



# Diesel Emission Technologies and Aftertreatment Devices

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## INTRODUCTION

As the U.S. Environmental Protection Agency introduces increasingly stringent restrictions for nonemergency engines, engine manufacturers have been challenged to rethink engine architecture to comply with the regulation.

With advancement in engine design and in-cylinder fueling techniques, a lower total cost of ownership, as well as, reducing the system footprint, fuel consumption, parasitic load, and installation complexity is now possible.

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## **BACKGROUND:**

### **INTRODUCTION OF CLEAN AIR ACT**

The Clean Air Act was introduced in 1955, with multiple amendments being passed since. Its primary objective is to reduce air pollutants which contribute to damaging greenhouse gases.

The U.S. Environmental Protection Agency (EPA) is responsible for implementing and enforcing regulations for pollutant emissions produced by on-highway and off-road engines.

The focus of the EPA is to reduce the six common pollutants (ozone, particulate matter, carbon monoxide, nitrogen oxides, sulfur dioxide, and lead). To do so they have implemented a set of standards to reach increasingly stringent emissions levels.

### **RICE NESHAP**

Title 40, Part 63, Subpart ZZZZ (63.6580) of the Code of Federal Regulations (CFR) covers the National Emission Standards for Hazardous Air Pollutants (NESHAP) for reciprocating internal combustion engines (RICE).

The regulation applies to both existing and new engines. However, new engines required to meet New Source Performance Standards (NSPS), such as a compression ignition (CI) engine, are compliant with RICE NESHAP, and no further requirements apply. Therefore, RICE NESHAP is a primary consideration of engines built prior to Model Year 2007. An existing engine not in compliance would typically require a field-added diesel oxidation catalyst (DOC) to become compliant.

## NONROAD DIESEL ENGINES

Title 40, Part 1039, of the CFR covers the EPA emission standards for nonroad diesel engines. The standard is applicable to a wide range of construction, agricultural, and industrial equipment.

The EPA classifies these engines as being used on nonhighway equipment meant to be movable—either by being propelled, such as skid-loader, or by transport, such as a mobile/towable generator. Therefore, diesel generators mounted on either a trailer or a skid meant for transport, must abide by nonroad diesel emission regulations, not the stationary emissions discussed later in this paper.

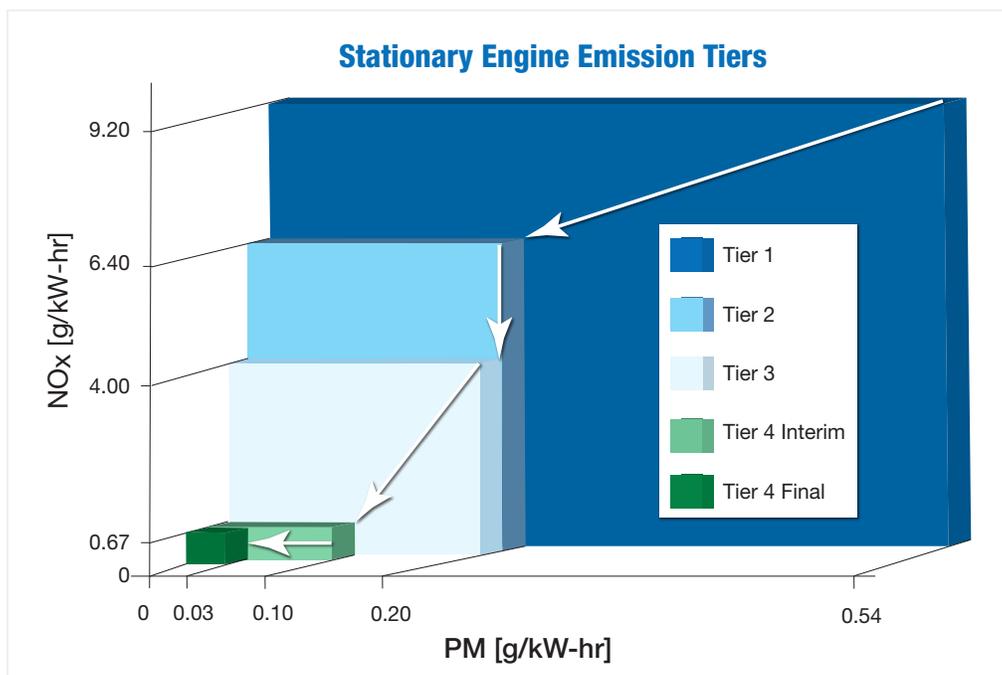
The standards for nonroad diesel engines were first introduced in 1994. Multiple iterations were made to enforce increasingly stringent regulations.

As shown in *Figure 1*, this phased approach has taken on an industry designation as tiers.

The latest Tier 4 regulation was announced in 2004 with a phase-in period from 2008–2015 to allow engine and equipment manufacturers time to prepare products to meet the stringent requirements.

Tier 4 regulations require the nitrogen oxide (NOx) and particulate matter (PM) levels of diesel engines to be reduced upwards of 90% from previous tiers. To achieve such levels exhaust aftertreatment systems are required.

*Figure 1*



# NSPS FOR CI STATIONARY ENGINES: NONEMERGENCY AND EMERGENCY GENERATORS

Title 40, Part 60, Subpart IIII of the CFR covers the NSPS for stationary RICE. The standard classifies stationary engines by brake horsepower and use type.

Depending on the classification of the engine, it must be below or at levels of emissions for nitrogen oxides (NO<sub>x</sub>), particulate matter (PM), carbon monoxide (CO), and nonmethane hydrocarbons (NMHC or simply HC).

The emissions levels of the various categories are based off emission levels enforced for various types of mobile equipment; therefore, no new engines emission levels were instituted with the ruling.

## PHASE-IN PROGRAMS

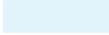
The standards were first introduced in 2005 and phased in completely by 2015. The phase-in program for the stationary nonemergency engines can be seen in *Figure 2*.

By the end of 2014, the phase in was complete, meaning all stationary nonemergency engines model year 2015 or newer are required to be Tier 4-certified in order to be sold into or operated in the U.S. To meet Tier 4 levels, a diesel engine will typically require at least one form of exhaust aftertreatment.

Figure 2

Phase-In Program for Stationary Nonemergency Engines												
Engine Generator		2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	
kWm	kWe											
8 <-19	10-15		6.6/7.5/0.40									
19 <-37	15-20		5.5/7.5/0.30					5.5/4.7/0.03				
37 <-56	20-40		5.0/7.5/0.30					5.0/4.7/0.03				
56 <-75	40-60		5.0/4.7/0.40				5.0/2.3/0.02			5.0/0.19/0.40/0.02		
75 <-130	80-100		5.0/4.0/0.30			5.0/2.3/0.02			5.0/0.19/0.40/0.02			
130 <-560	125-450		3.5/4.0/0.20			3.5/2.0/0.02			3.5/0.19/0.40/0.02			
560 <-900	500-800		3.5/6.4/0.20			3.5/0.40/0.67/0.10			3.5/0.19/0.67/0.03			
>900	900-2000		3.5/6.4/0.20			3.5/0.40/0.67/0.10			3.5/0.19/0.67/0.03			
>2200	>=2000		11.4/1.3/9.2/0.54			3.5/0.40/0.67/0.10			3.5/0.19/0.67/0.03			

CO/NMHC+NO <sub>x</sub> /PM (g/kW-hr)		TIER 1 Effective		TIER 4 Interim Effective
CO/NMHC/NO <sub>x</sub> /PM (g/kW-hr)		TIER 2 Effective		TIER 4 Effective
		TIER 3 Effective		

# NSPS SPECIAL EXEMPTIONS

## TAKING ACCOUNT OF THE LATEST DIESEL TECHNOLOGY

The NSPS regulation has special exemptions for engines used exclusively for emergency situations, e.g., a standby generator only meant to operate during power outages or service and maintenance activities.

The phase-in program for stationary emergency engines is shown in *Figure 3*. The highest levels reached were selected to avoid the use of aftertreatment equipment. Due to the low runtime hours of emergency engines, the environmental and health impacts are negligible from these sources.

Figure 3

Phase-In Program for Stationary Emergency Engines											
Engine Generator		2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
kWm	kWe										
8 -<19	10-15						6.6/7.5/0.40				
19 -<37	15-20						5.5/7.5/0.30				
37 -<56	20-40						5.0/4.7/0.40				
56 -<75	40-60						5.0/4.7/0.40				
75 -<130	80-100						5.0/4.0/0.30				
130 -<560	125-450						3.5/4.0/0.20				
560 -<900	500-800						3.5/6.4/0.20				
>900	900-2000						3.5/6.4/0.20				
>2200	>=2000						11.4/13/9.2/0.54				3.5/6.4/0.20

CO/NMHC+NOx/PM (g/kW-hr)		TIER 1 Effective		TIER 4 Interim Effective
CO/NMHC/NOx/PM (g/kW-hr)		TIER 2 Effective		TIER 4 Effective
		TIER 3 Effective		

## MEETING TIER 4 EMISSIONS LEVELS

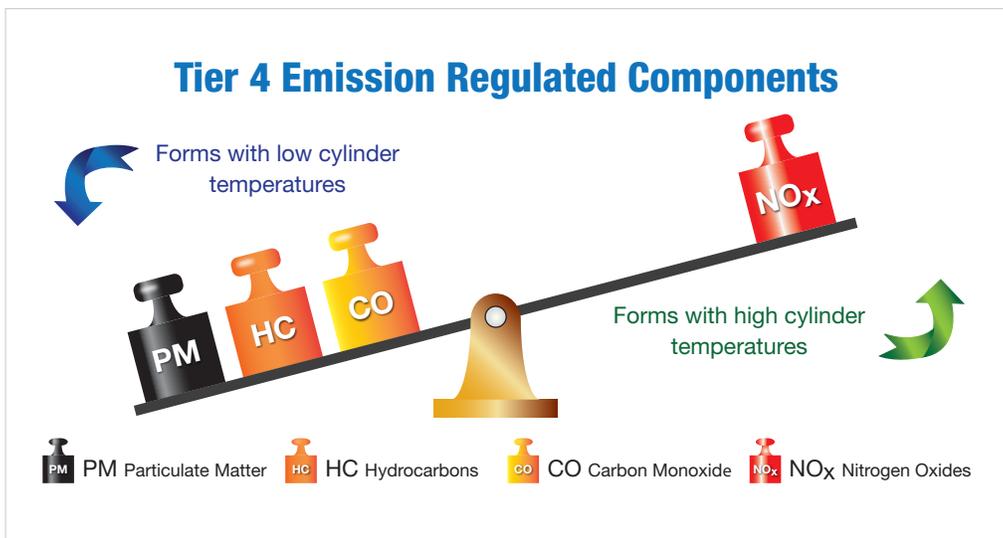
### ADDRESSING NOX AND PM LEVELS

Meeting Tier 4 emission levels without aftertreatment is not possible for most engines powering generators larger than 80–100 kWe. The primary reason is addressing NOx and PM levels. PM forms from partial combustion of diesel fuel in cooler parts of the cylinder. NOx is the result of high cylinder temperatures oxidizing some of the nitrogen from the air.

Unfortunately, the trade-off is an inverse relationship in *Figure 4*, when it comes to in-cylinder engine management for performance and emissions.

Advanced engines may be able to optimize combustion to minimize the formation of pollutants in the cylinder and only leave NOx to be addressed with an aftertreatment device. Engines not capable of this will require the use of multiple aftertreatment devices.

*Figure 4*



## DIESEL ENGINE POLLUTANT EMISSION REDUCTION TECHNOLOGIES

### CATEGORIES OF REDUCTION TECHNOLOGIES

Emissions reduction technologies can be grouped into two categories; in-cylinder or aftertreatment. In-cylinder is any effort made to reduce the pollutant emissions created by an engine. Aftertreatment comprises efforts made within the exhaust stream of the engine to further reduce created pollutants. Aftertreatment devices are added onto the engine; however to be a certified engine, the aftertreatment device is considered integral to the engine, and it cannot operate without it.

The following sections provide an explanation on a few of the most common in-cylinder and aftertreatment control technologies used for diesel generator engines.

## IN-CYLINDER CONTROL TECHNOLOGIES

### COMBUSTION CHAMBER

The air intake port and geometries of the combustion chamber on a diesel engine control the air motion and fuel–air mixing within the engine cylinder. Engine manufacturers have multiple configurations in use today on large nonroad diesel engines, including direct injection and indirect injection systems. Advancements of computer–aided engineering tools and computational fluid dynamics have evolved the ability to predict the performance of a cylinder design. This allows for optimization of the entire system for fuel consumption, pollutant emissions creation, torque, power, and transient performance.

### HIGH-PRESSURE COMMON RAIL FUEL INJECTION

A fuel system on a common rail diesel engine consists of a low-pressure system (up to 100 PSI) for supplying fuel from the tank to the engine and a high-pressure system (up to 32,000 PSI) for injecting the fuel into the cylinder.

The high-pressure system uses a secondary fuel pump to pressurize the fuel within a common fuel rail used to feed the injectors. Increasing the injection pressure allows for finer atomization of the fuel, improved air–fuel mixing, and greater control of injection timing. Diesel engines with mechanical fuel systems are limited in their injection pressures and fuel injection control capability.

### ELECTRONIC FUEL INJECTION

Injection rate shaping or fuel mapping are common terms used to describe the capability of a diesel engine with electronic fuel injection. In this system, fuel injections are controlled by the engine electronic control unit (ECU) with the use of solenoid actuated injectors.

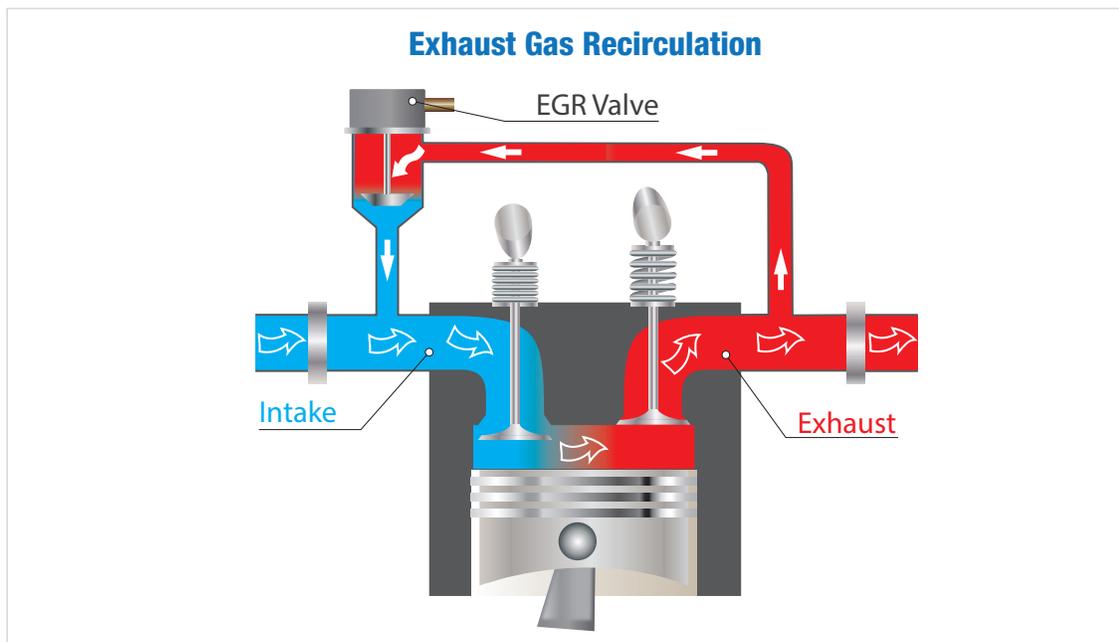
The engine is programmed for the ideal time for injection during the combustion cycle, including the ability to make multiple injections within a matter of milliseconds. Utilizing closed-loop feedback controls, the engines are also able to adjust the fuel injections to account for transient events, steady state operation, or environmental operating conditions. Electronic fuel injection improves every aspect of engine operation while reducing the creation of air pollutants.

### EXHAUST GAS RECIRCULATION

Commonly referred to as EGR, exhaust gas recirculation is a NO<sub>x</sub>-reduction technology widely used in on-highway and nonroad diesel engines, see [Figure 5](#).

During operation, exhaust gases are recycled back into the combustion chamber. The exhaust gases are mixed with intake air to reduce oxygen content and combustion temperature. It is considered an in-cylinder control technology since it is reducing the creation of NO<sub>x</sub>.

Figure 5



## AFTERTREATMENT TECHNOLOGIES

### DIESEL OXIDATION CATALYST

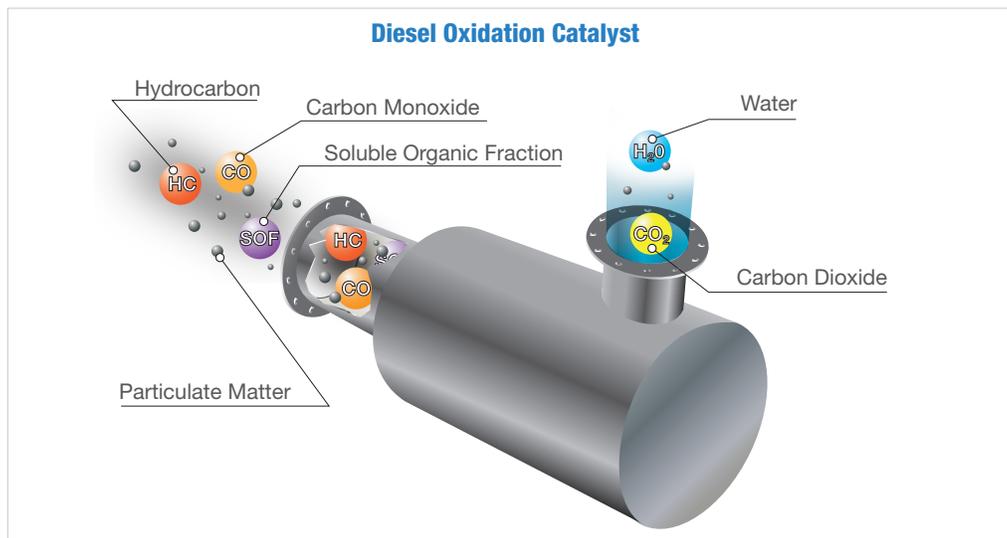
A diesel oxidation catalyst (DOC), see *Figure 6*, reduces CO, HC, and the organic fraction (OF) of diesel particulates by oxidizing chemical reactions converting to carbon dioxide and water in the presence of heat and catalyst materials.

A DOC is easy to implement as it consists of a flow-through substrate, adds little back pressure, and is relatively low cost. Additionally, little maintenance is required and DOCs have demonstrated excellent durability.

The downside of a DOC is a minimal reduction of PM and NO<sub>x</sub>, which are the primary reductions required to meet Tier 4 levels. Therefore, it is often used as a standalone device to meet RICE NESHAP requirements or in conjunction with another aftertreatment device such as a diesel particulate filter (DPF) or SCR.

When doing so, the DOC is typically used to increase nitrogen dioxide (NO<sub>2</sub>) production. NO<sub>2</sub> can enhance the performance of many SCR systems as well as the performance of a passive regeneration DPF.

*Figure 6*



## AFTERTREATMENT TECHNOLOGIES CONT.

### DIESEL PARTICULATE FILTER

Diesel particulate filter (DPF), see *Figure 7*, filters out the solid fraction of PM, commonly known as soot and seen as black smoke.

The exhaust gases pass through small pores in the ceramic substrate of the filter, trapping the particulate matter.

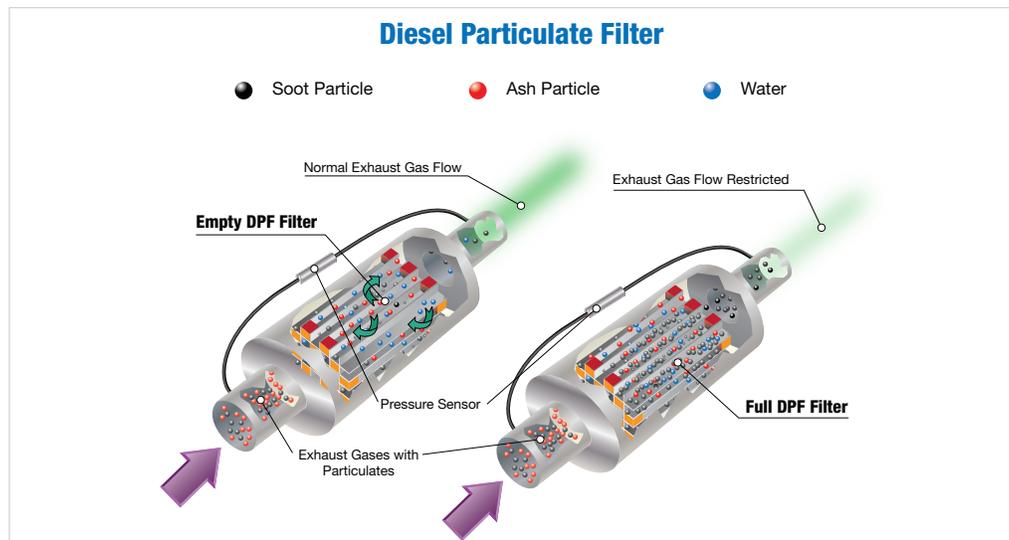
The layer of trapped soot builds up and increases back pressure to the point where it needs to be burned off periodically, known as regeneration.

DPFs are either a passive regeneration system or an active regeneration system.

Regeneration events require a minimum exhaust temperature to occur, which may happen during operation (passive) or require the addition of fuel or other heat input (active). Therefore, a generator application may require a minimum load on the engine to reach the proper exhaust temperatures.

A load bank is often required to maintain the minimum load on the unit and needs to be added to the system.

*Figure 7*



## AFTERTREATMENT TECHNOLOGIES CONT.

### SELECTIVE CATALYTIC REDUCTION

The best current technology commercially available for reducing NO<sub>x</sub> emissions is selective catalytic reduction (SCR), see *Figure 8*.

The system operates by injecting diesel exhaust fluid (DEF), consisting as a mixture of urea-derived ammonia and water, into the exhaust stream. The ammonia reacts selectively with the NO<sub>x</sub> in the exhaust to reduce it to nitrogen and water. The reaction occurs in the presence of the metal-based catalyst, such as tungsten and vanadium, to increase the rate of reduction reaction. Common components of the system include; DEF storage tank, DEF pump, DEF controls, DEF filters, DEF lines, DEF injectors, mixing chamber, and catalyst.

SCR systems are utilized in many industries and applications. In fact, most on-road diesel trucks are equipped with an SCR system. The technology has proven to be reliable and durable when deployed correctly. To help with this, systems typically include closed-loop control to optimize DEF injection using NO<sub>x</sub> and ammonia sensors. Also, considerations of operating temperatures and DEF storage conditions are crucial to the success of the system.

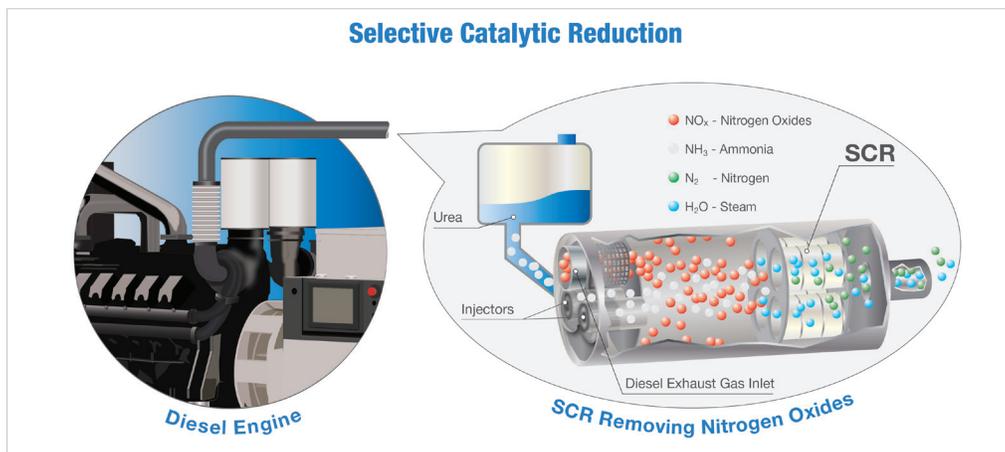
The chemical reaction cannot occur if the exhaust temperature and SCR are below 250°C. Therefore, systems will not inject while the unit is below that threshold. The system will also be susceptible to hydrocarbon loading under these low load conditions.

A specifying engineer should consult with the equipment manufacturer regarding expected operating conditions and load profile in the design stage of a Tier 4 application. The use of a load bank to control minimum loading of the generator may be recommended.

Proper maintenance of DEF fluid is critical to an SCR system. DEF is highly corrosive and has a freezing point of 12°F. To avoid corrosion, SCR systems will consist of a mixture of stainless steel and plastic composite components. To ensure DEF does not freeze, rendering the system inoperable, systems will include heating elements, insulated wrappings, and lines will be purged when not in use. These components are a large contributor to the price of an SCR system.

On the other side of the spectrum, DEF fluid is susceptible to degradation at elevated temperatures. When stored at average temperatures at or below 77°F, the shelf life will be in excess of 36 months. It can decrease down to six months under certain conditions. Consult the supplier for specifics on DEF storage requirements before purchasing.

*Figure 8*



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## **APPLICATION CONSIDERATIONS FOR TIER 4-CERTIFIED PRODUCTS.**

### **INDUCEMENT CONTROLS**

Per EPA regulations, in the event of an emissions aftertreatment system failure or fault the unit will enter into inducement. The inducement period allows a limited window for the operator to fix the fault before the unit begins to derate and eventually shut down completely.

A standard inducement for a generator is a four-hour window. The engine will first derate power to 20% if it is not corrected. A second malfunction when the unit is in inducement will cause the system to shut down. Once the fault is corrected, the unit will return to normal operation. However, if an additional fault occurs within 40 hours of a fault being corrected, the unit will not enter inducement and rather go straight into a shutdown.

Inducement is legally required for certified units.

### **MAINTENANCE OF AFTERTREATMENT SYSTEMS**

Aftertreatment systems require various levels of service and maintenance. The easiest is a DOC. They are fully contained units that require no maintenance if the engine is operated properly.

An SCR system is the next easiest to maintain. The SCR component is typically fully contained and requires no maintenance under normal operating conditions.

The DEF components will, however, require maintenance. DEF filters need periodic replacement and the quality of the DEF fluid needs continuous monitoring and potential replacement if it degrades below usable levels.

A DPF system requires the most maintenance of the three common aftertreatment devices. The primary concern revolves around the cleanliness of the filter. Maintaining proper operating conditions for regeneration is the most effective way of ensuring your generator runs properly. In addition, regular inspections of the filters are needed to identify when cleaning will be required.

Manufacturers will generally require cleaning of the filters at regular runtime or year intervals regardless of cleanliness. To clean a particulate filter, they must be removed from the unit and sent to an off-site facility. This renders the unit inoperable during this time.

### **PLAFTFORM AND PACKAGING**

Aftertreatment systems typically require custom supports, platforms, and packaging considerations. Guidelines for installation are provided from the manufacturer in an application guideline.

A specifying engineer will need to closely follow the guideline to ensure requirements for the system are met.

Common requirements include; mounting location of DEF tank, airflow requirements around SCR, allowable back-pressure, DEF lengths and routing, etc.

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## **ON-SITE INSTALLATION AND COMMISSIONING**

Aftertreatment systems for large diesel generators are too large to transport fully assembled.

On-site installation will include installing and connecting the various components of the system. Time must be allotted for this in the project schedule and a clear understanding of who is completing the installation of the components is recommended.

Commissioning of a Tier 4–certified unit includes an installation verification checklist that must be completed by a factory-trained representative.

## **SUMMARY**

### **TIER 4–CERTIFIED SYSTEMS**

Tier 4–certified systems are required to run in any nonemergency application in the U.S. and in some parts of Canada. Meeting the stringent emission levels requires the use of exhaust aftertreatment equipment.



## ABOUT THE AUTHOR

Justin Loritz joined Rehlko in 2007 and has held various roles within the organization. After graduating from Michigan Technological University with a B.S. in mechanical engineering, he began his career supporting the large diesel assembly team as a process engineer and progressed through a variety of roles, including lead design engineer for the diesel marine product line, production manager for large generator assembly, and principal engineer of manufacturing systems. Justin has extensive knowledge of the Rehlko KD Series™ products and the needs of customers within this product category.

## ABOUT POWER SYSTEMS

Power Systems, Rehlko's largest division, delivers worldwide energy solutions designed to ensure resilience for mission-critical applications of all sizes. Building on more than a century of expertise and dedication, the company offers complete power systems, including industrial backup generators (HVO, diesel, gaseous), enclosures, hydrogen fuel cells systems, automatic transfer switches, switchgear, monitoring controls, genuine parts and end-to-end services. As a global company with service partners in every country, Power Systems provides reliable, cutting-edge technology to keep industries and businesses running.

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