Diesel Emission Control – Sulfur Effects (DECSE) Program

Phase I Interim Data Report No. 4:

Diesel Particulate Filters – Final Report

January 2000

The test program and subsequent data analysis represent a collaborative effort of a technical work group consisting of representatives from the U.S. Department of Energy, national laboratories, the Engine Manufacturers Association, and the Manufacturers of Emission Controls Association. The work group prepared this report using methods believed to be consistent with accepted practice. All results and observations are based on information available using technologies that were state of the art at the time of this effort. To the extent that additional information becomes available, or factors which analyses are based change, the findings could subsequently be affected.

DECSE Interim Data Report #4: Diesel Particulate Filters—Final Report
Table of Contents

List of Acronyms and Abbreviations

bhp-hr – brake horsepower-hour
BPT – balance point temperature
BSFC – brake-specific fuel consumption
CDPF – catalyzed diesel particulate filter
CO – carbon monoxide
CO_2 – carbon dioxide
CR-DPF – continuously regenerating diesel particulate filter
cpsi – cells per square inch
DECSE – Diesel Emission Control Sulfur Effects
delta-P – change in pressure
DOC – diesel oxidation catalyst
DOE – U.S. Department of Energy
DPF – diesel particulate filter
EMA – Engine Manufacturers Association
EO – engine-out
ESC – European steady-state cycle
ETC – European transient cycle
ETS – Engineering Test Services
FLRS – full-load, rated speed
g/bhp-hr – grams per brake horsepower-hour
HC – hydrocarbon(s)
HDD – heavy-duty diesel
IC – ion chromatography
kPa – kilopascals
MECA – Manufacturers of Emission Controls Association
mg - milligram
ml – milliliter
mm - millimeter
NAAQS – National Ambient Air Quality Standards
NIST – National Institute of Standards and Technology
NO – nitrogen oxide
NO_2 – nitrogen dioxide
NO_3^- – nitrate
NO_x – oxides of nitrogen
nm – nanometer
NREL – National Renewable Energy Laboratory
OICA – Organisation Internationale des Constructeurs d'Automobiles
ORNL – Oak Ridge National Laboratory
OTT – Office of Transportation Technologies (of the U.S. Department of Energy)
PDP-CVS – positive displacement pump constant volume sampler
PM – particulate matter
ppm – parts per million
RE – reduction efficiency
RH – relative humidity
rpm – revolutions per minute
scfm – standard cubic feet per minute
SCR – selective catalytic reduction
SMPS – scanning mobility particle sizer
SO_2 – sulfur dioxide
$SO_4^=$ – sulfate
SOF – soluble organic fraction
μg – microgram

Section 1

Executive Summary

ES.1 Introduction

The Diesel Emission Control–Sulfur Effects (DECSE) Program is a joint government/industry program to determine the impact of diesel fuel sulfur levels on emission control systems whose use could lower emissions of nitrogen oxides (NO_x) and particulate matter (PM) from on-highway trucks in the 2002-2004 model years. The program is designed to enhance the collective knowledge base on engines, diesel fuels, and emission control technologies in a systems approach to (1) guide industry in developing lower emitting applications of their products, and (2) provide a portion of the technical basis for government decisions on regulating the content of sulfur in diesel fuel.

Phase 1 of the program was developed with the following objectives in mind:

(A) Evaluate the effects of varying the level of sulfur in the fuel on the emission reduction performance of four emission control technologies

(B) Measure and compare the effects of up to 250 hours of aging on selected devices for multiple levels of fuel sulfur.

Four emission control technologies are being tested in Phase 1 of the program: (1) NO_x adsorber catalysts; (2) diesel particulate filters (DPFs); (3) lean-NO_x catalysts; and (4) diesel oxidation catalysts (DOCs). The devices being tested include commercially available technologies as well as state-of-the-art technologies that are under development. The sulfur contents in the test fuels are 3, 16 (NO_x adsorber catalysts only), 30, 150, and 350 parts per million (ppm). The 3-ppm sulfur content fuel represents a diesel fuel that is essentially "sulfur-free." The engines in the DECSE program represent currently available models, and they were selected to provide a representative source of diesel exhaust and various exhaust temperature profiles to challenge the emission control devices. Important characteristics of the exhaust are exhaust flow rate, temperature, and concentrations of NO_x, hydrocarbons (HC), carbon monoxide (CO), and PM.

Participants in the program include representatives from the U.S. Department of Energy's Office of Heavy Vehicle Technologies within the Office of Transportation Technologies (OTT), the National Renewable Energy laboratory (NREL), Oak Ridge National Laboratory (ORNL), the Engine Manufacturers Association (EMA), and the Manufacturers of Emission Controls Association (MECA).

This is the fourth DECSE Interim Report, and the final report for the DPF test program. The first DECSE Interim Report, published September 1, 1999, reported on the status of the test programs being conducted on three of the technologies: lean-NO_x catalysts, DPFs, and DOCs. The second DECSE Interim Report, published in October 1999, discussed NO_x adsorbers. The third DECSE Interim Report, published in November 1999, summarized the test results on PM for four

technologies. The three previous interim reports are available on the DECSE section of the U.S. Department of Energy (DOE) OTT Web site at: http://www.ott.doe.gov/decse. This final report on DPFs covers the effect of diesel sulfur level on: a catalyzed diesel particulate filter (CDPF), and a continuously regenerating diesel particulate filter (CR-DPF).

ES.2 Program Overview

The CDPF and CR-DPF represent two approaches to passive regeneration of DPFs. Passive regeneration is preferred as opposed to active regeneration, because passive regeneration is less complex, and offers significant fuel consumption savings and lower system cost.

The CDPF and CR-DPF were designed to remove PM from the engine exhaust stream. In each device, PM was removed from the exhaust stream by collecting it on a filter, which, in these cases, is a ceramic wall-flow element. Unlike other diesel emissions control devices, primary removal of the targeted pollutant (PM) is fixed by the physical characteristics of the filter medium, and is relatively unaffected by the engine operating conditions. The critical issue, instead, is the cleaning or regeneration of the DPF (by oxidation of the collected PM) to prevent the DPF from plugging.

The CR-DPF accomplishes filter regeneration by continuously generating nitrogen dioxide (NO_2) from engine-emitted nitrogen oxide (NO) over a DOC placed upstream of the DPF. Other studies have established that NO_2 is a more effective low-temperature oxidizing agent for diesel PM than oxygen. However, sulfur in the exhaust (originating from the fuel and the lubricant) can be oxidized over the CR-DPF, forming sulfates (measured as PM). Sulfur oxides also compete for the same catalyst sites required for the critical NO and NO_2 reaction, making the regeneration characteristics less effective.

The CDPF accomplishes the DPF regeneration by using a catalyst coating on the DPF element to promote oxidation of the collected PM using available oxygen in the diesel exhaust. Sulfur in the exhaust can be oxidized over the CDPF to form sulfates. Exhaust-gas temperature and fuel-sulfur level are critical factors that affect the performance of both types of DPFs (CDPF and CR-DPF).

Engineering Test Services (ETS) in Charleston, South Carolina, was contracted to conduct the DPF test program. A Caterpillar 3126 engine rated at 205 kW (275 horsepower) and equipped with electronic controls was used for the tests. The 3126 engines are typically used for applications that result in relatively low-temperature exhaust (e.g., below 300ºC). For such applications, regeneration of the DPF at a low temperature is critical to proper operation of the emissions control system, and consequently, the engine operation (maintaining a low back-pressure by not allowing PM to build up continuously on the filter). Because fuel sulfur level is expected to affect the filter regeneration temperature, these low-temperature applications are an excellent test of the effects of fuel sulfur level.

ES.3 Diesel Particulate Filter Conclusions

The two DPF technologies chosen for the program, CDPF and CR-DPF, underwent (1) emission tests to measure reductions in total PM and selected gases, and (2) experiments to measure the effect of fuel sulfur level on the regeneration temperature required by the DPF devices (i.e., the balance point temperature [BPT]). These tests have resulted in the following conclusions:

- Increasing the fuel sulfur level from 3 ppm to 350 ppm produced an essentially linear 29% increase in the baseline (engine-out) PM emissions, from 0.0613 g/bhp-hr (grams per brake horsepower-hour) to 0.0793 g/bhp-hr. No significant changes in baseline gas phase emissions or baseline fuel consumption were observed as a result of increasing the fuel sulfur level.

- Fuel sulfur has significant effects on post-DPF total PM emissions. Both DPFs were effective in reducing PM emissions (95% over the OICA cycle), when used with 3-ppm sulfur fuel. With 30-ppm sulfur fuel, the PM reduction efficiencies dropped to 74% and 72% for the CDPF and CR-DPF, respectively (shown in Figure ES.3-1). When tested with the 150-ppm sulfur fuel, PM reductions were near zero (0% and -3%), and when tested with the 350-ppm sulfur fuel, PM reductions (actually increases) of –122% and –155% were observed for the CDPF and CR-DPF, respectively. Figure ES.3-1 shows that the increase in PM mass with fuel sulfur level is a result of increasing contribution from hydrated sulfuric acid. The filter samples are stabilized at 50% relative humidity for weighing and then analyzed for sulfate anion, $SO_4^=$. The sulfate must exist as sulfuric acid in order to pass through the DPF and be collected on the filter. At 50% relative humidity there are 7 molecules of water of hydration per molecule of sulfuric acid (Reference 1995 SAE Handbook). For all calculations, we have assumed that sulfate is present as $H_2SO_4 \cdot 7H_2O$, and thus multiplied the sulfate mass by 2.3333 (the ratio of molecular weights of hydrated sulfuric acid to sulfate anion) to determine the full sulfur contribution to PM mass.
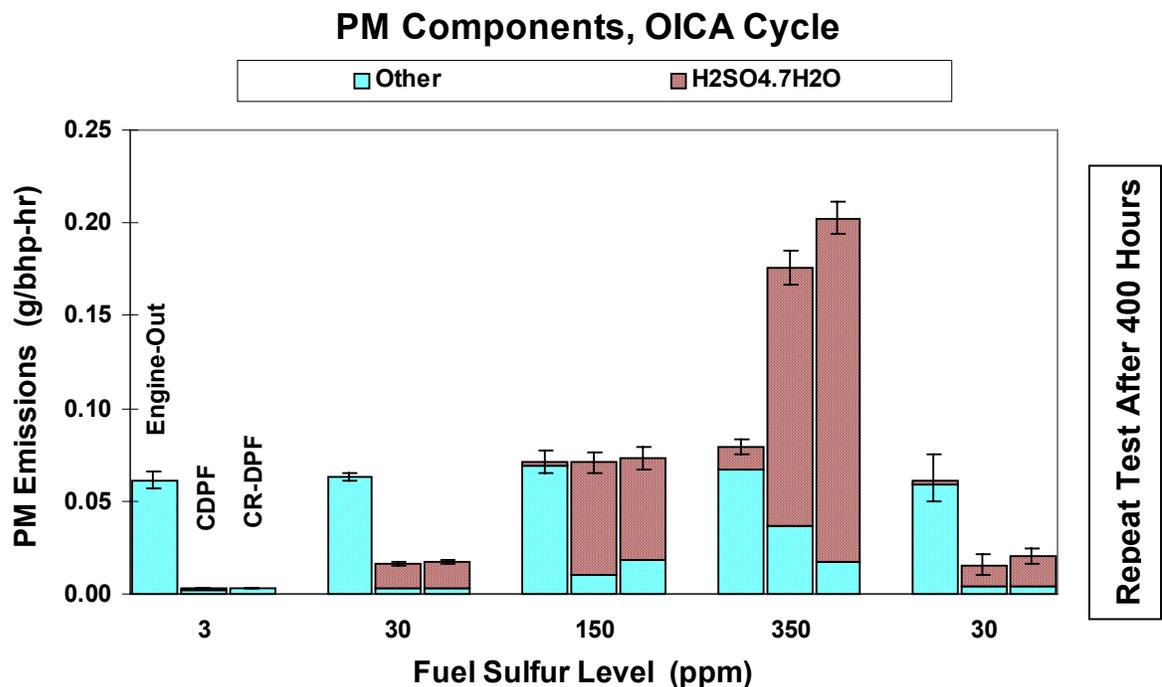

Figure ES.3-1. PM emissions components as a function of fuel sulfur level, by sulfate fraction and non-sulfate fraction for the OICA cycle

- Fuel sulfur levels below 150 ppm were required to obtain any reduction in total PM, and a sulfur level of 30 ppm was required to achieve total PM emissions below the 0.02 g/bhp-hr level being considered for 2007 regulations.

- Approximately 40% to 60% of fuel sulfur was converted to sulfate PM as measured over the 13-mode OICA cycle for both DPFs.

- The exhaust temperature required for regeneration of the DPF devices (as measured by BPT) increased by roughly 25°C when changing from 3-ppm to 30-ppm sulfur fuel. The BPT remained stable at higher sulfur levels for the CDPF device. Evidence suggests further increases in BPT for the CR-DPF when using the 150-ppm or 350-ppm sulfur fuels.

- Within the range of fuel sulfur levels required to achieve useful PM reduction (less than 150 ppm), the temperature required for filter regeneration was consistently higher for the CDPF than for the CR-DPF. The average difference when operating with the 3-ppm sulfur fuel was 54°C (ranging from 47°C at 1,440 rpm to 67°C at the 2,000 rpm test condition). When operating with 30-ppm sulfur fuel, the BPT of the CDPF device averaged 66°C (54°C to 100°C) higher than the BPT for the CR-DPF device.

- Both DPF devices recovered PM reduction performance (as measured by OICA emissions test with 30-ppm sulfur fuel) following approximately 400 hours of exposure to 30-ppm, 150-ppm, and 350-ppm sulfur fuels (shown in Figure ES.3-1). Pre-exposure OICA PM reductions of 74% and 72% (observed when using the 30-ppm sulfur fuel) were matched by PM reductions of 75% and 73% following high sulfur exposure. The CR-DPF device, however, required three replicate OICA tests to achieve this level, presumably because of sulfate storage and release mechanisms.

- Fuel consumption increases of 0% to 2% above baseline were measured when operating with the DPF devices. This increase, resulting from the additional exhaust back-pressure created by the DPF, was generally larger with the CR-DPF than with the CDPF.

- Both DPFs were effective in removing much of the HC. The CDPF, on the OICA cycle, has an HC reduction efficiency of about 70% (58% to 82%). The CR-DPF, on the OICA cycle, has an HC reduction efficiency of about 83% (68% to 91%). The DPFs were also efficient in oxidizing CO. The measured reduction efficiency for CO varies between 90% and 99% across the various fuel sulfur levels and three test modes.

ES.4 Future Work

The following recommendations are made for continued work with the CDPF and CR-DPF Program (within DECSE Phase 2):

- Investigate what effect sulfur has on PM size distribution at dilution ratios that represent the real world, as well as those representative of certification dilution tunnels.

- Analyze non-regulated/toxic materials (gaseous and PM) concurrently with the PM sizing effort.

- Determine the benefits, in an emission control system (fuel, engine, and emission control), of combinations of technologies: a selective catalytic reduction (SCR) device combined with a CR-DPF, and a NO_x adsorber combined with a CDPF. Research on both systems should include measurements for PM mass, size and composition, and air toxics. The effect of lubricant composition on these emissions could be determined in a related project.

Section 2

Description of Technologies and Tests

2.1 Technology Overview

The continuously regenerating DPF (CR-DPF) and the catalyzed DPF (CDPF) represent two approaches to passive regeneration of DPFs. Passive regeneration is preferred, as opposed to active regeneration, because passive regeneration is less complex and offers significant fuel consumption savings and lower system cost.

The CDPF and CR-DPF are designed to remove PM from the engine exhaust stream. A schematic diagram of the DPF system configurations used for this study is provided in Figure 2.1-1. In each device, PM was removed from the exhaust stream by collecting it on a filter, which in these cases are ceramic wall-flow elements. Unlike other diesel emissions control devices, primary removal of the targeted pollutant (PM) is fixed by the physical characteristics of the filter medium and is relatively unaffected by the engine operating conditions. The critical issue, instead, is the cleaning or regeneration of the DPF (by oxidation of the collected PM) to prevent the DPF from plugging.
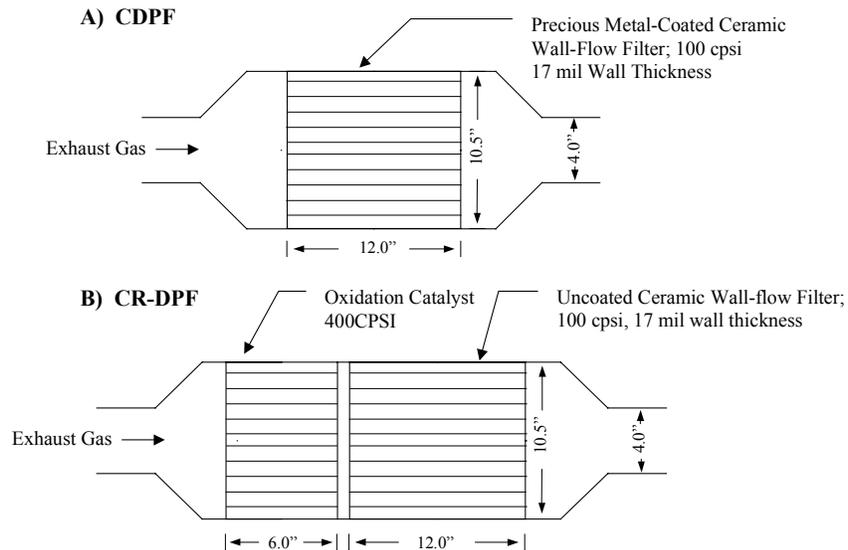
Figure 2.1-1. Schematic diagram of DPF system configurations

The CR-DPF accomplishes filter regeneration by continuously generating NO_2 from engine-emitted NO over a DOC placed upstream of the DPF. Other studies have established NO_2 as a more effective low-temperature oxidizing agent for diesel PM than oxygen. Sulfur in the exhaust (originating from the fuel and lubricant), however, can be oxidized over the CR-DPF, forming sulfates, which are measured as PM. Sulfur dioxide (SO_2) also competes effectively with NO for the same catalyst sites required by NO for critical NO_2 production. Therefore, higher fuel sulfur levels inhibit effective filter regeneration.

The CDPF is regenerated by using a catalyst coating on the DPF element to promote oxidation of the collected particulate. Sulfur in the exhaust can also be oxidized over the CDPF to form sulfate particulate.

Exhaust-gas temperature and fuel-sulfur level are critical factors that affect the performance of both types of DPFs.

2.2 Program Objectives

Two major components make up the DPF test program: (1) emissions tests to evaluate the direct impact of fuel sulfur on selected emission parameters, and (2) experiments to measure the effect of fuel sulfur on the regeneration temperature of the DPF devices.

The DPF test program was formulated to provide data to address the following study questions:

1) How does each DPF affect emissions of PM (including $SO_4^=$, soluble organic fraction [SOF], and NO_3^-), HC, CO, NO_x, and carbon dioxide (CO_2), as well as fuel consumption?

2) How does fuel sulfur affect engine-out emissions and post-DPF emissions?

3) Does DPF performance degrade over time?

4) To what degree does sulfur in the fuel affect the balance point (regeneration) temperature (BPT) of the DPF (at various engine speeds)?

5) Does the DPF performance vary as a function of engine operating conditions (exhaust-gas flow rate and temperature)?

6) How does the relationship between emissions and operating conditions change as a function of fuel sulfur level?

2.3 Experimental Design

The experimental design for the DECSE DPF test program is summarized in Table 2.3-1. Emissions tests and two types of BPT experiments were conducted on the CDPF and CR-DPF devices, using fuels with sulfur levels ranging from 3 to 350 ppm. Tests were performed in the order of increasing fuel sulfur levels, except for a second set of OICA emissions tests with 30-ppm fuel that were performed last. These repeat tests were used to evaluate the effects of aging. The purpose of the BPT and constant temperature tests was to determine how fuel sulfur affects the DPF BPT at various engine speeds.

Table 2.3-1.   Experimental Design for the DECSE DPF Test Program

Test	Fuel Sulfur Level (ppm)				
	3	**30**	**150**	**350**	**30**
Emissions Tests[a]	EO CDPF, CR-DPF (x2/x3)	EO CDPF, CR-DPF (x2/x3)	EO CDPF, CR-DPF (x2/x3)	EO CDPF, CR-DPF (x2/x3)	EO CDPF, CR-DPF (x3)[b]
BPT Test	5 temperatures, 3 speeds (x3)	5 temperatures, 3 speeds (x3)	5 temperatures, 3 speeds (x3)	5 temperatures, 3 speeds (x3)	
Constant Temperature Test[c]	T1, T2, T3, T4	T1* and T2*	T1* and T2*	T1* and T2*	

[a] Emission tests consist of triplicate tests using the OICA 13-mode test procedure and duplicate tests at peak torque and "road-load" steady-state test conditions.
Emissions parameters: PM, $SO_4^=$, SOF, NO_3^-, HC, CO, NO_x, and CO_2 in g/bhp-hr and brake-specific fuel consumption (BSFC) in lb/bhp-hr.
    EO = engine-out emissions
    CDPF and CR-DPF are post-DPF samples.
    Post-DPF PM collected on one filter across duplicate or triplicate runs.
[b] OICA tests only
[c] Temperature tests were performed for 10 hours with alternating speeds (1,440 rpm; 1,700 rpm; and 2,000 rpm), and matching torques to achieve fixed starting inlet temperatures, Ti (i= 1-4)
    (CR-DPF temperatures Ti = 225, 275, 325, 375°C)
    (CDPF temperatures Ti = 275, 325, 375, 425°C)
    T1* = 275°C and T2* = 375°C
Number of replicate tests indicated in parentheses.

2.4   Test Procedures

2.4.1 Emissions Testing

Emissions measurements were obtained from triplicate runs of the OICA 13-mode test cycle and duplicate tests under steady-state conditions corresponding to modes 2 and 4 of the OICA cycle. Mode 2 (1,047 Nm @ 1,440 rpm) is the "peak-torque" condition at which the engine-exhaust temperature reaches the maximum value. Maximum sulfate conversion is expected to occur at this engine operating condition. Mode 4 (733 Nm @ 1,783 rpm) corresponds to the "road-load" condition of a typical, on-highway, heavy-duty, diesel truck engine, where a truck spends much of its operating time.

All emission tests include measurements of HC, CO, NO_x, CO_2, and PM. PM filters were analyzed for SOF, sulfate ($SO_4^=$) and nitrates (NO_3^-). The solid portion (mostly carbon) was determined by subtracting the SOF, $SO_4^=$, and NO_3^- from the total PM. Blank PM filter samples were taken at each emissions test run for PM analysis correction purposes. Because of the high trapping efficiency of the DPFs, the PM loading on the sample filter was typically about 0.2 mg over an OICA cycle with the 3-ppm and 30-ppm sulfur fuels. To improve measurement accuracy, PM was collected on the same sample filter over 2 or 3 consecutive OICA or steady-state test cycles.

OICA and Steady-State Test Cycles. The PM sampling for the OICA cycle is automated to collect PM using a single-filter method. The PM sampling duration at each mode is weighted by time corresponding to the weighting factor of the OICA cycle. The total sampling time for the 13-mode OICA test is 20 minutes. The 13-mode speed and torque targets were determined using data from an 8-rpm-per-second, full-load, performance curve. During the OICA and steady-state cycles, the exhaust temperature and emissions are allowed to stabilize for 5 minutes prior to sampling gaseous and PM emissions. During the stabilization period, the secondary sample flow bypasses the 90-mm sample filters.

Table 2.4.-1 presents the gaseous and PM sampling times for the 13-mode OICA cycle. Table 2.4-2 presents the gaseous and PM sampling times for the steady-state mode conditions.

Table 2.4-1. Gaseous and PM Sampling Times for 13-Mode OICA Cycle

Mode	Engine Speed	Percent Load (%)	Weighting Factor	Stabilization Time (seconds)	Sampling Time (seconds)	Mode Length (seconds)
1	idle	-	0.15	300	180	480
2	A	100	0.08	300	96	396
3	B	50	0.1	300	120	420
4	B	75	0.1	300	120	420
5	A	50	0.05	300	60	360
6	A	75	0.05	300	60	360
7	A	25	0.05	300	60	360
8	B	100	0.09	300	108	408
9	B	25	0.1	300	120	420
10	C	100	0.08	300	96	396
11	C	25	0.05	300	60	360
12	C	75	0.05	300	60	360
13	C	50	0.05	300	60	360
Total			**1**	**3900**	**1200**	**5100**

A = 1,440 rpm
B = 1,783 rpm
C = 2,000 rpm

Table 2.4-2. Gaseous and PM Sampling Times for Steady-State Modes

Mode	Engine Speed (rpm)	Engine Load (%)	Stabilization Mode (seconds)	Sample Time (seconds)
Torque Peak	1,440	100	300	1200
Road Load	1,783	75	300	1200

The nominal primary dilution tunnel flow rate is set to 1,600 scfm. The flow rate of diluted exhaust drawn through the 90-mm filters is nominally set to 4–5 scfm, and the secondary dilution air is set to 2-3 scfm. The filters are conditioned in an environmental chamber at 21°C and 50% relative

humidity for a period of 8 to 48 hours, and pre-weighed prior to being exposed to engine exhaust. Following the test, the filters are again conditioned for 8 to 48 hours for post-weight.

The brake-specific PM emission is calculated according to equations outlined in the experimental design (as shown in Section 2.3). Because primary and secondary dilution air is filtered, the background PM is not routinely measured.

PM Sampling System. Dilution air and total engine exhaust are mixed and drawn through an 18-inch diameter stainless steel dilution tunnel by a positive displacement pump constant volume sampler (PDP-CVS). The tunnel flow rate is corrected to standard temperature and pressure using temperature and pressure measurements upstream of the PDP-CVS. ETS uses a double dilution method for the PM sampling outlined in the experimental design.

The emission sampling zone temperature in the primary dilution tunnel is maintained at 190°C (375°F) or less. Gaseous emission samples are taken at this sampling point. For PM sampling, an exhaust sample is diluted a second time to determine PM emissions. The secondary dilution system is used to maintain the double-diluted exhaust stream at a temperature of 52°C (125°F) or less at the PM filter face. A mass flow controller controls the sample and secondary dilution flows to a constant rate through the PM filter pair. PM samples are drawn through primary and secondary 90-mm Pallflex filters (TX40H120).

When performing OICA and steady-state emissions tests, a bypass system is used to allow for PM sampling during specified data collection periods. The bypass system allows for continuous flow through the mass flow controllers, eliminating delays associated with starting and stopping the sample flow during each mode.

PM SOF Determination. The exposed PM-sampling filters are conditioned for more than 18 hours at constant relative humidity (RH) and temperature at the analytical laboratory, and then weighed. The filters are then extracted with supercritical CO_2 under proprietary time and temperature conditions. The extracted filters are then re-conditioned for >18 hours at constant RH and weighed. The SOF is the simple difference between the pre-extraction weight and the post-extraction weight.

PM Sulfate and Nitrate Determination. After weighing, the filters are folded, placed in 1-ounce glass bottles with 25 ml of 60% deionized water (>10 megaohms conductivity): 40% isopropanol, and agitated briefly. Samples are extracted at room temperature for 24 hours. The samples are then analyzed.

The filtered extracts are analyzed for $SO_4^=$ and NO_3^- by ion chromatography (IC) using standard IC methods for anions. Samples are prepared by placing 1 ml of extract in 10 ml of deionized water. Peak identification is based on retention times compared to standard sulfate/nitrate solutions. A standard curve is developed from analysis of standards of 0.0, 0.05, 0.10, 0.50, 1.0, and 2.0 μg/ml sulfate and nitrate. Peak area is used for quantification, and the minimum quantifiable level is 0.02 μg/ml. All standard curves have a correlation coefficient, r^2, of 0.999 or better. The sample concentrations are then calculated from the linear regression equation for the standards. If a sample is more concentrated than the standard curve, dilutions are used to bring the sample within the limits. The concentrations are multiplied by the total volume (25 ml) of extract, the standard

10:1 preparation dilution factor, and any subsequent dilutions, to obtain the total mass of dry $SO_4^=$ on a PM sample filter. The dry $SO_4^=$ number is reported. The factor of 2.3 which was used for these calculations assumes a H_2O to $SO_4^=$ ration of 1.3, implying a PM sample weighing environment of 70°F and 50% relative humidity.

Blank filters are treated in the same way as exposed filters. A filter blank is included with each sample. Blank levels of $SO_4^=$ ranged from 4 to 9 µg/filter for $SO_4^=$, and ranged from 4 to 7 µg/filter for NO_3^-. Blank filter SOF is typically 0.5 mg. The $SO_4^=$ and NO_3^- masses on samples are corrected for the blank values before calculation of brake-specific emissions of sulfate and nitrate.

Sulfate Contribution to Total PM Weight. The extraction described above determines the total amount of sulfate ion present on the filter. On the filter, the sulfate exists as sulfuric acid (H_2SO_4) particles. During the test and/or during equilibration at ~50% RH in the filter-weighing chamber, these particles become hydrated with water molecules because sulfuric acid is an extremely hygroscopic substance. Studies[1] on hydration of H_2SO_4 have shown that approximately 1.3g H_2O are associated with each gram of sulfate at 50% RH.. This results in a multiplier of 2.3 for the dry sulfate weight to get the wet, or hydrated, sulfate contribution to total PM.

2.4.2 Multiple-Mode Balance Point Temperature Testing

The primary method of estimating BPT was the BPT test in which the CDPF or CR-DPF device is preloaded with PM, then operated at a constant speed (1,440 rpm, 1,700 rpm, or 2,000 rpm) while torque is increased to achieve specified exhaust temperatures. The pressure drop (delta-p) across the DPF is measured continuously to determine the temperature at which the rate of PM combustion equals, or balances, the rate of PM collection. Typical test results are shown in Figure 2.4-1. At lower temperatures, the delta-p increases with time as PM accumulates in the DPF. As the temperature increases, the rate of PM oxidation increases (and at some point exceeds) the rate of PM filtration which results in a decreasing pressure drop across the DPF. Therefore, the BPT is defined as the temperature at which the slope of delta-p (kPa/min) is equal to zero.
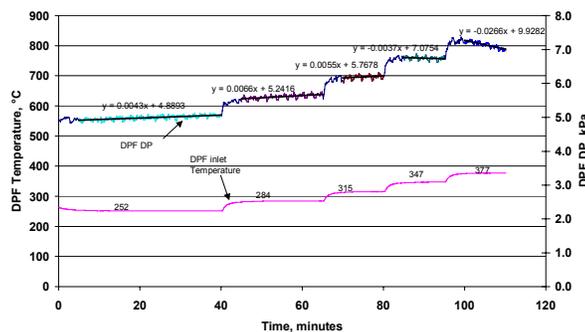

Figure 2.4-1.   Example test results from the BPT test

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[1] "Chemical Methods for the Measurements of Nonregulated Diesel Emissions", SAE Recommended Practice J1936, Warrendale, PA, October, 1989.

In developing the test plan, we learned that the selection of test temperatures could have a significant effect on the repeatability of BPT estimates. Two methods for selecting the range of test temperatures were considered. The first method was to test a broad range of temperatures on the initial trial, then to narrow the range on subsequent trials until the test temperatures were in the vicinity of the BPT. The second method specified a constant range of temperatures from trial to trial. Early results showed that the second method was more repeatable. It appeared that the level of PM regeneration that occurs at a given temperature was heavily dependent on the current condition of the DPF, and that the previous test temperatures determined the current condition.

For similar reasons, repeatability of the test results were also affected by the method of pre-loading the DPF. To prepare the DPF for the test, it was completely regenerated by operating the engine at the peak-torque condition for 30 minutes. The DPF was then reloaded with PM by operating the engine at 214 Nm and 2,000 rpm for about 5 hours.

The total duration for the final test protocol was 110 minutes, with temperature steps at 40, 25, 15, 15, and 15 minutes. The change in pressure across the filter was continuously recorded. Later in the test program, the BPT test was extended to seven modes, with temperature steps for modes 6 and 7 at 15 minutes. This was performed to extend the test to higher temperature ranges for the 150-ppm and 350-ppm sulfur fuels.

2.4.3 Constant Temperature Testing

The constant temperature test represents an alternative method for estimating the BPT at various engine speeds. Starting with a clean device, the engine is operated for 10 one-hour cycles in which the engine speed alternates between 1,440 rpm, 1,700 rpm, and 2,000 rpm every 20 minutes. At each speed, the torque is adjusted to maintain a constant DPF inlet temperature (shown in Figure 2.4-2). Exhaust gas inlet temperature and pressure drop across the DPF device were monitored continuously for up to 10 hours for each fuel. At each temperature and fuel sulfur level, the pressure drop trace (as a function of time) was expected to either: (1) continuously increase (PM depositing on the filter faster than it can be oxidized), (2) remain relatively stable (PM depositing on the filter equals the amount being oxidized), or (3) continuously decrease (PM depositing on the filter at a rate slower than it is being oxidized).
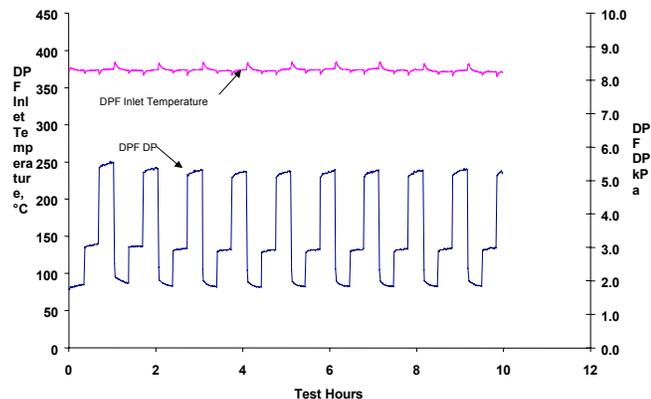

Figure 2.4-2.   Example test results from the temperature test

In between each exhaust temperature test, the engine was operated at full-load, rated speed (FLRS) for 2 hours (stabilization) to ensure that the DPF was "clean" and that its pressure drop returned to near baseline conditions.

Initially, the test was to be conducted at four temperatures with each fuel type. However, after reviewing the preliminary results (from tests conducted with 3-ppm sulfur fuel) it was decided to use the BPT test as the primary procedure for estimating the BPT. The constant temperature test is primarily used for confirmatory analysis. By cycling through various speeds, the test more closely resembles actual driving conditions. However, the method presents challenges for estimating BPT because of the limited number of temperatures that can be tested. Also, at most temperatures, the device will alternate between PM build-up and regeneration as engine speed is changed. Thus, it is often difficult to achieve a repeatable, steady-state condition.

2.4.4 Engine Performance Testing

Engine and DPF Break-In. To break in the engine and the DPF, the engine was operated at FLRS for 30 minutes, and then for 30 minutes at rated speed and a torque setting as required to give an exhaust temperature of 225°C. The cycle continued for 20 hours. The pressure drop across the DPF was monitored throughout the break-in period. After the break-in, the engine was operated at peak-torque condition for 30 minutes to "clean" the DPF. The engine was then operated at FLRS, and the clean (baseline) pressure drop across the DPF was determined.

Engine Performance Tests. The baseline performance curve without the DPF consisted of operating the engine at maximum load and varying the speed from rated to 1,000 rpm in 100-rpm increments. This test ensured that the engine met the manufacturer's specifications. An 8-rpm-per-second, full-load performance curve was run to determine the 13-mode OICA test cycle measurement points.

DPF Pressure Drop Measurement. The pressure transducer used was a Sensotec 0-34 kPa in Hg delta pressure range (Model #PDW2UA2D5A6N), and the calibration (performed by the manufacturer) was traceable to National Institute of Standards and Technology (NIST) standards. The pressure transducer was verified on a monthly basis, using two Drucks (Model DPI 510) dual-range pressure controllers that also had NIST-traceable calibration. The DPF pressure drop was validated at five independent points from 2 to 20 kPa in Hg delta.

2.5 Statistical Analysis

The following sections describe the statistical approaches used to analyze data from the emissions and BPT tests. The overall analysis plan was established to address the six study questions presented in Section 2.2.

2.5.1 Analysis of Emissions Data

Triplicate OICA 13-mode emissions tests and duplicate steady-state emissions tests (at peak-torque and road-load modes) were conducted separately on engine-out (without CR-DPF or CDPF devices) and post-filter (with CR-DPF or CDPF) exhaust streams. After the initial series of tests with 3-ppm fuel sulfur, it was decided that PM loadings on the sample collection filter used in the post-DPF emissions tests were insufficient for PM analysis. For that reason, the same PM filter was

used on each of the two or three replicate tests. The continuous emissions parameters included HC, CO, NO_x, and CO_2, in g/bhp-hr and BSFC in lb/bhp-hr. Filter analysis included PM, $SO_4^=$, SOF, and NO_3^- in g/bhp-hr. Filter analysis was used primarily to determine the sulfate conversion rate.

The effect of the DPF on emissions (study question 1) was evaluated in terms of emissions reduction efficiency. For example, the PM reduction efficiency of the DPF device is calculated as

$$RE = (1 - post\text{-}DPF\ PM/Engine\text{-}Out\ PM)\ x100\%.$$

For each fuel type (3-ppm, 30-ppm, 150-ppm, and 350-ppm sulfur), the statistical significance of the difference from 0% (indicating no DPF effect) was determined using a standard two-sample t-test on the log-transformed data. As is often the case with emissions data, the log transformation yields measurement errors that are normally distributed with common standard deviation. This common standard deviation was estimated by pooling the individual standard deviations of emissions measurements from the OICA, peak-torque, and road-load tests at engine-out and post-filter tests.

The effects of fuel sulfur on the engine-out and post-DPF emissions (study question 2) were also evaluated. The percent change in engine-out emissions is the measure of sulfur's effect on engine-out emissions. The effect of sulfur on DPF efficiency was calculated as the difference in reduction efficiency. The statistical significance of these effects (i.e., whether or not the measures were different from 0%) was determined using two-sample t-tests on the log-transformed data.

Degradation of the DPF performance over time (study question 3) is addressed by comparing reduction efficiencies with 30-ppm fuel at two different times, and tracking the degradation of the regenerated DPF delta-p over time. The second emissions test with 30-ppm fuel was conducted after the 150-ppm and 350-ppm fuel sulfur tests were performed.

The relationship between engine operating conditions (speed, torque, and temperature) and engine-out emissions or filter breakthrough (study questions 5 and 6) is addressed in part by comparing gaseous and PM emissions results from the road-load and peak-torque tests. Gaseous results from the 13 modes of the OICA test are also available for comparison.

2.5.2 Analysis of the BPT Test Results

The BPT test is used to measure the effect of fuel sulfur on the regeneration (PM combustion) temperature of the DPF (study question 4). The BPT is defined as the DPF inlet temperature at which the pressure drop across the DPF begins to decrease (i.e., the slope of delta-p across the DPF becomes negative). Each BPT test produces a single estimate of BPT. The experimental design specified the following test conditions:

- Four fuel sulfur levels (3 ppm, 30 ppm, 150 ppm, and 350 ppm)
- Two DPF types (CDPF and CR-DPF)
- Three engine speeds (1,440 rpm, 1,700 rpm, and 2,000 rpm)
- Three replicate evaluations

By testing at multiple engine speeds, the BPT tests also provide data to address study questions 5 and 6. Each of the 72 (4x2x3x3) tests include measurements of changes in pressure drop (slope of delta-p) at five DPF inlet temperatures. In some cases, DPF regeneration did not occur at the

highest temperature specified in the experimental design. When this occurred, testing was extended to include up to seven temperatures. Figure 2.4-1 shows an example of BPT test results.

The first step in the data analysis involves fitting a regression line and calculating the slope of the line relating delta-p with time using data collected following stabilization at each inlet temperature. Data are first reduced by selecting a linear portion of the delta-p-versus-time curve. Generally, this will be the 10-minute period beginning 5 minutes after the change in engine temperature. A lack-of-fit procedure is used to determine if a straight-line fit is appropriate. If not, a subset of data is selected according to a defined procedure.

Next, a regression model is fit to establish the relationship between delta-p slope and DPF inlet temperature. A segmented model with a baseline level followed by a quadratic decline in delta-p was selected from a list of candidate models. The general form of the regression model is

$$DPS(t) = \begin{cases} p & \text{if } t < t_0 \\ a + bt + ct^2 & \text{if } t \geq t_0 \end{cases}$$

where $DPS(t)$ = delta-p slope (kPa/min) at DPF inlet temperature t. The function is assumed to be smooth and continuous (as shown in Figure 2.5-1). BPT_0 is defined as the DPF inlet temperature at which the slope of delta-p equals 0. Assuming $p > 0$,

$$BPT_0 = \frac{-b + \sqrt{b^2 - 4ac}}{2c}$$
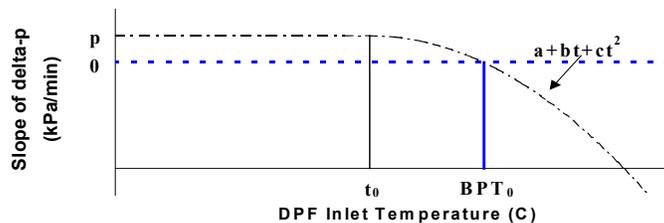
Figure 2.5-1.   Calculation of BPT

To account for possible run-to-run variability, a separate regression equation was fit for each test run using a non-linear curve-fitting routine. Also, a single equation was fit to the (pooled) data from all three runs combined. This dual approach is useful for interpreting results under various assumptions. For example, when there are run-to-run differences it is appropriate to calculate BPT estimates from individual runs, then use analysis of variance (ANOVA) techniques to estimate the average BPT at various combinations of engine speed and fuel sulfur level and to determine the statistical significance of fuel sulfur effects. The ANOVA model accounts for fixed effects of different engine speeds and the random effects of measurement and testing (run-to-run) errors. Figure 2.5-2 illustrates how the individual estimates of BPT_0 were calculated using data from different runs. An approximate 95% confidence interval for the mean BPT_0 across runs was then calculated with the assumption that these are independent measurements of BPT_0, and that the errors are normally distributed. BPT_0 was also calculated from data pooled across the 3 test runs, and the corresponding 95% confidence interval for BPT_0 was determined by calculating the

intercepts of the confidence bounds for the regression model. In some cases, this approach produces only a confidence bound. For example, as shown in Figure 2.5-3, the estimate of BPT_0 is approximately 315°C with a 95% upper confidence bound at approximately 345°C.
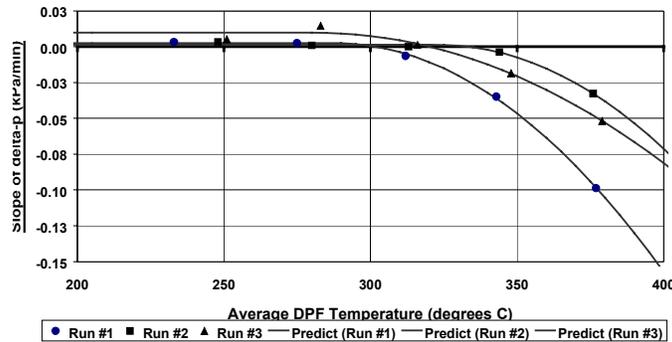

Figure 2.5-2.   Estimated delta-p slope versus DPF inlet temperature - by test run
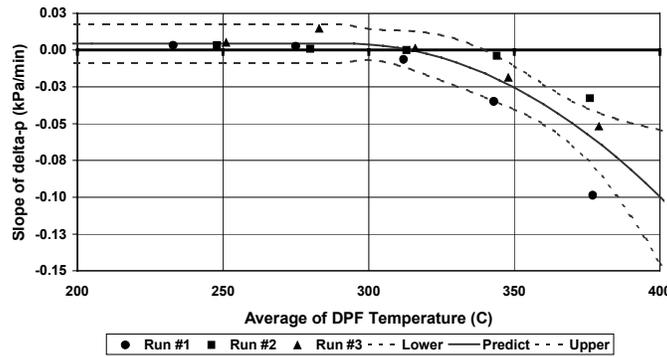

Figure 2.5-3.   Estimated delta-p slope versus DPF inlet temperature with 95% confidence limits - pooled model (all runs combined)

To evaluate the effect of fuel sulfur at various specific operating conditions (as opposed to the overall effect evaluated with the ANOVA model), the BPT was calculated for each fuel sulfur level at each of three engine speeds: 1,440 rpm, 1,700 rpm, and 2,000 rpm. Approximate 95% confidence intervals for the difference in BPT across fuel sulfur levels were calculated for both methods of analysis (average BPT and pooled BPT). If a 95% confidence interval does not contain the value zero, one can conclude with 95% confidence that the BPTs are different among fuel sulfur levels. It is possible, however, that the two methods of analysis will produce different conclusions. In such cases, it is often appropriate to accept the more conservative result (i.e., the one with the larger confidence interval). This will usually be the result based on the average of three test runs because it more accurately accounts for small, but statistically significant, run-to-run differences.

2.5.3 Analysis of Constant Temperature Test Results

The constant temperature tests are useful for demonstrating how the DPF devices perform under the dynamic conditions imposed by alternating engine speed and torque. For each fuel type and DPF device (CDPF and CR-DPF), this test was performed at each of the six combinations of two engine operating temperatures (275°C and 375°C) and three engine speeds (1,440 rpm, 1,700 rpm,

and 2,000 rpm). Early results demonstrated that after the first three hours of testing, the performance of the DPF device became fairly predictable in one of two ways: (1) the pressure drop (delta-p) across the device reached a state of equilibrium (illustrated in Figure 2.4.2), or (2) the pressure drop increased in a linear manner. Thus, the raw data (e.g., in Figure 2.4.2) were reduced to three key performance measures:

1. The <u>average slope</u> of delta-p within each 20-minute interval

2. The <u>slope of the average</u> delta-p over the final seven hours of testing

3. The <u>average</u> delta-p over the final seven hours of testing.

Data reduction was performed by selecting data from the 10-minute period that began five minutes after the change in engine speed. Only data from the final seven hours of testing were used. The slope of delta-p versus time was calculated using simple linear regression.

The average slope (measure #1) is used to determine whether the DPF is collecting PM (positive slope) or regenerating (negative slope) at each of test conditions (speed, temperature, and fuel type). The slope of the average delta-p (measure #2) and the average delta-p (measure #3) are used to describe how the device performs under the dynamic conditions imposed by alternating speeds.

These tests were primarily developed to support findings from the BPT tests. The analysis was not expected to produce estimates of BPTs. Instead, it is used for confirmation of the general behavior of the DPF devices under varying test conditions. Thus, the analysis involves plotting each of the three performance measures versus fuel sulfur level for each combination of engine speed and temperature.

Section 3

Results and Discussion

3.1 Engine Performance Data

3.1.1 Engine Performance Test

The engine performance curve without a DPF was generated at two different times. The performance test conducted at ETS showed that the engine met manufacturer specifications. Figures 3.1-1 and 3.1-2 present the performance curves for power and torque, respectively.
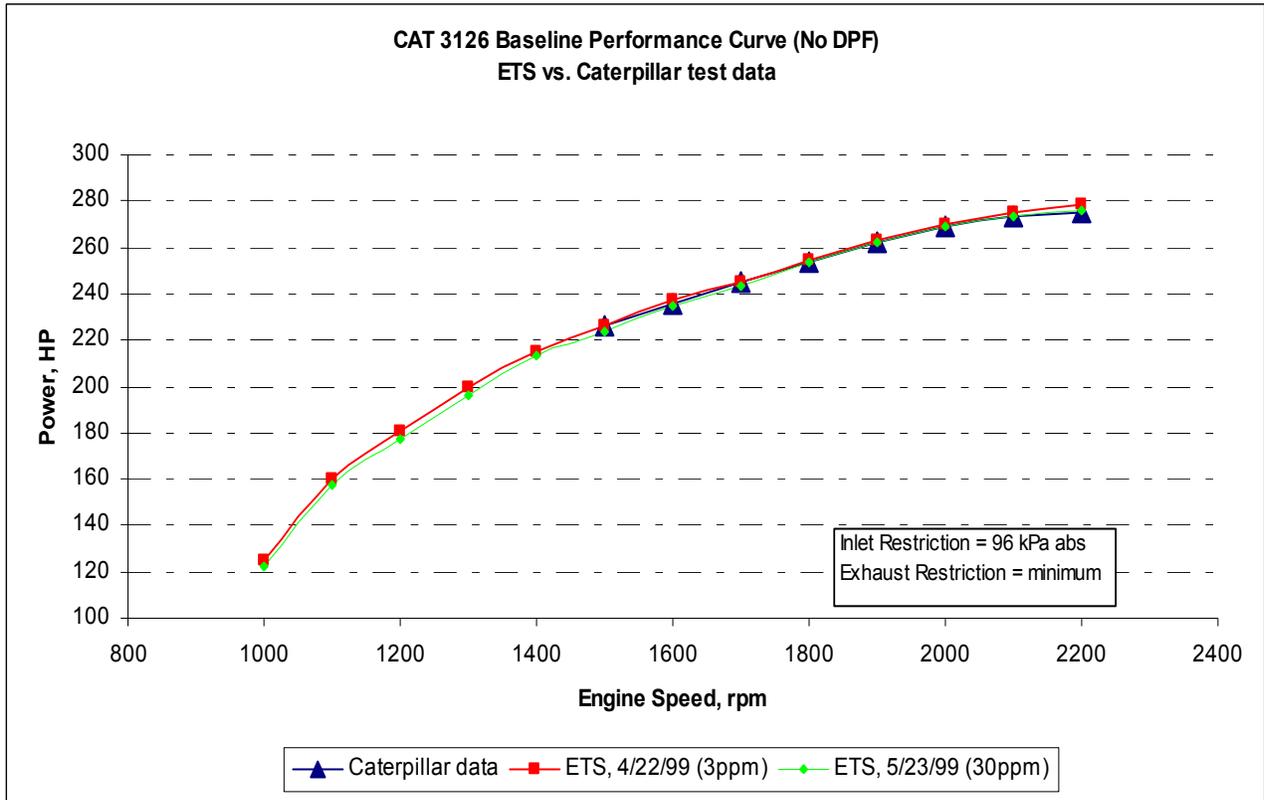
Figure 3.1-1. CAT 3126 baseline performance curve
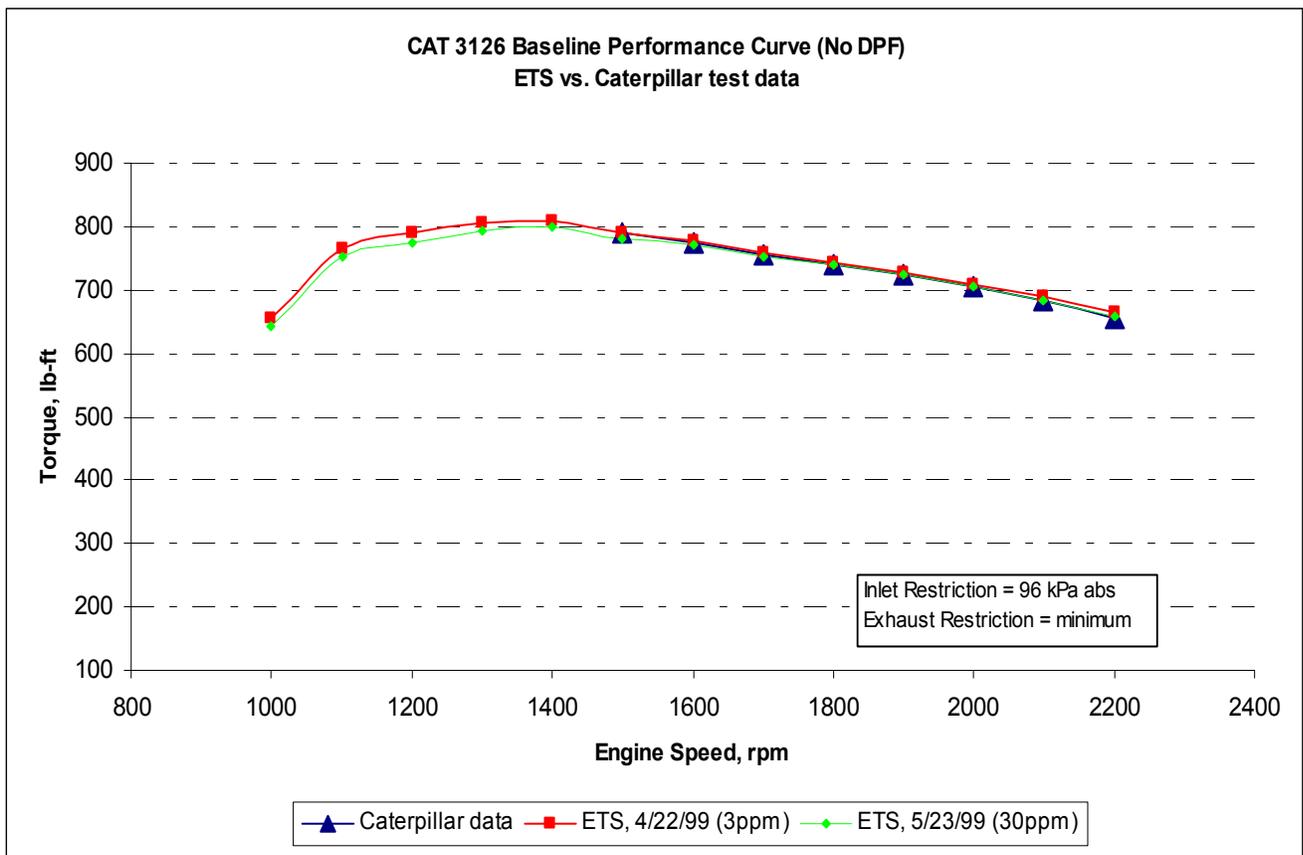
Figure 3.1-2. CAT 3126 baseline performance curve

3.1.2 DPF Clean Pressure Drop and Engine Restrictions

The clean DPF pressure drop at engine-rated condition (FLRS) was monitored throughout the DPF test program. Prior to all testing (emissions, BPT, constant temperature tests), the DPF was completely regenerated by operating the engine at peak torque condition for 30 minutes, or until the DPF pressure drop reached clean pressure drop. Then the clean pressure drop across the DPF was determined at the rated condition. Nominal engine-inlet and exhaust restrictions were set at the rated condition to 8.2 kPa and 7.4 kPa, respectively. Table 3.1-1 presents the average DPF clean pressure drop and restrictions at rated condition.

Table 3.1-1. Average DPF Clean Pressure Drop and Engine Restrictions at Rated Condition

DPF Device	DPF Clean Pressure Drop (kPa)	Intake Restriction (kPa)	Exhaust Restriction (kPa)
CDPF[1]	9.5	8.2	12.9
CR-DPF[1]	13.3	8.2	17.9
None (engine-out)	(not applicable)	8.2	7.4

(1) Exhaust restriction valve was in "open" position. Value represents restriction caused by DPF device.

3.2 Sulfur Effects on Emissions

3.2.1 Gaseous Emissions

Hydrocarbon Emissions. The HC emissions exist predominately in the gaseous phase, but there are some higher molecular weight HC that ultimately condense in the PM phase. PM HC were also monitored as the SOF of the total PM. Although this approach results in double counting of some HC, it is not important here. Results for HC are shown in Figure 3.2-1. Engine-out HC emissions were moderately affected by fuel sulfur level, increasing from 3% to about 8%, relative to the 3-ppm sulfur fuel on the OICA cycle. The peak-torque and road-load tests gave similar but more variable results. This HC increase is not significant. The mechanism for any HC increase with increasing sulfur is unclear. Both DPFs are quite effective at removing much of the HC, via oxidation on the catalyst of the DPFs. The CDPF, on the OICA cycle, has a HC reduction efficiency of about 70% (58% to 82%). The CR-DPF, on the OICA cycle, has a HC reduction efficiency of about 83% (68% to 91%). The reduction efficiencies from engine-out levels were statistically significant but changes with increasing fuel sulfur level generally were not statistically significant. The peak-torque and road-load tests showed similar results to the OICA cycle, with the CDPF removing 78% at peak-torque and 76% at road-load, and the CR-DPF removing 89% at peak-torque and 90% at road-load. The above comments on statistical significance of the OICA results also apply to the steady-state mode tests.

Carbon Monoxide. CO emissions in the engine-out exhaust appear independent of fuel sulfur level, but the DPFs are extremely efficient at oxidizing the CO to CO_2. Results for CO are shown in Figure 3.2-1. The measured reduction efficiency for CO varies between 90% and 99% across the fuel sulfur levels and the three test modes. The reduction efficiencies are all statistically significant, but changes with fuel sulfur level are not.

Nitrogen Oxides. The engine-out NO_X emissions show a mild decrease with increasing fuel sulfur level, with individual data points varying from 0.7% to -1.8% on the OICA cycle, and four of the six results (three test modes) showing a reduction that was statistically significant. Results for NO_X are also shown in Figure 3.2-1. Generally, the DPFs show a small reduction efficiency for NO_X, with individual data points varying from 4.9% to -1.5%, and 15 of the 19 results showing reductions that are statistically significant. The DPF reduction efficiency for NO_X also shows a statistically significant increase of a few percent with increasing fuel sulfur level.

Fuel Consumption. There is an increase in fuel consumption with incorporation of the DPFs, which is the engine response to increased exhaust back-pressure caused by the restricted airflow across the DPFs. Without the DPFs, baseline tests with increasing fuel sulfur level had fuel consumption values relative to the 3-ppm sulfur fuel test, of +1.2, -0.25, and +0.99% for the 30-ppm, 150-ppm, and 350-ppm fuel sulfur levels, respectively. These were all statistically significant changes. Thus, on average, additional fuel sulfur increased the engine fuel consumption by an average of 0.6%, in the present tests. With the CDPF, the fuel consumption increase averaged 0.5% relative to the baseline tests. With the CR-DPF, the average fuel consumption increase was 1.4%, consistent with the 40% to 50% higher back-pressure across the CR-DPF compared to the CDPF. Fourteen of the 16 comparisons of DPF fuel consumption relative to baseline were statistically significant. With the scatter in the BSFC data, it is difficult to discern any change in DPF BSFC with fuel sulfur level.
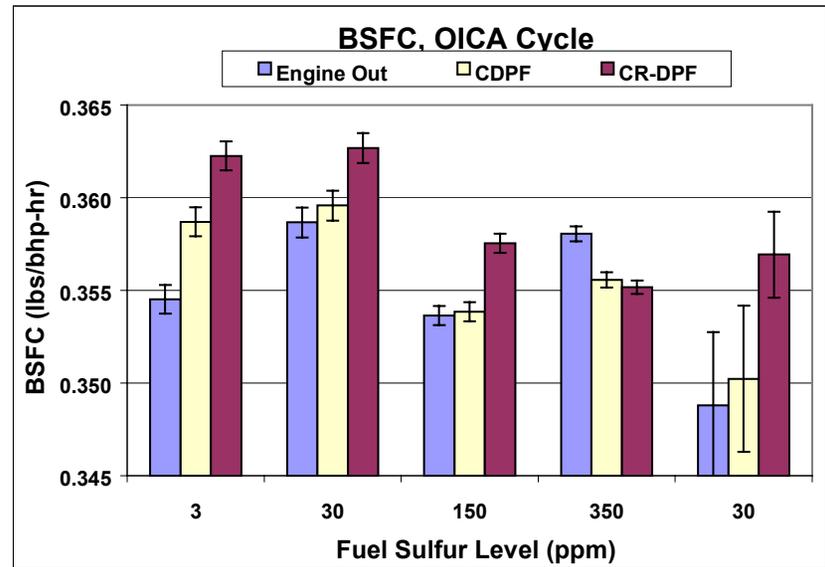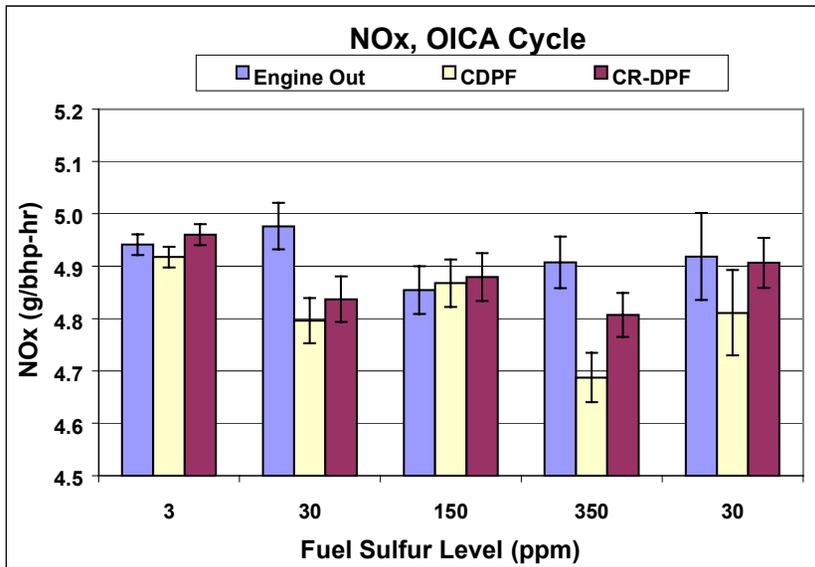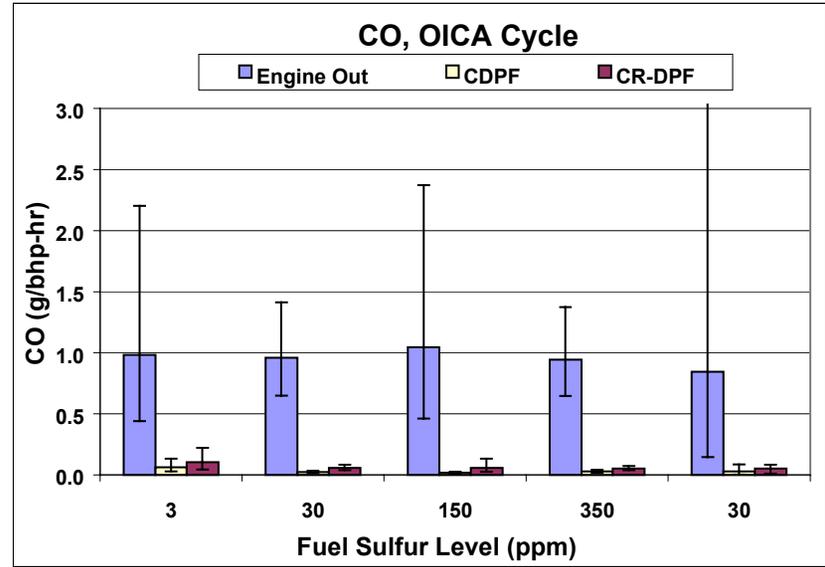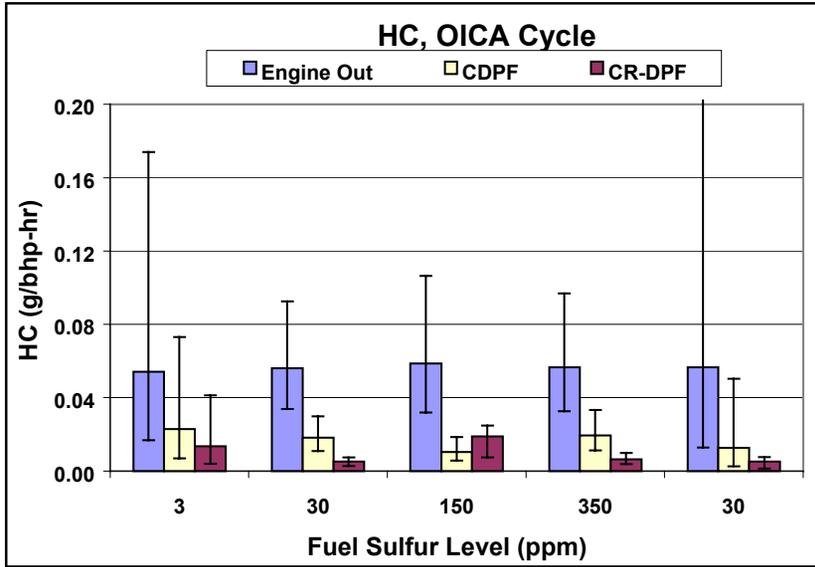
Figure 3.2.1-1. Gaseous emissions and fuel consumption response to fuel sulfur level for OICA cycle.

3.2.2 Particulate Matter Emissions

Previous research into the effects of fuel sulfur on PM emissions from DPFs has found that higher fuel sulfur can lead to an increase in mass emissions and an increase in the numbers of particles. Much of this earlier work compared 3000-ppm sulfur fuel to 500-ppm fuel. This study is one of the first that systematically looks at the effect of low levels of sulfur on PM mass emissions.

Baseline PM emissions measured over the OICA cycle indicated that the PM increased as fuel sulfur level increased. The PM values were 0.061 g/bhp-hr, 0.063 g/bhp-hr, 0.071 g/bhp-hr, and 0.079 g/bhp-hr for the 3-ppm, 30-ppm, 150-ppm, and 350-ppm fuel sulfur levels, respectively. The increase in PM was essentially linear with fuel sulfur, and the PM increase was 29% from 3 ppm to 350 ppm. Similar PM results were obtained at the peak-torque and road-load conditions.

The effects of fuel sulfur on the CDPF and the CR-DPF PM reduction efficiencies over the OICA test cycle and the peak-torque and road-load conditions are provided in Table 3.2-1. The data indicate that, as the fuel sulfur level increases, the reduction efficiency decreases to the point where the DPFs are ineffective at the 150-ppm and higher sulfur fuel levels. The change in reduction efficiencies from the 3-ppm baseline conditions were all statistically significant at the 0.05 level, except for the 150-ppm OICA cycle, where both DPFs had virtually no change from baseline.

Table 3.2-1. PM Reduction Efficiencies for OICA Test Cycle and Peak-Torque/Road-Load Conditions

Fuel Sulfur Level (ppm)	Device	PM Reduction Efficiencies[1]		
		OICA Cycle	Peak Torque	Road-Load
3	CDPF	95*	93*	94*
	CR-DPF	95*	91*	97*
30	CDPF	74*	72*	80*
	CR-DPF	72*	73*	81*
150	CDPF	0	18*	-25*
	CR-DPF	-3	19*	-38*
350	CDPF	-122*	-211*	-327*
	CR-DPF	-155*	-139*	-401*

(1) PM reduction efficiency = ([EO_{3ppm} – Post-DPF]/EO_{3ppm}) x 100
* Different from 0% at 0.05 level of statistical significance

PM compositional analysis was performed to investigate the increased PM levels. Basically, the PM collected on the 90-mm sampling filters contains SOF, solid material (carbon), nitrate, and hydrated sulfate. These DPFs incorporate a precious metal catalyst and are effective at reducing solids and oxidizing SOF, but they are also effective at oxidizing SO_2 in the exhaust to sulfate. Figure 3.2-2 provides the PM compositional analysis for the baseline, CR-DPF, and the CDPF for all fuel sulfur levels. The results indicate that as fuel sulfur increases, the sulfate fraction increases, leading to increased PM. The filter samples are stabilized at 50% relative humidity for weighing and then analyzed for sulfate anion, $SO_4^=$. The sulfate must exist as sulfuric acid in order to pass through the DPF and be collected on the filter. At 50% relative humidity there are 7 molecules of water of hydration per molecule of sulfuric acid (Reference 1995 SAE Handbook). For all calculations, we have assumed that sulfate is present as $H_2SO_4 \cdot 7H_2O$, and thus multiplied the sulfate mass by 2.3333 (the ratio of molecular weights of hydrated sulfuric acid to sulfate anion) to determine the full sulfur

contribution to PM mass. In all cases, the increased PM can be attributed to an increase in sulfate. The figure also indicates that the DPFs are effective in removing the solid and SOF portion of the PM. Figures 3.2-3 and 3.2-4 provide the PM compositional results for the peak-torque and road-load steady-state conditions. Again, the increased PM can be attributed to the increase in hydrated sulfuric acid. For completeness, Table C-1 in Appendix C contains the summarized PM data for the DPF program.
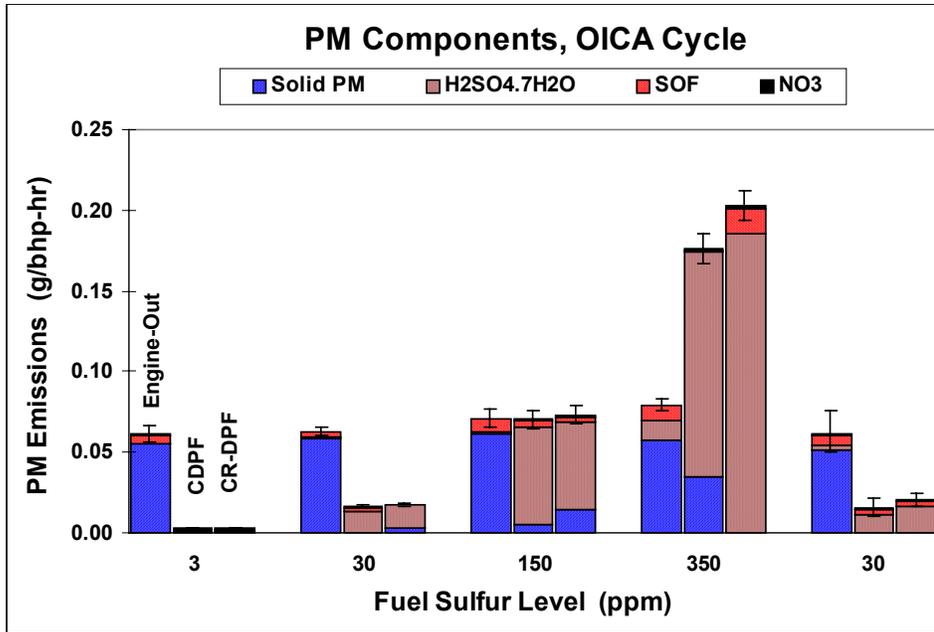
Figure 3.2-2. PM composition as a function of fuel sulfur level, for the OICA cycle (with 95% confidence intervals for average PM emissions)
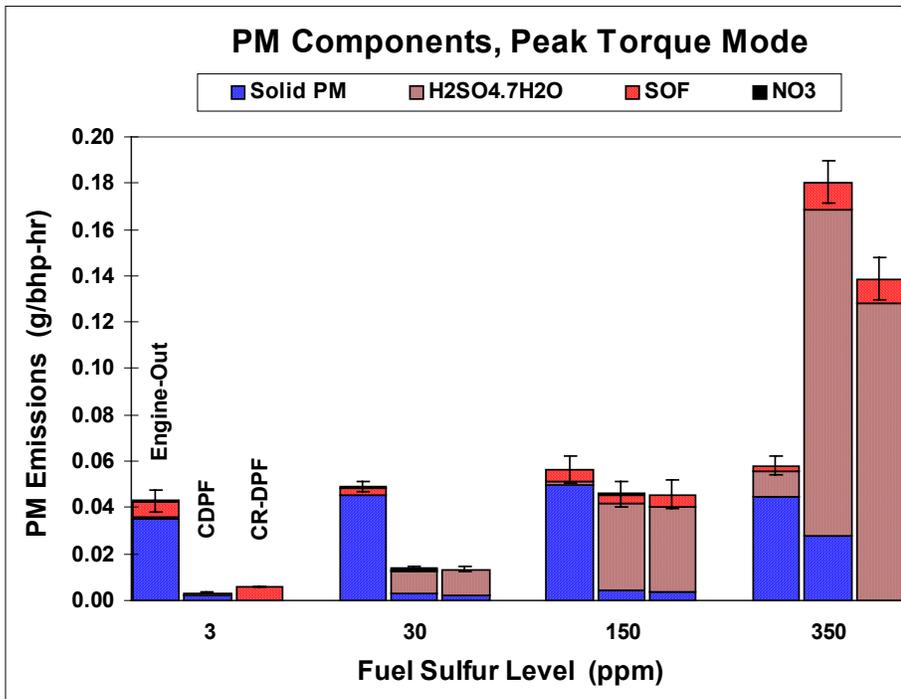
Figure 3.2-3. PM composition as a function of fuel sulfur level, for peak-torque mode (with 95% confidence intervals for average PM emissions)
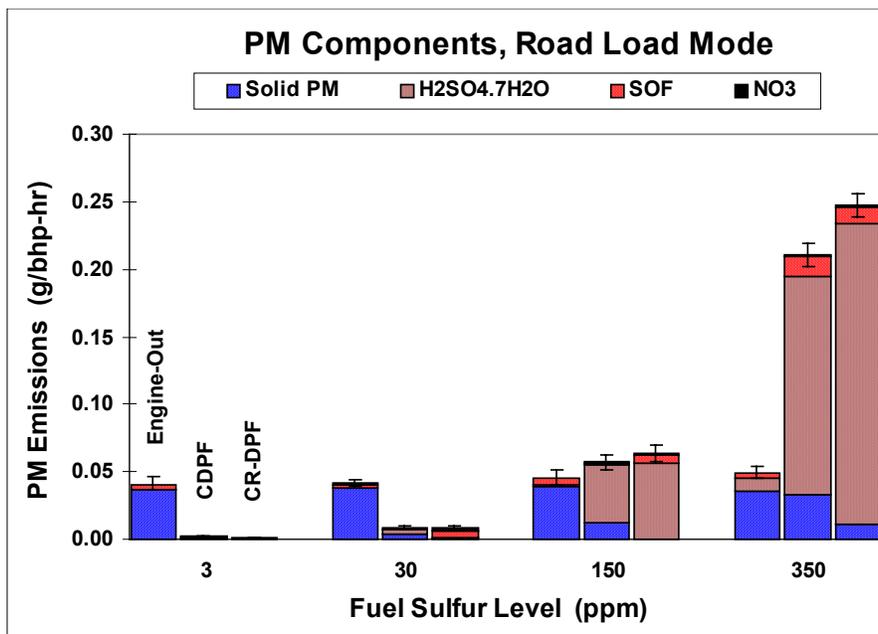
Figure 3.2-4. PM composition as a function of fuel sulfur level, for road-load mode (with 95% confidence intervals for average PM emissions)

With the two lower sulfur fuels, the mass emissions from the DPFs are reduced tremendously from engine-out levels. The makeup of these emissions is almost entirely SOF and sulfate.

In order to understand the percent of fuel sulfur that was converted to hydrated sulfate, sulfate emissions were calculated for various fuel sulfur levels assuming 40%, 50%, and 60% conversion. The calculated values are shown as the plotted lines in Figure 3.2-5. The individual data points shown in the figure are actual sulfate data (corrected for hydration) as measured during the DECSE DPF test program. From the results of this test program, it appears that approximately 40% to 60% of the available fuel sulfur is converted to hydrated sulfate using these DPFs. The implication of these data is that, even with 50-ppm fuel sulfur, the amount of sulfate PM generated by the CDPF and CR-DPF is approximately 0.025 g/bhp-hr.
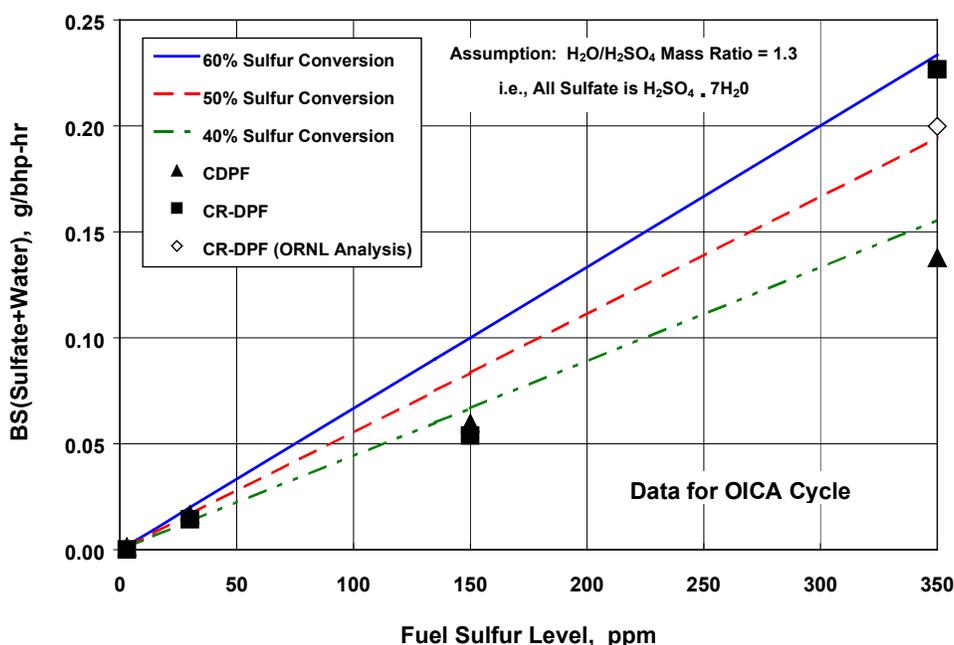
Figure 3.2-5. Effect of fuel sulfur on calculated and observed sulfate emissions

3.3 Effects of Fuel Sulfur on DPF Balance Point Temperature

3.3.1 Summary of Results

BPT tests were conducted with each fuel (3-ppm, 30-ppm, 150-ppm, and 350-ppm sulfur) and DPF device (CDPF and CR-DPF) at engine speeds of 1,440 rpm, 1,700 rpm, and 2,000 rpm. Results are summarized in Figures 3.3-1 and 3.3-2, which contain plots of the average BPT versus fuel sulfur level at three engine speeds for the CDPF and CR-DPF devices, respectively.

Statistical analysis supports the conclusion that BPT increases with higher levels of fuel sulfur. Specifically, BPT increased by an average of 33°C for the CDPF device, and 23°C for the CR-DPF

device, as fuel sulfur levels were increased from 3 ppm to 30 ppm. The BPT did not increase further with 150-ppm and 350-ppm sulfur fuels for the CDPF device. Although there appears to be a significant increase in BPT for the CR-DPF device with 150-ppm and 350-ppm sulfur fuels, these results require further explanation. In addition to the high-temperature regeneration occurring at 375° to 400°C, regeneration also occurred at temperatures as low as 250°C. Further discussion of this phenomenon is provided in Section 3.4. Because of these complications, we hesitate to make too much of the apparent 100°C increase in BPT for the 150-ppm and 350-ppm fuel results.

Results also demonstrate how engine speed affects BPT. As shown in Figures 3.3-1 and 3.3-2, BPT increases by approximately 80°C for CDPF and 30°C for CR-DPF as engine speed increases from 1,440 rpm to 2,000 rpm. This increase is relatively constant for all sulfur levels, and implies that fuel sulfur level does not affect the relationship between engine speed and BPT.
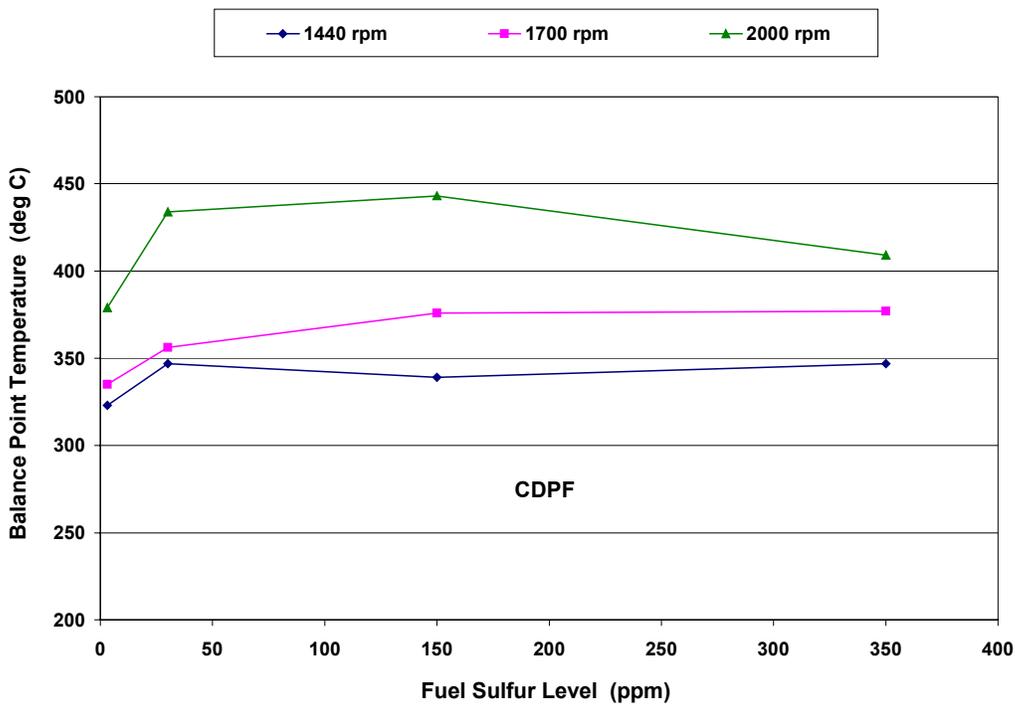
Figure 3.3-1. Estimated CDPF BPT versus fuel sulfur level and engine speed
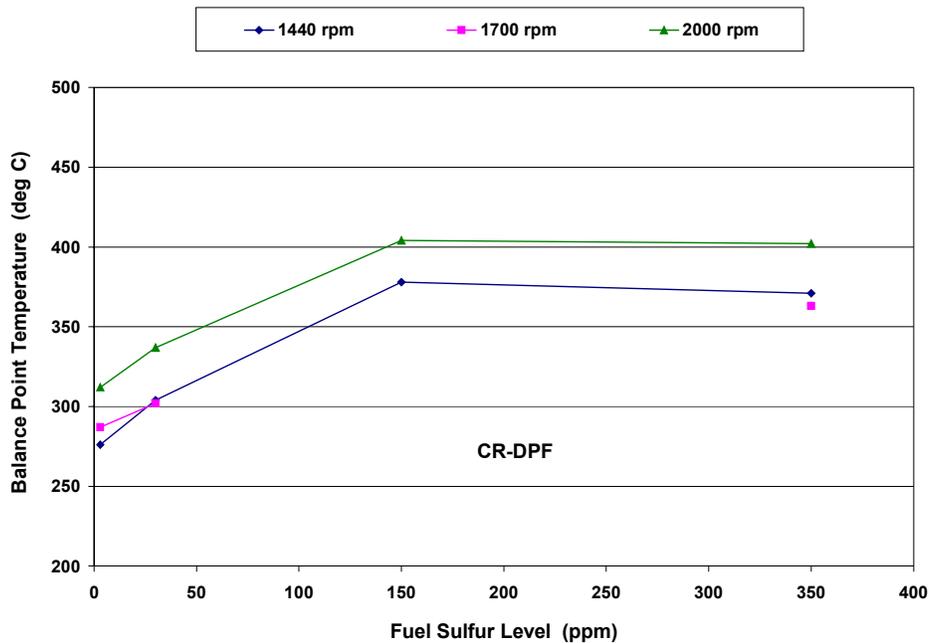
Figure 3.3-2. Estimated CR-DPF BPT versus fuel sulfur level and engine speed

3.3.2 BPT Estimates

Tables 3.3-1 and 3.3-2 contain BPT estimates with 95% confidence intervals for each combination of engine speed and fuel sulfur level. As discussed in Section 2.5, two methods of calculating BPT were employed: (1) the *average* of estimated BPTs determined from replicate tests, and (2) The estimated BPT obtained from data *pooled* across replicate tests. Generally, the results obtained by the two methods agree quite well. The only exceptions are the 3-ppm results for CR-DPF for which there was greater run-to-run variability in test results. The two methods of calculating BPT differ somewhat in the amount of statistical uncertainty that is associated with the estimates. The "averaging" method generally produces wider confidence bounds because it relies on fewer assumptions about how the data behave. On the other hand, the "pooling" method results in relatively tight error bounds, but it requires stronger assumptions about the independence of data and the absence of run-to-run differences in test conditions.

Table 3.3-1. CDPF BPT Estimates, °C (with 95% Confidence Intervals)

Engine Speed rpm)	Calculation Method	Fuel Sulfur Level (ppm)			
		3	30	150	350
1,440	Average[1]	323 (303, 344)	347 (331, 364)	339 (322, 356)	347 (318, 376)
	Pooled[2]	323 (<344)	349 (340, 357)	334 (<362)	347 (<400)
	Δ (Average)[3]		24 (-2, 50)	16 (-11, 42)	24 (-11, 59)
	Δ (Pooled)[3]		25 (2, 48)	11 (-24, 46)	24 (-33, 81)
1,700	Average	335 (314, 355)	356 (339, 372)	376 (359, 392)	377 (348, 406)
	Pooled	337 (323, 348)	344 (<367)	376 (355, 395)	377 (365, 387)
	Δ (Average)		21 (-5, 48)	41 (15, 67)	42 (7, 77)
	Δ (Pooled)		7 (-19, 33)	39 (15, 63)	39 (22, 56)
2,000	Average	379 (358, 399)	434 (413, 454)	443 (427, 460)	409 (380, 438)
	Pooled	380 (>350)	435 (427, 442)	426 (407, 441)	409 (399, 418)
	Δ (Average)		55 (26, 84)	65 (38, 91)	30 (-5, 66)
	Δ (Pooled)		56 (25, 87)	47 (13, 81)	30 (-1, 61)

[1] BPT is the average of estimated BPTs from individual runs
[2] BPT is estimated from pooled data
[3] Change in estimated BPT compared to 3-ppm test

Table 3.3-2. CR-DPF BPT Estimates, °C (with 95% Confidence Intervals)

Engine Speed rpm)	Calculation Method	Fuel Sulfur Level (ppm)			
		3	30	150[4]	350[4]
1,440	Average[1]	276 (248, 303)	304 (282, 327)	378 (356, 401)	371 (332, 410)
	Pooled[2]	262 (<294)	302 (<313)	378 (373, 382)	371
	Δ (Average)[3]		29 (-7, 64)	103 (67, 138)	95 (48, 142)
	Δ (Pooled)[3]		41 (7, 75)	117 (85, 149)	109
1,700	Average	287 (264, 309)	302 (263, 340)	-	363 (324, 401)
	Pooled	256 (<295)	NA[5]	-	363
	Δ (Average)		15 (-30, 59)	-	76 (31, 120)
	Δ (Pooled)		NA	-	106
2,000	Average	312 (289, 334)	337 (314, 359)	404 (365, 442)	402 (363, 441)
	Pooled	313 (307, 319)	336 (<347)	404	402
	Δ (Average)		25 (-6, 57)	92 (47, 137)	90 (46, 135)
	Δ (Pooled)		23 (10, 36)	91	89

[1] BPT is the average of estimated BPTs from individual runs
[2] BPT is estimated from pooled data
[3] Change in estimated BPT compared to 3-ppm test
[4] Used alternative method for calculating BPT based on limited data
[5] BPT estimate could not be calculated

Also shown in Tables 3.3-1 and 3.3-2 are the differences [Δ (Average) and Δ (Pooled)] in estimated BPTs at the higher fuel sulfur levels (30-ppm, 150-ppm, and 350-ppm) compared to the estimates with 3-ppm sulfur fuel. Confidence intervals on the differences are also provided. For a given test condition (speed and fuel sulfur level), the confidence intervals indicate whether or not the difference is significantly different from zero. If the interval contains the value zero, one can conclude, at the 95% confidence level, that there is a difference in BPTs among the fuel levels. For example, as shown in Table 3.3-1, the estimated differences in BPTs for 30-ppm sulfur fuel, compared with 3-ppm fuel, (21°C and 7°C for the two methods, respectively) are not significantly different from zero at the 95% confidence level. However, at higher sulfur levels (150- and 350-

ppm), both methods result in statistically significant differences. In some cases, it was not possible to construct confidence intervals. This is discussed in Section 3.3.3.

About half of the confidence intervals on the differences in estimated BPTs indicate a statistically significant effect of fuel sulfur level (i.e., the intervals do not contain the value zero). However, as discussed in the previous section, the analysis of variance performed on the entire set of estimated BPTs supports the conclusion that fuel sulfur affects the BPT. Specifically, the analysis supports the conclusion that BPT increases as fuel sulfur level is increased from 3-ppm to 30-ppm. Furthermore, the effect of sulfur on BPT is nearly the same at all engine speeds tested (i.e., there is no evidence of statistical interaction between fuel sulfur level and engine speed).

3.3.3 Data Collection and Analysis Issues

Initially, five exhaust temperatures, expected to span the range of possible BPT values, were selected for testing. However, under certain conditions, it was necessary to test one or two additional temperatures above the specified range in order to estimate the BPT. Some test results were excluded because the slope of delta-p remained positive at the highest temperature tested. The undesirable alternative is to extrapolate results.

The experimental design called for triplicate BPT tests for each experimental condition. Some additional tests were performed at selected conditions to verify results. Also, after reviewing emissions data and initial BPT test results with high sulfur fuel, it was decided that replicate tests would not be necessary for most of the 150-ppm and 350-ppm test conditions.

The low-temperature regeneration phenomenon involving the CR-DPF device, as discussed above, made it necessary to use an alternative method to estimate the BPT. Under most of the experimental conditions, the relationship between the slope of the DPF delta-p and test temperature was consistent with the segmented regression model discussed in Section 2.5. In other words, the slope is generally positive and constant over a range of temperatures, then decreases in a quadratic manner. This is illustrated in Figures 3.3-3 and 3.3-4. The BPT is estimated as the temperature at which the regression line becomes negative. However, the CR-DPF tests with the 150-ppm and 350-ppm sulfur fuels produced low-temperature regeneration. For this reason, an alternative method was used to obtain an estimate when "high-temperature" regeneration occurs. Essentially this method eliminated all data at temperatures prior to the point at which the delta-p became positive. The BPT was then estimated using only the remaining data. Because of the limited amount of data, simple linear regression was used to calculate the BPT, but confidence intervals were not calculated.
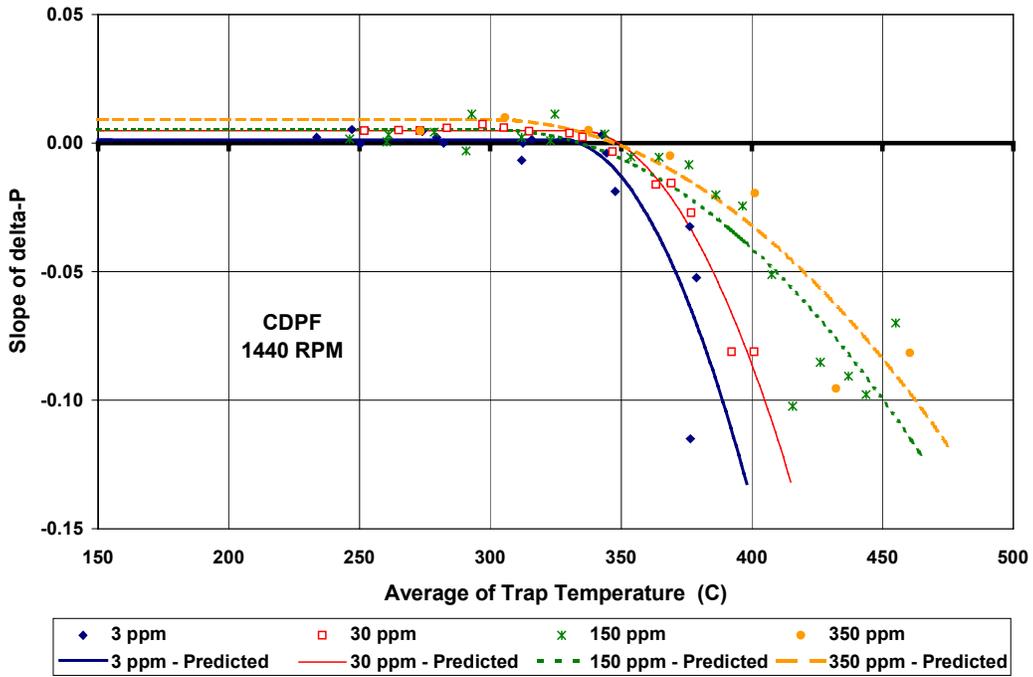
Figure 3.3-3. Calculation of CDPF balance point estimates by fuel sulfur level
(engine speed = 1,440 rpm)
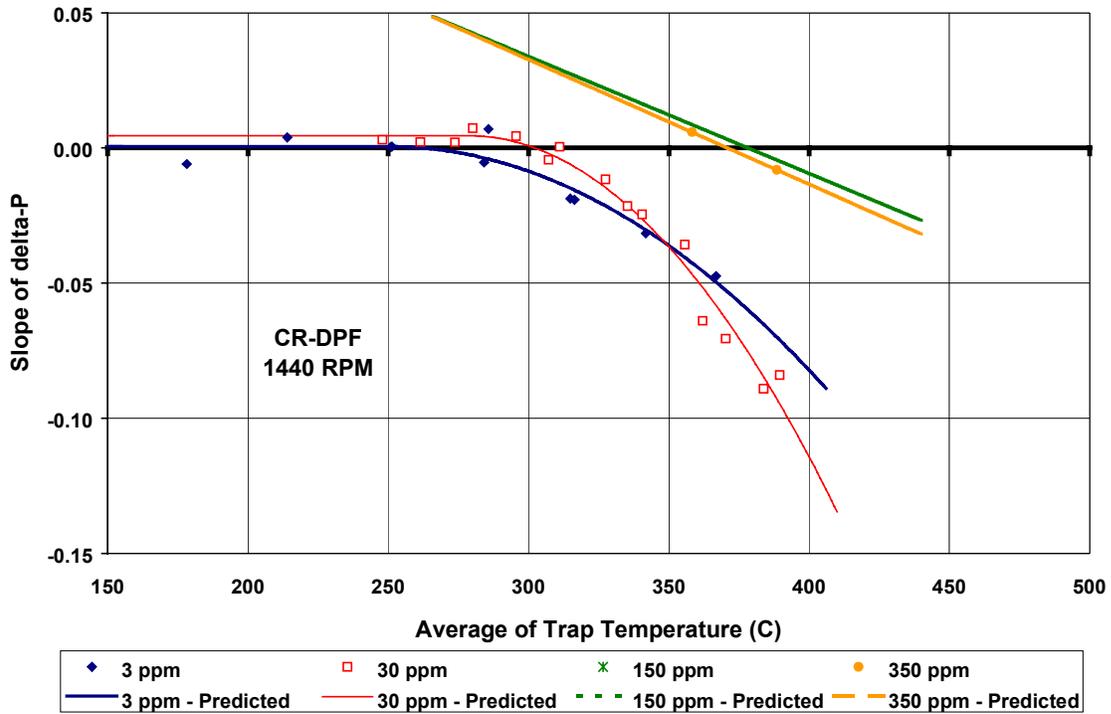
Figure 3.3-4. Calculation of CR-DPF balance point estimates by fuel sulfur level
(engine speed = 1,440 rpm)

3.4 Discussion of CR-DPF Low-Temperature Regeneration (with 150-ppm and 350-ppm Sulfur Fuels)

As noted in Section 3.3, puzzling results were obtained when attempting to run BPTs on the CR-DPF with both 150-ppm and 350-ppm sulfur fuels. In general, regeneration occurred at temperatures much lower than expected, in addition to the normal higher temperature regeneration. For example, when testing the CR-DPF on 3-ppm sulfur fuel, BPTs of 276°C, 287°C, and 312°C were obtained for the 1,440-rpm, 1,700-rpm and 2,000-rpm test conditions, respectively. Corresponding data with 30-ppm fuel yielded BPTs of 304°C, 302°C, and 337°C (shown in Table 3.4-1). For each of these tests, differential pressures measured at temperatures below the balance point showed a zero, or very slight, positive slope.

Table 3.4-1. BPT Temperatures, °C

Device	Engine Speed (rpm)	3 ppm	30 ppm	150 ppm	350 ppm
	Fuel Sulfur Level →	3 ppm	30 ppm	150 ppm	350 ppm
CDPF	1,440	323	347	339	347
	1,700	335	356	376	377
	2,000	379	434	443	409
CR-DPF	1,440	276	304	378*	371*
	1,700	287	302	---	363*
	2,000	312	337	404*	402*

* Ignored partial low-temperature regeneration

However, when testing with the 150-ppm fuel (at each of the three engine speed test conditions) at temperatures between 250°C and 300°C, increasingly negative slopes were observed, indicating rapid oxidation of accumulated PM. At temperatures between 300°C and 350°C, the rate of pressure decrease (delta-p) slowed with the slope becoming slightly positive (indicating a slow net accumulation) before once again turning negative at temperatures between 350°C and 400°C (see Figure 3.4-1). The high-temperature intercept of the zero-slope line was used as the balance point value for each of these tests, but clearly, some repeatable low-temperature regeneration was occurring during each test. Although not clearly understood, there appears to be some synergistic interaction between the NO_2 and SO_3 (formed from SO_2 by the oxidation catalyst of the CR-DPF) which together, form a more powerful oxidizing agent than the NO_2 alone.
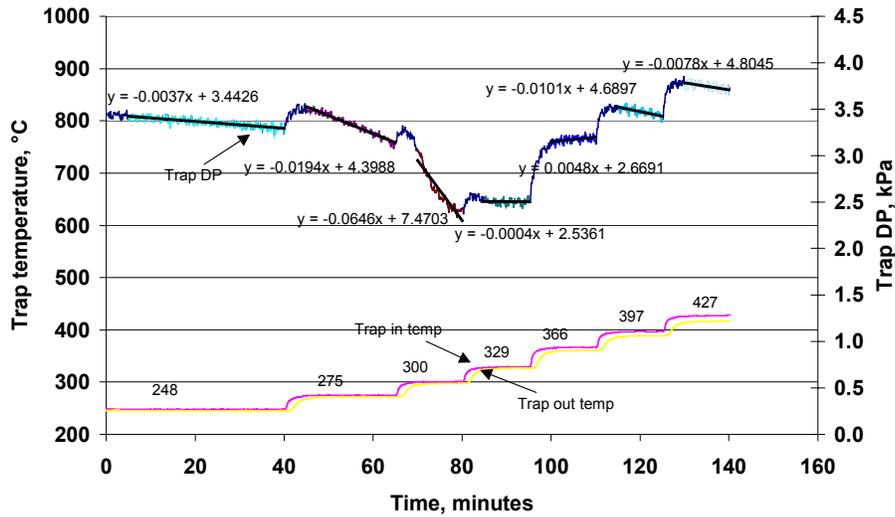
Figure 3.4-1. Example of low-temperature regeneration during BPT test with 150-ppm sulfur fuel
(CR-DPF at 1,440 rpm)

Quite possibly, either sulfate stored on the catalyst, or PM deposited during the particulate accumulation segment preceding the BPT test provides the source of the additional oxidant. Alternately, SO_3 formed during the BPT itself, could be the source. To test these hypotheses and differentiate between the two scenarios, several unique tests were designed and conducted. The first consisted of accumulating PM using 150-ppm sulfur fuel, then switching to 30-ppm fuel for the balance point determination. The second test reversed the order of fuels (i.e., accumulated with 30-ppm and ran the BPT test with 150-ppm sulfur fuel). Results of these tests, shown on Figure 3.4.-2, did little to clarify the situation.
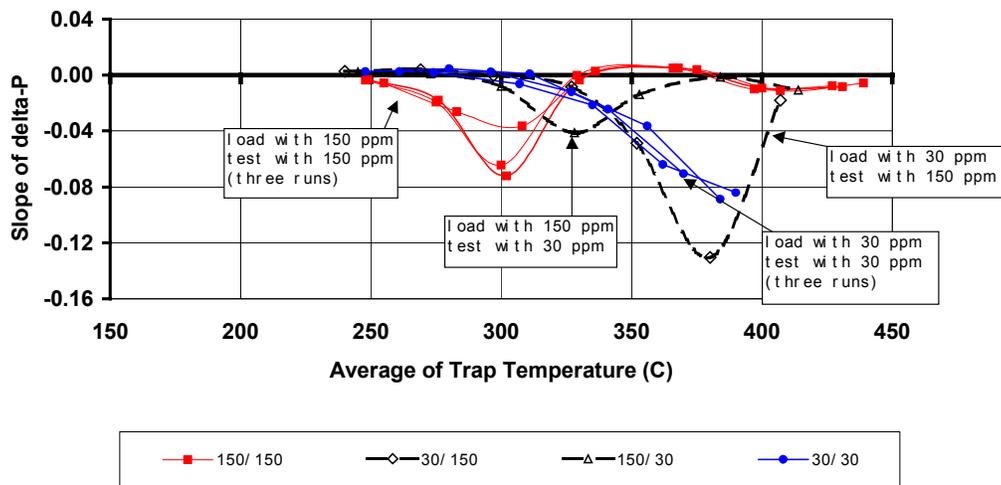
Figure 3.4-2. Summary of BPT test results with 30-ppm and 150-ppm sulfur fuel
(CR-DPF at 1,440 rpm)

Both of the special tests (load with 150/test with 30-ppm, and load with 30/test with 150) resulted in balance point curves different from either the standard 30-ppm or 150-ppm curves. The 150/30 test resulted in a partial regeneration centering at about 325° C; the 30/150 test produced a very strong regeneration centered around 375°C. Although academically interesting, this behavior is of little practical value, because at these elevated fuel sulfur levels, both of the DPFs tested produced near 0% PM reduction, making their use in this high-sulfur environment pointless.

3.5 Confirmatory Results from the Constant Temperature Tests

The constant temperature tests were performed to evaluate the DPF devices under the more dynamic conditions of alternating engine speed and torque. As discussed in Section 2.5.3, these tests were used primarily to support DPF regeneration findings from the BPT tests. In particular, there was interest in further evaluating the effects of CR-DPF low-temperature regeneration with high sulfur fuels.

For CDPF and CR-DPF devices, respectively, Figures 3.5-1 and 3.5-2 contain plots of the average slope of the DPF pressure drop (delta-p) versus fuel sulfur level for each combination of engine speed and trap inlet temperature. This average slope (or instantaneous change in pressure) indicates whether the device is in the regeneration (negative slope) or PM-build-up (positive slope) mode. The plots demonstrate that at all fuel sulfur levels, both devices are regenerating at slow speed (1,440 rpm) and high temperature (375°C). This is consistent with the CDPF and CR-DPF BPT estimates, at an engine speed of 1,440 rpm, which were generally less than 375°C. However, for the CR-DPF device, we also observe low-temperature (275°C) regeneration with high-sulfur fuels (150-ppm and 350-ppm), especially at low and moderate engine speeds. The same phenomenon was observed with the BPT tests.
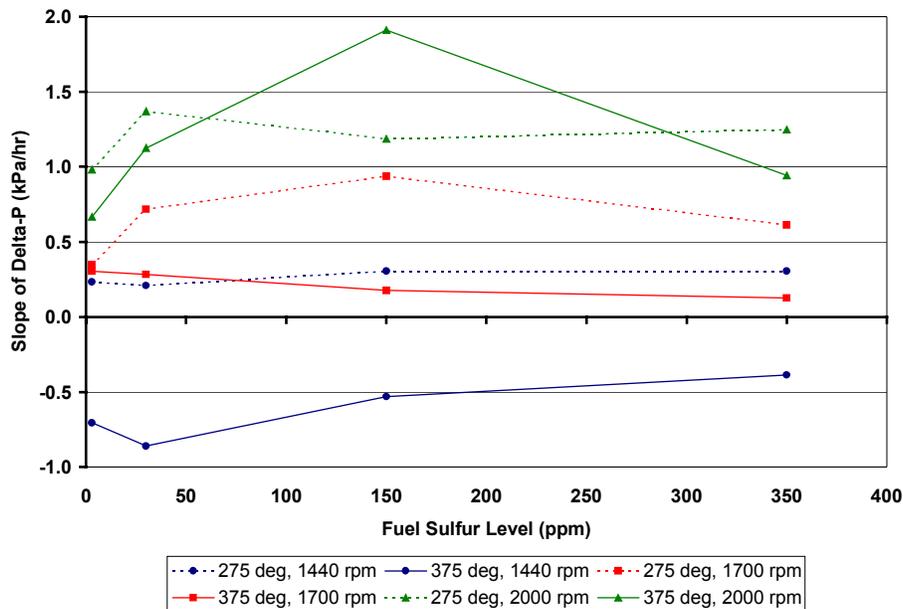
Figure 3.5-1. CDPF Slope of delta-p (average instantaneous change) versus fuel sulfur level
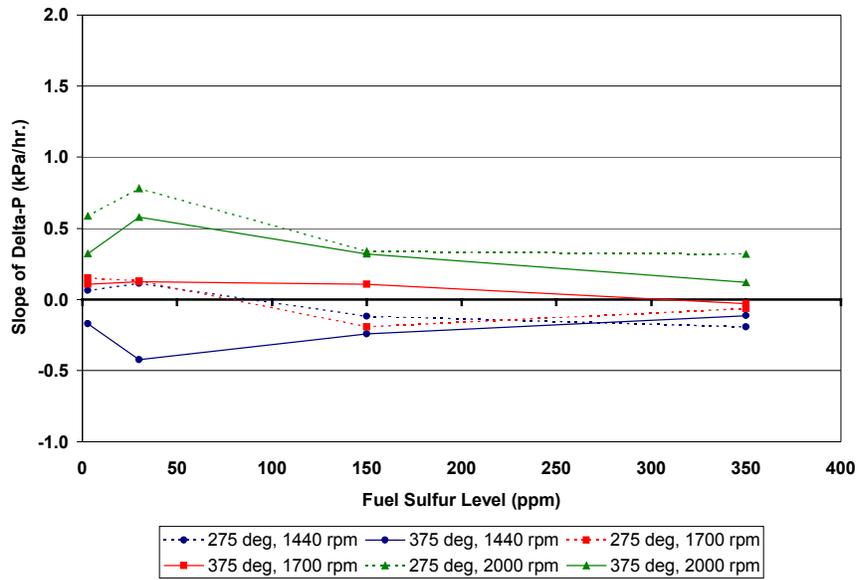
Figure 3.5-2. CR-DPF Slope of delta-p (average instantaneous change) versus fuel sulfur level

Figures 3.5-3 to 3.5-6 demonstrate how the average delta-p behaves over the 7-hour test period at various engine speeds and fuel sulfur levels. With 3-ppm sulfur fuel, we observe PM buildup at low temperatures and stable performance at high temperatures.   The latter is due to periodic regeneration at 1,440 rpm (20 minutes of every hour). As sulfur is increased to 30 ppm, both DPFs experience an increase in delta-p at the low temperature, caused by a significant buildup during the high-speed (2,000 rpm) cycle (also at 1,700 rpm for the CDPF). Finally, at higher sulfur levels (150-ppm and 350-ppm), the CDPF and CR-DPF devices perform quite differently. Delta-p for the CDPF device remains constant, as was observed in the BPT test. However, with the CR-DPF device, we observe the effects of low-temperature regeneration at the low (1,440 rpm) and moderate (1,700 rpm) engine speeds specifically, a decline in delta-p at low temperatures.
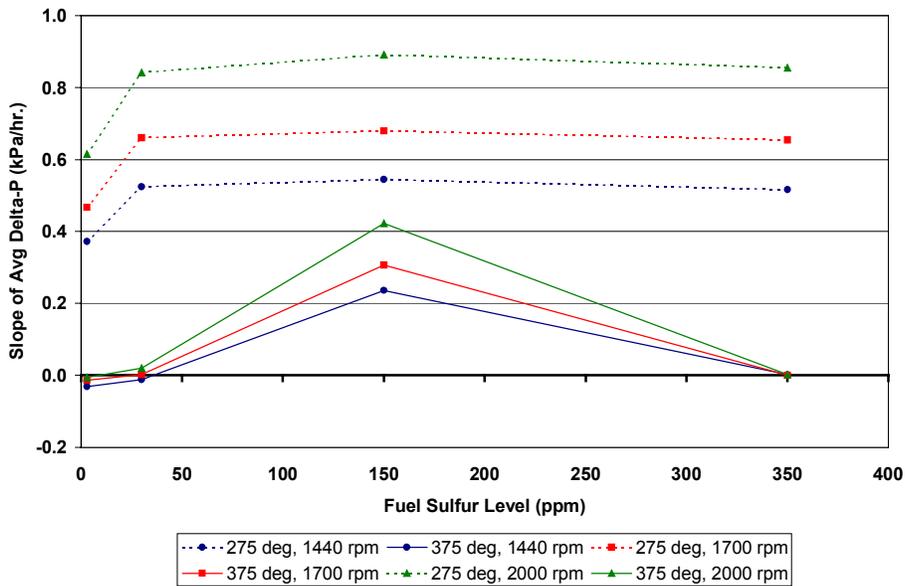
Figure 3.5-3. CDPF Slope of average delta-p (average change over time) versus fuel sulfur level
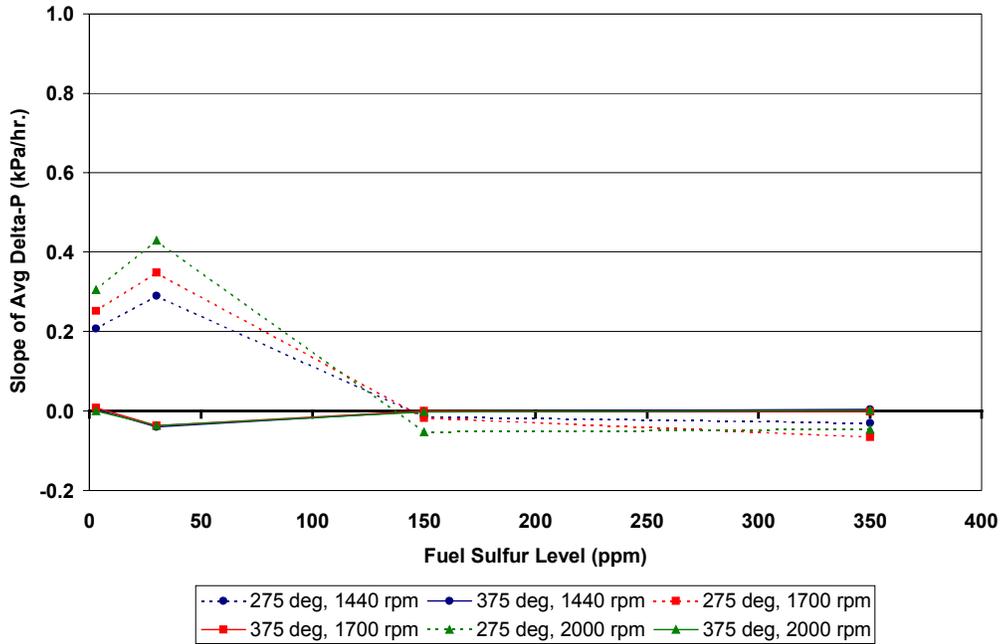
Figure 3.5-4. CR-DPF Average slope of delta-p (average change over time) versus fuel sulfur level
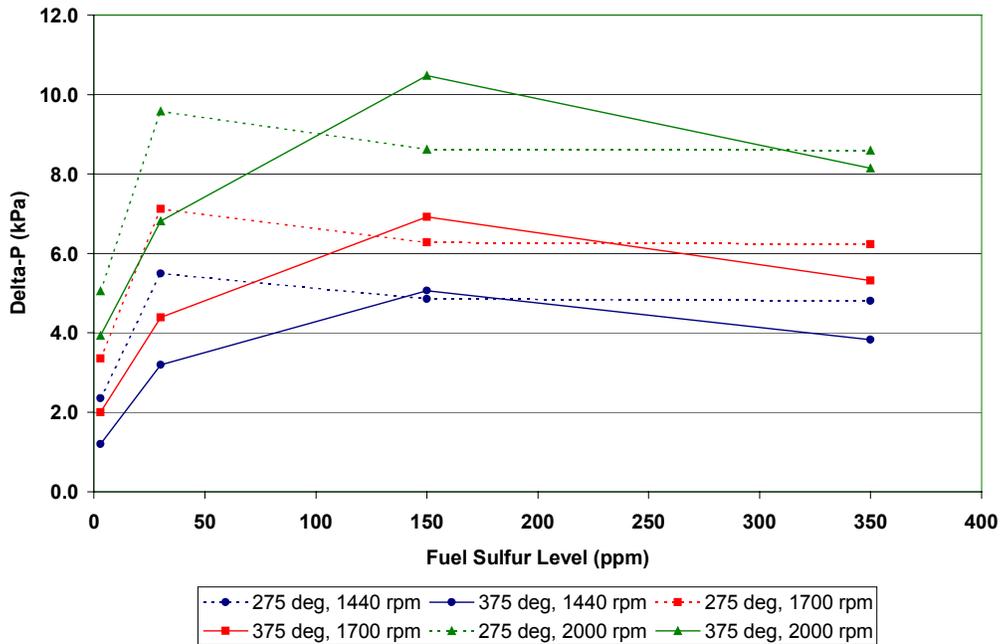
Figure 3.5-5. CDPF Average delta-p versus fuel sulfur level
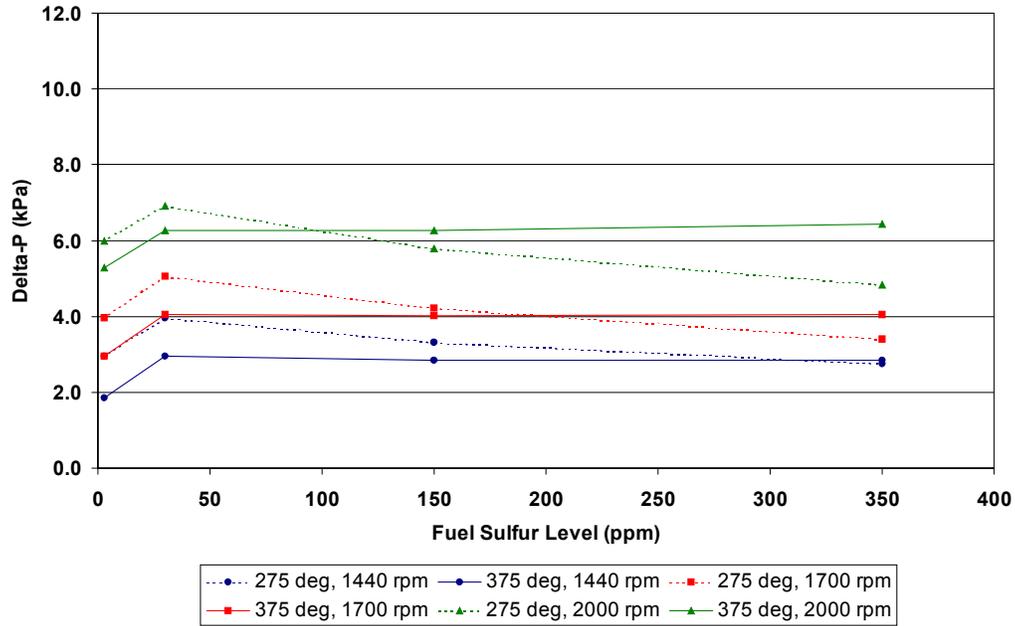
Figure 3.5-6. CR-DPF Average delta-p versus fuel sulfur level

The experimental conditions for the BPT and constant temperature tests were quite different. Thus, one should not expect an exact match in the performance of the DPF devices under similar temperature and speed conditions. However, the patterns observed in these tests do support the general findings and conclusions presented in the previous two sections.

3.6 Effect of Aging on DPF Performance

During the 9-month test period, each of the CDPF and CR-DPF devices were operated for a total of about 435 hours. This included OICA, road-load, and peak-torque emissions tests and special tests to estimate balance point temperatures. The same devices were used with all four test fuels.

Two methods are used to evaluate the potential effects of aging on DPF performance: (1) comparison of emissions from the initial and final OICA tests with 30-ppm sulfur fuel; and (2) monitoring of "clean DPF" pressure drop measurements made at rated conditions following regeneration at various times throughout the testing period.

Results of these analyses are presented in the following sections.

3.6.1 Effect of Aging on OICA Emissions

Following the initial OICA tests with 30-ppm sulfur fuel, each device was used for BPT testing with 30-ppm, 150-, and 350-ppm fuel and emissions testing with 150-ppm and 350-ppm fuel. This required approximately 325 hours of engine operation with each device. The 30-ppm OICA tests were then repeated in order to evaluate the effects of aging.

Two types of comparisons were made: (1) difference (final – initial) in engine-out and post-filter brake-specific emissions, and (2) difference in DPF reduction efficiencies (RE). Table 3.6-1 contains a statistical comparison of these differences. The asterisks indicate that the reported value (RE, difference in RE, or difference in emissions) is different from zero at the 95% level of statistical significance. For example, as discussed earlier, use of either of the two DPFs achieves a significant increase in $SO_4^=$, and a significant reduction in PM, NO_3^-, HC, and CO (and to a lesser degree, NO_x, and BSFC).

Generally, the comparison of initial and final emissions results suggest that the effects of 325 hours of DPF aging are minimal. Although there are statistically significant differences between the initial and final post-DPF emissions of NO_3^- (and, therefore, NO_3^- RE), the magnitude of NO_3^- emissions is so small, compared to other PM components, that this statistical finding may not be of any practical importance. The same can be said for the statistically significant differences for BSFC and NO_x.

Figure 3.6-1 highlights the comparison of total PM emissions between the initial and final 30-ppm OICA tests. The error bars are 95% confidence intervals for the average PM emissions. The wider error bars for the final test results are due to variability in replicate tests performed with the CR-DPF device. Although a single OICA measurement (triplicate cycles with a single PM filter) was planned for the "final" test, the test was repeated twice because the first result indicated a significant increase in post-DPF PM. The second repeat produced results that were more consistent with the "initial" test (73% RE versus 72% RE initially). This suggests that the CR-DPF device may have had a temporary loss in performance (sulfate storage and release) as a result of testing with high sulfur fuels, but the performance recovered after three tests with the 30-ppm fuel.

Table 3.6-1. Initial and Final OICA Emissions for DPFs with 30-ppm Sulfur Fuel

Emission Parameter	Source	Initial Test		Final Test		Difference	
		Emissions	RE (%)	Emissions	RE (%)	Emissions	RE (%)
PM (g/bhp-hr)	Engine-Out	0.063		0.0614		-0.0015	
	CDPF	0.0166	74**	0.0152	75**	-0.0014	2
	CR-DPF	0.0176	72**	0.0203	67**	0.0027	-5
SOF (g/bhp-hr)	Engine-Out	0.0034		0.0067		0.0032	
	CDPF	0.0022	36	0.0036	46	0.0014	10
	CR-DPF	0	100	0.0025	62**	0.0025	-38
SO_4 (g/bhp-hr)	Engine-Out	0.00011		0.00127		0.00116	
	CDPF	0.00723	-6602**	0.00603	-376**	-0.0012	6226
	CR-DPF	0.00626	-5703**	0.00793	-525**	0.0017	5178
NO_3 (g/bhp-hr)	Engine-Out	0.00056		0.00057		0.00002	
	CDPF	0.00075	-34**	0.00041	28**	-0.00033**	62**
	CR-DPF	0	100**	0.00052	9	0.00052**	-91**
HC (g/bhp-hr)	Engine-Out	0.056		0.0567		0.0007	
	CDPF	0.0182	68**	0.0126	78	-0.0056	10
	CR-DPF	0.0052	91**	0.0053	91**	0.0001	-0
CO (g/bhp-hr)	Engine-Out	0.96		0.85		-0.11	
	CDPF	0.02	98**	0.03	97**	0	-1
	CR-DPF	0.06	94**	0.05	94**	-0.01	-0
NO_x (g/bhp-hr)	Engine-Out	4.98		4.92		-0.06	
	CDPF	4.8	4**	4.81	2*	0.01	-1
	CR-DPF	4.84	3**	4.91	0	0.07**	-3**
BSFC (lbs/bhp-hr)	Engine-Out	0.359		0.349		-0.01**	
	CDPF	0.36	0	0.35	-0	-0.009**	-0
	CR-DPF	0.363	-1**	0.357	-2**	-0.006**	-1*

** Indicates that the estimate is different from zero at the 5% level of statistical significance

PM Components, OICA Cycle
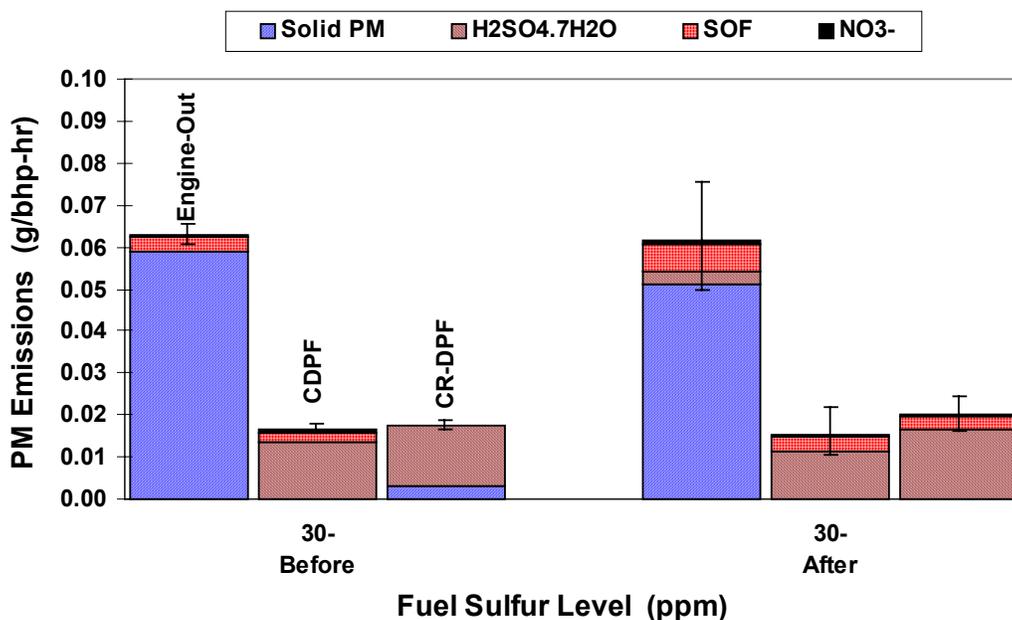
Figure 3.6-1. Comparison of initial and final PM OICA emissions with 30-ppm sulfur fuel

3.6.2 Effect of Aging on Clean DPF Pressure Drop

DPF pressure drop (delta-p) was measured immediately after each device was regenerated throughout the program. This was monitored to address the possible increase of DPF clean pressure drop caused by the accumulation of ash from the fuel or lube oil. Figure 3.6-2 shows the clean DPF pressure drop as measured throughout the duration of the program. Tests were performed on both devices (CDPF and CR-DPF) with all four fuel types (3-ppm, 30-ppm, 150-ppm, and 350-ppm). Testing was continuous from late April to early December 1999, so the date of testing is almost perfectly correlated with the number of hours of operations.

On June 16, 1999 a pressure transducer was replaced because of a possible flaw. Prior to that date, the pressure drop was lower. After June 16, 1999, the clean DPF pressure drop (data presented in Figure 3.5-2) did not show a significant change over the duration of the program. The modest change in CDPF pressure drop may be a residual degreening effect or a confounded effect of change in fuel types.
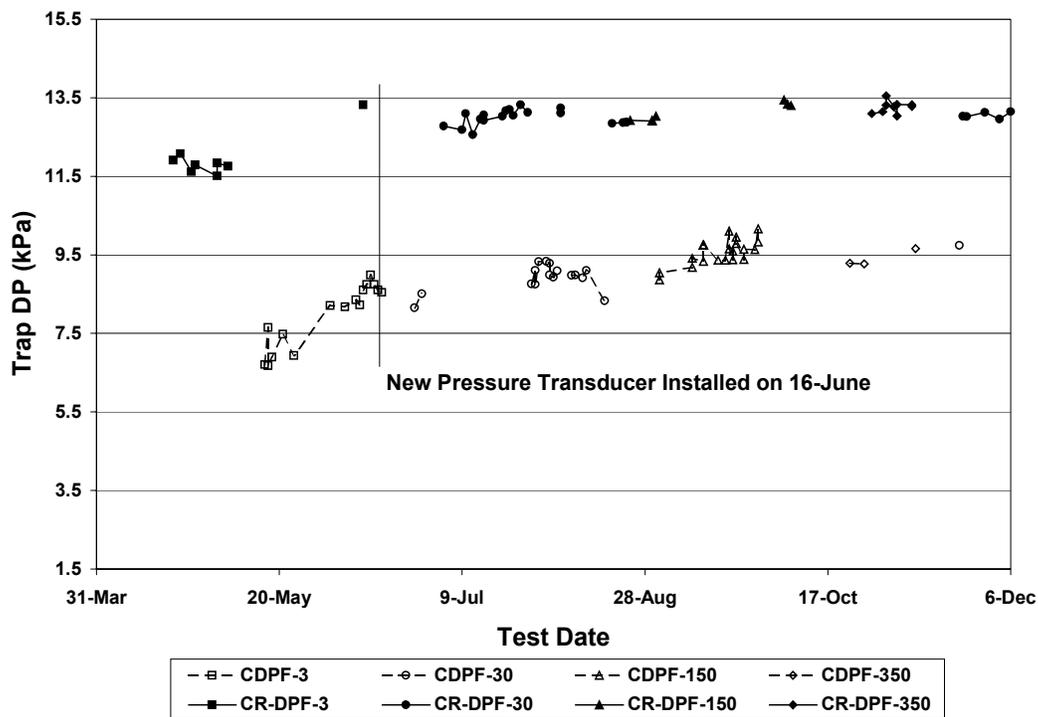
Figure 3.6-2. DPF clean pressure drop at rated condition versus test date

Section 4

Diesel Particulate Filter Conclusions

The two DPF technologies chosen for the program, CDPF and CR-DPF, underwent (1) emission tests to measure reductions in total PM and selected gases, and (2) experiments to measure the effect of fuel sulfur level on the temperature required by the DPF devices for regeneration. These tests have resulted in the following conclusions:

- Increasing the fuel sulfur level from 3 ppm to 350 ppm produced an essentially linear 29% increase in the baseline (engine-out) PM emissions, from 0.0613 g/bhp-hr to 0.0793 g/bhp-hr. No significant changes in baseline gas phase emissions or baseline fuel consumption were observed as a result of increasing the fuel sulfur level.

- Fuel sulfur has significant effects on post-DPF total PM emissions. Both DPFs were effective in reducing PM emissions (95% over the OICA cycle), when used with 3-ppm sulfur fuel. With 30-ppm sulfur fuel, the PM reduction efficiencies dropped to 74% and 72% for the CDPF and CR-DPF, respectively. When tested with the 150-ppm sulfur fuel, PM reductions were near zero (0% and -3%), and when tested with the 350-ppm sulfur fuel, PM reductions (actually increases) of -122% and -155% were observed for the CDPF and CR-DPF, respectively.

- Fuel sulfur levels below 150 ppm were required to obtain any reduction in total PM, and a sulfur level of 30 ppm was required to achieve total PM emissions below the 0.02 g/bhp-hr level being considered for 2007 regulations.

- Approximately 40% to 60% of fuel sulfur was converted to sulfate PM as measured over the 13-mode OICA cycle for both DPFs.

- The exhaust temperature required for regeneration of the DPF devices (as measured by BPT) increased by roughly 25°C when changing from 3-ppm to 30-ppm sulfur fuel. The BPT remained stable at higher sulfur levels for the CDPF device. Evidence suggests further increases in BPT for the CR-DPF when using the 150-ppm or 350-ppm sulfur fuels.

- Within the range of fuel sulfur levels required to achieve useful PM reduction (less than 150 ppm), the temperature required for filter regeneration was consistently higher for the CDPF than for the CR-DPF. The average difference when operating with the 3-ppm sulfur fuel was 54°C (ranging from 47°C at 1,440 rpm to 67°C at the 2,000 rpm test condition). When operating with 30-ppm sulfur fuel, the BPT of the CDPF device averaged 66°C (54°C to 100°C) higher than the BPT for the CR-DPF device.

- Both DPF devices recovered PM reduction performance (as measured by OICA emissions test with the 30-ppm sulfur fuel) following approximately 400 hours of exposure to 150-

ppm, and 350-ppm sulfur fuels. Pre-exposure OICA PM reductions of 74% and 72% (observed when using the 30-ppm sulfur fuel) were matched by PM reductions of 75% and 73% following high sulfur exposure. The CR-DPF device, however, required three replicate OICA tests to achieve this level, presumably because of sulfate storage and release mechanisms.

- Fuel consumption increases of 0% to 2% above baseline were measured when operating with the DPF devices. This increase, resulting from the additional exhaust back-pressure created by the DPF, was generally larger with the CR-DPF than with the CDPF.

- Both DPFs were effective in removing much of the HC. The CDPF, on the OICA cycle, has an HC reduction efficiency of about 70% (58% to 82%). The CR-DPF, on the OICA cycle, has an HC reduction efficiency of about 83% (68% to 91%). The DPFs were also efficient in oxidizing CO. The measured reduction efficiency for CO varies between 90% and 99% across the various fuel sulfur levels and three test modes.

Section 5

Future Work

5.1 Background

One of the main health concerns of the late 1990s has been the prevalence of fine particles, or $PM_{2.5}$, in the atmosphere. Recent EPA legislation has addressed these concerns by setting new National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$ and ozone (ozone participates in secondary aerosol formation). Other health researchers (University of Minnesota and Michigan Tech) have recently pointed out the importance of ultrafine PM (particles that are < 100 nm in diameter). Although both $PM_{2.5}$ and ultrafine particles can penetrate deeply into the lung, there is some evidence that ultrafine particles are never expelled, because of their incorporation into cellular function. Because modern high-pressure, direct-injection diesel engines generate more ultrafine particles than older diesel engines, there is much interest in characterizing them, and the effects of emissions controls on them.

Research conducted at the University of Minnesota and Michigan Tech has demonstrated an influence of emission controls and, perhaps more importantly, test dilution conditions on PM size. For instance, researchers found that under EPA-approved dilution conditions, production of ultrafine PM (size<100 nm) can increase with use of DPFs and DOCs. Comparing 0.3%-sulfur fuel to 500-ppm sulfur fuel, Michigan Tech demonstrated that the sulfur contribution to ultrafine PM was very important, thus providing further argument to reducing the level of sulfur in fuel. Researchers at the University of Minnesota and Michigan Tech have hypothesized that DPFs remove the larger soot carbon particles (>40 nm) that would normally see growth because of condensation of semi-volatile compounds and sulfuric acid, resulting in a gaseous mixture that favors homogenous nucleation. Furthermore, by increasing the dilution, the University of Minnesota demonstrated that there are fewer and smaller "particles."

ORNL recently evaluated a CDPF with No. 2 diesel fuel and performed particle size measurements using a Scanning Mobility Particle Sizer (SMPS). The results of engine-out and CDPF-out emissions at two dilution ratios are shown in Figure 5.1-1; more dilution means fewer chances to collide and coalesce.

Similarly, residence time in the dilution tunnel plays a big role in the formation of particles and can affect measured particle size. A new study being conducted by the Coordinating Research Council will investigate many of these dilution issues, which are critical to the sensitive issue of ultrafine particle formation.
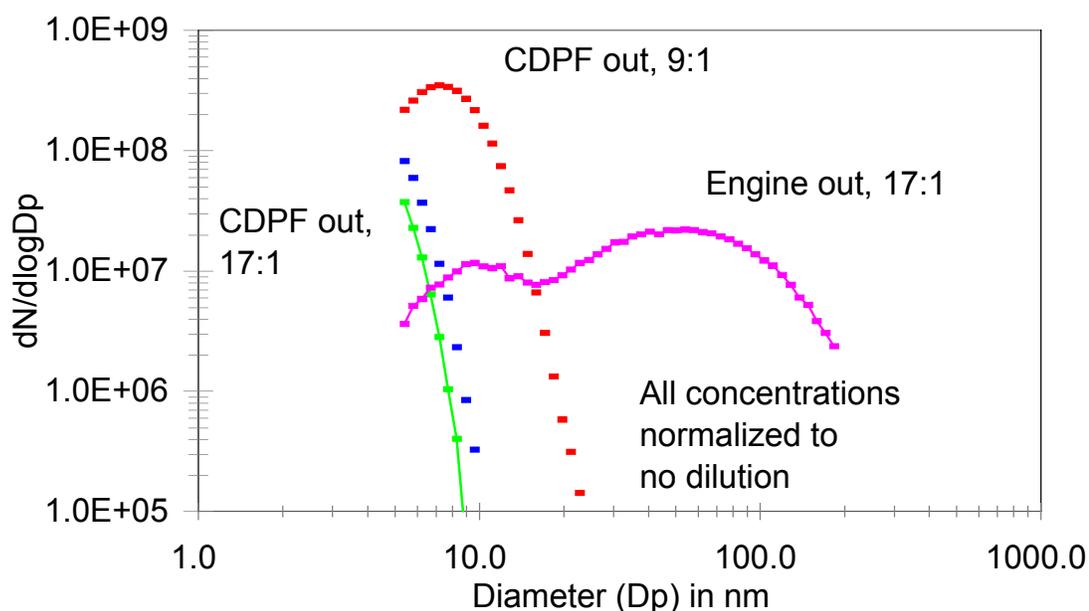
Figure 5.1-1 . Results of PM-sizing for a CDPF (engine: 1994 Navistar 7.3 L; fuel: No. 2 diesel [pump, <500-ppm sulfur]; setpoint: 1,900 rpm, 30% load)

5.2 Future Work

Within the DECSE program, ORNL has initiated some particle size measurements with the DECSE CR-DPFs and CDPFs. The intent is not to do a comprehensive study of dilution and residence time effects on PM size, but rather to illustrate what effect sulfur has on PM size distribution at dilution ratios that include those from the real world as well as those representative of certification dilution tunnels. The DECSE fuels will be used in these evaluations. Because sulfate compounds dominate the lowest size fractions, it is anticipated that under the same test conditions, a reduction in fuel sulfur will result in lower numbers of the nuclei mode particles.

5.2.1 HC Speciation and Non-Regulated Emissions

The CDPF and CR-DPF are likely to have a positive effect on non-regulated emissions, in particular air toxics such as benzene and formaldehyde. This effect may be tempered by the presence of sulfur in the fuel. Furthermore, the ability of the DPFs to remove/affect the SOF of the PM may be dependent on sulfur level. The ORNL study will analyze for light and heavy HCs and aldehyde/ketones concurrently with the PM sizing effort.

5.2 2 DECSE II Systems Work

Phase II of the DECSE program will take a systems approach to the effects of advanced petroleum-based fuels. The idea is to examine the fuel, lubricant, and emissions control system as all interacting to affect emissions. Two emission control systems may be examined; the first being made up of a urea-based SCR device in combination with a CR-DPF.   The second is a NO_x adsorber and CDPF-based system. In addition to regulated emissions, both studies may include measurements for PM mass, size and composition, and measurements of air toxics where appropriate. An additional project may focus on determining the effect of lubricant on emissions, including PM. As sulfur is removed from fuel, the sulfur in the lubricant will comprise an increasing fraction of the source of sulfur in the PM.

Appendix A

DECSE Fuel Selection and Composition

This appendix discusses information related to the selection and composition of the fuel for the DECSE program.

A.1   Introduction

A major DECSE program goal is to investigate the specific effects of diesel fuel sulfur levels on the operation of diesel exhaust emission control devices. The fuel selection and specification process was directed toward achieving this overall goal.

To isolate the effects of fuel sulfur content from other fuel properties, differences in fuel sulfur level were obtained by doping an ultra-low sulfur base fuel with sulfur-containing compounds. Except for the sulfur content, the properties of this base fuel were selected to be representative of diesel fuels sold and used in the United States. Sulfur doping levels of 30, 150, and 350 ppm were selected.

A.2   Base Fuel Properties

The base fuel is an ultra-low sulfur fuel that is otherwise representative of diesel fuels used in the United States. Table A.2-1 shows the specifications for this fuel, and the properties of the base fuel as blended. This fuel has a sulfur content of 3 ppm and is therefore designated as the 3-ppm base fuel. The measured property values were averages of analyses by Phillips Chemical, Southwest Research Institute, and Core Laboratories.

A.3   Achieving Desired Fuel Sulfur Contents

Diesel fuels of differing sulfur levels can be obtained by:

- Seeking available diesel fuels that have different sulfur contents
- Blending varying amounts of a low-sulfur diesel fuel and a high-sulfur diesel fuel to produce intermediate sulfur concentrations
- Adding varying amounts of sulfur to a low-sulfur diesel fuel.

All three options were considered. The first two options have the advantage that the sulfur will be in chemical forms that exhibit all the natural diversity of petroleum-based fuels. Another advantage is fully realized impacts from different refining processes for lowering sulfur on the diversity of the petroleum-based fuels.

Table A.2-1. Specifications and Measured Properties of 3-ppm Sulfur Base Fuel

Fuel Property	ASTM Test	DECSE Goal	DECSE Measured
Density, kg/m3	D1298/D4052	820-850	826.1
Viscosity @ 40°C, mm 2/s	D445	>2.0	2.42
Distillation IBP, °C	D86	171-182	185
5% recovery, °C	D86		198
10% recovery, °C	D86	210-226	207
20% recovery, °C	D86		222
30% recovery, °C	D86		238
40% recovery, °C	D86		251
50% recovery, °C	D86	254-271	259
60% recovery, °C	D86		266
70% recovery, °C	D86		274
80% recovery, °C	D86		287
90% recovery, °C	D86	310-321	314
95% recovery, °C	D86		338
FBP	D86	326-360	350
Carbon, mass %	D5291		86.3
Hydrogen, mass %	D5291		13.4
Sulfur, ppm	D5453**	<10	3.1
Avg.. molecular weight			196.5*
Saturates, vol %	D1319	55-70	70.7
Olefins, vol %	D1319	1-3	2.3
Aromatics, vol %	D1319	25-32	27.0
Aromatics, mass %	D5186		28.5
Polyaromatics, mass %	D5186	3-10	9.6
Non-aromatics, mass %	D5186		71.2
Sediment, water, vol %	D1796	<.0.05	< 0.01
Ash, mass %	D482		<0.001*
Ramsbottom carbon	D524		0.01*
Copper corrosion	D130		1A*
Heat comb, net, MJ/kg	D240		43.1*
Flash point, PMCC, °C	D93	>52	71
Cetane number	D613	42-48	44.8
Cetane index	D976		53.6*
Cloud point, °C	D2500		-21.0
Pour point, °C	D97		-21.0
HFRR** lubricity, μm	D6079		635/355* ****

Notes: * Value based on intermediate scale-up of fuel blend
            ** Phillips used ASTM D4045 for sulfur determination
          *** HFRR = high-frequency reciprocating rig
        **** Values without/with 205 ppm Octel FOA 35a additive

However, if the sulfur content were varied by changing the fuel, other fuel properties would change as well. Thus, as the identity of the fuel changed, the unavoidable changes in such fuel properties as density, aromatics content, polyaromatics content, and/or volatility could lead to questions about whether changes in these properties, and not changes in the sulfur content of the fuel, were responsible for any observed changes in emission control device effectiveness.

Keeping in mind the program objective and the issues outlined above, the DECSE technical committee chose the third option (adding varying amounts of sulfur-containing compounds to a low-sulfur fuel). This process is generally referred to as "doping" the fuel, and the sulfur compounds used for this purpose are sometimes termed "dopants."

A.4   Selection of Fuel Sulfur Levels

The sulfur contents selected for the test fuels were 3, 30, 150, and 350 ppm. Sulfur content is defined as the mass fraction of elemental sulfur in the fuel. The 3-ppm fuel is intended to represent a fuel that is essentially sulfur-free. A sulfur-dopant mix was used to increase the sulfur content of the 3-ppm base fuel to higher levels. For some tests, an intermediate 16-ppm sulfur fuel was used to obtain a finer differentiation between the essentially sulfur-free 3-ppm fuel and the 30-ppm fuel. The 30-ppm fuel is intended to represent a fuel that meets a proposed 30-ppm diesel fuel sulfur standard. The 150-ppm fuel is intended to represent a fuel of intermediate sulfur content, and was part of the oil industry's response to EPA. This was a sulfur level that the American Petroleum Institute indicated could be made available in the short term. The 350-ppm fuel is intended to represent a fuel of sulfur content consistent with the current U.S. average.

A.5   Selection of Sulfur Dopants

A.5.1 Technical Background

Virtually all the mass of the fuel is oxidized in the engine: the carbon in the fuel is oxidized to carbon dioxide, the hydrogen in the fuel is oxidized to water, and the sulfur in the fuel is primarily oxidized to sulfur dioxide. The composition of the engine-out exhaust is essentially a function only of the mass fraction of each of these fuel elements. According to this view, the amount and chemical identity of sulfur in the engine-out exhaust is independent of the identity of the sulfur compound(s) used to dope the fuel, and the effect of varying sulfur levels in the fuel could be duplicated by merely adding sulfur dioxide to the exhaust itself.

However, to increase the realism of the test and to allow for the possibility that some small amount of sulfur-containing compounds may remain unburned, sulfur dopants were used. This ensures that sulfur is contained in the test fuels in a way that is similar to the indigenous sulfur in diesel fuel. In this context, "similar" is defined by the following statements:

- The chemical forms of the sulfur compounds used to dope the fuel are similar to the chemical forms of sulfur compounds that are indigenous to diesel fuel.

- The volatility of the sulfur compound(s) used to dope the fuel is similar to the volatility of diesel fuel.

A.5.2 Information on Sulfur Compounds in Diesel Fuels

Information on the exact chemical identity of naturally occurring sulfur compounds in diesel fuel is sparse. Although there is consensus concerning the general classes of chemical compounds that are present, no complete information on the speciation of sulfur compounds in diesel fuel could be located. Conversations with industry sources and review of a comprehensive study of sulfur compounds in crude oil performed by the U.S. Bureau of Mines[2] showed that:

- Various substituted dibenzo[b]thiophenes and benzo[b]thiophenes are the most common sulfur-containing constituents of diesel fuel, with the dibenzo[b]thiophenes being more abundant than the benzo[b]thiophenes.

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[2] Sulfur Compounds in Crude Oil, U.S. Bureau of Mines Bulletin 659, (1972).

- Other sulfur-containing constituents include disulfides and sulfides. The sulfides include cyclic and alkyl/aryl sulfides.

A.5.3 Logistic Criteria

Because dopants must be commercially available in the necessary quantities, selection is limited in practice to those sulfur compounds offered by commercial chemical vendors in multi-kilogram quantities at reasonable cost.

A.6   Selection of Dopant Composition

A dopant composition was developed that represents each of these four classes of sulfur compounds: dibenzo[b]thiophenes, benzo[b]thiophenes, disulfides, and sulfides, and whose volatilities were within the diesel fuel range. Table A.6-1 describes this dopant composition, and properties of the dopants are shown in Table A.6-2.

Table A.6-1. Dopant Composition

Constituent	Dopant Mass/ Sulfur mass	Desired Mass Percent Sulfur	Percent Dopant by Weight
Dibenzo[b]thiophene	5.75	50	59.4
Benzo[b]thiophene	4.18	30	25.9
Di-t-butyl disulfide	2.78	10	5.7
Ethyl phenyl sulfide	4.31	10	8.9
Totals		100	100.0

Table A.6-2. Properties of Proposed Dopants

Constituent	CAS Number	MW	Sulfur Atoms	Sulfur (%)	Constituent mass/ sulfur mass	Boiling Point (ºC)	Melting Point (ºC)	Density (kg/L)
Dibenzo[b]thiophene	132-65-0	184.26	1	17.40	5.75	332	99	*
Benzo[b]thiophene	95-15-8	134.20	1	23.90	4.18	221	29	1.149
Di-t-butyl disulfide	110-06-5	178.36	2	17.98	5.56	200	*	0.923
Ethyl phenyl sulfide	622-38-8	138.23	1	23.20	4.31	204	*	1.021

*Data not available.

A.6.1 Sulfur Levels of Doped Fuels

Table A.6-3 shows the analysis values for the sulfur levels of several samples of the various doped fuels.

Table A.6-3. Sulfur Levels of Base and Doped Fuels

Nominal Sulfur Content (ppm)	Average Sulfur Content As Analyzed (ppm)
3	3
30	30
150	151
350	Est. 350

A.7   Fuel Quality Control Procedures

Quality control procedures were implemented to ensure that both the base and doped fuels met initial specifications and maintained their integrity as they are transported to the point of use.

The procedures included:

- Pre-cleaning of tanks, trucks, drums, and other containers used to transport fuel.
- Numbering of fuel containers to allow each test to be associated with a specific container of fuel.
- Sampling and analysis of each lot of fuel prior to shipment to verify that the fuel being shipped meets project specifications.
- Drawing samples from each container of fuel. These samples will be retained until the project is over. (Not all samples will be analyzed, but they will be available, if needed.)
- Analyzing the samples from the first, middle, and last containers in each separate delivery of fuel for sulfur and density. Examining these basic fuel properties will help verify that the correct fuel was used.
- Comparing pre- and post-shipment fuel analysis results.

Appendix B

DECSE Lubricating Oil Selection and Test Procedures

This appendix covers the selection and use of the engine lubricating oil for the DECSE program.

B.1   Objectives for Selection of Lubricating Oil

The selection of the DECSE lubricating oil was intended to meet the following objectives:

- Oils meeting the requirements of Advanced Petroleum Institute CH-4 are formulated to provide adequate lubrication, and to have the anti-wear, dispersant, detergent, and other necessary operational qualities required by heavy-duty diesel engines designed to meet modern emissions standards. Therefore, the lubricating oil should be a commercial product meeting CH-4 specifications.

- The viscosity grade should be 15W40 as defined by SAE J300. This is the predominant viscosity recommendation for heavy-duty diesel engines in the United States.

- The lubricating oil should be a product with significant market share, to be representative of those oils used in the marketplace.

- Consistent with the above three objectives, the sulfur content of the lubricating oil selected should be at the low end of the observed range.

- The lubricating oil should be purchased as a single batch to eliminate the possibility of formulation changes during the course of the study.

B.2   Results of Lubricating Oil Selection Process

Based on this information and analysis, the EMA recommended that Shell Rotella T 15W40 oil would meet commercial specifications, have a significant market share, and have a sulfur content of about 4,000 ppm, which is at the lower end of the range for commercial oils. For these reasons, and because supply of this oil was available in a single batch, the Shell Rotella T 15W40 lubricating oil was selected.

B.3   Procedures for Lubricating Oil Use

Several procedures were developed for the use of lubrication oil in the DECSE Program.

B.3.1 Aging

The lubricating oil is aged for at least 10 hours after each oil change to stabilize the oil consumption and to minimize the chance that sulfur release or PM formation related to the use of new oil will affect the variability of experimental results.

B.3.2 Oil Change Interval

The oil change interval will be 250 hours, maximum. The oil will be changed after each change in fuel-sulfur level. However, a double flush of oil will not be necessary. The amount of oil left in the pump and passageways is estimated to be negligible.

B.4   Lubricating Oil Sampling and Analysis

Lubricating oil samples are collected and analyzed periodically according to the following procedures.

B.4.1 Sample Collection Procedures

Oil samples are collected from the engine at "warmed up" conditions while idling. Samples are taken from the oil gallery, but methods of collection depend on the given engine's configuration. A 240-ml sample is adequate to complete all routine analyses, leaving additional samples available for confirmatory or additional analyses. After sampling, an identical amount of fresh oil is added to the engine to compensate for the drained sample. (The sample line is flushed prior to collecting the sample, and the oil drained from the line reintroduced to the engine.) Sample bottles are labeled to identify the test laboratory, test hours (hours since last oil change), engine type, fuel sulfur level, date sampled, and the corresponding catalyst.

For each 250-hour aging sequence, oil samples are taken at 0, 50, 100, 150, 200, and 250 hours. The initial oil sample (zero hour) for each sequence is not collected until the engine has warmed up and has had adequate time to circulate (about 30 minutes to 1 hour).

B.4.2 Oil Analysis Procedures

Table B.4-1 outlines the oil analysis procedures used for each oil sample.

Table B.4-1. Oil Sample Analyses

Property	Test Method	Significance
Kinematic Viscosity (at 40°C)	D 445	Low viscosity identifies fuel or coolant leaks. High viscosity indicates oxidation or soot thickening.
Total Base Number (TBN)	D 4739 or D 2896	A measure of the base reserve available for acid neutralization; depletes as oil ages. Rate of depletion may be dependent on fuel sulfur level
Additive Metals (Ca, Mg, Zn, P)	ICP	Confirms additive concentration (QC). Rise in Ca or Mg level can indicate base oil volatility.
Wear Metals (Fe, Pb, Cu, Cr)	ICP	Characterizes wear rates; can indicate abnormal wear or corrosion of certain components.
Contaminant Metals (Si, Na)	ICP	Indicative of coolant leaks
Soot	IR or TGA	High soot levels can thicken the oil and accelerate wear rates. IR methods are quicker and less expensive and are typically calibrated to correlate with TGA results.
Sulfur	X-ray Fluorescence D 4927	Lends insight into the fate of crankcase sulfur; will help in the interpretation of the test results.

B.5   Consideration of Lubricating Oil Sulfur Content

Sulfur from the lubricating oil can contribute to overall engine-out sulfur emissions. There is some sulfur in the lubricating oil base stock. However, much of this sulfur content is associated with detergents and anti-wear additives in the additive packages of commercial CH-4 lubricating oils. Specifically, the anti-wear additives typically contain sulfur and phosphorus in the form of zinc dithiophosphates. Many detergent packages contain alkyl sulfonates as well.

The net effect is that commercial diesel engine lubricating oils contain from 4,000-ppm to 10,000-ppm sulfur. Proven substitutes for the sulfur-bearing additives are not available and, overall, little research has been done to date on the development of a low-sulfur lubricating oil for diesel engines. Therefore, the near-term possibility of procuring a zero-sulfur lubricating oil equivalent to current commercial CH-4 oils was not considered favorable.

The use of a synthetic oil was also considered. Although synthetic oils do not use a petroleum-derived base stock and will not have any sulfur from the base stock, they still use sulfur-containing additives. Moreover, because petroleum-derived base stocks are highly refined and hydrotreated, lowering the base stock contribution to the overall sulfur content through the use of synthetic oils would be expected to provide only a minor advantage.

B.5.1 Oil Analysis Results

An analysis of three samples of fresh, unused Shell Rotella T 15W40 oil showed an average sulfur content of 3,520 ppm.

Appendix C

Diesel Particulate Filter Summarized Data

Tables C-1 and C-2 contain statistical summaries of the CDPF and CR-DPF PM and gaseous emissions results. For each emissions parameter (e.g., PM or HC) and each test type (OICA, peak-torque, and road-load) average brake-specific emissions (g/bhp-hr), RE, and differences in RE (relative to results with 3-ppm fuel) are presented. Statistically significant REs and RE differences are indicated with asterisks. The statistical analysis methods were described in Section 2.5. The following discussion is provided to illustrate how to interpret the statistical results.

Table C-1 shows that average OICA engine-out PM emissions with 3-ppm sulfur fuel was 0.0613g/bhp-hr. With 30-ppm fuel, engine-out PM was 0.063 g/bhp-hr, which was 3% higher than with 3-ppm fuel. However, this slight increase in average measured emissions was not statistically significant. On the other hand, the 15% and 29% increases in engine-out emissions with 150-ppm and 350-ppm fuels were statistically significant at the 5% level of significance. SO_4 emissions are reported as dry (see Section 2.4.1 for calculation of hydrated sulfate).

Post-filter emissions with 3-ppm fuel for the CDPF and CR-DPF devices were 0.0031 g/bhp-hr and 0.0032 g/bhp-hr, respectively. Thus, the estimated REs are approximately 95% for both devices. These estimates are significantly different from zero. With 30-ppm fuel, the REs decreased to 74% and 72% for the CDPF and CR-DPF devices, respectively. These estimates are also significantly different from zero. Furthermore, the 21% and 23% decreases in REs relative to the 3-ppm fuel were statistically significant. Finally, the negative REs observed with 350-ppm fuel represent statistically significant increases in PM emissions with high sulfur fuel.

Table C-1. Diesel Particulate Filter (CDPF and CR-DPF) PM Emissions

Test Type	Description/Filter Type		PM (g/bhp-hr)				SOF (g/bhp-hr)				SO_4^- (g/bhp-hr)				NO_3^- (g/bhp-hr)			
	Fuel Sulfur Level (ppm)		3	30	150	350	3	30	150	350	3	30	150	350	3	30	150	350
OICA	Baseline Engine-Out Test		0.0613	0.063	0.0708	0.0793	0.0052	0.0034	0.0076	0.0093	0.00008	0.00011	0.00052	0.00522	0.00041	0.00056	0.00056	0.0005
	Sulfur EO Effect rel. to 3 ppm (%)			3	15**	29**		-34	45	79		28	517**	6073**		37**	39**	24
	Post-Filter Test	CDPF	0.0031	0.0166	0.0707	0.176	0.0009	0.0022	0.004	0.0011	0.00063	0.00723	0.02597	0.05992	0.00099	0.00075	0.00113	0.00066
		CR-DPF	0.0032	0.0176	0.0729	0.2025	0.0009	0	0.0029	0.0149	0.00008	0.00626	0.02341	0.09853	0.00131	0	0.00141	0.00209
	RE (%)	CDPF	95**	74**	0	-122**	83	36	47*	88**	-641*	-6602**	-4882**	-1049**	-143**	-34**	-101**	-32
		CR-DPF	95**	72**	-3	-155**	83	100	62**	-60*	2	-5703**	-4390**	-1789**	-221**	100**	-150**	-315**
	RE-RE$_{3ppm}$ (%)	CDPF		-21**	-95**	-217**		-47	-36	5		-5961	-4241*	-408		109**	42	111*
		CR-DPF		-23**	-98**	-250**		17	-22	-143**		-5706**	-4392**	-1791**		321**	71**	-94
Peak-Torque	Baseline Engine-Out Test		0.043	0.0489	0.0563	0.0581	0.0068	0.0031	0.0046	0.0022	0.0002	0.00011	0.00069	0.00472	0.00023	0.00029	0.00025	0.00008
	Sulfur EO Effect rel. to 3 ppm (%)			14**	31**	35**		-54	-32	-68		-45	250*	2310**		27**	8	-66**
	Post-Filter Test	CDPF	0.0031	0.0137	0.046	0.1805	0	0.0011	0.004	0.0114	0.00041	0.00399	0.01604	0.06034	0.0002	0.0002	0.00046	0.00021
		CR-DPF	0.0039	0.0133	0.0456	0.1388	0.0057	0	0.005	0.0101	0.00099	0.00471	0.01554	0.05598	0.00011	0.00016	0.00041	0.00009
	RE (%)	CDPF	93**	72**	18**	-211**	100	65	14	-421**	-109	-3592**	-2239**	-1178**	12	31**	-84**	-168**
		CR-DPF	91**	73**	19**	-139**	17	100	-8	-360**	-407	-4264**	-2166**	-1086**	51**	45**	-66**	-9
	RE-RE$_{3ppm}$ (%)	CDPF		-21**	-74**	-304**		-35	-86	-521**		-3483*	-2130*	-1069		19	-96**	-180**
		CR-DPF		-18**	-72**	-230**		83	-24	-377*		-3857	-1759	-679		-6	-117**	-60**
Road-Load	Baseline Engine-Out Test		0.041	0.0414	0.0459	0.0493	0.004	0.0035	0.0047	0.0038	0.00002	0	0.0005	0.00387	0.0004	0.00053	0.00058	0.00053
	Sulfur EO Effect rel. to 3 ppm (%)			1	12*	20**		-13	18	-4		-100	2061**	16476**		34**	47**	33
	Post-Filter Test	CDPF	0.0026	0.0082	0.0574	0.2104	0	0	0.0013	0.0147	0	0.00197	0.01843	0.06941	0.00072	0.0005	0.00078	0.00048
		CR-DPF	0.0012	0.008	0.0637	0.247	0	0.0047	0.0062	0.0133	0.00007	0	0.02646	0.09513	0.00045	0.00242	0.00082	0.00039
	RE (%)	CDPF	94**	80**	-25**	-327**	100	100	73	-285**	100	.	-3551**	-1693**	-82**	7	-34**	10
		CR-DPF	97**	81**	-39**	-401**	100	-37	-32	-250**	-180	.	-5142**	-2357**	-13	-356**	-41**	26
	RE-RE$_{3ppm}$ (%)	CDPF		-14**	-119**	-420**		0	-27	-385**		.	-3651**	-1793**		89**	48**	92*
		CR-DPF		-17**	-136**	-498**		-137	-132	-350**		.	-4962**	-2177**		-343**	-28*	39

EO = Engine-out

Sulfur EO effect relative to 3-ppm (%) = $(EO-EO_{3ppm})/EO_{3ppm} \times 100$.

RE (%) = Reduction Efficiency = $(EO-\text{Post Catalyst})/EO \times 100$.

* Different from 0% at 0.10 level of statistical significance.

** Different from 0% at 0.05 level of statistical significance.

Table C-2. Diesel Particulate Filter (CDPF and CR-DPF) Gaseous Emissions and Fuel Consumption

Test Type	Description/Filter Type		HC (g/bhp-hr)				CO (g/bhp-hr)				NOx (g/bhp-hr)				BSFC (lbs/bhp-hr)			
	Fuel Sulfur Level (ppm)		3	30	150	350	3	30	150	350	3	30	150	350	3	30	150	350
OICA	Baseline Engine-Out Test		0.0542	0.056	0.0586	0.0565	0.98	0.96	1.04	0.94	4.94	4.98	4.85	4.91	0.355	0.359	0.354	0.358
	Sulfur EO Effect rel. to 3 ppm (%)			3	8	4		-2	6	-4		1	-2**	-1		1**	-0**	1**
	Post-Filter Test	CDPF	0.0228	0.0182	0.0105	0.0194	0.06	0.02	0.02	0.03	4.92	4.8	4.87	4.69	0.359	0.36	0.354	0.356
		CR-DPF	0.0136	0.0052	0.0189	0.0064	0.1	0.06	0.06	0.05	4.96	4.84	4.88	4.81	0.362	0.363	0.358	0.355
	RE (%)	CDPF	58	68**	82**	66**	94**	98**	98**	97**	0*	4**	0	4**	-1**	0	0	1**
		CR-DPF	75*	91**	68**	89**	90**	94**	94**	94**	0	3**	-1	2**	-2**	-1**	-1**	1**
	RE-RE₃ₚₚₘ (%)	CDPF		10	24	8		4	5**	3		3**	-1	4**		1**	1**	2**
		CR-DPF		16	-7	14		4	5	5		3**	0	2**		1**	1**	3**
Peak-Torque	Baseline Engine-Out Test		0.0238	0.0194	0.0292	0.0268	1.38	1.35	1.53	1.39	4.45	4.45	4.33	4.4	0.341	0.342	0.341	0.342
	Sulfur EO Effect rel. to 3 ppm (%)			-19	23	12		-1	11	1		0	-3**	-1*		0*	0	0*
	Post-Filter Test	CDPF	0.0064	0.0041	0.0027	0.0088	0.02	0.01	0.01	0.01	4.42	4.32	4.37	4.28	0.344	0.346	0.342	0.344
		CR-DPF	0.004	0.003	0.0032	0.0008	0.05	0.04	0.03	0.04	4.41	4.28	4.36	4.32	0.347	0.346	0.344	0.347
	RE (%)	CDPF	73	79**	91**	67**	99**	99**	99**	99**	1	3**	-1	3**	-1**	-1**	-0**	-1**
		CR-DPF	83*	85**	89**	97**	97**	97**	98**	97**	1**	4**	-1	2*	-2**	-1**	-1**	-1**
	RE-RE₃ₚₚₘ (%)	CDPF		6	18	-6		1	1	0		2**	-1*	2**		0	0**	0
		CR-DPF		1	6	14*		0	1	1		3**	-2*	1		1**	1**	0**
Road-Load	Baseline Engine-Out Test		0.0344	0.0352	0.0343	0.0484	0.66	0.68	0.78	0.68	4.26	4.36	4.24	4.2	0.344	0.346	0.344	0.344
	Sulfur EO Effect rel. to 3 ppm (%)			2	0	41		3	19	2		2**	0	-1**		1**	-0*	0
	Post-Filter Test	CDPF	0.0093	0.0067	0.0055	0.0167	0.02	0.03	0.02	0.01	4.22	4.25	4.05	4.06	0.347	0.347	0.344	0.348
		CR-DPF	0.004	0.0031	0.0043	0.0039	0.02	0.03	0.04	0.03	4.29	4.15	4.26	4.17	0.35	0.352	0.349	0.35
	RE (%)	CDPF	73	81**	84**	65**	98**	96**	97**	99**	1**	3**	5**	3**	-1**	0	-0**	-1**
		CR-DPF	88**	91**	87**	92**	97**	96**	95**	96**	-1*	5**	0	1	-2**	-2**	-2**	-2**
	RE-RE₃ₚₚₘ (%)	CDPF		8	11	-8		-1	0	1		2**	4**	2**		1**	1**	-0*
		CR-DPF		3	-1	4		-1	-2	-1		6**	0	1		0	0	0

EO = Engine-out

Sulfur EO effect relative to 3-ppm (%) = $(EO - EO_{3ppm})/EO_{3ppm} \times 100$.

RE (%) = Reduction Efficiency = $(EO - \text{Post Catalyst})/EO \times 100$.

* Different from 0% at 0.10 level of statistical significance.

** Different from 0% at 0.05 level of statistical significance