Catalytic exhaust aftertreatment is one of the key technologies that will enable engines to meet the forthcoming Tier 4 and equivalent standards. The introduction of a new class of component is always challenging, the more so when its function and control is very different to existing engine systems.

A new type of engine component

The Mark 1 Volkswagen Golf launched in the USA in 1974. It was one of the first mass produced cars to be fitted with an autocatalyst.

New to you, but not to us

Catalysts have been used as a standard component on cars for over 30 years and Johnson Matthey supplied the world's first production batch in May 1974. Since then, we have supplied more than 500 million autocatalysts, around one third of all the catalysts ever fitted to cars.

The Mark 1 Volkswagen Golf launched in the USA in 1974. It was one of the first mass produced cars to be fitted with an autocatalyst.
The timetable for Tier 4 is tight, and the cost of non-compliance is very high. The purpose of this booklet is to describe the catalyst technologies available and how Johnson Matthey (JM) can work with you to achieve the required emissions reductions while maintaining, and in some cases improving, the other features of diesel engines that are valued by your customers.
Diesel cars were first fitted with catalysts in the early 1990s, since when tighter regulations and increasing customer demands have driven the development of engine and aftertreatment technologies together.

Johnson Matthey catalysts and technologies have been inside most of the particulate filter systems retrofitted to heavy diesel engines around the world. JM invented the CRT® (catalytic regeneration technology) system and more than 100,000 have been used for retrofit applications. We are building on this success with the introduction of the retrofit SCRT® (CRT® + selective catalytic reduction (SCR)) system for integrated control of all regulated diesel pollutants.

Since 2005, tightening emissions regulations for truck and bus engines in Japan, Europe and the USA have led to the introduction of particulate filters, SCR systems and NOx adsorbers on new heavy diesel engines. Johnson Matthey has developed leading technology to meet the requirements in all markets. These types of catalysts are all in series production at JM.
Non-road machines represent a very different challenge to on-road vehicles. Indeed, it would be better to say that NRMM represents many thousands of different applications challenges.

Johnson Matthey has been supplying and applying retrofit aftertreatment systems to non-road machines for more than 15 years. Therefore, we have experience of the variety of operating requirements, engine duty cycles and packaging constraints found in non-road machines. We know the differences between a tractor and a tracked excavator. And we know the regulations. We are very well placed to understand the requirements on catalytic systems for Tier 4 compliance.
An emission control catalyst is usually a catalytic coating applied to a ceramic or metallic substrate. The catalyst has open channels and the gases react as they pass through. Some catalysts are designed to be able to store reagents (e.g., oxygen, ammonia) to enhance performance or even to act as a chemical trap, as in the case of NOx adsorbers.

A particulate filter is a physical trap. The most common type is a ceramic monolith like a catalyst substrate, but with channels closed at alternate ends so that the gases must pass through the channel walls, leaving the soot behind. These filters are nearly 100% efficient for solid particles. Partial filters, designed for a lower efficiency, are also available. A DPF does not always contain a catalyst, but catalysts are used to burn the accumulated particulate.

**Catalyst:** A substance which when present in small amounts increases the rate of a chemical reaction or process but which is chemically unchanged by the reaction.
When designing a catalyst, we make it **active** to give high conversions from smaller catalysts and to make the best use of precious metal.

We make it **selective** to ensure that it is active for the desired reactions and does not produce undesirable by-products.

And we make it **durable** to meet useful life requirements and to minimise the durability factors that must be applied to new systems. Designing durability requires an understanding of how the catalyst will be used in its application and the exhaust conditions that it will see throughout its life. It also requires knowledge of the deactivation mechanisms, both chemical and physical, of each type of catalyst.

**What are the properties of a good catalyst?**
PM Control

Particulate filters are used to trap particulate matter. Catalysts are needed to burn the PM collected in the filter, maintaining the performance of the system. There are two ways that catalysts can be used to keep DPFs clean, and these are often used together.

Nitrogen dioxide (NO₂) and oxygen (O₂) can both be used to combust the soot trapped in a filter. NO₂ has the advantage that it reacts with soot at the temperatures found in diesel exhaust. The O₂ reaction requires higher temperatures, but is much faster.
NO$_2$ reacts with soot trapped in a filter, making NO and CO$_2$. This reaction can occur from 200°C, so the temperatures found in diesel exhaust streams are sufficient and no additional energy is required. Some of the NOx emitted by an engine is NO$_2$ and more can be made by an oxidation catalyst designed to oxidise NO to NO$_2$. This system – an oxidation catalyst to make NO$_2$, followed by a particulate filter which is regenerated by the NO$_2$ – is the CRT® system, a Johnson Matthey invention.

Using the CRT® effect to regenerate a filter has two great advantages: it is continuous (helping to maintain a low and even exhaust back pressure) and it requires no additional energy.

**Particulate matter collected in a filter can be oxidised very quickly using the oxygen (O$_2$) in the exhaust gases.** This reaction requires higher temperatures (>550°C) than are reliably found in most diesel engine applications, so some mechanism is required to raise the temperature of the exhaust periodically.

An oxidation catalyst placed before the filter is a very efficient way of doing this. When the filter needs regenerating, the hydrocarbon content of the exhaust stream is increased. The catalyst burns the hydrocarbon, producing the heat required. The catalyst can also be designed to make NO$_2$ during normal operation to provide additional regeneration. The hydrocarbon enrichment can be achieved in-cylinder using electronic fuel systems, or by injecting fuel directly into the exhaust system.
An SCR system reduces NO\textsubscript{x} to nitrogen (N\textsubscript{2}) and is capable of more than 90% conversion, depending on conditions. To achieve this reaction in normal, lean (i.e., high oxygen, low hydrocarbon) diesel exhaust, a chemical reductant is needed. In most systems, ammonia (NH\textsubscript{3}) is used, and this is delivered as an aqueous solution of urea (“AdBlue” in Europe). The urea decomposes in the exhaust stream to form ammonia, which reacts with the NO\textsubscript{x} to make nitrogen and water.

An SCR system requires a means of storing the urea and injecting the amount required to reduce the NO\textsubscript{x} emitted by the engine. Careful control is needed for transient cycles. The SCR catalysts usually have an oxidation catalyst, often called a slip catalyst, at the end as a guard to ensure that no ammonia is emitted.
NOx adsorber catalysts

NOx adsorber catalysts or NACs, also known as lean NOx traps (LNTs), operate in two modes. In normal diesel exhaust conditions, they adsorb the NOx from the exhaust gas, storing it chemically. In "rich" exhaust conditions, with little or no oxygen (O2), they release the stored NOx and react it with components of the rich exhaust gas - carbon monoxide (CO), hydrocarbons (HC) and hydrogen (H2) - to make nitrogen.

Like any trap, chemical or physical, NACs have a finite capacity so the engine or some auxiliary system must create rich exhaust conditions at intervals to regenerate the catalyst and this reduces the stored NOx to nitrogen. NACs also store sulphur and this reduces their capacity to trap NOx, so periodic "desulphurations", requiring increased exhaust temperatures, are necessary.
Each new Johnson Matthey catalyst formulation is the product of four decades of development experience and a fundamental understanding of catalyst properties. Research into new types of catalysts and catalytic properties is undertaken at JM’s own research facilities. Teams around the world develop new formulations to meet the requirements of different engines, regulations and applications.

Coatings are developed specifically to exploit the properties of different substrate types.

Test work starts in the laboratory using bottled gases to simulate exhaust gas with precise control of gas mix and temperature. Testing then moves to engines for performance and durability testing.
Johnson Matthey has its own test cells dedicated to diesel engine testing in Europe, the USA and Japan, many capable of transient operation. These cells are used to test and prove catalysts for catalyst ageing and for collaborative development programmes using customer engines. Our facility in Detroit also performs contract testing (see www.jmtesting.com).

JM develops proprietary catalyst-specific accelerated ageing procedures for its own and customer testing. These are based on catalyst deactivation mechanisms and are validated against catalyst aged in real world operation on vehicles and machines.
JM works to develop new aftertreatment systems and makes them available for new engines and retrofitting. This work covers not just the catalysts themselves, but the operating principles of the whole system. An example of this is the CRT® (Continuously Regenerating Trap) particulate filter system. Johnson Matthey developed its operating principle in the late 1980s. It has been used in the majority of retrofit particulate filter systems supplied around the world and has also been employed in many OEM applications.

JM’s work in this area has moved beyond particulate filter systems to include systems for NOx and NO2 control and integrated 4-way systems, which simultaneously reduce emissions of PM and NOx as well as CO and HC.
Having worked on retrofit applications since the early 1990s, Johnson Matthey has direct, hands-on experience in the non-road market. This is based primarily on particulate filter systems for construction and materials handling machines, but we also have experience of other systems and of rail and agricultural applications. This long experience has given us an understanding of the particular challenges of non-road mobile machinery: the variable and sometimes extreme duty cycles, the physical demands placed on the exhaust system, the packaging constraints, heat rejection, performance monitoring and control.
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Catalytic systems for PM or NOx control almost always contain more than one component. An SCR system will have an oxidation catalyst after the SCR catalyst and sometimes before. A particulate filter usually has an oxidation catalyst before the filter and a catalytic coating on the filter itself.

Systems to control PM and NOx are more than a simple combination of PM filter and NOx control system. It is best when the two are designed to work together: NOx from a PM filter can help an SCR system downstream; NOx adsorber desulfation cycles can be used to regenerate particulate filters.

To assist packaging, the components themselves can be integrated, for example with SCR or NAC coatings on particulate filters.
Manufacturing Technology

Johnson Matthey has ten TS16949-certified manufacturing plants around the world, with two more under construction. JM’s proprietary coating technology enables very precise control over the amount of washcoat and precious metal applied to each part, giving consistent high performance and efficient use of raw materials. It also allows different catalytic coatings to be applied to different areas of the substrate, further enhancing performance, efficiency and, in some cases, durability. It also enables more than one function to be built into a single component, reducing the complexity and cost of the finished system.

JM is in full series production of diesel oxidation catalysts for active filter systems, catalyzed particulate filters for light and heavy duty engines, SCR catalysts and NOx adsorbers.
Most emission control catalysts for mobile applications contain precious metals. Johnson Matthey is an acknowledged authority on precious metal markets and sole marketing agent for Anglo Platinum Ltd, the world’s largest producer of platinum group metals. JM is able to advise customers on the methods of sourcing, pricing and managing their precious metal requirements in the way that best suits their needs. For further information on the platinum group metals markets, visit www.platinum.matthey.com.

Johnson Matthey is also the world’s largest refiner of secondary platinum group metals; at the end of a machine’s life, we are able to recover the precious metals from the exhaust catalysts and reuse them.
## Regulations

### US EPA non-road emissions limits

### Engines <56kW

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### Engines 20-37kW

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### Engines 37-56kW

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### Additional Information

- Original Tier 2/3 limit of 0.4g/kWh may be used if 0.03g/kWh limit is introduced in 2012.
Tier 4 phase-in
Manufacturers may certify all their engines according to the 4a and 4b standards shown in the table. Alternatively, they may phase-in the NOx + HC standard as follows:
- 130-560kW engines PM/CO 100% compliance from 2011; NOx/HC 50% compliance in 2011-3
- 56-130kW engines PM/CO 100% compliance from 2012; NOx/HC 25% compliance in 2012-4

Test cycles and fuels
Tier 1-3 test cycle is the NRSC (=ISO8178-C1); fuel sulphur <2000ppm
Tier 4 engines must meet limits over NRSC and NRTC; fuel sulphur 7-15ppm; NTE (not to exceed) limits apply

Notes
These tables are intended for general guidance only. Manufacturers refer to regulatory authorities. Standards for engines >560kW not shown.
Johnson Matthey is a speciality chemicals company focused on its core skills in catalysts, precious metals and fine chemicals.

The group's principal activities are the manufacture of autocatalysts and pollution control systems, catalysts and components for fuel cells, pharmaceutical compounds, process catalysts and fine chemicals, and the refining, fabrication and marketing of precious metals.
Johnson Matthey has continued to develop its technology for almost 200 years, demonstrating the company's ability to maintain world leadership by adapting constantly to rapidly changing customer needs. Rigorous in its own environmental policies, many of Johnson Matthey's products have a major beneficial impact on the environment and enhance the quality of life for millions around the world.

JM's Emission Control Technologies business is part of the Environmental Technologies Division. It is the world leader in the development and manufacture of emission control catalysts for internal combustion engines. It provides exemplary customer service through a global network of technology centres, manufacturing plants and sales offices, local to customer needs.