Final Report

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Title: *Measurement of Emissions from both Active and Parked Regenerations of a Diesel Particulate Filter from Heavy Duty Trucks*

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ES-I Background and Introduction

The need for a parked active regeneration of a Diesel Particulate Filter, DPF, occurs for vehicles that have a low exhaust temperature duty cycle, and these vehicles may or may not be able to change their duty cycle to a more aggressive and high exhaust temperature highway cycle. More technical information is needed concerning “Parked” regenerations, since a large amount of PM mass and a very large number of ultrafine volatile and semi-volatile particles are released in the immediate vicinity of the truck diesel engine. A clearer understanding of the emitted PM composition, toxicity, and exposure potential is needed if DPFs are found to increase average vehicle total particle number emissions when regeneration is included in testing protocols. By knowing more information concerning PM physical properties, and the time and space distribution of these particles researchers can begin to understand and evaluate the possible health effects.

ES-II Methods

As part of the investigation a unique small wind tunnel has been constructed at the CARB MSOD Depot Park Facility for the purpose of capturing and measuring the exhaust emissions during an active regeneration. This wind tunnel has a simple geometry and an average air flow velocity of 8 mph, and these conditions allow for direct measurements of the development and aging of the exhaust plume during active regenerations. The small wind tunnel was designed to be a high dilution flow channel that mixes ambient air with the exhaust gases from the truck diesel engine. The system was designed in order that enough ambient air is added to the diesel exhaust to keep the mixed gases below a temperature of 40 °C, since this temperature is below the temperature of which filters are used to collect particles in CVS tunnel testing.

The small wind tunnel is shown in Fig. ES-1, and it consists of six sections of length 5 feet and a square area of 4 feet by 4 feet. Attached to the rear or exit section of the tunnel is a fan that produced a volume flow rate of 9000 cfm, cubic feet per minute. At the center of the entrance section a five inch circular steel pipe was inserted and supported, and this pipe was connected to the diesel engine exhaust pipe. For the present experimental work a mixing plate was attached to the exhaust of the entrance pipe, and the purpose of the mixing plate was to encourage mixing of the ambient air with the engine exhaust gases.

Figure ES-1 Small wind tunnel designed for parked and active regenerations

Close to the exit of the tunnel a 2 inch diameter sampling tube was supported at the center of the tunnel. The sampling tube was connected to an emission instrumentation package, and a vacuum pump created a steady flow of 160 liters per minute. Both PM emission instrumentation and particle number and size instrumentation was used in the testing:

ES-III Results

A duty cycle of approximately 30 hours of driving in stop and go traffic with the maximum velocity of 30 mph and some idling was required to load both 2007 and 2010 DPFs for a parked regeneration. In general much more material was accumulated in the 2007 certified DPF compared to a 2010 certified DPF. In fact for the 2007 DPF, the team was able to obtain a critical condition in the DPF, and a flashing light on the truck console indicated that DPF regeneration should be carried out immediately. The number of Parked Regenerations that were carried out was five, and some of the regenerations had more than one part associated with them.

The first test of the 2007 DPF had the most PM emissions of all the tests, and the PM1.0 emissions from the DustTrak are shown in Figure ES-2. The emissions during the test consisted of two parts: (1) The first part was many large particles; and (2) the second part was many smaller particles. In fact during the first part of Test1(a) there were a substantial number of particles larger than PM1.0, as shown in Figure ES-3. The emission levels in Figures ES-2 and -3 are enormous, and they have occurred at a dilution ratio of approximately 30, where dilution ratio is the amount of ambient air to diesel engine exhaust gases. The total emissions are defined as all particles less than ten microns, and it can be seen that large particles play a significant role during the early phase of the Parked Regeneration.

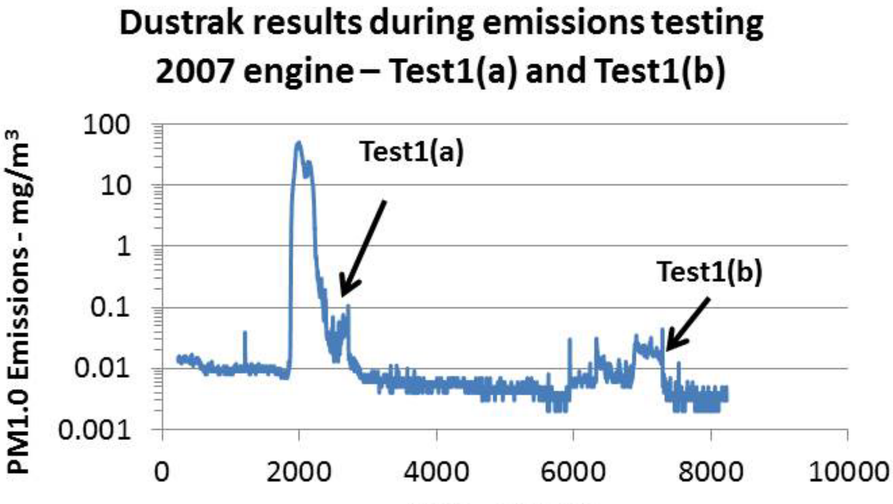


Figure ES-2 PM1.0 Emissions from the DustTrak during the entire regeneration event.

During the testing all of the instrumentation had some problems with measuring particles in the different size ranges. For example the DustTrak instrumentation did not record ultrafine particles, since the lower limit of the DustTrak for particle size is 100 nm, and the mass results in the latter part of Test1(a) and Test1(b) are under recorded in Figure ES-2 and ES-3. To obtain a better understanding of the particles emitted during the regeneration event the results from the EEPS instrumentation are presented in Figure ES-4. At the start of the regeneration near 2000 seconds large particles are emitted for approximately 400 seconds, and small particles are emitted for another 500 seconds. In terms of the number of total particles emitted small particles dominate, and mainly small particles were emitted during Test1(b)

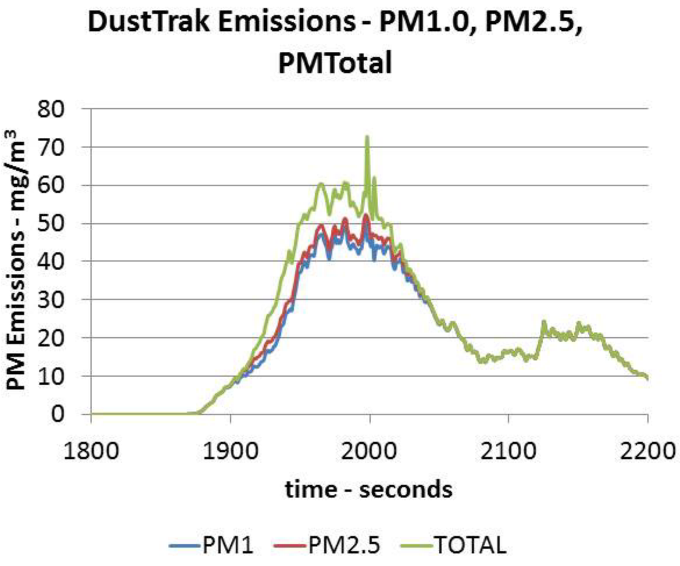


Figure ES-3 - PM1.0 and Total Emissions from the DustTrak during the high emission part of the regeneration event, Test1(a).

in Figure ES-2. It should be pointed out that the EEPS instrument does not record particles greater than 0.56 microns in electrical mobility size, and these particles are very important for mass emissions, since mass emissions are proportional to the cube of the particle size.

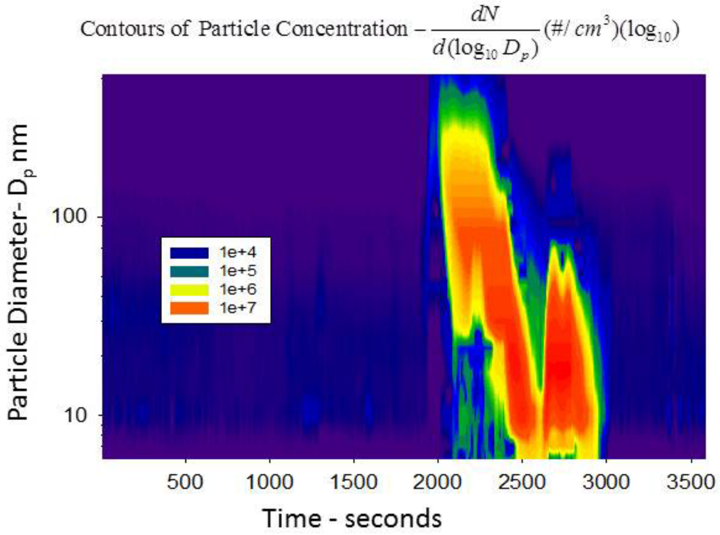


Figure ES-4 EEPS particle number concentration emissions during the initial part of the regeneration event. Test1(a)

The total particle number emissions are presented in Figure ES-5 for Test1(a) for a dilution ratio of 30/1 for the ambient air to exhaust gas ratio, and they exhibit some important characteristics of the regeneration event. The first peak in the figure corresponds to large particle emissions, and this peak is closely followed by an increase in small particles. The number of total particles then decreases, since the DPF outlet temperature exceeded its design value and the mass emissions were very large. After a cooling period the total number of particles increased, and these particles were almost entirely ultrafine particles. Test1(a) was the only test where the DPF design temperature was exceeded.

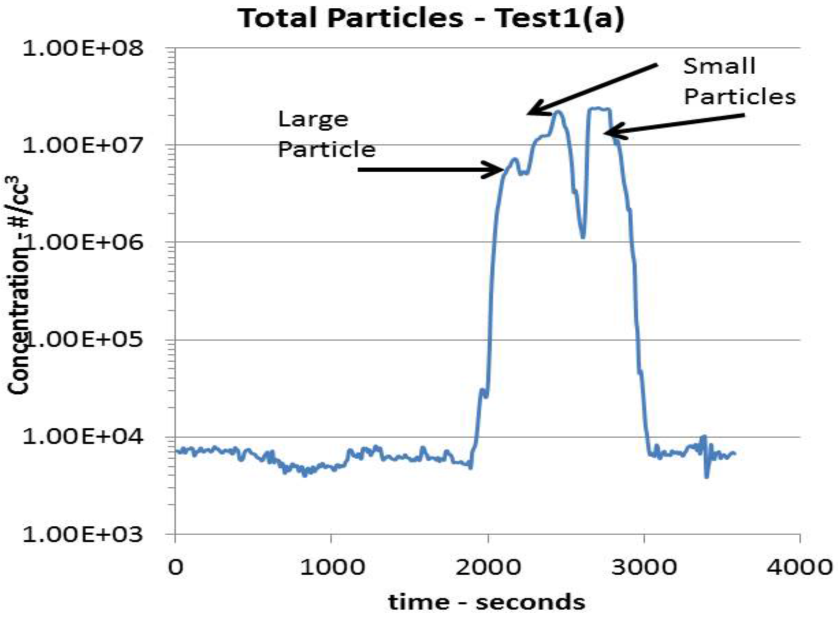


Figure ES-5 EEPS total particle number concentration emissions during Test1(a)

The two other tests of the 2007 DPF, Test2 and Test3, had many similarities with Test1, and there were PM emissions levels with magnitudes of the order 10 mg/m^3 or greater. Test2 did not have a flashing console light while Test3 did, but the overall PM levels were less than Test1. All tests of the 2007 DPF involved PM particles greater than 560 nm. However, only when the DPF was very full with a flashing console light were very large particles emitted in the PM10 size range.

Two successful parked regeneration tests from a 2010 DPF have been performed and all parked regenerations test of the 2010 DPF yielded much smaller values of PM emissions, since the maximum values DustTrak emissions were of the order of 0.35 or smaller mg/m^3 during the initial phase of the regeneration. During the testing a fully loaded 2010 DPF was not obtained, and it appears that a substantial amount of passive regeneration occurred during DPF loading. The initial and final phases of the regenerations contained large numbers of ultrafine particles, and they did appear to exceed or almost exceed the recording capacities of the EEPS.

High ultrafine particle number emissions were very similar for all 2010 and 2007 DPF regenerations, and it appears to be closely related to the fuel being injected into the DOC. It has been estimated that the ultrafine particles are mainly sulfate particles. From the present testing results the high ultrafine particle phase of the testing seems to be the same for both 2010 and 2007 DPF technologies, and the total number of particles and the DPF exhaust temperatures are the same in the latter part of the testing.

Some regulated emissions were recorded during DPF regeneration of both the 2007 and 2010 DPFs with the use of PEMS instrumentation. The primary regulated emissions obtained during the testing of the 2007 DPF were NO_x and THCs. As expected by NOx and THCs increased during DPF regeneration. For all tests the NO_x emissions leveled off to 400 ppm for the 2007 DPF when large numbers of ultrafine particles were emitted, and the emissions remained at these values until the end of the testing. THCs appeared to be a function of the state of loading of the DPF, and THCs reach values between 400 and 600 ppm during high emissions.

The testing of the 2010 DPF yielded lower values of the THCs and significantly lower NO_x, and this was expected due to the advanced after treatment on the 2010 DPFs. Both tests of the 2010 DPF started from a cold condition and the NO_x values rose to levels between 400 and 600 ppm during the initial phase of the regeneration. The NO_x levels remained high for approximately 300 seconds, and they reduced sharply to values of the order of 100 ppm for the remainder of the testing.

Estimates were made and calculated for PM mass flow rates for Test3 of the 2007 DPF with all of the experimental instrumentation used in the small wind tunnel, Figure ES-6. The predictions from all the instrumentation contain serious uncertainties since the particle shape, composition, and density, and a different size range was measured by each instrument.

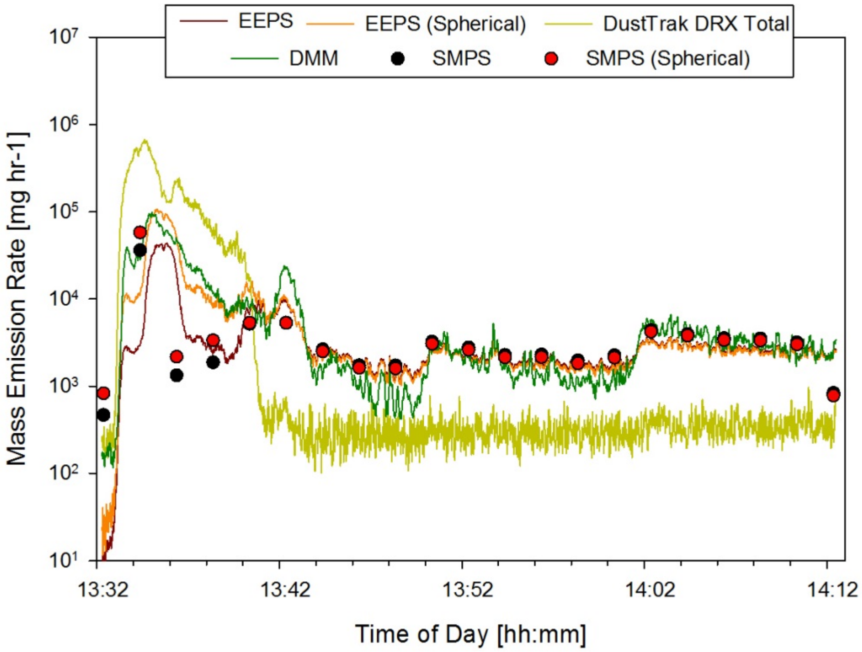


Figure ES-6 Estimates of time dependent PM mass flow rates from particle instrument used during Test3 of 2007 DPF

There is a need to perform more research in the following areas:

- Relate real time PM measurement instrumentation to filter measurements of total PM emitted during a Parked Regeneration.
- Extend the use of the small wind tunnel to the chassis dynamometer that will be

constructed at Depot Park.

- Determine the PM chemical composition emitted during all phases of the regeneration.
- With the use of the chassis dynamometer perform active regeneration of DPFs under high temperature road conditions.
- Investigate passive DPF regeneration with a partially loaded DPF. For example, carry out high speed road driving on the chassis dynamometer to observe the passive DPF regeneration.
- Extend the small wind tunnel by 15 to 30 feet, and locate two particle instruments 30 feet apart to investigate changes in particle size as the ultrafine particles are absorbed by larger particles in the ambient background air.
- Investigate the possible ways that particle shape and density can be determined for all phases of active and passive regeneration of DPFs.

I. BACKGROUND AND INTRODUCTION

Diesel particulate filters (DPFs) collect Particulate Matter (PM) and this PM must be periodically removed from the DPF or the vehicle performance will be degraded. The process of removing the PM is known as regeneration, during which there is an increase in emissions. Depending on the duty cycle of the Heavy Duty Diesel, HDD, vehicle the regeneration of the DPF can take many different forms and frequency of occurrence. The present study is concerned with active regeneration processes, which typically generate a very large number of ultrafine volatile and semi-volatile particles from both highway vehicles and parked vehicles. The need for an active regeneration occurs for vehicles that have a low exhaust temperature duty cycle, and these vehicles may or may not be able to change their duty cycle to a more aggressive and high exhaust temperature highway cycle. It is important that more information be obtained concerning "Parked" regeneration, particularly concerning the nature and importance of the very large number of ultrafine volatile and semi-volatile particles that are released in the immediate vicinity of the diesel truck. A clearer understanding during regeneration of emitted PM composition, toxicity, and exposure potential is needed if DPFs are indeed found to increase average vehicle total particle number emissions when regeneration is included (Note: Total particles include solid, volatile, and semi-volatile particles). By knowing more information concerning PM physical properties, and the time and space distribution of these particles researchers can begin to understand and evaluate the possible health effects.

At the present time corrections for regeneration during testing are included in emission testing, and the manufacturers must verify that their DPFs will meet a certification standard for a specified number of miles or time period. Therefore, in order to meet a given verification standard the DPF manufacturers must have a successful regeneration strategy. Since there is sparse knowledge concerning the frequency of occurrence of active regenerations, the numbers of ultrafine particles, and their chemical composition, the entire area is open for new research. Also, the engine operating conditions and the rate of occurrence of an active regeneration under real life conditions have to be known in order for the testing to be carried out in an efficient manner. This is particularly important for a "Parked Regeneration" since the emissions are dispersed in the immediate vicinity of the truck, and it is not well known how often a "Parked Regeneration" occurs.

As part of the investigation a unique small wind tunnel has been constructed at the CARB MSOD Depot Park Facility for the purpose of capturing and measuring the exhaust emissions during an active regeneration. This wind tunnel has a simple geometry and an average velocity of 8 mph, and these conditions allow for direct measurements of the development and aging of the exhaust plume during active regenerations. It is also expected that the data from the wind tunnel will be very valuable to modelers of the physical and chemical properties of diesel exhaust systems, and it will serve as a real world complement to Constant Volume Sampler, CVS, measurements that have been and will be carried out at CARB's heavy duty emissions laboratory located in Los Angeles.

There have been a limited number of studies of active regenerations of DPFs (1,2,3,4,5), but to our knowledge no studies have been completed for a "Parked" regeneration. For the completed studies there is an increase in PM mass during DPF regeneration, but the overall PM mass levels during regeneration were small compared to diesel engines without a DPF. What is not clear at the present time is whether DPFs reduce total particle numbers where regeneration is included in the counting process (Note: Total particles include solid, volatile, and semi-volatile particles), and what is the composition of the particles released during regeneration. When regeneration is not occurring, the particles numbers are quite low, and the numbers are typically below modern gasoline vehicles. However, recent testing by CARB and CRC, (1), (3), (4) suggests that the total particle numbers during regeneration can increase to values that are larger than without a DPF. It should be mentioned that the general emissions characteristics of the active regenerations in references (1) and (3) are similar in terms of particle number concentrations, size distributions, and the fact that the majority of the particles were volatile or semi-volatile.

In California and the United States the concern for emissions during regeneration is greatest for HDD engines that have a duty cycle with an exhaust temperature that is low. Some examples of vehicles of this type are both highway and off highway construction equipment, inner city transportation, and local haulers of bulk materials. The regeneration problem is less of a concern for HDD vehicles primarily driven on the highway where exhaust temperatures are high. In fact, the 2010 Volvo highway trucks have eliminated the need for an active regeneration event on their highway trucks with the use of their highly integrated SCR/DPF after treatment system. For the highway version of the 2010 Volvo trucks PM is removed from the DPF by a passive regeneration, which makes use of catalytic chemical reactions in the DPF.

The necessary steps for an active regeneration event are clearly described in “Cummins EPA 2010 Driver Trips”. If a regeneration event is required, there are two options available to the driver, and they are the following:

1. *Change to a more challenging duty cycle, such as highway driving, for at least 20 minutes.*
2. *Perform a “Parked” regeneration.*

The initial part of our emissions testing will involve a “Parked” regeneration and the “Parked” regenerations have been carried out in a novel small wind tunnel facility. The small wind tunnel facility will be designed to measure how the ultrafine particles are dispersed in the vicinity of the heavy duty truck. An example of the motivation for the use of the small wind tunnel comes directly from the Cummins directions for a “Parked” regeneration event, and they are the following:

1. *Park the vehicle in an appropriate location, set parking brake, and place transmission in Park*
   (if provided) or Neutral, and allow at least 40 minutes for the regeneration.
2. *Set up a safe exhaust area. Confirm that nothing is on or near the exhaust system surfaces.*
3. *Push the Manual Regeneration Switch to begin a Parked regeneration. Note: Engine speed will increase and there may be a noticeable change to the sound of the turbocharger during the regeneration process. Once the diesel particulate filter is regenerated, the engine will automatically return to the normal idle speed.*
4. *Monitor the vehicle and surrounding area during regeneration. If any unsafe condition occurs, shut off the engine immediately. To stop a parked regeneration, depress the clutch, brake, or throttle pedal.*
5. *Once regeneration is complete, exhaust gas and exhaust surface temperatures will remain elevated for 3 to 5 minutes.*

It is clear from the above description that a “Parked” regeneration event could release a very large number of volatile and semi-volatile ultrafine particles in the immediate vicinity of the HDD vehicle. Almost all manufacturers of HDD vehicles have procedures for “Parked” regenerations, and there are other types of “Parked” regenerations such as electrical and fuel based regenerations with the HDD vehicle engine turned off.

The situation for an active regeneration on the highway is much different than a “Parked” regeneration, since the regeneration emissions are distributed over a large highway area, and the ultrafine particles are quickly absorbed by larger background particles (6). For a “Parked” regeneration the ultrafine particles will be released in the immediate vicinity of the truck, and it is not known at the present time how quickly the particles are absorbed into larger particles. It is one of the primary purposes of the proposed study to determine the physical properties of PM and especially ultrafine particles released during a “Parked” regeneration event, as well as gaseous emissions.

II. TEST METHODS USED AND DEVELOPED FOR EXPERIMENTS

A. Design and Construction

The small wind tunnel of this project was designed to be a high dilution flow channel that mixes ambient air with the exhaust gases from the truck diesel engine. The system has been designed in order that enough ambient air is added to the diesel exhaust to keep the mixed gases below a temperature of 40 °C, since this temperature is below the temperature of which filters are used to collect particles in CVS tunnel testing. It is assumed that a temperature of 40 °C will result in the condensation of the semi-volatile gases in the diesel exhaust gases.

The small wind tunnel is shown in Fig. II-1, and it consists of six sections of length 5 feet and a square area of 4 feet by 4 feet. The material used for construction was 18 gauge galvanized steel ductwork. Attached to the rear or exit section of the tunnel is a fan that produced a volume flow rate of 9000 cfm, cubic feet per minute. The front or entrance section of the wind tunnel is shown in Figure II-2, and at the entrance there is a six inch long aluminum honeycomb section with channels of diameter of ½ inch to provide a more uniform entrance flow. At the center of the entrance section a five inch circular steel pipe was inserted and supported, and this pipe was connected to the diesel engine exhaust pipe with a twelve foot long flexible extension pipe. It should also be mentioned that PEMS instrumentation for regulated emissions was employed outside the tunnel on the circular steel entrance pipe.

For the present experimental work a mixing plate was attached to the exhaust of the entrance pipe as shown in Figure II-3, and the mixing plate consisted of an eight inch circular plate with some holes drilled in it. The purpose of the mixing plate was to encourage mixing of the ambient air with the truck exhaust gases, and thus encourage formation of semi-volatile condensation particles in the gases. The mixing plate can be easily detached if a more natural mixing of the diesel exhaust gases with the ambient air was desired for another possible experiment.

B. Design and Construction of Emission Sampling System

Close to the exit of the tunnel a 2 inch diameter sampling tube was supported at the center of the tunnel as shown in Figure II-4, and the entrance of the sampling tube was located at 27.75 feet from the wind tunnel entrance. The 2 inch sampling probe was approximately two and one and half feet long, and the sampling tube gases entered a 5 inch diameter settling chamber

Figure II-1 – Small wind tunnel with attached whole house fan. Tunnel length is 30′ and the cross-sectional area is 4′ by 4′.

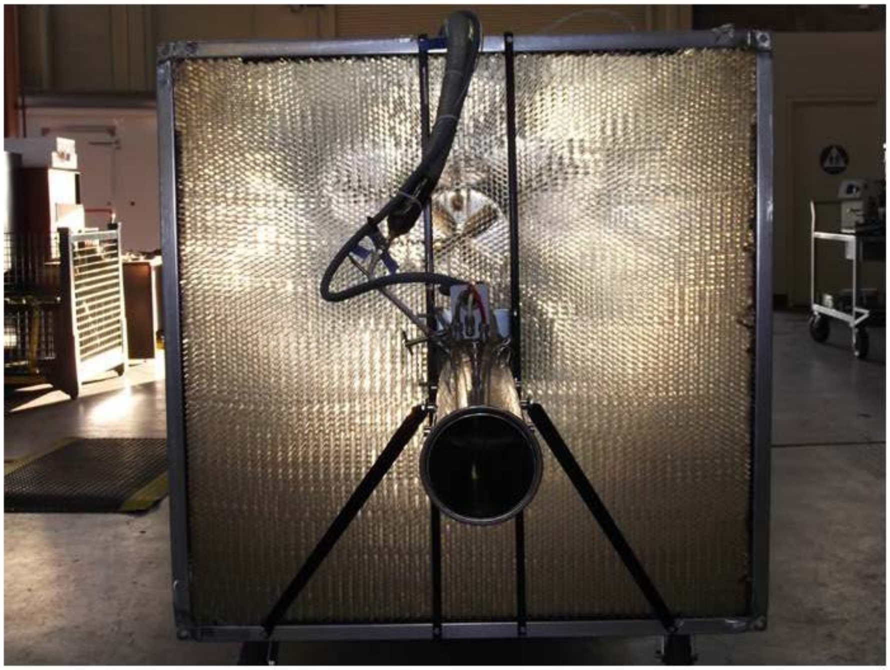


Figure II-2 – Honeycomb inlet section of small wind tunnel with connection pipe for the truck exhaust pipe.

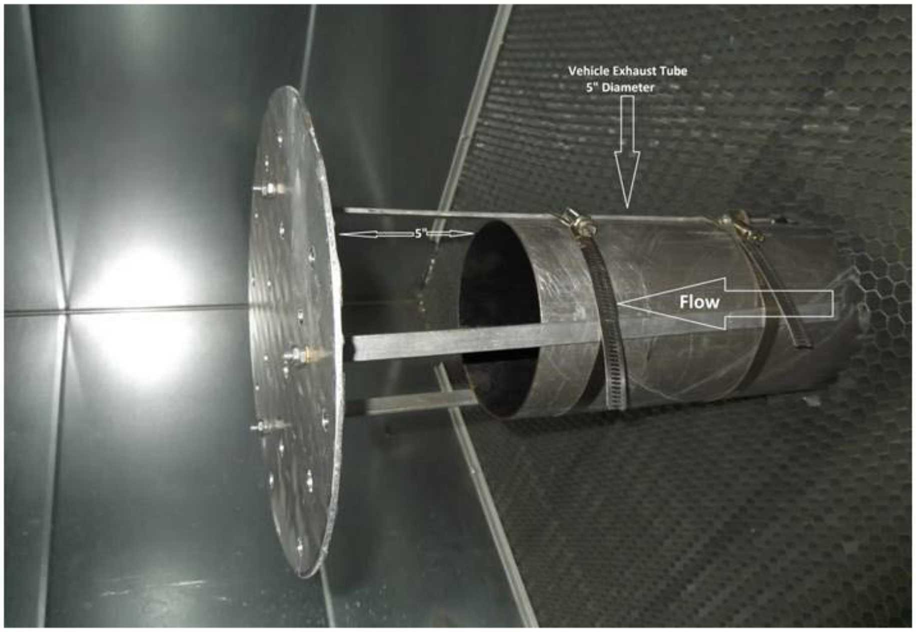


Figure II-3 – Entrance deflection plate for mixing exhaust gases with ambient gases

Figure II-4 – Sampling probe used for tunnel emission equipment and CO_2 probe.

outside the tunnel that was approximately one foot long. The exit of the settling chamber was attached to a vacuum pump, as shown in Figure II-5, and the vacuum pump created a steady flow of 160 liters per minute. Under these conditions it is estimated that more than 99% of all particles greater than 5 nm will pass thru the sampling tube without diffusional loses to the wall. The only measurements taken inside the tunnel were temperature at various locations and CO_2/CO/relative humidity with the use of a Q-Trak Plus near the sampling probe entrance.

A list of the instrumentation used and their location are given below:

Entrance Tube: (1) Portable Emission Measurement System, PEMS, (SEMTECH-DS, Sensors Inc.) for regulated emissions and diesel exhaust gas flow rate; (2) Thermocouples for measuring the temperature of exhaust gases entering the small wind tunnel.

Inside the wind tunnel near the sampling probe: (1) Temperature of gases entering the sampling tube, CO2, CO, and relative humidity with the use of a Q-Trak Plus (TSI).

Instruments connected to settling chamber: (1) EEPS (TSI); (2) SMPS (TSI) with water based CPC (TSI); (3) DustTrak DRX–model 8533; (4) Temperature (Thermocouples); and (5) and DMM-230 during the last two regenerations.

On Board Diagnostics, OBD, from Truck Engines: Some information was made available and recorded from the OBD system of the engine manufacturer. Of particular importance was the outlet temperature from the DPF.

An external view of the settling chamber with sampling tube connections for instrumentation is shown in Figure II-6 and the entire experimental testing setup is shown in Figure II-7. Detailed methods for sampling diesel aerosols can be found in references (7), (8), and (9).

C. Performance of the small wind tunnel

Since the present experiment was designed to provide a homogeneous mixture of ambient air and exhaust gases to the sampling tube, it is important to measure the quality of the flow being sampled. The flow in the small wind tunnel has been measured by performing temperature and velocity measurements at various sections as shown in Figures II-8 and II-9. Shown in Figure II-8 are both vertical and horizontal temperature traverses at two locations along the wind tunnel, and the mixing plate was not installed at the entrance of the wind tunnel. The closest measurement location to the five inch exhaust pipe was approximately 8 diameters from the exhaust pipe exit and it is expected that this location is near the end of the core region of the axisymmetric jet flow. As shown in series 2 and 3 of Figure II-8 the temperature at the center of the channel was approximately 12 °C below the exhaust inlet temperature of 65 °C, and that the symmetry between the horizontal and vertical traces was good. Further down the wind tunnel at the location of the sampling tube, 24.75 feet from the entrance, both the vertical and horizontal, series 4 and 5, are quite uniform, and it can be concluded that the exhaust gases and the ambient air are well mixed. It should also be noted that the measurements were not taken inside 6 inches from the wall, in order to avoid wall contact with the temperature probes.

After the mixing plate was installed both velocity and temperature traces were performed at the location of the sampling tube, and a higher engine rpm, exhaust temperature, and exhaust mass flow rate was used as shown in Figure II-9. In general the temperature distribution is more uniform than the velocity, but both traverses are good. The velocities at the center of the channel are close to 8 mph and this is significantly larger than the 5 mph average velocity that would yield 7000 scfm, which was the rated output of the fan. It appears that the resistance offered by the wind tunnel is significantly smaller than that of a home for which this fan is typically used as a whole house fan to exchange inside air with ambient air. It should be mentioned that the small

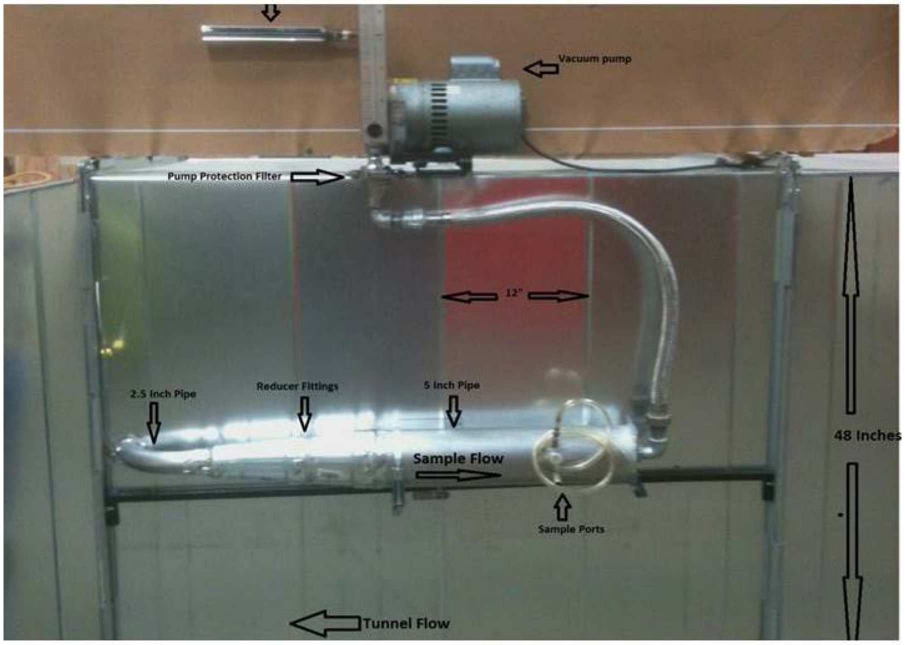


Figure II-5 – External view of sampling probe and pump

Figure II-6– Individual probes to emissions equipment

Figure II-7 – Total view of the testing experiment for a Parked Regeneration at Depot Park

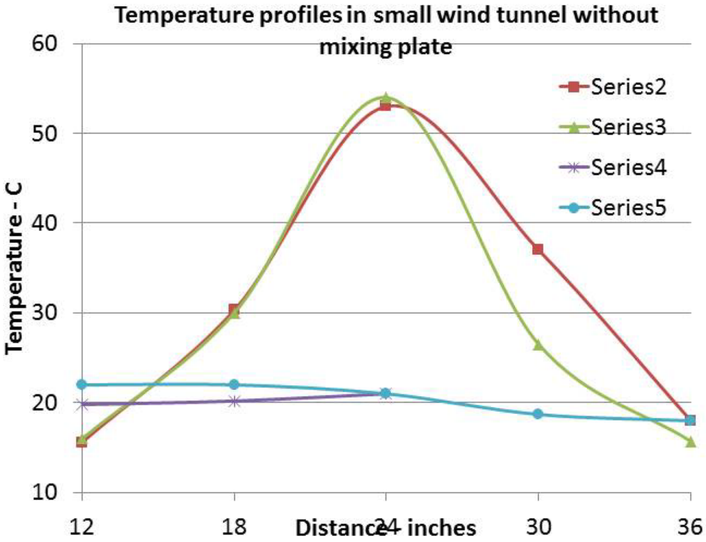


Figure II-8 Temperature traverses in small wind tunnel; Series2 – Horizontal at 64" from entrance; Series3 – Vertical at 64"; Series4 – Horizontal at 333"; Series5 – Vertical at 333" Note1: The exhaust pipes extends 18" into the wind tunnel from the tunnel entrance. Note2: The engine RPM was approximately 720, the mass flow rate of exhaust gases was 78 scfm, ambient temperature 14 °C, and diesel exhaust inlet temperature 65 °C.

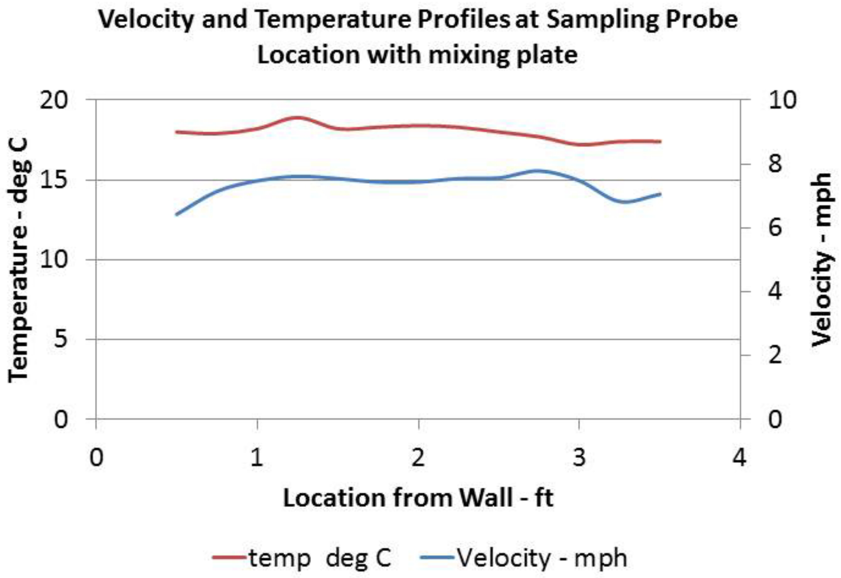


Figure II-9 Temperature and velocity traverses in small wind tunnel, ambient temperature – 16 deg C, engine rpm – 1200, diesel exhaust temperature – 106 deg C, and mass flow rate – 330 scfm

Figure II-10 – Small wind tunnel positioned on Depot Park trailer wind tunnel was designed to be portable, and the small wind tunnel is shown in Figure II-10 mounted in a truck trailer.

In order to perform a rough check of this fan volume output an analysis of the pressure drop due to the honeycomb and the wall friction in the tunnel was performed, and this analysis is given in the Appendix I. The minimum calculated power for a fan of 100% efficiency was 117 watts, while a poor efficiency fan of 25% would require 468 watts. The measured power to the motor driving the fan was 800 watts, and it appears that a flow rate of 9000 scfm is reasonable. Also, this type of result would be expected if the fan was design to run at constant power, and the fan was connected to a low resistance system such as the present wind tunnel.

D. Description of test vehicles

The two HDD vehicles used in the testing were supplied by Depot Park, and both vehicles had Cummings engines and after treatment. The older vehicle was 2007 compliant with an engine displacement of 14.9 liters and the newer vehicle was 2010 compliant with an engine displacement of 14.9 liters. The major difference between the vehicles was that the 2010 compliant vehicle had Selective Catalytic Reduction, SCR, system to reduce NO_x emissions. However, it should be mentioned that the DPF for the 2010 vehicle had substantially enhancements over the 2007 DPF. The primary enhancements for the 2010 DPF were improvement of the catalyst materials to increase passive regeneration and the increased use of NO_2 to burn out PM in the DPF.

E. DPF regeneration events

The number of Parked Regenerations that were carried out was five, and some of the regenerations had multiple parts associated with them. The labeling of the regenerations is given in Table I, and this labeling will be used in the discussion of the results. The reasons and rational for the testing sequences will be discussed with the results for each particular test.

Table I – Labels for the Parked Regeneration

Regeneration Test	Test Description of Parked Regeneration
Test1(a)	First test of the 2007 DPF, Light flashing, stopped in middle of test
Test1(b)	Continuation of Test1(a) until pump failed. Light On at beginning
Test1(c)	Continuation of Test1(b) until completion
Test1(d)	Forced regeneration of 2007 DPF after a short break, Light Off
Test2	Second test of the 2007 DPF, Light On, Completed
Test3	Third test of the 2007 DPF, Light Flashing, Completed
Test4(a)	First test of the 2010 DPF, Light On, Completed
Test4(b)	Forced regeneration of 2010 DPF after a short break, Light Off
Test5(a)	Second test of the 2010 DPF, Light On, Completed
Test5(b)	Forced regeneration of 2010 DPF after a short break, Light Off

III-RESULTS

When the project started there was a large amount of uncertainty concerning the time and effort that would be required to accumulate enough material in the DPF for an active regeneration to be carried out. A recent in investigation, Ref.(10) ACES), it was found that active regenerations for 2010 certified DPFs did not occur during a 16 hour test cycle, and this 16 hour cycle had produced active regenerations with 2007 certified DPFs. It appears that the 16 hour had too much high temperature driving, and this resulted in enough passive 2010 DPF regeneration to avoid a need for an active regeneration.

For the present project it required a driving duty cycle that consisted of approximately 30 hours of driving in stop and go traffic with the maximum velocity of 30 mph and some idling in an industrial park. This type of driving decreases the amount of passive regeneration in the DPF, and a DPF condition is reached where the pressure drop in the DPF becomes a problem for the efficiency of the engine. In general much more material was accumulated in the 2007 DPF compared to a 2010 DPF. In fact for the 2007 DPF, a critical condition in the DPF was obtained, and a flashing light on the truck console indicated that a DPF regeneration should be carried out immediately. This condition was never obtained for 2010 DPF and the amount of mass accumulated was orders of magnitude less for the 30 hours of driving of the truck with the 2010 DPF.

The results section will be begin with the Parked Regenerations of the 2007 DPF, followed by the 2010 DPF, and ending with regulated emissions that occurred during the Parked Regenerations.

A. Parked Regenerations of 2007 DPF

For the truck with the 2007 DPF three Parked Regenerations were performed, and these regenerations will be referred to as Test1, Test2, and Test3. For the Test1(a) regeneration the DPF was in a critical state, and the truck console light was flashing, which indicates that an active regeneration must be performed. The testing for the first regeneration was carried out in the following way:

- When all measuring instruments were ready for recording data, 10 to 15 minutes of ambient background conditions were recorded.
- Next, the truck engine was started from a cold condition and 10 to 15 minutes of normal truck idling was recorded.
- After truck idling an instruction was sent to the engine control unit to perform a Parked Regeneration.
- For Test1 only, the Parked Regeneration was stopped after the amount of mass emitted decrease substantially, and the Parked Regeneration was continued approximately 50 minutes later, Test1(b). The purpose of stopping and restarting the regeneration was to better understand the startup process of a regeneration event.

First Regeneration of 2007 DPF, Test1(a) and Test1(b). The presentation of the emissions begins with the results from the DustTrak, and these are shown in Figure III-1. The PM1.0 emissions contain a very large amount of PM which lasted for approximately 1000 seconds, Test1(a), and these PM1.0 emissions reached a value of almost 50 mg/m^3 in the wind tunnel. This level of PM has occurred at a dilution ratio of approximately 30/1 with the ambient air and diesel exhaust, and this level of emissions is almost four orders of magnitude higher than typical ambient levels. The regeneration event was turned off at 3500 seconds in the figure, and restarted again at 5500 seconds. Although the PM1.0 emissions during Test1(a) decrease rapidly in Figure III-1, it will be shown that particle number emissions remain very high while regeneration is occurring. However, before moving on to particle number emissions the total emissions and PM2.5 emissions captured by the DustTrak are presented, and these are shown in Figure III-2 on an expanded time scale. The total emissions include both PM2.5 and PM10 particles, and it can be seen from Figure III-2 that the total PM emissions reached a value greater than 70 mg/m^3. It should also be noted that

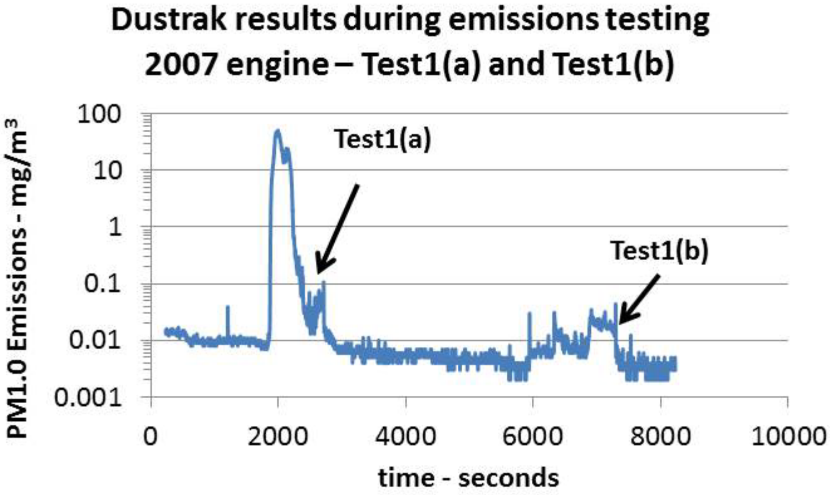


Figure III-1 PM1.0 Emissions from the DusTrak during the entire regeneration event.

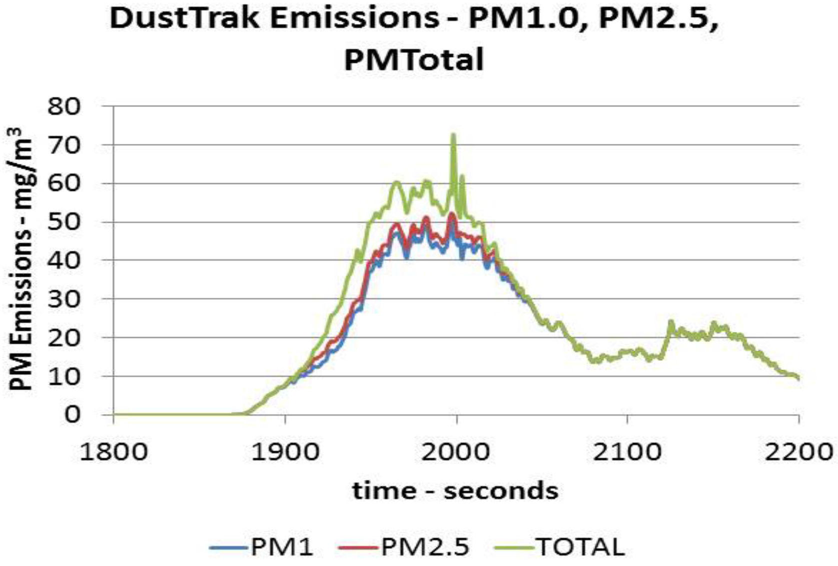


Figure III-2 PM1.0, PM2.5 and Total Emissions from the DusTrak during the high emission part of the regeneration event, Test1(a).

after the peak emissions in Test1(a) there is not a noticeable different between PM1.0 and PMTotal emissions. The PM2.5 emissions are only slightly different than PM1.0. Therefore, this test indicates that there is a substantial amount of relatively large particles emitted from the DPF.

The emissions from the EEPS are shown in Figure III-3, and it is seen that the maximum particle number concentrations occur for particles less than 100 nm. The regeneration event occurred for over 1000 seconds, and during this event the particle number concentrations slightly exceeded the maximums of some of the EEPS channels that range from 10^6 to 10^8 particles/cm^3. The EEPS emissions during the first 1500 seconds of Test1(a) are shown in Figure III-4, and this is the time period where the 800 seconds of ambient and 700 seconds of engine idling occur. As can be seen from the Figure III-4 there is essentially no significant change in particle number or size range when the truck engine is started, and this is partially due to the DPF being full of PM and very efficient.

To understand the relationship between DustTrak results and particle concentration it is useful to present particle number and volume concentration results at the start of the regeneration on an expanded time scale, and these results are shown in Figures III-5 and 6. The particle volume concentration has been calculated under the assumption of a spherical particle, and it is quite probable there is some error associated with this assumption. However, it is a very useful assumption to show that large particles are being emitted near the start of the Parked Regeneration.

The particle number concentration results in Figure III-5 reach their maximum values at a time greater than 2400 seconds, and these maximums occur in a particle size range between 10 and 30 nm. The particle volume concentration results in Figure III-6 reach their maximum values at a time greater than 2000 seconds, and these maximums occur in a particle size range between 100 and 400 nm. Figure III-6 contains both particle number and particle volume information, the z-axis is particle number concentration and the contour scale is particle volume concentration. The particle volume depends on the cube of the diameter, and it is very clear that large particles during the early part of the regeneration are responsible for the large mass emissions from the DustTrak. Since the largest diameter channel of the EEPS is located at 560 nm, it can be observed from Figure III-6 that particle volume concentrations are large at this channel, and the EEPS instrument is not capable of giving detailed data above this channel diameter.

Although the DustTrak does respond to large particles it should be mentioned again that the shape of these particles or their density is not known at the present time. Also, the source of the particles is from the soot cake in the DPF, and this soot cake has been cycled thermally as the truck engine has been driven during its duty cycle. As a final note it should be mentioned that the DustTrak and the EEPS were started at slightly different times since the DustTrak can be used continuously for very long periods of time, and the EEPS and PEMS instrumentation are limited to approximate running times of 90 minutes.

Returning again to the particle number emissions in Figure III-3, it is seen that very large number emissions occur until the regeneration was forced to stop, and the DustTrak mass emissions have returned to values which are similar to ambient mass values. These results indicate that the majority of the mass has been eliminated from the DPF, but the regeneration procedure is setup to continue to clean out the DPF. It appears that the large number of small particles are the result of fuel being injected from the Diesel Oxidation Catalyst, DOC, to

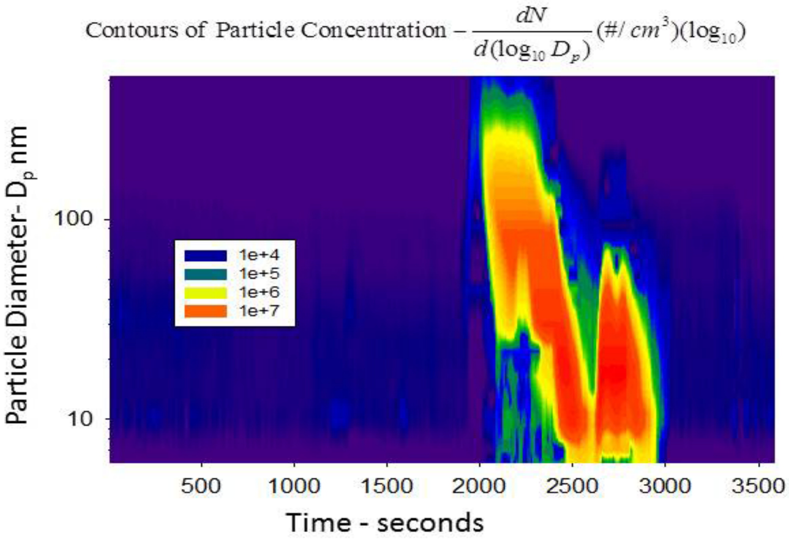


Figure III-3 EEPS particle number concentration emissions during the initial part of the regeneration event. Test1(a)

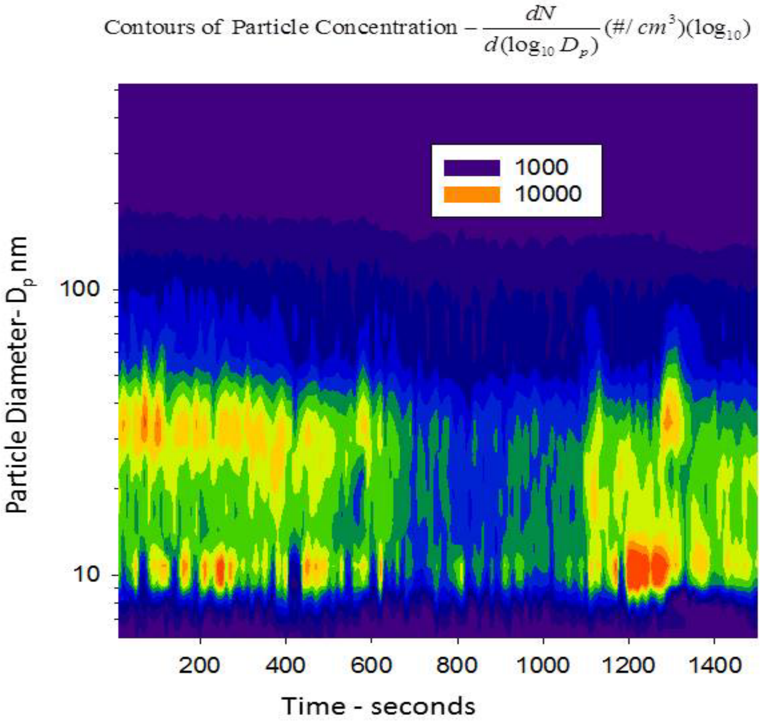


Figure III-4 EEPS particle number concentration emissions during the background and idling part of the regeneration event. Test1(a)

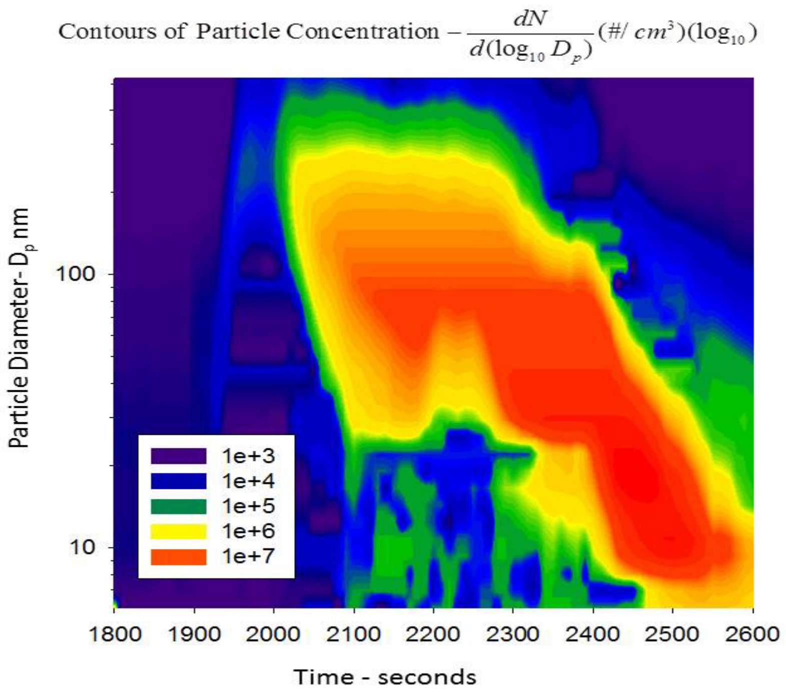


Figure III-5 Expanded view of EEPS particle number concentration emissions during the initial part of the regeneration event. Test1(a)

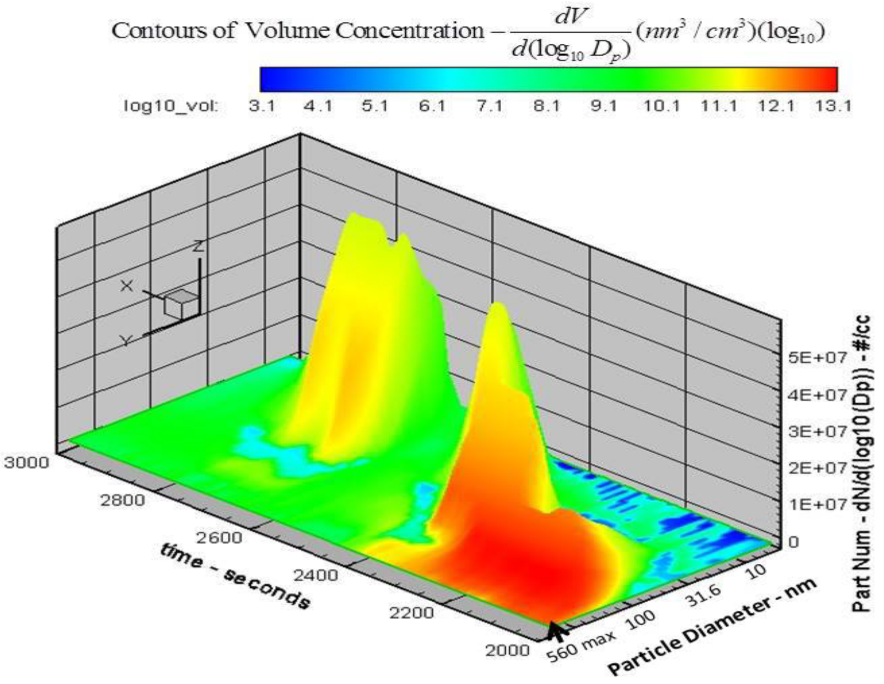


Figure III-6 Expanded view of EEPS particle number and volume concentrations emissions during the initial part of the regeneration event. Test1(a).

regenerate the DPF. It should also be noted that the DustTrak has a recording minimum size limit of 100 nm, and the mass of smaller particles is not recorded by the DustTrak.

The regeneration process was restarted after a period of 45 minutes, since the light on the truck console indicated that the regeneration was incomplete, Test1(b). The EEPS results are shown in Figure III-7 for the event, and Test1(b) was stopped when the pump for the sampling tube malfunctioned. The high particle number part of the continued regeneration occurred for almost 600 seconds, and both the particle number and size range are very similar to the later time results in Figure III-3. Thus, indicating again that the large numbers of small particles are being generated by the DOC. The result from references (1), (4) and (5) indicate that sulfate particles are most likely being emitted from the DPF during an active regeneration. The DustTrak results in Figure III-1 do indicate that an increase in mass emissions has occurred during the continuation of the regeneration, Test1(b), but it is expected that the mass is under recorded by the DustTrak due to the small size range of the particle emissions.

During the high particle number part of the continuation of the regeneration the particle concentrations exceeded some of the channel capabilities of the EEPS. The channels where the maximum particle concentrations were exceeded centered around 20 nm, and this seemed to cause the EEPS to not record properly in channels generally between 60 nm and 100 nm. The particle number concentrations from the EEPS were close to zero in this range, and it is very apparent in the particle volume concentrations in Figure III-6 for the time period between 2600 and 2900 seconds. Fortunately, measurements of particle number concentrations were simultaneously taken with a SMPS whose channel maximums were not exceeded. The particle samples from the SMPS were recorded every 2 minutes compared to the 10 seconds averages from the EEPS, which have been presented in this paper. While the experiments were being performed it was not possible to obtain the use of a particle diluter, and it is felt that a particle diluter would correct the problem associated with the EEPS. It should be mentioned that the EEPS was cleaned and serviced after each test, and the EEPS channel problem only occurred when certain channels of the EEPS exceeded their maximum design value.

It is instructive to observe the outlet temperature from the DPF during the Parked Regeneration event and these results are shown in Figure III-8 for the first part of the regeneration event, Test1(a). During the testing the ambient temperature varied between 60 °F and 67 °F, and the truck engine was started cold. As seen from Figure III-8 the temperature increased slowly, and then increased rapidly as a large amount of mass was emitted from the DPF. In fact, the outlet temperature of the DPF exceeded the maximum outlet recommended temperature, 1060 °F by more than 100 °F, and it is clear that fuel to the DOC was almost shut off to lower the DPF exit temperature to almost 600 °F. This behavior implies that the amount of mass being burned out of the DPF was exceeding DPF design conditions. After a cooling period of almost 6 minutes the DPF outlet temperature was increased again, and the DPF outlet temperature returned to the design condition. This second maximum in Test1(a) of Figure III-8 corresponds to the emission of a very large number of small particles in the ultrafine size range.

In order to complete the discussion of the Test1 regeneration event the temperature and the CO_2 values at the sampling location are shown in Figure III-9 for the entire regeneration event with a time scale the same as Figure III-1. The temperature plot shows that the temperature at the sampling location never exceeded 90 °F, even though the DPF outlet temperature exceeded 1200 °F in Figure III-8. The low sample temperature is due to the large amount of ambient air mixed with the engine exhaust gases, and it insures that semi-volatile material will condense in a natural

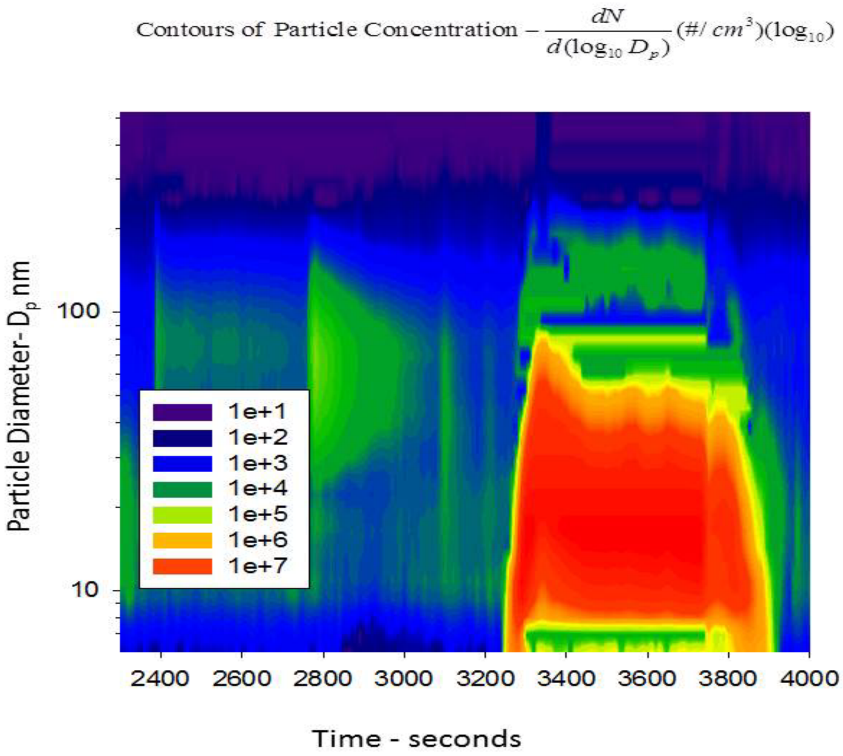


Figure III-7 EEPS particle number concentration emissions during the high emission part of the continued regeneration event. Test1(b)

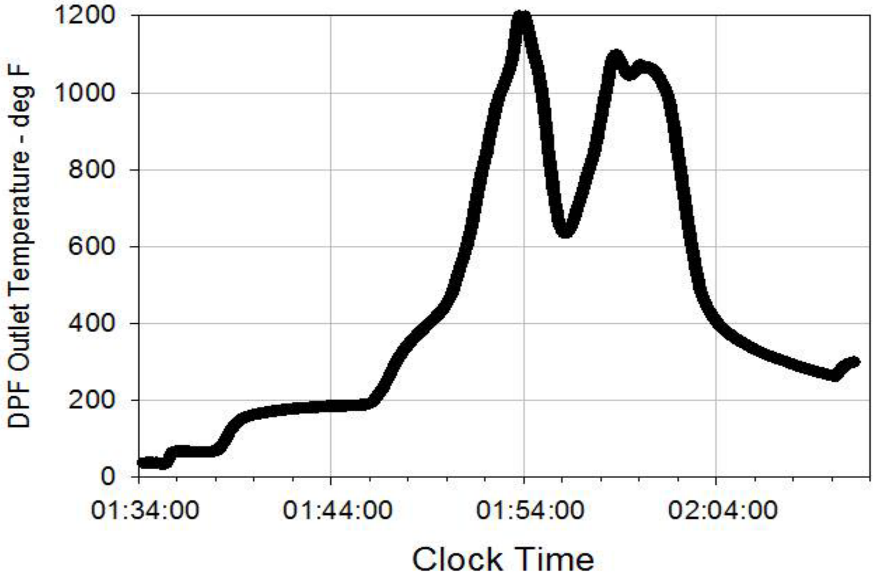


Figure III-8 DPF outlet temperature during regeneration test. Test1(a)

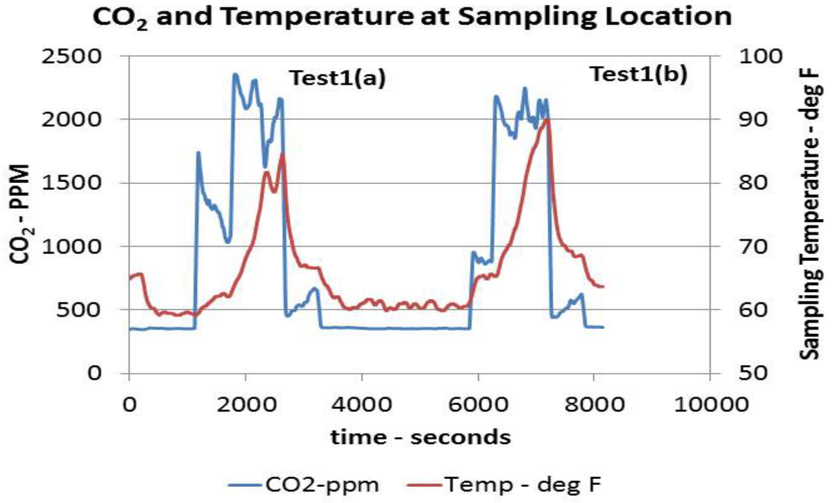


Figure III-9 CO$_2$ and temperature at the sampling location during the entire regeneration event. Test1(a) and Test1(b)

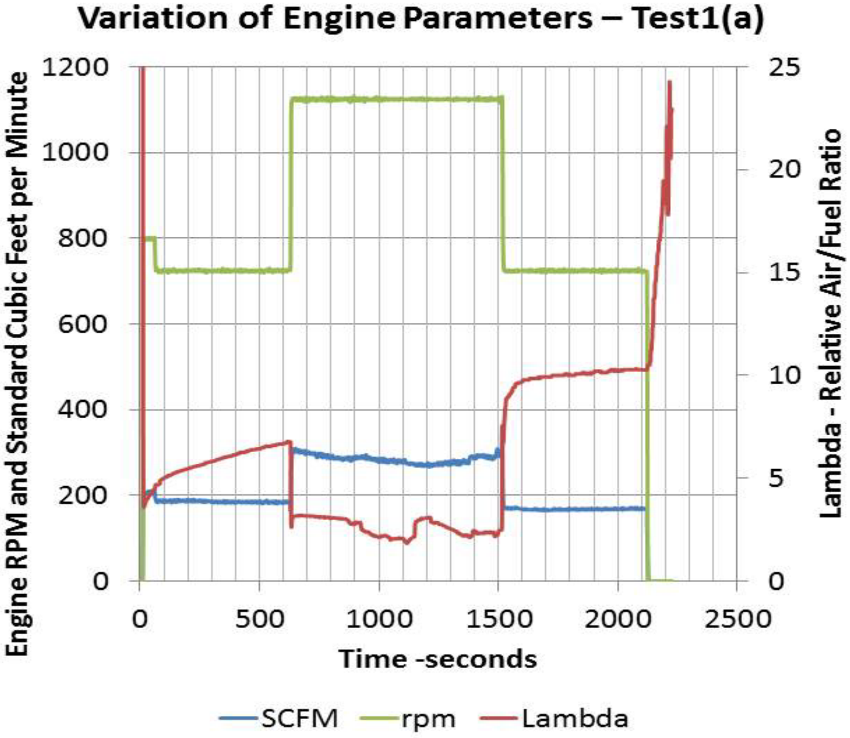


Figure III-10 Variation of RPM, SCFM, and Lambda. Test1(a)

way compared to artificially condensing on filters kept at a fixed temperature. The sampling temperature during the restarting of the regeneration, Test1(b) is actually higher than the initial high mass emission part of the regeneration, and this is most likely due to the rise in ambient temperature from 60 °F to 67 °F during the testing. The increase in CO_2 during the regeneration is very similar for both parts of the regeneration event, and the CO_2 increase is due to an increase in engine idle speed to 1200 RPM, increased fuel to the DOC, and the operation of the turbo charger. Figure III-10 exhibits the changes in engine RPM, exhaust flow rate, and lambda (relative air fuel ratio) during Test1(a), and these changes are typical of all the regeneration events in this paper

Continued Regeneration of the 2007 DPF, Test1(c) and Test1(d). Since there was a failure of the pump used for the sampling tube, the regeneration test of the 2007 DPF was continued after pump repairs a week later without the truck being used during the delay period. The regeneration test was run to completion, and the console light went off indicating the regeneration was complete, Test1(c). However, a **"forced"** Parked Regeneration, Test1(d) was also initiated on the DPF, although the DPF was completely regenerated, and most engines with DPFs have this capability to force a regeneration. This test was carried out to further understand the processes that are employed to initiate DPF regeneration.

The discussion begins with the DustTrak PM1.0 results shown in Figure III-11, and it can be seen that the PM emissions are much lower than the first regeneration of the 2007 DPF, Test1(a). The EEPS particle number concentration results are given in Figure III-12, and the majority of the high concentration particle results are below 100 nm. The particle number concentrations in Figure III-12 exhibit the spikes shown in the DustTrak results, and the time scales between Figure III-11 and III-12 are not the same due to the recording time of the different instruments. The regions of highest particle number concentration occur at 20 nm at the end of the regeneration event, and the results are very similar to later parts of Test1(a) and Test1(b).

Since the DustTrak underreports ultrafine particles, the particle volume concentrations for the SMPS are presented in Figure III-13, and the figure shows that the largest volume concentrations occur for 40 nm particles at later times in the regeneration. Therefore, the DustTrak results in the later part of Figure III-11 underestimate the mass emissions by a substantial amount, as will be shown at a later section of the report.

Since most DPFs have the capability of forcing a Parked Regeneration even though it is not needed, a forced regeneration was performed after a wait of one and a half hours. The DustTrak PM1.0 results in Figure III-14 are similar in magnitude to the later part of Figure III-11, and the EEPS particle number concentrations in Figure III-15 are very similar to the later part of Figure III-12. These similarities suggest that the later part of DPF active regeneration is a semi-forced event with the purpose to clean out the DPF of a small amount of mass. In fact, the amount of PM resulting from the fuel burning in the DOC may be the dominate source of PM and not the PM in the DPF. For completeness the DPF outlet temperature is shown in Figure III-16.

The latter part of all the active regenerations in this study have shown that an enormous number of ultrafine particles in the size range 10 to 40 nm are emitted from the DPF, and these particles have relatively small mass. Also, these very high particles levels have occurred at a high dilution ratio and a sample temperature less than 90 °F.

Second Regeneration of the 2007 DPF, Test2. The second Parked Regeneration of the 2007 DPF occurred with the console light on but not flashing. The DustTrak emissions from Test2 are

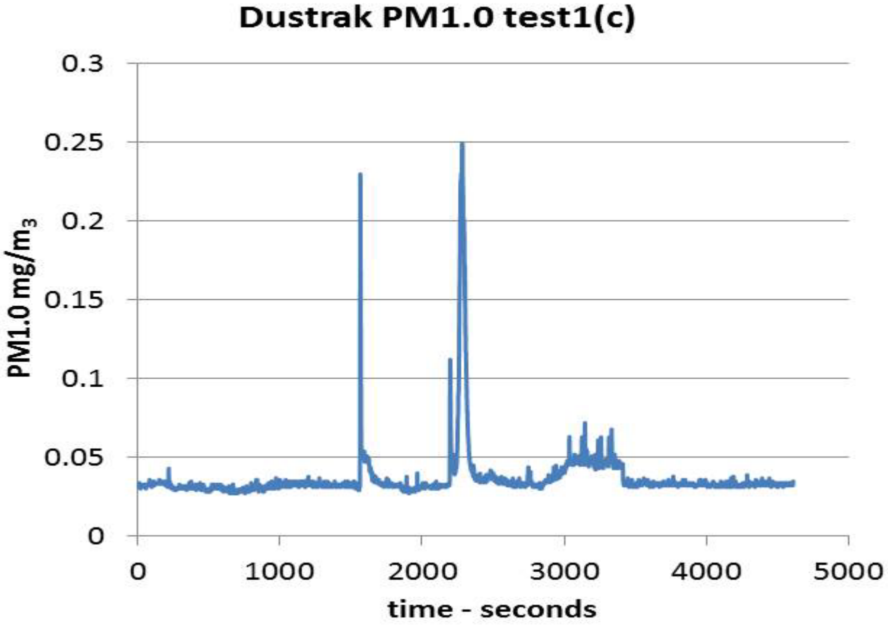


Figure III-11 PM1.0 Emissions from the DusTrak during the entire regeneration event. Test1(c)

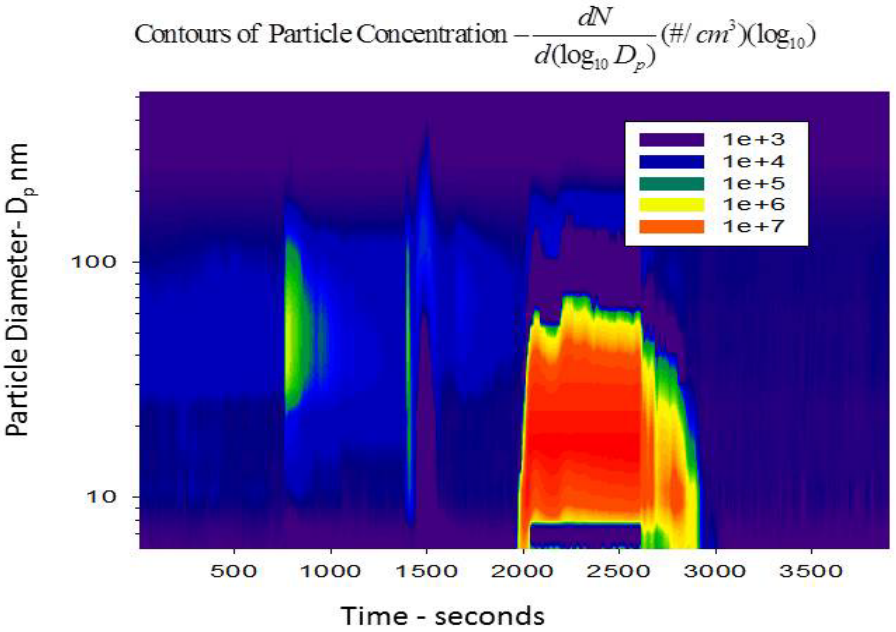


Figure III-12 EEPS particle number concentration emissions during the regeneration event. Test1(c)

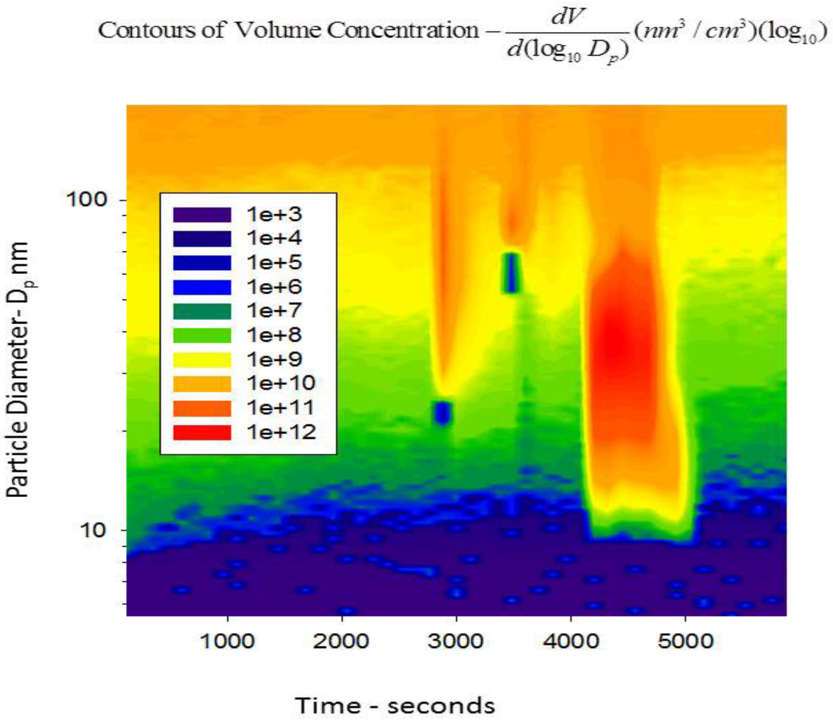


Figure III-13 SMPS particle volume concentration emissions during the regeneration event. Test1(c)

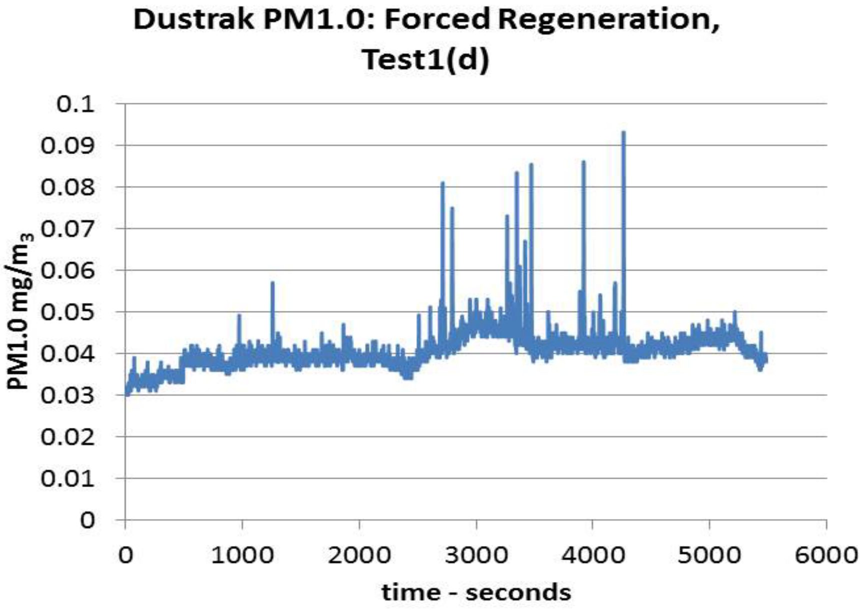
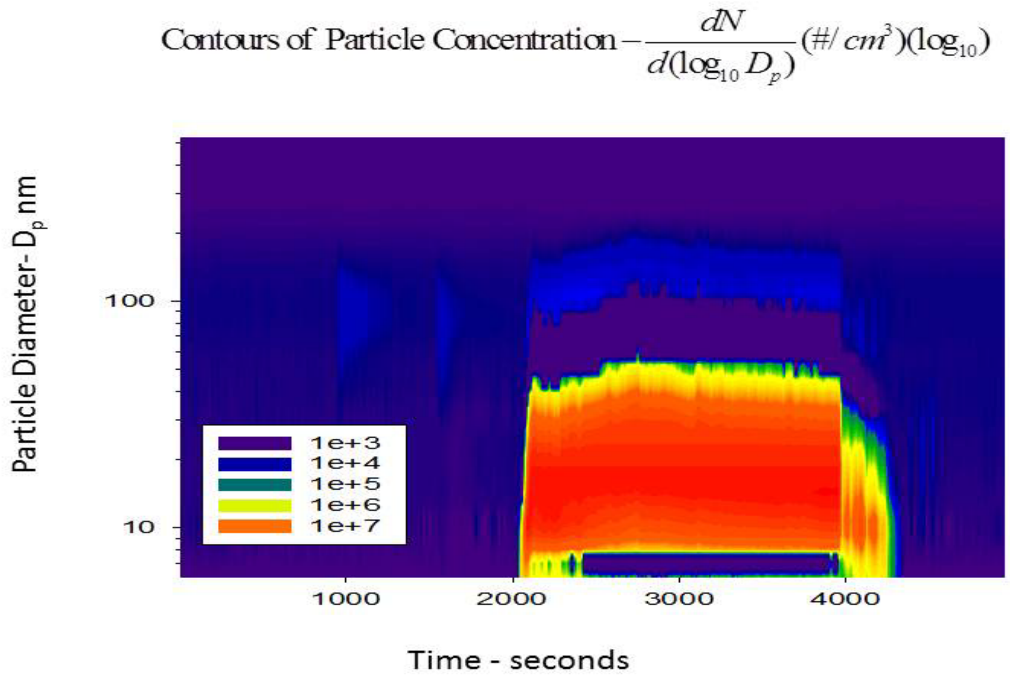


Figure III-14 PM1.0 Emissions from the DusTrak during the entire forced regeneration event. Test1(d)



Contours of Particle Concentration $-\frac{dN}{d(\log_{10} D_p)} (\#/cm^3)(\log_{10})$

Figure III-15 EEPS particle number concentration emissions during the forced regeneration event. Test1(d)

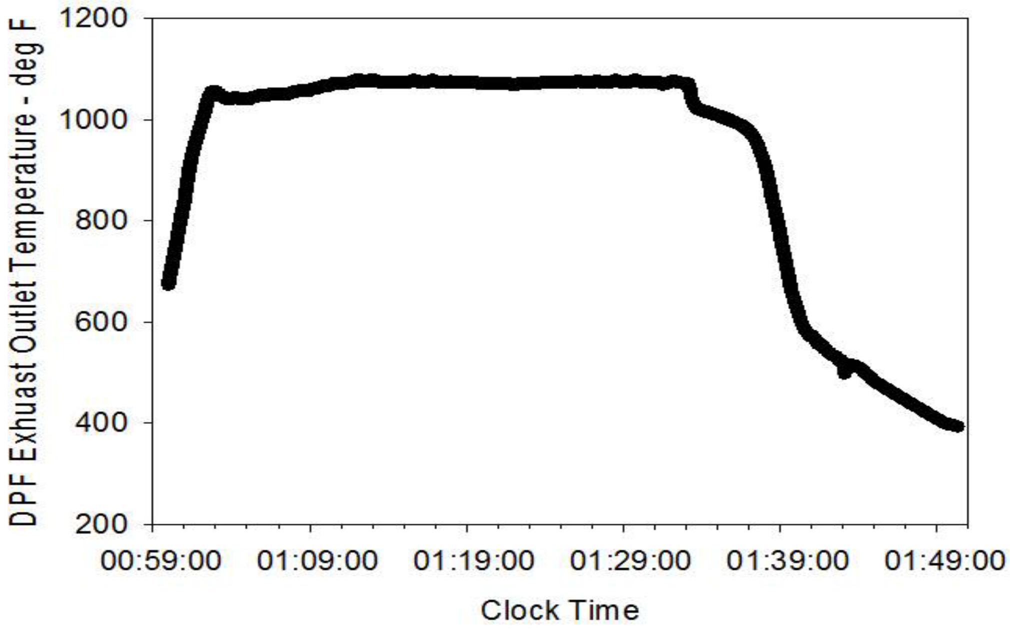


Figure III-16 DPF outlet temperature during the forced regeneration test. Test1(d) shown in Figure III-17, and the regeneration event lasted for approximately 1800 seconds. Test2 was continued until completion and the console light went out. Also, there was no significant difference between PMTotal and PM1.0, although the emissions reached a large value of 8 mg/m^3. The general characteristics between Test1(a) and Test2 are similar, and there is an initial period of large particles being released, which is followed by an extended period of the emission of many small particles. Shown in Figure III-18 are the EEPS particle number concentration results during the event, and large particles are emitted starting at 700 seconds and small particles dominate emissions after 1200 seconds. The particle volume concentration results from the EEPS are presented at early times in Figure III-19, and it is seen that particle volume concentration or mass is maximum in the largest diameter channels of the EEPS. Thus it is clear that particles larger than the size range of the EEPS and SMPS play a major role in the PM emission of the 2007 DPF.

Third Regeneration of the 2007 DPF, Test3. The third Parked Regeneration of the 2007 DPF occurred with a flashing console light, which indicated that an active DPF regeneration was necessary. Shown in Figure III-20 is the DustTrak PM1.0 emissions during the entire regeneration event, and in Figure III-21 for both the PM1.0 and PM-Total emission during the high mass emission part of the regeneration. Although these DustTrak emissions for the third 2007 DPF test, Test3, are slightly lower than the first regeneration, they have very similar magnitudes and character. The length of time of the heavy mass emissions in Figure III-2 and Figure III-21 are similar. Test3 had significant amounts of PM greater than 1 micron as shown in Figure III-21, and it appears that a flashing console light is an indication of the possibility of large particles being emitted. As in Test1(a) the difference in mass emissions between PM1 and PMTotal are mostly particles larger than PM2.5.

The particle number concentrations from the EEPS are given in Figure III-22 and III-23 for the total regeneration time and for the early high mass emission period, respectively, and these results are quite similar to the first regeneration of the 2007 DPF, Test1(a). The particle volume concentrations at early time from the EEPS are shown in Figure III-24, and it is clear that the large volume or mass region exceeds the capacity of the EEPS's channel range. Both the EEPS particle number and particle volume concentration contours can be seen simultaneously in Figure III-25, where the z-axis is particle number concentration and the contours are the particle volume concentrations. At early times in Figure III-25 the particle volume concentrations contours are very large, and at latter times the particle number concentrations are large. It can be seen from Figure III-25 that there are significant particle volume contributions at latter times from the large number of small particles. Also, the problem of the EEPS losing channels due exceeding maximum channel capacity can be seen in Figure III-25 in the approximate diameter range 60 to 100 nm.

The volume concentrations from the SMPS for the entire regeneration are presented in Figure III-26, and the problem of exceeding maximum CPC channel capacities does not occur for the SMPS. The exhaust temperature from the DPF is presented in Figure III-27 for Test3, and it is clearly seen that there is not an overshoot as in Figure III-8, Test1(a). Therefore, it appears that extra amount of PM mass accumulated in Test1(a) relative to Test3 was enough to cause the temperature of the DPF to exceed its design value.

Before the presentation of the Parked Regeneration emissions for the 2010 DPF the total particle number concentrations will be given for the 2007 DPFs. Shown in Figure III-28 is the total particle concentrations for Test1(a) from the EEPS. Clearly shown in Figure III-28 are the

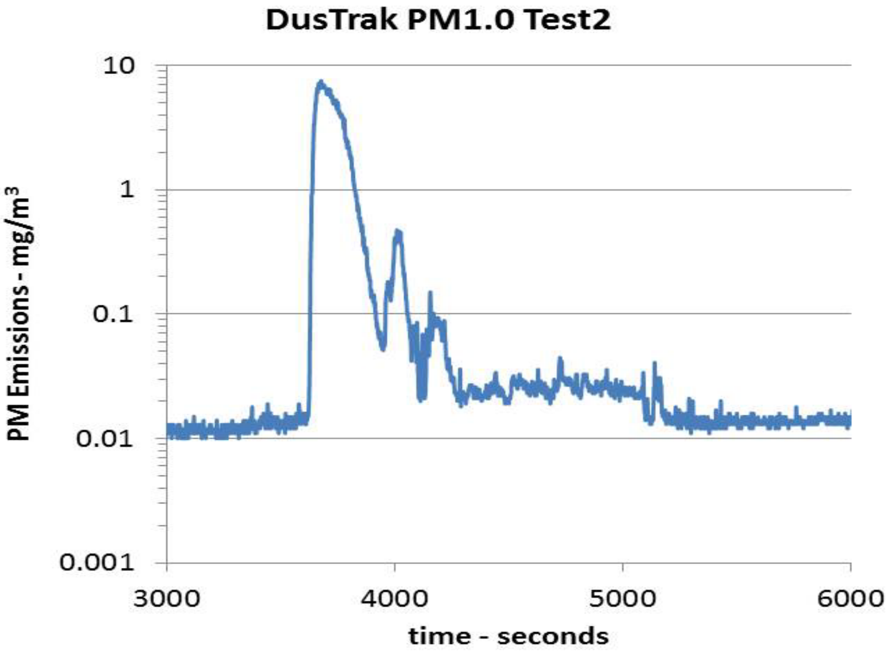


Figure III-17 PM1.0 Emissions from the DusTrak during the entire regeneration event. Test2

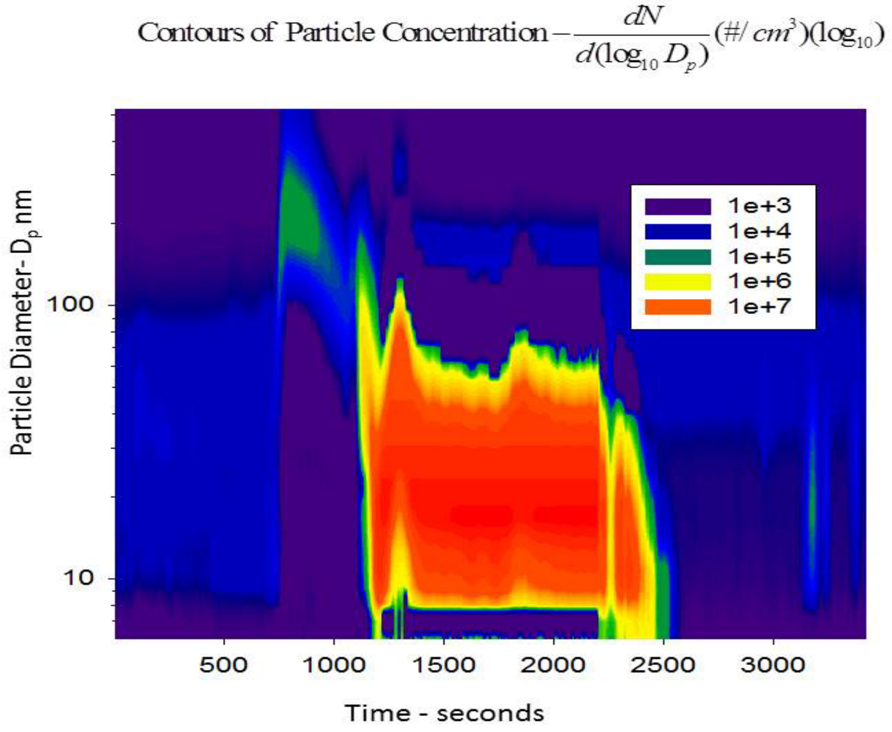
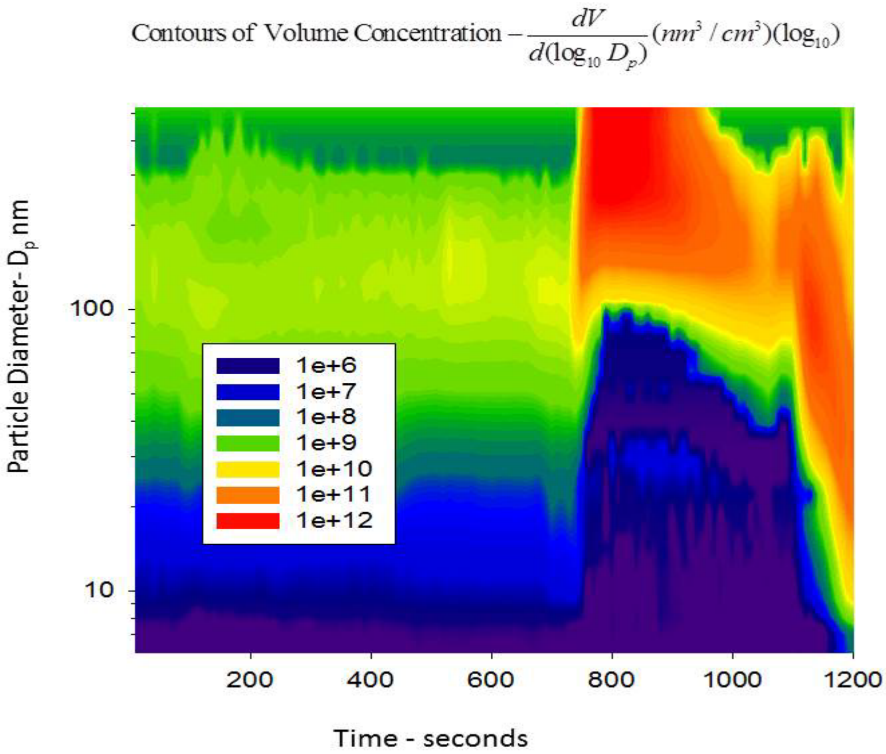
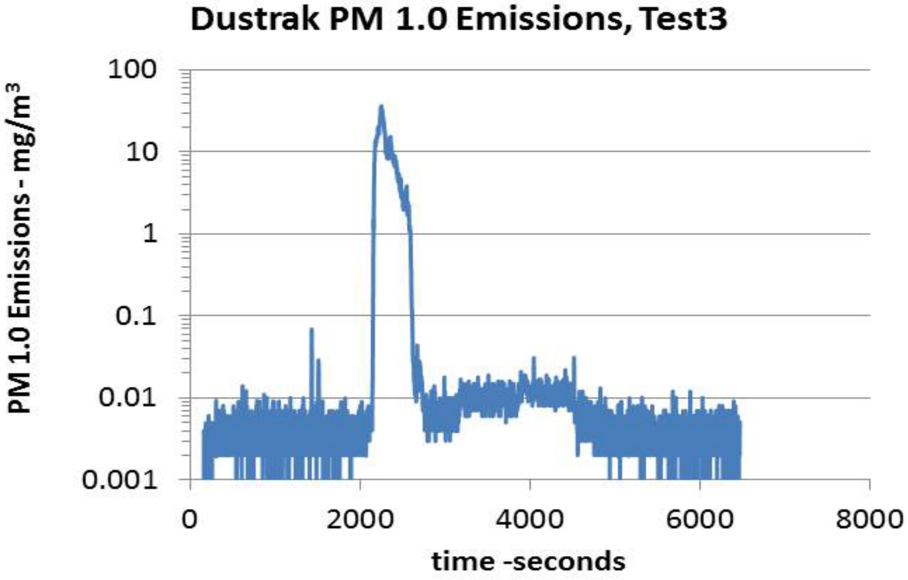


Figure III-18 EEPS particle number concentration emissions during the forced regeneration event. Test2



Contours of Volume Concentration $-\frac{dV}{d(\log_{10} D_p)}(nm^3/cm^3)(\log_{10})$

Figure III-19 EEPS particle volume concentration emissions during the forced regeneration event. Test2



Dustrak PM 1.0 Emissions, Test3

Figure III-20 PM1.0 Emissions from the DusTrak during the entire regeneration event. Test3

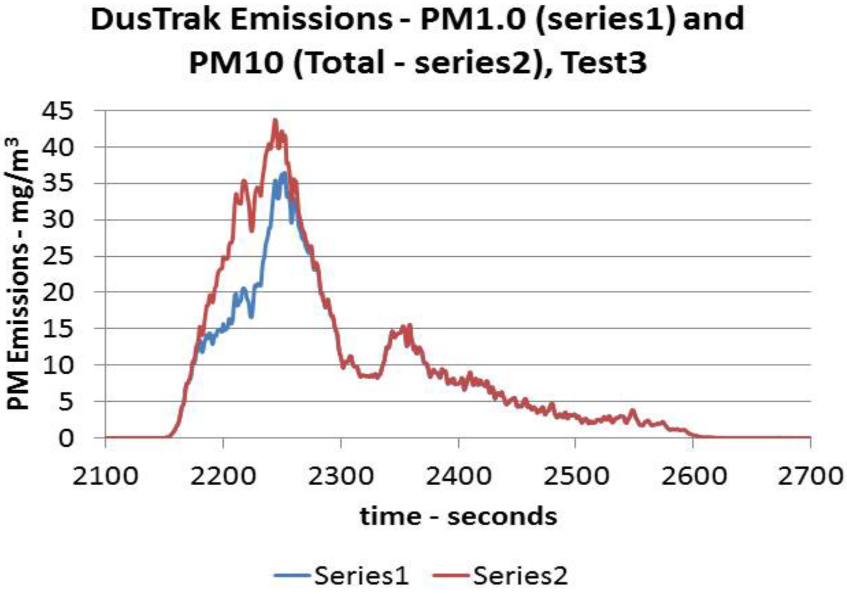


Figure III-21 PM1.0 and Total Emissions from the DusTrak during the high emission part of the regeneration event. Test3

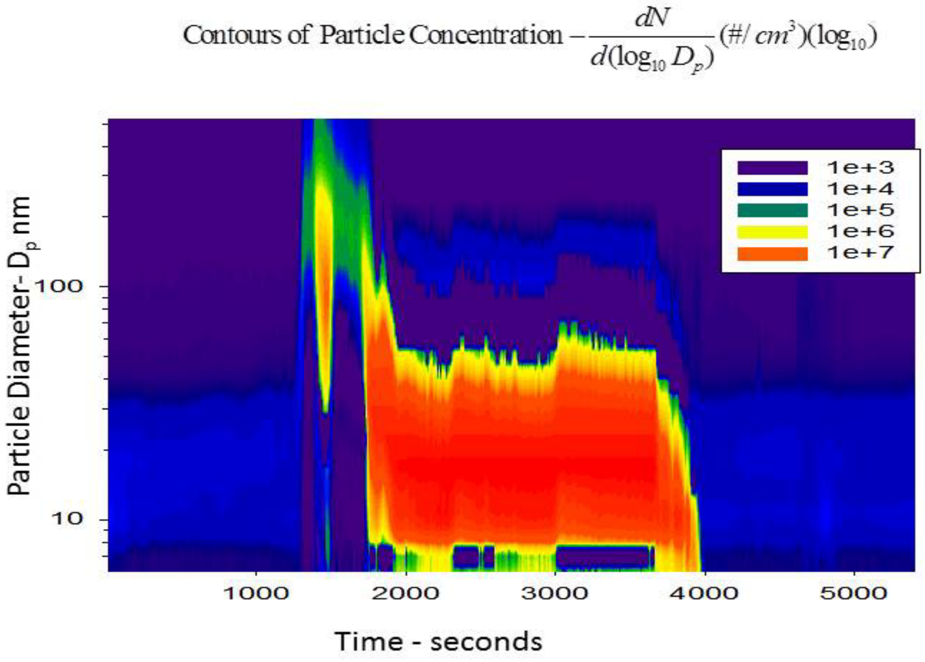


Figure III-22 EEPS particle number concentration emissions during the regeneration event. Test3

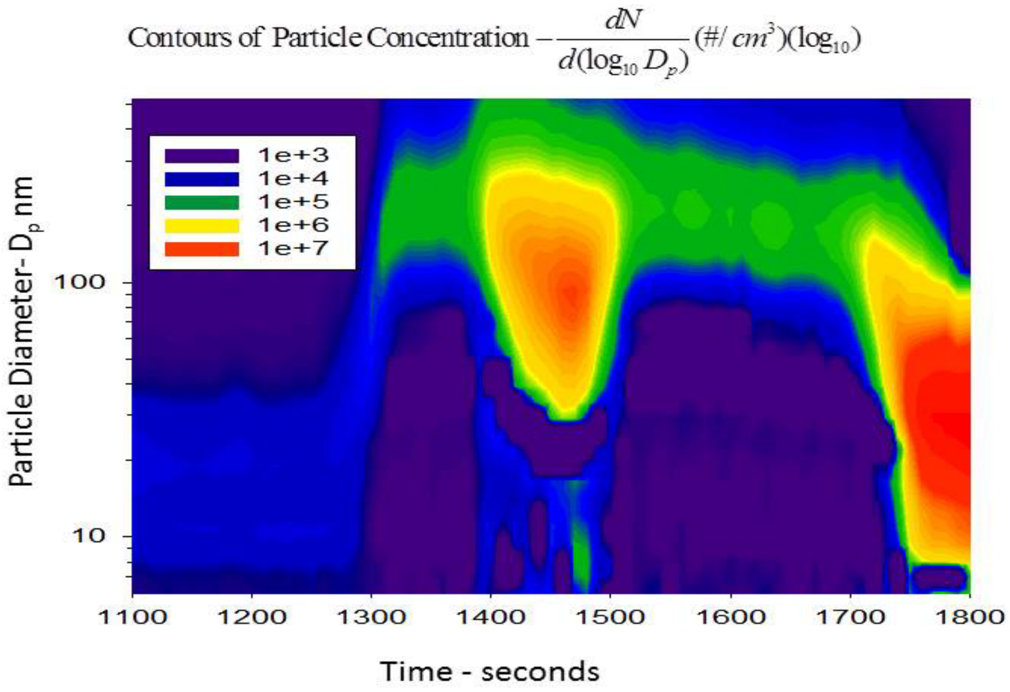


Figure III-23 Expanded view of EEPS particle number concentration emissions during the initial part of the regeneration event. Test3

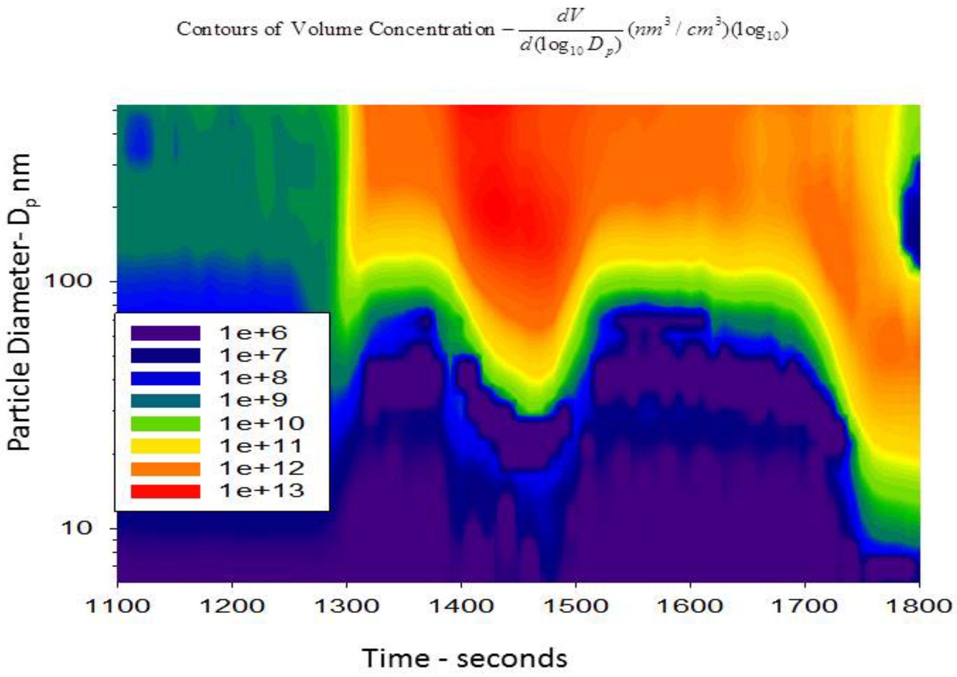


Figure III-24 Expanded view of EEPS particle volume concentration emissions during the initial part of the regeneration event. Test3

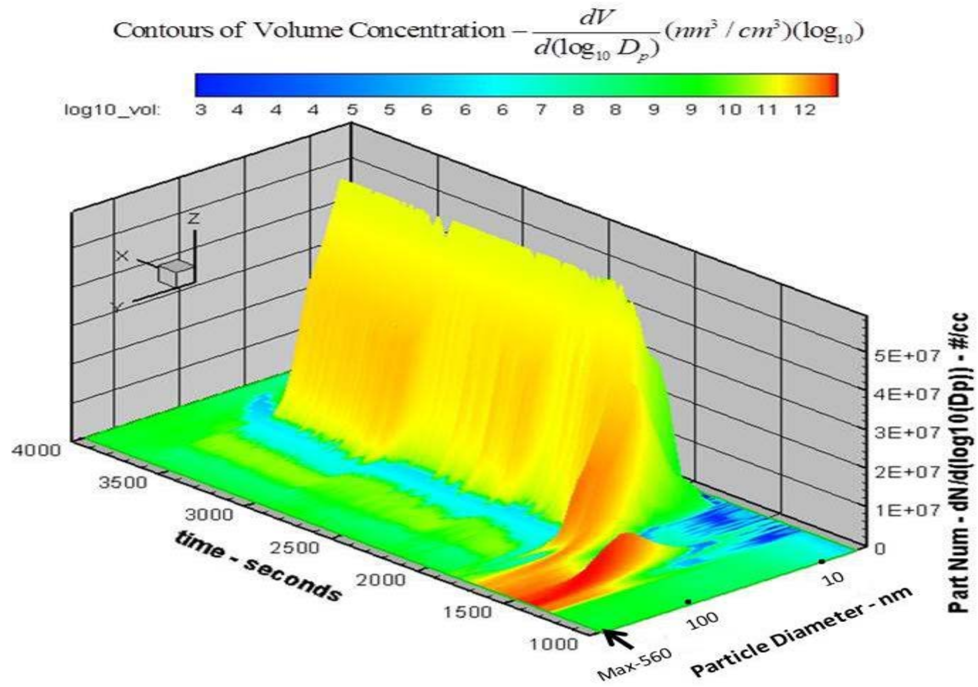


Figure III-25 EEPS particle number concentration and particle volume contours emissions during the regeneration event. Test3

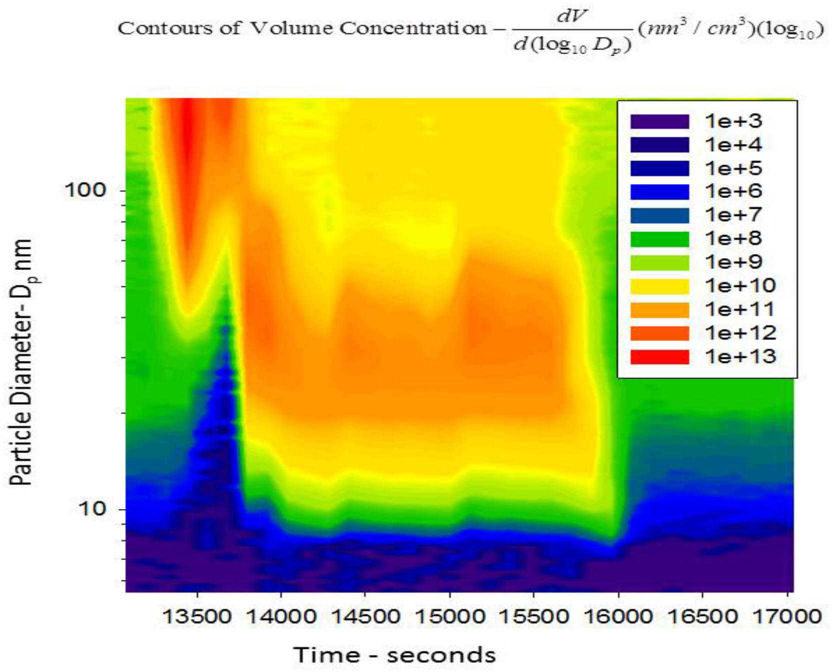


Figure III-26 SMPS particle volume concentration emissions during the regeneration event. Test3

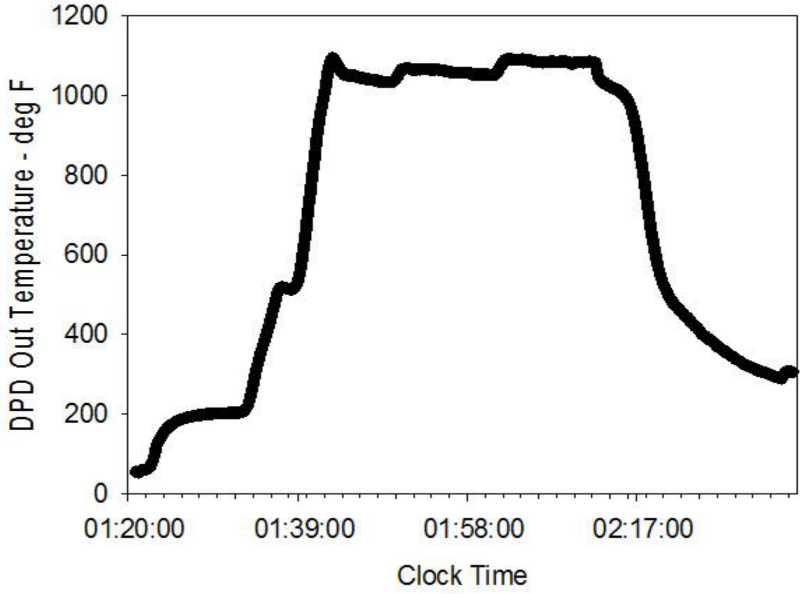


Figure III-27 DPF Outlet Temperature – Test3

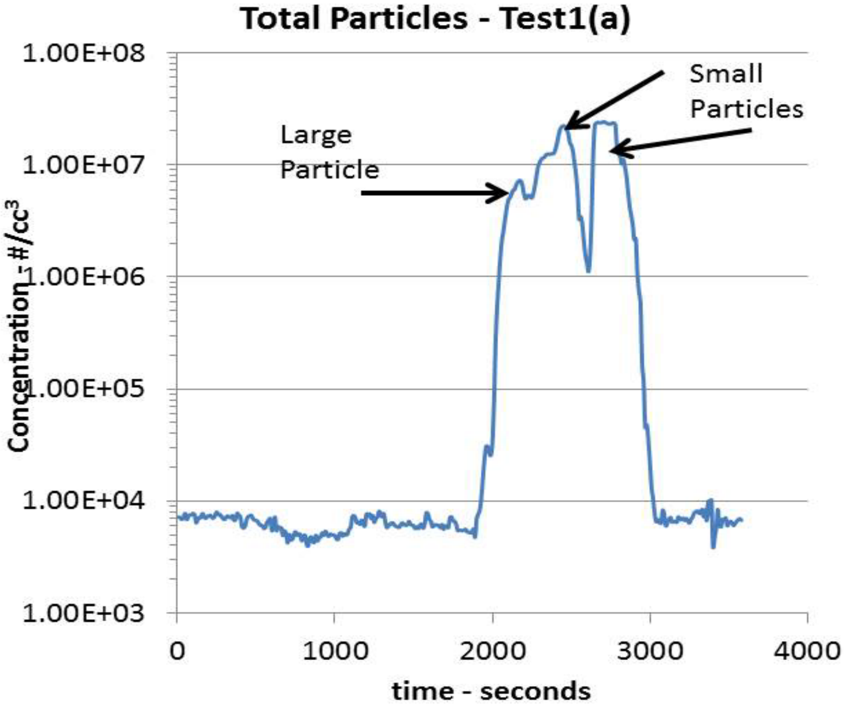


Figure III-28 EEPS total particle number concentration emissions during Test1(a) emission of many large particles beginning at 2000 seconds and many small particles before the DOC exhaust temperature decreased, see Figure III-2 and III-8. The large emission of small particles again appears in Figure III-28 as the exhaust temperature of the DOC increases to the design condition. For the continuation of the regeneration, Test1(b), the particle concentrations in Figure III-29 reach the same value as the later times in Figure III-28, and these concentration levels are at, near, or very close to the maximum concentration levels that can be recorded by the EEPS. It should also be noted that large particles in Figure III-28 are being under recorded due to the EEPS maximum size limitation of particles greater than 560 nm.

The particle number concentrations for the continued test of the 2007 DPF, Test1(c), are presented in Figure III-30, and this test had a smaller amount of mass emitted compared to Test1(a) and Test3. The total particle number emissions are again dominated by the small size particles during the latter part of the regeneration, and this result is also shown in Figure III-12. The maximum particle concentration levels in Figure III-30 are similar to all tests carried out for the 2007 DPF, and the large number of small particles have relatively small total mass. The EEPS total particle number concentrations for Test3 are presented in Figure III-31, and this test had a large amount of material emitted in the large particle size range. The general trend is very similar to Figure III-28, Test1(a), except for the decrease in particles in Figure III-28 due to the temperature overshoot and undershoot in the DPF.

B. Parked Regenerations of the 2010 DPF

First Test of the 2010 DPF The first test of the 2010 DPF, Test4(a), was carried out to completion and the DustTrak results are given in Figure III-32. The console light for an active DPF regeneration was on but not flashing, and the amount of mass emissions were at least two orders of magnitude lower than Test1(a) for the 2007 DPF. The spectrum of particle number and volume concentration are shown in Figures III-33 and 34 respectively for the SMPS (Note: Partial EEPS data during the latter part of the regeneration is shown in Figure III-35). The particle number concentrations in Figure III-33 and 35 are large and reflect closely the large number of small particles. The DustTrak results seem to be very spiky, and this spikiness is not seen in the SMPS and EEPS particle number concentration spectrums. Therefore, it is possible that the DustTrak results, Figure III-32, indicate particles larger than the channel capacity of the EEPS are being emitted by the DPF. Additional results comparing size distribution between 2007 and 2010 DPFs can be found in Appendix II for the latter part of DPF regeneration.

The total particle concentration in shown in Figure III-36 from the SMPS, and the maximum number of particles is similar to the maximum of all tests including both the 2007 DPF and 2010 DPF. The large numbers of small particles are most likely sulfate particles that are generated by the fuel used in the DOC to raise the temperature of the DPF. The outlet exhaust temperature from the DPF is given in Figure III-37, and it seen that same temperature is reach for both 2007 and 2010 technologies. Therefore, the latter part of DPF regeneration has not changed from 2007 to 2010 DPF, and very large numbers of small particles are emitted.

In order to complete the analysis of the 2010 technology, it is useful to explore the importance of PMTotal emissions, since the PM1.0 emissions in Figure III-32 are only two or three times background. Shown in Figure III-38 are the PMTotal emissions during Test4(a), and it appears that there is a release of large particles at 4200 seconds in the Figure III-38. This peak in emissions occurs at the same point of the peak in PM1.0 emission, and the PMTotal peak reaches a value of .343 mg/m^3 compared to .11 mg/m^3 of the PM1.0 emissions. Thus it appears

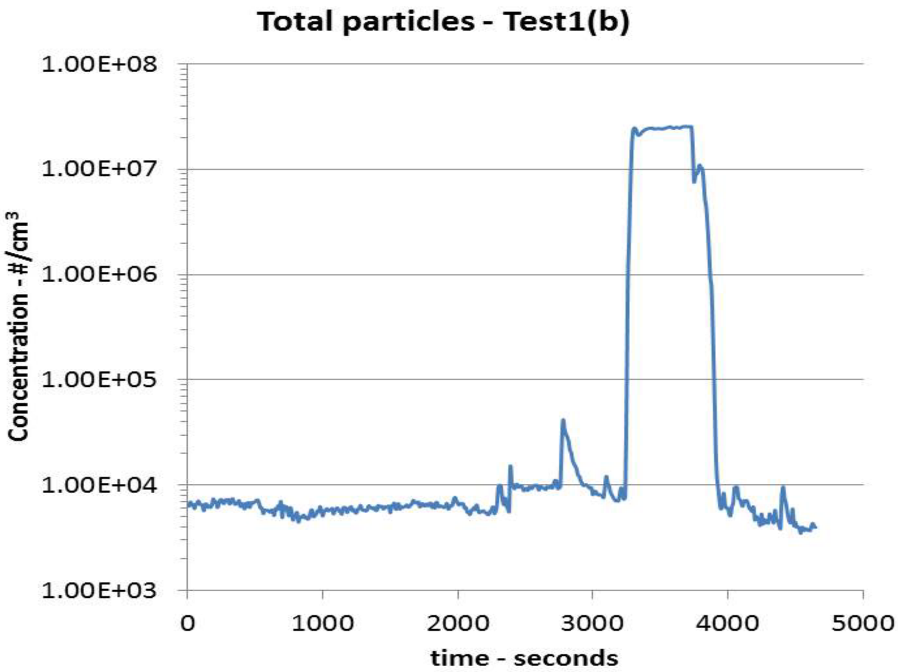


Figure III-29 EEPS total particle number concentration emissions during Test1(b)

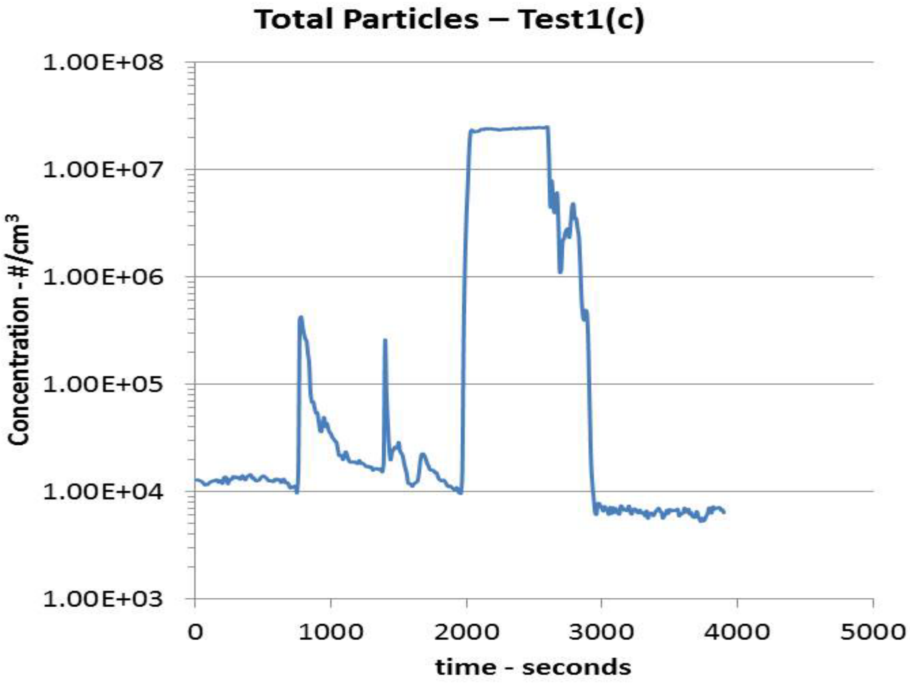


Figure III-30 EEPS total particle number concentration emissions during Test1(c)

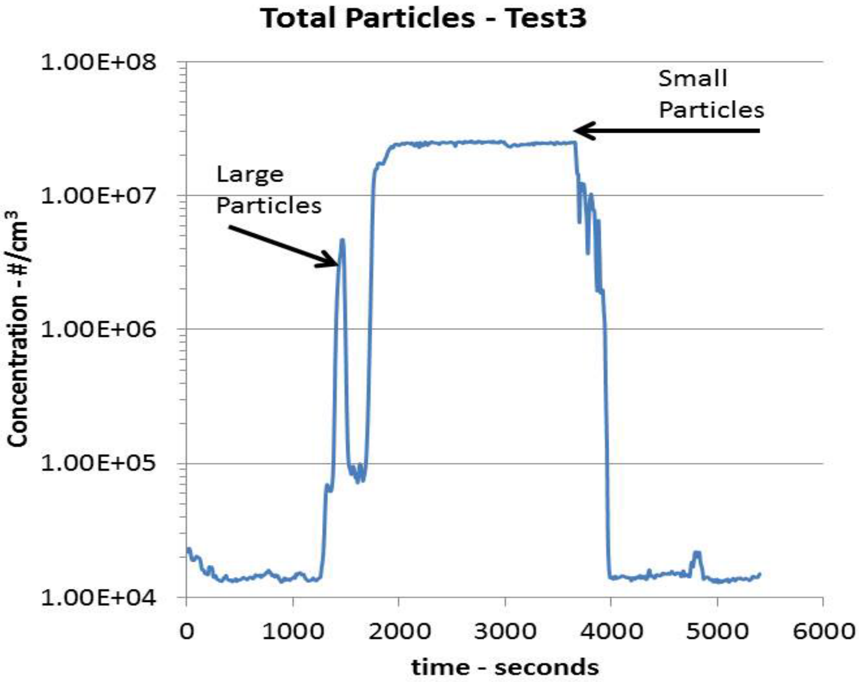


Figure III-31 EEPS total particle number concentration emissions during Test3

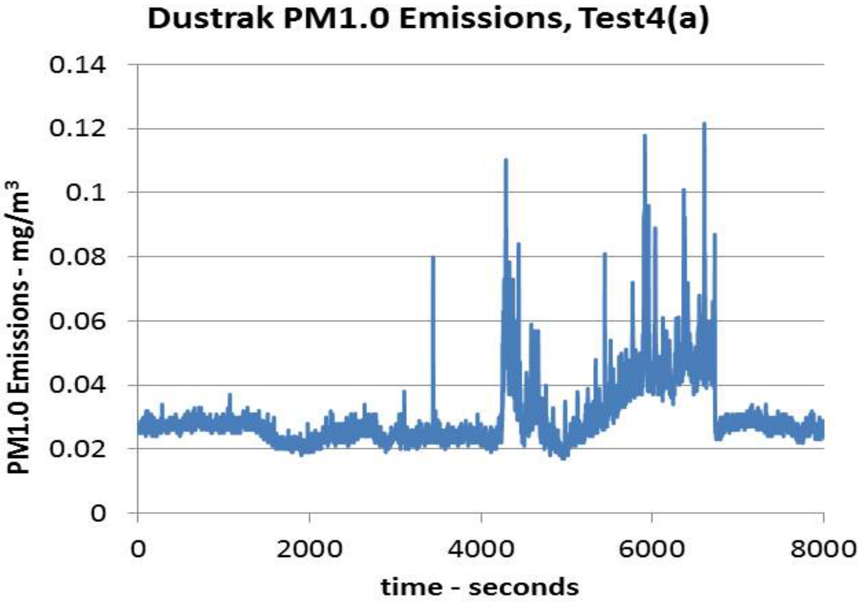


Figure III-32 PM1.0 Emissions from the DusTrak during the entire regeneration event. Test4(a)

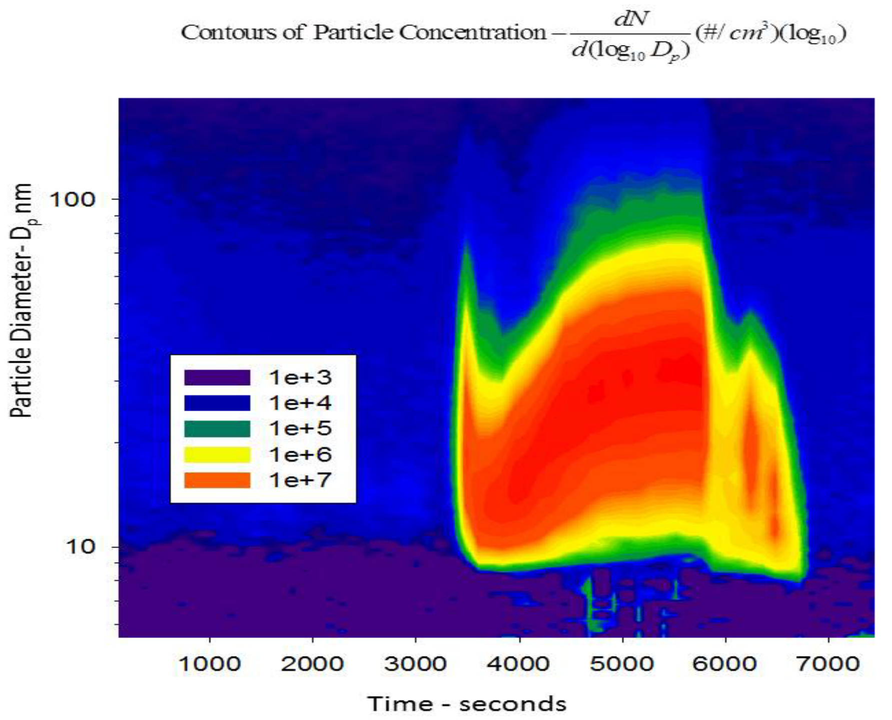


Figure III-33 SMPS particle number concentration emissions during the regeneration event. Test4(a)

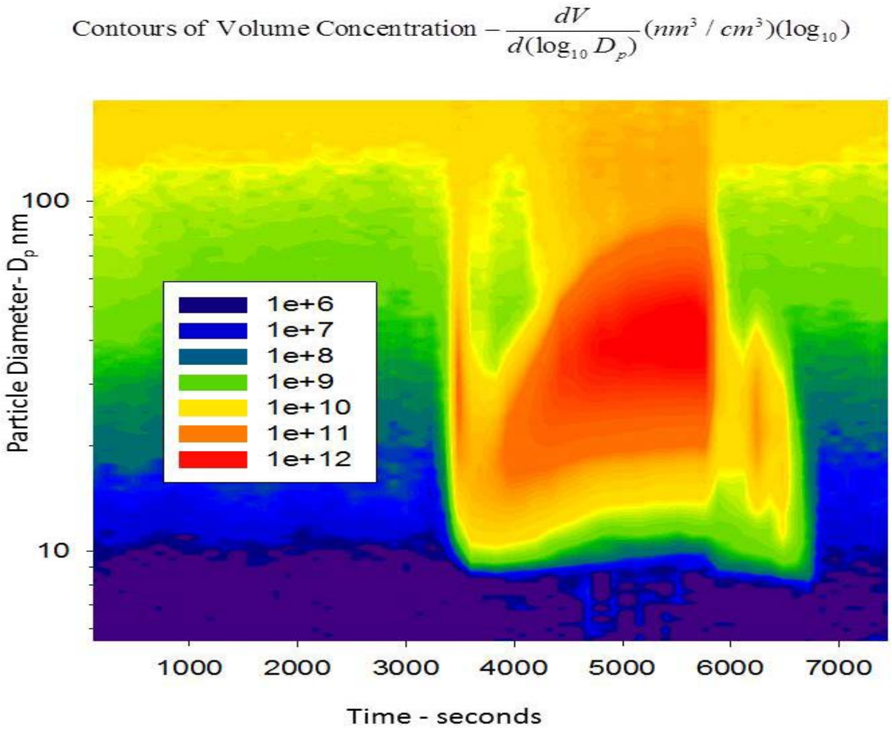


Figure III-34 SMPS Volume concentration emissions during the regeneration event. Test4(a)

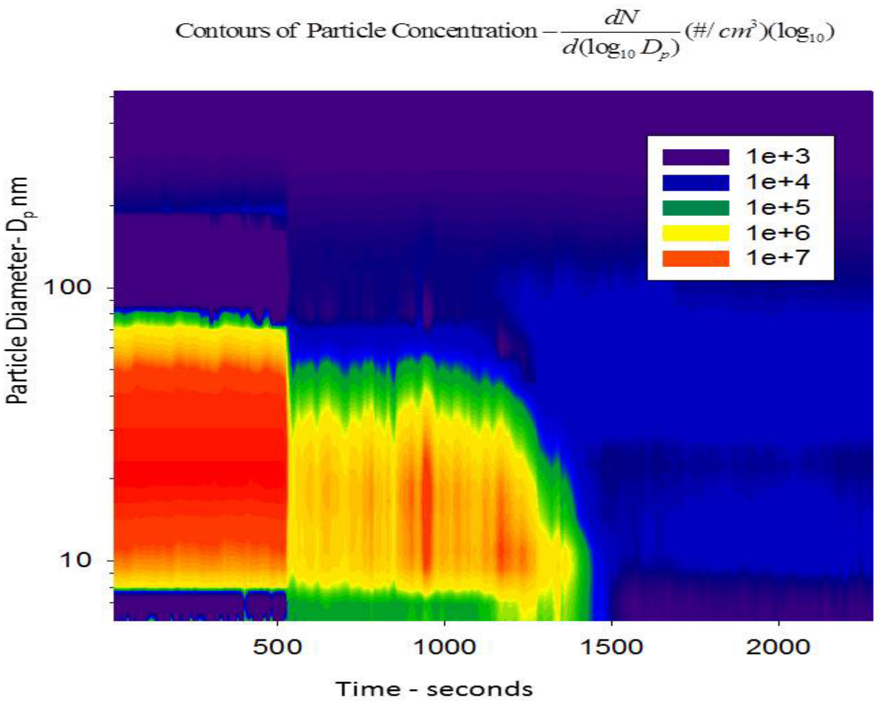


Figure III-35 EEPS particle number concentration emissions during the regeneration event. Test4(a)

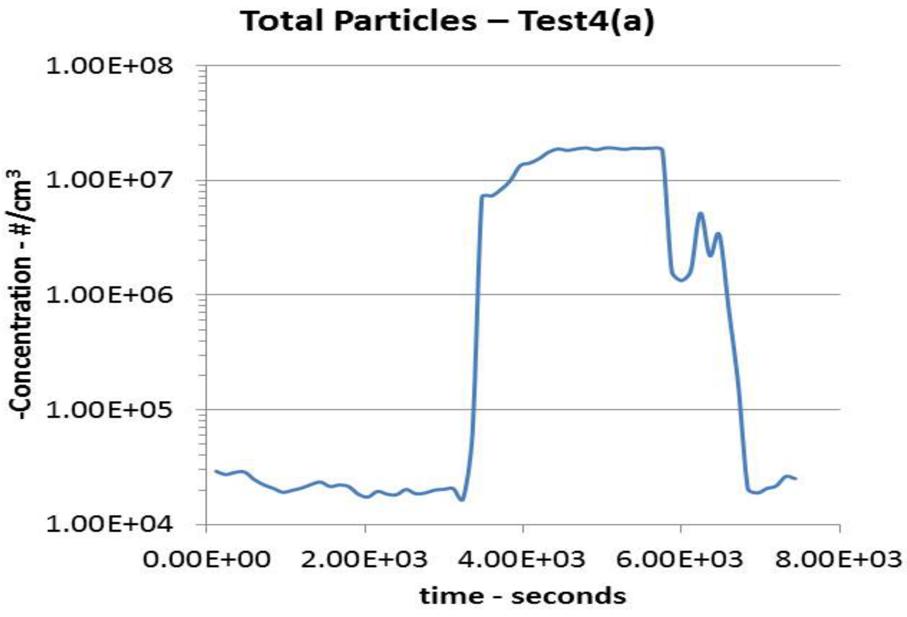


Figure III-36 SMPS particle number concentration emissions during regeneration event. First regeneration of 2010 DPF

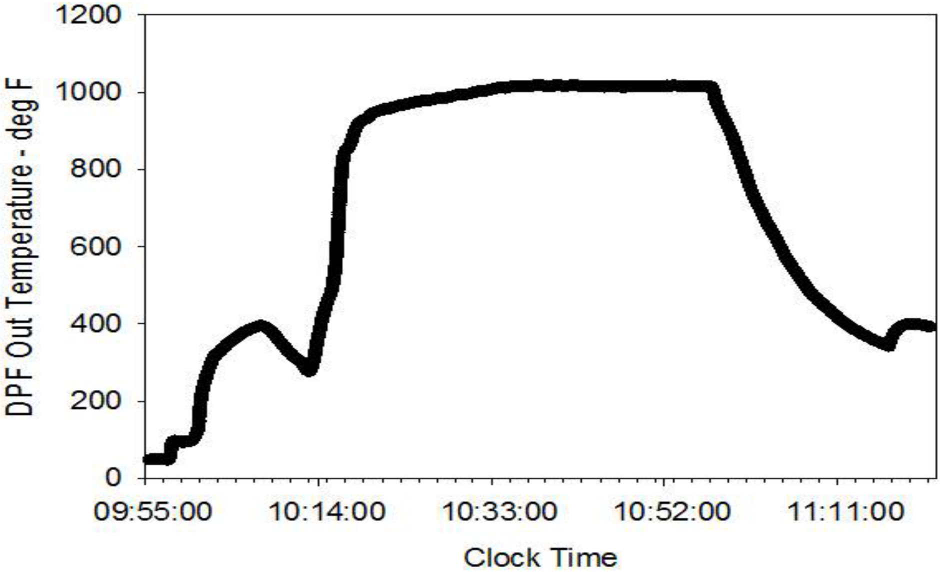


Figure III-37 DPF Outlet Temperature - First regeneration of the 2010, Test4(a)

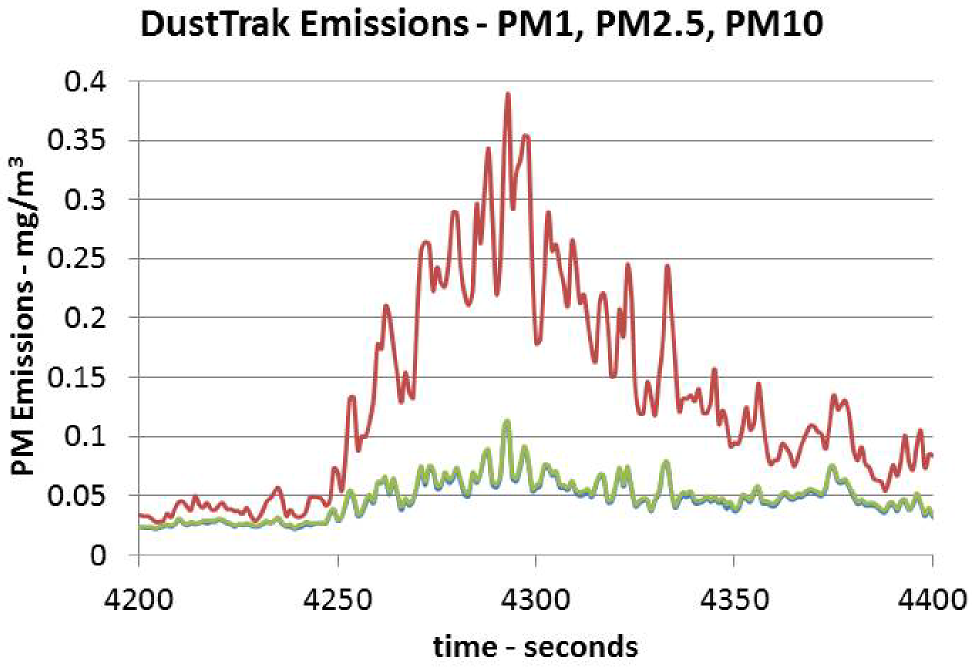


Figure III-38 PM1 and PMTotal Emissions from the DustTrak during large particle emissions. Test4(a) that large particles do play a role in active regeneration of both 2007 and 2010 technologies.

Second Test of the 2010 DPF The second test of the 2010 DPF, Test5(a), was carried out to completion and the DustTrak results are given in Figure III-39. The console light for an active DPF regeneration was on but not flashing, and the amount of mass emissions were at least two times lower than Test4(a) for the 2010 DPF. The spectrum of particle number concentration is shown in Figure III-40 from the SMPS. The particle number concentrations in Figure III-40 are large, and they have same order of magnitude as Test4(a). However, the length of time of Test5(a) is approximately half of Test4(a). Test5(a) had the least amount of PM in the DPF of all our tests, but the level of total particles was similar. Therefore, it should be emphasized again that the 2010 certified DPF has reduced PM dramatically relative to the 2007 DPF, but the total number of particles emitted from an active regeneration are similar.

The testing of the second test of the 2010 DPF was carried out on the same day as the third test of the 2007 DPF, and the SMPS was able to record Test5(a), Test5(b), and Test3 all in a single entire day's activity. Shown in Figure III-41 is the total particle number concentration emissions for all three tests, and it is seen that there are considerably more particles generated by the 2007 DPF, Test3. The total particle concentration emission levels of Test5(a) reach values close to Test3 of 2007 DPF, but the amount of time for the regeneration is shorter for Test5(a). The forced regeneration test for the 2010 DPF, Test5(b), has less particles than all other forced tests.

The particle number and volume spectrum concentrations for Test5(a), Test5(b), and Test3 from the SMPS are shown in Figures III-42 and III-43, and they support the result that large particle number concentrations are due to small particles with a small amount of mass. The DustTrak results shown in Figure III-39 under estimate the mass emitted during the regeneration by more than an order of magnitude, since the DustTrak does not record ultrafine particles, and there is substantial volume associated with ultrafine particles in Figure III-43 for Test5(a).

C. Regulated Emission occurring during Parked Regenerations

2007 DPF During all the Parked Regeneration testing the PEMS equipment was able to measure some regulated emission at the entrance of the small wind tunnel, although PM was not measured with the PEMS. For all the tests the trucks were parked outside overnight, and the tests were started from a cold start the next day. This procedure allowed us to obtain information on the influence of the truck starting condition on active regenerations, as well as some information on the influence of a cold engine on regulated emissions. Shown in Figure III-44 is the variation of NO_x concentration and lambda, the relative fuel air ratio, during Test1(a). When the engine of the 2007 truck was started the NO_x concentration attained a value of more than 1000 ppm, parts per million, with a starting value for lambda of 4. For the next ten minutes the values of NO_x decreased and lambda increased until the active regeneration started. At the start of regeneration the values of NO_x increased rapidly to values more than 1000 ppm and lambda attained values between values between 3 and 4. For a time period of almost 300 seconds lambda was almost constant, and this time period corresponds to the large mass emission associated with Test1(a). For the remainder of Test1(a) the values of NO_x and lambda remain relatively constant until the end of the regeneration with values of NO_x near 400 ppm and lambda between 2 and 3. The latter time period lasted approximately 600 seconds and is associated with the emission of a very large number of ultrafine particles in the size range between 20 and 40 nm.

With an analysis of all the testing it was determined that engine coolant temperature played a role at the start of the DPF regeneration, and engine coolant temperature and total hydrocarbon emissions, THC, are presented in Figure III-45 for Test1(a). During the ten minutes of engine idling the coolant temperature rises from the cold start condition and THCs remain

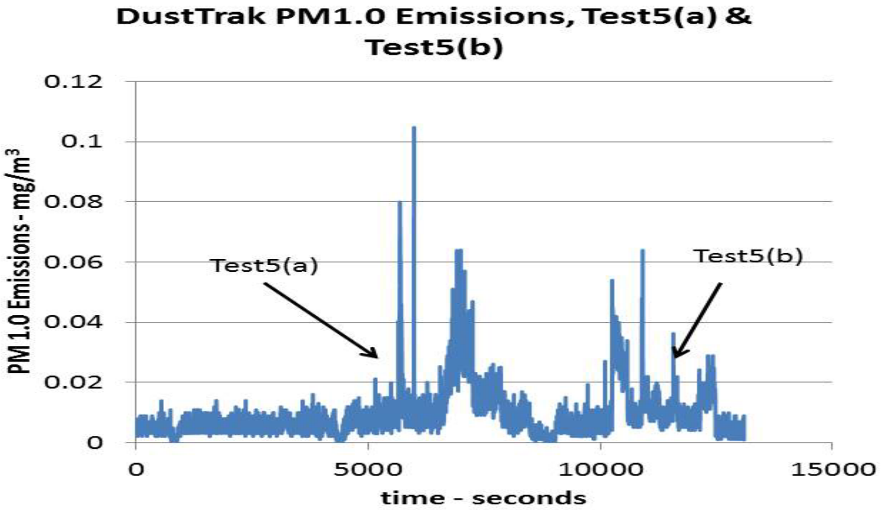


Figure III-39 PM1.0 Emissions from the DustTrak during the entire regeneration event. Test5(a)

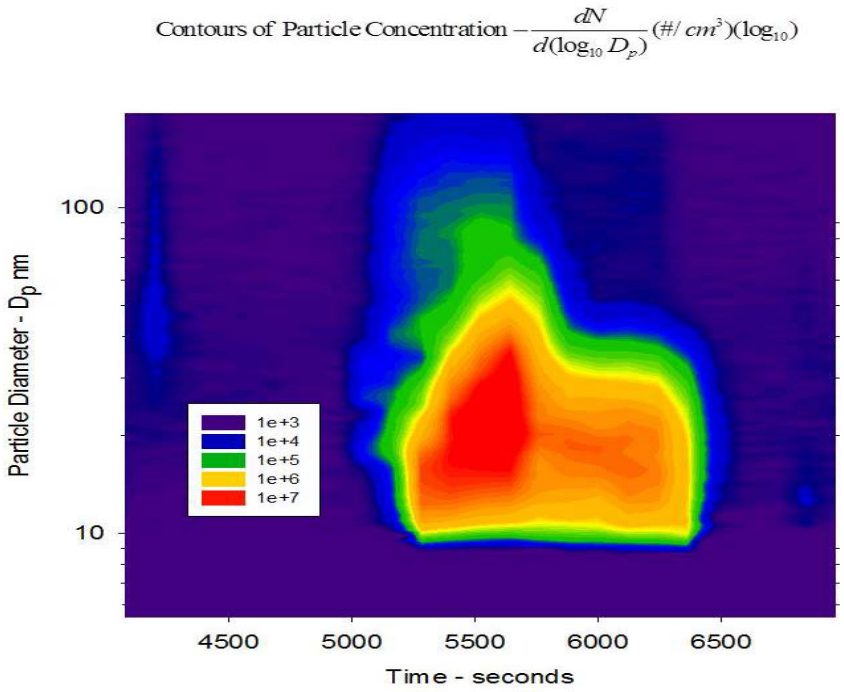


Figure III-40 SMPS particle number concentration emissions during three regeneration events. Test5(a)

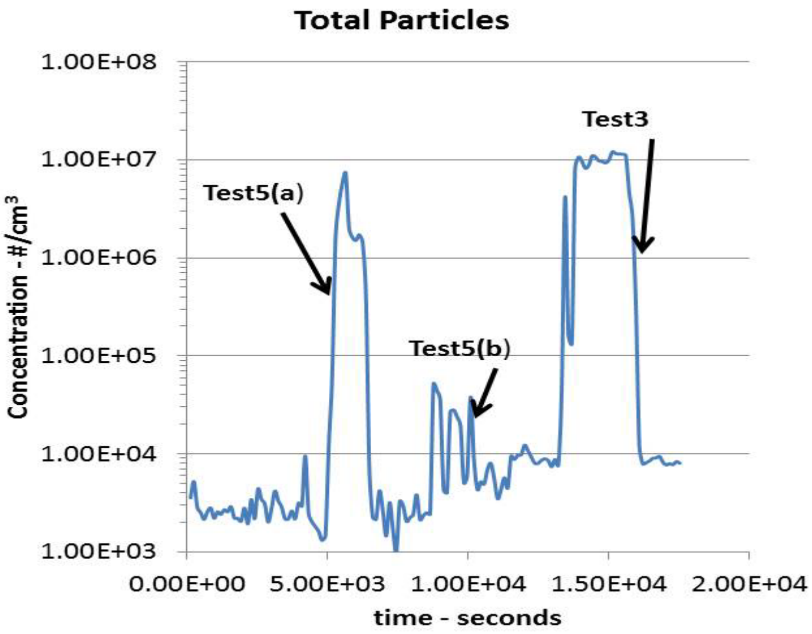


Figure III- 41 SMPS total particle number concentration emissions during three regeneration events. Test5(a), Test5(b), and Test3

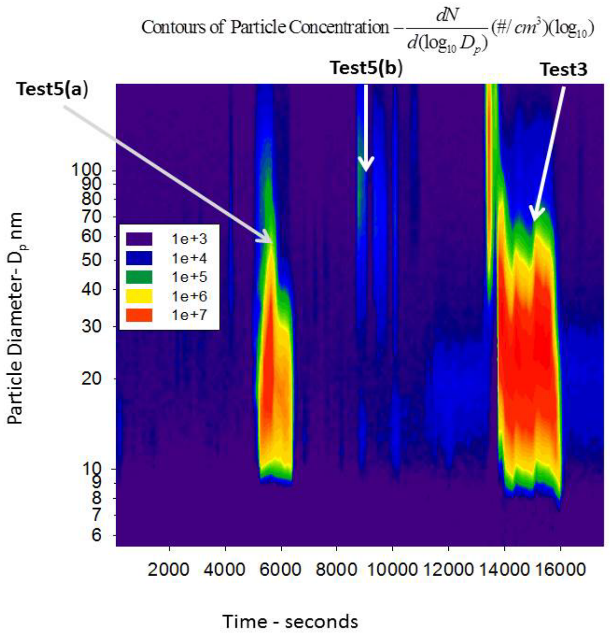


Figure III-42 SMPS particle number concentration emissions during three regeneration events. Test5(a), Test5(b), and Test3

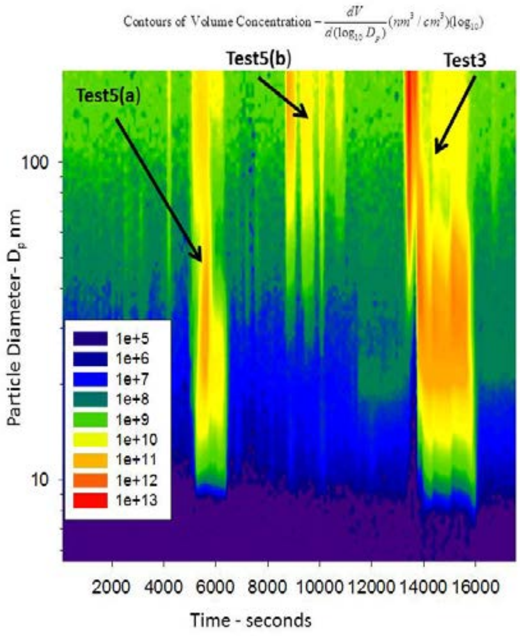


Figure III-43 SMPS volume concentration emissions during three regeneration events. Test5(a), Test5(b), and Test3

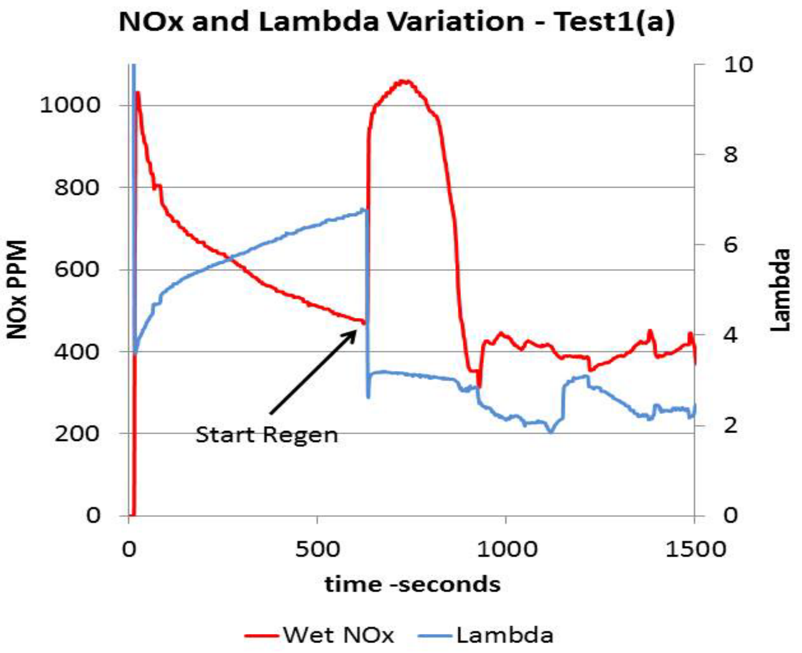


Figure III-44 Variation of wet NOx and lambda during regeneration of the 2007 DPF. Test1(a) Ambient Temperature = 62 °F

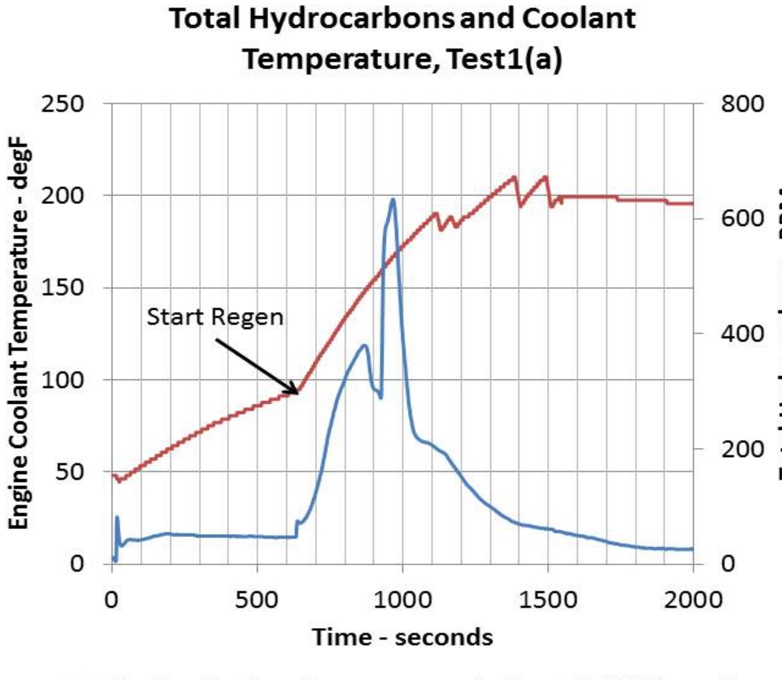


Figure III-45 Variation of coolant temperature and total hydrocarbons during regeneration of the 2007 DPF. Test1(a) constant at approximately 30 ppm. At the start of the regeneration both engine coolant temperature and THCs increase rapidly, and they attained maximum values of 600 ppm for THCs and approximately 200°F for the coolant temperature. After the period of high mass emissions for Test1(a) the emissions of THCs decrease rapidly and the engine coolant temperature remained constant.

The continuation of the Test1 was restarted at approximately 45 minutes after Test1(a), and Test1(b) was begun. Shown in Figure III-46 are the variation of NO_x and lambda during Test1(b). The truck idling started at approximately 1000 seconds in Figure III-46, and NO_x starts from a much lower value of 200+ ppm, and lambda at a higher value near nine. The reason for these changes can be seen from Figure III-47 where engine coolant temperature and THCs are presented for Test1(b), and it is seen that the engine coolant temperature is warm compared to Test1(a). After the start of idling the THCs begin to increase rapidly when the regeneration is begun at approximately 1400 seconds in Test1(b). Over a period of approximately 400 seconds the THCs increase and decrease rapidly in the final period of the regeneration, where the THCs oscillate between values of 5 and 30 ppm. Overall, it is seen that both NO_x and THCs are considerable smaller for Test1(b) compared to Test1(a).

The results from Test1(c) will now be presented, and this test will again show the importance of engine coolant temperature compared to DPF loading. If the DustTrak results for Test1(a) and Test1(c) are compared, it is seen that the total amount mass emitted by Test1(a) is two orders larger than Test1(c), but the results in Figure III-48 for Test1(c) show NO_x emissions are slightly larger than for Test1(a) emissions. At the start of idling for Test1(c) changes in coolant temperature and THCs are similar to Test1(a) as shown in Figure III-49, but the THCs during the regeneration are ten times smaller. Therefore, it appears that there is strong dependence of NO_x emissions on engine coolant temperature, and a strong dependence of THCs on DPF loading during an active loading of a 2007 DPF. Test2 was begun from a cold start like Test1(a), and the variation of NOx and lambda in Figure III-50 are similar to Figure III-44 for Test1(a).

Test3 for the 2007 DPF had the highest starting temperature of 82 °F, and it also had a large amount of mass in the DPF with the console light flashing. Shown in Figure III-51 are the values of NO_x and lambda, and the trend of lower NO_x with engine coolant temperature is confirmed in Figure III-52. Also, the higher THCs with larger mass loading of the DPF are confirmed in Figure III-52.

2010 DPF It is to be expected that regulated emissions from 2010 DPFs will be much improved over 2007 DPFs due to the introduction of SCR, selective catalytic reduction, after treatment technology as well as basic diesel engine improvements. Shown in Figure III-53 are the NO^x emissions from Test4(a), and NO_x is considerably reduced compared to the 2007 DPF with a cold engine start conditions. For example, NOx is down more than one half during the start of the DPF regeneration. Other results for Test5(a) and Test5(b) are given in Figures III-54 and III-55, and the NOx levels are reduced from 2007 DPFs. In Figure III-53 the general trend between Test4(a) and Test5(a) are quite similar, but the NOx levels at the start of Test5(a) are larger even though the DPF was lightly loaded. Test5(b) was a forced regeneration that occurred after Test5(a) was completed, and the engine coolant was warm at the start of the test. The NOx levels for Test5(b) are the lowest of all testing during DPF regeneration, but they did reach levels approaching 200 ppm.

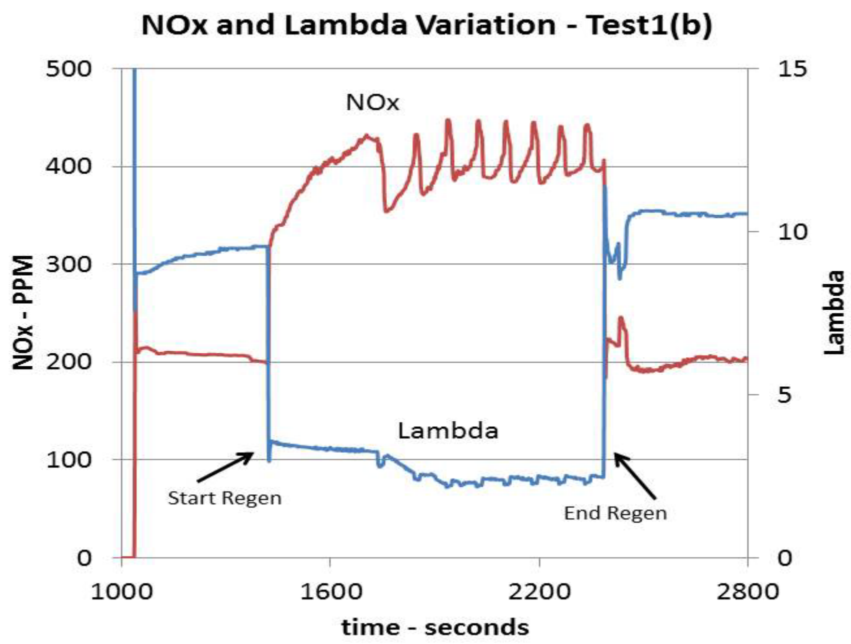


Figure III-46 Variation of wet NOx and lambda during regeneration of the 2007 DPF. Test1(b) Ambient temperature = 65 °F

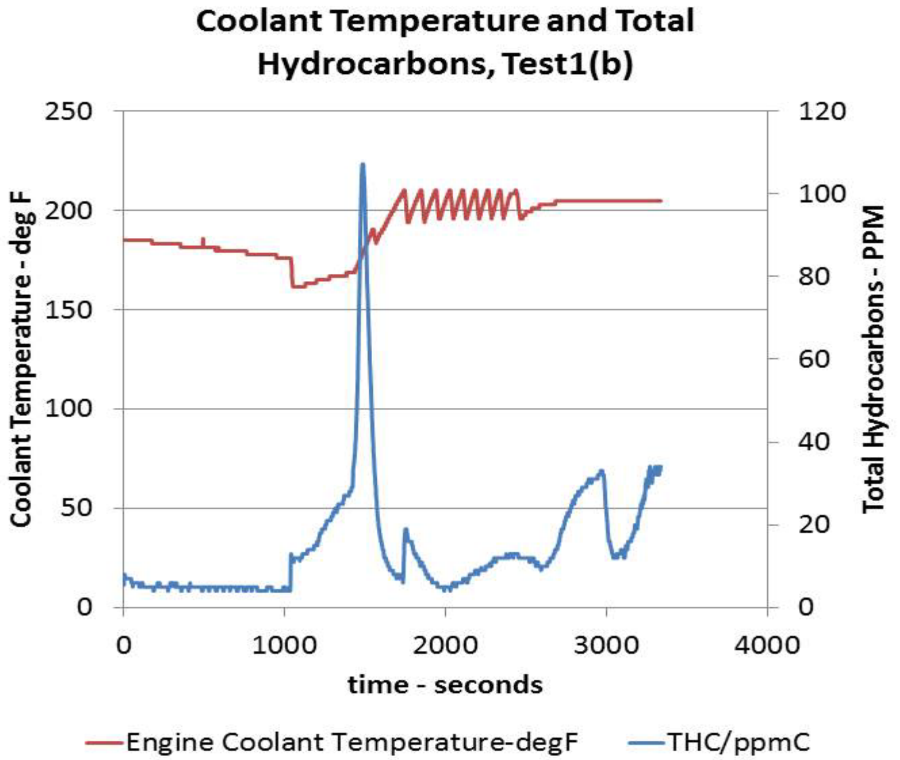


Figure III-47 Variation of coolant temperature and total hydrocarbons during regeneration of the 2007 DPF. Test1(b)

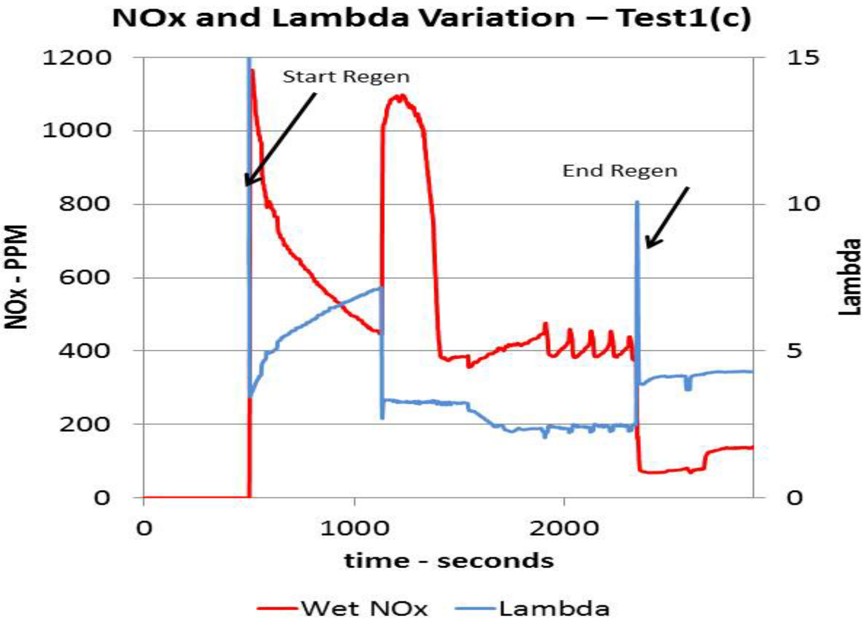


Figure III-48 Variation of wet NOx and lambda during regeneration of the 2007 DPF. Test1(c) Ambient temperature = 54 °F

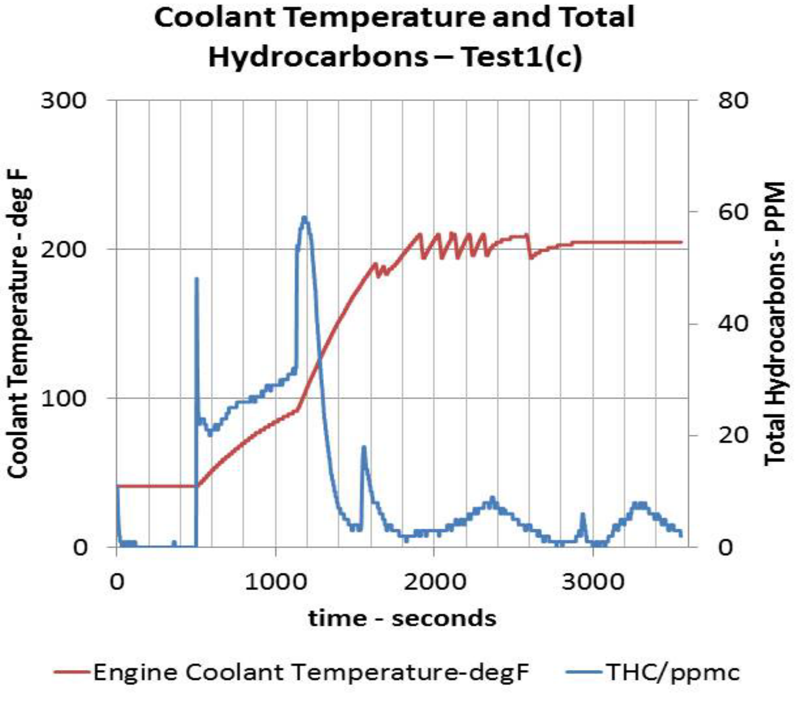


Figure III-49 Variation of coolant temperature and total hydrocarbons during regeneration of the 2007 DPF. Test1(c)

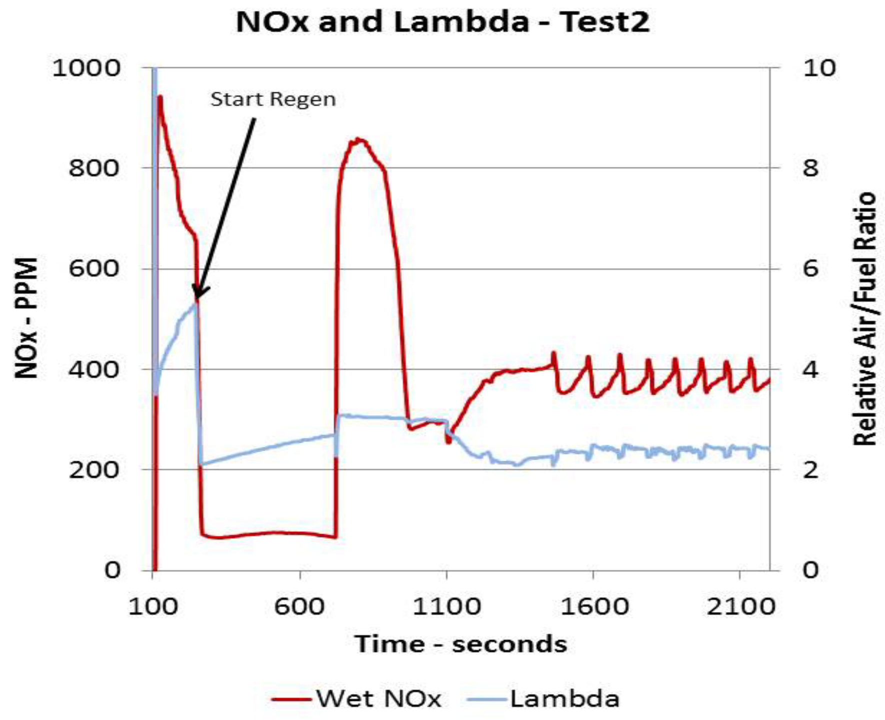


Figure III-50 Variation of NOx and lambda during regeneration of the 2007 DPF. Test2 Ambient temperature = 54 °F

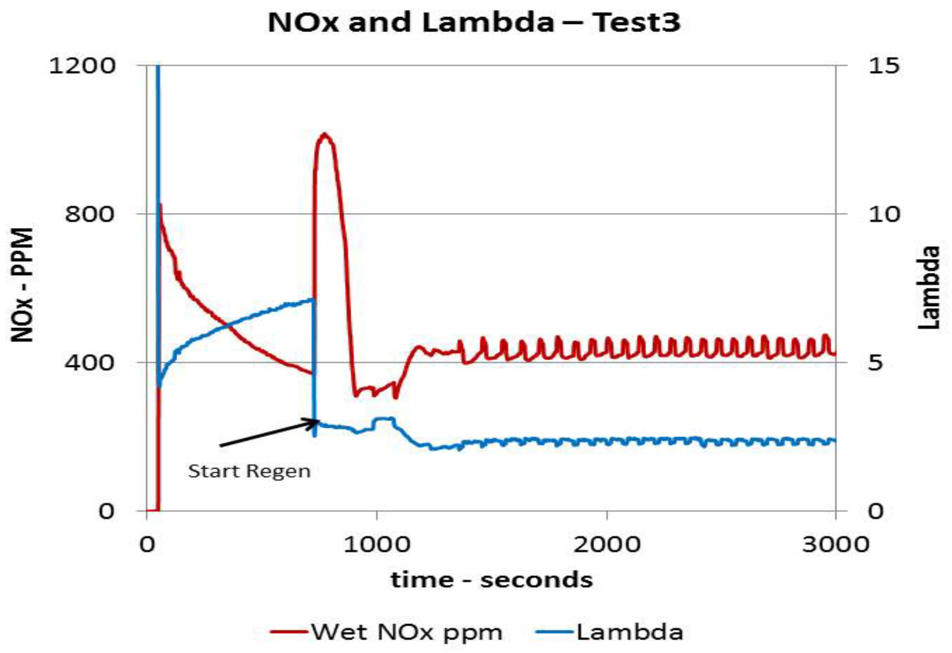


Figure III-51 Variation of wet NOx and lambda during regeneration of the 2007 DPF. Test3 Ambient temperature = 82°F

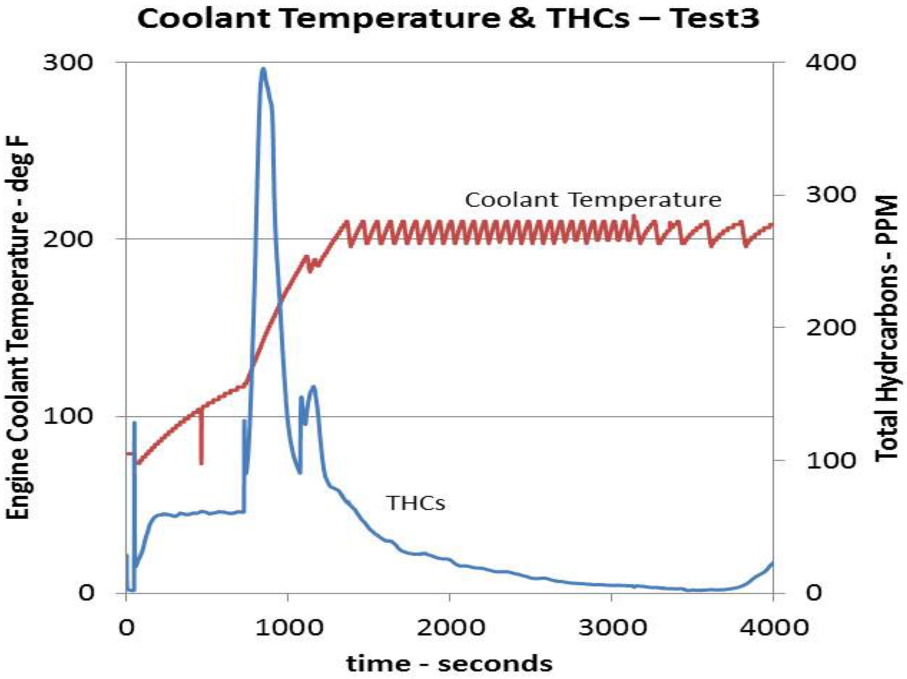


Figure III-52 Variation of coolant temperature and total hydrocarbons during regeneration of the 2007 DPF. Test3

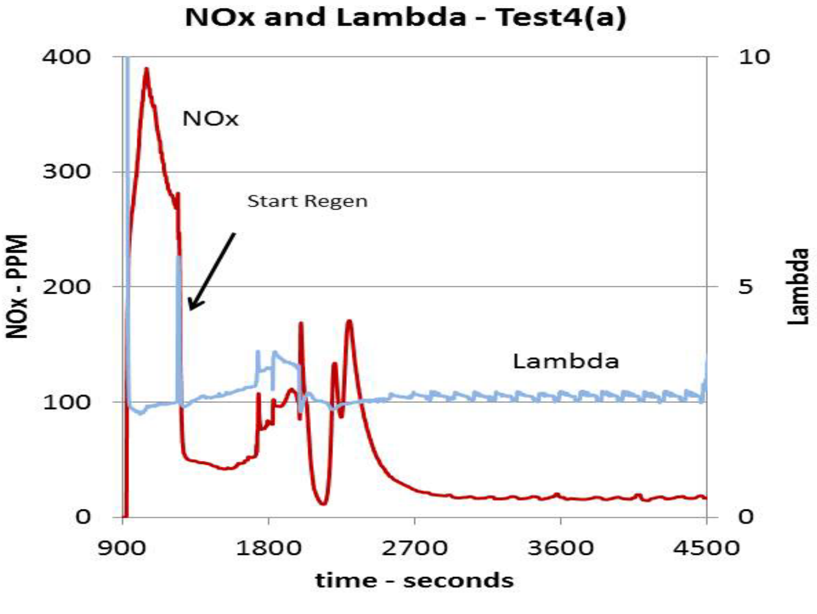


Figure III-53 Variation of NOx and lambda during regeneration of the 2010 DPF. Test4(a) Ambient temperature = 62 °F

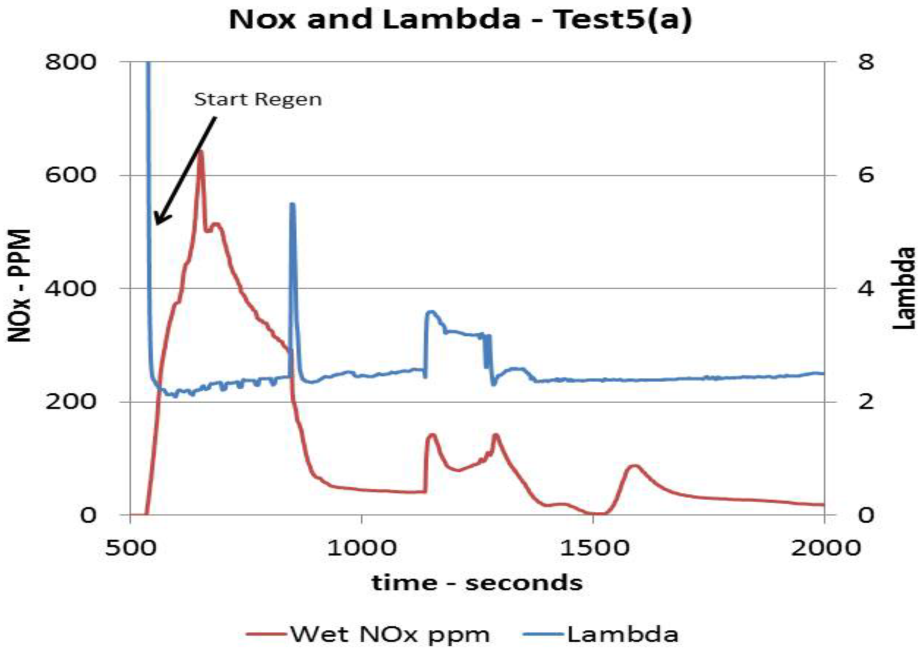


Figure III-54 Variation of NOx and lambda during regeneration of the 2010 DPF. Test5(a) Ambient temperature = 70°F

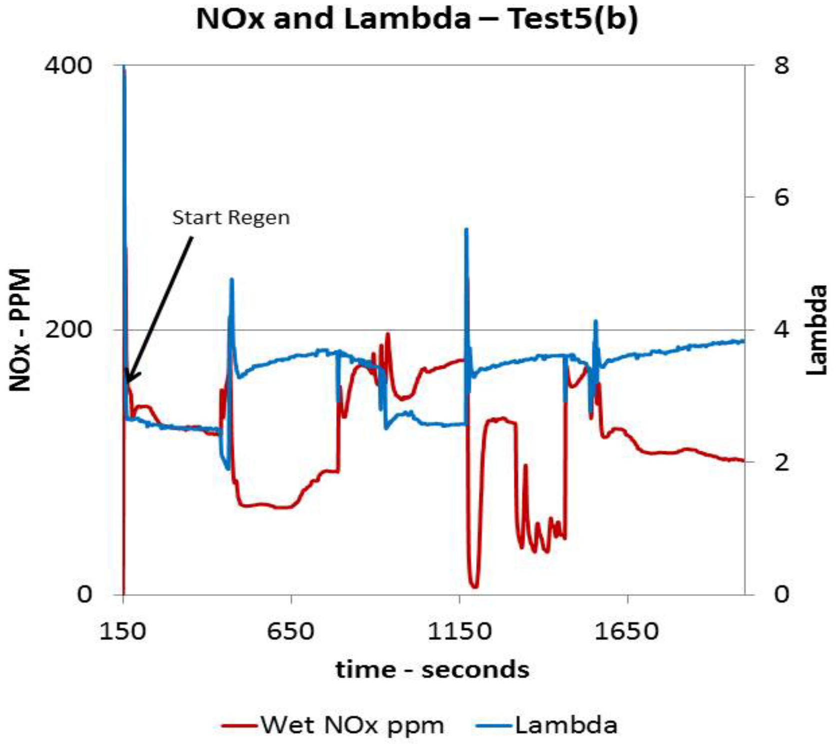


Figure III-55 Variation of wet NOx and lambda during regeneration of the 2010 DPF. Test5(b) Ambient temperature = 75 °F

The THCs generated from the 2010 DPF showed significant variation for the two tests that were performed. Shown in Figure III-56 is the variation of THCs with engine coolant temperature for Test4(a) of the 2010 DPF, and this test had the most PM for the 2010 DPF. The maximum level of THCs was the highest of all the tests including both the 2007 and 2010 DPFs, and the time period of THCs emissions was substantial but shorter than the 2007 DPF tests. Also, the THCs dropped off to values close to zero after the engine coolant temperature reached its typical steady state temperature. For Test5(a) the THCs emissions were the lowest for all testing, Figure III-57, and this is reflective of the very light PM loading for this parked regeneration.

Additional results for NOx emissions from the forced regeneration tests can be found in Appendix II.

D. Estimating Mass Emission Rates from the Instrumentation Used in the Study

In this section preliminary results will be presented for the estimates and calculations of the PM mass flow rates for all of the experimental tests performed in the small wind tunnel. Shown in Figure III-58 for Test3 are the mass emissions rate estimates for all of the instrumentation used in the testing. The predictions from every piece of instrumentation contain uncertainties since the particle shape, composition, and density are not known accurately, and there is a limited diameter range for all instrumentation. However, it is a useful exercise to examine the qualitative values and trends in Figure III-58.

At early times the DustTrak emissions are the largest due to the large number of large particles generated from the Test3 DPF. Also both the DMM and EEPS give larger values than the SMPS during the large mass emission phase, and this is to be expected, since the EEPS and DMM cover a larger range of particle sizes. During latter times in Figure III-58 the SMPS seems to give slightly larger values, since it is very good in the ultrafine region, although the EEPS and DMM are close to SMPS values. The DustTrak values are quite low during the ultrafine particle phase compared to other instrumentation, and this is to be expected since the DustTrak was below its detection limit.

IV – SUGGESTIONS FOR FUTURE RESEARCH

There is a need to carry more research in the following areas:

- Relate real time PM measurement instrumentation to filter measurements of total PM emitted during a Parked Regeneration.
- Extend the use of the small wind tunnel to the chassis dynamometer that will be constructed at Depot Park.
- Determine the PM composition emitted during all phases of the regeneration.
- With the use of the chassis dynamometer perform active regeneration of the DPF under high temperature road driving conditions.
- Investigate passive DPF regeneration with a partially loaded DPF. For example, carry out high speed road driving on the chassis dynamometer to observe the passive DPF regeneration.
- Extend the small wind tunnel by five meters, and locate two particle instruments ten meters apart to investigate changes in particle size as the ultrafine particles are absorbed by larger particles in the ambient background air.
- Investigate the possible ways that particle shape and density can be determined for

all phases of active and passive regeneration of DPFs.

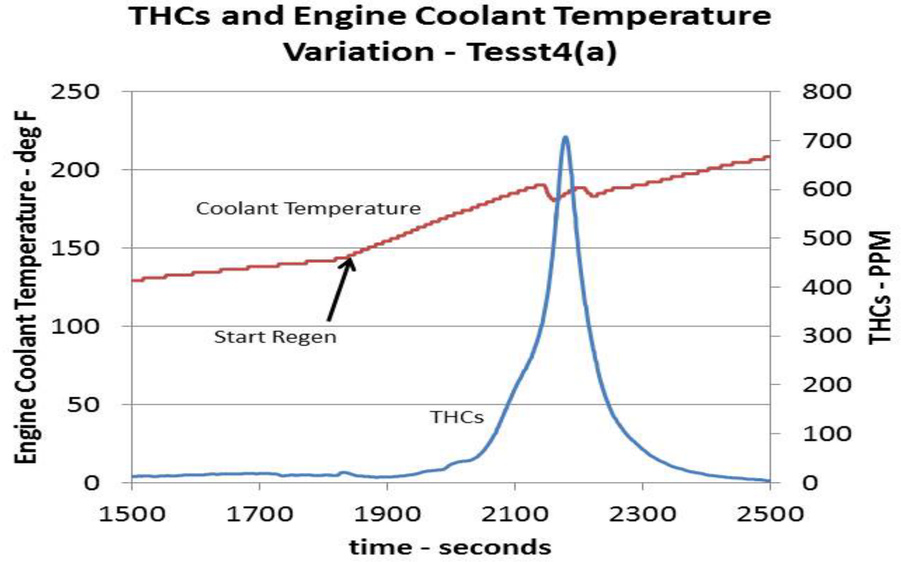


Figure III-56 Variation of coolant temperature and total hydrocarbons during regeneration of the 2010 DPF. Test4(a)

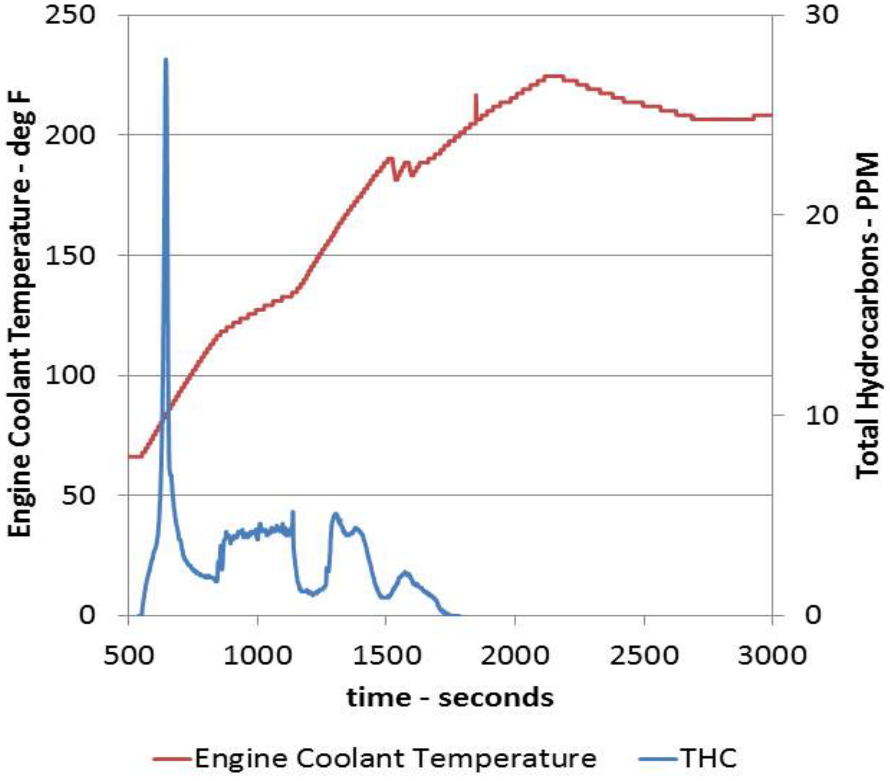


Figure III-57 Variation of coolant temperature and total hydrocarbons during regeneration of the 2010 DPF. Test5(a)

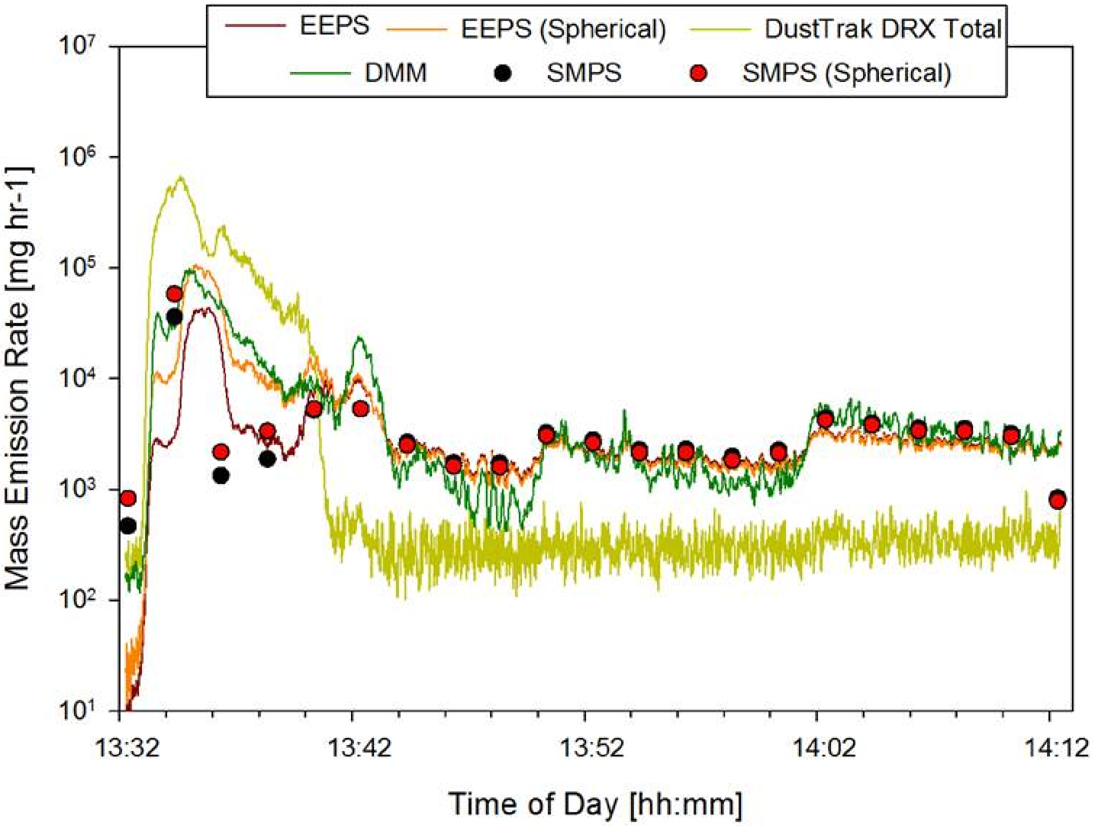


Figure III-58 Estimates of time dependent PM mass flow rates from particle instrument used during Test3

V. CONCLUSIONS AND SUMMARY

The testing of the emissions from Parked Regeneration for DPFs with 2007 and 2010 technologies has been successfully completed, and a summary of the major results are the following:

Small Wind Tunnel – The construction and use of the small wind tunnel has been highly successful and a summary of its characteristic are given below:

- The flow quality of the tunnel with the use of the mixing plate was very good and it delivered a homogeneous mixture to the sampling tube.
- The large total flow rate of 9000 cfm enabled dilution ratio of approximately 30/1 during the high temperature and high engine mass flow rate emission tests during Parked Regenerations.
- Due to the high dilution ratios the temperatures entering the sampling tube never exceeded 90°F during all DPF testing.
- The high sampling rate of 160 liters per minute for the sampling tube allows for the use of many emission instruments without the loss of ultrafine particles to the walls of the sampling system.
- The small wind tunnel can be easily expanded to higher flow rates and to a longer length. In the present configuration the small wind tunnel is easily mounted in a trailer typical of heavy duty diesel road vehicles.

PM and particle emissions from a 2007 DPF – Three successful parked regeneration tests from a 2007 DPF have been performed and the following results have been obtained:

- All parked regenerations test of the 2007 DPF yielded very large PM emissions with maximum values of the order of 10 or larger mg/m^3 during the initial phase of the regeneration with a dilution ratio of 30/1.
- The initial phase of the regenerations lasted approximately 600 seconds, and they were characterized by the emission of particles that are larger in diameter than the recording capacities of the EEPS and SMPS instrumentation.
- For a fully loaded 2007 DPF with a flashing console light, the PM emission greater than PM1.0 are substantial and total emissions including PM10.0 should be measured. PM 1.0 and PM2.5 measurements are essentially the same, since the larger particles are greater than PM2.5 particles.
- After the initial phase of high mass flow rates the DPF regeneration is characterized by a second phase of very large number emissions of small ultrafine particles less than 100nm. In terms of total particle numbers the second phase dominates over the first phase, since it lasts for a longer time.
- The second phase of high ultrafine particle numbers was very similar for all 2007 regenerations, and it appears to be closely related to the fuel being ejected into the DOC. It has been estimated that the ultrafine particles are mainly sulfate particles.
- The mass of the very large number of ultrafine particles is not well recorded by the DustTrak, and it is indicated by the EPPS and SMPS instrumentation that these particles contain substantial amount of mass during the latter phase of the DPF regeneration. An estimate of the under recording of the DustTrak during the latter phases of 2007 DPF regeneration is one order of magnitude.
- The number of particles created during DPF regeneration is very near or over the particle

concentration capacity of the EEPS instrumentation. Future tests should consider the use of a thermal particle diluter.

- Currently, particle instrumentation does not have the capability of recording the entire range of particles created during DPF regeneration. The EEPS and SMPS can treat ultrafine particles well and the DustTrak can record the large particles.
- At the present time the particle shape, density, and composition of the particles created during DPF regeneration are not known accurately. More detailed research in these areas is needed and should be carried out.

PM and particle emissions from a 2010 DPF – Two successful parked regeneration tests from a 2010 DPF have been performed and the following results have been obtained:

- All parked regenerations test of the 2010 DPF yielded much smaller values of PM emissions, the maximum values were of the order of 0.35 or smaller mg/m^3 during the regeneration with a 30/1 dilution ratio.
- The initial and final phases of the regenerations contained large numbers of ultrafine particles, and they did appear to exceed or almost exceed the recording capacities of the EEPS and SMPS instrumentation.
- During the testing a fully loaded 2010 DPF was not obtained, and it appears that substantial amount of passive regeneration occurred during DPF loading.
- During the entire testing the DustTrak results are very spiky, and this may indicated that large particles are released by the DPF. The spiky release of PM was not seen by the EEPS and SMPS instrumentation, and there are limited results showing that particles larger than PM1.0 are released.
- The second phase of high ultrafine particle numbers was very similar for all 2010 and 2007 regenerations, and it appears to be closely related to the fuel being ejected into the DOC. It has been estimated that the ultrafine particles are mainly sulfate particles. From the present testing the high ultrafine particle phase of the testing seems to be the same for both 2010 and 2007 DPF technologies, and the total number of particles and the DPF exhaust temperatures are the same in the latter part of the testing.
- The mass of the very large number of ultrafine particles is not recorded by the DustTrak, and it is indicated by the EPPS and SMPS instrumentation that these particles contain substantial amount of mass during the latter phase of the DPF regeneration. An estimate of the under recording of the DustTrak during the latter phases of 2010 DPF regeneration is one order of magnitude.
- The number of particles created during DPF regeneration is very near or over the capacities of the EEPS instrumentation. Future tests should consider the use of a thermal particle diluter.
- Currently, particle instrumentation does not have the capability of recording the entire range of particle sizes created during DPF regeneration. The EEPS and SMPS can treat ultrafine particles well and the DustTrak can record the large particles.

Regulated emissions during DPF regeneration – Some regulated emissions were recorded during DPF regeneration of both the 2007 and 2010 DPFs. The conclusions that were obtained are the following:

- The primary regulated emissions obtained during the testing of the 2007 DPF were NO_x and THCs. As expected both NOx and THCs increased during DPF regeneration. During the initial phase of the 2007 DPF regeneration the NOx emissions were larger if the engine coolant temperature was low at the start of the DPF regeneration. The lower the engine coolant temperature the higher the NO_x emissions, and NO_x concentrations in the raw exhaust ranged between 900 and 1200 ppm. If the engine coolant temperature was warm the initial NOx levels were lower and rose to a maximum of approximately 400 ppm, and they remained at this value until the conclusion of the test. For all tests the NO_x emissions leveled off to 400 ppm during the phase where large numbers of ultrafine particles were emitted, and the emissions remained at these values until the end of the testing. THCs appeared to be a function of the state of loading of the DPF, and the largest values were recorded for Test1(a) and Test3 with the flashing console light. During the large mass emission phase THCs reach values between 400 and 600 ppm, and the THCs dropped slowly to values less than 20 ppm during the emission of large numbers of ultrafine particles phase. If the console light was on but not flashing, the THCs never exceeded values greater than 100 ppm, and achieved values below 20 ppm later in the testing.

- It was expected that the NO_x performance would be better due to the advanced after treatment on the 2010 DPFs, and the results were better. Both tests of the 2010 DPF started from a cold condition and the NO_x values rose to levels between 400 and 600 ppm during the initial phase of the regeneration. The NO_x levels remained high for approximately 300 seconds, and they reduced quickly to values of the order of 100 ppm for the remainder of the testing. It is assumed that the SCR after treatment is responsible for this decrease in NO_x, and that the DOC fuel injector raised the exhaust temperature to a level that NO_x was reduced by the SCR system. The THCs emissions emitted during regeneration were a function of the loading of the DPF, and the largest values occurred for the more loaded DPF. In general substantial THCs were only emitted during the initial phase of the regeneration process, and the total amount of THCs were much lower than the 2007 DPF. However, the maximum levels of THCs during all tests occurred for the 2010 DPF.

Estimating Mass Emission Rates from the Instrumentation Used in the Study

- Results were determined for estimates of the PM mass flow rates for Test3 with all of the experimental instrumentation used in the small wind tunnel. The predictions from every piece of instrumentation contain uncertainties since the particle shape, composition, density are not known accurately, and all of the instrumentation used does not record the entire spectrum of particle sizes.
- At early times the DustTrak recorded a maximum emission rate of approximately 700 g/hr due to the large particles generated from the Test3 DPF. Also both the DMM and EEPS give larger emission rates than the SMPS during the large mass emission phase, and this is to be expected, since the EEPS and DMM cover a larger range of particle sizes. During latter times the SMPS seems to give slightly larger values, since it is very accurate in the ultrafine region, although the EEPS and DMM are close to SMPS values. The DustTrak values are quite low during the ultrafine particle phase compared to other instrumentation, and this is to be expected since the DustTrak was below its detection limit.

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Appendix I: Calculations of Flow Losses in the 4'x4' Small Wind Tunnel at Depot Park

(Reference: Fluid Mechanics by Frank M. White, 5th edition)

The small wind tunnel at Depot Park is powered by a whole house fan that is rated to deliver approximately 7000 CFM under standard atmospheric conditions. The purpose of this short note is to calculate the flow losses thru the small wind tunnel, in order to determine if these losses are compatible with the electric motor attached to the whole house fan. A sketch of the small wind and its dimension are shown in Figure (1)

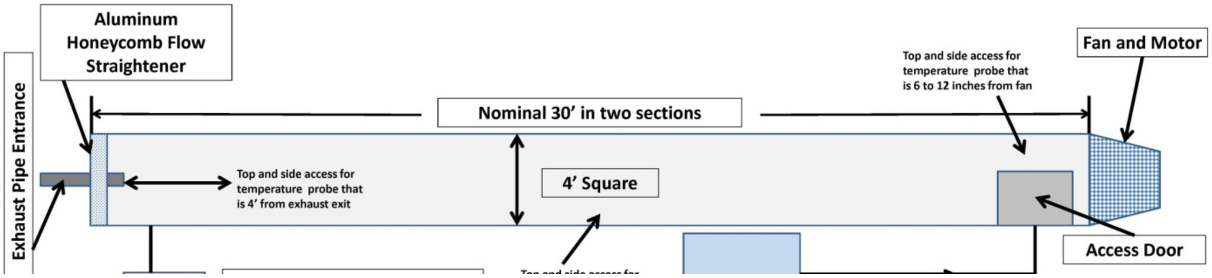

Figure (1) Sketch of small wind tunnel

We begin this exercise with some basic properties of the flow, and we will now show that a flow rate of 5 mph in the small wind tunnel yields a volume flow rate of approximately 7000 CFM.

$$Velocity = U = 5mph = 5\frac{5280}{3600} = 7.33\frac{ft}{s} = 7.33x.3048 = 2.23\frac{m}{s}$$

$$Volume\ Flow\ Rate = \dot{V} = UA = 7.33x16x60 = 7037\frac{ft^3}{\min} = 7037\ cfm$$

The mass flow rate thru the small wind tunnel at STP can be calculated as

$$for\ a\ density = 1.2\frac{kg}{m^3}\ \ and\ an\ area\ of\ = 1.49m^2$$

$$mass\ \ flow\ rate = \dot{m} = \rho UA = 1.2x2.23x1.49 = 3.98\frac{kg}{s} = 14354\frac{kg}{hr}$$

The pressure losses thru the small wind tunnel are due to the entrance honeycomb and the wall losses along the 30’ foot long tunnel with square walls of 4’ by 4’.

Pressure Drop Due to Honeycomb

The total pressure needed to pass thru the honeycomb can be expressed as

$$\left.\frac{\Delta p}{\rho}\right|_{Total} = \frac{U^2}{2} + \frac{fL}{D}\frac{U^2}{2} \; where \; f \; is \; the \; friction \; fractor$$

The friction factor *f* depends on the nature of flow in the honeycomb, and it can be shown that the flow is laminar and not fully developed. Since the average velocity of the flow in the honeycomb is approximately equal to the average velocity in the wind tunnel, the Reynolds is calculated as

$$Re(honeycomb) = \frac{UD}{\nu} = \frac{2.23x1.27x10^{-2}}{1.8x10^{-5}} = 1.57x10^3 where \; \nu \; is \; the \; kinematic \; viscosity$$

The laminar and fully developed value of the friction factor is

$$f = \frac{64}{Re} = 4.08x10^{-2}$$

But this value is low due to entrance effects in the honeycomb, therefore a value of *f*=.1 is a reasonable upper approximation.

The total pressure drop thru the honeycomb, which has a L/D of 12, can be calculated as

$$\left.\frac{\Delta p}{\rho}\right|_{Total} = \frac{U^2}{2} + \frac{fL}{D}\frac{U^2}{2} = \frac{U^2}{2}\left(1 + \frac{fL}{D}\right) = 5.5\frac{J}{kg}$$

Note on fully developed laminar flow: For laminar flow in a tube the accepted entrance pipe length correlation for the flow to be fully developed is the following:

$$\frac{L_e}{D} \approx 0.06Re = 94.2$$

Since the L/D for the honeycomb is 12, the flow is far from being fully developed.

Pressure Drop Due to Tunnel Walls

The Reynolds based on the tunnel diameter is given as follow

$$Re\left(tunnel\right) = \frac{UD}{\nu} = 1.51x10^5$$

Although this Reynolds number implies turbulent flow in the tunnel, it is not the appropriate Reynolds number to characterize this flow, since the flow is far from being fully developed. The appropriate Reynolds number is based on the distance along the wall of the tunnel, and this distance is 30'. Using this length scale we obtain

$$Re\left(wall\right) = \frac{UL}{\nu} = 1.24x10^6$$

With a Reynolds number of this value the wall flow is laminar over an entrance region of 12.1' or $Re\left(x\right) = \frac{UL}{\nu} \approx 5x10^5$, and then transitions to turbulent flow. Assuming a flat plate boundary layer and smooth walls for the small wind tunnel, the average Drag Coefficient, C_D, has been determined from experiments as

$$C_D = \frac{3.1x10^{-2}}{Re(L)^{1/7}} - \frac{1.44x10^3}{Re(L)} = \frac{D(\,force)}{\frac{\rho U^2 A(wall)}{2}}$$

Where *A*(*wall*) is the total surface area of the small wind tunnel walls. **Note:** Since there is a small favorable pressure gradient in small wind tunnel, the transition to turbulent flow could be somewhat delayed. However, since turbulent flow has a higher drag coefficient than laminar flow, we will use the above formula with a higher wall drag.

Note on fully developed pipe flow in the small wind tunnel: For flow in a pipe at a high Reynolds number of 1.24x10^6 another semi-empirical formula could be used, since the flow is partially turbulent, and this formula is the following:

$$\frac{L_e}{D} \approx 4.4 Re^{1/6} = 45.6$$

Since the L/D for the small wind tunnel is 7.5, the flow is far from being fully developed.

Note on a boundary layer simulation along the small wind tunnel walls: A numerical simulation of the boundary layer flow in the small wind tunnel wall has been performed, and this simulation has determined some characteristics of this smooth wall flow. An important characteristic is the boundary layer displacement thickness, δ_1, which is a good measure of blockage or decrease of the channel area due to the no slip velocity condition at the solid wall. At the end of the small wind tunnel the displacement thickness was determined as

$$\delta_1 = 0.021m, .069\ feet, or\ less\ than\ 2\%\ of\ the\ diameter\ of\ the\ small\ wind\ tunnel$$

Therefore it is expected that the flow across most of cross-sectional area of the wind tunnel will not be influence by the wall boundary layer.

The pressure drop due to the walls can be determined from the wall drag as follows

$$D(force) = \Delta p A_C\ where\ A_C\ is\ the\ cross\ sectional\ area\ of\ the\ wind\ tunnel$$

The pressure drop is thus determine as

$$\left.\frac{\Delta p}{\rho}\right|_{WT} = \frac{D}{\rho A_C} = \frac{43.7}{1.2x1.49} = 24.4\frac{J}{kg}$$

Determination of Power Required for Wind Tunnel

The total pressure drop in the wind tunnel is just the sum of pressure drops in the honeycomb and due to the wall friction, and is given as

$$\left.\frac{\Delta p}{\rho}\right|_{System} = \left.\frac{\Delta p}{\rho}\right|_{honeycomb} \left.\frac{\Delta p}{\rho}\right|_{Walls} = 5.5 + 24.3 = 29.8\frac{J}{kg}$$

The minimum power = $\dot{m}\frac{\Delta p}{\rho} = 117.1\,Watts$ where $\dot{m}$ is the mass flow rate, but the actual power is determined by the efficiencies of the axial fan and electric motor. The types of axial fans used in whole house fans are inefficient, and an estimate of the overall efficiency is 25%. Therefore, an estimate of actual power required is

$$Real\ Power = \frac{117.8}{.25} = 471\,W = .632\ hp$$

This value is consistent with the voltage and current specifications for the motor that is currently used with the whole house fan and connected to the small wind tunnel.

Appendix II. Additional Results

The purpose of this appendix is to include some additional results in the report. The results compare 2007 and 2010 regeneration in a relative manner.

Direct comparison of number and volume concentrations during the emission of small particles

During the later phase of the regeneration of 2007 and 2010 DPFs it appears that the regeneration process is very similar for both DPFs. Shown in Figures A-1 and A-2 are the particle number concentration for Test3 and Test4(a) from the SMPS, and both regenerations were completed in a single test. Figure A-1 is for the 2007 DPF and Figure A-2 is for the 2010 DPF, and the results strongly indicate that the regeneration process have much in common for both the 2007 and 2010 DPF technology. The SMPS results are for a 90 second average, and the specific times in Figures A-1 and A-2 refer to Figures III-26 and Figure III-34.

Shown in Figures A-3 and A-4 are the particle volume concentrations for Test3 and Test4(a) from the SMPS, and particle volume concentration accentuates any differences between the two graphs due to the dependence on particle diameter cubed. As seen from the figures the particle volume concentrations are very similar, and this indicates that the 2007 and 2010 technologies have much in common.

NO_x emissions during forced regenerations of the of 2007 and 2010 DPFs

Shown in Figures A-5 and A-6 are the variation of NO_x and lambda during forced regenerations of the 2007 (Test1(d)) and 2010 (Test4(b)). In general the characteristics are very similar to a normal regeneration with the console light on, which indicates that a DPF regeneration should be performed. For example, the NO_x results for the forced regeneration of 2007 DPF was performed when coolant water was warm. The NO_x levels at the start of idling and the start of regeneration are the lowest for all 2007 DPF tests, and the NO_x levels quickly reach the same levels of NO_x during regeneration as the normal DPF regenerations, Figure III-47. The 2010 DPF forced regeneration in Figure A-6 has the same general trends and levels as Test4(a) in Figure III-53.

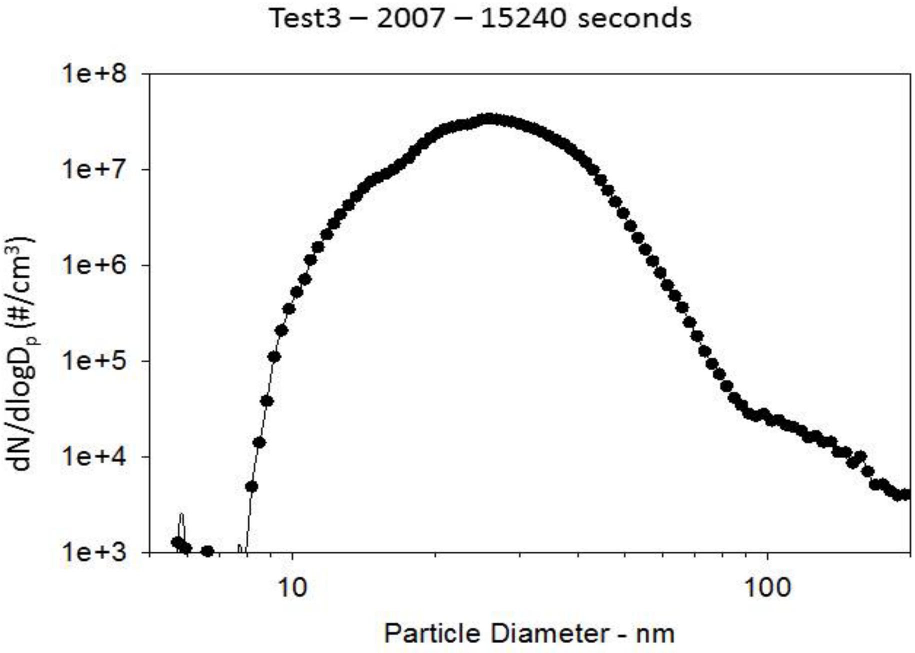

Figure A-1 Particle number concentration size distribution from the SMPS during the small particle size emissions, Test3 2007 DPF

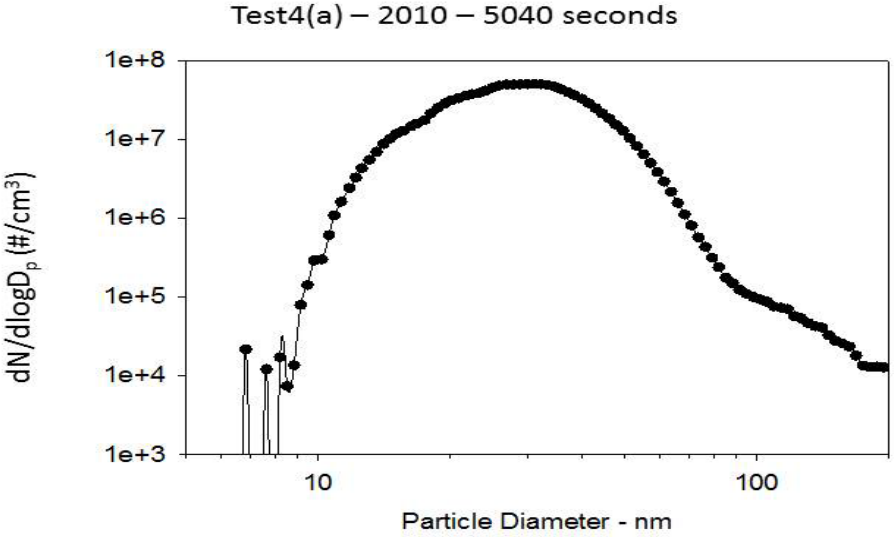

Figure A-2 Particle number concentration size distribution form the SMPS during the small particle size emissions, Test4(a) 2010 DPF

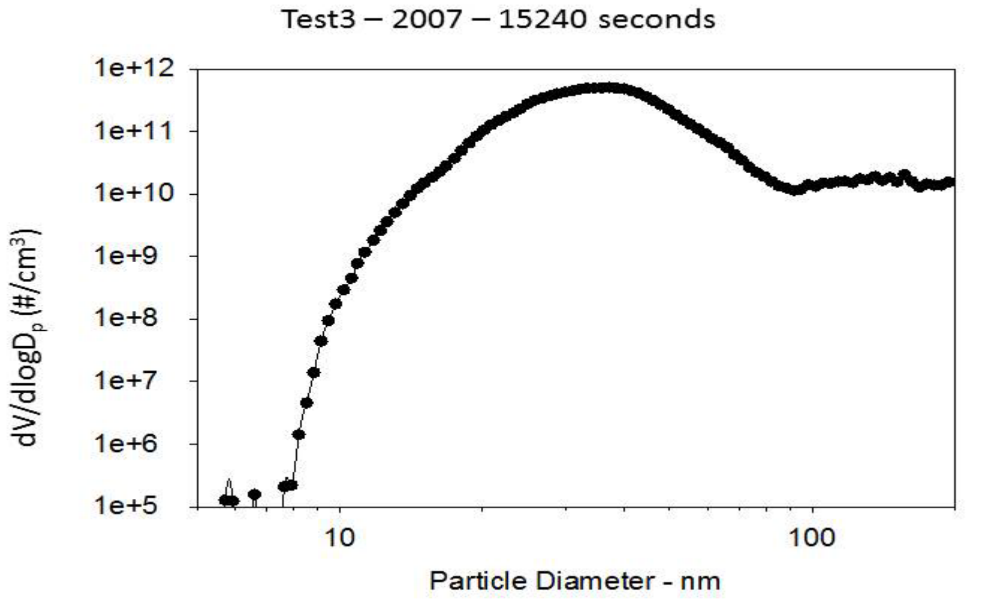
Test3 – 2007 – 15240 seconds

Figure A-3 Particle volume concentration size distribution from the SMPS during the small particle size emissions, Test3 2007 DPF

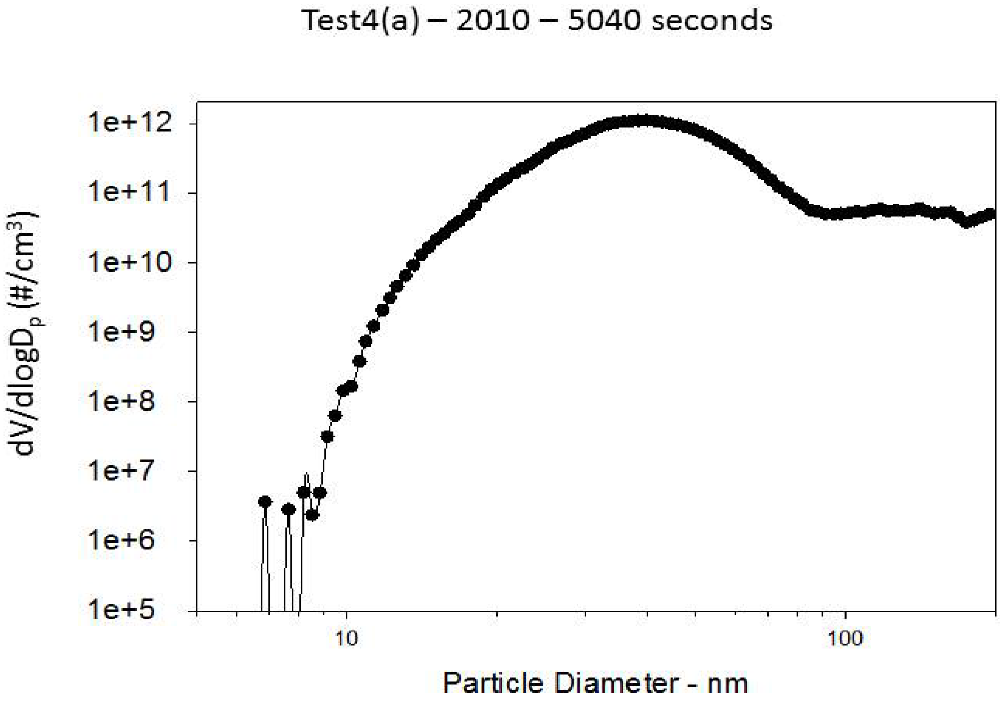
Test4(a) – 2010 – 5040 seconds

Figure A-4 Particle volume concentration size distribution form the SMPS during the small particle size emissions, Test4(a) 2010 DPF

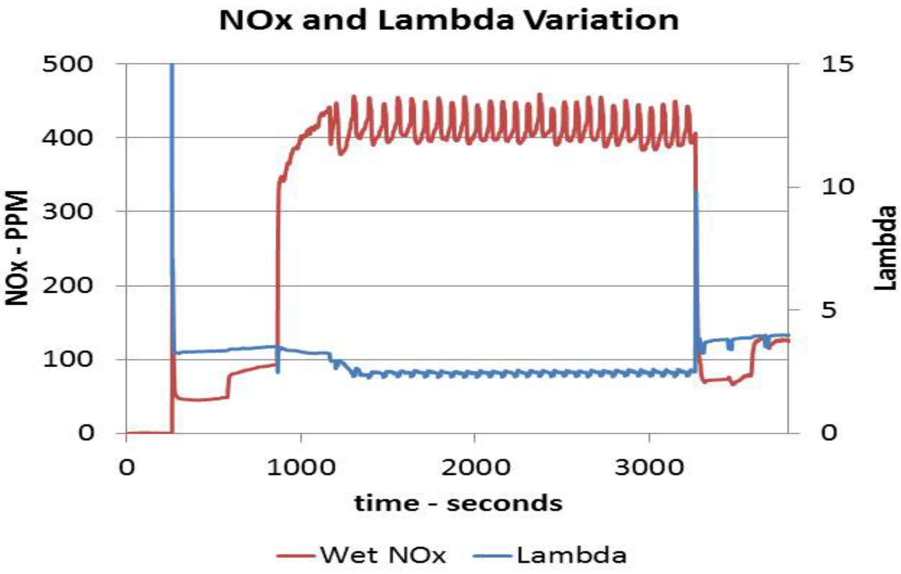

Figure A-5 Variation of wet NOx and lambda during regeneration of the 2007 DPF. Test1(d) Ambient temperature = 54 °F

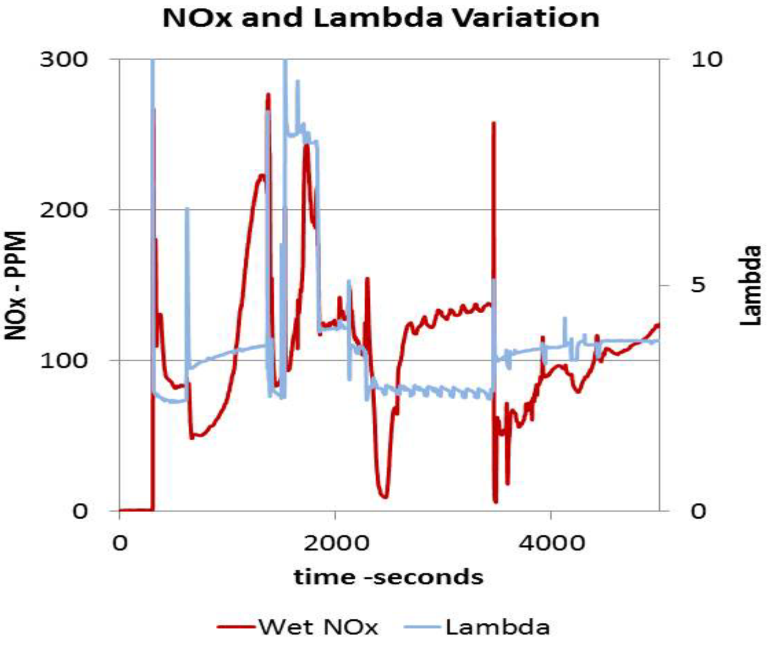

Figure A-6 Variation of NOx and lambda during regeneration of the 2010 DPF. Test4(b) Ambient temperature = 62 °F