# Global Emissions Management

## Focus on Selective Catalytic Reduction (SCR) Technology

Special Feature
February 2012

**Contents**

Follow the development and progress of SCR technology as featured in articles published in Global Emissions Management from 2002 to 2011.

JM
Johnson Matthey

# Advanced Catalysts for Combined (NAC + SCR) Emission Control Systems

Photo: courtesy of Daimler AG

Systems to reduce emissions of nitrogen oxides ($NO_x$) from vehicles are now well established, generally based on single technologies, either selective catalytic reduction (SCR) or $NO_x$ adsorber catalysts (NACs). Global Emissions Management looks at work to combine the two to achieve even higher $NO_x$ conversions than each of the separate technologies.

## Introduction

NAC and SCR systems have advantages depending on operating conditions. NAC systems utilise on-board diesel fuel to reduce $NO_x$ emissions but need complex engine control strategy and platinum group metal (PGM) catalysts that can add significant cost. SCR systems can achieve high $NO_x$ reductions at a wider operating temperature window, but require a reductant such as urea.

Ammonia ($NH_3$) can be generated over a NAC under certain conditions during $NO_x$ regeneration. By placing an SCR catalyst downstream of the NAC, the SCR component can store the ammonia and make use of it to reduce $NO_x$ that slips through the NAC under lean operation conditions. Such a combined system can thereby achieve a higher overall $NO_x$ conversion and may require less frequent $NO_x$ regeneration. Other potential benefits are the possibility of reducing secondary emissions such as $NH_3$ and $H_2S$, as well as the opportunity to reduce the amount of PGM on the NAC component.

Combining the two technologies gives rise to different requirements to those when they are operating individually. For example $NH_3$ formation over the NAC can be desirable in a combined system, although it is not when operating alone. For an SCR catalyst in an SCR-only system, high $NH_3$ storage capacity could potentially complicate the urea injection strategy, but in a combined system could significantly improve the overall efficiency of the system.

## Experimental

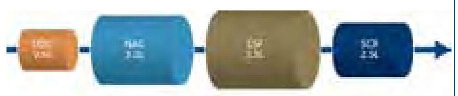
Core samples of both NAC and SCR catalysts were tested separately in a laboratory reactor capable of switching between lean and rich gas mixtures. The gas flow rate was maintained at 6.4L/minute, giving a gas hourly space velocity of 30,000h-¹, and $NO_x$ conversion efficiency of the NAC was measured under 60 seconds lean and 5 seconds rich cycling conditions at different temperature set points. At each temperature, 25 lean/rich cycles were repeated to allow the catalysts to reach their steady state. Average conversions were measured over the last five cycles. Steady state $NO_x$ reduction efficiency of the SCR catalysts was measured as a function of catalyst bed temperature.

Following the testing of individual catalysts, the combined system was tested under the same conditions as the NAC only test. It was then aged under lean/rich cycle conditions at 600˚C for twelve hours to test SCR catalyst durability. Cycle frequency was changed to five seconds lean and 15 seconds rich to simulate conditions required to desulphate the NAC component. After ageing the SCR catalysts were evaluated individually and as part of combined systems.

## Vehicle Evaluation

Performance of the catalysts was evaluated on a 3.0L 2007 Mercedes E320 Bluetec car equipped with a NAC + SCR emissions control system. The diesel oxidation catalyst (DOC) had a Pt:Pd ratio of 2:1 with a loading of 105 g/ft³, and the 84 g/ft³ NAC had a Pt:Pd:Rh ratio of 10:8:3. The catalysed soot filter had a Pt loading of 20 g/ft³, and was followed by a copper SCR catalyst.

Figure 1: Diagram of catalyst configuration as equipped on the test vehicle.



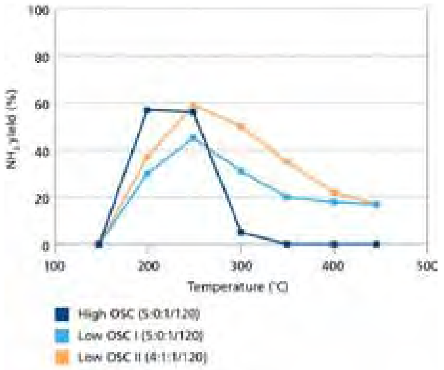
To evaluate the system's performance, all of the catalysts were aged and then subjected to repeat cold start FTP-75 tests preconditioned by two hot start FTP-72 tests. Samples were taken after the NAC and the SCR catalyst to measure the $NO_x$ conversion efficiency of the components. $NH_3$ concentration after each of the catalysts was also measured.

## Catalysts to Improve $NH_3$ Formation

In NAC only systems, $NH_3$ produced either under $NO_x$ regenerations or desulphation conditions would be seen as a secondary (undesirable) emission. To minimise $NH_3$ generation, oxygen storage capacity (OSC) in the catalyst is generally high. In a combined system however, a catalyst with low OSC is a way of forming $NH_3$ for the SCR section to utilise.

Two catalysts with the same PGM loadings but different OSC were tested to compare $NH_3$ yield as a function of temperature. Figure 2 shows that at lower temperatures, the high OSC catalyst produced more $NH_3$, whereas the low OSC product generates more in the range above 350˚C. Based on this data, a new (Low OSC II) catalyst containing 80g/ft³ Pt, 20g/ft³ Pd and 20g/ft³ Rh was developed, with similar OSC content to the Low OSC I product, but with palladium added to promote $NO_x$ reduction. As Figure 2 shows, low temperature $NH_3$ formation was similar to the high OSC catalyst, and significantly better than Low OSC I at higher temperatures.

Figure 2: $NH_3$ yield as a function of temperature over different NAC components under the standard NAC testing conditions.

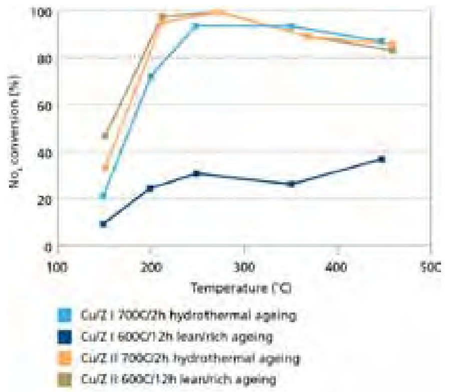


## Improved SCR catalyst Durability

High $NH_3$ storage capacity and good low temperature SCR activity are two highly desirable features for an SCR catalyst in a combined NAC + SCR system. Of the catalyst types previously discussed in GEM (November 2010 Update), the generally higher $NH_3$ storage activity and better low temperature activity of copper zeolite (Cu/Z) catalysts suggests that they could be most appropriate in this situation.

A major limitation preventing them from being used in combined systems however is that they are not durable after being exposed to lean/rich cycles at high temperatures. To overcome this, a new support material was developed, giving excellent durability to the new Cu/Z II catalyst after hydrothermal ageing, as seen in Figure 3.

Figure 3: Comparison of a newly developed Cu SCR catalyst (CU/Z II) with a commonly available Cu zeolite catalyst (CU/Z I) after exposure to different ageing conditions.



## Evaluation of Combined Systems

Two combined NAC + SCR systems were evaluated on a laboratory reactor, both using the newly developed Low OSC II NAC component. An iron zeolite SCR catalyst was placed downstream in one system, and in the other a Cu/Z II part was used. A third test was carried out on a NAC component on its own, for the purposes of comparison. Figure 4 shows the greatly improved (~20%) efficiency of the Cu/Z II catalyst at 200˚C as a result of improved durability and low temperature activity.

The next step was to evaluate the chosen components on a vehicle, a 3.0L 2007MY E320 Bluetec. The NAC was based on the Low OSC II formulation detailed above, but with a relatively low PGM loading (Pt:Pd:Rh = 10:8:3 at 84g/ft³). This was selected to demonstrate the potential for cost reduction and to demonstrate the high $NO_x$ conversion possible from the Cu/Z II SCR component.

$NO_x$ conversion over the NAC was 76%, with 73% of the remaining 24% being converted over the SCR catalyst. This equates to an overall $NO_x$ reduction of 93% over the combined system. The SCR out trace on Figure 5 clearly demonstrates that the $NH_3$ storage capacity of the new SCR catalyst is sufficient to use the $NH_3$ generated over the NAC.

Figure 4: Cycle $NO_x$ conversion as a function of gas inlet temperature under the standard NAC testing conditions.

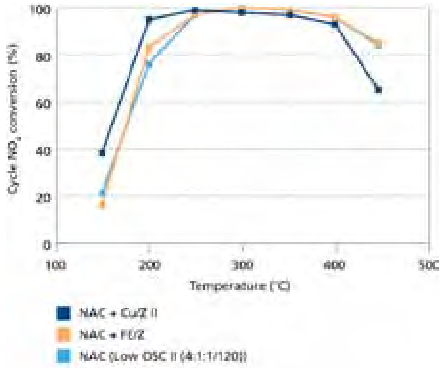
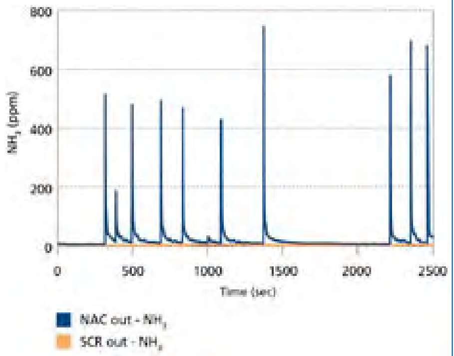


Figure 5: The typical $NH_3$ concentration measured from the outlet of the NAC component or from the tailpipe during an FTP test.



## Summary

Newly developed NAC and SCR components have shown that very high $NO_x$ reductions can be achieved when they are designed to work together. The $NO_x$ conversion seen with this combined system was achieved without any optimisation of the engine control strategy, so it is possible that system performance could be further enhanced.

A copy of the technical SAE paper 2010-01-0302 on which this article is based, can be bought via the SAE International website.

# Selective Catalytic Reduction: The $NO_x$ Removal Method of Choice from Passenger Cars to Power Plants

There is continued focus on controlling the emissions of pollutants from engines around the world. The Three Way Catalyst (TWC) has been successfully removing carbon monoxide (CO), hydrocarbon (HC) and nitrogen oxide ($NO_x$) emissions from gasoline engines since the early 1970s. These catalysts operate under so-called stoichiometric conditions, in which there is a balance between the respective concentrations of oxidising and reducing species in the vehicle exhaust. This means that both oxidation (CO to $CO_2$ and HC to $CO_2$ and water) and reduction ($NO_x$ to nitrogen) reactions can be carried out simultaneously, leading to the very high conversions (over 90%) seen in these systems.

The control of emissions from diesel engines presents additional challenges, since the gaseous environment in which the catalyst needs to operate is strongly oxidising. This means that, providing the temperature is high enough, the oxidation of CO and HC are both strongly favoured, but the reduction of $NO_x$ is not. This challenge of $NO_x$ reduction under highly oxidising conditions has led to the development of two sets of catalyst, both capable of carrying out this function.

In $NO_x$ adsorber catalyst (NAC, also called lean $NO_x$ traps) operation it is acknowledged that it is easier to reduce $NO_x$ under reducing conditions. These catalysts store $NO_x$ (as nitrate species) on the catalyst during normal (oxidising) engine operation, and then reduce it to nitrogen by moving the engine operation for a short time (a couple of seconds or so) to a state in which it emits a net reducing gas stream. The high levels of hydrogen, CO and HC emitted during this engine mode react and reduce the $NO_x$ species on the catalyst, generating nitrogen. This strategy was successfully introduced by Cummins in the 2007 diesel-powered Chrysler Dodge Ram vehicle in North America, using Johnson Matthey catalysts. The alternative approach, which continues to find more widespread application, is selective catalytic reduction (SCR). This strategy uses a reductant species that prefers to react with $NO_x$ rather than the far more plentiful oxygen – hence "selective reduction". The reductants normally present in the exhaust from diesel engines (hydrogen, CO and HC) strongly prefer to react with oxygen, so these are not suitable species, especially when high $NO_x$ conversions are required. However, many years ago it was discovered that, over certain catalysts, ammonia is highly reactive with $NO_x$, even when excess oxygen is present. This reaction proceeds as outlined in Equation 1:

$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O$$

This approach has been used, in association with vanadium-based catalysts, to control $NO_x$ emissions from power plants for many years. In coal-fired power plants the exhaust can contain a significant amount of fly ash, which can lead to catalyst abrasion and blockage, thereby increasing backpressure. These are significant problems when conventional coated catalysts (in which a relatively thin layer of catalyst is coated onto an inert substrate, such as the cordierite used in automotive applications) are used. There are other options. One is to use a plate catalyst, a coated steel substrate which is then shaped and stacked in a manner that optimises catalytic activity to pressure drop. A second approach is to use extruded catalysts, in which the whole catalyst is made of active material. In these extruded catalysts if the top layer of catalyst is abraded away it simply reveals further active material below, which greatly increases catalyst longevity. A further benefit of using extruded catalysts is that they have a higher specific activity, since there is more effective catalyst volume per unit volume than is the case in conventional coated products.

These extruded vanadium-based catalysts are also used to control $NO_x$ emissions in a wide range of applications including: industrial processes ranging from cement kilns to coffee processing to green houses; power generation including coal, waste and biomass-fired power plants; gas turbines; stationary engines running on diesel, gas or bio oil; and ship propulsion using large engines or boilers.

Large coal fired power plants are the most significant point sources of air pollution. To remove more than 90% of $NO_x$ from the exhaust, SCR is required, which has the synergistic effect of oxidising mercury, making it easier to contain. The move towards renewable fuels, combusting biomass and waste, have brought new challenges, but JM and its partners have designed catalyst systems to successfully deal with this. In commercial greenhouses all the main products of diesel engine combustion, $CO_2$, heat and electricity are utilised. Valuable green electricity is exported to the grid whilst the heat from the engine helps maintain optimum temperature for growth. The $CO_2$ acts as a feed, although $NO_x$, CO and unburned fuel cause problems such as spoilage and are removed from the exhaust by a combination of oxidation and SCR catalysts.

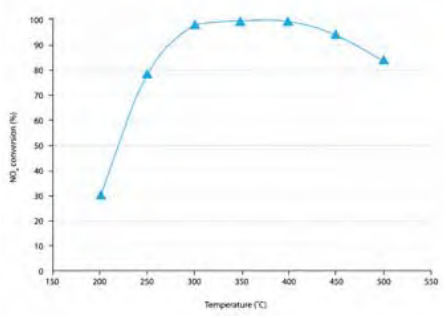
Ships continue to use fuel with high levels of sulphur and produce significant emissions of $NO_x$ and $SO_x$ (oxides of sulphur). European studies have predicted that emissions from marine sources will overtake those on land by 2020. Regulatory bodies and the IMO (International Maritime Organisation) have acted and by 2016 new build vessels operating in Emission Control Areas will have to reduce their $SO_x$ and $NO_x$ emissions significantly. The use of lower sulphur fuels will solve the $SO_x$ problem but aftertreatment such as SCR will be required for the 80% reduction in $NO_x$. Norway, whose coastline is particularly vulnerable, established the "$NO_x$ Fond" to reduce emissions in 2007. This has stimulated an early market for marine SCR, with hundreds of vessels from tankers to fishing vessels being fitted – many with Johnson Matthey's SINOx® systems and catalysts.

Vanadium-based catalysts are very effective, since they enable high conversions of $NO_x$ over a wide operating temperature range, as shown in Figure 1.

In addition, they are highly resistant to inhibition from the other gas phase species present in exhaust streams, such as CO and HC, and they are also tolerant of the sulphur species that can be present at high concentrations in some applications (e.g. marine).

In 2005 the Euro IV regulations were introduced for heavy duty diesel (HDD) vehicles in Europe, requiring significant reductions in both $NO_x$ and particulate matter (PM, also called diesel soot). The majority of engine manufacturers met these emission standards by calibrating their engines to emit very low levels of PM and using vanadium-based SCR catalysts to reduce the $NO_x$ emissions. Such engine calibrations also result in optimum engine fuel economy, which is both good for the operator and for the vehicle's $CO_2$ emissions (which are also minimised). Both coated and extruded vanadium-based catalysts were used to meet these Euro IV and the subsequent Euro V (2008) HDD emission regulations. Successful operation for one million kilometres has been demonstrated by such systems [1].

Figure 1: Typical Operating Temperature Window of Vanadium-based SCR Catalysts

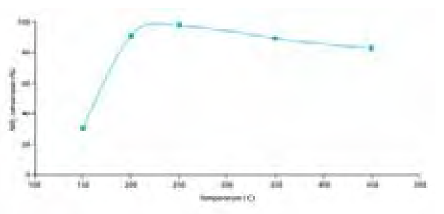


Since engines do not emit ammonia, the ammonia for these applications is derived from aqueous urea, which is carried in a separate tank on board the vehicle. In HDD applications this tank is replenished periodically by the driver, at the thousands of outlets of aqueous urea at vehicle depots, service centres and gas stations globally. Ammonia is generated from urea as outlined in Equation 2.

$$(NH_2)2CO + H_2O \rightarrow 2\ NH_3 + CO_2$$

In North America the EPA introduced its 2010 (EPA10) emission regulations for both light and heavy duty diesel applications. These regulations are met by using a combination of diesel particulate filters (DPFs) to control PM emissions and SCR to remove $NO_x$. Filters generally use high temperature active regeneration to remove the soot that builds up in the DPF during normal operation. This active regeneration involves raising the temperature of the DPF to around 600° C, at which temperature the oxygen in the exhaust reacts rapidly with the trapped soot to clean the filter and to form $CO_2$. As a consequence of this DPF active regeneration process, the SCR catalysts used in such combined DPF + SCR systems need to be able to withstand very high temperatures. Vanadium-based products do not have the required thermal durability, so alternative SCR catalysts based on iron and copper zeolite are used. As an example, Figure 2 shows that copper zeolite catalysts have outstanding activity even following prolonged exposure to high temperature.

Figure 2: SCR Performance of Cu/Zeolite SCR Catalyst Following Ageing at 670˚C for 64 Hours



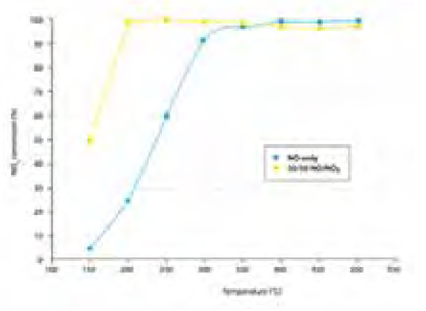
These combined DPF + SCR systems, which will also be used to meet future HDD and light duty diesel emissions regulations in Europe, are able to remove all four major pollutants, CO, HC, $NO_x$ and PM, with efficiencies exceeding 90%. An additional benefit of combining DPFs with SCR is that the oxidation catalysts that form an integral part of the DPF system convert some of the engine-out NO into $NO_2$, and this $NO_2$ promotes the low temperature performance of the downstream SCR catalyst, by the reaction shown in Equation 3, as illustrated in Figure 3 for an Fe/Zeolite catalyst.

$$2\ NH_3 + NO + NO_2 \rightarrow 2\ N_2 + 3\ H_2O$$

In conclusion, it is clear that SCR systems are pivotal technology for present and future $NO_x$ control systems, and will be used for years to come in a wide range of applications from passenger cars, through trucks and buses, to power plants, locomotives and ocean-going ships. Johnson Matthey has invested in world class facilities for development and manufacture of coated, extruded and plate SCR catalysts, and is well positioned to play a key role as demands from these sectors increase over the coming years.

References [1] Long Term Experiences with HDD SCR Catalysts, A Funk, M Brandmair and L Hofmann, DEER Conference 2008, Dearborn, MI

Figure 3. Promoting Effect of $NO_2$ on the SCR Reaction Over Fe/Zeolite SCR Catalyst



# Development of Thermally Durable Copper SCR Catalysts

Copper zeolite SCR catalysts are being used to meet tighter $NO_x$ standards around the world. Global Emissions Management looks at work undertaken to improve their thermal stability by stabilising ammonia storage capacity. SAE paper 2009-01-0899, given at the 2009 SAE World Congress, describes the development of a new generation of SCR catalysts.

## Introduction

Three types of selective catalytic reduction (SCR) catalysts used in urea-SCR systems are showing great potential for use in original equipment systems in diesel powered engines. Vanadium based catalysts have been used successfully in OEM and retrofit applications in Europe to meet the Euro IV and V emissions standards. Iron (Fe) and copper (Cu) zeolite catalysts are also being developed, as the performance of vanadium based catalysts deteriorates significantly after ageing at high temperatures (e.g. greater than 650°C). The Fe and Cu based SCR catalysts are required in exhausts with actively regenerating diesel particulate filters (DPFs) as the catalysts will be exposed to these high temperatures during the active regeneration process.

Although $NO_x$ conversion over Fe zeolite catalysts is high at temperatures over 350°C, at lower temperatures more typical for normal diesel engine exhaust, high conversions are only obtained in the presence of high levels of $NO_2$. For many applications (particularly in the heavy duty diesel area) this is not an issue, because the upstream DPF system is designed to maximise passive filter regeneration, which involves the generation and use of $NO_2$ in this upstream system. The $NO_2$ that leaves the filter system then promotes the low temperature performance of the downstream Fe- or Cu-based SCR catalyst.

Cu zeolite catalysts are able to achieve high $NO_x$ conversions at low temperatures in the absence of $NO_2$. Although Cu catalysts are not as effective as Fe-based catalysts at higher temperatures, this deficiency can be compensated for by increasing the amount of urea injected into the system. Considerable work is therefore being carried out on copper catalysts in order to realise the potential that they hold for implementation in commercial systems.

Long term hydrothermal stability of Cu SCR catalysts has been a concern, with $NO_x$ conversions suffering particularly after exposure to high temperatures in the presence of moisture (significant levels of water vapour are always present in engine exhaust). Zeolite dealumination, copper sintering and thermally-induced zeolite collapse are the three key deactivation mechanisms, and these are investigated below.

## Investigation

A previous generation, degreened Cu Zeolite catalyst was tested in a lab reactor at a temperature of 200°C, a space velocity of 30,000h$^{-1}$, and an NO-only feed (i.e. no $NO_2$). The resulting steady state $NO_x$ conversion was 94%. This level of $NO_x$ reduction was also seen in engine tests prior to high temperature ageing. However, after just 64 hours ageing at 670°C, the catalyst showed noticeable degradation, with $NO_x$ conversion dropping by around 10%. The importance of testing in this range is that aftertreatment systems with actively regenerated filters either upstream or downstream could expose the SCR catalyst to temperatures greater than 600°C. Further testing was carried out to determine degradation beyond 64 hours. This testing showed a slower rate of decline in $NO_x$ conversion in the subsequent ageing, suggesting that a majority of the deactivation occurs in the early stage of ageing. Significant improvement in thermal stability of Cu zeolite catalysts is therefore needed.

> "Dealumination is the key parameter in catalyst deactivation"

Acidity, Cu dispersion and zeolite crystallinity were analysed as a function of catalyst ageing to determine the most likely cause of this deactivation. Structural stability of the zeolite was tested by x-ray diffractometry and surface area measurements. Catalyst crystallinity declined gradually over time, although it was still around 60% of initial values after 500 hours.

Figure 1: Catalyst B relative $NH_3$ storage capacity (at 200°C) with increasing hydrothermal ageing time at 670°C compared to Catalyst A

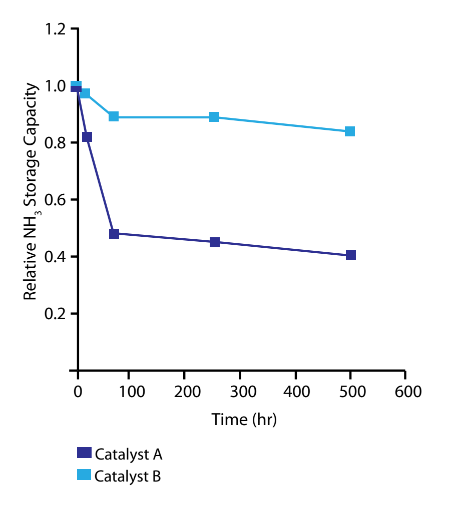


Figure 2: Steady-state SCR performance of Catalyst B after severe hydrothermal ageing at 900°C (SV = 30,000 h$^{-1}$)

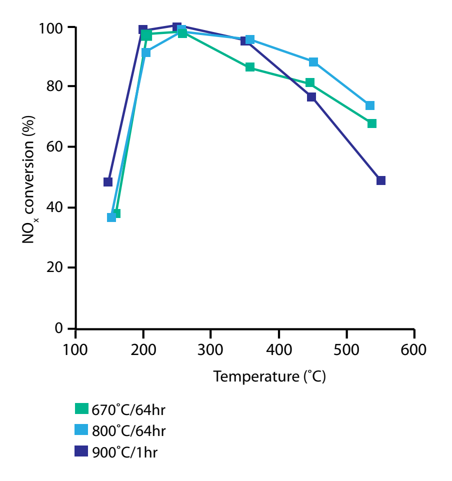


Figure 3: Steady-state SCR performance of Catalysts A (hydrothermally aged at 670°C for 64 hours) and B (hydrothermally aged at 800°C for 64 hours) on engine

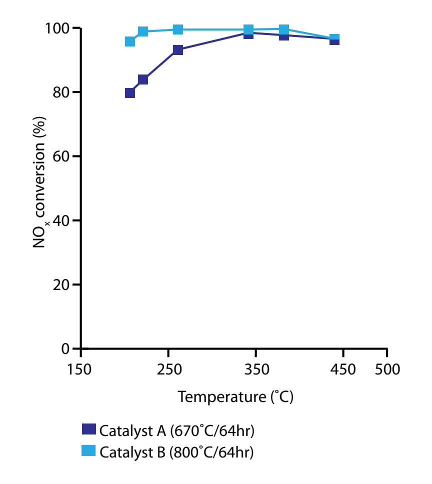
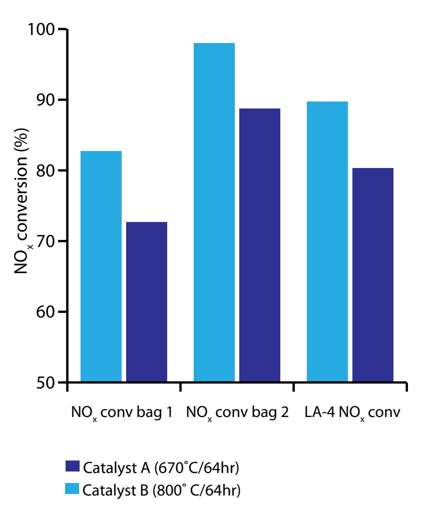


Figure 4: $NO_x$ conversion over the LA-4 cycle for Catalyst A (aged hydrothermally at 670°C for 64 hours) and B (aged hydrothermally at 800°C for 64 hours)



Copper dispersion also showed a steady, gradual deterioration with time. The surface area of the catalyst actually showed a slight increase with age.

Ammonia ($NH_3$) storage capacity (Figure 1) was used to determine the catalyst acidity, with the results showing a similar pattern to the ageing tests. The retention of surface area, along with the low rate of decline in copper dispersion, suggests that catalyst activity should still be maintained as a result of reactants being able to diffuse in the zeolite to the active metal sites.

The sharp initial decline in catalyst acidity and the correlation of the acidity loss with activity loss pointed to the former as the main deactivation mechanism during thermal ageing. This acidity loss is likely due to zeolite dealumination.

This leads to the conclusion that dealumination is the key parameter in catalyst deactivation.

## Catalyst Development

Given these results, development work was undertaken to reduce the loss of acidity. On testing the new catalyst (Catalyst B) after 64 hours of ageing, it had only lost about 10% of its $NH_3$ storage capability, compared with the 50% lost by the previous generation Catalyst A. Even after 500 hours at 670°C, Catalyst B retained more than 80% of its acidity.

When $NO_x$ conversion of the two catalysts was compared, it became clear that the newly developed catalyst had an increased operating temperature window due to its improved low temperature activity. Increases of approximately 10% at 200°C are seen after 64 hours of ageing, with maximum conversion of almost 100%.

Catalyst B also demonstrated significantly improved long-term hydrothermal stability at higher ageing temperatures than Catalyst A. The Catalyst B low temperature activity was maintained even after 64 hours at 800°C, or an hour at 900°C (Figure 2).

Successful exposure to these kinds of temperatures suggests that it could be a candidate for further testing as a catalyst coated onto a catalysed soot filter, where temperatures during regeneration can reach the levels tested here.

## Engine Testing

To enable further validation of the catalyst performance, testing was carried out on an engine. Catalysts A and B were tested under steady state conditions from 205 - 440°C (Figure 3), with Catalyst A having been aged at 670°C for 64 hours, and Catalyst B after ageing at 800°C for the same time. In spite of the higher ageing temperature, Catalyst B gave much higher $NO_x$ conversion at low temperatures than Catalyst A, confirming the previous laboratory reactor results.

The transient performance of the new catalyst was confirmed by running Hot LA-4 tests (Figure 4). The Hot LA-4 consists of the first two bags of the US FTP run immediately after a defined engine warm-up procedure. $NO_x$ conversion in Bag 1 was 83% for Catalyst B and 73% for Catalyst A, and in Bag 2 was 98% and 89% respectively. This gave a total LA-$NO_x$ conversion of 90% for Catalyst B and 80% for Catalyst A, demonstrating that tighter $NO_x$ emissions standards should be achievable with this new formulation.

## Conclusion

A clear understanding of the deactivation mechanisms seen during thermal ageing has enabled a new copper SCR catalyst to be developed. The loss of ammonia storage capacity as a result of zeolite dealumination was identified as the major cause of catalyst degradation. Focusing on stabilising $NH_3$ storage capacity improved the durability of the new catalyst after long-term ageing at 670°C as well as shorter term ageing at more extreme temperatures. This increased thermal stability was matched by improvements in engine performance, meaning that the catalyst has promise for achieving the most stringent $NO_x$ emissions.

# Combining SCR Catalyst Technology with DPFs

Past issues of Global Emissions Management have looked at selective catalytic reduction and diesel particulate filter technologies. In this issue, we look at combining them in order to reduce overall catalyst volume in aftertreatment systems. This article is based on paper 2009-01-0910, presented at the SAE World Congress in April 2009.

## Introduction

Many diesel engine manufacturers have chosen to use SCR catalysts with urea injection to meet US Tier 2 requirements for oxides of nitrogen (NO$_x$). Vehicles will contain a combination of selective catalytic reduction (SCR), diesel oxidation catalyst (DOC) and catalysed diesel particulate filter (CDPF) technologies in various configurations, depending on light-off, regeneration, urea mixing and packaging requirements. Future emissions regulations will require even lower NO$_x$ emissions, which can be achieved by increasing the SCR catalyst volume to improve NO$_x$ conversion, although this in turn can cause packaging issues and cost increases.

In this work, SCR coated filters (SCR-DPFs) were prepared with advanced copper (Cu) zeolite SCR catalysts coated on a range of high porosity filters. These advanced SCR catalysts have been demonstrated to be durable at temperatures up to 900°C and have a high resistance to coking. The SCR-DPFs were oven-aged and tested on an engine dynamometer to demonstrate NO$_x$ conversion, confirm backpressure, and confirm the ability to regenerate soot filtration capacity in a time comparable to a current CDPF.

## Background to Testing

High porosity cordierite and silicon carbide (SiC) filters, both 300 cells per square inch (cpsi) and 12 mil wall thickness, were coated with advanced Cu zeolite SCR catalysts. A second cordierite filter was coated with a reduced washcoat loading (WCL) to investigate the effect of lower loadings on NO$_x$ conversion and backpressure. Finally, a 2008 model year (MY) production CDPF consisting of a SiC filter (200 cpsi/16 mil) coated with an oxidation catalyst was included for further comparison.

All of the catalysts were oven aged to simulate a ten minute regeneration every 300 miles over the minimum lifetime required (120,000 miles) for a light duty diesel vehicle. The catalyst volume in each case was 2 x engine displacement.

Steady-state testing was carried out on a 2008 model year (MY) diesel engine with a prototype 2010 calibration mounted on a dynamometer. FTIR analysers were used to measure NO$_x$ and carbon monoxide (CO) emissions and an HFID analyser was used to measure hydrocarbons. Backpressure was measured with a pressure transducer, and filter soot loadings were measured by weighing the filters when warm.

## NO$_x$ Conversion Results

As anticipated, the advanced Cu SCR catalysts gave high NO$_x$ conversions across the whole temperature range tested, from 200-440°C, with more than 90% on both filter types. This showed that it would be possible for a DOC + SCR-DPF combination to meet Tier 2 emissions requirements. For the reduced washcoat loading filter, NO$_x$ conversions were slightly lower, but nevertheless still above 90% across the temperature window (Figure 1). There was therefore potential to optimise the catalyst loading in order to reduce overall backpressure, without compromising performance.

Figure 1: Steady-state NO$_x$ conversion of aged SCR-DPF catalysts tested on engine

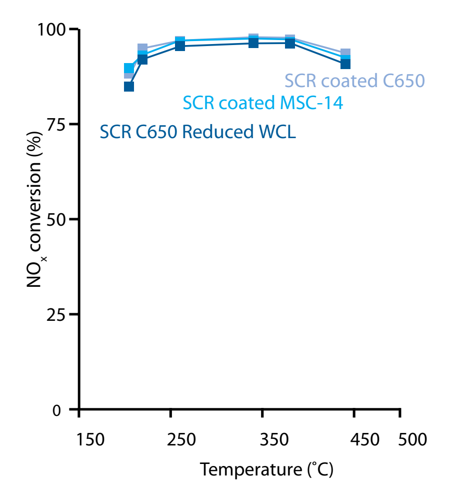


Figure 2: Steady-state NO$_x$ conversion of soot loaded SCR-DPF tested on engine

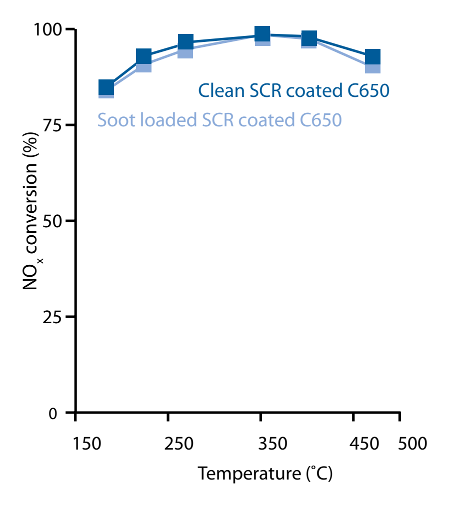
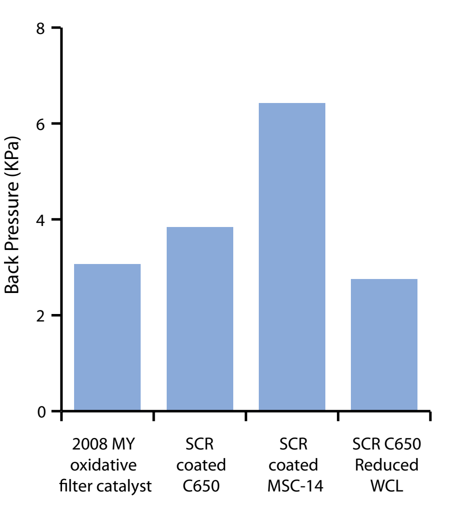


Figure 3: Back pressure of various coated filters measured on engine at 220°C



As the SCR catalysts were coated onto filters, and would therefore come into very close contact or be covered by soot, it was important to test how the SCR activity would be affected by the presence of soot. The cordierite filter was loaded with 2.0g/L of soot, and tested for steady-state NO$_x$ activity (Figure 2). The soot-loaded filter was shown to have very similar activity to the same filter with no soot, demonstrating that it was not adversely affected by soot accumulation.

In addition to steady-state testing, the experimental catalyst system was subjected to the LA-4 and US06 transient tests. Under both of the regimes, conversions for all SCR-DPF configurations were at a level that suggested Tier 2 limits would be achieved if rapid warm-up strategies were used to optimise catalyst light-off.

## Impact on Filter Backpressure

SCR-DPF catalysts have a higher washcoat loading than CDPFs, and would therefore be expected to give higher backpressure. In spite of the greater porosity of the cordierite C650 filter (65%) used for the SCR-DPF, the SCR coated cordierite filter still gave higher backpressure readings than the 42% porosity 2008MY SiC CDPF. The SCR-DPF coated on the lower porosity SiC MSC-14 filter (59%) did have higher backpressure than was measured for the C650 coated filter. The SCR-DPF with reduced washcoat loading did however reduce backpressure to levels comparable to the 2008MY CDPF (Figure 3). These comparisons highlight the importance of substrate properties and washcoat loading on the ultimate performance of the product.

> "SCR and filter combinations must perform in a similar way to a conventional catalysed soot filter"

## Soot Filtration Functionality

Key to the choice of SCR and filter combinations is that they must perform in a similar way to a conventional catalysed soot filter during soot regeneration, both in terms of the time it takes to regenerate the filter, and its ability to oxidise any HC or CO that has not been converted by the DOC.

To test the former, all of the filters were loaded with 5g/L soot, and fuel post injection was used to raise the filter temperature and initiate regeneration. After a gradual temperature ramp-up to 650°C, backpressure was allowed to stabilise. The time taken to achieve this stability was taken as the regeneration time, and was similarly effective for all filters.

Conversion of HC and CO slip was measured during the final stage of the regeneration strategy. The CDPF had reductions of 98% and 97% respectively, whereas the SCR-DPFs show conversions of 72-77% HC and negative CO conversion. When taken across the whole DOC + SCR-DPF system, HC is reduced by 97-98% on the SCR-coated filters, and CO by 59-67%, compared to nearly 100% on the CDPF. NO$_x$ conversions were also measured, with the SCR-DPF systems showing between 31 and 34%, compared to 0% on the non-SCR-containing system. Including an SCR catalyst on the filter is therefore shown to have a negligible impact on HC conversion, a slight negative impact on CO reduction, and a positive impact on NO$_x$ emissions.

## Conclusions

The development of high durability Cu zeolite SCR catalysts has enabled SCR and filter technologies to be combined in order to reduce the volume of catalyst and the cost of exhaust aftertreatment systems. NO$_x$ reductions of more than 90% are achievable and, by optimising washcoat loadings, neither emissions nor backpressure are compromised. As regeneration times are also comparable to existing commercial catalysed filters, these SCR-catalysed filters have the potential to be included in future systems.

Johnson Matthey is developing SCR-DPF products at its network of technology centres, for incorporation into the next generation of vehicles. Future work is focused on developing advanced coating methods to allow high SCR catalyst loads to be coated on the wide variety of existing and proposed filter materials with the minimum backpressure increase.

# Retrofit SCRT® Field Trial Proves Successful in Reducing $NO_x$ as well as Particulate Emissions

With increasing concerns about levels of oxides of nitrogen ($NO_x$) in the atmosphere, retrofit $NO_x$ reduction technology is now also being sought to provide a cost-effective means of achieving lower emissions levels from operators' existing vehicles. GEM looks at a real-world field trial in London, where combined $NO_x$ and particulate matter (PM) abatement technologies were successfully applied to 14 city buses.

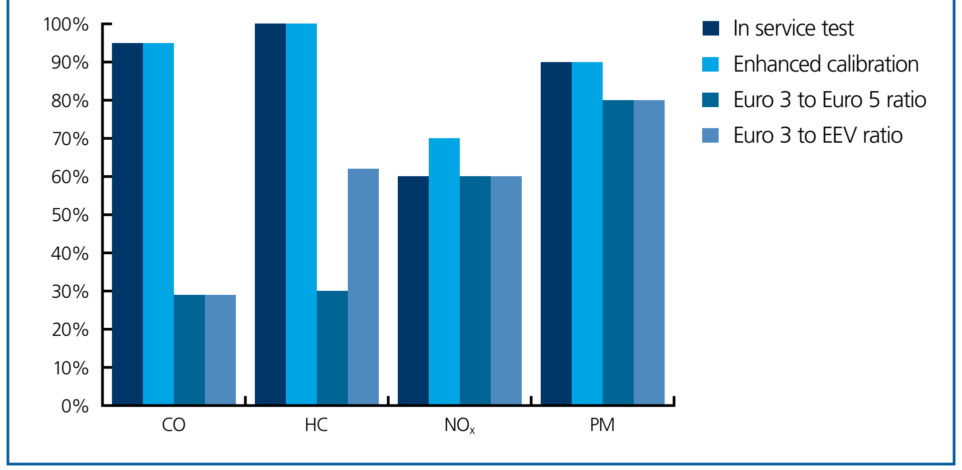
## Background to the trial

Like many other large cities, London has air quality issues and has for many years taken a strong environmental stance with regard to its own bus fleet. It now has the cleanest fleet in the UK. Transport for London (TfL), the publicly owned body that oversees all of the capital's transport operations, was one of the first to mandate the use of diesel particulate filters (DPFs) on its buses and this has been successful in dramatically reducing PM emissions from those vehicles. It has also stated its desire to go further by ensuring that a significant number of these buses are low $NO_x$ as well as low PM.


Dennis Dart buses were used in the field trial

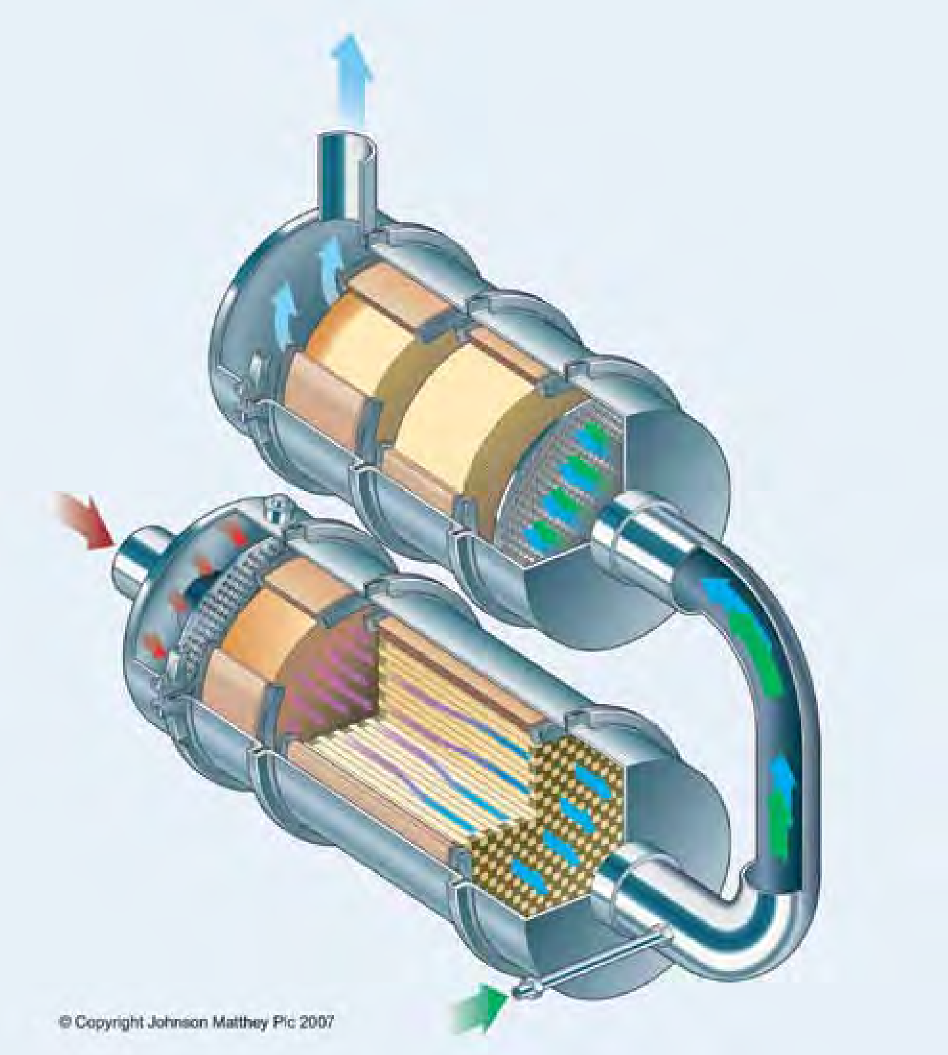
TfL was therefore the ideal partner for Johnson Matthey and systems integrator Eminox to work with on a field trial to prove the efficiency, reliability and durability of their SCRT® system. The technology had been successfully trialled in smaller numbers before, but the reliability of the components had never been tested by monitoring a fleet of this size. The vehicle type selected by TfL was the single-decker 3.9 litre Dennis Dart, one of the most commonly operated buses in the London fleet. Two bus operators, First and London United, were selected by TfL to run the trials. This would ensure that the technology was tested on a wider variety of routes.

Figure 1: Proportional Emissions Improvements



A total of 14 buses, all of which had already been operating successfully with CRT® systems, were fitted with an integrated package that included Selective Catalytic Reduction (SCR) catalysts, $NO_x$ sensors, a urea tank, pump and dispensing system, as well as an electronic control unit (ECU) to provide data logging capability in addition to its primary function of controlling the interaction between components. The SCRT® system was designed to incorporate as many commercially available and proven components as possible, so that the partners could focus on system integration and calibration.

The trial was carried out in two phases; Phase 1, which demonstrated that the system could meet the agreed emissions targets, and Phase 2, the system durability phase. Phase 1 consisted of some component and system shakedown that resulted in improvements to performance and robustness. It also proved possible, by careful calibration of the system, to obtain emissions below the target levels set by TfL. These were set to specifically reduce climate change gases, in order to achieve optimum environmental performance. Phase 2 then started. The performance of each trial bus was monitored using the various sensors in the system and logging the data. Together with other operating parameters such as urea consumption, this was analysed and reported weekly to TfL and the bus operators.


© Copyright Johnson Matthey Plc 2007

SCRT® systems combine SCR and CRT® technology

## System performance

In well controlled conditions, it is possible to achieve $NO_x$ reduction of 90% or more. However, the actual level obtained during real-world operation is a function of the exhaust gas temperature in the SCR catalyst, as well as the system response to transient operation. Due to the low temperatures prevalent in these city bus applications, and due to the need to avoid increases in secondary emissions, the $NO_x$ conversion target agreed with TfL was 65%.

As well as continual monitoring of the system in situ, independent emissions testing was carried out at Millbrook Proving Ground, using the well established MLTB (Millbrook London Transport Bus) Cycle, which is representative of a London bus route. The results of this testing showed not only that the TfL $NO_x$ target had been met, but also that the SCRT® retrofit system gave very low ammonia slip as well as maintaining the low PM, gaseous hydrocarbon and carbon monoxide levels achieved with CRT® technology.

Although the system was not tested on the cycles used to determine compliance with Euro standards, the emissions reductions achieved against engine-out emissions from the Euro 3 buses infers that they would meet Euro 5 and also EEV limits (figure 1).

## System reliability

System reliability was also determined to be critical in evaluating the success of the project, and after Phase 1 of the project was complete, a target of 95% reliability over a further six month period was set. During the first 'shakedown' phase, the system had been operating for more than 70% of the time, but Eminox and Johnson Matthey were confident that the 95% target could be met with the optimised components and calibration. Phase 2 was therefore devoted to ensuring that the performance targets were met consistently and reliably.

As stated above, commercially available components were selected for the trial, and many of these are already in use as line fit items on Euro 4 and 5 vehicles. Nevertheless, there had been some issues with them during Phase 1, but Johnson Matthey and Eminox worked with suppliers to implement improvements, some of which had been identified on the Euro 4 compliant original equipment systems. This work enabled the target to be exceeded, with more than 98% operating reliability across the fleet achieved during the final nine months of the trial.

## Conclusions

The success of this extended field trial was due not only to the catalyst and systems technology, but to a large extent the calibration and systems integration expertise that went into the design and development of the SCRT® systems. Johnson Matthey's CRT® technology has been combined with SCR technology used in many new vehicles, with the result that owners of older vehicles now have the option of upgrading them cost-effectively. This will enable operators to meet emissions limits in air quality improvement areas, tender for business that will only be awarded to operators of the cleanest trucks and buses, and extend the useful life of those vehicles, whilst contributing to air quality improvements in the cities in which they operate.

# SCR Long-Term Durability Proven in U.S. Field Trials

In the Spring 2003 issue of Global Emissions Management, we unveiled the Compact SCRT® from Johnson Matthey. In this issue, we provide an update on SCR durability trials, taken from paper 2004-01-1289 given at the SAE 2004 World Congress in Detroit.

## Background

Selective Catalytic Reduction (SCR) has emerged as the preferred solution for achieving the Euro 4 limits, which come into force in 2005. It will also be one of the candidate technologies for Japan 2005 and USA 2007/2010 legislation. With tight limits for oxides of nitrogen ($NO_x$) being introduced, SCR's high $NO_x$ conversion efficiency makes it very attractive to install on trucks and buses. Whilst widely used to control emissions in stationary power plants, its durability has to be proven in mobile applications, where the conditions are more transient and very high mileages are driven.

To investigate SCR catalyst durability, Johnson Matthey devised a test programme for its SCRT®, a combination of SCR and its Continuously Regenerating Trap (CRT®) diesel particulate filter (DPF) system. This programme involved bench testing followed by a field trial. Although the testing was to be on SCRT® technology, the results would be relevant to all SCR systems.

## The catalysts

Vanadium-based catalysts developed for stationary applications formed the starting point for the SCR part of the system. Although these catalysts are sulphur tolerant, and are known to have a high $NO_x$ conversion efficiency, new catalysts were formulated to be resistant to thermal deactivation and poisoning from oil-derived species such as phosphorous.

The system was tested using a specially formulated diesel oxidation catalyst (DOC) upstream of the SCR catalyst.

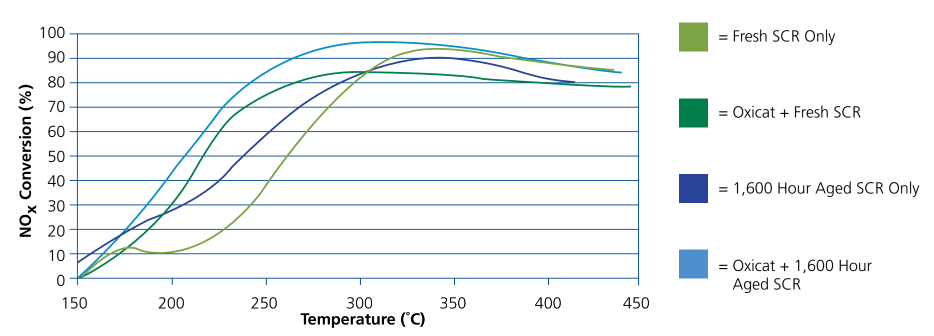
## Bench testing

Prior to undertaking field trials, the catalyst was subjected to rigorous bench testing. Tested on its own, the SCR catalyst gave 88.4% conversion over the European Steady-State Cycle (ESC), with a catalyst volume/engine swept volume ratio of just 1.7 (17 litres of catalyst on a 10 litre engine). $NO_x$ emissions were less than half of the proposed Euro 5 limit of 2g/kW-hr.

Using an optimised oxidation catalyst upstream of the SCR catalyst, the $NO_x$ conversion efficiency increased to a remarkable 95.7%, with $NO_x$ emissions approximately one sixth of the proposed limit.

To test for thermal deactivation, the catalysts were subjected to an extended ESC ageing cycle, taking them to a maximum temperature of 510°C. No change in their activity was observed during the 250 hour ageing, demonstrating thermal robustness. In some applications however, catalyst systems can be exposed to temperatures much higher than this, and they were therefore exposed to an even more aggressive cycle comprising steady state operation at 550°C.To fully test the durability of the catalysts, it was decided to subject them to a regime involving doping lubricating oil into the fuel for 200 hours to accelerate the appearance of poisoning effects from oil. Based on oil consumption, this accelerated ageing corresponded to approximately 100,000 km of real-world operation. Again, no deactivation was observed. A worst-case scenario ageing cycle was therefore devised, lasting 1,600 hours, and involving the use of 4 different lubricating oils, each for 400 hours. In addition, the maximum temperature during the ageing was 480°C, and the catalyst ran at this temperature for 800 of the 1,600 hours. Therefore, this ageing also probed the long-term thermal durability of the catalyst.

Figure 1: $NO_x$ Light-Off Conversion Performance of Fresh and Aged SCR Catalyst, with and without Upstream Oxidation Catalyst



After exposure to high levels of potential catalyst poisons such as calcium, phosphorous and zinc for this period of time, the aged catalysts were tested and compared with the fresh data. High temperature performance is similar to that of the fresh SCR catalyst, whilst at low temperatures the performance actually increases as a result of ageing. Figure 1 also shows the impact of placing the optimised oxidation catalyst upstream of the SCR system. There is no deterioration at all over the course of 1,600 hours, and it does appear that the aged system is more active than the fresh system at almost every temperature tested.

## Field trials

Given the exceptional performance of these new catalysts, field trials were planned to assess performance and durability in real-world operation. A United States long-haul application was chosen for two key reasons: to accumulate a high mileage rapidly; and to expose the catalyst system to high temperatures to assess its real-world thermal durability. Given that it was impractical to supply ultra low sulphur diesel on the chosen route, regular US diesel fuel with 350ppm sulphur was used.

In addition to the catalysts discussed above, the SCR catalysts were combined with the CRT® technology, already proven to be highly efficient at removing carbon monoxide (CO), hydrocarbons (HC) and particulate matter (PM). PM is removed as a result of $NO_2$ generated by the upstream oxidation catalyst reacting with carbon trapped in the DPF. The technology has also proved its durability in more than 70,000 heavy duty diesel retrofit applications worldwide. The DOC, CRT® filter, and SCR catalyst, along with a clean-up catalyst, were installed in a US Class 8 truck containing a Cummins ISX, 15 litre, 425 horsepower engine (Figure 2: main image above). The configuration was as shown in Figure 3, with the CRT® (DOC and DPF) system upstream of the SCR part of the system.

The truck was used in regular revenue service on a mid-west to west coast round trip route of 5,000 miles, taking approximately 110 hours. At intervals throughout the course of the trial, the efficiency of the SCRT® system was assessed. To ensure this could be done in a controlled and repeatable manner, an 850km (530 mile) round trip was devised. At the end of the field trial, after 125,000km on the road, the $NO_x$ conversion level was measured at 82%. As the urea injection rate was set such that the Ammonia-to-$NO_x$ Ratio (ANR) was only 0.85, giving a maximum possible $NO_x$ conversion of 85%, this 82% conversion put the true efficiency of the system at 96%, with no reduction in system efficiency over the course of the trial. Figure 4 shows the on-road $NO_x$ conversion over the duration of the trial, as a function of mileage.

## Conclusions

The results obtained from testing in the laboratory as well as in the field clearly demonstrate the high activity and durability of this new family of SCR catalysts. As well as its high thermal durability, the system has demonstrated excellent sulphur tolerance and $NO_x$ conversion levels.

Figure 2: This SCRT®-fitted truck drove 125,000 miles with no loss of $NO_x$ conversion efficiency

Commenting on the results Dr David Prest, Director of Johnson Matthey's Heavy Duty Diesel business said, "The outstanding performance and durability of the four-way SCR-Filter system will give truck and engine manufacturers the confidence that upcoming legislative targets can be met. This is an example of how our SCR catalyst technology can be used, either alone or with the CRT®, to provide a clear path towards lower emissions from heavy duty diesel vehicles."

Figure 3: Schematic of SCRT® system as fitted

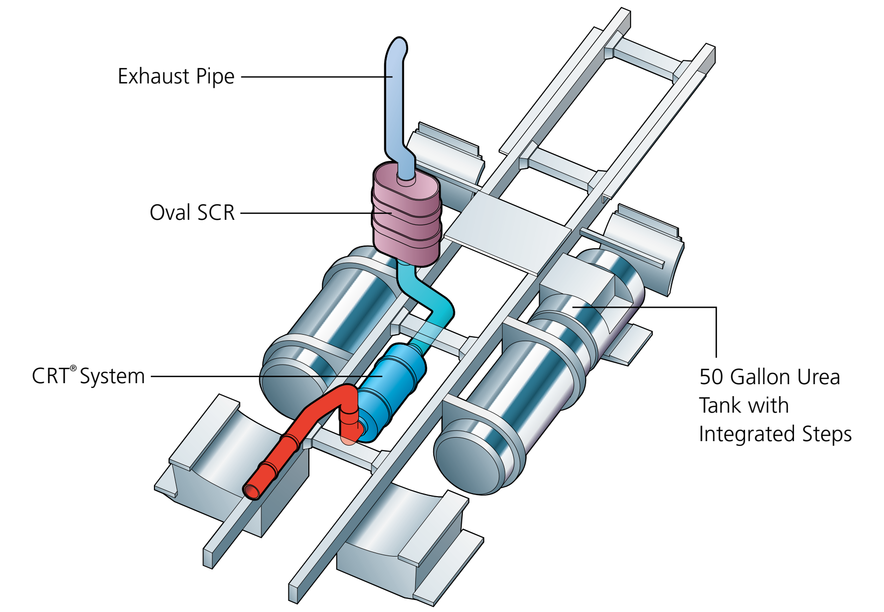
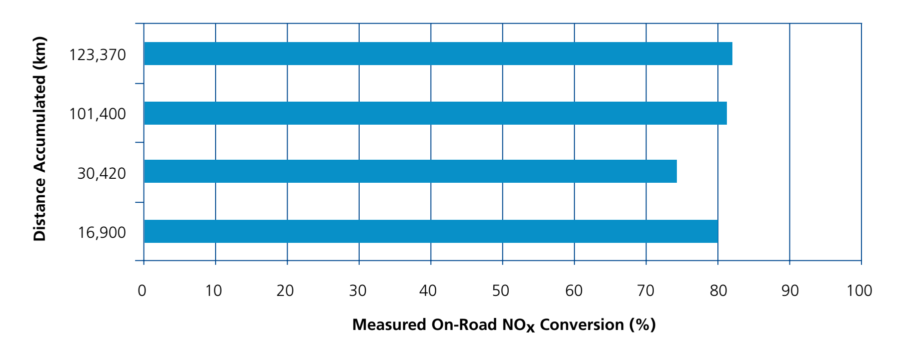
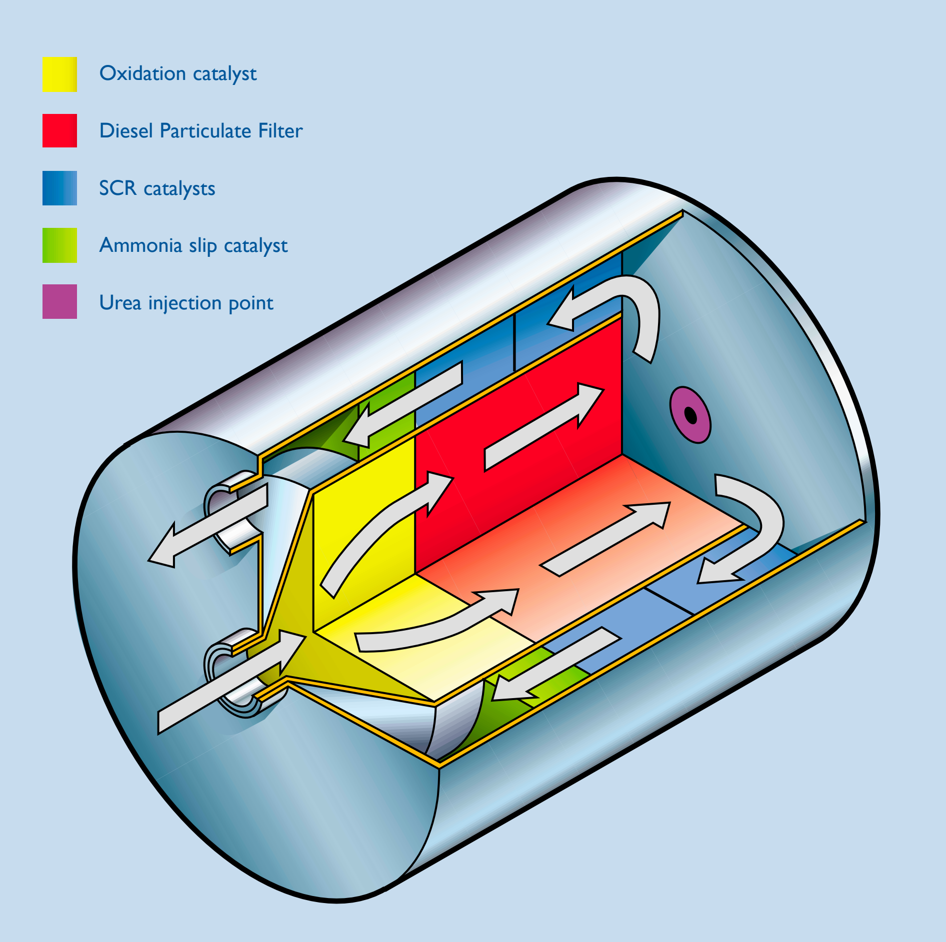


Figure 4: Measured on-road $NO_x$ conversion



'Compact SCRT™' Schematic



# The Compact SCRT™ Unveiled

The SAE 2003 World Congress in Detroit provided an ideal opportunity for Johnson Matthey to give an update on its innovative SCRT™ concept. As well as unveiling a new 'Compact SCRT™' design, Johnson Matthey reported on testing work confirming emissions performance and system durability.

## Background

The SCRT refers to the combination of Continuously Regenerating Trap (CRT®) technology with Selective Catalytic Reduction (SCR). First presented at the SAE World Congress in March 2000, the SCRT attracted immediate attention as the first catalytic approach capable of delivering a 90% reduction of all four regulated pollutants. This marked it out as a means by which diesels could meet the toughest emissions regulations.

Among the European engine manufacturers, SCR is considered a favoured route by which trucks can achieve Euro 4 and 5 because it allows engine tuning for enhanced fuel economy by tackling the resulting increases in nitrogen oxides ($NO_x$). SCRT offers this same opportunity to simultaneously improve $NO_x$ emissions and fuel economy but with the additional opportunity to retain a filter – something considered essential by the sponsors of many urban bus fleets.

In seeking to further develop the SCRT concept, Johnson Matthey catalyst scientists needed to address potential barriers to its application. These were identified as packaging constraints, durability and cost.

## Compact Packaging

Initial SCRT development focused on 'linear' configurations where the CRT was followed by an in-line SCR unit. It was recognised that this approach might suit long wheel base buses, or trucks with vertical stacks, but would be unsuitable for vehicles with space constraints where a drum silencer would be preferred. The challenge was to work out how vehicles that only just had enough space for a CRT could accommodate the additional SCR unit required in an SCRT. To address this Johnson Matthey looked at a number of different designs, focusing particularly on the opportunities afforded by novel substrate configurations. This work resulted in the 'Compact SCRT' design.

The key feature of the Compact SCRT is the use of metallic annular substrates for the SCR catalysts – that is catalysts with a hole in the middle. By making the central aperture big enough to fit a diesel particulate filter (DPF), the SCR catalysts could effectively wrap around the filter, thereby increasing the width without necessarily adding to the length of the CRT-based exhaust. As with a linear SCRT configuration, the inlet to the SCRT channels the exhaust gas through the oxidation catalyst of the CRT, cutting HC and CO emissions and generating $NO_2$ to burn soot in the filter and boost the rate of downstream SCR reactions. The filter traps the soot, leaving an exhaust gas free from HC, CO and PM emissions, into which the urea-water solution can be injected to generate the ammonia needed for the $NO_x$ reduction. This dosing of the urea solution takes place a comparatively short distance away from the SCR catalysts but the internal design ensures the effective mixing of urea sprays and exhaust gases, before the flow is turned 180° to enter the SCR catalysts. The final ammonia slip catalyst helps ensure that ammonia slip is negated.

## Durability

The durability of the CRT has been proven through the many thousands of hours of trouble-free operation accumulated on vehicles. Furthermore, the factors influencing CRT durability, including fuel sulphur content, $NO_x$/PM ratio, exhaust gas temperature (duty cycle) and filter maintenance are well understood. SCR catalyst durability has been proven, in units employed to clean up the emissions of power plant. However, for vehicular applications, SCR and SCRT durability is just beginning to be demonstrated.

> "Encouraged by the performance of the SCRT™ Johnson Matthey has supplied systems to Volvo for field trials on haulage trucks in North America."

Annular Catalyst

> "Encouraged by the performance of the SCRT Johnson Matthey has supplied systems Volvo for field trials on haulage trucks in North America."

To prove SCR catalyst durability, the effects of long-term operation were simulated using catalyst ageing and then emissions performance measured using engine dynamometer testing. In unison with this work, SCRT units have been field-tested in real-world operation.

The internal packaging of the SCRT holding the substrates in place is more complex than the illustration indicates, given that the structure must provide the necessary noise attenuation and strength of a conventional silencer, whilst allowing access to the filter for maintenance purposes as a modular CRT would. To demonstrate the mechanical durability of the 'Compact SCRT' units were subjected to shake testing and pressure pulse testing.

## Emissions Performance

When the SCRT was first unveiled, the emissions target for HDD applications was the Euro 5 limit of 0.02 g/kWh PM and 2 g/kWh $NO_x$ on the European Steady-state Cycle (ESC). Subsequently both the United States and Japan have applied stringent emissions legislation targeting $NO_x$ and PM control, with the US2007 limits of 0.01 g/bhp.hr PM and 0.2 g/bhp.hr $NO_x$ recognised as the most stringent regulations yet devised for heavy-duty diesels. Given this new target, the emissions measurement and system optimisation work focused on achieving a very high $NO_x$ conversion efficiency.

When tested on the ESC the SCRT comfortably met the proposed Euro 5 emissions limits for all four pollutants, demonstrating an 84% $NO_x$ conversion when employing 2 SCR catalysts and a 92% conversion with an extra SCR catalyst added. For these systems HC and CO conversions were exceptionally high at 98% and 100% respectively. The PM conversion was lower at around 70% but this reflected the inherently low PM emissions of the engine, which at 0.022 g/kWh, were almost low enough to meet Euro 5 without a filter!

In this system the ammonia slip levels measured before the slip catalyst were inside the accepted industry target of 10 to 15ppm max, which illustrates what can be achieved with an optimised injection strategy (matching urea solution injection to $NO_x$ exhaust requirements). With a clean up catalyst added, ammonia slip was eliminated.

In contrast to ESC testing, the US Heavy-Duty Transient (HDT) test starts with the engine cold and thereby emphasises cold start emissions. Because urea only hydrolyses to ammonia in hot exhaust gas it is not possible to inject urea during the early stages of the test and consequently $NO_x$ emissions reduction fell to just 56%. However, on a hot start US HDT test the $NO_x$ conversion improved to reach 83%. Using weighted emissions (1/7th cold, 6/7th hot), $NO_x$ emissions reduction reached 79% with HC and CO conversions of 96% and 94% respectively.

## The Next Steps

Encouraged by the performance of the SCRT, Johnson Matthey has supplied systems to Volvo for field trials on haulage trucks in North America. These trucks will accumulate high annual mileages, providing an effective guide to real-world durability. Commenting on the compact SCRT design, Johnson Matthey's Dr Barry Cooper said "Our Compact SCRT design provides an easy-to package emission control device capable of providing very high conversions of all four major pollutants. I am confident that the field trials on Volvo trucks will help confirm the Compact SCRT durability together with the excellent emissions performance demonstrated in our testing to-date."

'Compact SCRT™' and CRT packaged by Eminox

# Pace of Progress Quickens for SCR

As the engine and emissions management industries focus on solutions for upcoming regulations, there has been a flurry of activity around Selective Catalytic Reduction (SCR) based emissions control. Johnson Matthey is actively developing SCR catalysts for both light and heavy-duty diesels and its latest investigations into passenger car diesel SCR have been published as an SAE paper, a copy of which is enclosed in this issue of Global Emissions Management.

Demonstration of co-fuelling of diesel and urea for a Diesel Ford Focus vehicle, designed to meet Californian ULEV II emission standards

As the emissions management sector prepares for the upcoming diesel regulations two $NO_x$ control techniques, $NO_x$ traps and Selective Catalytic Reduction (SCR), vie for development time. The former has traditionally held sway but the latter is attracting growing interest as technology develops and barriers to uptake are overcome. The use of SCR as a means of controlling nitrogen oxides ($NO_x$) in lean engine exhaust is proven technology for industrial plant but its use on vehicles has only recently reached a demonstration stage. In many respects SCR is a less complex approach to emissions management than the use of $NO_x$ traps but uncertainty over the choice of reductant and consequent absence of a distribution infrastructure have made it the higher risk option. However, support for SCR in Europe is encouraging fuel and engine suppliers to work together to overcome these barriers.

SCR is coming to the fore as some engine manufacturers' preferred solution for the upcoming Euro 4 and Euro 5 heavy-duty diesel regulations. In a significant move the motor industry, through Germany's Verband der Automobilindustrie e.V. (VDA), has agreed ground rules for the implementation of SCR solutions. Critical among these was a joint agreement as to the reductant of choice for onboard storage and distribution. The SCR reaction itself is between ammonia and nitrogen oxides ($NO_x$) in the engine exhaust. For optimum reaction kinetics ammonia would be used. However, ammonia is considered hazardous, making storage and distribution problematic. Instead the VDA agreed to focus industry efforts on the use of aqueous solutions of urea. The reasons were two-fold. Firstly, urea readily decomposes to ammonia in hot engine exhaust. Secondly, urea is a benign chemical already manufactured in bulk for use as a fertiliser and therefore well suited to the role of an additive supplied through a pan-European distribution network. Having made this decision, the industry can focus its development work whilst establishing a dialogue with regulators as to industry standards for the physical and chemical specifications for aqueous urea, as well as filling nozzle and tank interfaces.

## Passenger car SCR

Interest in SCR has not been confined to the truck and bus sector. The availability of a urea distribution network would make SCR an attractive option for passenger car emissions control, particularly as diesel emissions legislation tightens. The ability of diesels to meet the most stringent of emissions limits depends on the control of $NO_x$ emissions. SCR is one of the few potential pathways by which to achieve the very high conversion efficiencies, typically up to 90 percent for the reduction of nitrogen oxides ($NO_x$) to nitrogen, needed for some of the strictest limits on the statute book. This potential was recently illustrated by a diesel powered Ford Focus that used SCR to demonstrate Californian ULEV II standards.

Fleet trials are underway for SCR on trucks

## Catalyst development

In addition to the continued development of $NO_x$ traps, Johnson Matthey has been focusing its development efforts on new SCR catalyst formulations offering high activity across a wide temperature window. This approach promises high $NO_x$ conversion as well as offering engine and vehicle manufacturers compact systems capable of being applied to both cars and trucks. Johnson Matthey's previously published work on SCR catalysts has been for heavy-duty diesels and in combination with the CRT™, as the SCRT™. However, recognising the interest and opportunities for SCR on lighter vehicles, Johnson Matthey has run a development programme on a Euro 2 vehicle weighing 1800 kg, to test its latest catalyst formulations and explore the impact of calibration, catalyst activity, temperature and engine load on emissions compliance.

Johnson Matthey's development work has yielded a formulation capable of delivering high activity at low exhaust gas temperatures and a high temperature alternative to vanadium-based catalysts. In combination, the two widen the temperature window at which high SCR conversion efficiency can be achieved, as shown in Figure 1. High activity at low temperature allows for a smaller volume of catalyst to be used.

A second lesson learnt from SCRT™ development is that increasing the $NO_2$ concentration in the exhaust gas helps boost SCR reaction rates, favouring the use of a specially formulated oxidation catalyst ahead of the SCR catalyst. However, for lighter vehicles, SCR catalyst efficiency drops as exhaust gas temperatures are typically lower. In these circumstances the SCR catalyst may be best placed close to the engine manifold to take advantage of available heat. The oxidation catalyst can then be added after the SCR catalyst to oxidise carbon monoxide (CO) and hydrocarbons (HC).

The results in Figure 2 show that excellent $NO_x$ conversion efficiencies can be achieved once the emissions control reaches operating temperature. For the Federal Test Procedures this is on the second hill (under 250 seconds) of the test starting, clearly illustrating the promise of SCR particularly as early emissions could have been further reduced through engine calibration targeting rapid catalyst light-off. Overall the results demonstrate a capability relevant both to the passenger car and light van sector.

Figure 1: SCR Catalyst Activity

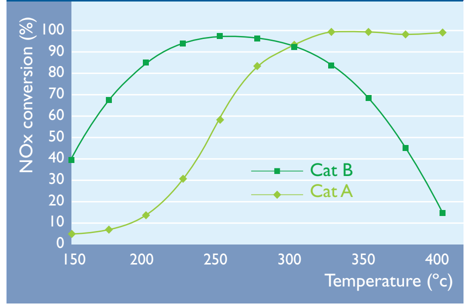
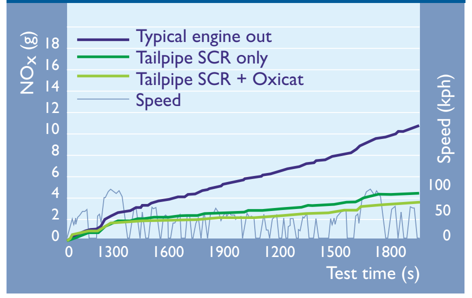


Figure 2: SCR Results



Johnson Matthey is grateful to the following
for their help in providing these images for
Global Emissions Management:
Daimler AG
Eminox Ltd.
Ford Motor Company

Johnson Matthey