall are low, even in comparisons with the upcoming proposed NTE standards. Since PEMS1, 2 and 4 had accurate flow measurements, the source of the difference must be in the measured concentration. The manufacturer of PEMS2 said the values in the raw gas were outside the range the instrument design.

Two manufacturers, PEMS1 and PEMS3, measured the particulate matter (PM). For PEMS1 results were significantly lower than the FRM at all ranges. For PEMS3 values were within ~20% of the FRM at higher loads, with a larger deviation at the lower loads. For PEMS3,
the PM/CO₂ ratios for the 5 and 25% load points were 22-25% lower than those measured by the FRM.

In addition to the testing with the backup generator, comparative emissions testing between FRM and PEMS was conducted at the ARB heavy-duty vehicle chassis dynamometer facility in Los Angeles using a truck and transient cycles. The truck was a 1993 model year Kenworth T600 truck equipped with a 2003, 475 hp Caterpillar C-15 ACERT engine certified to the 2.5 g/bhp-hr NOₓ + NMHC and 0.1 g/bhp-hr PM standards. The J1939 signal was obtained from the vehicle to determine the brake horsepower for each of the test runs.

A total of four test cycles were used during testing designed to represent both steady state and transient conditions and to provide a range of NTE events. The four test cycles used during testing were as follows:

1) Three-mode steady-state NTE test cycle run.
2) Stepped NTE test cycle
3) The Urban Dynamometer Driving Schedule (UDDS)
4) The 50-mph Cruise mode from the ARB 5-mode HHDDT test cycle

The steady-state modes were run at three different engine speeds and were designed to contain events in the NTE region. Within each engine speed, three loads were tested, nominally 40%, 70%, and 100%. Two full tests were conducted at each engine speed. A second NTE cycle was designed with a "stepped" pattern, intended to simulate NTE-type vehicle/engine operation in a predictable and controlled manner (i.e., gentle accelerations between modes and steady-state operation at each load point). This test cycle was designed to clearly delineate entry into, operation within, and exit, from the NTE-defined zone of engine operation. For the NTE stepped cycle, two sets of three runs were performed. The UDDS and 50-mph cruise cycle were intended to represent 'real-world' operation and are most useful for comparisons with data in current emissions inventories. Seven runs were conducted for both the UDDS and 50-mph cruise cycles.

4.4.1 Integrated Values (NTE steady state, NTE stepped, 50 mph cruise, UDDS)

The integrated emissions measurements over each of the four cycles were compared for each of the PEMS. The NTE steady state and stepped cycles were integrated over the entire cycle period of a particular speed (for the NTE steady state cycle) and over all steps (for the NTE stepped cycle). The complete cycles discussed further in the main text. Figures Figure 4-8 and
Figure 4-9 show the results for NO\textsubscript{x} and CO\textsubscript{2} on a g/hr basis. Error bars presented as 95% confidence limits, except for tests where only a single data point was available, in which case no error bars are included. The emission comparisons are important since these are the primary gaseous emission that will be targeted in the first phase of the NTE regulation implementation. The NO\textsubscript{x} readings for the PEMS were all higher than those obtained by the FRM. PEMS2 showed the closest agreement with the FRM with reading between 5 to 12% higher than the FRM over the different cycles. For PEMS3, NO\textsubscript{x} emissions ranged from 14 to 21% higher than the FRM. PEMS4 showed the largest differences in NO\textsubscript{x} emissions with readings generally ranging from 19 to 40% higher than the FRM. Some of these differences could be related to the calibration differences seen in the primary audit bottle concentrations. PEMS4 also indicated software issues in the prototype unit contributed to the observed differences.

CO\textsubscript{2} emissions are important for the determination of fuel specific (fs) emissions. CO\textsubscript{2} emissions also showed a trend with the PEMS having generally higher emissions than the FRM. The PEMS2 CO\textsubscript{2} emissions were within 5% of those measured by the FRM for most of the test runs, with no statistically significant differences for NTE 1290 rpm, 1500 rpm and 1770 rpm steady state cycles. These differences are comparable to those found between the exhaust flow rates for the FRM and PEMS2, as discussed below. The differences in CO\textsubscript{2} for PEMS3 ranged from 9 to 14% higher over the difference cycles. The CO\textsubscript{2} emissions for PEMS4 were between 11 and 26% higher than the FRM. For comparison, the calibration for PEMS4 was approximately 17% high on the audit bottle.
Comparisons were also made for emissions normalized by CO\textsubscript{2}. The CO\textsubscript{2} normalized NO\textsubscript{x} emissions for PEMS2 show slightly better percentage differences with the FRM than the unnormalized NO\textsubscript{x} emissions, ranging from 3 to 10%. For PEMS3, the agreement with the FRM improves considerably for the normalized NO\textsubscript{x} emissions, with agreement within 5% for most cycles, except the UDDS which was 10%. This indicates that differences in exhaust flow measurements could be a primary source of the differences between the FRM and PEMS3. The agreement between PEMS4 and the FRM also improves considerably for normalized NO\textsubscript{x} emissions, which differed from the FRM by between 0 to 17%. While this could be attributed in part to flow, it is important to note that the fairly large calibration differences found for PEMS4 for NO\textsubscript{x} and CO\textsubscript{2} would also be normalized using these units.

Work continues on the evaluation of portable and real-time instruments for measuring particulate matter (PM).

### 4.5 MEL and IPETS Equivalence

Emission factors (EFs) measured via certification tests may not account for all parameters that affect emissions under the real world conditions, such as the age, level of maintenance, and individual practice in the fleet. Generally, only a limited of number of emission sources is routinely tested due to the significant effort required for each test. In addition, the variability of the air pollutant EFs in the same categories cannot be assessed.

A field study was conducted in December, 2004, to compare emission rates measured by both the mobile laboratory and the IPETS described Section 4.1 and Section 4.2. As described above, the MEL is an instrumented semi trailer designed to measure gas and PM emissions, according to the standards specified by 40 Code of Federal Regulations (CFR) Part 86 and 40 CFR Part 89. The whole diesel exhaust stream flows into the primary constant volume sampling (CVS) dilution tunnel. A small fraction of the air in the primary dilution tunnel is drawn for continuous (1 Hz) measurements of CO, CO\textsubscript{2}, CH\textsubscript{4}, NO\textsubscript{x}, and total hydrocarbons (THC).
concentrations. A secondary dilution tunnel is used for collecting PM on Teflon membrane filters for gravimetric analysis. The temperature of primary and secondary dilution air is maintained at 25±5°C so that, the diluted exhaust has a temperature below 191 deg C in the primary dilution tunnel and slightly below 52°C in the secondary tunnel. The reminder of the diluted exhaust in the primary tunnel is vented through a bypass fan into the ambient air.

The IPETS measures fuel based EFs (in grams pollutant per kg fuel) from a large number of emission sources, in-situ and operating under real world conditions. The sampling inlet location was adjusted so that the exhaust is close to ambient temperature (±5 deg C) and RH (±10%). Sample air in the vicinity (1 m) of the MEL exhaust plume was drawn to IPETS and routed to the measurement systems for CO, CO₂, NO, NO₂, NH₃, SO₂, PM mass concentrations and particle size distributions described in Section 4.2. PM mass and chemical speciation over the duration of the sample are measured by laboratory analysis of the filter samples exposed throughout the tests.

The time shift between real time measurements from different instruments is determined by a “match” test at the beginning of the test and the end of the test. The match was lit at the inlet of the IPETS and was blown out immediately. The induced spike in gas and particle concentrations is used to verify that the instruments are responding and to synchronize their signals, some of which are offset by different locations in the sample flow.

The nonroad diesel engine used during these comparison tests was a Kamatzu SA6D125E-2 engine (Japan), with power output grading at 303 kW and size of 11 L displacement mounted in a 250kW (actual electrical output) DEWYO Model # DF-3300K power generator. The engine was manufactured in 2000 and had logged 316 service hours prior to and 332 service hours after these tests. The test protocol followed the 40 CFR Part 89 non-road CI engines, subpart §89.410, a 5-mode test cycle at 100%, 75%, 50%, 25% and 10% of the engine load. MEL emission factors (EFs) were determined from five minutes measurements at each mode, whereas IPETS EFs were based on the total time the engine was operated at a particular mode (up to 20 minutes).

Since the incremental CO₂ concentration in the exhaust over ambient concentrations is the denominator for calculating carbon fuel based EFs, determining the CO₂ contribution from emission sources and the background ambient CO₂ concentration can greatly affect their accuracy.

The FTIR spectrometer was operated under the relative mode, which measured at the difference between the sample air and the ambient background. The background gas concentrations were measured between engine load changes (approximately every 10-20 minutes). The pollutant concentration in the background air may vary during measurements due to a number of factors including diurnal variations (increasing height of the mixing layer), changes in transport, and changes in local emissions. This is especially important for gases such as NO₂ that has low concentrations. These changes in background gas concentration can results in FTIR spectrometer measurement biases that may result in negative concentrations. Therefore, the lowest negative gas concentration during each test was set as the new background (baseline) to correct for negative gas concentrations. Gas concentrations less than the FTIR spectrometer detection limits were then removed.
The two LI-840 measured background and source CO\textsubscript{2} concentrations at two different inlets. Spurious signal outliers (spikes) of background CO\textsubscript{2} were present during this study in the measurements. The presence of outliers may bias the determination of the baseline if not filtered out. To reduce the bias we used an approach that is similar to test-for-discordancy:

\[
C_{\text{time}=i} = \frac{\text{CO}_2 \text{ concentration}_{\text{time}=i} - \text{CO}_2 \text{ concentration}_{\text{time}=i+2}}{\text{standard deviation of CO}_2 \text{ concentration}_{\text{time}=i+2}}
\]

(4-9)

where \( C_{\text{time}=i} \) is the ratio of the differences between the CO\textsubscript{2} concentration at time \( i \) and the 5-s running average CO\textsubscript{2} concentration to the 5-s running standard deviation of CO\textsubscript{2} concentrations in the background air. When \( C_{\text{time}=i} \) is larger than three, the corresponding background CO\textsubscript{2} measurement is considered an outlier (with a 99% confidence level, assuming the noise is normally distributed) and is considered as an invalid data point. The real time PM concentration was the differences between ELPI and DustTrak mass concentrations to the daily average ambient PM concentration (determined by the filter sample).

4.5.1 Calculation of gases and PM emission ratios from IPETS measurements

To compare the emission ratios determined by the IPETS and MEL, it is assumed that: 1) there are no further chemical reactions either among air pollutants or with the ambient air between the sampling points for MEL and IPETS, and 2) air pollutant emission rates are constant and have low variability (<10%) when the engine operates at steady state. Three approaches were explored to calculate emission ratios for IPETS.

In Approach A, the net changes of concentrations for a pollutant relative to the ambient background levels are divided by the corresponding changes in carbon (i.e., CO\textsubscript{2} and CO) concentrations.

\[
\text{Emission Ratio} = \frac{\sum_{i=\text{StartTime}}^{\text{EndTime}} (\text{Pollutant}_{i} - \text{Pollutant}_{\text{bgd}})}{\sum_{i=\text{StartTime}}^{\text{EndTime}} [12/44 \times (\text{CO}_{2,i} - \text{CO}_{2,\text{bgd}}) + 12/28 \times (\text{CO}_{i} - \text{CO}_{\text{bgd}})]}
\]

(4-10)

In Approach B, a least square linear fit of the pollutant concentrations versus carbon concentrations is calculated for each test period. The slope represents the emission ratio and the intercept is the offset of the pollutant concentrations.

In Approach C, the mean of emission ratios of a pollutant concentration to carbon concentrations at time \( t \) over the entire test (i.e., average of the ratios) is determined.

\[
\text{Emission Ratio} = \text{mean} \left\{ \frac{(\text{Pollutant}_{i} - \text{Pollutant}_{\text{bgd}})}{[12/48 \times (\text{CO}_{2,i} - \text{CO}_{2,\text{bgd}}) + 12/28 \times (\text{CO}_{i} - \text{CO}_{\text{bgd}})]} \right\}_{i=\text{StartTime}}^{\text{EndTime}}
\]

(4-11)

where the standard deviation and coefficient of variance (COV) of the emission ratios in each test were also calculated. Test cycles whose emission ratio COV>0.25 were considered invalid data sets for comparison purposes.

4.5.2 Comparisons of Gas Emission Factors

The MEL EFs were reported as mass (in g) of pollutant/cycle; therefore, air pollutant EFs could only be calculated using Approach A. A total of 13 sets of data were used for the comparison. The plots of IPETS CO, NO\textsubscript{2}, and NO EFs to MEL EFs are shown in Figure 4-10.
through Figure 4-12 and summarized in Table 4-3. The IPETS and MEL CO EFs are highly correlated ($R^2 > 0.89$) with slopes very close to unity, regardless of which approach for calculating EFs was used. The ratios of mean IPETS to MEL CO EFs are in the range of 0.87-0.92, with one standard deviation between 0.23-0.19.

IPETS NO$_2$ concentrations measured were very close to FTIR spectrometer detection limit (1 ppm). The plot of three IPETS NO$_2$ EFs v.s. MEL NO$_2$ EFs is shown in Figure 3. The slopes determined by Approach A and B were both around 0.5 and only moderate to poor correlation was found ($R^2 = 0.49$) for Approach A (Table 4-3). Applying the criteria of selecting mean IPETS NO$_2$ EFs with COV less than 0.25 in Approach C reduces the number of valid test to six and increases the agreement between IPETS and MEL NO$_2$ EFs (slope = 0.78, $R^2 = 0.82$). The reduced agreement between IPETS and MEL NO$_2$ EFs in approaches A and B respect to approach C is due to the lack of suitable and rigorous criteria to exclude suspicious values in these approaches.

The IPETS and MEL NO EFs (Figure 4-12) were highly correlated (Table 4-3). However, IPETS NO EFs were 50% higher than those from MEL, suggesting a systematic bias in NO EFs. It is unlikely that such bias is due to the interference of H$_2$O in FTIR spectroscopy. NO concentrations can be accurately quantified with careful selection of wave number regions in FTIR spectroscopy. The cause of the bias in NO EF is unclear since data reduction procedures for MEL are not available.

4.5.3.2. EF Comparison for PM$_{2.5}$

The PM$_{2.5}$ EFs measured by ELPI, DustTrak, and filter mass are shown in Table 4-4. The mean, geometric mean, median, and the standard deviation are calculate for the ratios of the average ELPI and DustTrak PM$_{2.5}$ mass concentrations to filter mass for the 13 tests. The geometric mean, median, and mean of the mass ratios are similar; thus, the mean mass ratios of 9.17 and 1.42 were applied to correct for ELPI and DustTrak PM$_{2.5}$ mass concentrations, respectively.

The mean and the standard deviation of IPETS ELPI and DustTrak PM$_{2.5}$ EFs were shown in Table 4-5. Mean ELPI and DustTrak PM$_{2.5}$ EFs were reproducible (<15%). The COV of ELPI and DustTrak PM$_{2.5}$ EFs are in the range of 0.5-1 and did not vary, regardless the number of measurements taken for the replicates. For example, ELPI PM$_{2.5}$ EFs and COV were very similar between the replicate tests using JP8 fuel at 50% engine load, although the numbers of measurements were 1425 and 752. This suggests that IPETS can estimate mean and variation of PM$_{2.5}$ EFs for a specific test condition (engine type, load, fuel, etc) in a short time (as short as 150 seconds).

IPETS PM$_{2.5}$ EFs were generally 3.5-5 times higher than those determined by filter mass concentrations in MEL dilution method. The differences between IPETS and MEL PM$_{2.5}$ EFs were not due to instrumental bias (ELPI and filter mass), since 1) both CO and NO$_2$ EFs between IPETS and MEL were in very good agreement; and 2) ELPI PM$_{2.5}$ mass concentration was corrected to IPETS filter mass. The higher IPETS PM$_{2.5}$ EF is probably due to the different measurement methodologies, i.e. in-plume vs. dilution methods. Several studies have suggested that residence time in dilution methods may be important to account for condensable PM mass (Chang, et al, 2004; Hildemann, et al, 1989; Chang and England 2004; Watson, 2002). Condensational growth of particles depends on the chemical properties of condensable species, characteristics of pre-existing particles in the exhaust (such as hyroscopicity and particle
surface area), and the different fraction and concentration of condensable to solid PM of different emission source types (such as natural gas exhaust vs. cement kiln). Yet, the minimum residence time for condensational growth is not specified in dilution method for mobile sources.

Second, the temperature of the sample air and filters for PM collection in MEL were maintained at slightly less than 52°C, while the sample air temperature for IPETS was closer to the ambient, ranging from as low as 4°C in the morning to 23°C at noon. The lower sample r temperature in the IPETS may allow more condensable species to condense on PM prior to collection (Plee and MacDonald, 1980) due to the gas-particle equilibrium processes. Additionally, potential PM losses in the MEL secondary dilution sampler were not quantified and accounted for in this analysis.

Another factor which can result in different EFs between IPETS and MEL is the mixing pattern in dilution process. The ratio of CO₂ concentrations in the exhaust in the primary tunnel (~1%) to that measured in the IPETS (800-2,500 ppm after correcting for ambient CO₂) reflects the ambient air dilution of the exhaust from the bypass fan (i.e., in the primary dilution tunnel). Therefore, the dilution air ratio of the exhaust in primary tunnel was estimated to be 4-8, which was very close to that used in the secondary dilution tunnel in MEL. The exhaust air in the primary dilution tunnel was rapidly mixed and diluted with air passing through a sintered metal tube in secondary dilution tunnel, but it was slowly mixed with ambient air (i.e., Gaussian plume). Many studies reported that different dilution air flow patterns for mixing affects size distributions in number concentrations for particles smaller than 0.3µm in mobility diameter (Abdul-Khalek, et al, 1999, Maricq, et al, 1999, Hall and Dickens, 2000, Lyyränen et al, 2004). Yet, PM mass in this size range was a smaller fraction of PM₂.₅, and it is not clear how the different mixing pattern will affect PM mass.
Table 4-3. Comparison of CO, NO, and NO\textsubscript{2} emission rates between the IPET and MEL tests.

<table>
<thead>
<tr>
<th>Species</th>
<th>Statistics</th>
<th>Approach A</th>
<th>Approach B</th>
<th>Approach C</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>EF Regression Slope</td>
<td>1.03</td>
<td>0.95</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td>R\textsuperscript{2}</td>
<td>0.99</td>
<td>0.89</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Intercept (g/kg fuel)</td>
<td>-0.34</td>
<td>0.04</td>
<td>-0.34</td>
</tr>
<tr>
<td></td>
<td>N (tests)</td>
<td>13</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Mean of IPETS EF to HDDML EF</td>
<td>0.88</td>
<td>0.92</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation of IPETS EF to HDDML EF</td>
<td>0.23</td>
<td>0.34</td>
<td>0.20</td>
</tr>
<tr>
<td>NO\textsubscript{2}</td>
<td>Regression Slope</td>
<td>0.46</td>
<td>0.52</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>R\textsuperscript{2}</td>
<td>0.49</td>
<td>0.84</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>Intercept (g/kg fuel)</td>
<td>0.74</td>
<td>-0.05</td>
<td>-0.30</td>
</tr>
<tr>
<td></td>
<td>N (tests)</td>
<td>13</td>
<td>13</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Mean of IPETS EF to HDDML EF</td>
<td>1.03</td>
<td>0.45</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation of IPETS EF to HDDML EF</td>
<td>0.74</td>
<td>0.17</td>
<td>0.10</td>
</tr>
<tr>
<td>NO</td>
<td>Regression Slope</td>
<td>1.68</td>
<td>1.61</td>
<td>1.37</td>
</tr>
<tr>
<td></td>
<td>R\textsuperscript{2}</td>
<td>0.89</td>
<td>0.60</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>Intercept (g/kg fuel)</td>
<td>-2.19</td>
<td>-1.83</td>
<td>-1.95</td>
</tr>
<tr>
<td></td>
<td>N (tests)</td>
<td>13</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Mean of IPETS EF to HDDML EF</td>
<td>1.54</td>
<td>1.50</td>
<td>1.55</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation of IPETS EF to HDDML EF</td>
<td>0.09</td>
<td>0.18</td>
<td>0.09</td>
</tr>
</tbody>
</table>
Table 4-4. Comparison of PM$_{2.5}$ emission factors based on ELPI, DustTrak and filter mass.

| Test Series | Average ELPI PM$_{2.5}$ (mg/m$^3$) | Valid ELPI measurement (N) | Average DustTrak PM$_{2.5}$ (mg/m$^3$) | Average of DT PM$_{10}$ (mg/m$^3$) | Valid DustTrak measurement (N) | Filter Based Mass Conc (mg/m$^3$) | Filter based Mass Conc (ug/m$^3$) | Average PA BC Conc (ug/m$^3$) | Count of EF ELPI | Count of EF DT | Count of EF PA |
|-------------|----------------------------------|-----------------------------|----------------------------------------|-----------------------------------|------------------------------|-----------------------------------|-------------------------------|-----------------|---------------|---------------|
| JP8-1-100   | 2.5                              | 609                         | 0.83                                   | 0.82                              | 519                          | 0.51                              | 509.49           | 544             | 50            | 1.6           | 0.19          |
| JP8-2-100   | 4.0                              | 611                         | 1.20                                   | 1.18                              | 523                          | 0.73                              | 728.40           | 769             | 79            | 5.5           | 1.6           |
| JP8-1-050   | 5.9                              | 1425                        | 1.27                                   | 1.27                              | 1203                         | 0.71                              | 709.26           | 836             | 84            | 8.3           | 1.8           |
| JP8-2-050   | 6.4                              | 752                         | 1.37                                   | 1.39                              | 657                          | 0.80                              | 799.22           | 1087            | 171           | 8.0           | 1.7           |
| JP8-1-025   | 7.4                              | 271                         | 1.04                                   | 1.01                              | 216                          | 0.98                              | 976.61           | 978             | 130           | 7.6           | 1.1           |
| JP8-2-025   | 5.9                              | 571                         | 0.74                                   | 0.72                              | 511                          | 0.54                              | 540.84           | 521             | 130           | 10.8          | 1.4           |
| JP8-1-010   | 3.4                              | 602                         | 0.33                                   | 0.32                              | 498                          | 0.54                              | 544.44           | 272             | 84            | 6.2           | 0.6           |
| JP8-2-010   | 2.9                              | 150                         | 0.32                                   | 0.29                              | 119                          | 0.73                              | 728.40           | invalid         | invalid        | 4.0           | 0.4           |
| ULS-D-1-050 | 3.6                              | 495                         | 0.85                                   | 0.84                              | 421                          | 0.53                              | 534.72           | 487             | 150           | 6.7           | 1.6           |
| ULS-D-2-050 | 3.3                              | 604                         | 0.78                                   | 0.77                              | 533                          | n.a.                              | n.a.             | 424             | n.a.          | n.a.          | n.a.          |
| ULS-D-1-025 | 6.7                              | 500                         | 1.19                                   | 1.19                              | 420                          | 0.95                              | 947.92           | 800             | 267           | 7.0           | 1.3           |
| ULS-D-2-025 | 5.7                              | 850                         | 1.13                                   | 1.11                              | 740                          | n.a.                              | n.a.             | 698             | n.a.          | n.a.          | invalid       |

n.a.: no filter sample was collected for this test cycle.

Table 4-5. Summary of PM emission factors from IPET and MEL measurements.

<table>
<thead>
<tr>
<th>Group</th>
<th>Ratio ELPI to HDDML PM EF</th>
<th>HDDML PM EF (g/kg fuel)</th>
<th>ELPI PM$_{2.5}$ EF (g/kg fuel)*</th>
<th>Stdev of ELPI PM$_{2.5}$ EF (g/kg fuel)*</th>
<th>Stdev of DustTrak PM$_{2.5}$ EF (g/kg fuel)</th>
<th>Stdev of EF PA (ug BC/kg Fuel)</th>
<th>Stdev of EF PA (ug BC/kg Fuel)</th>
<th>Stdev of EF PA (ug BC/kg Fuel)</th>
<th>Stdev of EF PA (ug BC/kg Fuel)</th>
<th>Stdev of EF PA (ug BC/kg Fuel)</th>
<th>Count of EF PA</th>
<th>Count of EF PA</th>
<th>Count of EF PA</th>
</tr>
</thead>
<tbody>
<tr>
<td>JP8-1-100</td>
<td>3.46</td>
<td>0.89</td>
<td>3.10</td>
<td>2.25</td>
<td>6.79</td>
<td>6.44</td>
<td>5.10</td>
<td>4.16</td>
<td>615</td>
<td>519</td>
<td>388</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JP8-2-100</td>
<td>3.39</td>
<td>1.01</td>
<td>3.42</td>
<td>3.89</td>
<td>4.86</td>
<td>2.06</td>
<td>3.85</td>
<td>1.38</td>
<td>809</td>
<td>523</td>
<td>445</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JP8-1-050</td>
<td>4.02</td>
<td>0.46</td>
<td>1.87</td>
<td>1.92</td>
<td>1.76</td>
<td>0.70</td>
<td>1.62</td>
<td>0.85</td>
<td>1428</td>
<td>1203</td>
<td>893</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JP8-2-050</td>
<td>3.95</td>
<td>0.44</td>
<td>1.72</td>
<td>1.34</td>
<td>1.73</td>
<td>0.48</td>
<td>1.32</td>
<td>0.31</td>
<td>855</td>
<td>657</td>
<td>278</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JP8-1-025</td>
<td>3.57</td>
<td>0.41</td>
<td>1.47</td>
<td>1.04</td>
<td>1.02</td>
<td>0.33</td>
<td>1.35</td>
<td>0.75</td>
<td>271</td>
<td>216</td>
<td>155</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JP8-2-025</td>
<td>4.39</td>
<td>0.36</td>
<td>1.57</td>
<td>0.75</td>
<td>1.03</td>
<td>0.25</td>
<td>1.08</td>
<td>0.25</td>
<td>571</td>
<td>511</td>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JP8-1-010</td>
<td>5.93</td>
<td>0.28</td>
<td>1.66</td>
<td>1.79</td>
<td>0.64</td>
<td>0.42</td>
<td>0.76</td>
<td>0.61</td>
<td>621</td>
<td>498</td>
<td>419</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JP8-2-010</td>
<td>4.09</td>
<td>0.28</td>
<td>1.14</td>
<td>0.51</td>
<td>0.64</td>
<td>0.14</td>
<td>0.65</td>
<td>0.12</td>
<td>150</td>
<td>119</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ULS-D-1-050</td>
<td>3.28</td>
<td>0.40</td>
<td>1.32</td>
<td>0.91</td>
<td>1.62</td>
<td>0.56</td>
<td>1.23</td>
<td>0.50</td>
<td>495</td>
<td>421</td>
<td>324</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ULS-D-2-050</td>
<td>3.58</td>
<td>0.36</td>
<td>1.28</td>
<td>0.72</td>
<td>1.59</td>
<td>0.49</td>
<td>1.15</td>
<td>0.36</td>
<td>605</td>
<td>533</td>
<td>440</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ULS-D-1-025</td>
<td>3.37</td>
<td>0.46</td>
<td>1.54</td>
<td>0.85</td>
<td>1.44</td>
<td>0.44</td>
<td>1.29</td>
<td>0.39</td>
<td>500</td>
<td>420</td>
<td>342</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ULS-D-2-025</td>
<td>7.06</td>
<td>0.21</td>
<td>1.45</td>
<td>0.70</td>
<td>1.47</td>
<td>0.37</td>
<td>1.22</td>
<td>0.33</td>
<td>850</td>
<td>740</td>
<td>647</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ULS-D-1-010</td>
<td>3.78</td>
<td>0.62</td>
<td>2.35</td>
<td>1.91</td>
<td>1.66</td>
<td>1.11</td>
<td>1.57</td>
<td>0.98</td>
<td>730</td>
<td>604</td>
<td>508</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* assuming 0.86 g C/g fuel, and a factor 9.17 and 1.42 were applied to correct for ELPI and DustTrak mass concentration measurements

4-18
Figure 4-10. Comparison of IPETS to MEL CO measurements for three different approaches.

Figure 4-11. Comparison of IPETS to MEL NO$_2$ measurements for three different approaches.
Figure 4-12. Comparison of IPETS to MEL NO measurements for three different approaches.
5. ENGINE TESTS AND RESULTS

5.1 Mobile Laboratory Tests

Tests continued of the diesel engines and stationary sources that are representative of those used at military facilities with a number of fuels. One deviation from the 2002 plan is the larger data set for renewable fuels because of the greater current emphasis on renewable fuels on federal facilities. An overview of the 15 tests completed thus far is summarized in Table 5-1. When measurements were conducted on the same engine, a direct comparison is possible between each fuel. We are planning more work in 2006 at March AFB.

Table 5-1. Description of emissions tests using a variety of fuels and diesel engines.

<table>
<thead>
<tr>
<th>Unit</th>
<th>CARB</th>
<th>JP-8</th>
<th>CARB-UL</th>
<th>B20/Soy</th>
<th>B20/YGA</th>
<th>B100</th>
<th>E-diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>DDC 6V92 (350kW)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAT 3406B (300kW)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cummins 6BT (100kW)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deere TBG (60kW)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deere 6076 (125kW)</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Komatsu/SA6D125E (250kW)</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deere RDJ 01978 (60kW)</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

Work also continued on the measurement of emissions from mobile sources as indicated in the table below. As with the stationary sources, the total characterization of the hydrocarbon and particulate matter speciation is being carried out as part of the work. Thus far, 21 tests were completed for a wide variety of mobile sources to include both trucks and busses (Table 5-2). The project has tested diesel engines from a wide variety of military facilities, including Vandenberg AFB, Camp Pendleton, 29 Palms Marine Base, Peterson/Cheyenne AFB and North Island (San Diego).

Table 5-2. Mobile sources tested with at CE-CERT.

<table>
<thead>
<tr>
<th>Unit</th>
<th>EPA</th>
<th>JP-8</th>
<th>CARB-UL</th>
<th>B20/Soy</th>
<th>B20/YGA</th>
<th>B20/YGB</th>
<th>B100</th>
<th>E-diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ford F-350 (Nav 7.4L)</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ford F-700 (Cum 9.9L)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ford F-9000 (Cat 3406)</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thomas Bus (Cat 3126)</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bus (Cum ISB245)</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bus (Cum plus catalyst)</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humvee (GM6.5L)</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.2 In-Plume Emission Measurements at Camp Pendleton

Measurements from non-road diesel engines were conducted in Camp Pendleton, CA in Nov 13-17, 2004 (Task 4.3). The IPETS measurements are used for calculating carbon fuel based emission factors for air pollutants. Table 5-3 shows the measurements matrix in the field study. The test engines were selected based on a wide range of operating hours, engine manufactures, generator manufactures, and manufactured year, etc, which were recorded in field data sheet (Table 5-4).
The test engines were arrayed in an open lot, as shown in Figure 5-1. Emissions were measured at 10%, 25%, 50%, 75%, and 100% engine load for all engines. Each engine load ran for approximately 5 minutes. In addition, emissions from cold start (within 5 minutes of engine start up) were measured. JP fuel is the fuel used for the diesel engines in the base. IPETS sampling inlet was approximately 1 m away from the diesel engine exhaust pipe and was supported by a tripod (Figure 5-2). Measurement time difference among instruments in IPETS was determined by a “match” test (Figure 5-3) before and after the measurement each day.

Table 5-3. In-Plume Sampling Test Matrix in Camp Pendleton, CA, from Nov 14 to 16, 2004.

<table>
<thead>
<tr>
<th>Generator Rated Power</th>
<th>Sampling Date</th>
<th>Number of Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 kW</td>
<td>Nov 14, 2004</td>
<td>3</td>
</tr>
<tr>
<td>30 kW</td>
<td>Nov 15, 2004</td>
<td>5</td>
</tr>
<tr>
<td>60 kW</td>
<td>Nov 15, 2004</td>
<td>4</td>
</tr>
<tr>
<td>100 kW</td>
<td>Nov 16, 2004</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 5-4. An example of the field data sheet which records the parameters for the tested engines

<table>
<thead>
<tr>
<th>Generators</th>
<th>Engines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Make</td>
<td>Model</td>
</tr>
<tr>
<td>JEWY Co. L't DF-3300K 608928 250</td>
<td>Makatzu SA6D125E-2 2000 85806 11.045</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Libby corp MEP803A RZCO2845 10</td>
<td>ONAN CORP 1999 450017910DN4WA72 10</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>LIBBY CORP MEP803A RZCO2061 10</td>
<td>ONAN CORP 1994 44037910DN4WA72 10</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>LIBBY CORP MEP803A RZH01043 10</td>
<td>JOHN DEERE 4039TF002 May-95 T0439TF479803 30</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 5-1. Engines arrayed in Camp Pendleton, CA in the study

Figure 5-2. IPETS sampling inlet and support during the test
Measurements of ambient gas and PM concentrations were determined to correct for gas concentrations from sources in FTIR and PM chemistry. Ambient gas concentrations were measured via IPETS at least at least three times a day: 1) at the beginning of the test day, 2) between the change of engine types, and 3) the end of the test day for continuous measurements. Figure 5-4 shows the setup for ambient PM collection for gravimetry mass and chemistry. Each day ambient PM were collected using two filter packs: 1) 47mm PTFE filter (gravimetry mass) followed by quartz fiber filter (volatilized PM organic carbon), and 2) quartz fiber filter (water soluble ions, OC/EC) followed by sodium carbonate coated cellulose fiber filter (for sulfur dioxide). The filter pack flow rate was monitored and adjusted to the specified flow rate at least every 30 minutes to assure the PM$_{2.5}$ size selection. Ambient temperature and RH were monitored and recorded every hour.

Four JP 8 fuel sample were collected: two from camp fuel dispenser, one from a 60kW diesel engine fuel tank, one from the 100kW diesel engine fuel tank.. Fuel samples were sent to laboratory for fuel analysis.

We are in the process of reducing the collected IPETS real time data. The gas and PM emission factor will be calculated for each engine load and size; so the standard deviation of the measurements will be. The PM gravimetry mass and chemistry will be analyzed.
5.3 Source Profiles

Our test team has obtained a number of samples for subsequent source profile analysis across backup generators and fuel composition. We continue to analyze and compile data for speciated polyaromatic compounds, carbonyl species, elemental and organic carbon, and other gas-phase toxic species. An example of the data obtained is provided below for a subset of ten generators operating on ultralow sulfur diesel fuel. (Table 5-5)

Table 5-5. Partial list of tested BUGs

<table>
<thead>
<tr>
<th>Bug ID</th>
<th>Manufacturer</th>
<th>Model Number</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Caterpillar</td>
<td>3508</td>
<td>2002</td>
</tr>
<tr>
<td>B</td>
<td>Caterpillar</td>
<td>3512</td>
<td>2000</td>
</tr>
<tr>
<td>C</td>
<td>Caterpillar</td>
<td>3516</td>
<td>2000</td>
</tr>
<tr>
<td>D</td>
<td>Caterpillar</td>
<td>3406C</td>
<td>2000</td>
</tr>
<tr>
<td>E</td>
<td>Caterpillar</td>
<td>3406C</td>
<td>2000</td>
</tr>
<tr>
<td>F</td>
<td>Detroit Diesel</td>
<td>V92</td>
<td>1985</td>
</tr>
<tr>
<td>G</td>
<td>Cummins</td>
<td>6BT</td>
<td>1990</td>
</tr>
<tr>
<td>H</td>
<td>Caterpillar</td>
<td>3408B</td>
<td>1990</td>
</tr>
<tr>
<td>I</td>
<td>John Deere</td>
<td>Kohler</td>
<td>2001</td>
</tr>
<tr>
<td>J</td>
<td>John Deere</td>
<td>Kohler</td>
<td>1991</td>
</tr>
</tbody>
</table>

Figure 5-4. Setup of the ambient PM samplers for determining background PM gravimetry mass and chemistry.
Shown in Figure 5-5 is the carbonyl compound emissions for the set of ten generators. Several clear trends emerge including the general trend of higher to lower emission rates as the BUGs operation moves from 10 to 100% load with a small increase seen at the highest loads. Emissions are found to highly variable between engine manufacturers and engine technologies. A comparison across the relative intensities of the carbonyl species is found in Figure 5-6 demonstrating that there is little variability in the relative formaldehyde and acetaldehyde emissions relative to total carbonyl emissions regardless of gross emission rates, engine manufacture, engine age, or engine technology.

The division of particulate emissions between elemental and organic carbon provides a first step towards speciation of the BUG emissions. Figure 5-7 shows the EC and OC emission factors for the BUGs on an energy consumption \( [g \ (bhp \ hr)^{-1}] \) basis, as a function of engine load. All BUGs show the trend of decreasing emissions with increasing engine load, although BUGs G, H, and I show significantly higher emissions at 100% load than at 75% load. We observe that BUGs A, B, and C (all large BUGs from the same engine family) have the lowest total carbon emission factors by mode relative to the other BUGs tested. BUG H lies on the other end of the scale, with the highest total carbon emission factors by mode of all BUGs tested.

Figure 5-8 shows the relative contributions of EC and OC to the total carbon emission factor. We observe that the EC contribution is typically greater than 50%, with BUG F being a significant exception. This is an older BUG (model year 1985) manufactured by Detroit Diesel, and shows EC contributions in the range of 30%. These results are qualitatively similar to those obtained for EC and OC contributions for on-road HDD trucks in another work (Shah et al., 2004), where engines from this manufacturer also showed lower EC contributions, and thereby greater OC contributions, relative to the other engines tested.

Focusing on BUGs A through E, we observe that not only do these BUGs show similar relative EC and OC contributions across modes, but also across individual BUGs; the only other BUG that shows a similar trend is BUG H. BUGs A-E and H all have relative EC contributions in the range of 55-80%, irrespective of engine load. We note that BUGs A through E are all newer BUGs (model year 2000 or later), while BUG H is somewhat older (model year 1990). All these BUGs (A-E, H) are from the same manufacturer (Caterpillar), although they span a wide range of output power (300kW-2000kW) and absolute EC and OC concentrations (e.g., BUG H total carbon emissions are 5-10 times higher than A-C total carbon emissions). If we consider BUG H and compare it with BUGs from similar model years (BUG G, 1990; BUG J, 1991) but different manufacturers (Cummins and John Deere, respectively), we observe almost no similarity in relative EC and OC contributions.

Based on the observations from the last two paragraphs, we conclude that engine manufacturer (one measure of engine technology) is a strong determinant of relative EC and OC contributions for the BUGs tested, more significant than model year (another measure of engine technology). This is true even if there is large variation in absolute EC and OC concentrations. It will be interesting to observe whether this will change for current and future (model year 2005 and later) BUGs, due to the introduction of more stringent regulations. Further testing should provide more insight into this.
Figure 5-5. Carbonyl emission factors for 10 in-use BUGs over the ISO 8178 5-mode cycle [g (bhp hr)$^{-1}$].

Figure 5-6. Relative carbonyl concentrations for in-use BUGs over the ISO 8178 5-mode cycle.
Figure 5-7. EC and OC emission factors for 10 in-use back-up generators on g/bhp-hr basis

Figure 5-8. Relative contributions of OC and EC for 10 in-use back-up generators.
6. INTEGRATION WITH EPA EMISSION MODELS

Emissions modeling is an inherently data sparse activity. It is well known that exhaust emissions are influenced by engine age, maintenance record, fuel, engine type, engine temperature, and engine operating cycle. Given the unique history and usage of each piece of equipment, population emissions must be simulated using sparse matrices of data. For example, the influence of engine age on emissions may be determined on just a few engines that are repeatedly tested over their useful lifetimes. These patterns are then used to fill in engine degradation for the entire population of similar engines. While this gap-filling approach may be prone to errors, it generally produces the most realistic results with the available data. Due to the complexity and diversity of engine populations, all emissions models employ gap-filling as a means to most accurately estimate total emissions.

The original scope of work for this project detailed the development of a spreadsheet based emissions modeling system for use by environmental managers at military bases. The purpose of the model is to provide an integrated platform for users to estimate total exhaust emissions from military diesel engines. For this project, we intend to leverage the extensive resources that EPA has invested to develop standardized modeling platforms for on-road and off-road engines. This approach has numerous advantages over developing a new emissions modeling system. The user base for the standardized models is larger since these models are used by state, local, and federal air quality planners. The software and documentation are more complete and error free since they have been distributed and tested with a large number of users. Finally, mechanisms are in place by EPA to debug and upgrade the models over time.

In the past, EPA has supported two emissions models for on-road (MOBILE) and non-road (NONROAD) emissions estimation. The MOBILE model is used to estimate emissions based on grams per mile of hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx), carbon dioxide (CO2), particulate matter (PM), and toxics from cars, trucks, and motorcycles under various conditions. Appropriate emission factors are applied for cold starts and operating modes specified by traffic demand and forecasting models. The NONROAD Model is a software tool for predicting emissions of HC, CO, NOx, PM, and SO2 from small and large nonroad vehicles, equipment, and engines. Grams per mile emission factors are not relevant for many non-road sources since they are either stationary or their mobility is not a major source of their emissions. The NONROAD model uses an emission factor basis of grams per brake horsepower hours (g/Bhph) to estimate emissions. Activity data such as equipment population, available horsepower (HP), average load (i.e. fraction of available HP), activity hours are input to estimate total emissions. Other factors such as engine deterioration, fuel composition, and ambient temperature are also considered. Generally, environmental planners must run both of these models to create emission inventories for an urban area.

Recently, EPA has developed MOVES, or MOtor Vehicle Emission Simulator to integrate the two models. MOVES, also known as the "New Generation Model," encompasses all pollutants and all mobile sources at the levels of resolution needed for the diverse applications of the system. MOVES2006 will complete the on-road component of the model, adding HC (including non-exhaust emissions), CO, NOx, PM, Toxics, CO2, NH3 and SO2. MOVES2006 will be the draft replacement for MOBILE6, with an extensive review period planned before finalization with the release of MOVES2007. Off-road sources including commercial marine, aircraft and locomotive will be included in draft form in MOVES2007, with finalization planned for 2008.
An advantage of the MOVES platform is that engine modal cycles are used as an independent input. That is, emission factors collected during the Federal Test Procedure (FTP) test cycle can be remapped for a domain that has a very different driving cycle than the FTP (e.g. urban stop and go or highway cruising). The same will be true for non-road emission simulations. For example, an operating cycle for a cement mixer would involve the engine operating at a variety of conditions that are not well represented by distances traveled or total engine hours. Rather, a modal cycle would account for the different engine loads associated with start up emissions, driving transients, and near constant load when the cement is being mixed.

The scope of the emissions model development task for this project includes importing our measured military diesel engine emission factors for use in the current version of the NONROAD emissions model. We will also provide thorough documentation to instruct military facility environmental managers how to modify and operate the NONROAD model for their domain.

At the same time, we will document all parameters needed for the future integration of this data into the MOVES2007/2008 model. For example, emissions from generators are quantified for start up conditions and steady state loads at 10%, 25%, 50%, 75%, and 100% of the rated power. These emission factors will be tabulated in a MOVES ready format so more detailed simulations of emissions can be performed when additional data is available about usage activity. For mobile sources such as trucks and HUMVEEs, emissions data will be tabulated based on vehicle speed and vehicle specific power. Gap-filling techniques will be used to fill in bins were measurements are sparse. For example, a dynamometer test of a HUMVEE operating on a known test cycle may produce second by second data that relates emissions to speed and vehicle specific power (VSP), a proxy for engine load. This data may not be available for 5-ton trucks, but remotely sensed data may exist for the truck operating over a very limited range of loads. The HUMVEE’s emission’s relationship with speed and VSP can then be used to scale the remotely sense emissions form the 5-ton truck. This gap filling technique will integrate all emissions measurements and improve the accuracy and representativeness of the model results.

6.1 NONROAD Emission Factor Database Integration

Emission factor data within the NONROAD model are stored in lookup tables within the DATA/EMSFAC subdirectory of the NONROAD program directory. Each ASCII tables within the directory assembles the emissions from the type of source (i.e. crankcase, exhaust, spillage, evaporative) as well as a break specific fuel consumption factor that permits the translation from Bhp emission factors to fuel based emissions factors.

Factors in the EMFAC directory are based on brand new (0 hour) engines. NONROAD uses a set of deterioration factor lookup tables to simulate the emissions from aging engines. Since the dataset produced from the study will not be sufficiently large to quantify deterioration factors from the engines tested, we will used the default deterioration factors from NONROAD and the age of the military engines tested to calculate the 0-hour emission factors.

Emission factors are defined in the NONROAD model by the Source Classification Code (SCC), the power level range in HP, and the engine technology type (i.e. 2-stroke gasoline, 4-stroke gasoline, diesel, etc.). The SCC is a hierarchical numbering system defined by the EPA and used to describe all types of emission sources. When less specific emission factors are
available for a certain class of equipment, the NONROAD model defaults to the more general equipment classification. An example list of NONROAD SCCs is shown in Table 6-1.

Table 6-1. List of SCCs for NONROAD equipment. The xx in the SCC number refers to the fuel/technology types of the equipment (‘60’ for 2 stroke gas, ‘65’ for 4 stroke gas, and ‘70’ for diesel). The ‘yyy’ and ‘zzzzzz’ refer to the specific equipment types as denoted in the examples and the numbers in parentheses.

<table>
<thead>
<tr>
<th>SCC</th>
<th>Equipment Types</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>22xx001yyy</td>
<td>Recreational Vehicles</td>
<td>Snowmobiles (020), ATVs (030), Golf Carts (050),</td>
</tr>
<tr>
<td>22xx002yyy</td>
<td>Construction</td>
<td>Pavers (003), Surfacing equipment (024), Off-highway trucks (051)</td>
</tr>
<tr>
<td>22xx003yyy</td>
<td>Industrial</td>
<td>Forklifts (020), Sweepers (030), Refrigeration (060)</td>
</tr>
<tr>
<td>22xx004yyy</td>
<td>Lawn and Garden</td>
<td>Lawn mowers (010), Snow blowers residential (035), Chippers and stump grinders (066)</td>
</tr>
<tr>
<td>22xx005yyy</td>
<td>Agricultural</td>
<td>Combines (020), Balers (025), Tillers (040)</td>
</tr>
<tr>
<td>22xx006yyy</td>
<td>Commercial</td>
<td>Generator set (005), Pumps (010), Welders (025)</td>
</tr>
<tr>
<td>22xx007yyy</td>
<td>Logging</td>
<td>Chainsaws (005), Shredders (010), Skidders (015)</td>
</tr>
<tr>
<td>22xx008005</td>
<td>Airport Ground Support</td>
<td>All types</td>
</tr>
<tr>
<td>22xx009010</td>
<td>Underground Mining</td>
<td>All types</td>
</tr>
<tr>
<td>22xx010010</td>
<td>Oil Field</td>
<td>All types</td>
</tr>
<tr>
<td>2282zzzzzz</td>
<td>Recreational Marine</td>
<td>Gasoline outboard (005010), Diesel inboard (020005), Diesel Sailboat Auxiliary (020025)</td>
</tr>
<tr>
<td>2285zzzzzz</td>
<td>Railway Maintenance</td>
<td>Diesel (002015), 4-stroke (004015), LPG (006015)</td>
</tr>
<tr>
<td>To be determined</td>
<td>Tactical Military</td>
<td>Generators, Humvees, 5-ton Trucks, etc.</td>
</tr>
</tbody>
</table>

We will introduce a unique class of SCC’s for this project to represent the largest fuel consuming equipment types used by the different branches of the military. We will pursue a cooperative effort with EPA staff to add these SCCs and emission factors to the default NONROAD model.

6-3
The list of files to be modified as part of this project are shown in Table 6-2.

Table 6-2. List of files to be modified in the NONROAD model.

<table>
<thead>
<tr>
<th>NONROAD Sub Directory</th>
<th>Filename</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>data/emfac</td>
<td>Bsf起重机</td>
<td>Brake specific fuel consumption factors</td>
</tr>
<tr>
<td>data/emfac</td>
<td>Exhco.emf</td>
<td>Emission factors data for exhaust CO emissions</td>
</tr>
<tr>
<td>data/emfac</td>
<td>Exhnox.emf</td>
<td>Emission factors data for exhaust NOx emissions</td>
</tr>
<tr>
<td>data/emfac</td>
<td>Exhpm.emf</td>
<td>Emission factors data for exhaust PM emissions</td>
</tr>
<tr>
<td>data/emfac</td>
<td>Exhthc.emf</td>
<td>Emission factors data for exhaust THC emissions</td>
</tr>
</tbody>
</table>

A portion of the Exhpm.emf data file is shown in Figure 6-1. The results of this study will be appended to this file using units of g pollutant/gallon fuel consumed.

Figure 6-1. Example of emission factor data table from NONROAD model.

6.2 Running the modified NONROAD model for a military facilities

Ultimately, an environmental manager will input the equipment populations, activity (i.e. fuel usage), fuel specifications, and ambient conditions into the NONROAD model. The model will use the measured emission factors and to calculate emissions of CO, NOx, PM, and THC from a military facility.

In addition to the documentation already supplied by the EPA for the use of the NONROAD model, a step by step example of how to use the model to calculation emissions for a military facility will be provided as a product of this project.
7. PROJECT MANAGEMENT

7.1 Project Leveraging

Leveraging of this project with the needs of other sponsors is important because it amortizes the cost of hardware, method development, and procedure testing over a number of projects, thereby allowing more of the SERDP resources to be allocated to specific source testing at military bases. Since several of the other sponsors are air pollution control agencies (California Air Resources Board, Idaho Department of Environmental Quality, Clark County Air Quality Division, Community Planning Association of Southwest Idaho), their sponsorship guarantees acceptance of the novel results obtained from this project in their air quality planning efforts.

Several of the leveraging projects are summarized below:

- Development of in-plume and cross-plume system. The Federal Transit Administration supported much of the development of the cross-plume sensor during CY2005. This project was completed in September, 2005.
- CARB x-plume shoot out. An inter-comparison study is planned by CARB to evaluate the PM remote sensing technologies.
- Emissions from ethanol-diesel fuels (funded by Wright Patterson AFB)
- Emissions from biodiesel used in military equipment (ESTCP project)
- Emissions from controlled diesel engines (ESTCP) project
- Controlling Emissions from busses used in the Cheyenne Mountain Complex (funded by AF and ESTCP)
- Diesel emissions from diesel engines operating in the ports (numerous funding agencies)

Applicable results from these and other leveraged studies were integrated into the information used to create the emissions model.

7.2 Project Publications

The following publications acknowledged SERDP support and appeared in print in 2004:


In addition, the papers and posters were presented at national conferences:


• A.A. Sawant, M. Barth, D.R. Cocker, "Influence of Traffic Density on Heavy Heavy-Duty Diesel Vehicle Emissions," CRC 15th On-Road Vehicle Emissions Workshop, San Diego, CA, April 2005, 22, 2005


• A.A. Sawant, A. Nigam, T. Durbin, J.W. Miller, D.R. Cocker, "Relative Emissions Impacts of In-use and Experimental Diesel Fuels," American Association for Aerosol Research, Austin, TX, October, 2005.

• A.A. Sawant, D.R. Cocker, "Real-World and Real-Time PM Emissions From Heavy-Duty Diesel Vehicles," American Association for Aerosol Research, Austin, TX, October, 2005.


The following manuscripts are under preparation:

• “Real-world emission changes for fuel switching from diesel to biodiesel” This article was rejected by Science and Nature and is currently under consideration by Environmental Science and Technology.

• “In-plume measurement method for fuel-based emission factors from combustion sources” A draft is under internal review.

• “Comparison of cross-plume and in-plume measurements of gasoline and diesel emissions” A draft is under internal review.

• “Comparison of in-plume and mobile laboratory measurements of diesel engine exhaust.” A draft is under internal review.
“Sensitivity of cross-plume lidar detection of vehicle exhaust to particle size, shape, and composition” In preparation.

7.3 CY 2005 Accomplishments
Major accomplishments during CY2004 were:

- The literature survey and review was updated.
- Procedures and testing were completed for the IPET system.
- Infrared gas sensing systems were added to the cross-plume VERSS.
- On-board monitoring systems were evaluate.
- An intercomparison study is being designed for the first half of CY2005 to evaluate ones that might be appropriate for on-board tests scheduled for CY2006.
- Four quarterly reports and one annual report were submitted.

7.4 Problems and Solutions

- Access was gained to Camp Pendleton to perform real-world stationary diesel tests. This was a breakthrough over the previous year, in which other commitments mitigated against using base facilities and personnel for the emissions tests.
- Progress has been made in arranging for mobile source tests at Twenty-Nine Palms during the spring of 2006. It appears that the staff will accommodate the in-plume, cross-plume, and on-board monitors in this experiment.
- Changes in staff, decreased budgets, and military demands have made it difficult to obtain example diesel engines for testing from military bases. Meetings with base personnel are being scheduled for the first part of CY2005 to determine how real-world emissions tests might be made with minimal disruption to normal base operations.
REFERENCES

Abdul-Khalek, I., D. Kittelson and F. Brear, 1999. The influence of dilution conditions on diesel exhaust particle size distribution measurements, Detroit, MI, SAE.


APPENDIX A - STANDARD OPERATING PROCEDURE FOR IN-PLUME EMISSIONS TEST SYSTEM (IPETS)
APPENDIX A  GENERAL DISCUSSION

1.1 Purpose of procedure

The purpose of the In-Plume Emissions Test Stand (IPETS) is to measure and characterize the exhaust from combustion sources. IPETS has been deployed to characterize emission sources, including: diesel and spark ignition on-road vehicles, wood combustion from heating appliances and non-road diesel power generators. The IPETS measures the concentrations of gaseous species, as well as mass and number concentrations for particulate matter (PM) in the size ranges from 30 nm and 10 μm. This procedure details the general information about the measurement principles, as well as how to clean, maintain, prepare calibration standards, setup, collect information and verify data for IPETS.

1.2 Measurement principle

The backbone instrument in IPETS consists of five commercially available real time continuous emission monitoring instruments These real time monitoring instruments include a Fourier Transform Infrared spectrometer (FTIR, Illuminator series 107-I, Midac, Costa Mesa, CA) for gaseous components, two Li-840 CO2/H2O gas monitors (Li-Cor Corp. Lincoln, NE) for CO2, a Electric Low Pressure Impactor (ELPI, Dakiti, Finland) for particle size distributions in number and mass concentration in the range of 0.007 to 10 μm, and two light scattering DustTrak™ for PM2.5 and PM10 mass concentrations. When chemical speciation for PM is needed, time integrated PM filter samplers can be added to the system but not affecting the performance. The schematic for instrument setup is shown in Figure 1. In addition, other instruments can be integrated in IPETS with minor modification.

Figure 1

![Diagram of IPETS setup](image-url)
The sampled air is drawn to the IPETS through a 3/4" ID electric conductive tubing and is split off to the instruments, generally, in three carts. One cart carries the real time gaseous sampler, which contains the FTIR spectrometer, and the ELPI, DUSTTRAK™s and the LI-840s locate in the second cart. When PM chemical speciation is required for studies, the sample air is drawn through a flow mixer where size selective cyclones are installed before PM collection on filter packs. All of the instruments are connected to a serial port server mounted on a rack on the bottom shelf of the real time particulate cart, which is connected to a field computer mounted on the real time gaseous sampling cart. This computer stores all data controls and stores all data collected from the instrument platform while in use.

1.3 Measurement interferences and their minimization

The primary interferent for the IPETS system lies with the FTIR Spectrometer and is caused by water vapor, whose light absorption in the infrared is very strong and broad. It interferes primarily with the FTIR’s measurement of NO and NO2; it is much less of an interferent with the other gaseous species, such as NH3 and SO2. In the presence of high water vapor concentration, it may not be possible to collect usable data on these species from the FTIR if NO and NO2 have a low concentration. Water vapor being as ubiquitous as it is and a primary combustion product, there is not much one can do to remove from the sampling line, short of install a water trap upstream of the instruments. The data analysis SOP describes how to determine if the measured NO and NO2 are valid readings, and how to filter them out if they are not.

1.4 Ranges and typical values of measurements, lower quantifiable limits, precision, and accuracy for IPETS

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Measurement Type</th>
<th>Range of Sensitivity</th>
<th>Typical Value</th>
<th>Detection Limit</th>
<th>Accuracy (%)</th>
<th>Response Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTIR CO2</td>
<td>Gaseous</td>
<td>50-7500 ppm</td>
<td>1000 ppm</td>
<td>9.5 ppm</td>
<td>5</td>
<td>1.5 sec</td>
</tr>
<tr>
<td>FTIR CO</td>
<td>Gaseous</td>
<td>1-1005 ppm</td>
<td>10 ppm</td>
<td>1.3 ppm</td>
<td>5</td>
<td>1.5 sec</td>
</tr>
<tr>
<td>FTIR NO</td>
<td>Gaseous</td>
<td>1-120 ppm</td>
<td>20 ppm</td>
<td>2.2 ppm</td>
<td>5</td>
<td>1.5 sec</td>
</tr>
<tr>
<td>FTIR NO2</td>
<td>Gaseous</td>
<td>0.5 – 20 ppm</td>
<td>2 ppm</td>
<td>0.96 ppm</td>
<td>5</td>
<td>1.5 sec</td>
</tr>
<tr>
<td>ELPI</td>
<td>Particle Concentration</td>
<td>0.001 mg/m3 – 100 mg/m3</td>
<td>0.1 mg/m3</td>
<td></td>
<td>5 sec</td>
<td></td>
</tr>
<tr>
<td>DUSTTRAK™</td>
<td>Particle Concentration</td>
<td>0.001 mg/m3 – 9 mg/m3</td>
<td>0.1 mg/m3</td>
<td></td>
<td>1 sec</td>
<td></td>
</tr>
<tr>
<td>Li-Cor CO2</td>
<td>Gaseous</td>
<td>5-3000 ppm</td>
<td>1000 ppm</td>
<td></td>
<td>3%</td>
<td>1 sec</td>
</tr>
</tbody>
</table>

1.5 Responsibilities of personnel for carrying out portions of this procedure

The user/operator is responsible for understanding the basic principles by which the instruments operate. The user is responsible for preparing the instruments for field use, setting them up in the field, operating and collecting data, and processing data after field work is finished. The user/operator should read the SOPs for FTIR, ELPI, DUSTTRAK™, and Li-840 monitor.

Standard Operating Procedures for Fourier Transform Infrared (FTIR)
Standard Operating Procedures for Electric Low Pressure Impactor (ELPI)
Standard Operating Procedures for DUSTTRAK™
Standard Operating Procedures for Li-Cor 840 CO2/H2O gas monitor.
2. APPARATUS, INSTRUMENTATION, REAGENTS, AND FORMS

2.1 Apparatus and instrumentation

2.1.1 Description

Fourier Transform Infrared (FTIR) Spectrometer

The IPETS uses a FTIR spectrometer as its primary gaseous concentration measurement. A Michelson interferometer is used to make an interferogram from a carbon blackbody source and a 639.9 nm laser. Measurement of gaseous concentration is made by comparing the difference between a nitrogen background taken prior to sampling, and the absorption characteristics of sampled gas. Since the photonic absorption characteristics of light are a unique identifier of chemical species, and since absorption is approximately linear with concentration due to Beer’s Law, the instrument can determine the concentration of sampled gas using a piecewise linear classical least squares algorithm. The collection of calibration species of known concentration are together known as a method, and the process of making one are described in detail in the FTIR SOP. IPETS FTIR uses a custom sampling cell, with a folded path length of 10 m. Typical flow rates through the sampling cell are 60 lpm. More detailed information about the FTIR spectrometer is included in the FTIR SOP. With our current method, the FTIR Spectrometer measures and outputs the concentration of CO, CO2, NO, NO2, ethylene, propane, hexane, ammonia, SO2 and N2O.

The FTIR Spectrometer has a response time of approximately 1.5 seconds in proper operation. This corresponds to the time needed to replace the air in the sampling cell, and is also a function of the movement of the interferometer. Since the response time depends on the physical motion of the mirrors on the interior of the unit, this time can differ from sample to sample by several milliseconds.
Electronic Low Pressure Impactor (ELPI)

The ELPI (Dekati Instruments, Finland) uses a unipolar corona charger to impart a positive charge on the measured aerosol. The particles then travel through a cascade impactor and are deposited on one of 12 substrates (0.007 µm to 10.0 µm) based on their aerodynamic diameter. The substrates are electrically isolated with Teflon supports and the accumulating charge on each of the substrates is measured by an array of electrometers. The measured current on each of the stages is proportional to the number of particles depositing on the stage. The ELPI measures the number concentration of particles based on their aerodynamic size at a frequency of 1 Hz. The response of the ELPI is changeable in the software. In its most sensitive mode, the ELPI has a response time of 30 seconds. In its least sensitive mode, the response time is approximately 1 second. In most instances, the faster response time is used. More detailed information about the ELPI is included in the ELPI Manual and SOP.

DUSTTRAK™

The DUSTTRAK™ (TSI, Lakeshore, MN) measures particle scattering at a wavelength of 780 nm in a cone of scattering angles near 90 degrees. PM$_{10}$ and PM$_{2.5}$ aerodynamic size cut inlets may be installed upstream of the analytical chamber to limit the size of measured aerosol particles. The DUSTTRAK™ has a flow rate of 1.7 lpm and is calibrated using NIST Arizona Road Dust standard. The calibration material is lightly absorbing with a median diameter of approximately 2 µm. The instrument is most sensitive to
non-absorbing particles with diameters on the same length scale as the light source (0.78 µm). The sensitivity is reduced for particles with sizes above and below this maximum. Exhaust particles have a similar DUSTTRAK™ mass scattering efficiency to the calibration aerosol despite their difference in size and index of refraction. As a result, the DUSTTRAK™ provides reasonable (within a factor of 2) measurements of aerosol mass for both exhaust and dust particles. In an evaluation of the DUSTTRAK™ and other real time instruments, Moosmüller et al., (2001) determined that the DUSTTRAK™ provided a useful fast response measurement of particle concentration. Accurate real time measurements of aerosol mass are possible if the DUSTTRAK™ is calibrated with filter-based measurements of particle mass. The response time of the DUSTTRAK™ is 1 second. Although DUSTTRAK™ can be set to a longer averaging interval, IPETS records data every second.

LI-840 CO2/H2O Gas Analyzer

The LI-840 CO2/H2O Gas Analyzer (Li-Cor Corp, Lincoln, NE) is an absolute, non-dispersive, infrared (NDIR) gas analyzer based upon a single path, dual wavelength, infrared detection subsystem. The CO2 and H2O measurements are a function of the absorption of IR energy as it travels through the optical path. Concentration measurements are based on the difference ratio in the IR absorption between a reference and sample signal. Reference and sample channels measure infrared gas absorption in a single path through the use of narrow band optical filters with appropriately selected bands. The CO2 sample channel uses an optical filter centered at 4.26 micrometers, corresponding to the absorption band for CO2. The reference channel for CO2 has an optical filter centered at 3.95 micrometers, which has no absorption due to CO2. The H2O sample channel uses an optical filter centered at 2.35 micrometers, which is outside the absorption band of H2O. The response time of the Li-Cor is 1 second. This, like the FTIR spectrometer, is flow dependant, so if flow differs from the normal 1 lpm, the response time can change.

2.1.2 Maintenance

Prior to any study, the following maintenance procedures should be followed. In the case of a particular long or high emission concentrations study, it may require performing maintenance between measurements. Maintenance of instruments should be conducted in a good housekeeping environment to secure parts during maintenance.

FTIR Spectrometer

There are two types of maintenance needed for the FTIR Spectrometer. Before each field project, the interior of the sampling cell needs to be cleaned. This procedure is described below. Every year, the interior of the main unit needs to be cleaned and readjusted. This is described fully in the FTIR SOP ****. Conduct the maintenance with extreme caution.

- Make sure the FTIR is turned off and unplugged before doing any maintenance.
- On the outside of the sampling cell, opposite the FTIR unit, there are 6 hex screws. Use a 15/32” hex wrench from the tool kit to loosen and remove these screws.
- Remove the side of the cell by slowly rocking the plate back and forth. Avoid dropping the side plate when it comes loose.
- Pull the plate out and avoid touching the mirror on the opposite side of the plate. This is covered in gold foil and is very fragile. Slight contact can damage the surface, leading to reduced instrument response.
- Place the plate somewhere safe, making sure the mirror does not touch anything. Look inside the sampling cell, using a flashlight if necessary. If there is much material inside the cell, use a vacuum to clean out as much as possible.
- After cleaning the inside of the unit, it’s time to clean the mirror with a spray cleaner. DO NOT touch the mirror. Any soap water solution with a spray applicator will work. Also, you can use isopropynol or
methanol and spray the surface. Give the mirror a few minutes to dry, and then wash with clean water. Repeat if necessary. Once the surface is clean, wash again with alcohol and set down to dry.

- Allow the mirror an hour to dry.
- Replace the plate on the side of the sampling cell and refasten the screws. Make sure all the screws are tight; otherwise the alignment can be thrown off.

**ELPI**

- The impactor stages need to be cleaned before any field experiment. Open the front panel of the ELPI and unscrew the connector wing nuts at the top of the impactor column. Remove connector and all BNC connectors. Carefully push upwards from the bottom of the charger. Pull out the impactor column, following the track. Make sure to keep track of both rubber gaskets.
- On the top of the impactor column, raise both levers, releasing the stages. Carefully remove the stages, make sure not to lose any pieces.
- Place the acceleration nozzle plates and impaction substrates of the impactors in a sonicator, which is filled with distilled deionized water (DDW) with small amount of non-aggressive detergent or soap. Run the sonicator for 30 minutes to loosen up any material on the surface of the stages, and to remove any grease or oil remaining. If excessive particulate deposit is observed on the impaction substrate, repeating the sonication process again with 15 minutes run time.
- Remove all pieces from the sonic cleaner. Wash all items with DDW, to remove all soap and loosened grime. Wash again with an alcohol, such as isopropylol or methanol, followed by DDW again, to remove potential residual organic material. Blow the acceleration nozzle plates with clean compressed air to reduce potential clogging of the nozzles by the residual solvent if drying is too slow. Place all pieces on a drying mat covered with Kimwipes and let dry.
- Use a pipette to place 0.2 ml of mineral oil (Leybold HE 125/FG Export, PA) on the middle of each impaction substrate. The oil will spread out to the edge of the stage.
- Using a high vacuum grease, replace all the O-rings on the impactor column. Be careful not to spread any vacuum grease onto the sintered plates or the Teflon separators.
- Reassemble the impactor column. The order of impactor stages is determined by the number etched on the side. The stage marked “1” goes on the bottom, and proceeds upwards. The spacer stage goes between “10” and “11”, which should be written on the side.
- When reassembling the column, it is important not to use gloves. These can have a static charge, which can transfer to the Teflon dividers during handling. This can affect the performance of the instrument. Refer to the ELPI manual for more information on handling.
- Secure stages in place using both red latches on the top of the impactor column shell. Make sure the latches are equally tight on both sides.
- Make sure that the cable on the bottom stage is turned entirely and secured to the side of the column. If not, the column leaks which affects the accuracy of ELPI.
- Place the rubber gasket back on the impactor column, reapplying grease if necessary. Place column back inside the ELPI casing, making sure it is mounted on the rail at the bottom, slowly pushing all the way towards the back of the casing.
- Replace rubber gasket on the top of the column, and gently pull down charger until snug against gasket.
- Reattach the connector piece and tighten using wing nuts.
- Reattach all cables. The unit is now cleaned and reassembled.
- If the charger needs to be replaced, unplug all cables and remove column. Pull down on charger gently, until charger comes out. Take new charger and inspect the O-rings. There should be a slight grease
coating, to maintain a vacuum seal. If not, grease the O-rings. Place new charger column inside the ELPI and gently push up as far as possible. Plug cables back in and reinsert column.

**DUSTTRAK™**

- Remove DUSTTRAK™s from case and plug into an electrical outlet. Turn on DUSTTRAK™ by pressing the power switch on the front.
- Once the startup has finished, attach the flow meter in the case to the inlet of the DUSTTRAK™. Ensure that it is reading 1.6-1.7 lpm. If it is out of this range, take the screwdriver and turn the flow control screw on the top of the DUSTTRAK™ unit to adjust the flow rate. If you can’t bring the flow to 1.6 lpm, the pump may need to be serviced.
- Remove the flow meter and attach the filter. Read the front of the display. The reading should fall to -0.01 to 0.01 ug/m³. If it is out of this range the instrument needs to be rezeroed. To do this, leave the filter attached. Hold down the calibrate button for 5 secs until a countdown appears on the display. When the display reads 0, release the button. Now press the sample button again, the timer should reappear and countdown from “60”. Once it reaches 0, the instrument is rezeroed. Remove the filter and check that the instrument is reading +/-0.01.
- Power down the DUSTTRAK™ and turn over.
- Unscrew the two circular panels on the back, using the tool in the DUSTTRAK™ case. Pull out and examine the filters. If there is significant discoloration, the filters should be replaced. There should be several replacement filters in the case.
- Replace the circular panels. The DUSTTRAK™ is now ready for operation.

### 2.1.3 Spare parts list

**FTIR**

- 1 extra heated sampling cell (Midac, Irving, CA 919-577-2216)
- 1 extra A/D card (Midac, Irving, CA 919-577-2216)
- 2 extra Infrared sources (Midac, Irving, CA 919-577-2216)
- 1 extra set KRS-5 windows (Midac, Irving, CA 919-577-2216)
- 2 inspection mirrors
- 2 flashlights
- 2 sets Allen Wrenches

**ELPI**

- Mineral Oil (Leybold HE 125/FG Export, PA)
- Extra Impaction plates – Dekati Ltd, Finland, 358 3 3578 100
- 2 extra corona chargers - Dekati Ltd, Finland, 358 3 3578 100
- Zeroing HEPA filter

**DUSTTRAK™** - (all from TSI incorporated, Shoreline, MN, 651-490-2811)

- Screwdriver
- Impaction grease
- Extra pm 2.5 and pm 10.0 sampling heads
- RJ-45 to DB9 cable
- Zeroing filter
- Flowmeter

**Li-Cor** (all from Licor Biosciences, Lincoln, NE, 402-467-3576)

- Cotton Swabs
- Extra terminal block
- Extra fuses
• Power supply

2.1.3.1 Reagents and supplies

• Mineral Oil (Leybold HE 125/FG Export, PA)
• Methanol
• Distilled deionized water
• Vacuum grease
• Soap solution
• Sonicator
• 1” conductive tubing (TSI, Shoreview, MN)
• 1/2” conductive tubing (TSI, Shoreview, MN)
• 1/4” conductive tubing (TSI, Shoreview, MN)
3. CALIBRATION STANDARDS

3.1 Preparation of working standards, ranges of standard values, and traceability to primary standards

Both a gaseous and a particle standard are needed for the IPETS. An Environics 2300 gas mixer (Environics, Tolland, CT) is used to prepare gaseous standards, along with tanks of research grade calibration gas to create a known gas mixture for use as a standard.

Environics Gas Mixer

1. On the back of the Environics gas mixer are 4 ports labeled 1-4. These connect to 4 mass flow controllers inside the unit. Each port has a maximum flow rate, port 1 is 10 lpm, port 2 is 5 lpm, port 3 is 2 lpm and port 4 is 1 lpm. Depending on the calibration/nitrogen ratio needed, hook up the gas tanks to the appropriate port.

2. Turn on the Environics. Press “maintain ports” and then use the arrow keys to highlight ports 1 and 2. You need to program the Environics with the correct gasses and their cylinder concentrations. Press ‘select gas” and choose the calibration gas. Enter the concentration in the tank, and press “calculate k”. Exit out to the front screen.

3. Connect Teflon line from the output port on the back of the gas mixer to the bottom port on the side of the FTIR sampling cell. Make sure the solid shutters are in place and firmly seated and that both valves are open.

4. Press “Concentration Mode” on the Environics. On the port connected to the calibration gas, choose the desired concentration. For the nitrogen check that it is marked “balance”. Choose the total desired flow rate. Try to have a total flow rate above 2 lpm. Press “start” to begin mixing gas.

5. Allow several minutes for the calibration gas to displace the ambient gas in the sampling cell. The FTIR measurement should approach the programmed concentration on the Environics. If it stabilizes within 5% of this value, we consider this quality verified.

6. For CO2, we can also use the Environics to verify the Li-Cor’s reading. Connect a sampling line from the top port of the Spectrometer sampling cell to the inlet on the Li-Cor. When the FTIR reading stabilizes, check the Li-Cor reading as well. It should be within 3% of the Environics concentration.

3.2 Usage of standards

Standards are used to test that the instruments are reading accurately within the calibrated range. Prior to any major testing project, a standard should be made and tested for each of the gaseous species, and at several points bridging the calibration range. If the instruments report within 5% of the standard, the instrument is calibrated correctly.

3.3 Typical accuracy of calibration standards

The Environics Gas Mixer creates gas mixtures that are within 1% accuracy.
4. **PROCEDURES**

4.1 **Start-Up**

- **Power Requirement for IPETS**
- The Total power requirements of the IPETS system is approximately 8kw. The load can depend on the number of pumps used for drawing air through the filters. This total assumes 4 total pumps, 3 for the filters and 1 for the spectrometer. Each pump requires approximately 1.1kw, so if less or more are needed, the total draw changes accordingly. The power draw by cart with 4 total pumps is as follows.
  - FTIR Spectrometer Cart – 2 kw
  - ELPI Cart – 2.5 kw
  - Filter Cart – 3.5 kw
  - Pumps, when first turned on, draw more power than during stable operation. Its best to turn on pumps one at a time, and let warm up for 15-30 seconds before turning on the next.
- If there is no onsite power, set up the generator downwind from the IPETS sampling inlet so the emissions from the power generator is sampled. There are 100’ power cords in one of the storage boxes; it shouldn’t be necessary to place the generator this far away, 25-30’ is sufficient. If using onsite power, there is an adapter on the exterior of the driver’s side of the van. This runs to a 360 V adapter on the inside of the van. Attach this to the yellow power distribution box. This converts to 15 amp/120volt, as is required by the carts. Each of the carts has a power strip mounted on the underside of the top shelf. The power load for each cart is balanced so that this strip is capable of powering all instruments mounted on the cart using 15 amps. As such, make sure all instruments on the cart are plugged into that carts strip.
- To turn on the generator, make sure it has enough gasoline and oil. Set the choke switch and fuel tank lines on the side to open. Make sure the breaker on the front is closed. Pull on the rip cord until the generator starts up. Close the choke to stabilize the motor.
- Power up all the instruments except the pumps and check that they are receiving power. To check that it is working, when it is turned on all the other LEDs should light for several seconds.

**FTIR Spectrometer**

- Now that the instruments are powered, fill the spectrometer with liquid nitrogen. This is used to regulate the internal temperature of the spectrometer and to cool the detector. It’s important that the liquid nitrogen levels are kept high, the Spectrometer will not work correctly if it runs low. Pour liquid nitrogen into the funnel on the top of the unit., until liquid nitrogen gushes out of the funnel. This indicates that the internal reservoir is full. When first filling the instrument, allow 30 mins for the temperature to stabilize before collecting data.
- Make sure that all the communication cables are properly attached. There should be a tag on each cord indicating where it should be connected. Note that the ELPI’s communication cable doesn’t go to the serial port box on the ELPI’s cart, but rather to the one on the FTIR Spectrometer cart.
- Attach the regulator to the N2 canister. Make sure that the solid shutters are in place and firmly seated in the FTIR Spectrometer sampling cell. Attach a Teflon line from the N2 tank to the bottom port on the side of the sampling cell. Make sure that both the bottom and top valve are open, and open up the N2 tank. Open the regulator a little, only 4 liter per minute or so is necessary. Let the nitrogen gas flow through the sampling cell for several minutes, displacing the ambient gas with nitrogen gas. After several minutes, close off the valves and close the N2 regulator.
- Setup the laptop computer on the FTIR spectrometer and turn on. Attach the ribbon cable adapter from the FTIR into the PCMCIA card in the laptop. Connect the computer to the Serial adapter box on the FTIR spectrometer cart by USB cable and to the Moxa server on the ELPI cart with an RJ-45 crossover cable. This cable looks like a standard Ethernet cable, except that it has yellow coating on the adapter pieces. It is
important that if this cable is lost and needs to be replaced, that a crossover cable is used. A standard Ethernet cable will NOT work.

• The order in which you turn on the programs used to control the instruments is important. As such, if a program crashes or is accidentally quit, it is best to turn off all the programs and start them again in the order listed below.

- First, check that the computer is communicating with the Moxa serial port server. Open the N-Port Administrator Suite under the start menu. Right click on the monitoring icon and select broadcast search. If the Moxa server is communicating properly, an ip address should appear in the table. If nothing is showing, check that the Moxa server is turned on, and that a crossover cable is connecting the laptop and the Moxa server.

- If the MOXA server is working, the next step is to start Autoquant Pro, located on the desktop. The current version is 4.0.0.104, updates are available from Pete Zemeck at 919-577-2216. This is the program used to communicate with the FTIR Spectrometer. Once the program has loaded up, click on the “connect” button located near the upper right of the screen. The button should change in several seconds to “disconnect”; this indicates that the program is communicating with the Spectrometer. If it doesn’t change, or the program prompts you with an error message, something is wrong with the connection. Make sure that the spectrometer is turned on and that the cable is firmly attached. If the program attempts to communicate with the instrument too soon after the instrument starts up, it will cause errors. To solve this, turn off the instrument and let sit for a minute. After a minute, turn on the instrument and let sit for another minute. At this point, press the “connect” button again. This usually works, but if it doesn’t try again.

- Now it’s time to check that the FTIR spectrometer is properly aligned and cooled. Click on the “align” button near the upper left of the screen. Now make sure the “show voltages” button near the bottom is unchecked.
If the instrument is correctly cooled and aligned, the maximum should be around 20000 and the min should be 25000. If these values are higher than this, that is fine. If they are significantly below this value, make sure the nitrogen reservoir is filled. Also, try restarting the program, there is a bug causing it to occasionally misreport the detector values. If these don’t resolve the problem, the instrument may need to be realigned or cleaned. Refer to the FTIR SOP for detailed instructions on how to do this.

Click on “File” and then “open method”. The current method we are using is SVP_DRI.aq4, and is located under C:/documents and settings/all users/shared documents/aq4/method.

Click on the parameters button, and then on “cells”. Make sure that “use default temperature” and “use default pressure” are UNCHECKED.

- Click the “background” button. The FTIR spectrometer will start collecting data from the instrument to form a background reading which future readings will be compared against. Note that it is important that the sampling cell is filled with nitrogen for this. If more than 30 mins has passed since the cell was purged with N2, purge as described above.

Once background is finished, click on the “method” tab. Check that the method listed is the most current. Methods are stored in the directory. Check the buttons in the top window marked “CO2” and “water” are checked, and no others. Press the calibrate button.

- The FTIR spectrometer is now ready to start collecting data. Press the analyze button, and then make sure that the “continuous” button is checked. Press “start” to start collecting data.

- Minimize AutoQuant Pro.

Li-Cor 840 CO2/H2O gas monitors

- Next, its time to open the programs to communicate with the Li-Cor CO2 monitors. Open li840 v1.0.0 on the start menu. Open a second copy of the program as well. For the first instance, press the connect icon in the upper left. Make sure the com port is set to 20, and that data output is set to once a second. Press “connect”. Now press “logging” and then “start”. Choose a filename for the data. Make sure that the file name includes the date, type of sampling the serial number of the Li-Cor. An example would be “5-25-05_BK_LiCor0104”.

- Now repeat for the second instance of li840 v1.0.0, except making sure the com port is set to 21. Also, note that the serial number is different for the save file.

Make sure a filter is placed inline upstream of both Li-Cor units. This protects the interior of the units from damage caused by particulates.

DUSTTRAK™ and GRIMM counter

- Open “Inplume serial.llb” on the desktop and double-click “Inplume serial instruments.VI”. Press the “setup” tab and fill out all the fields. Note that the “project name” field determines where the data will be saved. Press control+r or the run arrow in the upper left of the screen. This will run the program and begin collecting data from the DUSTTRAK™s and the GRIMMs.

ELPI

- Start up the ELPI control program with ELPIVI 3.1 in Window. Choose “Start Measuring” when prompted. On this first page, it’s important to enter a filename for the saved data. Generally we use a naming convention that includes the date and some description of the sampling site. An example might be “12-02-05DR1stagingbay”. Once a name is chosen, fill in the other blanks with information about the location and operator, these will be saved in the data file. Click on the communications tab, make sure that serial port is set to Com 2 and that the baud is 19200. All other variables should be correct by default. A copy of the proper settings is stored in c:/programfiles/elpi and is named init.bin.

* Press “ok” and the ELPI software will attempt to communicate with the ELPI hardware. It may take a minute or two for communications to stabilize, before that time it may only update every 10 secs or so, rather than
Once the ELPI is communicating without error, the unit needs to be zeroed. ELPI requires 30 minutes warm-up time, during which the electrolyzer is stabilizing in this time. Zeroing or sampling before this is finished can cause increased noise level in the sampling.

Press the “range button” on the consol panel, and choose 400,000 fA. Attach the HEPA filter to the barb at the top of the ELPI. Turn on the ELPI pump, mounted on the bottom right of the ELPI cart. Reading the pressure indicator on the numeric values panel, adjust the valve on the ELPI vacuum line on the bottom of the top shelf of the ELPI cart until the gauge reads 100 ±5 torr.

Press the “flush”, “charger” and then “zero” button on the console panel. They should light up and a new panel will appear. Leave the instrument alone for 30 secs, during which time the ELPI will be zeroing. Once this is done, the ELPI is ready for operation.

The IPETS platform has the capability to add new instrumentation easily. For example, at the moment Pat Arnott’s Photoacoustic sampler is mounted on the ELPI cart. It shares a sampling line with the Li-Cor and DUSTTRAK™. The Photoacoustic control software is not integrated with the IPETS laptop, and it has its own control computer. Refer to the Photoacoustic SOP **** for instructions on properly operating this system.

Now that the instruments are communicating properly, its time to connect all of the sampling lines. Most of the lines are connected to the carts already, and you simply need to make sure the correctly labeled lines are connected to the correct instrument.

Take the stainless steel adaptor from the tubing bin and attach to holder in the ceiling, above the side door. There is 1 source flow line and 3 outflow lines. The source flow line goes to the source, either the road sampler in the case of road sampling, or directly to the exhaust in the case of generator or chimney sampling. The first outflow line is 1/2” and goes to the barb at the upper right of the ELPI cart. The second line is 1” and goes to the sampling cell of the spectrometer. The last line goes to the filter sampling cart, which also serves as a bypass flow if no filters are being used. When running sampling line, it is important to avoid any kinks or sharp bends, as this can cause impaction and particle loss.

4.2 Routine Operation

Make sure the “continuous” tab is marked in the analysis tab in AutoQuant Pro. Press “start” to begin sampling. The spectrometer will now start collecting data and automatically saving it. Results will be updated on the analysis tab.

On the ELPI software console panel, press the “save” button to begin saving data. Note that the ELPI software DOES NOT SAVE DATA BY DEFAULT, so it is vital not to skip this step. Data is saved in C:\program files\ELPI\Data.

Li-Cor software should already be saving data, but open each of the li840 v1.0.0 screens and check that the window marked “pc logging” reads 1 sec.

Depending on the project, different numbers of filters or size cuts will be collected. Each of the filter mounts on the filter sampling unit is customizable. Install filters by unscrewing caps at the bottom of the metal cylinders. Remove blank caps and install filter holders from bags supplied by the lab. Be careful not to touch filter, and to only use filters from a single bag at a time. Filters will come with a data sheet, fill this out and keep stored in the bag. To set the size cuts on the filters, open or close the valve at the top of the cylinder to adjust the flow rate. Setting the flow rate to 113 lpm results in a PM 2.5 cutoff, and a flow rate of 25 lpm corresponds to a PM 10 cutoff. While sampling, monitor this flow to make sure it doesn’t wander.

If no filters are being used, it is still important to run the pumps on the filter sampler in order to provide a bypass flow. Use a set of filter holders as dummy filters to maintain the same sampling condition. Keep the empty filter holders screwed in and set a total flow rate through the sampler to 270 lpm.
A pump is mounted on the bottom of the FTIR Spectrometer cart. Plug this pump in and use the flow meter on the line between it and the back of the FTIR sampling cell to adjust the flow rate through the spectrometer to 40 lpm.

Plug in the small pump on the bottom of the ELPI cart to pull air through the Li-Cor CO2 monitors. There are 2 flow meters mounted in line, adjust the valve to set each to 1 lpm.

At this point, the instruments should be collecting and saving data, and all of the sampling line should be properly installed. The user needs to monitor the instruments though as well as perform several maintenance tasks while the experiment is in progress.

Every 2 hours, the liquid nitrogen reservoir in the FTIR needs to be refilled. Pour liquid nitrogen into the funnel, and top off, as described in the previous section. Also, the instrument needs to be rezeroed. Press the “stop” button in the analysis tab on Autoquant Pro. Repeat the backgrounding procedure for the FTIR Spectrometer from the previous section. Now press the “resume current” button in the analysis tab.

The filters will need to be replaced once they are loaded. Depending on the sampling source, dilution factor and flow rate, they can become loaded in anywhere from 10 mins to 6 hours. A good rule of thumb is to watch the flow rate through the filter. Once it starts decreasing, there is sufficient material on the filter medium to create resistance meaning it is almost time to replace the filter. To replace, close off the large valve on the top of the filter sampler. Now close off the valve behind the filter, then turn off the pump. Carefully unscrew the filter holder and place within the bag provided by the lab. Finish filling out data sheet, and place filters in the cooler. Carefully remove the last set of filters and store. Screw in empty caps.

The ELPI and Li-Cors, once set up, shouldn’t need any user intervention to continue working properly. The user should, however, monitor the appropriate software to ensure that the data is being saved correctly and that there is no malfunction. In particular, the user should watch the current and voltage gauges on the “numeric values” panel for the ELPI. The voltage should remain at 5 ±1 kV, and the current at 1 ±.1 A. If the values fall out of this range, something is wrong with the measurement. The unit may need to be cleaned.

If an instrument fails during sampling, restart the instrument and software as described in the above steps. It is important to note, however, that most of the programs will save over old data files, rather than append to them. It is vital therefore to change the file name rather than use the same ones used earlier in the day. To indicate this, we generally add the letter “a” to the end of the new file name to indicate. For example, if the ELPI begins the day saving to “5-22-05DRIstagingbay” and fails, when we restart we need to make a new filename so as not to save over this one. Following our standard convention, we would name it “5-22-05DRIstagingbay-a”. If the instrument were to fail again, we would name this “5-22-05DRIstagingbay-b” and so on. The exception to this is the FTIR Spectrometer, which will automatically save data to a new directory, rather than save over old data.

4.3 Shut-Down

First, maximize AutoQuant Pro and press the “stop” button in the analyze tab. Press “disconnect” on the “instrument” tab, then close down AutoQuant Pro and turn off the FTIR Spectrometer by flipping the power switch on the transformer at the back of the cart.

Bring up the li840 v1.0.0 windows and hit “logging” and then “stop”. Press “disconnect” and close the program.

In Inplume Serial Instruments, click the stop button near the top.

On the “console” panel of the ELPI software, press “exit” and then “ok”.

Turn off all the pumps. Carefully remove the last set of filters and store. Screw in empty caps.

If a portable drive is available, back up all data collected. FTIR Spectrometer data is stored in C:\Documents and Settings\All Users\Documents\AutoQuant4\collect. ELPI data is located in C:\programfiles\elpi. Li-Cor files are located wherever the user chose to save them, usually the desktop. GRIMM and DUSTTRAK™ data is stored under d:\teststanddata\"projectname".
• Disconnect all sampling line upstream of the steel adaptor and carefully store in the tubing bin.
• If sampling is done for the experiment or if van needs to be moved before next sampling, load all spare parts bags and generator. Remove Li-Cors and place within protective cases.
• Always bring cooler with filter samples inside after finishing sampling. Filters need to be kept cool, and should not be left outside or in the back of the van if possible.

4.4 Checklists
Nicholas, summarize the checklist in procedures.

5. QUANTIFICATION
5.1 Calibration procedures
FTIR Spectrometer
The FTIR Spectrometer shouldn’t need to be recalibrated very often, unless some fundamental change is made to the system. For example, if the laser is replaced, it may be necessary to also recreate the calibration spectra. Follow the directions in the FTIR SOP to do so.

ELPI
Send the ELPI back to the manufacturer to be recalibrated, which is required every 3 years.

DUSTTRAK™
Send the DUSTTRAK™s to TSI every 2 years to be recalibrated. Consult the DUSTTRAK™ manual for vendor contact information.

Li-Cor CO2 Monitor
To calibrate the Li-Cor CO2 monitor, follow these steps
- Turn on li840 v1.0.0 in the start menu.
- Begin communicating with the instrument and press “view” and then “calibration”.
- Use the Environics gas mixer to create a 100% N2 gas mixture and run gas through inlet.
- Press “zero” and wait for instrument to finish.
- Now set gas mixer to provide a 3000 ppm CO2 source.
- Enter 3000 in the “span” window and press “span”.
- Instrument should now be calibrated, choose several values between 0 and 3,000 ppm on the gas mixer to check calibration.

5.2 Calculations (including background subtraction, interference corrections, and precision calculations)

6. QUALITY CONTROL
6.1 Performance testing
The instruments should be tested for performance at least a month prior to any sampling experiment; this gives time to correct any problems encountered before scheduled testing.

6.2 Reproducibility testing
6.3 Data validation feedback

7. QUALITY ASSURANCE
7.1 Performance audit schedule
Performance should be tested at least a month prior to sampling experiment, or in event of extended nonuse, monthly.
Table 2. Description of instrumentation of In-Plume monitoring system.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Measurement</th>
<th>Method</th>
<th>Response Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Midac I-Series FTIR</td>
<td>Molecular gas species concentration</td>
<td>Dispersive IR</td>
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</tr>
<tr>
<td>Dekati Electronic Low Pressure Impactor (10 lpm)</td>
<td>Aerodynamic number size distribution of particles</td>
<td>Current dissipation arising from deposition of charged particles to impactor substrates</td>
<td>5</td>
</tr>
<tr>
<td>TSI DUSTTRAK™</td>
<td>Particle mass</td>
<td>780 nm laser light scattering of particle stream at 90 degrees</td>
<td>1</td>
</tr>
<tr>
<td>Nuclepore filter sampler</td>
<td>Mass and chemical composition of particles and gases</td>
<td>Collection and analysis of exposed filters</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>TSI 4043 Mass Flow Meters</td>
<td>Mass flow through filter</td>
<td>Hot wire anemometer</td>
<td>&lt;1</td>
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