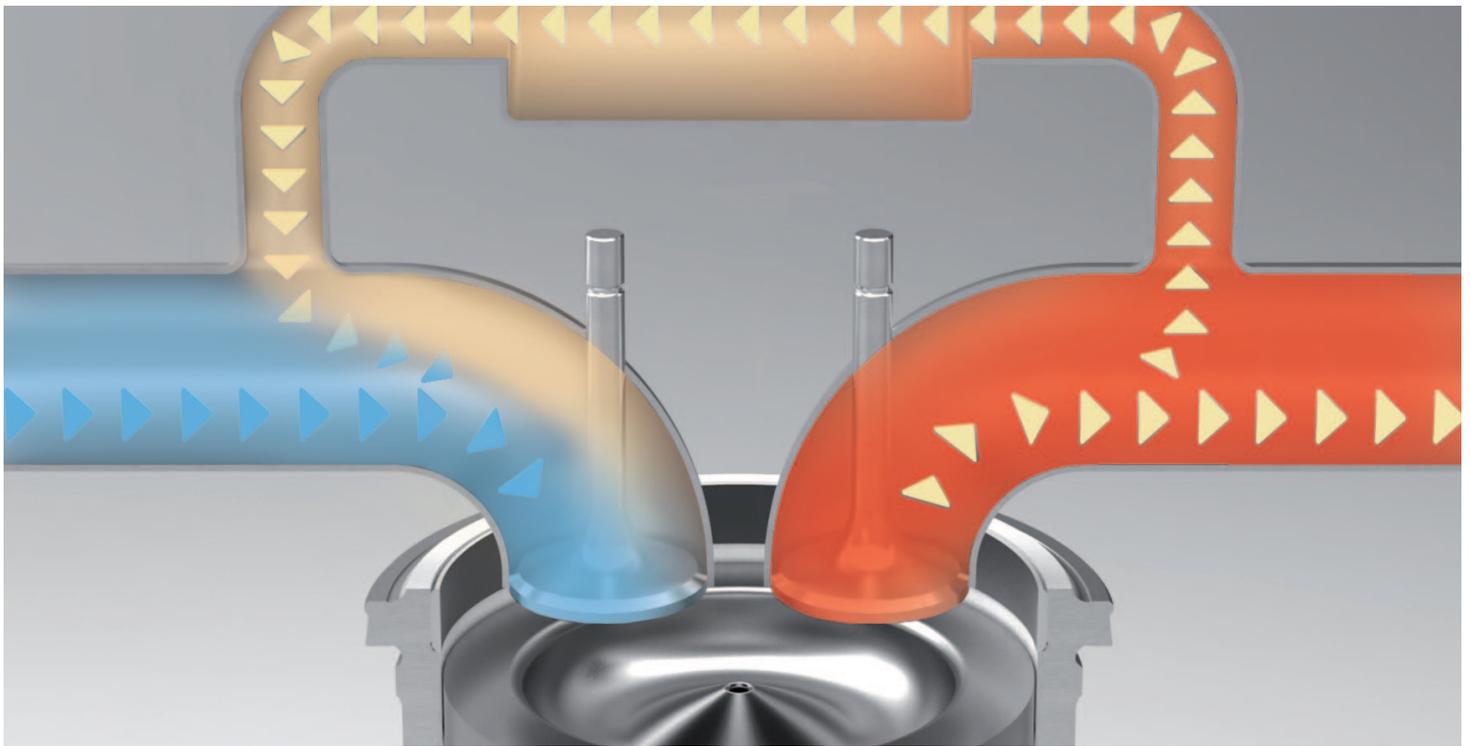


# Exhaust Gas Recirculation: Internal engine technology for reducing nitrogen oxide emissions



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Nitrogen oxide ( $\text{NO}_x$ ) emissions can be reduced using internal engine technology by cooling some of the exhaust gas, which is then redirected back into the charge air. This results in the reduction of the combustion temperature and less nitrogen oxide is produced. This process is known as exhaust gas recirculation (EGR) and is one of the principal methods used to reduce nitrogen oxide emissions from diesel engines. MTU has been developing this important technology and the functions and components associated with it since the beginning of the 1990s. It was first introduced in series production in mid-2011 for Series 4000 Oil and Gas engines in hydro-fracking applications (EPA Tier 4 emissions standard). It was likewise introduced in rail engines subject to EU IIIB emissions regulations which came into force in 2012.

**Ways to reduce nitrogen oxide emissions**

One of MTU's aims for its engines is to reduce the emission of soot particles and nitrogen oxides in order to achieve compliance with increasingly strict emissions regulations around the world. The main approach pursued by MTU is low-emission combustion, in other words an internal engine

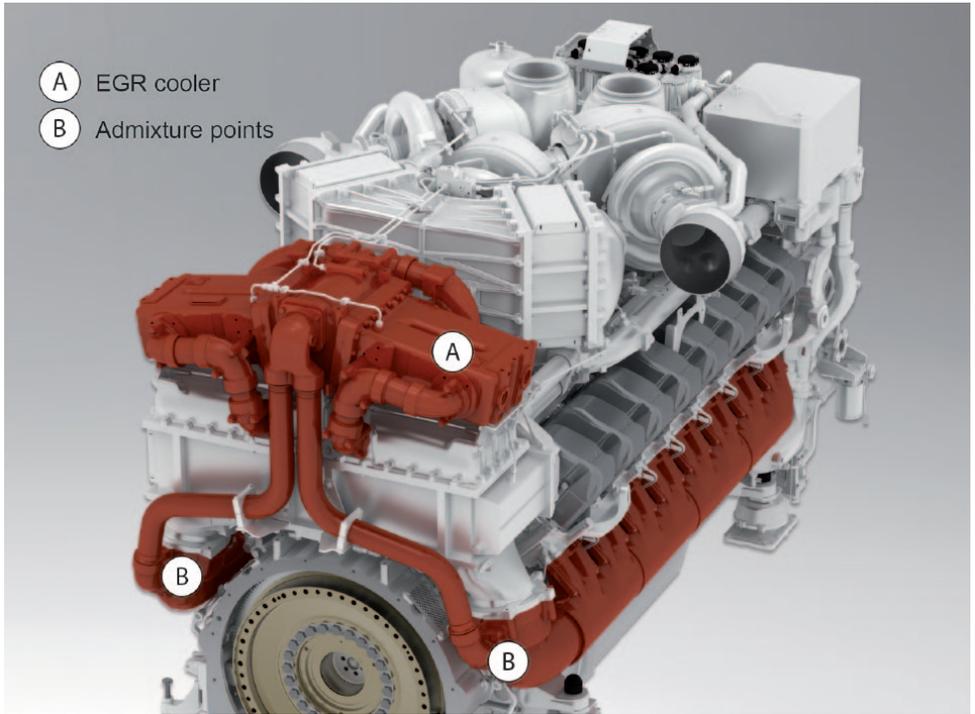
solution. However, this means taking into account a basic principle that governs the process of combustion – if the fuel burns at a higher temperature inside the cylinder, little soot is produced, but a large amount of nitrogen oxide. At lower combustion temperatures, nitrogen oxide emissions are low, but the production of soot

particulates is high. To find the right balance, therefore, all the key technologies that affect combustion must be perfectly matched. When combined with fuel injection and turbocharging in particular, the use of exhaust gas recirculation results in a combustion process that produces significantly lower levels of nitrogen oxide.

The second way of reducing nitrogen oxide emissions is to use exhaust gas aftertreatment with an SCR catalytic converter (selective catalytic reduction, short: SCR). Very low limits for both nitrogen oxide and diesel particulates can make the use of such an SCR system necessary. Exhaust gas recirculation can reduce nitrogen oxide emissions by around 40 percent. Depending on the application, SCR systems remove up to 90 percent of the nitrogen oxide from exhaust gases. In the case of particularly stringent emission standards, exhaust gas recirculation and a SCR system must be combined to ensure the limits are met.

**Examples of EGR use in MTU drive systems**

For mobile applications in excess of 560 kW, US EPA Tier 4 interim emissions regulations which have been in force since 2011 stipulate maximum emissions of 3.5 g/kWh. This applies to MTU Series 1600, 2000 and 4000 engines. Series 2000 and 4000 units meet the targets using exhaust recirculation technology. Series 1600, 2000 and 4000 locomotive engines subject to European EU Stage IIIB emissions rules in force since 2012 are also equipped with EGR systems. Nitrogen oxide and hydrocarbon (HC) emissions combined may not exceed 4.0 g/kWh. By contrast, the limit for NO<sub>x</sub> emissions for railcars in the same EU Stage IIIB emission standard is only



**Fig. 1: Integration of exhaust gas recirculation in engine design concept**  
 MTU has integrated the exhaust gas recirculation system into the engine design so that it has very little effect on space requirements.

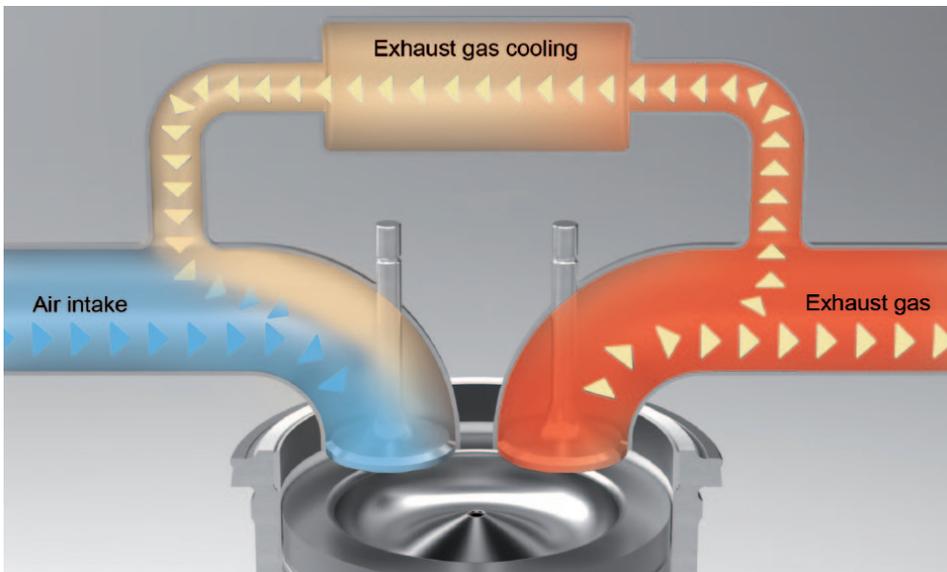
2.0 g/kWh. For this reason, MTU is equipping its Series 1600 engines for underfloor drive systems with an SCR exhaust aftertreatment – with no exhaust gas recirculation.

The US EPA Tier 4 final regulations which came into force for mobile machines below 560 kW in 2014 are particularly stringent. In this case, the nitrogen oxide limits are down 90 percent to

0.4 g/kWh compared with EPA Tier 3 regulations. To meet these demanding targets, MTU uses both exhaust recirculation technology and an SCR system. As the introduction of Tier 4 final emissions regulations involves no further tightening of NO<sub>x</sub> values, MTU will retain its exhaust gas recirculation technology. MTU's aim is to use in-engine technology to achieve compliance with the stricter particulate limits. This will involve optimization and further development of the injection and combustion systems and of turbocharging technology

**Benefits of exhaust gas recirculation from MTU**

Generally speaking, systems designed to reduce emissions must be modified to match the drive systems. MTU has produced a very compact design that permits all the exhaust gas recirculation components to be integrated into the engine concept (see Figure 1), so that any modifications to the engine have relatively little effect on space requirements and the exhaust system. It is necessary to modify the radiator, however, in order to cope with the increased cooling capacity of the engine. Compared to engine modifications involving an SCR system, this makes it much easier for customers to convert their units to meet new emissions standards because EGR systems for reducing nitrogen oxides require no additional operating media and thus involve no further expense or work on extra tanks and lines. The customer benefits in terms of reduced costs for handling and maintenance.



**Fig. 2: Schematic diagram of exhaust gas recirculation**

In exhaust gas recirculation, some of the exhaust gas is returned to the fresh air intake. The resultant mixture of fresh air and exhaust gas has a lower calorific value in terms of the volume. This lowers combustion chamber temperatures, thus reducing the production of nitrogen oxide (NO<sub>x</sub>).

## High and low-pressure exhaust recirculation

The exhaust gas recirculation system widely used today draws off part of the exhaust flow upstream of the turbocharger turbine and feeds it back into the air intake system downstream of the compressor. It works at the level of the boost pressure generated by the turbocharger and is therefore referred to as high-pressure exhaust gas recirculation. In the case of low-pressure exhaust gas recirculation, the exhaust is drawn off downstream of the turbocharger turbine and returned upstream of the compressor, so that the pressure level is roughly equivalent to ambient pressure. Compared with high-pressure exhaust recirculation, low-pressure recirculation has serious drawbacks: the compressor has to work harder, with the result that the heat to be removed from the intercooler increases. In addition, the system requires a diesel particulate filter, as otherwise particulates in the exhaust gas could damage components of the recirculation system or the compressor and intercooler. By comparison, high-pressure exhaust gas recirculation is inherently more robust so that no particulate filter is required. Low-pressure exhaust gas recirculation could be a means of subsequently upgrading an existing engine design to comply with stricter emission standards. Due to the considerable drawbacks of the system, particularly with regard to the maintenance requirement for the customer, MTU is not currently working on this version.

### Principle of operation

In exhaust gas recirculation, some of the exhaust gas is drawn off from the exhaust system, cooled and redirected back into the cylinders (see Figure 2). Although the exhaust fills the combustion chamber, it is not involved in the combustion reaction that takes place in the cylinder due to its low oxygen content. The speed of the combustion process overall is thus reduced, with the result that the peak flame temperature in the combustion chamber is lowered. This dramatically reduces the production of nitrogen oxides.

### Patented solution from MTU: the donor cylinder concept

Exhaust gas recirculation places higher demands on exhaust gas turbocharging, since higher boost pressures have to be achieved with reduced mass flow in the turbocharging system. These high boost pressures are required to direct the increased mass flow resulting from the exhaust gas recirculation rate into the cylinder during the gas cycle. In addition, the exhaust gas can only be redirected back into the cylinders when there is a pressure drop between the exhaust and the charge air systems. This pressure drop must be established with an appropriately configured turbocharging system, which

results in a reduction in turbocharging efficiency. The pressure drop between the exhaust and the charge air systems leads to gas cycle losses. These factors tend to result in lower engine performance or higher fuel consumption. To improve the combined effect of exhaust gas recirculation and turbocharging, MTU has developed what is known as the donor cylinder exhaust gas recirculation system (see Figure 3).

MTU's patented system only uses some of the engine's cylinders as the donor for exhaust gas recirculation. An exhaust valve (donor valve) holds back the exhaust gas flow downstream of the donor cylinders and thus creates the necessary pressure drop between the exhaust and the charge air systems. This means that the turbocharging system can be optimized to a very good efficiency level, with gas cycle losses only affecting the donor cylinders. Compared with conventional high-pressure exhaust gas recirculation (as in the case of the Series 1600 engine), the donor cylinder concept (Series 2000 and 4000) achieves lower fuel consumption, since it reduces the gas cycle losses in the engine and permits higher turbocharger efficiency levels. For this purpose, an additional donor cylinder exhaust valve is required in comparison with

high-pressure exhaust gas recirculation. Dirt build-up on components and the amount of servicing required over the service life of the application are lower with the donor cylinder concept, as is the case with high-pressure exhaust gas recirculation: unlike the situation with low-pressure exhaust gas recirculation, the exhaust gas is not fed into the intake air until immediately before it enters the cylinder, which means that only clean air flows through the compressor impeller and the intercooler and not exhaust gas containing particles as well.

### Cooling system for exhaust gas recirculation

The exhaust gas drawn off for recirculation has a temperature of around 650 degrees Celsius. It is therefore far too hot to be fed directly into the cylinders; it would increase the temperature of the combustion chamber even further, thereby defeating its actual purpose – that of reducing nitrogen oxide formation by lowering the combustion temperature. For this reason, the exhaust gas is first cooled to around 120 degrees Celsius (see Figure 4). In the case of industrial engines with high intake air and exhaust mass flow rates that requires high cooling capacities, which have to be supplied by high-performance heat exchangers. In principle, proven volume-production coolers as

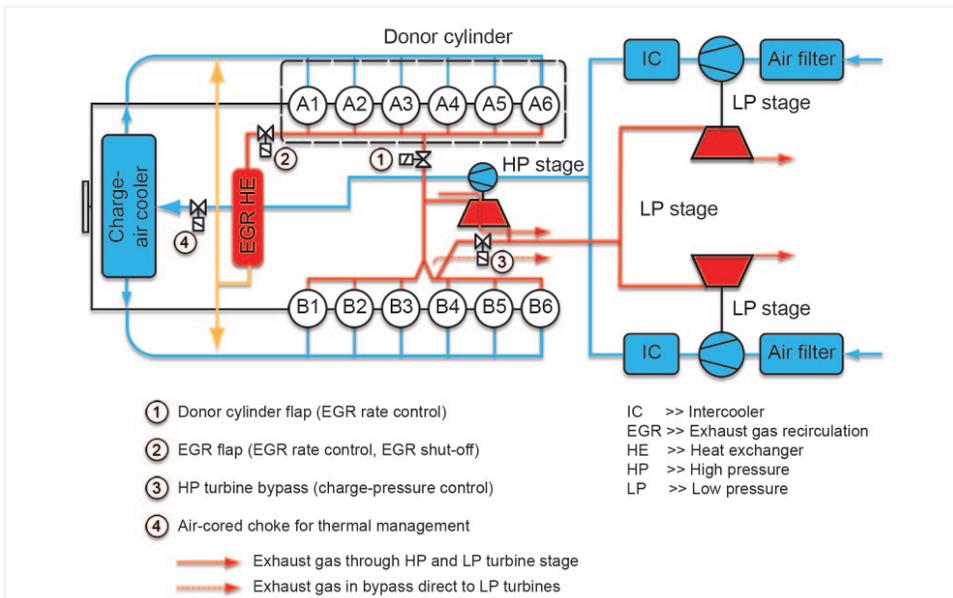
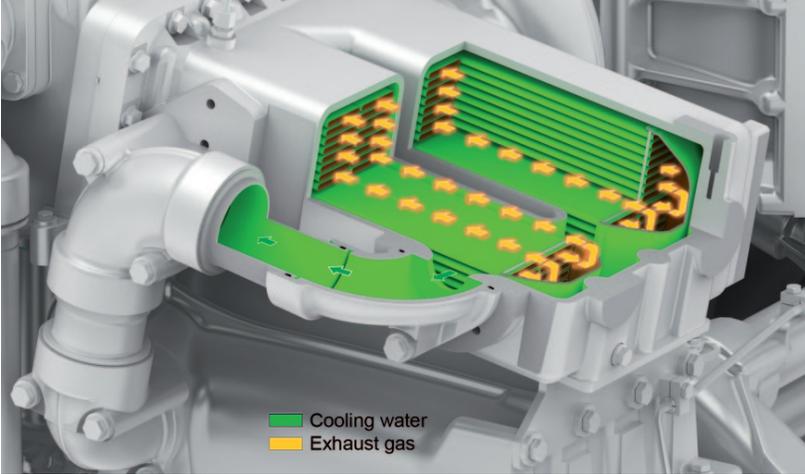


Fig. 3: EGR donor cylinder concept  
 Compared with conventional high-pressure exhaust gas recirculation, MTU's patented system achieves lower fuel consumption, since it reduces the gas cycle losses in the engine and permits higher turbocharger efficiency levels. This requires an additional donor cylinder exhaust valve.



**Fig. 4: Section through a radiator**

The exhaust gas drawn off for recirculation at a temperature of around 650 degrees Celsius is far too hot to be fed directly into the cylinders. For this reason, the exhaust gas is first cooled to around 120 degrees Celsius. The cooling system is optimally integrated into the engine design concept, so that the customer needs only to allow for a very small space requirement.

used in the commercial vehicle sector can be adopted for the purpose. However, to cover the cooling capacity required for a 16-cylinder engine with a capacity of 4.8 liters per cylinder, depending on the supplier, four to eight conventional commercial vehicle radiators of the highest capacity available would be needed for exhaust gas recirculation. Using this number of single radiators with the required mechanical strength is not possible in a mobile application.

MTU is therefore working with its suppliers to develop integrated cooler solutions in which only the internal components of the heat exchangers from proven commercial vehicle applications are adopted and the highly integrated cast housing is developed specifically to match individual requirements. The heat exchanger body is designed to match the contours of the engine perfectly and incorporates all connecting pipes. The benefits for the customer are a smaller space requirement, high functional reliability and low maintenance. MTU uses as many common parts as possible for engines within the same series with different numbers of cylinders. Due to the advanced stage of development maturity, this also results in a high level of functional reliability.

**Interaction with other key technologies**

Although exhaust recirculation results in lower nitrogen oxide emissions, soot particulate emissions increase to an undesirable degree if no counter-measures are taken. To prevent this happening, MTU has further refined both fuel injection and turbocharging. Whether a diesel particulate filter

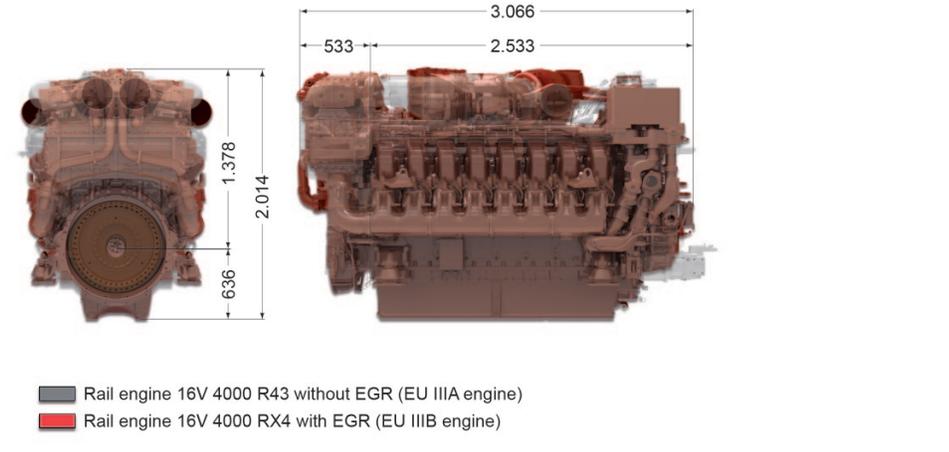
(DPF) is needed in addition to these internal engine modifications to further reduce emissions depends on the limits specified in the emission standard applicable to the individual application.

**Summary**

Exhaust gas recirculation is one of MTU's key internal engine technologies for reducing emissions. It can be used to reduce nitrogen oxide formation inside the cylinder by 40 percent and more, with the result that many applications – depending on the applicable limits in each case – can meet the required emission stan-

dards without the need for additional exhaust aftertreatment for NO<sub>x</sub> removal. In cases where emissions legislation is particularly strict, an SCR system or even a combination of exhaust gas recirculation and SCR system is required. MTU has produced a compact solution to integrate all the exhaust gas recirculation components into the engine design concept so that no additional installation space is required (see Figure 5). It means that customers can upgrade their applications to comply with new emission standards with no great effort involved. The system also requires no additional consumables.

**Fig. 5: Comparison of 16V 4000 R43 engine for rail applications with no EGR and 16V 4000 RX4 with EGR**  
 MTU first introduced exhaust gas recirculation in series production in mid-2011 for Series 4000 Oil and Gas engines in hydro-fracking applications (EPA Tier 4 emissions standard). It was likewise introduced in rail engines subject to EU IIIB emissions regulations which came into force in 2012. As the individual components are efficiently integrated on the engine, virtually no additional space is required (see illustrated comparison with Series 4000 rail engine without exhaust gas recirculation).



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