

FINAL REPORT

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Mobile Off -Road Retrofit SCRT System Demonstration Program

Prepared by:

Ray Conway and Mark Schmale
Johnson Matthey

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Abstract

Off-road construction equipment is a significant source of the pollutants carbon monoxide (CO), hydrocarbons (HC), particulate matter (PM) and oxides of nitrogen (NO_x) in California. A retrofit Continuously Regenerating Technology (CRT®) and other Diesel Particulate Filter (DPF) technologies provided by ECS and HUSS have been verified by ARB for significant reduction of CO, HC and PM from On-road and Off-road vehicles. The focus of this project was to evaluate the combination of a Selective Catalytic Reduction (SCR) system with the CRT to reduce the NO_x from off-road equipment. Previous work has demonstrated that installing a CRT upstream of a SCR system can enhance the performance of the SCR catalysts along with the reduction of HC, CO and PM. The proposed retrofit SCR system uses NH₃ stored in aqueous urea to reduce the NO_x in the machine's exhaust. The urea is dosed into the exhaust by an air assisted urea dosing pump. The system is very similar to a retrofit system currently being considered by ARB for verification for use in on-road applications. This paper will outline the process of equipping two pieces of off-road equipment operated by the LA Sanitation Department with the retrofit SCRT® system. The SCRT® system is a combination of the CRT filter system and urea SCR (CRT + SCR = SCRT). The SCCRT® is a combination of the CCRT filter system and urea SCR. (SCR + CCRT = SCCRT). Data will be presented that demonstrates the performance of the system along with a description of the challenges unique to adapting this technology to off-road equipment.

Introduction

The objective of this project was to demonstrate the performance of the Johnson Matthey combined retrofit emission control technology known as SCRT on off-road equipment. The SCRT/SCCRT system combines the CRT Filter with a urea based SCR system to reduce PM, NO_x, HC and CO. The SCRT/SCCRT systems have demonstrated consistent NO_x reductions of 60-80% in on-road applications. In this project the product was

adapted to work on two Front End Loaders operated by the Los Angeles Sanitation Dept. The systems were installed in 2 Phases. First the PM control was installed and monitored for 6 months, and then the SCR system was installed and activated. There were some challenges to adapting the on-road system to the off-road equipment.

- The on-road system uses compressed air to assist with injection of the urea. Compressed air is used on most Heavy Duty Diesel powered trucks to activate the brakes. Off-road equipment is hydraulically controlled and usually does not have compressed air on board.
- The operational loads and shock loading on off-road vehicles is higher than for on-road vehicles
- The line of sight requirements are more stringent than for on-road vehicles

The complete systems were installed and operated for 6 months. Unfortunately the installation of the system could not be completed on one of the machines because communication could not be established with the engine control unit. Since the SCRT system needs to get engine information so that the proper amount of urea can be calculated and injected, the SCR portion of the project was not completed on this vehicle. The other machine did demonstrate approximately 70% NO_x reduction. PM reduction was not actually measured during this trial. The fact that the back pressure showed no increase implies that the system was working and achieving at least the verified 85% reduction.

This report is the final element of the ICAT grant program 06-06 for the demonstration of SCRT technology on off-road equipment

Innovative Technology

The emissions standards for Heavy Duty Diesel (HDD) vehicles have been progressively tightened around the world. In order to meet these standards a systems approach of advanced engine technology, ultra low sulfur diesel fuel and advanced emission control after treatment is required. Attention is also focused on the emissions of legacy vehicles, since comprehensive pollution control requires the reduction of emissions from all vehicles, not just the newest ones. A large number of HDD retrofit programs have been introduced across the world to evaluate the effectiveness of fitting new technologies on older on-road and off-road equipment. The initial target was the reduction of Particulate Matter (PM) emissions of these vehicles via the installation of Diesel Particulate Filter (DPF) technologies. One system that has been very widely used in these programs is the Continuously Regenerating Technology (CRT) diesel particulate filter, which was developed and patented by Johnson Matthey. The CRT filter comprises an oxidation catalyst followed by a wall-flow Diesel Particulate Filter (DPF). The DPF traps the PM and the oxidation catalyst oxidizes a portion of the engine-out nitric oxide (NO) to generate nitrogen dioxide (NO₂). PM will combust in the presence of NO₂ at a much lower temperature (around 250 °C) than in the presence of oxygen (around 600 °C). This low temperature combustion of PM by NO₂ enables the passive operation (with continuous PM removal) of the CRT filter on a wide range of HDD applications (e.g.

buses, trucks, garbage trucks) and is the basis of the CRT filter. The CRT filter has been used very successfully for retrofit over a wide range of HDD applications most of which have duty cycles that have exhaust temperatures sufficiently warm to guarantee continuous regeneration of the CRT filter. For applications with lower operating temperatures or lower NO_x/PM ratios, the Johnson Matthey CCRT® filter is used. The CCRT filter combines a DOC and Catalyzed Soot Filter (CSF) and is also based on the use of NO₂ to combust soot but can operate at a lower temperature. The primary difference between the CCRT and CRT filters is that NO₂ is generated in the wall-flow filter as well as the DOC. This allows the CCRT filter to be applied to applications with colder operating cycles or with lower NO_x/PM ratios.

Recently more attention has been focused on the reduction of NO_x emissions through retrofit. In the European HDD OE market, Selective Catalytic Reduction (SCR) was introduced in 2005 to control NO_x emissions under the Euro 4 standard. The selective reduction of NO_x is based on the use of a reductant being injected into the exhaust stream before it comes into contact with the SCR catalyst. The reductant, ammonia, is the hydrolyzed product of urea. SCR has been widely and successfully used for NO_x emission control from stationary power generation applications as well as industrial applications for more than thirty years. Therefore, one effective way to control all four major pollutants from diesel engines is to combine two proven technologies, DPF and SCR systems. Johnson Matthey has developed the SCRT and SCCRT retrofit systems for on-road applications. These systems combine the CRT or CCRT filters with urea SCR system see figure (1). The systems use an air assisted urea dosing pump manufactured by Grundfos A/S to inject the urea through a specially designed nozzle that atomizes and distributes the urea into the exhaust between the CRT filter and SCR Catalyst Modules. The entire process is controlled by an ECU that calculates the precise amount of urea to inject based on engine conditions, measured engine out NO_x and exhaust temperature. The system includes a urea tank which stores and filters the urea on the vehicle. The air used for the system is taken from the braking system air tanks on the vehicle and filtered, dried and regulated before being used by the urea pump.

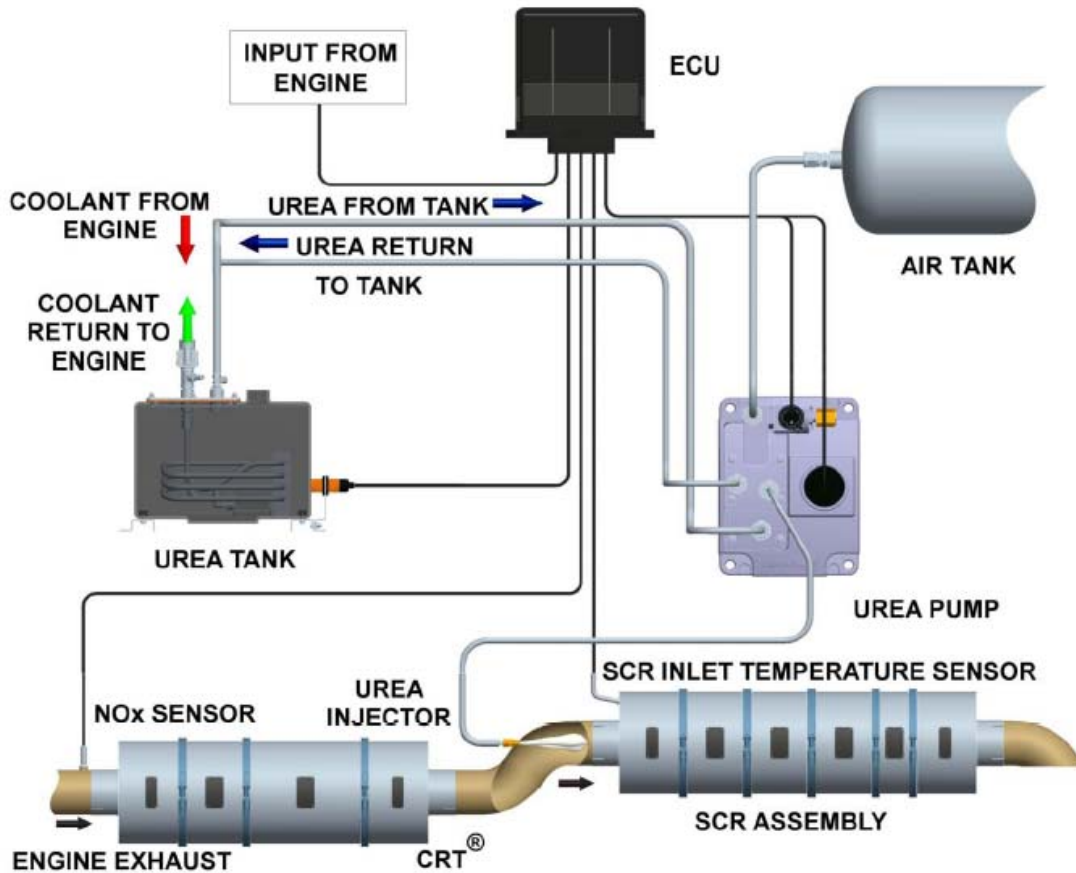


Figure 1 SCRT System Diagram

To date these combined systems have demonstrated NOx reduction between 60 and 85% in test cell and on the field. Figure (2) shows the NOx reduction performance of the SCCRT over a Hot Federal Transient Protocol (FTP) cycle. The SCCRT demonstrated an 80% reduction in NOx in this test. Figure (3) shows the daily NOx reduction achieved during a 1000 hour durability trial of the SCRT that was installed on a Class 8 Grocery Delivery Truck operating in southern California. The truck was equipped with engine out and tail pipe NOx sensors that were used to determine NOx reduction.

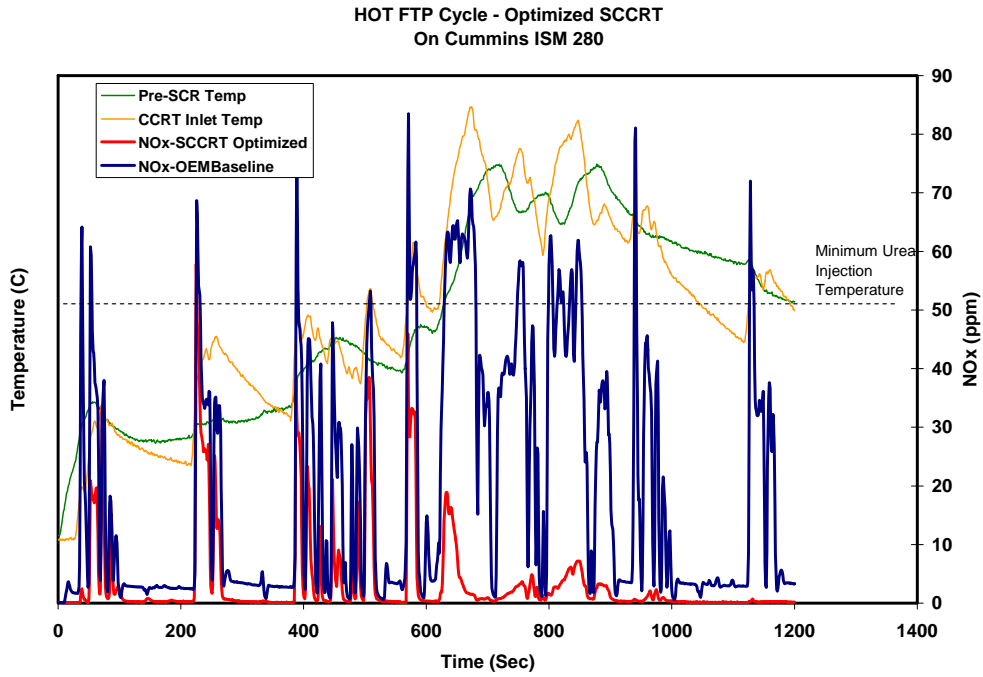


Figure 2 - SCRT Performance over FTP

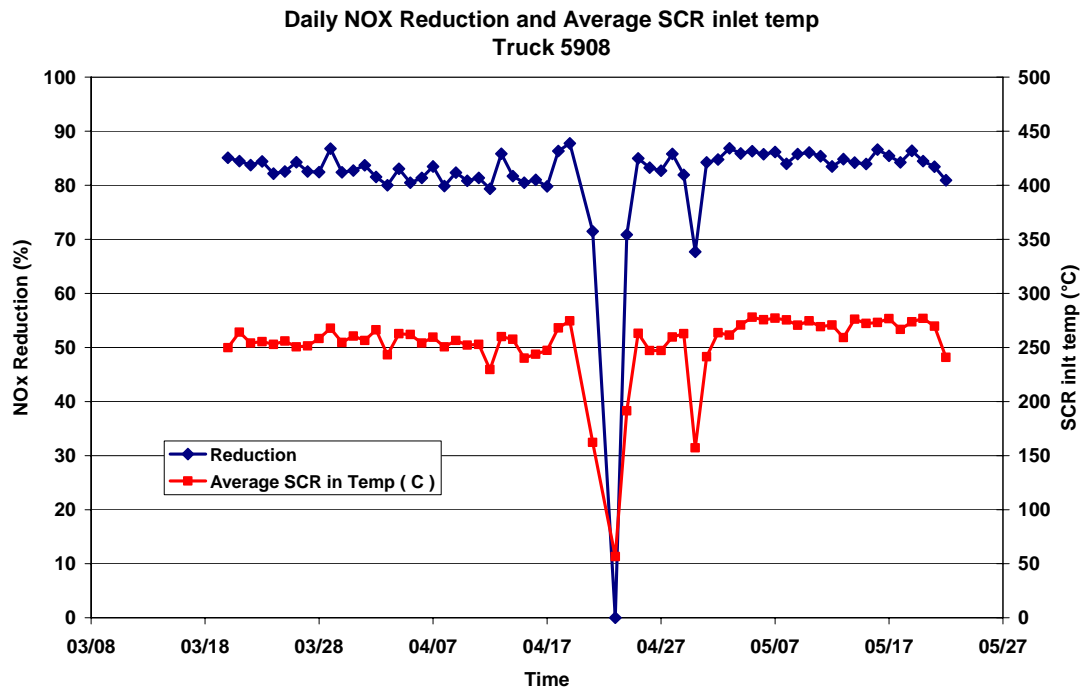


Figure 3 SCRT On-Road Performance

The objective of this project was to apply the SCRT and SCCRT systems to off-road vehicles to determine if similar reductions in emissions could be achieved.

ICAT Project

Background: Johnson Matthey Inc. installed the SCRT system on two off-road machines operated by the Los Angeles County Sanitation Department (LASD) at their facility located in Carson CA. The systems were installed in two separate phases. The first phase evaluated the CRT on the machine by itself prior to installing the SCR portion of the SCRT system. The second phase was the addition of the SCR components with the dosing system. The machines used for the demonstration program were front-end loaders (FEL) with the following specifications:

Fleet Operator	Los Angeles Sanitation District (Carson)	
Operator Identification Number	8231	8239
Machine Make	Hyundai	Caterpillar
Machine Model	HL 740-7	966 GII
Model Year	2005	2003
Machine Identification Number	LF0110523	0AXJ01440
Engine Make	Cummins	Caterpillar
Engine Model	ISC	3176C
Engine Displacement	8.3 L	10.3 L
Engine Emissions Family	5CEXL0359AAD	3CPXL10.3ESK
Engine Power	140 HP	327 HP

Table [1]: Machine Specifications

System Sizing: Using the information from Table [1], the following SCRT systems were specified for each installation:

Component	Hyundai		Caterpillar	
DOC	1 - 10.5x6	91106KDSC	1 – 11.25x5	K90115MD
DPF	1 – 10.5x12	99100KDSC	1 – 12x12	9199MD
SCR	2 – 10.5x6	70100MD	2 – 12x6	70120MD
Slip Catalyst	1 – 10.5x3	K70103MD	1 – 12x4	K70124MD
Tank Size		960000		960000
JM JDE SO#	8110452		8110451	

Table [2]: SCRT System Sizes

System Installation: The systems were installed on the machines in two phases. The first phase installed the DPF portion of the system. Both units had the DPF portion of the system (DOC and DPF) installed on October 30, 2008 by Exhaust Emissions Reduction Specialists (EERS) of Corona CA. The second phase of the installation occurred after a 6

month evaluation period of the DPF regeneration performance. The SCR portion of the system was installed on August 14, 2009 at LASD's Carson location. This phase of the installation included the mounting of the Diesel Exhaust Fluid tank, dosing controller, dosing pump, lines, harness, sensors, compressed air system (tank and compressor) and the SCR catalysts.

The Caterpillar FEL was never made operational due to a problem with communication engine CAN network. The SAE J1939 CAN communication protocol is used by the SCRT system to collect vital information to estimate exhaust flow through the SCRT system, and control the urea dosing system and the NOx sensors. Johnson Matthey (JM) entered the installation with the understanding the SAE J1939 CAN network was available on the machine primarily since JM has installed the SCRT on other Caterpillar engines for on-road applications. It wasn't until the final stages of the installation that it became known that the SAE J1939 network is not available on Caterpillar off-road machines. The SAE J1939 communication protocol is used on Caterpillar on-road engines to allow communication between the engine and vehicle systems. On off-road machines Caterpillar uses a proprietary communication protocol to communicate between the engine and the machine. Johnson Matthey solicited the assistance of several Caterpillar distributors for a solution but one was not found. Therefore, the NOx reduction system on the Caterpillar FEL was not made operational during the second phase of the evaluation period.

The Hyundai FEL was made operational and satisfied all of the post-installation check-outs.



Figure 4 Caterpillar FEL with SCRT system Installed

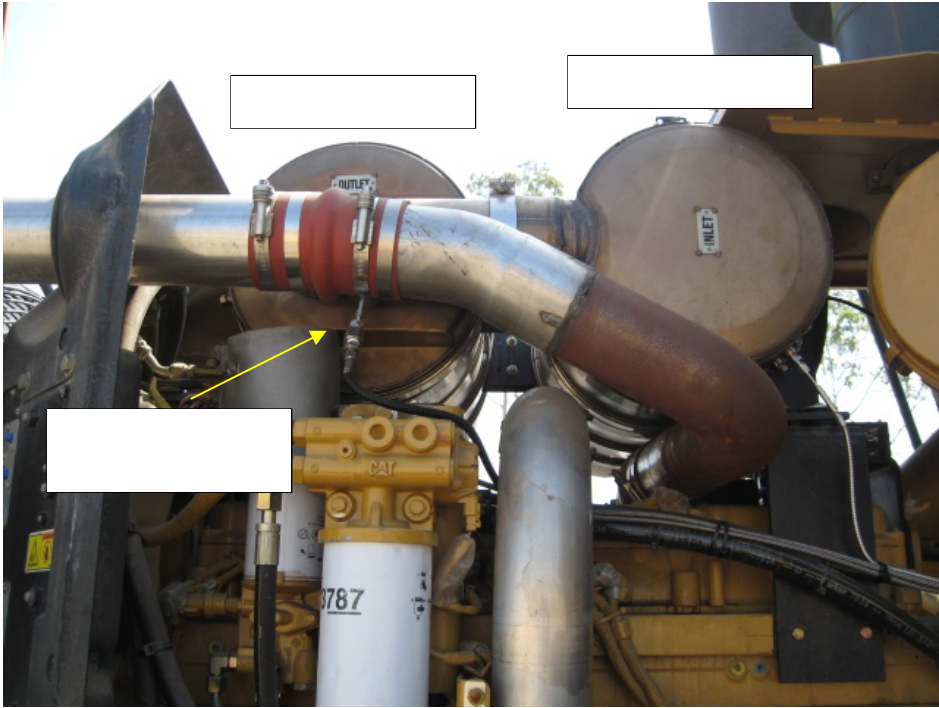


Figure 5 Caterpillar FEL Engine Compartment with SCRT installed



Figure 6 Hyundai FEL with SCRT installed



Figure 7 Hyundai FEL Engine Compartment with SCRT installed

System Performance:

After first phase of the project the FELs were allowed to operate for approximately 6 months to evaluate the backpressure profile of the DPF. This was done since the operating cycle for these units were very low in temperature. The units did not accumulate many hours during the evaluation period and operated for very short durations of time. Figures [8] and [9] show the peak backpressure of the CRT during the first phase of the demonstration.

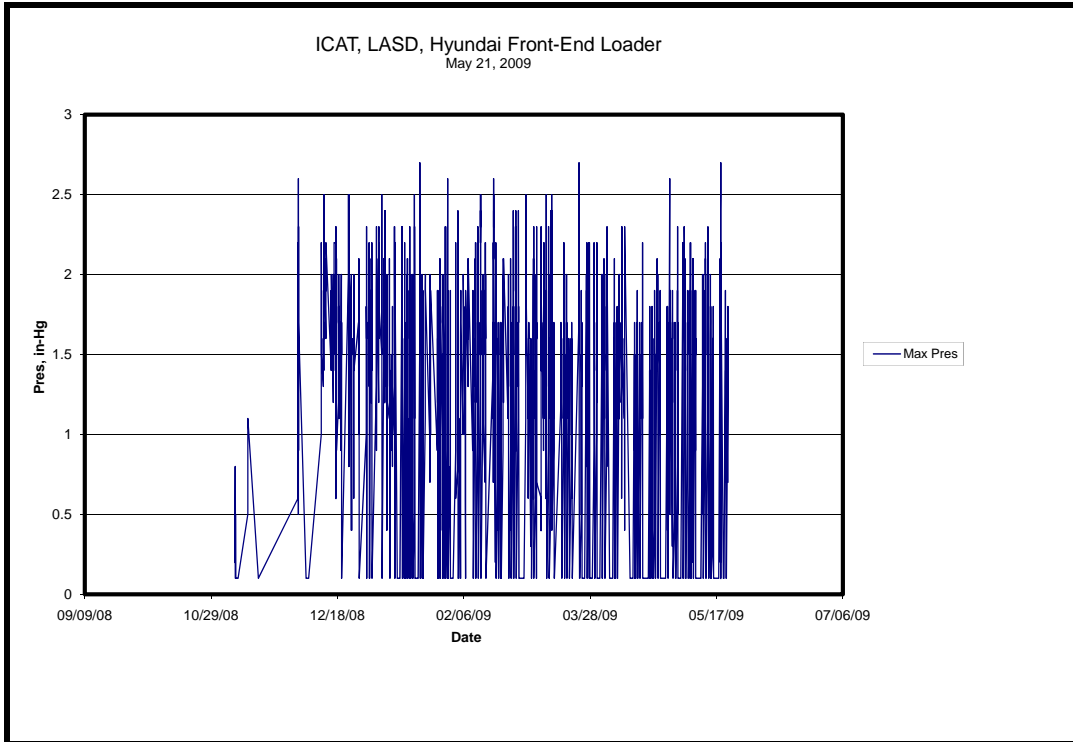


Figure 8 Hyundai FEL Backpressure profile (Max Backpressure over 5 minute time intervals)

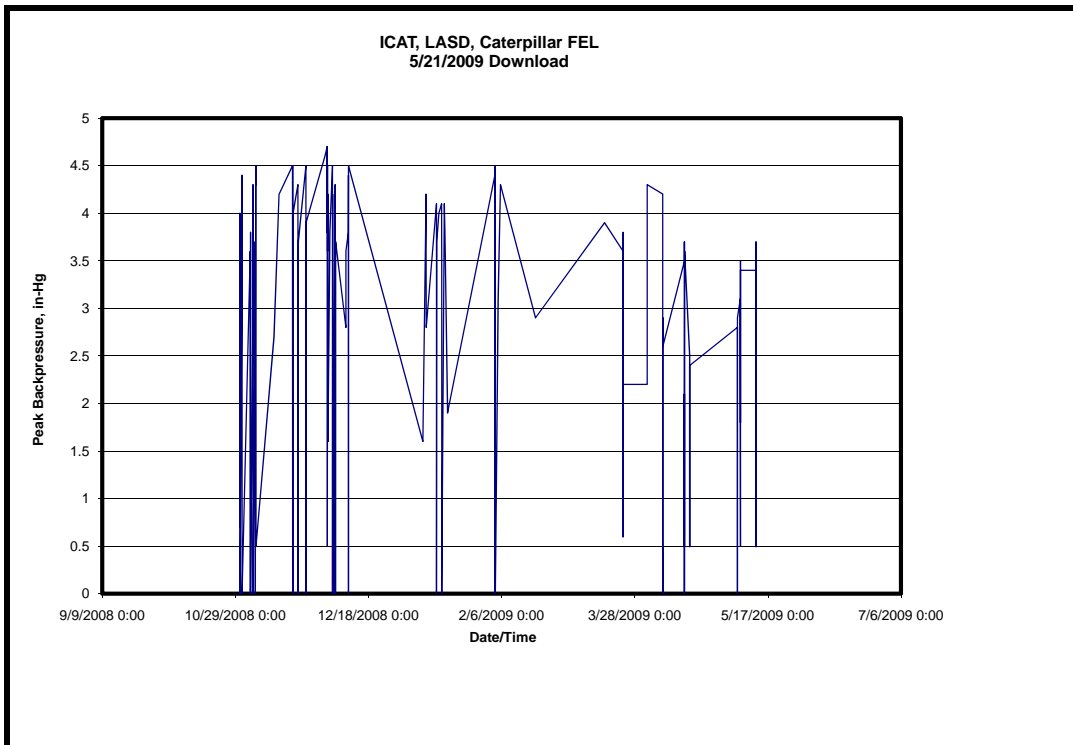


Figure 9 Hyundai FEL with CCRT Installed Backpressure profile (Max Backpressure over 30 minute time intervals)

As the figures indicate the backpressure peaks indicate that the CRT is able to oxidize the soot and maintain a uniform backpressure over long durations. It should be noted that the evaluation period for this had to be extended for several months due to the low number of hours that the machines accrued. The Caterpillar loader only accrued 43.5 hours of run time over a 6 month period. The Hyundai loader accrued 93.5 hours of data for the same period.

After the second phase of the installation, the NOx reduction performance of the machines was evaluated. The Hyundai unit operated from August until the beginning of October for a total of 9 running hours. At which time the unit was taken out of service for repairs not related to the SCRT system. However during that repair the SCRT system was rewired to the batteries and was inadvertently connected to the 24V electrical system. Since some components in the SCRT system require 12V to operate correctly, the system failed and ceased operating. This was not discovered until January 2010 when data was downloaded. During that January visit, troubleshooting eventually revealed that the system was mis-wired during the repairs which caused the NOx sensors and the auxiliary air compressor system to malfunction. It was during and after this service period that the SCRT System's diagnostic system logged errors in the operation of the dosing system. Table [3] summarizes the errors observed in the data log; it is important to notice that the first error was not observed until after the start of the machine's service event:

Name	Time for first error	Number of errors	Time for last error
20:Nozzle prs sensor	02/16/2010 14:21:42	6	02/16/2010 14:40:14
36:Air/Urea flow	01/06/2010 16:15:52	2	02/09/2010 14:14:32
41:Low nozzle prs	11/04/2009 11:44:51	10	11/09/2009 15:10:33
50:Dosing failure alarm	01/07/2010 11:44:41	4	02/09/2010 14:14:32
51:Low nozzle prs alarm	11/09/2009 15:10:33	2937	11/16/2009 13:12:47
52:NOx Pre-filter Log	11/04/2009 17:20:39	4	01/29/2010 16:05:56

Table [3]: Hyundai FEL SCRT's Error Log

All of the errors observed in Table [3] are due to either a malfunctioning NOx sensor or a malfunctioning compressed air system. Both the NOx sensor and the compressed air system used on the SCRT system can only be operated on a 12V electrical system. Since, during the service event of the machine the electrical system was rewired to 24V, it can be inferred that the NOx Sensor and air compressor system malfunctioned and were no longer able to operate after the service event. Johnson Matthey did not become aware of the service event until we visited the vehicle on October 21, 2009 at which time we

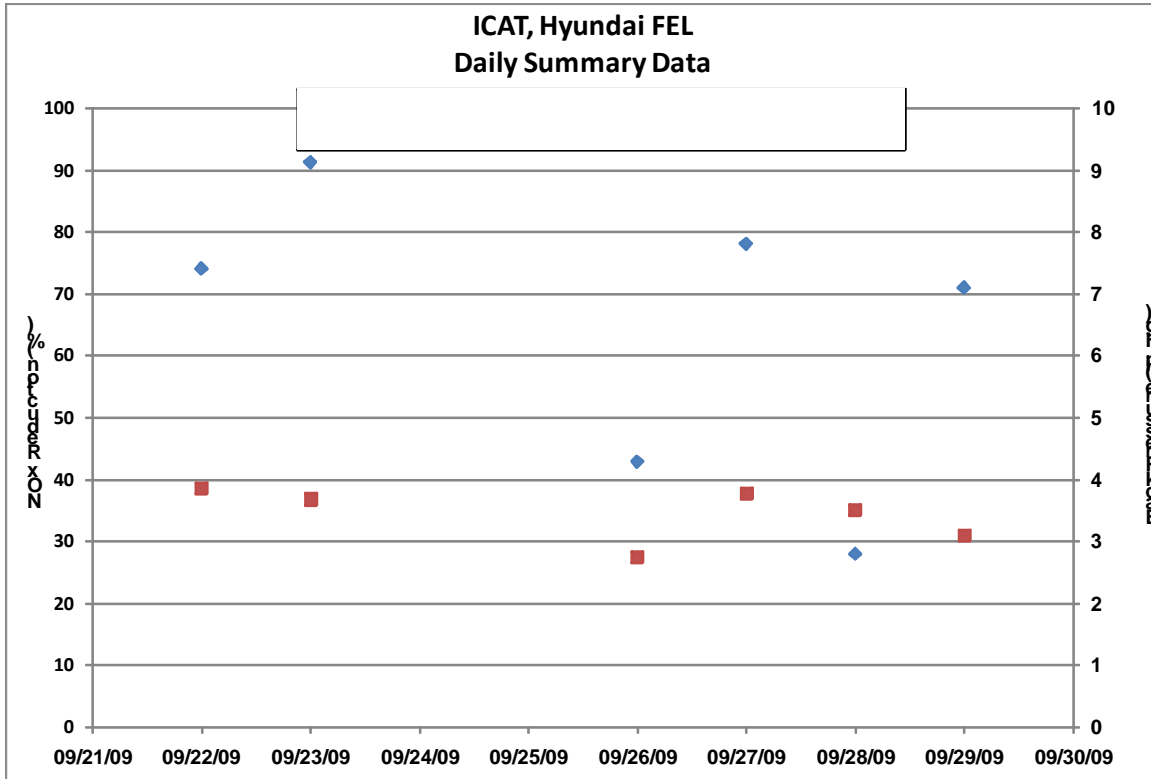


Figure 11 Daily Summary data for Hyundai FEL

The Caterpillar FEL operated from August to October 2009 with only the DPF portion of the system operational. Since the NOx reduction portion of the system was disabled due to not being able to communicate with the engine using the J1939 network, a backpressure monitor was installed to make sure the engine backpressure never reached an excessive level. Figure [12] shows that the backpressure on the engine never went above 6 inches of mercury (Hg). Johnson Matthey learned that the Caterpillar FEL was not used after October 2009. Johnson Matthey made two visits to LASD in January 2010 to check on the operation of the systems. During the first visit in January it was observed that the battery voltage on the Caterpillar FEL was too low to allow communication with the on-board data logger. This implies that the battery voltage was below 6 volts. Based on the observed condition of the machine during the performance checks in January it was surmised that the machine had not operated at all between our visit in October and our visit in January. During our visit in February 2010 we were informed that the Caterpillar machine was out of commission and not available for us to download data.

ICAT, LASD, Caterpillar FEL
10/21/2009 Download

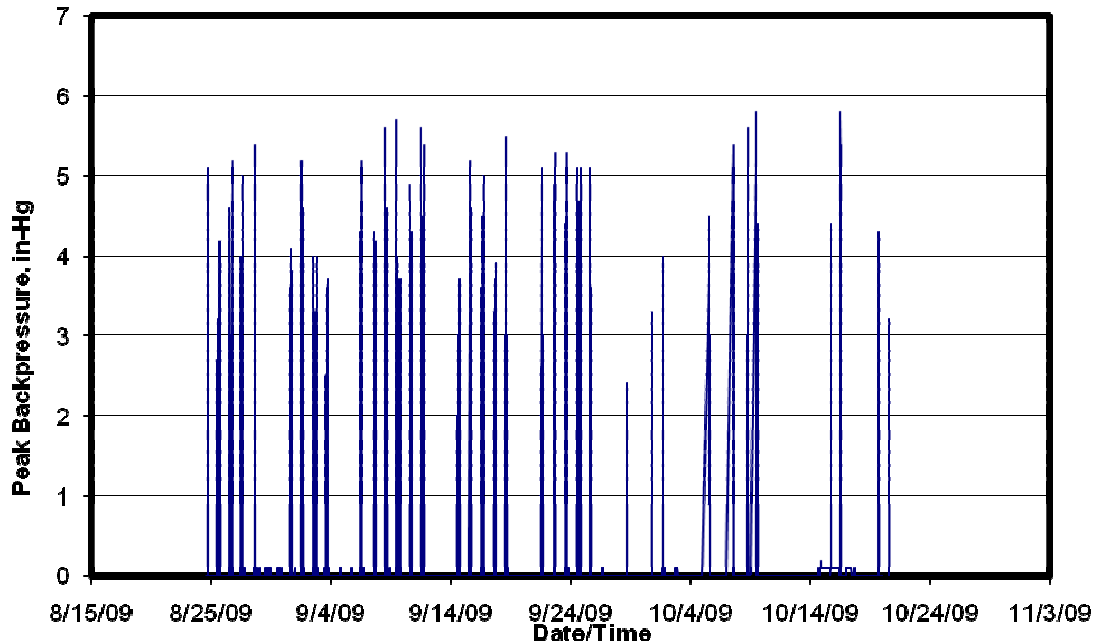


Figure 12 Caterpillar FEL with SCRT installed Backpressure (Max over 5 minute intervals).

Conclusion:

The performance on the Hyundai FEL suggested that a reasonable NO_x reduction could be expected on a machine with a similar application and duty cycle. However the number of hours generated by the test machine and maintenance interference with the system prevented the system from having an adequate demonstration opportunity. The NO_x reduction portion of the Caterpillar FEL's SCRT system was never operational due to an integration issue with the engine. It can be concluded that future installations on off-road machinery will require a more extensive application review prior to installation and that applying on-road vehicle integration experience on similar engines may not be appropriate. Regardless of the NO_x performance measured on the two machines, the Particulate Matter reduction was operational and stable, thus further demonstrating the ability of a passively regenerating DPF system to be applied to select off-road machines.

Status of the Technology

While this program demonstrated that the SCCRT and SCRT can be used effectively on off-road equipment some technical issues still need to be addressed before the system can be considered commercially ready. The areas that need to be addressed are:

- On-board air. Any supplemental air supply system needs to work with power supplies that range from 10 to 30 VDC and be able to handle voltage spikes as high as 45V. A smaller air tank should also be considered in order to minimize line of site issues.
- The interface with the engine needs to be flexible. The current system uses the SAE J1939 communication protocol to get information from the engine. The J1939 Controller Area Network (CAN) protocol is used internationally for communication between components used in on-road vehicles. Many of the major components on modern on-road vehicles use Electronic Control Modules (ECMs) that communicate via a J1939 network. By using this standard it is possible for all different types of engines, transmissions and brake systems to be used in combination on trucks. Typically an engine in an on road vehicle is configured to broadcast certain engine parameters on the network. Johnson Matthey needs some of these parameters to calculate the exhaust flow from the engine. For off-road equipment electronic communication between the engine and vehicle is not always necessary. Many of the machine subsystems are mechanically or hydraulically controlled. For Caterpillar machines a proprietary communication protocol is used for communication between the engine and the vehicle. We were not aware of this because Caterpillar engines used in on-road applications use the J1939 protocol. For off road machines Caterpillar can use their own communication protocol since they build the entire machine. During this project the Cummins engine on the Hyundai machine was able to broadcast the data needed using the J1939 protocol. The Caterpillar distributors we contacted tried to adapt a “translation” box that would read the engine data and convert it to the J1939 protocol but were unsuccessful. In developing the SCRT for off road applications it may be possible to use a mass air flow sensor mounted in the engine air inlet to calculate the air flow if J1939 communication is not available. All current air flow sensors need to be calibrated for the vehicle they are installed on so this solution would add time and cost to the installation of the system.
- Line of sight. While this program was being conducted, CalOSHA was doing a study of the impact of retrofit emission technology on the line of sight of the operators. Even though we were able to put some of the components under the hood of the vehicle, other components were mounted on the outside of the vehicle. Once the requirements are specified for line of sight they can be incorporated into our system design guidelines
- Environmental Factors. The systems used in this tested were designed to withstand on-road environmental and Electrical conditions. Before we could warrant a system for long term use in a off-road application we would have to design and test the components to ensure that they can operate properly under off-road conditions.

Future plans

The primary market factor driving the development of the off-road version of the SCRT SCCRT is the California Off-road rule. The comprehensive nature of this rule would justify the effort necessary to develop the product so that it could be applied to the wide range of vehicle sizes and types found in the off-road market. Because of the recent decision by ARB to delay the implementation of the off-road rule, JM has also delayed the development of the product. Since we intend to develop the product to meet the revised goal of the ARB program we are still willing to participate in demonstration programs that will provide data to regulators and operators regarding the viability of SCR retrofits.