ADVANCED AFTERTREATMENT SYSTEM DEVELOPMENT FOR A LOCOMOTIVE APPLICATION

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ABSTRACT

For the first time in the locomotive industry, an advanced exhaust aftertreatment system for a locomotive application was successfully demonstrated to reduce nitrogen oxides from 6.46 g/kW·hr to 1.21 g/kW·hr to meet the needs of local NOx reduction requirements for non-attainment areas.

Five 2,240 kW (3,005 horsepower) PR30C line-haul repowered Progress Rail locomotives were equipped with diesel oxidation catalyst and selective catalytic reduction technologies to accumulate more than 27,000 hours in total in revenue service.

Full emissions performance including carbon monoxide, hydrocarbons, nitrogen oxides and particulate matter was conducted at Southwest Research Institute on a regular basis to measure the change of emissions performance for two selected locomotives.

The emissions performance of the aftertreatment system did not show any degradation during 3,000 hours operation. After 3,000 hours operation, 0.13 g/kW·hr carbon monoxide (89-91% reduction), 0.027 g/kW·hr hydrocarbons (91% reduction), 1.08-1.21 g/kW·hr nitrogen oxides (81-83% reduction) and 0.05-0.08 g/kW·hr particulate matter (38-58% reduction) were measured on the line-haul cycle. The baseline emissions levels of the engine are within Tier 2 EPA locomotive limits. The newly developed close loop control software successfully controlled targeted nitrogen oxides reduction with minimum ammonia slip during the locomotive emission cycle tests.

INTRODUCTION

In 2008 the U.S. Environmental Protection Agency (EPA) adopted more stringent emissions standards for diesel locomotives. The new standards are applied to existing and newly built locomotives depending on the date remanufactured or built. For newly built locomotives Tier 3 (2012) and Tier 4 (2015) standards will be applied. The Tier 4 standards require 80% and 90% nitrogen oxides (NOx) and particulate matter (PM) reduction, respectively compared to engines meeting the current Tier 2 standards. [1] The finalized standards resulted in bringing earlier emissions reductions of NOx from the locomotive with Tier 4 NOx requirements for line-haul locomotives two years earlier (from 2017 to 2015) than initially proposed. The motivation of tightening and early adoption of the emissions regulations for locomotives is based on locomotive diesel engines becoming significant air pollution contributors over the next few decades according to EPA estimation. This is because conventional major emissions sources including cars, trucks and nonroad vehicles have been successfully regulated with stringent emissions regulations. Aftertreatment technologies for these applications have been developed successfully to meet the challenging regulations.

Prior to US EPA Tier4 emission regulation was finalized, Caterpillar Inc. began to develop a locomotive emission solution for customers in non-attainment areas. In 1998 a Memorandum of Mutual Understandings and Agreements (MOU) between ARB (Air Resource Board) and BNSF and UP Railroads was signed, requiring fleet owners to meet fleet average NOx emissions to Tier 2 line-haul level (7.38 g/kW·hr) by 2010 [2]. In order to meet this customer’s demand Caterpillar Inc. developed PR30C line-haul locomotives designed for 1.74 g/kW·hr NOx emissions and placed them into...
demonstration service in 2009. The PR30C was equipped with a Tier 2 Caterpillar 2,240 kW 3516C-HD diesel engine and an advanced aftertreatment system.

Although Selective Catalytic Reduction (SCR) technology is considered as a new and unproven technology for the locomotive industry, the NOx abatement technologies using urea as a reductant have been well developed and widely used for various diesel engine applications including stationary gen-sets, and both on-road and non-road mobile applications. Numerous diesel engine manufacturers developed urea-SCR technologies to meet Euro IV (2005), Euro V (2008) and US On-highway truck (2010) emissions standards for their engines.

This paper covers the description of key aftertreatment technologies (substrates and washcoat) and the introduction of the first advanced aftertreatment system for a locomotive application, which successfully demonstrated meeting all functional expectations as well as significant reliability and durability for a locomotive application.

METAL SUBSTRATE TECHNOLOGY

A large portion of the operating expense of a large-bore diesel engine is fuel cost and the flow restriction of the aftertreatment system is one of the influences on fuel consumption. The additional work that the engine has to perform in order to exhaust the combustion products from the engine translates into additional fuel used.

In an effort to keep this additional flow restriction to a minimum the maximum frontal area of the catalyst within the aftertreatment system is needed. A catalyst is made up of the substrate or honeycomb and the washcoat where the chemical reactions take place. The substrate will influence the flow of the exhaust gas and provide surface area for washcoat. For the aftertreatment system tested, both round and square substrates with dimensions of 606mm were used to maximize the total catalyst volume and frontal area in available package space. Figure 1 shows these substrates:

![Figure 1: Round and square substrates with 606mm dimension](image)

An additional measure to keep the flow restriction low is a large open flow area. This pointed to a coarse cell density (100cpsi) to provide large channels for gas flow. In this cell density range traditional ceramic substrates need to have thicker walls (> 125 µm) for structural integrity. To solve this issue, Emitec thin-wall metal substrate technology was employed, allowing the combination of a thin wall (50µm thickness) at coarse cell density to maximize the open frontal area and reduce flow restriction and fuel consumption. [3] The coarse cell density also reduces the risk of face plugging. Another substantial benefit of the metal substrate technology is that the substrate is made as one piece rather than being assembled from smaller pieces as is necessary with larger ceramic bricks. This feature enhances durability and further maximizes open flow area.

SUBSTRATE CONFIGURATION

Two different types of catalysts were developed for this locomotive application: a diesel oxidation catalyst (DOC) and a selective catalytic reduction (SCR) catalyst. The final functionality of the catalyst is determined by the active coating that is applied to it. A different shape was chosen for each functionality, based on their location in the aftertreatment system. The DOC was chosen to be a round ø606x90mm, 100cpsi substrate. Four individual substrates were arranged in a 2+2 configuration (two in series with two parallel legs). The course cell density combined with the thin-walls, large frontal area and short matrix length yielded the desired low flow restriction.

A different substrate shape was chosen for the SCR catalysts. Based on the large SCR catalyst volume required and the demand for a large frontal area to keep the flow restriction low, a square shape (606x606x90mm, 100 cpsi) was used. The 4+4 configuration (four in series with four parallel legs) yielded the low flow restriction at the large catalyst volume. Compared to the ø606x90mm substrate, the square substrate provided an even larger volume per piece, keeping the number of required substrates down. For enhanced durability, the 606x606x90mm substrate were not a perfect square as seen in figure 1. Allowing for rounded corners, the durable technique of winding and brazing foil packs could be utilized.

SUBSTRATE DURABILITY

The demanding durability requirements for the locomotive application require the robust nature of the Emitec metal substrate. Not only will the aftertreatment system consistently be exposed to track and engine vibrations but locomotive shunting events will expose the aftertreatment system to considerable shock loads. The foil material is a high-grade stainless steel that provides superior high-temperature durability. The substrates are made by winding three or four
packets of foil around a common center and then brazing this honeycomb (matrix) into a mantel (tube).

This arrangement allows for each foil layer to not only be attached to the neighboring layer but also to the mantel in two places. This foil configuration eliminates telescoping, which is known to happen with spiral-wound substrates. For the square substrates, the corners were rounded off to enable the use of the same winding technique and enhancing the robustness.

To provide superior durability the substrates are brazed in two areas: the matrix within itself at inlet and outlet and the matrix to the mantel. [4] This provides structural robustness within the matrix itself and secures the matrix inside the mantel. The Emitec winding and brazing technology has been in production since 1986. Figure 2 shows the areas of brazing:

![Matrix Brazing and Mantel/Matrix Brazing](image)

Figure 2: Example of the Areas of Brazing in an Emitec Substrate [4]

An additional benefit of the metal substrate is that the substrate can be integrated into the aftertreatment system without need for a retention mat and further canning effort. The substrate mantel can be welded directly into the aftertreatment system. This reduces the overall integration effort and further increases system durability. The lack of required matting also increased the total available flow area, since a portion of the outer radius is not taken up by the retention mat and this has a positive impact on the flow restriction.

**RESONANCE FREQUENCY ANALYSIS**

During operation, vibrations are transmitted into all components of the locomotive. These vibration come from the rails and engine. The effect that these vibrations have on all the components of the system is not only determined by the amplitude of the vibration but also its frequency. Every system has a frequency at which it will start to amplify any vibrations that it is exposed to, known as the resonance frequency. If a component of the system is repeatedly exposed to its resonance frequency, the component has the potential to fail more quickly. In the case of the metal substrate, the foil material has the potential of vibrating when the part reaches its resonance frequency. This can also lead to challenges in terms of washcoat adhesion. These frequencies need to be shifted out of the frequency range during operation or to as high of a frequency as possible.

Various excitation frequencies were measured at different operation conditions including various speeds, accelerations, decelerations and couplings. Excitation frequencies at a high-speed operation (97 km/hour) on the locomotive are shown in appendix 1, figures 1 & 2. These data were generated by instrumenting a locomotive with accelerometers in different locations, including the mantels of the DOC and SCR substrates. The accelerations experienced at the mantel are important as the vibrational loads are transferred into the matrix via the mantel. The main excitation peak of the DOC substrate is observed at 121Hz in the spectrum of axial substrate direction, which is the most critical direction based on aspect ratio (ratio of diameter to length). For the SCR substrate excitation peaks are observed in the range of 116 to 135 Hz. This potential excitation frequency range of substrates is identified for further investigation to ensure the long-term durability of the aftertreatment system.

In order to have a basis of comparison, the substrates were measured using a laser scanning vibrometer (LSV). The substrate were suspended using wires to achieve a free-free boundary condition and were subsequently excited with a small shaker (stinger) in the radial direction with a frequency sweep. Figure 3 shows the test setup:

![Figure 3: Experimental setup for resonance frequency analysis. Substrate are suspended with wires and attached to stinger. Measurement points of the scanning laser is show for reference Left: ø606x90mm round; Right: 606x606x90mm square](image)

During the frequency sweep of the stinger, the substrate can be excited in several different modes, including the ovalization...
modes and the 1\textsuperscript{st} matrix mode. The former indicates a deformation of the substrate to an oval shape with either two nodes (n=2) or three nodes (n=3). The latter indicates a movement of the matrix in the opposing direction to the mantel. An example of both ovalization modes with two and three nodes and the 1\textsuperscript{st} matrix mode are shown in figures 4 and 5 respectively:

Figure 4: Left: Ovalization mode n=2 (with two nodes) of substrate; Right: Ovalization mode n=3 (with three nodes) of substrate

Figure 5: 1\textsuperscript{st} Matrix mode of substrate. Mantel and matrix are moving in opposing directions (radially)

The resonance frequency spectrum of the ø606x90mm and 606x606x90mm substrates are shown in appendix 1 (figures 3 & 4). The frequencies are also summarized in table 1 below:

<table>
<thead>
<tr>
<th>Vibration Mode</th>
<th>ø606x90mm</th>
<th>606x606x90mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ovalization n=2</td>
<td>152 Hz</td>
<td>73 Hz</td>
</tr>
<tr>
<td></td>
<td>85 Hz</td>
<td>118 Hz</td>
</tr>
<tr>
<td>1\textsuperscript{st} Matrix Mode</td>
<td>241 Hz</td>
<td>125 Hz</td>
</tr>
<tr>
<td>Ovalization n=3</td>
<td>297 Hz</td>
<td>165 Hz</td>
</tr>
</tbody>
</table>

Table 1: Summary of resonance frequencies for the round and square substrate configurations

When compared to the vibrational excitation of the application (120Hz for the round and 116 to 135 Hz for the square, see appendix 1), it is apparent that the round substrate has a resonance frequency that lies outside the excitation frequency and should not lead to any durability challenges.

The square substrate, which has a larger frontal area, exhibits a lower resonance frequency in all modes. The resonance frequencies of the square part do fall into the area of operation for the locomotive at high speed operation. This could be a possible area of concern for the long-term durability of the SCR substrates and warranted further investigation of the durability in a full-scale locomotive test.

CATALYST SELECTION

The key emissions reduction goals for the Progress Rail locomotive program was to provide sufficient NO\textsubscript{x} reduction to meet the Tier 4 NO\textsubscript{x} requirement of 1.74 g/kW·hr. A catalyst package including DOC and SCR catalysts was formulated to address the variety of environmental stresses to which the catalyst system would be exposed during the range of operating modes and situations that occur for both line-haul and switcher locomotive use. Key environmental concerns that were considered include temperature, ash accumulation and chemical deactivation due to exposure to sulfur, phosphorus, and other contaminants in the exhaust gases.

OXIDATION CATALYST TECHNOLOGY SELECTION

Although the engine meets locomotive Tier 2 HC, CO and PM requirements without aftertreatment, a DOC system was applied for optimal system performance. Potential backpressure increase caused by soot accumulation during extended idles was expected due to the low estimated turbo outlet temperature of 140°C. To mitigate this concern, a DOC with low HC light-off temperature as shown in figure 6 was selected as the first catalyst exposed to exhaust gas to reduce the soluble HC fraction of the soot at the low idle temperature, thereby reducing the risk of complete substrate face coverage. A second DOC includes some base metal oxides to more fully oxidize the soluble organic fraction (SOF) portion of the particulate matter. The second DOC includes a low loading of precious metal to oxidize any CO byproduct that results from SOF oxidation. [5]
By reducing the SOF content of the soot, the adhesion characteristics of the soot become less, reducing the risk of backpressure increase over time that results from soot buildup within channels of the catalyst substrates.

The DOC formulation selection has a significant impact on the SCR performance as well. While the sensitivity varies by SCR catalyst formulation, catalyzed NO\textsubscript{x} reduction with Ammonia (NH\textsubscript{3}) occurs with (3) fundamental reactions:

\begin{align*}
\text{NO} + \text{NO}_2 + 2\text{NH}_3 & \rightarrow 2\text{N}_2 + 3\text{H}_2\text{O} & \text{Fastest} \\
4\text{NO} + 4\text{NH}_3 + \text{O}_2 & \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O} & \text{Faster} \\
6\text{NO}_2 + 8\text{NH}_3 & \rightarrow 7\text{N}_2 + 12\text{H}_2\text{O} & \text{Fast}
\end{align*}

In terms of NO\textsubscript{3} reduction, the reaction of NH\textsubscript{3} with both NO and NO\textsubscript{2} reaction is fastest, followed by the NO only reaction. Greater than 50% NO\textsubscript{2} slows the reaction rate and increases NH\textsubscript{3} consumption, however, so dependence on the NO\textsubscript{2} only reaction should be avoided. Due to the difference in reaction rates, it is preferred to optimize the NO\textsubscript{2} at the inlet to the SCR at 50% for best SCR activity.

The DOC system oxidizes some of the engine-out NO to NO\textsubscript{2}, thereby providing a net increase in NO\textsubscript{2}/NO\textsubscript{x} ratio at the SCR inlet across a broad temperature range. The increased NO\textsubscript{2} content improves the SCR performance relative to a near NO only emissions stream. This improvement allows a net reduction in the required SCR catalyst volume, contributing to a compact catalyst package.

The net effect of this DOC system results in a significant reduction in HC, CO, and a measureable reduction in PM.
AFTERTREATMENT SYSTEM DESIGN CHALLENGES

<table>
<thead>
<tr>
<th>Aftertreatment Functional Requirements</th>
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</thead>
<tbody>
<tr>
<td>NO_x emissions</td>
</tr>
<tr>
<td>System backpressure</td>
</tr>
<tr>
<td>Vibration</td>
</tr>
<tr>
<td>Ambient temperature: continuous</td>
</tr>
<tr>
<td>Ambient temperature: intermittent</td>
</tr>
<tr>
<td>Noise limit</td>
</tr>
<tr>
<td>Altitude emissions compliance</td>
</tr>
<tr>
<td>Skin temperature</td>
</tr>
</tbody>
</table>

Table 2: The list of aftertreatment specifications

Functional requirements of the aftertreatment system are listed in Table 2. There are many technical challenges to design an aftertreatment system meeting all those requirements as well as fit into the very limited space in the locomotive body. The radiator, dynamic brake and car body have been redesigned to provide space for the aftertreatment system. A 950 L (250 gallon) urea (diesel exhaust fluid or DEF) tank was added under the body to provide DEF. This tank has to be filled approximately every 4 fuel tank fillings, based on the EPA line-haul cycle. In order to accommodate the DEF tank the fuel tank was resized from 15,000 to 12,000 L (4,000 to 3,200 gallon). Figure 8 shows the fully re-powered locomotive:

CATERPILLAR EMISSIONS MODULE DESIGN

The configuration of the aftertreatment system is shown in Figure 9:

Figure 9: Configuration of aftertreatment system (cross-section pictured to show exhaust flow path)

The aftertreatment system, patented by Caterpillar Inc.[7], is mounted directly above the engine to achieve a compact installation. The two engine exhaust turbo outlets are coupled to the two separate inlets of DOC housing. The DOC housing is designed with easily accessible doors for necessary service. While they are not expected to be replaced throughout the emissions useful life, the DOC substrates can be removed to be cleaned if necessary. After passing through DOC substrates the exhaust gets combined and then flows through a mixing tube. A specially designed mixer and an injector lance are located in the mixing tube to enhance mixing urea with exhaust gas stream. An air assisted injector system is utilized to maximize urea spray quality and minimize urea deposit and clogging issue. The air is provided by the locomotive which has an existing air compressor. The exhaust gas stream mixed with DEF runs down to the end of the mixing tube, is divided in two and passes through each SCR housing placed in parallel to the mixing tube. Perforated plates placed in front of the first SCR substrate layers with different hole sizes and several layers of SCR substrates provide the function of diffusers to achieve even flow distribution. The exhaust manifolds are installed each side of SCR outlet to protect SCR catalysts and NO_x sensors from environmental influences. Two NO_x sensor signals were averaged to serve as a complete closed loop feedback control system combined with a NO_x sensor located upstream in the mixing tube which is set for feed forward control. This complete feedback and feed forward control strategy is a key enabler to achieve targeted NO_x reduction with minimum DEF injection and tight control NH_3 slip. This aftertreatment unit demonstrated compliance with 40CFR201 noise requirement without addition of further noise abatement devices.

DEF INJECTION PUMP

The injection of DEF is a critical aspect of the system functionality. The DEF dosing rate dynamically varies according to operating conditions by close loop control. Insufficient or excess DEF will result in un-optimized NO_x performance or ammonia slip. An Emitec DME60 dosing pump was selected to supply DEF to the system. This pump has been used for pumping chemicals for many other applications. From rigorous testing including bench and vehicle the pump proved its applicability for accurate urea dosing (±2%) and durability for locomotive application.
LOCOMOTIVE DURABILITY TESTING

1) Emissions Performance

As with any aftertreatment system, the final durability check has to be done on the vehicle. For the presented case a fleet of five locomotives were equipped with working aftertreatment systems and operated in line-haul service in California and Arizona. A total of more than 27,000 hours have been accumulated on those 5 aftertreatment systems for long term durability assessment. For those hours no major issue have been reported.

Two of the locomotives (PRLX 3002 and 3004) were inspected in detail at defined intervals as well as the emissions performance of the system evaluated. Table 3 summaries the emissions data from both locomotives.

<table>
<thead>
<tr>
<th></th>
<th>g/kW-hr</th>
<th>Engine-out</th>
<th>0hr</th>
<th>3,000hr</th>
<th>% Conv. at 3,000hr</th>
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</thead>
<tbody>
<tr>
<td>PRLX 3002</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>NOx</td>
<td>6.4</td>
<td>1.1</td>
<td>1.1</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td>PM</td>
<td>0.13</td>
<td>0.09</td>
<td>0.08</td>
<td>38</td>
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<tr>
<td>HC</td>
<td>0.34</td>
<td>0.03</td>
<td>0.03</td>
<td>91</td>
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</tr>
<tr>
<td>CO</td>
<td>1.1</td>
<td>0.1</td>
<td>0.1</td>
<td>91</td>
<td></td>
</tr>
<tr>
<td>PRLX 3004</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>NOx</td>
<td>6.4</td>
<td>1.2</td>
<td>1.2</td>
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<tr>
<td>PM</td>
<td>0.12</td>
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<td>HC</td>
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<td>0.9</td>
<td>0.3</td>
<td>0.1</td>
<td>89</td>
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</table>

Table 3: The summary of aftertreatment EPA line-haul cycle emissions performance

For both locomotives the NOx emissions was maintained below 1.74 g/kW-hr with plenty of margin for extended emissions useful life. Other gas constituents including CO, HC, and PM do not show any degradation during 3000 hours operation. Except PM, all the emissions levels are below US Tier 4 standards. Although PM reduction was not in scope for this development, high PM conversion, 40-56%, was observed. When considering the Tier 2 engine calibration, this level of PM reduction is very promising. The results may warrant Tier 4 level capability for all emissions constituents with minor engine calibrations without using a diesel particulate filter (DPF) technology.

More details of the emissions results from PRLX locomotive are being presented in other bodies of work. [8&9]

2) Substrates

A detailed visual inspection of the aftertreatment system was also performed at the given intervals. The DOC substrates were removed from the aftertreatment system and visually inspected for any damage (cracked foils, mantel/matrix retention) that could be attributed to in-service conditions. All DOC substrates inspected were in good condition. No damage was found that could be attributed to the in-service conditions. Figure 10 shows the inlet and outlet sides of a DOC substrates after 3,000h of operation. A fine layer of soot is seen on the inlet of the DOC substrate. The soot is dry and loosely bonded to the surface, so it rubs off easily when the substrate surface is touched. The soot does not agglomerate into larger particles, so there is no indication of face plugging. The large channel diameter and total open frontal area of the coarse cell density also mitigated the risk of face and channel plugging.

![Figure 10: Inlet (left) and outlet (right) of DOC substrate after more than 3,000h of operation](image)

The durability of the SCR substrates was also found to be good. No mechanical defects or indications of in-service fatigue of the substrates was found. The lack of mechanical damage to the substrates reduced the concerns about the mechanical robustness of the substrates that were raised from the resonance frequency analysis.

Based on these test results, the mechanical durability of the DOC and SCR substrates for the emissions useful life is expected.

3) Aftertreatment System Body

Complete inspection was conducted on welding workmanship, bolted joints, fittings, connectors, gasket etc. There was no sign of damage or deformation. All parts were very good condition and structurally intact. Bolts were in good shape and torque met to manufacturing standards. Welds did not show any sign of cracks. Insulation was intact at all areas and did not show any wear or tear.

4) Injection System

DEF Pump, valves, and manifold showed no leakage. Wiring harness, urea tank and strainer maintained their original condition. No sign of corrosion or damage were observed. DEF injector also showed good condition. No urea deposit or clogging was observed in the injector nozzle as well as the mixing tube.

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CONCLUSION

After several years of dedicated collaboration, an aftertreatment system to reduce emissions was successfully developed and commercialized for repowered PR30C locomotives equipped with Caterpillar 3516C HD engines. This aftertreatment system demonstrated NOx emissions below Tier 4 for the first time in the locomotive industry for extended operation hours (more than 27,000 hours accumulated for 5 locomotives). The robustness of the aftertreatment system including hardware and software was proved during the validation tests at the locomotive level. Various aftertreatment components including DOC, SCR and mixing tube were compactly designed into the aftertreatment system so that it maintained the same space claim as the existing exhaust box on the locomotive but provided better sound attenuation with minimum back pressure increase. Although it is a space efficient design, the aftertreatment system emissions did not show degradation for 3,000 operation hours in the very harsh locomotive conditions that include extended idling and high vibration. The aftertreatment system was designed to control NOx emissions below Tier 4; however, the aftertreatment system provides substantial reduction of CO, hydrocarbons and PM emissions, thereby showing promising potential to meet Tier 4 legislation with minor system development.

ACKNOWLEDGEMENT

The authors would like to acknowledge the contributions made to the work presented in this paper by California Air Resources Board (ARB) for their funding for aftertreatment evaluation, Southwest Research Institute (SwRI) for their installation and validation efforts and Union Pacific Railroad Company for providing revenue service work for the locomotive demonstration.

The successful demonstration was a result of several years dedicated collaboration of Caterpillar Inc. who designed and developed the locomotive aftertreatment system, Progress Rail who redesigned the PR30C locomotives, and key suppliers, Emitec and BASF who developed catalyst substrates and washcoat, respectively.

REFERENCES


2. Memorandum of Mutual Understandings and Agreements: South Coast Locomotive Fleet Average Emissions Program between California Air Resources Board and The Burlington Northern and Santa Fe Railway Company and Union Pacific Railroad Company, 1998


APPENDIX 1

Figure 1: Acceleration data recorded on locomotive during 60 mph operation (axial substrate direction). For clarity the data has been truncated at 600Hz. Orange band shows the resonance frequency band of the DOC substrate as determined in the LSV measurement.

Figure 2: Acceleration data recorded on locomotive during 60 mph operation (FA & V: radial substrate direction; SS: axial substrate direction). For clarity the data has been truncated at 600Hz. Orange band shows the resonance frequency band of the SCR substrate as determined in the LSV measurement.
Figure 3: Resonance frequency spectrum of ø606x90mm substrate

Figure 4: Resonance frequency spectrum of 606x606x90mm substrate