Advanced Aftertreatment System Development for Locomotive Applications

Dr. Paul Park,
Caterpillar Inc, Mossville IL, USA

M. Sc. Markus Downey, Dipl. Ing. Claus Brüstle
Emitec Inc., Rochester Hills, MI, USA

Abstract

An advanced aftertreatment system for a locomotive application was successfully demonstrated for the first time in the locomotive industry to reduce NOx from Tier2 engine out level down to Tier4 level. Five 3,005 horse powered line-haul Progress Rail locomotives were equipped with diesel oxidation catalyst (DOC) and selective catalyst reduction (SCR) technologies to accumulate more than 20,000 hours in total on rail track. The emission performance of the aftertreatment system maintained and did not show any degradation for 3,000 hours operation.

Introduction

Large reductions in the emissions from passenger cars and on-road trucks have been made in the past decades, due to the implementation of advanced aftertreatment systems. The regulation for large-bore non-road and locomotive engines on the other hand have largely been met with engine management. With the phase-in of the Environmental Protection Agency (EPA) Tier 4 Final legislation for stationary and non-road engines in the timeframe of 2014 to 2016, aftertreatment systems will need to be implemented across the board. Tier 4 legislation for locomotives, starting in 2015, will require significant reductions in particulate matter and nitrogen oxide tail pipe emissions (see figure 1).
Figure 1: Nitrous oxide and particulate matter emissions limits for EPA locomotives [1]

Locomotive engines are controlled in discrete throttle settings also known as notches. These notches run from 1 to 8, with 8 being rated power and idle being 1. The EPA test cycle [1] for locomotives (figure 2) starts with a preconditioning of the engine (warm-up period) around maximum engine speed at maximum torque. After ramping down to idle, the test cycle must begin within 15 minutes. Each throttle notch is sampled for 300 seconds with the exception of notch 8, which is sampled for 600 seconds (10 minutes). Depending on if the locomotive is being certified as a line-haul or switcher locomotive, different weighting factors are assigned to each notch and the cycle average is calculated.
Separate from the EPA Tier 4 locomotive legislation, a memorandum of understanding (MOU) was signed in 2008 between the California Air Resources Board (CARB) and the two class I rail road's Union Pacific and BNSF, to reduce the fleet-average NOx emissions in the South Coast Air Quality basins to EPA locomotive Tier 2 line-haul levels (7.4 g/kW\*hr (5.5 g/bhp\*hr)) by 2010. [2] In support of this MOU Caterpillar developed and commercialized a DOC+SCR aftertreatment system for a repowered line-haul locomotive. [3,4,5]

While urea SCR has been state-of-the-art NOx abatement technology for heavy-duty trucks in Europe and the United States for many years, the application of this technology to locomotive application is novel. The challenge of urea SCR NOx abatement is that a system with passive catalysts in no longer sufficient. Ammonia is required to react with the NOx on a catalyst surface. Urea is used as a precursor to ammonia. Conversion of the urea to ammonia and the mixing of the ammonia and NOx are significant challenges that need to be met.

**Substrate Technology**

With aftertreatment systems being novel in the locomotive industry, robustness and low flow restriction are among the most important factors in choosing all components of the final system. The catalyst is made up of two main components: First the wash coat,
where the chemical reactions take place; secondly, the substrate will influence the flow of exhaust gas through the channels with providing geometric surface area for the wash coat.

Emitec’s metal substrate technology was chosen for this application based on the company’s long history of producing robust metal substrates with low flow restriction. The demand for low flow restriction dictated the use of substrates with a large frontal area. Based on the substrate technology that has been used and refined since 1986, new substrate sizes and shapes were developed for this application. A radial dimension of 606mm was defined to fit the aftertreatment system. Two different shapes were used, depending on the functionality of the catalyst: round was chosen for the DOC and a square with rounded corners (“theta” shape) for the SCR. Both of these substrates are shown in figure 3:

![Image of substrates with 606mm dimension](image)

Figure 3: Round and theta-shaped substrates with 606mm dimension for DOC and SCR functionalities respectively

In addition to the large frontal area, a coarse cell density of 100 cpsi was used to maximize the open flow area and keeping the flow restriction as low as possible. One of the advantages of metal substrate technology is that even at a coarse cell density, a thin wall thickness can be used. [6] For this application a 50µm thick foil material was chosen. These factors potentially reduce the risk of face plugging as well.

Both the round and theta shaped substrates are one piece substrates. Unlike ceramic brick of sizes larger than about 300mm diameter, which need to be glued together from smaller segments, the metal substrates are of a one-piece construction. This eliminates
the loss of flow area due the interface between segments as well as the potential area of failure at the interface.

**Substrate Durability**

The high durability requirements of the locomotive application demand the use of the most durable substrate technology. The aftertreatment system and substrates will not only be exposed to engine and track vibrations but also be exposed to potentially high shock loads during coupling events. The patented three stack winding technique (SM-winding) that has been successfully used by Emitec since 1991, was applied for the large diameter (ø606mm).

For the theta shaped substrate, a four stack winding technique was developed. Four stacks of foil were wound around a common center. An additional round matrix piece was added in the center to facilitate the filling of the cross-section (figure 4). This allows the corners for the substrates to be filled, while retaining the robust winding technique.

![Theta shaped substrate with four stack winding technique](image)

**Figure 4: Theta shaped substrate with four stack winding technique**

Both the three- and four-stack winding patterns allow the foils to be attached not only to both adjacent foil layers but also to the mantel on each end of each foil. This configuration eliminates the issue of telescoping that can be present in spiral wound substrates.

To provide superior durability, the substrates are brazed in two areas: first, the matrix is brazed within itself at the inlet and outlet; secondly the matrix is brazed to the mantel
(tube). [6] Brazing the substrate in these areas provides structural integrity within the matrix and secures the matrix inside the mantel. Both the matrix brazing and the mantel/matrix brazing can be tailored specifically for different applications (i.e. higher flexibility for high thermal transients). Figure 5 shows an example of the areas of brazing:

![Matrix Brazing](image)

![Mantel/Matrix Brazing](image)

Figure 5: Examples of the Areas of Brazing in an Emitec Substrate [6]

**Caterpillar Emissions Module**

The aftertreatment system is patented by Caterpillar Inc. [8] A cross-section is shown in figure 6:
Figure 6: Configuration of aftertreatment system (cross-section pictured to show exhaust flow path) [8]

Since the Caterpillar 3516C-HD engine has a turbo-charger for each bank of cylinders, the aftertreatment system is initially a dual leg system. The round DOC substrates are arranged in a 2+2 substrate (2 parallel flows with 2 substrates in series) configuration closest to the turbo-charger turbine outlets. After the flows combine in the center mixing pipe, where the urea is injected, the exhaust flow reaches the banks of SCR substrates. The “theta” shaped SCR substrates are arranged in a 4+4 substrate (4 parallel flows with 4 substrates in series) configuration. The large substrate volume of the “theta” shaped substrate was able to keep the total number of substrates down, even with the large required total SCR volume. The aftertreatment system is arranged conventionally downstream of the turbine outlet. Advanced future systems may have an installation upstream of the turbine saving package space, weight and substantial cost [9]

The aftertreatment system installed on a repowered locomotive is shown in figure 7:
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 NOx performance or ammonia slip. An Emitec DME60 dosing pump (figure 8) 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.
Resonance Frequency Analysis

During operation, vibrations are transmitted into all components of the locomotive. These vibrations are induced by the rails and the 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 of the system or to as high of a frequency as possible.

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. Measurement points of the scanning laser are shown for reference. Figures 9 & 10 show the test setup:

![Diagram of Scanning Laser Vibrometry Setup](image)

Figure 9: Schematic of Scanning Laser Vibrometry Setup to Determine the Resonance Frequency of the Substrates
Figure 10: Experimental setup for resonance frequency analysis.

During the frequency sweep of the stinger, the substrate can be excited in several different modes, including the ovalization modes and the 1st 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 1st matrix mode are show in figures 11 and 12 respectively:

Figure 11: Left: Ovalization mode n=2 (with two nodes) of substrate; Right: Ovalization mode n=3 (with three nodes) of substrate
Figure 12: 1st Matrix mode of substrate. Mantel and matrix are moving in opposing directions (radially)

<table>
<thead>
<tr>
<th>Vibration Mode</th>
<th>(\sigma606\times90\text{mm} )</th>
<th>606\times606\times90\text{mm}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ovalization n=2</td>
<td>152 Hz</td>
<td>73 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>85 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>118 Hz</td>
</tr>
<tr>
<td>1st 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: Resonance frequencies of the round DOC and "theta" shaped SCR substrates as determined by LSV measurement

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 figures 13 for the DOC substrate and figure 14 for the SCR substrate:
Figure 13: Acceleration data recorded on locomotive during 60 mph operation (axial substrate direction). For clarity the data has been truncated at 600Hz. The shaded band shows the resonance frequency band of the DOC substrate as determined in the LSV measurement.

Figure 14: 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. The shaded band shows the resonance frequency band of the SCR substrate as determined in the LSV measurement.

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.

**Substrate Component Durability Testing**

With the development of a new substrate size or shape, some component level testing is important to characterize the fatigue behavior of the substrate. The 606mm diameter of the round DOC substrate was above the current experience range and for the “theta” shape both the 606mm dimension and the substrate shape were new. So both substrates were tested on the shaker bench.

The challenge in an component level test is to find a correlation between the results of the bench test and the durability in the real world application. [10] A component test needs to replicate the failure mechanisms seen in the application. If the test is too severe, new failure mechanisms can be introduced, that do not occur in real life. Since the application of an aftertreatment system to the locomotive is novel, no application field data is available for comparison, making the a fatigue life prediction from the shaker test a real challenge. For this work the component testing gave a durability behavior of the substrates under given boundary conditions and also yields a baseline durability for any potential changes made to the substrate (brazing configuration, etc).

The high aspect (diameter over length) ratio of the substrates (606mm diameter to 90mm length) indicate the axial direction as the “worst-case” direction. A horizontal shaker setup was used and is shown in figure 15:

![Horizontal shaker setup for round substrate](image)

Figure 15: Horizontal shaker set up for round substrate
During the application of the vibration spectrum, the substrate was also heated via a hot gas flow from a burner rig to simulate the elevated operating temperatures that will be seen in the application. Based on the acceleration data that was recorded on locomotive, a vibration profile was derived for the component test. An individual spectrum was derived for the round DOC and “theta” shaped SCR substrates based on their location in the aftertreatment system (reference figure 6).

During the test, the substrates were observed to show considerable flexing in the axial direction. Under the applied boundary conditions, both the DOC and SCR substrate showed a fatigue life of around 20 hours. The main damage that was seen was fractures in the foil material. No indication of mantel/matrix separation were seen. Further evaluation of the tested substrates show damage consistent with low-cycle fatigue, indicating an overstressing of the foil material.

As already mentioned, the lack of durability data from the field makes it difficult to extend these test results to a fatigue life on the locomotive. The results of the inspections of the aftertreatment systems in the locomotive test fleet will give more insight into the real stresses in the application.

Results

1. Emissions Performance

From the test fleet of five repowered locomotives, two were called back to the rail yard at Southwest Research Institute in San Antonio TX for a more detailed characterization of the emissions reduction performance. The hydrocarbon (HC), carbon monoxide (CO), oxides of nitrogen (NOx) and particulate matter (PM) reduction levels were determined in the EPA line-haul locomotive cycle in fresh condition and at defined intervals for locomotives PRLX 3002 and PRLX 3004. More details of the testing procedures has been discussed in two publications by J. Osborn, et al. [3,4] Figures 16 & 17 show the emissions reduction performance for the two locomotives PRLX 3002 and PRLX 3004 after 3000h respectively:
Figure 16: Emissions Performance of Locomotive 3002 in EPA Line-Haul Cycle after 3000h

Figure 17: Emissions Performance of Locomotive 3004 in EPA Line-Haul Cycle after 3000h
As can be seen in the previous figures, the HC and CO reductions of both locomotives were around 90% after 3000 hours. The NOx reductions were 83% and 81%. Even the PM emissions were reduced between 38% and 58%. The emissions reduction performance was shown to be stable in the 3000h inspection interval.

Even though this repowered locomotive system was not intended to meet the EPA Tier 4 locomotive line-haul legislation, all emissions other than PM were within the legislation specified limits. Figure 18 shows a comparison of the PM and NOx emissions performance from the two test locomotives to the EPA Tier 4 standard, both relative to the line-haul cycle:

![Graph showing PM and NOx emissions performance](image)

**Figure 18: Comparison of Emissions Performance of PRLX 3002 & 3004 Locomotives to EPA Tier 4 Locomotive Line-Haul Emissions Standard**

It is evident that both aftertreatment systems meet the Tier 4 NOx standard. Both are about 30% lower than the standard. The PM emissions on the other hand are above the Tier 4 standard. Locomotives 3002 and 3004 are 37% to 50% higher than required. Keeping in mind that this aftertreatment system in conjunction with the Tier 2 certified Caterpillar 3516C-HD (69 liter displacement) engine was developed for NOx reduction, this PM reduction efficiency is an excellent result. With additional engine measures to reduce the engine-out PM emissions, it should be possible to fulfill the EPA Tier 4 line-haul standards.
2. Substrate Durability

The DOC substrates were removed from the housing and inspected for any signs of damage (mantel/matrix retention, foil cracks) that could be attributed to in-service conditions. All substrates inspected were in good condition. No damage was found that could be attributed to the in-service condition. A fine layer of soot was found covering the inlet side of the DOC. This soot is dry and loosely bound to the surface. It rubs off easily when the substrate surface is touched. There is no indication of face plugging, as the soot does not agglomerate into larger particles. Figure 19 shows the inlet and outlet faces of a DOC substrate after 3000h of operation:

![Image](image_url)

Figure 19: Inlet (left) and outlet (right) faces of DOC substrate after 3000h of operation

Also no durability issues were found on the SCR substrates. There was no indication of fatigue from in-service conditions. The lack of mechanical damage reduced the concerns that were raised by the resonance frequency analysis.

The DOC and SCR substrates are expected to be mechanically robust for the emissions useful life.

3. Emissions Module Durability

Complete inspection was conducted on welding workmanship, bolted joints, fittings, connectors, gasket etc. There was no sign of damage or deformation. All parts were in 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 Durability

DEF Pump, valves, and manifold showed no leakage. Wiring harness, urea tank and strainer maintained their original condition. No signs 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 which demonstrated good flow guidance and mixing performance.

Conclusion

A DOC+SCR aftertreatment system for a repowered 3,005hp line-haul locomotive was developed and commercialized. The test fleet of 5 locomotives accumulated more than 20,000h of operation without any durability issues. A detailed characterization of two locomotives showed stable emissions reduction performance in a 3,000h operation interval. With the exception of PM, all tail-pipe emissions met the EPA Tier 4 line-haul locomotive cycle. Further improvements on the engine-out PM emissions should allow the remanufactured locomotive to meet Tier 4 limits. Both the metallic DOC and SCR substrates were found to be in excellent mechanical condition after 3000h of operation.

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


