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CONTRACTOR REPORT

ON TRUCK DEMONSTRATION OF THE XONOND™ NOx REDUCTION SYSTEM FINAL REPORT

CATALYTICA ENERGY SYSTEMS, INC.

NOVEMBER 2005

TEXAS COMMISION ON ENVIRONMENTAL QUALTY

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Executive Summary

Catalytica Energy Systems Incorporated (CESI) is developing a novel catalytic exhaust aftertreatment NOx reduction system for medium to heavy duty diesel engines. As part of this effort, the Texas Commission of Environmental Quality (TCEQ) sponsored a demonstration of this technology on two refuse trucks operating in the city of Denton Texas. This is the final summary report covering the one-year effort.

Purpose

The purpose of the XononD Demonstration program was three fold:

1. To validate the applicability of XononD on vehicles heavily represented in Texas non-attainment areas and confirm CESI's intended verification emissions control group (ECG) will maximize NOx reduction for TCEQ

2. Capture initial field durability data required for verification process and identify any problems which may delay verification

3. Identify Texas retrofit market specific characteristics to assist in completing the failure modes and effects analysis required in conjunction with verification.

Objectives

CESI defined a set of specific project objectives for this demonstration that include:

- Accumulate three months of on-road testing on Denton refuse trucks (goal of 400 hours per vehicle) with a 85% system reliability
- Achieve 50% or higher integrated average NOx reduction with a fuel penalty of less than 8%
- Evaluate the mechanical integrity of the container, mounts, instrumentation, fuel system, fuel injector and the control system harnesses
- Evaluate catalyst durability and estimate the performance of the system at the end of the target life (5,000 hours) using full scale, subscale and materials analyses

Project Technical Outcomes

CESI successfully completed the on-road demonstration at the end of August, 2005. Although not all of the initial objectives were met with technical success, the overall program delivered significant technical and performance achievements. The outcomes for each of the technical objectives are summarized in the paragraphs that follow.

On Road Testing Results

The program completed the three month on-road testing program in August 2005. Table 1 shows the hours accumulated for the trucks, the XononD system and the system reliability.

The goal of 400 hours of XononD operation per vehicle was not met primarily due to mechanical issues hampering the availability of the trucks. Early infant mortality issues associated with the fuel system prevented us from meeting the 85% reliability goal. It should be noted that once the infant mortality issues were solved, the system reliability for both units exceeded 90%.

Truck # / Xonon-D S/N	Truck Hours	Xonon-D Up Hours	Cumulative Xonon-D System Reliability
9858 / AD001	432	359	83%
9735 / AD002	358	290	82%

Table 1: Summary of XononD hours accumulation and system reliability

NOx Performance and Fuel Penalty

The NOx reduction performance was measured during actual refuse pickup with on-board NOx sensors. The NOx reduction was then integrated and averaged over the entire operating time for both vehicles to arrive at a single number. A fuel consumption estimation based on the control system fuel flow demand was used to calculate the integrated fuel penalty. A summary of the NOx reduction performance and the fuel penalty is shown in Table 2. The figure clearly shows that the overall NOx performance for the refuse pickup cycle falls short of our 50% goal. The fuel penalty met the <8% goal for the Denton demonstration program.

Truck # / XononD S/N	Neighborhood NOx Reduction	Neighborhood Fuel Penalty
9858 / AD001	31.4%	5.8%
9735 / AD002	39.9%	5.3%

Table 2: Denton Neighborhood NOx reduction and fuel penalty

Mechanical Integrity

The major mechanical issues observed during the field demonstration were associated with the fuel delivery system. Early failures of fuel pumps and motors caused XononD reliability issues but little, if any, vehicle dispatch issues. In addition, one of the fuel injectors had to be replaced midway through the demonstration due to poor flow control. The overall condition of the other mechanical hardware inspected after the demonstration was generally excellent. No long term mechanical issues were identified other than the fuel injectors.

Catalyst Durability and Life Estimate

The XononD is an assembly of individual components functioning as a integrated system and as such, it is often difficult to pinpoint the specific reasons for a performance shortfall. An overall system performance comparison using standardized test cycles is shown in Table 3 for pre and post Denton operation. The NOx reduction performance of the system

was found to be degraded by as much as 51% at the end of the testing program. Subsequent sub-scale testing and materials analysis point to catalyst degradation as just one of the possible contributors.

Truck # / Xonon-D S/N	Cycle	Pre Denton NOx Reduction	Post Denton NOx Reduction	NOx Reduction % Change
9858 / AD001	FTP	65%	44%	-32%
9735 / AD002		65%	66%	2%
9858 / AD001	CBD	87%	43%	-51%
9735 / AD002		99%	60%	-39%

Table 3: Pre and Post Denton NOx reduction for the FTP (Federal Test Protocol) and CBD (Central Business District) cycles

CESI developed a life model to estimate system performance at the target end of life (5,000 hours) using the FTP as the benchmark cycle. The model integrated data from the full and sub scale test rigs as well as the materials analyses findings into a predictive model. Because of the limited number of data points, the model had to be extrapolated out to 5,000 hours which results in a very large range of predicted NOx reduction. The model predicts that the end of life FTP NOx reduction is between 20% and 65%.

I. Introduction

1.1 Need for Diesel Engine Emissions Reductions

Recent EPA data show that nearly 160 million people live in nonattainment areas for ground-level ozone, also called smog, which is formed by NOx and other pollutants. About 65 million people live in areas that violate air quality standards for particulate matter (PM)[1]. The EPA estimates that the adverse health effects of these emissions will result in 12,000 premature deaths, 8,900 hospitalizations, and one million work days lost by 2030[2]. Other driving factors include the possible loss of federal highway administration funds, EPA sanctions, and restrictions on new business permitting for failure to meet air quality standards. With diesel sources accounting for up to 70 percent of the harmful air pollutants[3], the need to replace, retire or retrofit high emitters has driven some area air boards and districts (primarily CA, TX, Northeast US) to establish funding initiatives to combat this growing problem.

In April of 2004, the EPA announced the adoption of the new 8-hour ozone standard. The new 8-hour ozone standard is 0.08 parts per million (ppm), averaged over eight hours. The previous 1-hour standard was 0.12 ppm averaged over one hour periods. The new designation, while more stringent, allows for a later compliance date for the most severe areas when compared to the previous 1-hour standards. The designations and classifications took effect on June 15, 2004, and require state, tribal and local governments to prepare plans which describe their efforts to reduce ground-level ozone. By law, nonattainment areas may be subject to certain mandated requirements to reduce ozone-forming pollution[4].

Many areas were categorized as basic nonattainment areas requiring compliance with the more general nonattainment requirements of the Clean Air Act. EPA classifies ozone nonattainment areas based on the severity of their ozone problem. Classified areas fall into five categories: marginal, moderate, serious, severe, or extreme. EPA is expected to revoke the 1-hour standard one year after the effective date of designating attainment and nonattainment areas for the 8-hour standard. Figure 1.1.1 shows the new EPA 8-hour nonattainment areas.

The new 8-hour ozone regulations include 138 additional nonattainment counties that did not fall under the previous 1-hour standards. In all, nearly 160 million people live within the 474 nonattainment counties (see Table 1.1.1).

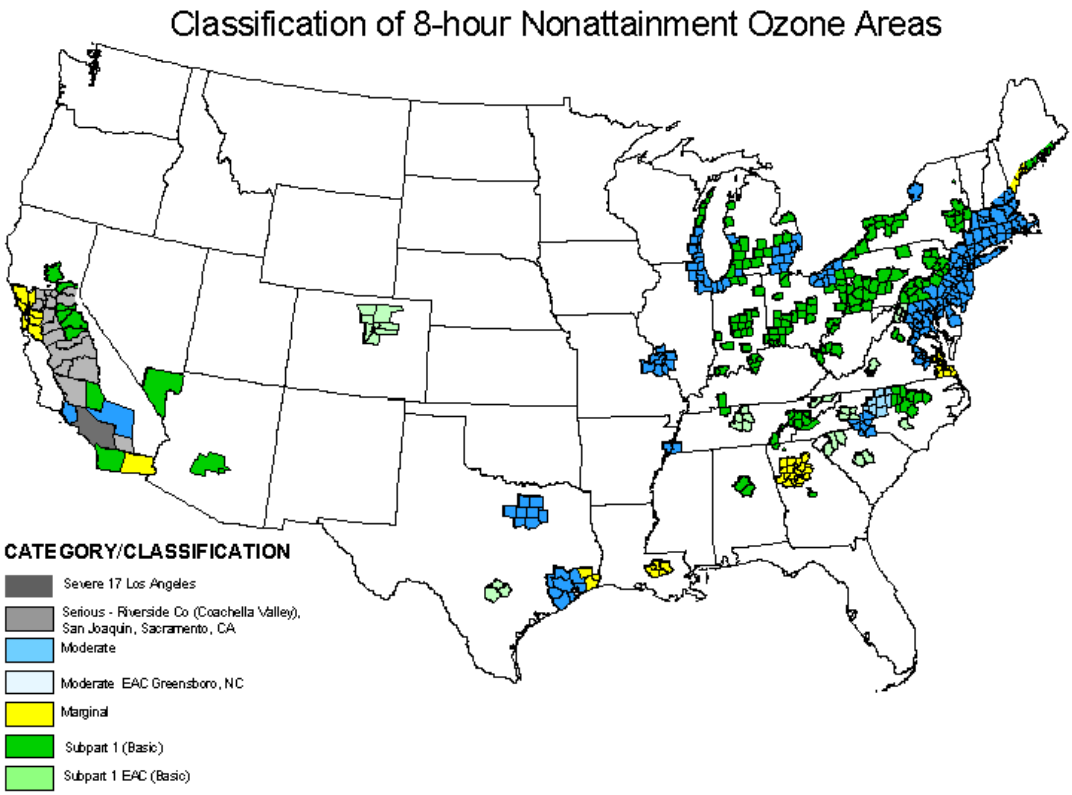

Figure 1.1.1: New EPA 8-hour ozone attainment and nonattainment areas[5]

Category / Classification	Number of Areas	Number of Counties	Population	Attainment Date
Severe 17	1	4	14,593,587	6/2021
Serious	3	15	5,494,465	6/2013
Moderate	30	185	81,010,125	6/2010
Marginal	7	55	13,932,637	6/2007
SUBTOTAL:	**41**	**255**	**115,030,814**	
Subpart 1	72	175	34,831,267	6/2009
SUBTOTAL:	**72**	**175**	**34,831,267**	
Moderate EAC	1	8	1,285,879	12/2007
Subpart 1 EAC	12	38	8,150,860	12/2007
SUBTOTAL:	**13**	**46**	**9,436,739**	
GRAND TOTAL:	**126**	**474**	**159,298,820**	

Table 1.1.1:EPA 8-hour oOzone Are Summary[6]

1.2 Catalytica Energy Systems

Catalytica Energy Systems Inc. (CESI) has been developing catalytic solutions for NOx abatement for the last 17 years. CESI has commercialized and is marketing Xonon Cool

Combustion®, a breakthrough pollution prevention technology that enables natural gas-fired turbines to achieve ultra-low emissions power production through a patented catalytic combustion process.

In an effort to address the growing area of diesel NOx control, CESI devoted significant research and development resources focused on commercializing our proprietary diesel fuel processing technology. This technology, when combined with a NOx adsorber, is designed to facilitate significant NOx reduction from mobile, stationary and off-road diesel engines to help diesel OEMs, government agencies and power producers meet the growing diesel emissions challenge. The first product to utilize the diesel fuel processing technologiy is the XononD diesel retrofit system.

II. Technology Approach

2.1 XononD System Definition

The XononD system is shown in Figure 2.1.1 below. The system consists of a fuel injector, mixer, fuel processor (XFP), thermal mass and Lean NOx Trap (LNT). During the trapping mode the engine exhaust passes through the LNT where the NOx is "trapped" on the catalytic surface. During the regeneration mode, the XFP converts the exhaust flow and diesel fuel into hydrogen (H_2) and carbon monoxide (CO) which act to release the NOx stored in the LNT. The NOx is transformed into Nitrogen, CO_2, and water during the regeneration process. Depending on several engine/vehicle operating parameters, an LNT regeneration is performed every two to eight minutes of operation. Over time, sulfur (which is contained in Diesel fuels) can begin to build up on the catalytic surfaces in the XFP and LNT resulting in poor NOx trapping performance. If left unchecked, the build up of sulfur could eventually lead to irreversible poisoning of the catalytic components. To address this problem, the system periodically enters a desulfation mode to liberate the sulfur from the catalytic sites. During desulfation, the XFP heats the LNT to the required desulfation temperature and makes CO and H_2 as reductants for efficient sulfur liberation. Depending on several engine/vehicle operating parameters, an LNT desulfation is performed every 30 to 300 hours of operation.

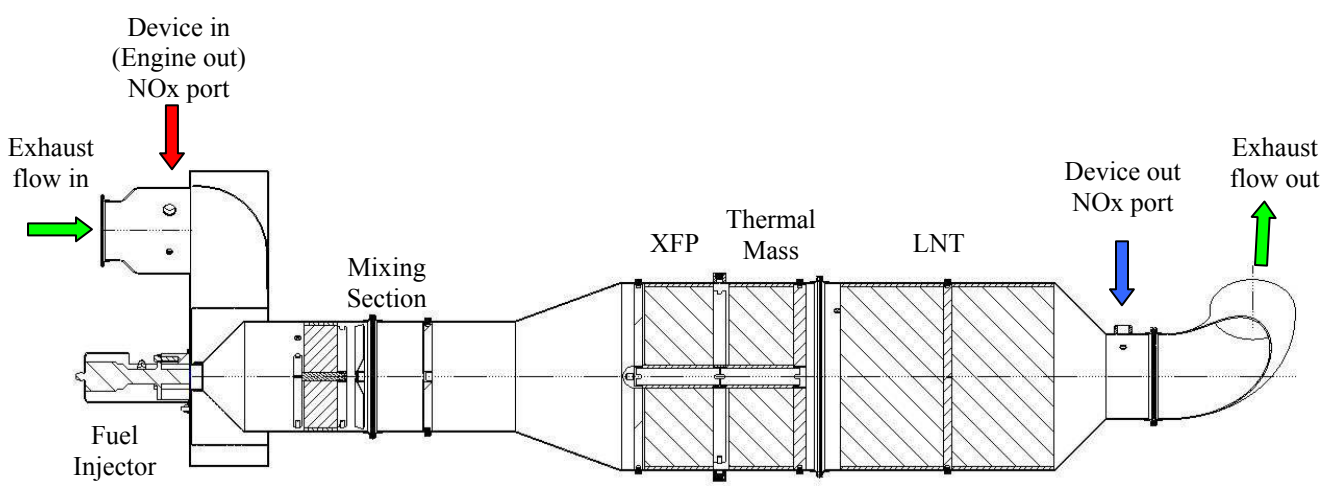

Figure 2.1.1: XononD system configuration

2.2 XononD System Targets

The commercial XononD system targets are:

- 50% NOx reduction for heavy duty EPA FTP cycle
- Passive solution needing only standard sensor inputs (air flow, O_2, Temperature)
- Sized for 5.9 – 8.0 L engines (medium-heavy duty engines)
- Scaleable design to accommodate larger engine displacements
- Minimum or no maintenance for the 5 yr/150k mile product warranty
- CARB/EPA verified to validate high performance, robust design
- Quick installation within existing exhaust system space
- Integration with third party DOC or PM filter for complete emission solution to allow for NOx/PM/HC/CO control
- System weight < 150 lbs
- Fuel penalty < 5%

2.3 Engine Platform Selection

The initial engine platform for XononD verification is the International (ITEC) DT466. This engine has been the most popular medium duty engine over the last 10-15 years and has a large installed base. ITEC enjoys a nearly 40% market share of the medium duty market and nearly 60% of the school bus market (40% of which are DT466 engines). Annual production volumes of the DT466 are 50,000 to 75,000 units (1991-2002)[7]. Figure 2.3.1 below show the market share of medium duty ITEC engines.

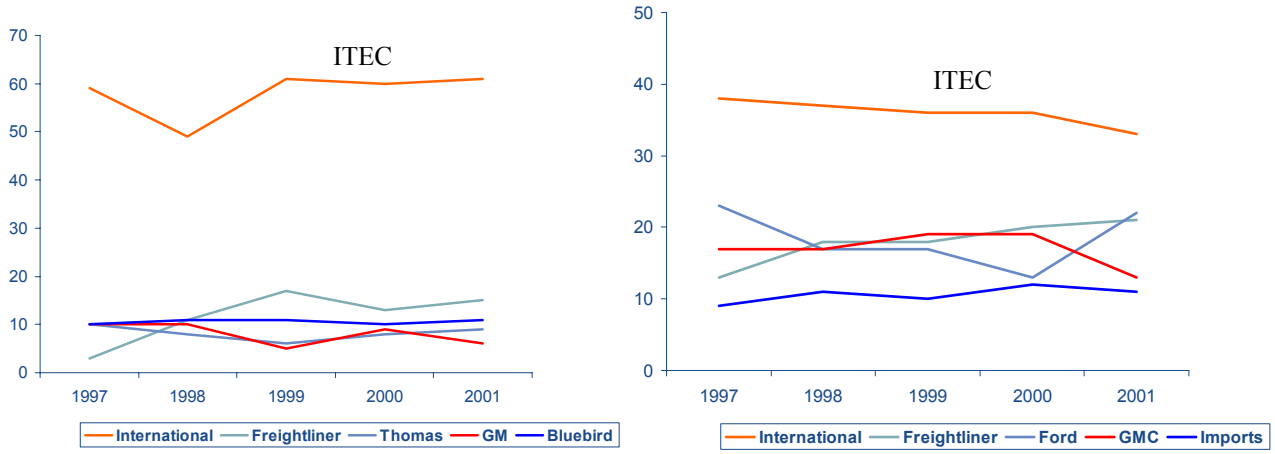

Figure 2.3.1: Share of the school bus market (left) and medium duty market (right) for International engines (ITEC)

III. CESI Testing Facilities and Test Cycles

3.1 CESI Testing Facilities

CESI has extensive testing and analytical facilities at both the Gilbert AZ and Mountain View CA locations. The Gilbert facility houses the Dyne Systems eddy current dynamometer that is capable of testing diesel engines up to 600 HP. Figure 3.1.1 shows a picture of the dynamometer with a 250 HP ITEC DT-466 engine installed. Most of the full scale development and validation work was performed on the Gilbert dynamometer. The dynamometer test facility has state-of-the-art emissions analyzers measuring NOx, Sulfur, CO, CO_2, O_2 and unburned hydrocarbons. The test cell also has the capability to monitor numerous temperature and pressure sensors installed on the test device.

Figure 3.1.1: CESI eddy current dynamometer test cell

The Mountain View facility houses a 8.3L diesel generator test rig, sub-scale reactor test rigs and analytical laboratories. The facilities are described in more detail in the following paragraphs:

- **8.3L diesel test rig** - The engine and XononD controllers were automated to allow for 24/7 unattended operation making it ideal for durability testing. Like the Gilbert dynamometer facility, the diesel generator test rig facility is equipped with a full array of emissions monitoring equipment. Figure 3.1.2 shows the Mountain View diesel engine test rig.

Figure 3.1.2: Mountain View diesel generator test rig

- **Sub-scale reactor test rigs** – CESI has designed and installed several sub-scale rigs for the testing and evaluation of diesel fuel reforming catalysts. These rigs can test up to two inch diameter test pieces with very accurate control of temperature, flow and oxygen levels. Sub-scale testing is faster and much less expensive than full scale testing and is ideally suited for catalyst screening, catalyst validation and durability testing. The test rigs are automated to allow for 24/7 unattended operation.
- **Analytical laboratories** – The CESI Research and Development Center is located in Mountain View, California. CESI's R&D facilities include state-of-the-art

Intrument Name	Intrument Type	Capabilities
Micromeritics Chemisorb 2800, ASAP 2010 Chemi, AutoChem 2910	Chemisorbtion	Determination of metal surface areas by chemisorption of a reactive gas. Useful for evaluating activity of catalyst and studying catalyst poisoning and sintering
Micromeritics ASAP 2010	Nitrogen Adsorbtion	Determination of surface area and pore size distribution (3 to 1000Å) by nitrogen adsorption. Used for choosing appropriate catalyst or studying catalyst deactivation due to loss of surface area or porosity.
Micromeritics Autopore-II Mercury Porosimeter	Mercury Intrusion	Determination of pore size distribution (100Å to 30μ) by mercury intrusion. Used for choosing appropriate catalyst or studying catalyst deactivation due to loss of porosity
Amray 1830 Scanning Electron Microscope (SEM) with iXRF Iridium Energy Dispersive X-ray Spectrometer (EDS)	Electron Microscope	Characterization of morphology and physical structure at magnifications >100,000X. EDS provides elemental analysis of materials at % and trace levels.Metallurgical cross sections, corrosion and failure studies, routine microscopy are all commonly performed.
Scintag XDS2000 X-ray Powder Diffractometer (XRD)	X-ray Diffraction	Structural characterization of crystalline solids. Identification of phases present by comparison to known materials. Studies of crystallinity and morphology. High temperature studies to 1500°C.

Table 3.1.1: Analytical Laboratories List of Equipment and Capabilities

experimental and analytical equipment needed for the development of catalytic products and processes. A partial listing of some of the key analytical equipment and capabilities are shown in Table 3.1.1.

3.2 Engine Test Cycles

Over the course of the program, several engine or vehicle test cycles were developed to approximate the on-road or verification duty cycles. Each cycle has a distinctive combination of rpm, torque, temperature and time that affects the response and performance of the XononD system. The sections that follow will provide a description of each cycle. Performance data for each cycle can be found in subsequent sections of this report.

3.2.1 EPA FTP test cycle (Pre and Post Denton Testing)

The FTP transient cycle consists of four phases: the first is a NYNF (New York Non Freeway) phase typical of light urban traffic with frequent stops and starts, the second is LANF (Los Angeles Non Freeway) phase typical of crowded urban traffic with few stops, the third is a LAFY (Los Angeles Freeway) phase simulating crowded expressway traffic in Los Angeles, and the fourth phase repeats the first NYNF phase. It comprises a cold start after parking overnight, followed by idling, acceleration and deceleration phases, and a wide variety of different speeds and loads sequenced to simulate the running of the vehicle that corresponds to the engine being tested[8]. The EPA FTP speed and torque profiles are shown in Figure 3.2.1.1. The FTP transient cycle is the predominant cycle used for verification testing of diesel retrofit emission systems.

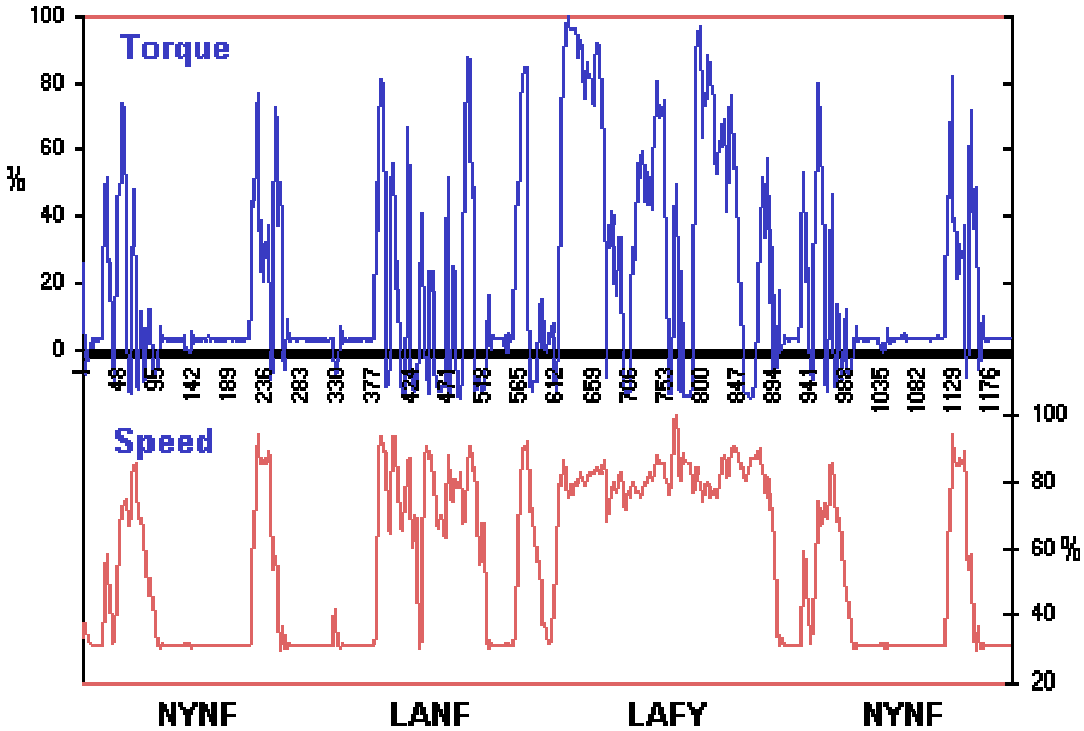

Figure 3.2.1.1: EPA FTP speed and torque profiles

3.2.2 Central Business District Test Cycle (Pre and Post Denton Testing)

CESI has developed a customized cycle based on the EPA (CBD) Central Business District cycle as a reasonable approximation of the vehicle duty of the Denton refuse trucks. The customized cycle was developed by combining (1) the measured engine speeds from a CESI owned DT466E equipped delivery truck while replicating the vehicle speed profile shown in Figure 3.2.2.1 and, (2) the measured Denton exhaust gas temperature data collected under Task 1 as defined in the grant activities. The throttle and torque settings were established on the dynamometer to maintain the appropriate upper and lower exhaust gas temperature limits coupled with the appropriate engine speed ranges and excursions. Since other pertinent data like engine exhaust flow rates, oxygen or torque levels were not available during the development of the cycle, some simplifying assumptions were made to establish the "CESI equivalent" CBD cycle.

The CBD cycle contains a repeating series of accelerations from zero to 20 mph over 10 seconds, a 20 second constant speed (20 mph) condition followed by a deceleration to zero speed in 5 seconds. This transient sequence repeats 14 times over approximately 10 minutes. A graphical depiction of the cycle is shown in Figure 3.2.2.1.

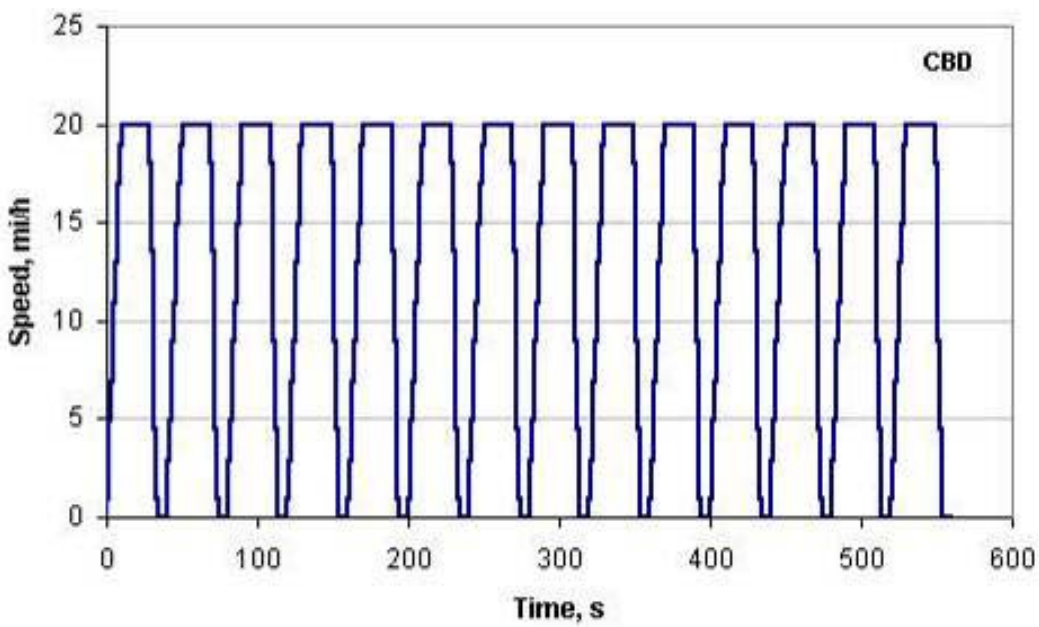

Figure 3.2.2.1: Central Business District test cycle profiles

3.2.3 AVL8 Test Cycle (Pre and Post Denton Testing)

The AVL 8-Mode test is a steady-state engine test procedure, designed to closely correlate with the exhaust emission results over the US FTP heavy-duty engine transient cycle. The test involves 8 steady state modes with distinct speed and torque settings for each mode and is engine specific. An overall composite emission value is calculated by applying weighing factors on the individual modal results. Table 3.2.3.1 shows the sequential engine operating parameters for the DT466 engine test bed.

Mode	% Rated Speed	DT466 Speed (rpm)	% Rated Load	Torque (ft*lbs)	Approximate EGT (°C)	Weighting Factor
1	0	700	0	0	100	35
2	11	898	25	92	176	6.34
3	21	1078	63	265	338	2.91
4	32	1276	84	423	482	3.34
5	100	2500	18	55	245	8.4
6	95	2410	40	208	342	10.45
7	95	2410	69	358	400	10.21
8	89	2302	95	503	457	7.34

Table 3.2.3.1: AVL 8 mode test cycle for the DT466 engine

3.2.4 Gilbert AZ test cycle (Pre Denton testing)

The inaugural on-road test with an on-board transient control system occurred on a drive cycle through the city of Gilbert, AZ. The cycle included six miles of surface streets with speeds varying from 0 to 45 mph and 18 miles of highway with near-constant speeds up to 60 mph (see Figure 3.2.4.1). The truck was loaded with approximately 4,500 lbs of water to increase the vehicle load on the engine. This cycle was designed to provide a sufficiently high EGT to operate the XFP and regenerate the NOx trap.

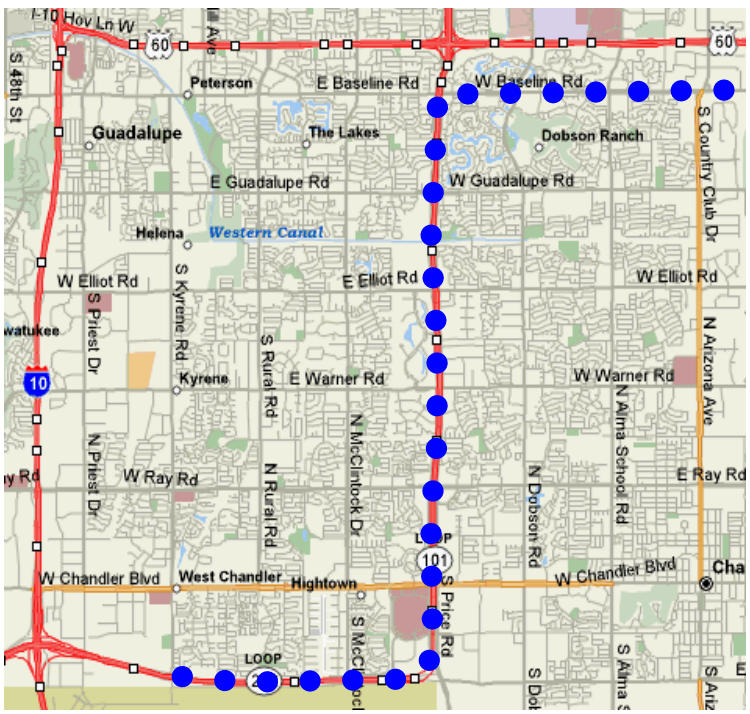

Figure 3.2.4.1: Route for Gilbert AZ test cycle

3.2.5 Loop 288 Denton Cycle (Denton testing)

The Loop 288 cycle was developed to provide a repeatable "quasi" steady-state point for the Denton refuse vehicles. The loop is relatively flat and lightly-traveled express way on the outskirts of Denton. Several passes were usually made to get at least ten LNT

regenerations from which the integrated NOx performance could be calculated. The Loop 288 cycle is shown in Figure 3.2.5.1 below.

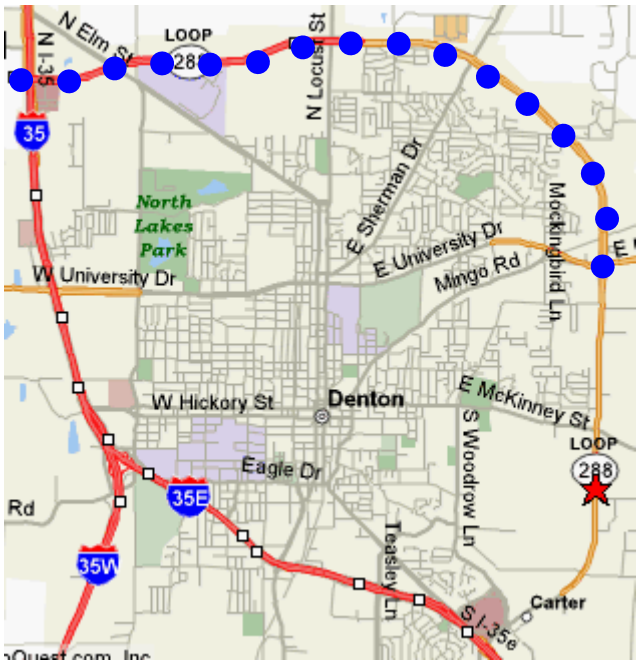

Figure 3.2.5.1: Route for Loop 288 test cycle

3.2.4 Denton Neighborhood Refuse Pickup Cycle (Denton Testing)

This cycle is defined by the operation of the refuse vehicles during actual residential refuse pickup through the city of Denton. The vehicles usually picked up refuse four days a week and ran for 8-10 hours each day. The route and drivers would vary from day to day but the cycle would usually consist of one to two hours of refuse pickup followed by a 30 minute drive to the city refuse dump. This cycle would repeat three to four times per day.

IV. Grant Activities Summary

4.1 Capture Vehicle Information (Task 1)

4.1.1 Vehicle Duty Cycle Temperature

A team from CESI traveled to Denton to measure the duty cycle temperatures for the two target vehicles during the last week of October 2004. Three type-K fast response thermocouples were installed on each vehicle as shown in Figure 4.1.1.1 below. The two exhaust thermocouples measure engine out (TC1) and approximate XononD inlet temperature (TC2). The ambient air temperature in close proximity of the XononD inlet was also measured. The temperature data was recorded on a pair of DaqPro 5300 eight channel data loggers recording at 1 Hz intervals.

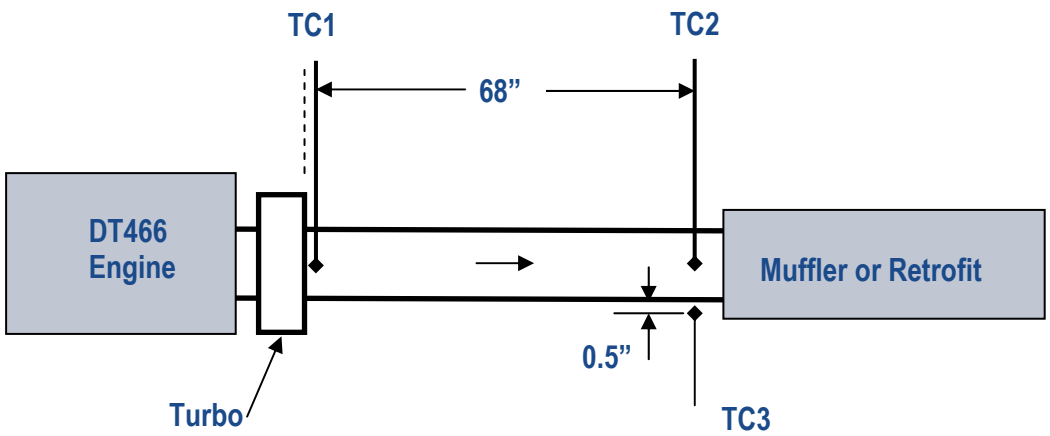

Figure 4.1.1.1: Location of the thermocouples on the test vehicles (thermocouple locations denoted by TC1 – TC3)

The temperature data is shown in Figures 4.1.1.2 through 4.1.1.5. Figures 4.1.1.2 and 4.1.1.3 show the results for the DT466 powered dump truck. Both figures clearly show that a large part of the overall duty cycle is spent at low exhaust temperatures (<150C). The XononD system performs best when the catalyst temperatures are consistently above 200° C. The combination of low exhaust temperatures and long idle periods exhibited in this duty cycle profile does not make it a good candidate for the XononD system.

Figures 4.1.1.4 and 4.1.1.5 show the temperature plots for the DT466 powered refuse truck. These figures clearly show a “warmer” temperature profile than the dump truck cycle. The combination of high exhaust temperatures and relatively short idle periods are better suited for the XononD system.

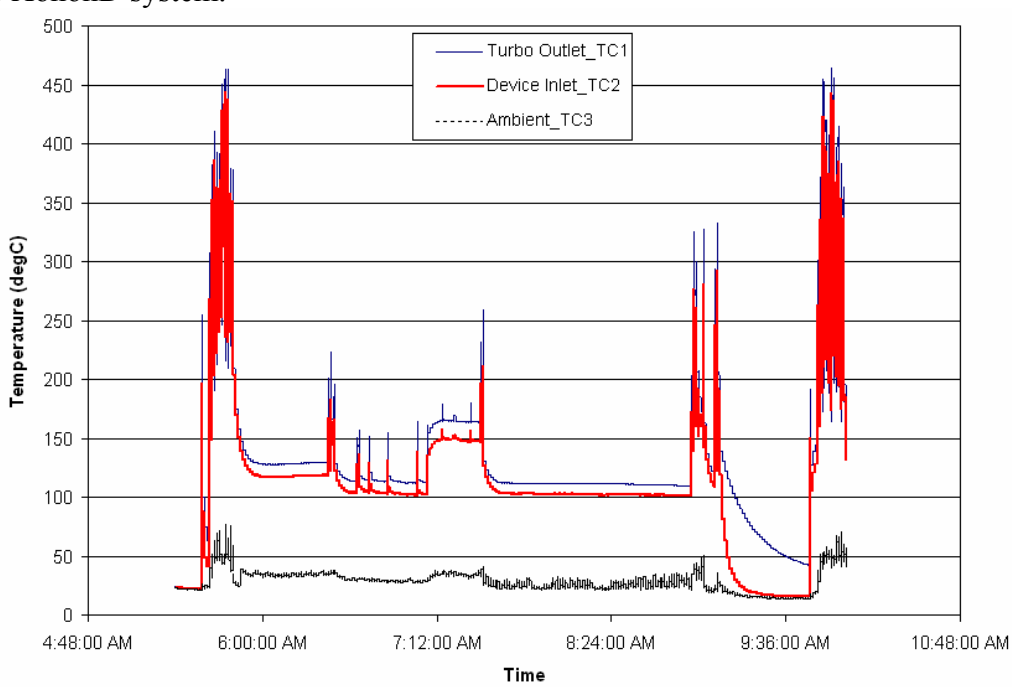

Figure 4.1.1.2: Temperature data for the dump truck. Note extended idling periods.

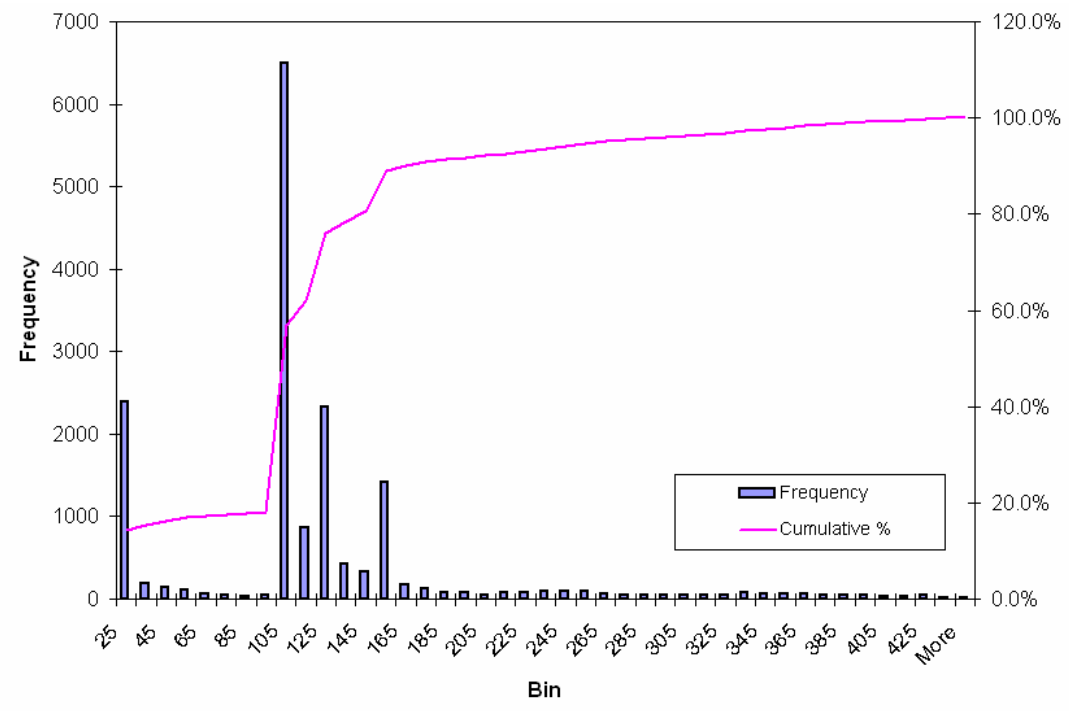

Figure 4.1.1.3: Histogram of temperature data for the dump truck

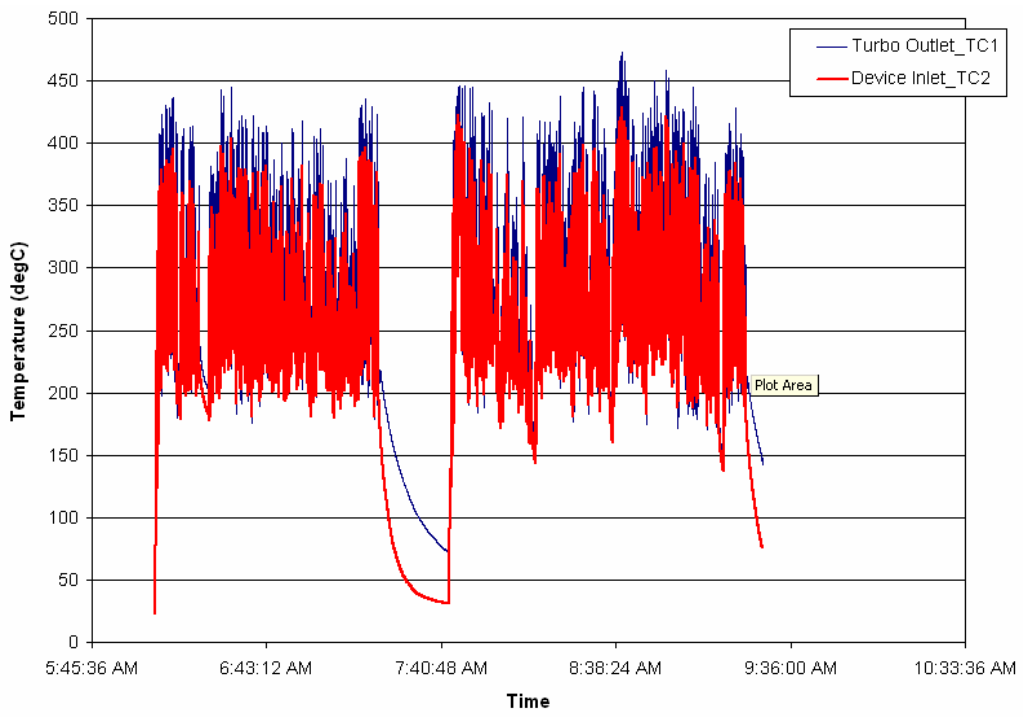

Figure 4.1.1.4: Temperature data for the refuse truck

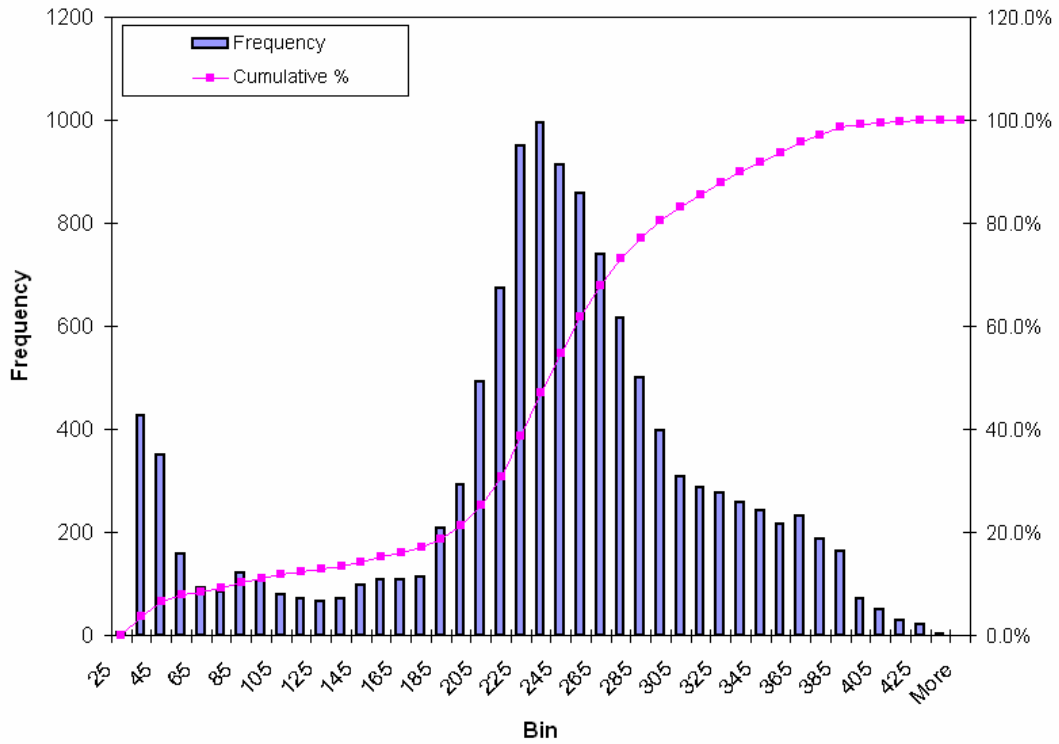

Figure 4.1.1.5: Histogram of temperature data for the refuse truck.

Due to the extended idle times for the dump truck CESI asked for and received permission from the city of Denton and the TCEQ to replace the dump truck with another refuse vehicle for the demonstration project. The Denton test vehicles are:

- 1996 International Refuse Truck, VIN: 1HTSHAAR5TH398948, Engine Model: DT466E, 250 HP (Truck 9858).
- 1997 International Refuse Truck, VIN: 1HTSHAARXWH497687, Engine Model: DT466E, 250 HP (Truck 9735).

4.1.2 Vehicle Dimensional Data

A team of CESI engineers traveled to Denton to complete a detailed dimensional assessment of the under carriage of the refuse vehicles. The data was used to create a three-dimensional CAD model of the vehicle frame and XononD system. The CAD model proved invaluable in highlighting potential vehicle integration issues and ultimately facilitating a smooth system installation. Figures 4.1.2.1 and 4.1.2.2 show the CAD model results

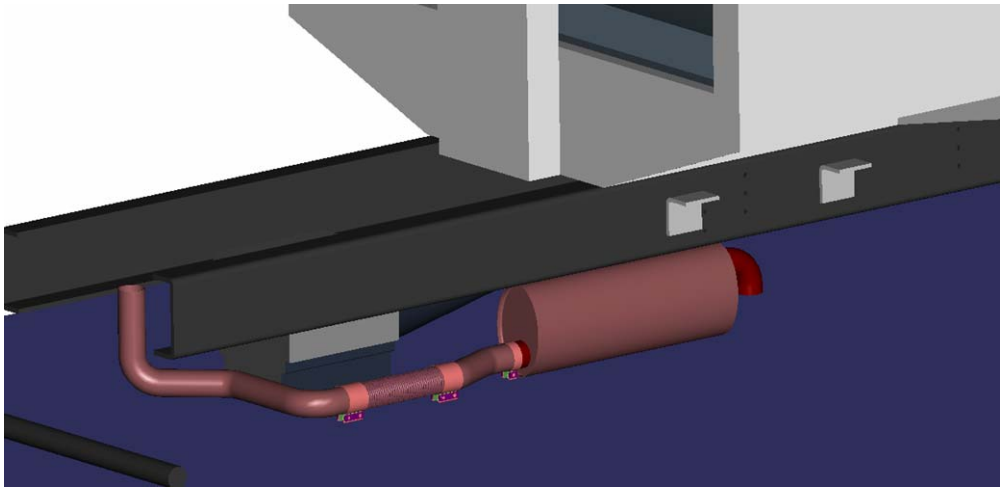

Figure 4.1.2.1: Three dimensional CAD model of the refuse vehicle exhaust system

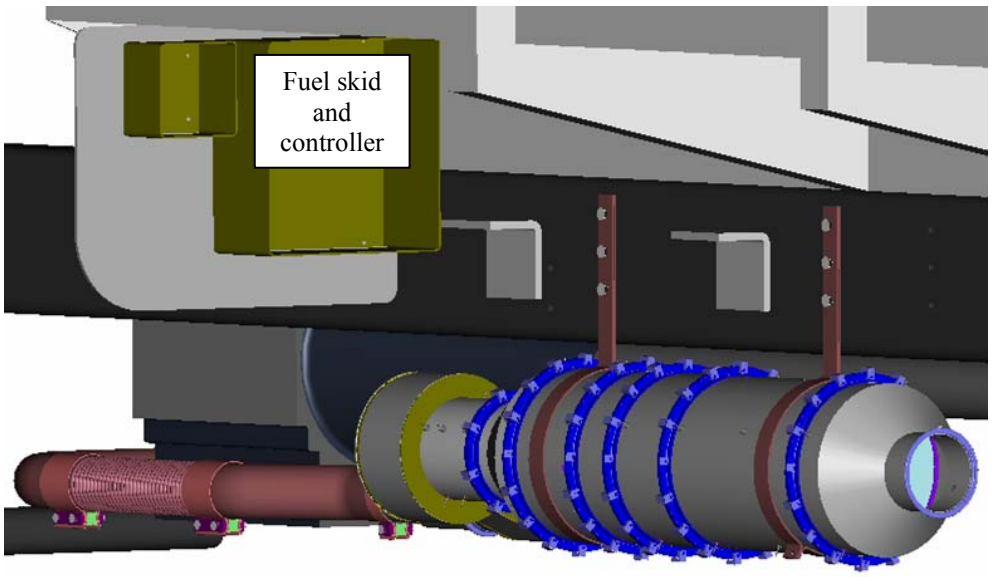

Figure 4.1.2.2: Aft looking forward view of the installed XononD system

4.2 Dynamometer Testing Using XononD Prototype (Task 2)

Figure 4.2.1 shows the XononD test rig installed in the dynamometer cell. A series of tests were performed on the XononD prototype test rig prior to the fabrication of the Denton on-road units. The purpose was to verify that the prototype units would perform acceptably under the conditions determined by the duty cycle temperature measurements described in Task 1. A series of FTP, AVL-8 and CBD cycles were run while changes were made to the control system and mixing sections to optimize system performance. By the conclusion of the testing, the prototype performance for the FTP and CBD cycles was consistently above 60% NOx reduction.

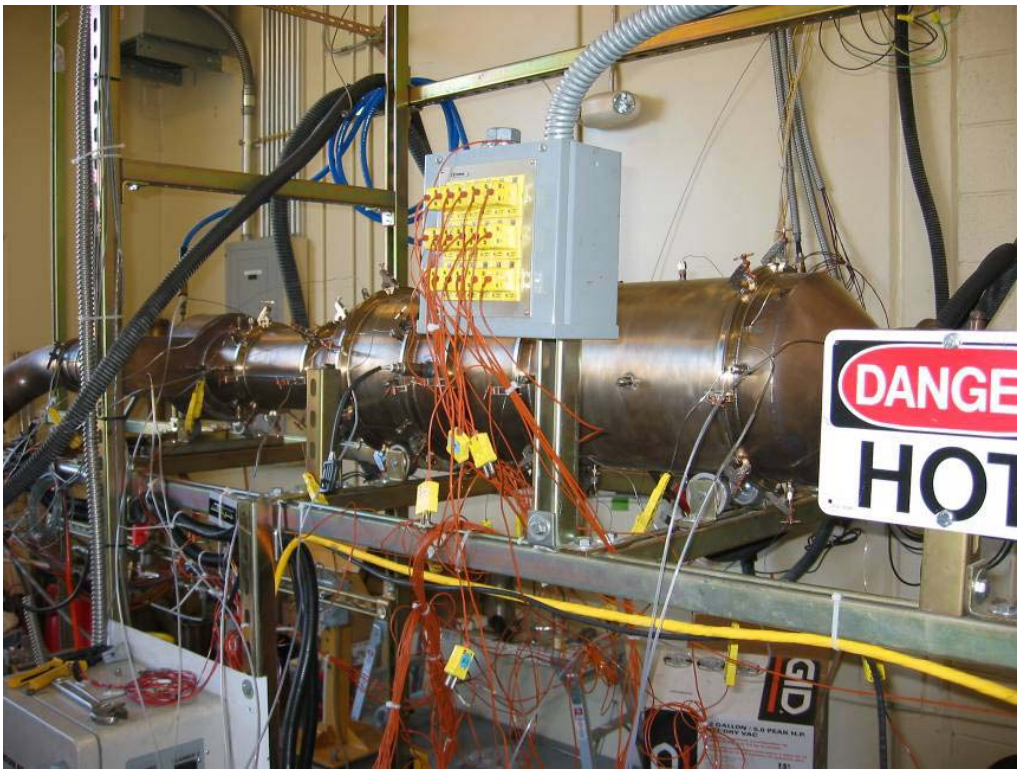

Figure 4.2.1: XononD prototype test rig installed in the dynamometer cell.

4.3 Fabricate and Procure XononD Field Prototype Hardware (Task 3)

After the successful completion of the dynamometer testing of the prototype described in section 4.2, CESI began procuring the hardware needed to field two complete on-road units for the Denton demonstration. Some photos of the hardware are shown below.

Figure 4.3.1: Denton aft container with catalyst (left) and assorted container hardware (right)

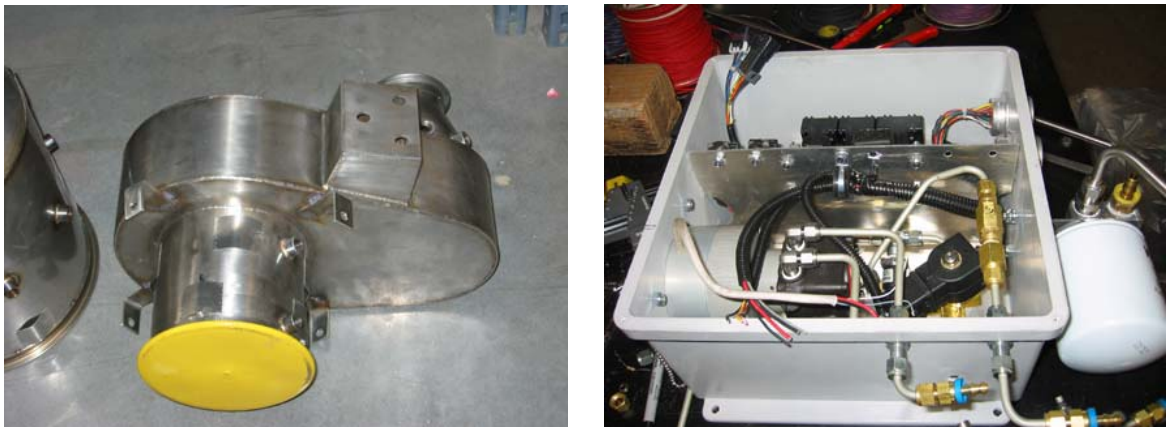

Figure 4.3.2: Denton head end container (left) and fuel skid assembly (right)

Figure 4.3.4: LNT inlet showing TFA retainer (left) and LNT exit in the container (right)

4.4 XononD Prototype "green-run" and Field Test Preparation (Task 4)

CESI developed a testing program for the Denton retrofit units using industry recognized AVL 8 mode cycle procedures and simulated FTP cycles for the "green run" testing at the CESI Gilbert dynamometer facility. These cycles are described in Section 3 of this report. The purpose of the "green run" testing was to identify any mechanical or durability issues which might hamper the on-road testing in Denton.

The FTP cycle contains segments which are intended to replicate both urban and highway driving cycles making it a good surrogate for the Denton refuse vehicle cycle. The testing serves several purposes including: (1) providing a baseline measure of system performance from which field degradation effects can be determined and, (2) highlights any early infant mortality issues related to the base field unit or any of its supporting sub-components including the fuel and electrical systems.

The pre-Denton performance and durability test of the first field units (denoted AD001 and AD002) consisted of a continuously repeating "loop" of AVL 8 mode points preceded each day by a full FTP cycle sequence. The FTP cycle speed and torque profiles are shown below for reference. Following an overnight soak, the morning FTP sequence consisted of a cold

start followed by three subsequent warm restarts with 20 minute engine off periods between each individual cycle.

4.4.1 Engine Information

The testing was performed on the following engine platform at the CESI Arizona facility:

Year: 1997
Make: International
Model: DT466E
Engine S/N: 670528-137 2019672
EPA engine family: VNV466D8DARW

4.4.2 Endurance Results

Each unit was installed in the Gilbert, AZ dyno test facility for "degreening" and limited endurance testing. The units consisted of the entire XononD system which included the on-truck fuel delivery, fuel nozzle, control, monitoring, and interface hardware. Unit AD001 accumulated approximately 149 hours of dynamometer operation and unit AD002 accumulated approximately 29 hours of dynamometer operation with incident. The time accumulation is shown in Table 4.4.2.1 below. Figure 4.4.2.1 shows unit AD001 after 149 hours of operation. After testing, the units were disconnected, partially disassembled and packed for shipment to Denton.

S/N	FTP/AVL8 cycle (hrs)	CBD cycle (hrs)	Other cycles (hrs)	Total (hrs)
AD001	100	5	44	149
AD002	24	5	0	29

Table 4.4.2.1 Summary of performance and durability testing

Figure 4.4.2.1: Unit AD001 after 149 hours of dynamometer operation

4.4.3 Green Run NOx Emission Results

An emissions test sequence was performed after each unit completed the endurance testing. During the performance testing control system parameter "tunables" were optimized since the catalysts were in relatively fresh condition. Table 4.4.3.1 below lists the ranges on the overall performance for both units for the durability tests. Fuel penalty data for the AD002 CBD cycle is not available due to a failure in the test cell fuel meter.

	FTP		CBD	
Denton Unit	NOx Conversion (%)	Cycle Fuel Penalty (%)	NOx Conversion (%)	Cycle Fuel Penalty (%)
AD001 (149 hrs)	48.9 - 78.3	4.3 - 7.5	47.6 - 85.2	5.0 - 10.0
AD002 (29 hrs)	72.5	6	80.6 - 88.1	No data

Table 4.4.3.1: Composite performance numbers for Denton units (AD001 and AD002)

The FTP performance results shown in Table 4.4.3.1 contain significant, but not unexpected variations in composite NOx conversion due to normal, day-to-day test parameter variations. Some of those variations include: "degreening effects" on the LNT bricks, sulfur loading effects, control system effects, other thermal effects within the system and initial NOx loading. The ranges listed however encompass the overall performance range for successive, repeating EPA cycle types. During verification testing, the integrated average NOx reduction over the course of several test cycles will determine the final verified NOx reduction level.

4.5 XononD Field Durability Testing/Monitoring (Task 5)

4.5.1 Field Demonstration Testing Summary

The Denton units were installed on the refuse vehicles in late May. On-road testing began in June and finished at the end of August. Figure 4.5.1.1 shows the vehicles with the XononD systems installed. Figures 4.5.1.2 and 4.5.1.3 show NOx reduction efficiencies for a variety of cycles measured during the demonstration program.

Figure 4.5.1.1: Denton refuse vehicles with installed XononD units

The initial emissions testing plan included periodic chassis dynamometer testing to be conducted every 21-30 days to establish the temporal changes in NOx reduction efficiency over the course of the demonstration. During the initial baseline chassis dynamometer testing, both refuse vehicles suffered mechanical problems which resulted in the trucks being taken out of service until they could be repaired. Consequently, the Denton fleet manager requested that no additional chassis dynamometer testing be conducted on either of these vehicles. In lieu of the chassis dyno testing, CESI developed the Loop 288 cycle (described in section 3.2.2) and the neighborhood simulation cycles. CESI also developed the capability to measure on-vehicle NOx performance during actual neighborhood trash pickup.

As the name implies, the neighborhood simulation cycle was designed to simulate the actual neighborhood pickup cycle. During the neighborhood simulation cycle, the empty trucks were driven around a predetermined circuit with frequent starts/stops and the periodic operation of the hydraulic ram. It was difficult to obtain repeatable XononD system operation during the neighborhood simulation cycle because the empty trucks could not load the engine enough which resulted in low exhaust gas temperatures. In some cases, the system would never "light off" and no NOx conversion was possible. When the system did operate during this cycle, the NOx reduction efficiencies were on par with the actual neighborhood conversions.

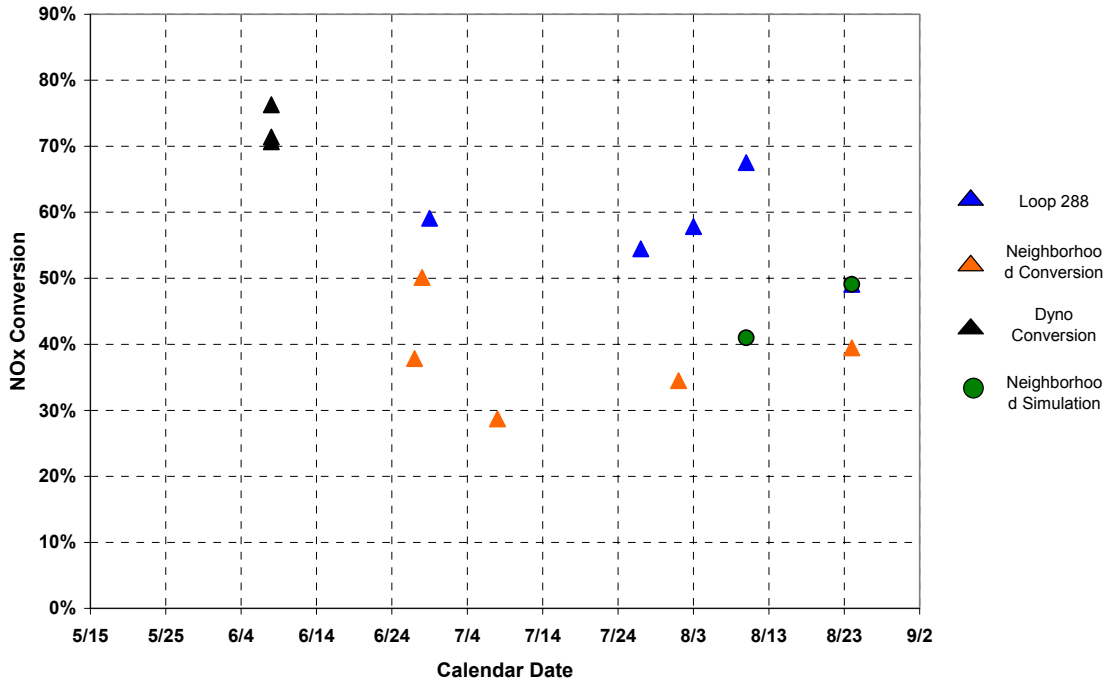

Figure 4.5.1.2: Cumulative NOx reduction data for truck 9735

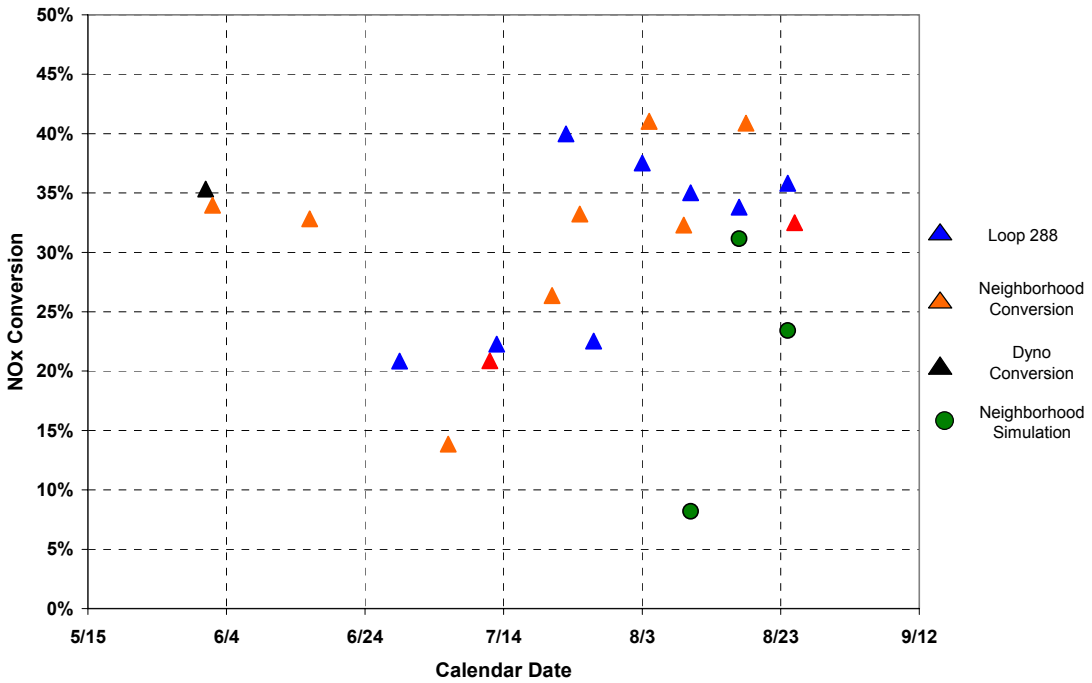

Figure 4.5.1.3: Cumulative NOx reduction data for truck 9858

Table 4.5.1.1 shows neighborhood performance during refuse pickup at Denton. The NOx reduction values are calculated as an integrated average over the entire duration of the demonstration (3 months). The system reliability values are calculated as a percentage of the total vehicle operating time. AD001 on truck 9858 completed 359 hours of operation with a reliability rating of 83%. The neighborhood NOx reduction was 31.4% with a fuel penalty (not including desulfation) of 5.8%. AD002 showed a similar reliability rating of 82% but with a markedly better NOx reduction of 39.9% and slightly lower fuel penalty of 5.3%.

Note that the 8.6% overall fuel penalty of AD001 included several desulfation cycles. Multiple desulfation cycles were performed as part of our control system development, evaluation and improvement. In theory, only one desulfation cycle was needed which would have resulted in an overall fuel penalty of 6.3%.

Truck # / XononD S/N	Truck Hours	XononD Hours	Cummulative System Reliability	Neighborhood NOx Reduction	Neighborhood Fuel Penalty (with desulfation)	Neighborhood Fuel Penalty (without desulfation)
9858 / AD001	432	359	83%	31.4%	8.6%	5.8%
9735 / AD002	358	290	82%	39.9%	5.3%	5.3%

Table 4.5.1.1: Summary of Neighborhood NOx Reduction

4.5.2 Denton Field Issues

The NTRD funded Denton on-road demonstration program provided invaluable "real world" field experience for the XononD product. As stated in our NTRD proposal, the purpose of the on-vehicle demonstration was to "capture initial durability data and assist in

identification of any potential device failure modes." During the course of the demonstration, the XononD system suffered several component failures that resulted in poor system performance and/or limited the system availability. Most of the initial problems were minor in nature and the CESI team instituted design changes that successfully addressed those problems. Table 4.5.2.1 below shows a summary of the failure modes, failure causes and corrective actions taken during the course of the on-road demonstration.

CESI is concerned with the fuel injector issues identified during the demonstration testing. The injectors on both vehicles needed to be replaced midway through the test due to poor flow control issues. Subscale accelerated durability testing of the injector showed that the injector performance severely degrades at end of life (5,000 hours). Redesigning the injector would take up to 12 months to complete and would delay XononD product verification.

Failure Mode	Failure Cause	Corrective Action
Pump Seizure	1. Mis-alignment of pump/ motor shaft 2. Rigid fuel lines cause bending of pump shaft	1. Redesign pump/motor interface 2. Replace rigid fuel lines with flexible rubber lines
Electrical Motor Seizure	1. Motor overheating due to lack of ventilation	1. Added heat sink to motor and cooling fan to enclosure. Replaced prior design electric motor with new design and modified pump/motor torque coupling
Poor NOx conversion	1. Injector calibration curve shift 2. Injector wear causing lower fuel flow	1. Recalibrate injector 2. Redesign injector (proposed not completed)
Damaged electrical wiring and blown fuses	1. Wire gauge too small for current draw on motor	1. Rewired power circuit with larger gauge wire
Battery combiner interference with normal system operation	1. Vehicle alternator charge fell below battery combiner required minimum	1. Removed battery combiner from the electrical system
Fuel injector-degraded flow control	1. Poor contamination robustness	1. Provided finer filtration capability

Table 4.5.2.1: Failure Modes, Failure Causes and Corrective Actions

4.6 Post-program XononD Evaluation and Reporting (Task 6)

4.6.1 Full Scale Dynamometer Results

Full scale testing was performed on the Gilbert, AZ dynamometer with the goal of comparing pre and post Denton system performance on the FTP, CBD and AVL 8 mode test cycles. Tables 4.6.1.1 and 4.6.1.2 show the performance results of both units before and after the Denton demonstration. Table 4.6.1.1 shows the data for the pre and post Denton FTP and CBD cycles. The values reported are an average over multiple FTP or CBD cycles. AD001 pre Denton FTP average of 65% was calculated from 12 FTP tests (3

cold starts plus 9 warm starts) with a spread ranging from 55 to 70% NOx reduction. AD001 post Denton FTP average was only 44% but was calculated from a single cold and 3 warm FTP tests. Additional post Denton FTP tests would have been desirable to determine the range of NOx conversion.

Table 4.6.1.1 shows drops in CBD cycle conversion for both units after service in Denton as compared to pre Denton results. So even though AD002 did not demonstrate a performance difference pre and post Denton for the FTP cycle, the performance difference resulting from the CBD cycle test would seem to indicate a change in the AD002 activity.

Table 4.6.1.2 shows the results for the AVL8 mode cycle. NOx reduction values are not available for AVL points 1, 3 & 5 due to low exhaust temperatures. The NOx conversion over the range of AVL8 points dropped 20-55% depending on the cycle point when compared to pre Denton data. The lower NOx conversion measured on the AVL8 tests are consistent with the lower NOx conversion performance measured on the CBD cycle. AD002 during the pre Denton and post Denton testing had higher fuel penalty than AD001. This higher fuel penalty was also observed in the field at Denton. In general, the pre and post Denton NOx reduction for AD001 was poorer than for AD002.

Truck # / XononD S/N	Cycle	Pre Denton NOx Reduction	Pre Denton Fuel Penalty	Post Denton NOx Reduction	Post Denton Fuel Penalty	NOx Reduction % Change
9858 / AD001	FTP	65%	7%	44%	6%	-32%
9735 / AD002		65%	6%	66%	8%	2%
9858 / AD001	CBD	87%	9%	43%	6%	-51%
9735 / AD002		99%	NA	60%	9%	-39%

Table 4.6.1.1: Pre and Post Denton System Performance for the FTP and CBD Duty Cycles

Truck # / XononD S/N	AVL Point	Pre Denton NOx Reduction	Pre Denton Fuel Penalty	Post Denton NOx Reduction	Post Denton Fuel Penalty	NOx Reduction % Change
9858 / AD001	1	--	--	--	--	--
	2	--	--	--	--	--
	3	83%	8%	43%	6%	-48%
	4	51%	3%	41%	2%	-20%
	5	--	--	--	--	--
	6	65%	7%	34%	7%	-48%
	7	53%	5%	40%	4%	-25%
	8	77%	3%	43%	2%	-44%
9735 / AD002	1	--	--	--	--	--
	2	--	--	--	--	--
	3	98%	9%	51%	7%	-48%
	4	83%	3%	51%	6%	-39%
	5	--	--	--	--	--
	6	97%	9%	61%	7%	-37%
	7	86%	5%	39%	4%	-55%
	8	92%	3%	53%	3%	-42%

Table 4.6.1.2: Pre and Post Denton AVL 8-Mode Test Results

4.6.2 Subscale Test Results

After the full scale testing, the units were disassembled and small samples of the catalytic materials from the XFP and LNT were removed for subscale testing at the CESI Mountain View, CA facility. The results from each component will be discussed individually in the sections that follow.

4.6.2.2 XFP Subscale Results

Two samples were taken from each respective XFP. One sample was taken near the outer diameter (5" D) and the other was taken near the catalyst center (1.3" D). Reforming tests were performed on the post Denton samples to quantify performance changes from fresh samples. These performance tests measure the XFP's reforming performance over a range of operating conditions (inlet temperature, face-velocity and phi). Reforming test results are plotted on Figure 4.6.2.2.1 as normalized reforming performance versus operating condition. Overall, as expected, post Denton performance of the XFPs were poorer than fresh for both AD001 and AD002. The reforming performance at most test points were generally lower than fresh. One of the more stressful operating conditions (condition #1) resulted in significantly reduced reforming performance. However, a majority of the test points showed that the post Denton reforming performance of AD001 was very similar to the post Denton reforming performance of AD002. This result would rule out the XFP as the root cause of the integrated system performance differences observed between AD001 and AD002.

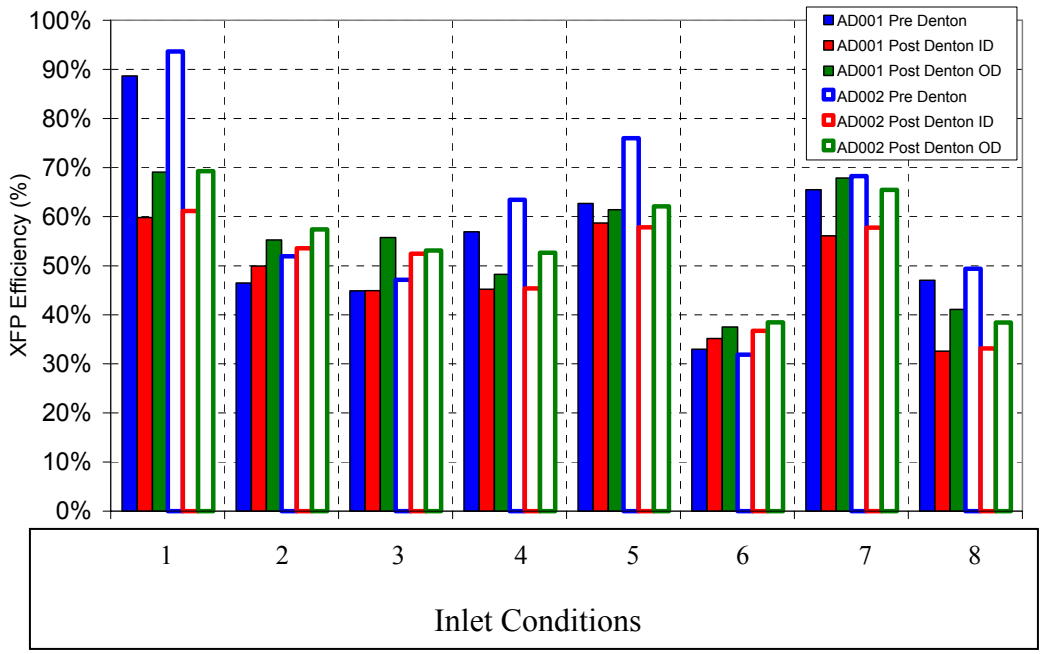

Figure 4.6.2.2.1: Comparison of Pre and Post XFP Test Results

4.6.2.3 LNT Subscale Results

1” OD x 3” long sample cores were taken from the inlet (0-3”), middle (3”-6” and 6”-9”) and the exit (9”-12”) of the LNT bricks of AD001 and AD002. Subscale tests were conducted to evaluate NOx reduction performance over the 225-575°C gas temperature range. Since sulfur adsorbed on the LNTs during the Denton test reduced the trap’s NOx reduction performance, the samples were also desulfated to determine sulfur loading and then retested for NOx reduction performance.

The subscale results show that, although cores from AD001 and AD002 are not identical, they are sufficiently similar in performance that they do not explain the difference in the integrated system NOx conversion differences observed in AD001 and AD002 during full scale post-Denton dynamometer testing. The results also show that NOx conversion after subscale desulfation is recovered to about the same amount in both AD001 and AD002, suggesting that the differences in the LNTs post-Denton were related to sulfur accumulation. The NOx conversion performance curves for AD002 are slightly shifted to higher temperatures, suggesting AD002 may have been thermally aged more than AD001, but the shift is only 10°C and within the subscale measurement error. In all cases, the samples after desulfation perform slightly worse at lower temperatures but much better at higher temperatures.

Core samples underwent multiple regeneration cycles at each temperature and were exposed to regeneration cleaning pulses of H_2+CO to release the NOx from the trap before each temperature test point. The targeted temperatures were 575°C, 515°C, 455°C, 395°C, 335°C, 275°C, and 225°C. At each temperature, H_2+CO was pulsed for 3.5 s every 87.5 s to regenerate the LNT. NOx conversion plotted in Figures 4.6.2.3.1 through 4.6.2.3.4 is taken after NOx conversion stabilized at each temperature (10-30 min). The plots shown in Figures indicate that the 6-9” and 9-12” sections of both LNT sets had better performance than the 0-3” and 3-6” sections.

The most obvious difference between the AD001 and AD002 LNT cores is the performance of the 3-6” section (the back halves of the upstream LNTs). Desulfation on AD001 was attempted in Denton, while AD002 never experienced desulfation conditions. The results suggest that sulfur was removed from the upstream section of the AD001 LNTs, cleaning the 3-6” section and improving NOx conversion.

Subscale desulfation was performed after the initial NOx performance tests on each of the LNT cores. The results clearly show a much higher loading of sulfur on the upstream side of the LNTs than on the downstream side, as expected. The 0-3” section of the AD001 LNT released about 10 g S/L-LNT.

After desulfation, NOx conversion vs. temperature was measured again at the same seven temperatures as before. Results show that the LNTs recovered a significant amount of performance as shown in Figures 4.6.2.3.1 through 4.6.2.3.4. The slight shift in the curves of the AD002 cores to higher temperature vs. the AD001 curves suggest overall they are less impacted by Sulfur poisoning (increased high temp performance) and more impacted by thermal aging (decreased low temp performance) than the AD001 cores.

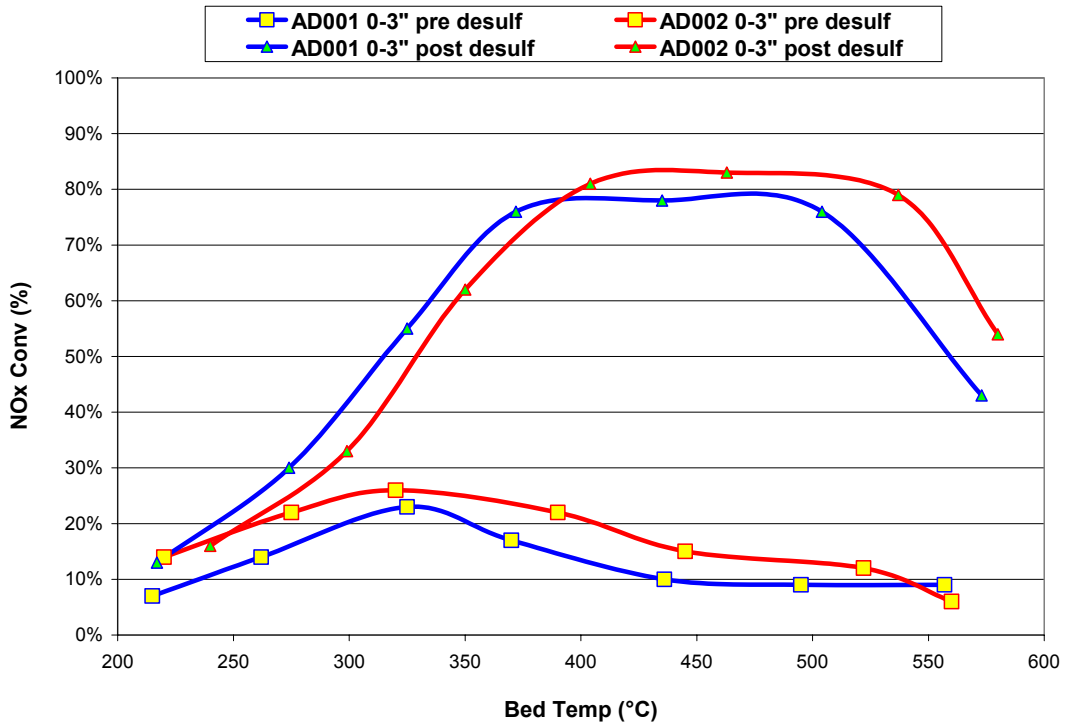

Figure 4.6.2.3.1: Subscale LNT NOx conversion on AD001 and AD002, 0-3" sections, before and after desulfation

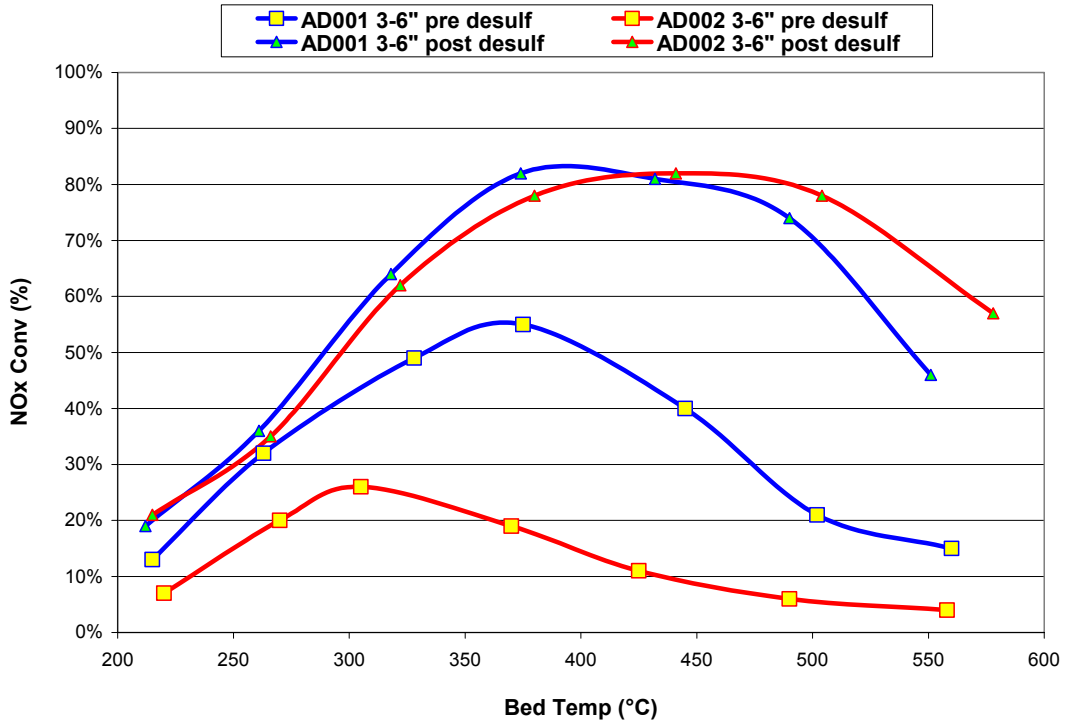

Figure 4.6.2.3.2: Subscale LNT NOx conversion on AD001 and AD002, 3-6" sections, before and after desulfation

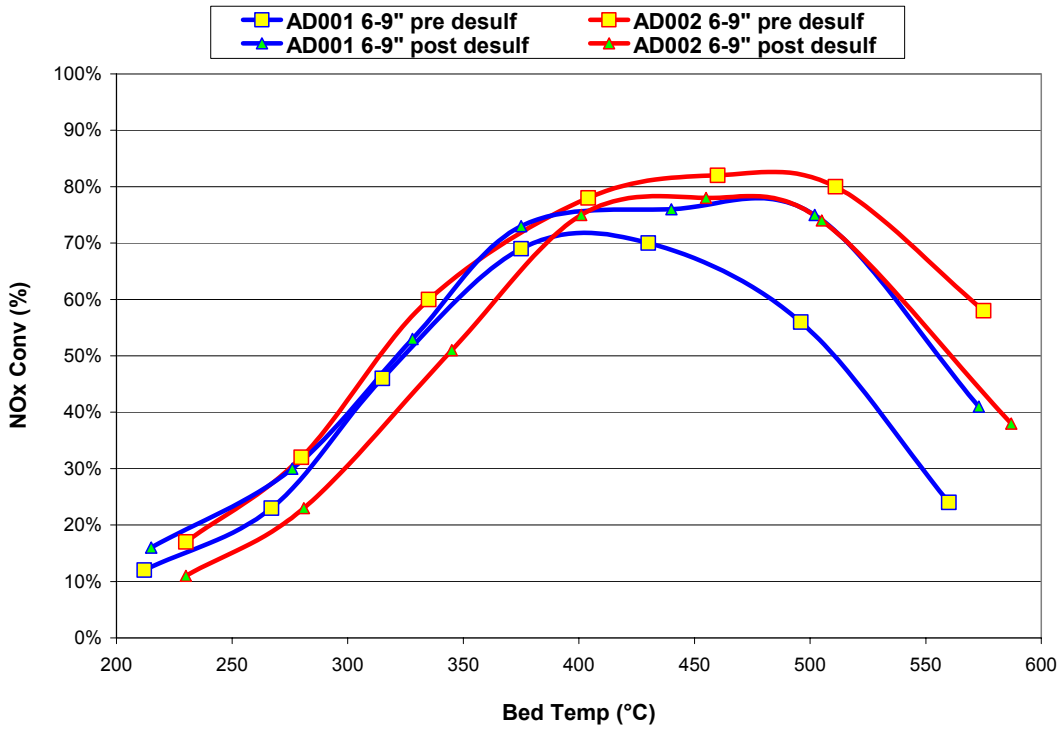

Figure 4.6.2.3.3: Subscale LNT NOx conversion on AD001 and AD002, 6-9" sections, before and after desulfation

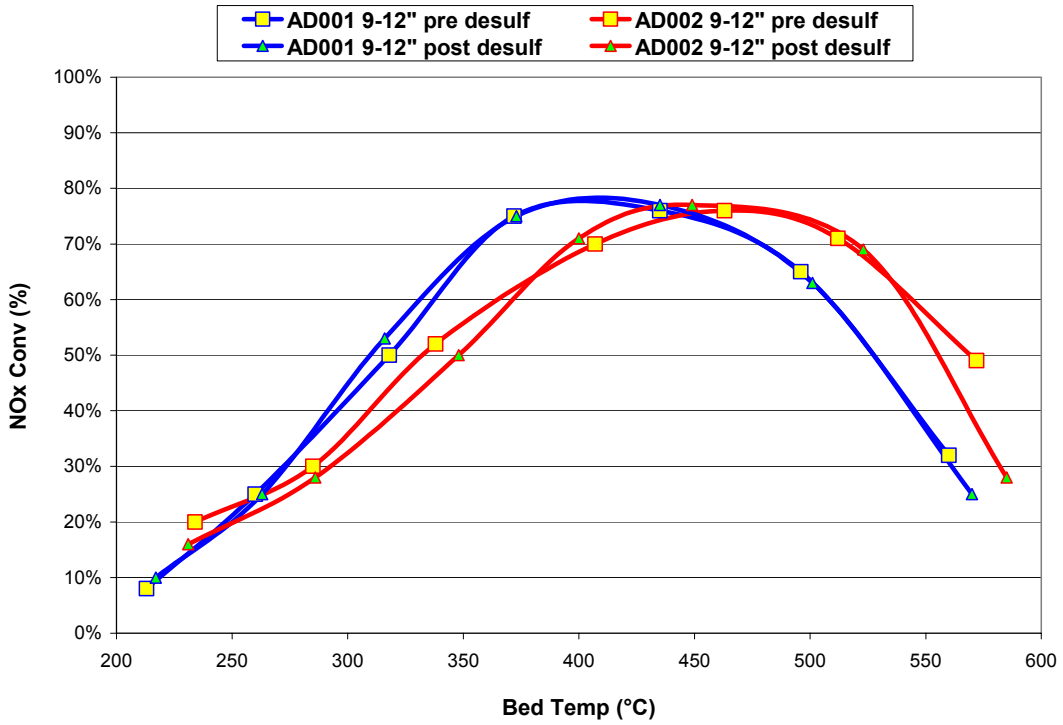

Figure 4.6.2.3.4: Subscale LNT NOx conversion on AD001 and AD002, 9-12" sections, before and after desulfation

4.6.2.4 Life Prediction Model

Figure 4.6.2.4.1 shows the trended FTP performance change for both units before and after Denton. On the graph also are trend-lines extrapolated to 5000 hours. 5000 hours is the projected end of life estimate for the unit based on a 150,000 mile requirement traveling at an average speed of 30 miles per hour. Using an exponential trend curve consistent with catalyst deactivation that was observed during full endurance testing, AD001 has a projected end of life estimated performance of ~20% NOx conversion. AD002 has a projected performance of 65%. The large difference in predicted performance can be attributed to the limited number of data points and the lack of any long term durability data.

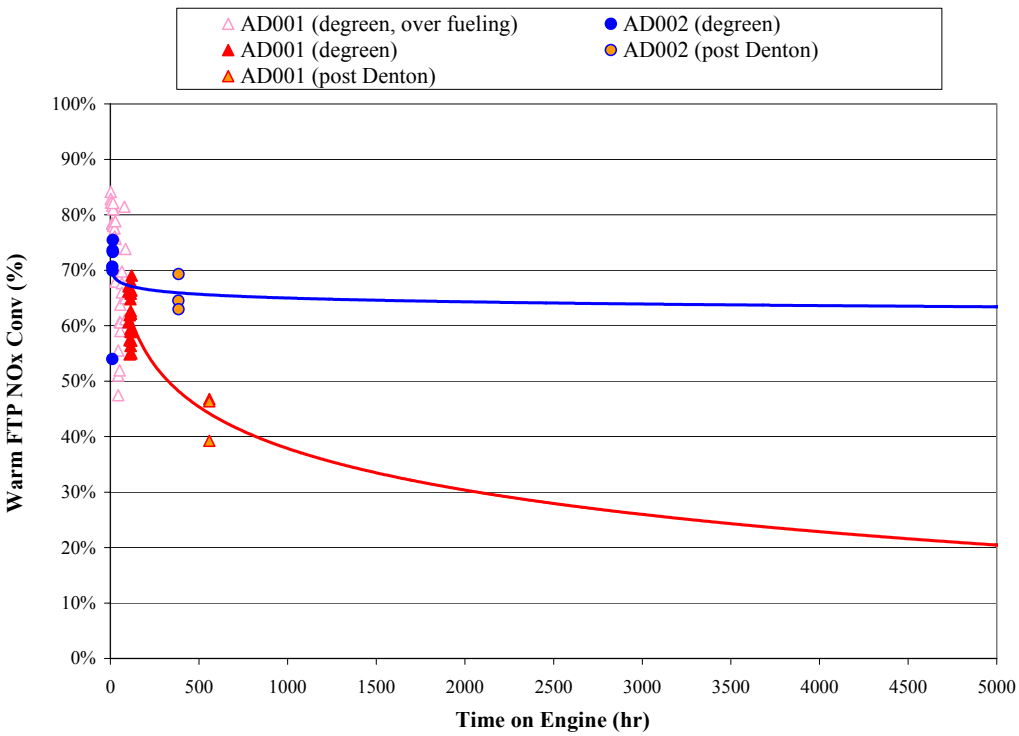

Figure 4.6.2.4.1: Projected NOx reduction performance at 5,000 hours

4.6.3 Materials Analysis

The analytical characterization is used to assess the degree of reduction in active metal surface area of the used catalysts that can be attributed to thermal aging. This material analysis reports the results of standard post-production analyses (PPA) of catalyst samples taken from both the catalyst retained from original production and several selections of catalyst representative of the Denton tested monoliths from both AD001 and AD002 modules.

PPA characterization measurements consist of:

1) N_2 BET total specific surface area (m^2/gm) including cumulative pore volume (mL/gm) from integration of the measured pore volume distribution (PVD) over the range, 1- to 100-nm pore size

2) Thermal-gravimetric analysis (TGA) of weight loss by reduction with 4-vol H_2 in 1-atm flowing N_2 at 500°C which is determined as the reduction of stoichiometric platinum group metal (PGM) oxide.
3) H_2 Chemisorption by surface titration of reduced (400°C in 1-atm pure H_2 for 1-hour) defined as exposed reduced PGM (µmol/gm).

Samples were scraped powders from both the retained production lots and the Denton aged XFP catalyst. Due to non-analysis agreements with the LNT suppliers, no material analysis was performed on the LNT components.

4.6.3.1 BET Characterization

BET surface area was determined using a Micromeritics ASAP 2010 (Accelerated Surface Area and Porosimetry) automated instrument. CESI's standard BET measurement is described briefly as follows. The powder samples are first degassed (dehydrated) at a temperature of 250°C over a period of ~2 hours. During analysis, the weighed samples are evacuated to low vacuum of 10^{-5}-mm Hg, cooled to cryogenic temperatures, and then exposed to doses of analysis gas (ultra-pure nitrogen) at a series of five precisely measured (equilibrated) pressure points. An analysis of the volume adsorbed vs. pressure according to the Brunaer-Emmett-Teller (BET) adsorption isotherm, then determines the specific surface area (m^2/g) of the powdered samples. Table 4.6.3.1.1 summarizes results from BET surface area analysis performed on powders scraped from retained and on-board aged foils from the AD001 and AD002 modules. The table shows significant reduction in surface areas ranging from 32% to 62%.

Component	Sample Description	BET Surface Area Change from Fresh (pre Denton)
XFP	AD001 Sample 1 - 1.3" diameter	-62%
	AD001 Sample 2 - 10.5" diameter	-56%
	AD001 Sample 3 - 1.3" diameter	-38%
	AD001 Sample 4 - 10.5" diameter	-32%
	AD002 Sample 1 - 1.3" diameter	-44%
	AD002 Sample 2 - 10.5" diameter	-45%
	AD002 Sample 3 - 1.3" diameter	-40%
	AD002 Sample 4 - 10.5" diameter	-32%

Table 4.6.3.1.1: BET analysis results

4.6.3.2 TGA Characterization

Thermogravimetric analysis (TGA) is used to quantitatively determine metal loadings in scraped powder catalyst samples. CESI's in-house procedure consists of the following steps. Scraped powders from both retained and post Denton catalysts are placed in tared alumina crucibles, heated in an ambient air furnace to convert the precious metal into the oxide form, and analyzed via TGA with a Mettler Toledo TGA-851E instrument. During analysis, the sample is subjected to dynamic heating in nitrogen and then isothermal reduction in flowing dilute hydrogen at elevated temperature (typically 500°C) to fully reduce active metal oxides to the metal phase. The sample weight loss during hydrogen reduction is used to calculate the

total percent of metal in the catalyst by the known stoichiometry of the oxides. Because the 851E is subject to a drift in weight during thermal cycling, a blank crucible is used to determine a background (zero weight-loss) reference. Also each TGA run includes a reference standard material and duplicate samples. Table 4.6.3.1.1 shows the results from the TGA analysis.

Component	Sample Description	Ratio of %PGM 1 to %PGM2
XFP	AD001 Sample 1 - 1.3" diameter	18%
	AD001 Sample 2 - 10.5" diameter	24%
	AD001 Sample 3 - 1.3" diameter	184%
	AD001 Sample 4 - 10.5" diameter	206%
	AD002 Sample 1 - 1.3" diameter	21%
	AD002 Sample 2 - 10.5" diameter	20%
	AD002 Sample 3 - 1.3" diameter	242%
	AD002 Sample 4 - 10.5" diameter	226%

Table 4.6.3.2.3: TGA analysis results

4.6.3.3 Characterization by Chemisorption (Hydrogen Titration)

The characterization of exposed metal (surface area) for the catalyst powders was quantitatively determined using two automated Micromeritics ChemiSorb 2800 analyzers. CESI's in-house hydrogen titration and chemisorption method is briefly described as follows. Scraped powder samples are loading into to tared sample tubes using an external balance and placed in one of five ports on the 2800 instruments. The samples are heated to 400°C for 60-min in flowing pure hydrogen where the metal oxide undergoes complete reduction. Following evacuation and cooling to a pre-determined temperature, oxygen is exposed to the samples at 0.05-atm to remove impurities such as carbon and sulfur and to passivate the surface with an adsorbed monolayer of oxygen. Following evacuation to very low pressures and leak checking, hydrogen is then introduced in aliquots at 100°C until a series of target equilibrated pressures are reached. CESI's low pressure chemisorption procedure uses four pressure targets (4-, 6-, 9- and 12-mm Hg). This method was used for Denton samples while the temperature during the static oxygen exposure step was maintained at 50°C.

Results from the chemisorption analyses on retained and aged powders are included and summarized in Table 4.6.3.3.1. The numbers reported in the table are average values obtained from duplicate runs.

Component	Sample Description	Exposed Metal Surface Area Change from Fresh (pre Denton)
XFP	AD001 Sample 1 - 1.3" diameter	-92%
	AD001 Sample 2 - 10.5" diameter	-90%
	AD001 Sample 3 - 1.3" diameter	-44%
	AD001 Sample 4 - 10.5" diameter	-50%
	AD002 Sample 1 - 1.3" diameter	-92%
	AD002 Sample 2 - 10.5" diameter	-47%
	AD002 Sample 3 - 1.3" diameter	-79%
	AD002 Sample 4 - 10.5" diameter	-21%

Table 4.6.3.3.1: Chemisorption analysis results

4.6.3.4 Materials Analysis Summary

The Denton catalysts aged in the Denton road tests show significant loss of exposed PGM area (i.e., surface area of reduced PGM oxide catalysts). This significant decrease is corroborated by larger than expected drop in BET total specific surface area. Excessive thermal aging is implicated by these results, although additional analyses are planned (beyond the scope of this program) to determine the extent to which (if any) contaminants influenced the exposed metal analyses. It cannot be determined from the material analyses whether the observed thermal aging occurred as very short period at very hot temperatures over particular system control responses or as result of moderately hot temperatures typical thermal cycling during lean NOx trap regeneration.

4.6.4 Denton Teardown Observations

The overall condition of the Denton hardware was good with some minor mechanical issues observed during the teardown. Listed below are some of the key findings:

Unit AD001

- There were no signs of mechanical damage or deformation, cracks or corrosion on the container, exhaust stack or other structural elements
- Some minor surface damage at mounting ring locations, possible fretting from movement of ring-style support brackets.
- All of the control thermocouples were found to be functional, although upon removal from the container several broke.
- Most of the diagnostic thermocouples were found to be functional
- A moderate amount of soot buildup on the exposed areas of the fuel injector as shown in Figure 4.6.3.5.
- XFP outlet deformation evident on the OD of the foil pack, XFP inlet had some minor soot and debris on the face

- LNT inlet on brick #1 had some minor soot and/or debris build up on the face as shown in Figure 4.6.3.4.

Unit AD002

- There were no signs of mechanical damage or deformation, cracks or corrosion on the container, exhaust stack or other structural elements.
- Contamination from what appears to be a hydraulic fluid leak from the vehicle onto the surface of the head-end
- Some minor surface damage at mounting ring locations, possible fretting from movement of ring-style support brackets.
- Minor leaking as evidenced by soot buildup around the inlet cone flange as shown in Figure 4.6.3.2.
- The V-band clamps that hold the XFP inlet cone assembly and the LNT inlet cone assembly together have deformation in area of the fastener, as seen in Figure 4.6.3.2. This indicates the fastener was over-tightened
- All of the control thermocouples were found to be functional, although upon removal from the container, several broke.
- All of the diagnostic thermocouples were found to be functional
- XFP outlet deformation evident on the OD of the foil pack, XFP inlet had some minor soot and debris on the face
- LNT (bricks 1 and 2) looked clean on both inlet and outlet faces

Figure 4.6.3.1: The "as received" condition of AD001 (left) and AD002 (right). Note the buildup of dirt and grim on the exterior of the units.

Figure 4.6.3.2: Soot at head/XFP inlet cone flange on serial no. AD002 (left) - Evidence of stud/nut over-tightening. Circled areas are locations of deformation (right).

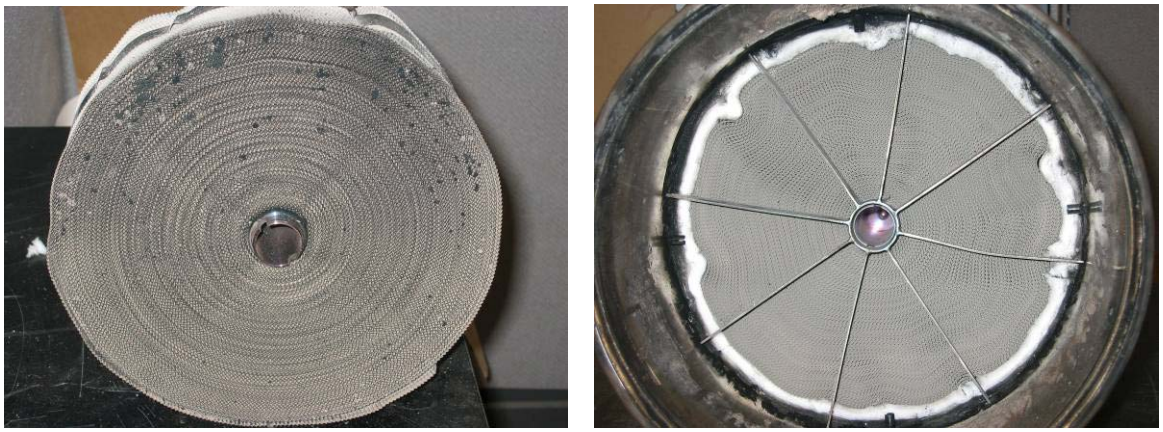

Figure 4.6.3.3: AD002 XFP inlet (left) and outlet (right)

Figure 4.6.3.4: LNT inlet face for AD001 (left) and AD002 (right).

Figure 4.6.3.5: Injector tip showing soot buildup for AD001 (left) and AD002 (right)

V. Conclusions

CESI has completed a one-year project to demonstrate the performance and durability of the XononD diesel retrofit NOx solution. The Denton demonstration represented the first on-road and in-service operation of the XononD technology. In general, the system performed reasonably well, however, it is clear that additional development work is needed in order to field a high performing and durable product. Some of the key overall program conclusions are:

- The overall NOx reduction for the neighborhood refuse pick up cycle was well below the 50% target (actual values ranged between 31% and 39.9%)
- The poor system NOx reduction performance is likely due to a combination of poor fuel injector durability, XFP catalyst aging and LNT sulfation (which is partially reversible)
- The fuel nozzle will likely need to be redesigned to address the durability issues associated with solenoid flow control and nozzle tip coking
- The 3-month average XononD system reliability was 82%-83%, however the last month's average reliability was over 90%, beating the demonstration project target of 85%.
- The ability to commercialize the XononD product will hinge on the quick solution to the performance issues in order to enter the verification market in a timely manner
- The mechanical components performed well after the initial infant mortality issues were addressed. The structural components showed no signs of distress or damage.
- The XononD system performance in the FTP cycle was 65% for pre Denton and ranged from 44%-66% for post Denton. Although these values are within the target goals, the low number of operational hours accumulated at Denton makes it difficult to accurately extrapolate for end of life performance degradation.

- The XononD system performance in the CBD cycle ranged from 87%-99% for pre Denton and ranged from 43%-60% for post Denton. It is clear from these values that the CESI designed CBD cycle simulation does not accurately represent the Denton neighborhood pick up cycle (values ranged from 31% to 39.9%).

Notes and References

[1] Source: EPA website, http://www.epa.gov/nonroad-diesel/basicinfo.htm
[2] Source: EPA website, http://www.epa.gov/nonroad-diesel/basicinfo.htm
[3] http://www.4secat.org/
[4] Source: EPA website, http://www.epa.gov/oar/oaqps
[5] Source: EPA website, http://www.epa.gov/oar/oaqps/greenbk/naa8hrgreen.html
[6] Source: EPA website, http://www.epa.gov/oar/oaqps/greenbk/gnsum.html
[7] Source: G. Campbell, diesel engine consultant
[8] Source: Internet website: http://www.dieselnet.com/standards/cycles/ftp_trans.html

Glossary

CBD - Central Business District cycle which approximates a refuse pick up cycle
CESI - Catalytica Energy Systems, Inc.
CO - Carbon Monoxide
Desulfation - A process to remove sulfur from the LNT catalyst surfaces. Requires time at temperature and active reductants to be effective
EGT - Exhaust Gas Temperature. This is the limiting parameter for gas turbine power. The turbine control system uses measured EGT to adjust the fuel schedule for operation at maximum design capacity under normal operating conditions
FTP - Federal Test Protocol – the accepted heavy duty diesel engine test cycle used for verification of retrofit solutions
HD - Heavy Duty (as related to diesel engines)
L - Liter (metric measurement of volume)
LNT - Lean Nox trap – the catalytic component that traps the NOx in the exhaust stream and then releases the NOx in the form of elemental Nitrogen and CO_2 during trap regeneration
NO_x - Nitric Oxides
PGM - Platinum Group Metal
PM - Particulate Matter
S - Sulfur
UHC - Unburned Hydro-Carbons
XFP - CESI's proprietary diesel fuel processor which creates reductants to clean up LNT's
XononD™ - CESI's diesel emissions system for NO_x control