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Catalytic Mufflers for LPG Engines

v3.0

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What is LPG?

Liquefied Petroleum Gas (LPG) is often incorrectly identified as propane. In fact, LPG is a mixture of petroleum and natural gases that exist in a liquid state at ambient temperatures when under moderate pressures (less than 1.5 MPa or 200 psi). The common interchanging of the two terms is explained by the fact that in the U.S. and Canada LPG consists primarily of propane (see Table 1). In many European countries, however, the propane content in LPG can be as low as 50% or less.

Table 1. Composition of LPG (U.S. HD-5 standard)

Propane:	85% min. by liquid volume
Propylene:	5% max. by liquid volume
Butane & Heavier HC:	2.5% max. by liquid volume
Sulfur:	120 ppm max. by weight

The major sources of commercial LPG are natural gas processing and petroleum refining. Raw natural gas often contains excess propane and butane which must be removed to prevent their condensation in high-pressure pipelines. In petroleum refining, LPG is collected during distillation, from lighter compounds dissolved in the crude oil, as well as generated in the "cracking" of heavy hydrocarbons. Therefore, LPG can be considered a by-product and its exact composition and properties will vary greatly with the source.

LPG provides about 8% more energy per unit weight (LHV = 19,757 BTU/lbm) than gasoline. Theoretically, vehicle operation with LPG should be more efficient than with gasoline, i.e., the vehicle should attain better specific fuel consumption and improved mileage. However, this will only happen if the engine design is optimized for LPG fuel. If a gasoline engine is converted to operate on LPG this increased efficiency will not be realized due to the lower density of LPG compared to gasoline and also its slightly higher oxygen demand (LPG stoichiometric A/F = 15.8). The lighter density fuel displaces air in the intake manifold, and thus, less air per cycle is induced to the cylinders. This translates to a decreased volumetric efficiency and a loss of power compared to the original gasoline rating of the engine.

What are LPG Emissions?

The major harmful emissions from LPG engines are similar to those from other internal combustion engines:

- Carbon monoxide (CO)
- Hydrocarbons (HC)
- Nitrogen oxides (NO_X)

Unlike diesel engines, there are practically no particulate emissions from LPG engines. Concentration ranges of the above emissions are listed in Table 2.

Table 2. Emissions from LPG Engines

CO vol. %	HC ppm C1	NO_X vppm
0.2 - 2.0	50 - 750	250 - 2,000

Carbon monoxide is generated in the exhaust as the result of incomplete combustion of fuel. CO is a very toxic, colorless and odorless gas. LPG emissions may contain considerable amounts of CO. When engines operate in enclosed spaces, such as warehouses, buildings under construction, or tunnels, carbon monoxide can accumulate quickly and reach concentrations which are dangerous for humans. It causes headaches, dizziness, lethargy, and death. CO is usually the major concern whenever LPG engines are used indoors.

Hydrocarbons are also a product of incomplete combustion of fuel. LPG emissions, because of fuel composition, contain only short chain hydrocarbons. They are not likely to contain toxic components which are found in gasoline HC emissions. Also, the environmental impact of LPG hydrocarbon emissions (ozone reactivity contributing to smog) is much smaller than that of gasoline. However, hydrocarbon derivatives are responsible for the characteristic smell which is often a nuisance when LPG engines operate indoors.

Nitrogen oxides are generated from nitrogen and oxygen under the high temperature and pressure conditions in the engine cylinder. NO_X consists mostly of nitric oxide (NO) and some nitrogen dioxide (NO_2). Nitrogen dioxide is a reactive gas, very toxic for humans. Accumulation of NO_X in a warehouse atmosphere may also be detrimental for the stored goods. For example, only a few ppm of NO_X in the ambient air can change the color of paper stock from white to yellowish. NO_X emissions are also a serious environmental concern because of their ozone reactivity and important role in smog formation.

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How Clean are LPG Engines?

LPG was introduced to the market as a "clean-burning" fuel. Is it still clean today, many years down the road? LPG definitely had the potential to become a clean fuel. The reasons for the superior emissions performance were the following:

- Reduced emissions of carbon monoxide compared to gasoline engines (but not as low as in diesel engines)
- No heavy hydrocarbon emissions. HC, which are emitted, are of short carbon chain and low ozone-forming reactivity
- Low emission of toxic air contaminants such as benzene and 1,3-butadiene
- Low cold-start emissions
- Likely better emissions durability than that of gasoline engines. LPG emissions should not increase as dramatically with the engine wear and deposit build-up
- Zero evaporative and running losses due to the sealed fuel system

For a variety of reasons LPG is not considered the alternative fuel of the future anymore. Its place has been taken by natural gas competing with diesel and biodiesel. Consequently, there has been little development in dedicated LPG engine technology. On the other hand, gasoline engines and their emissions have improved tremendously over the last decade. As a result of that development, some of the used-to-be advantages of LPG fuel, especially the low CO emissions, are now less pronounced.

Essentially all LPG engines are gasoline engine conversions. As such, they are not engineered to take advantage of the low emission potential of LPG. Their engine/fuel control system is not optimally calibrated for the new fuel, often sacrificing performance, fuel economy, and emissions. The performance and emissions vary between different engines and conversion kits. Electronic LPG conversion kits are available now which should provide the lowest emissions and best fuel economy, but little data exists so far to verify that statement. Many of the mechanical conversions produce engines not even remotely resembling the ideal, low-emission LPG picture. It is wise to request emission data from the vendor when buying an LPG vehicle for indoor application. Unfortunately, brand new LPG conversions emitting CO levels of 2 to 4% are not uncommon. As a generous guideline, an acceptable LPG engine should have an exhaust CO concentration of less than 1% under any steady-state condition.

Emissions from LPG engines also depend heavily on the engine's state of tune. An example plot illustrating the CO levels for different air to fuel ratios is shown in Figure 1. Carbon monoxide emissions skyrocket when the mixture becomes rich. The importance of proper engine tune-up and maintenance for low emissions cannot be overestimated.

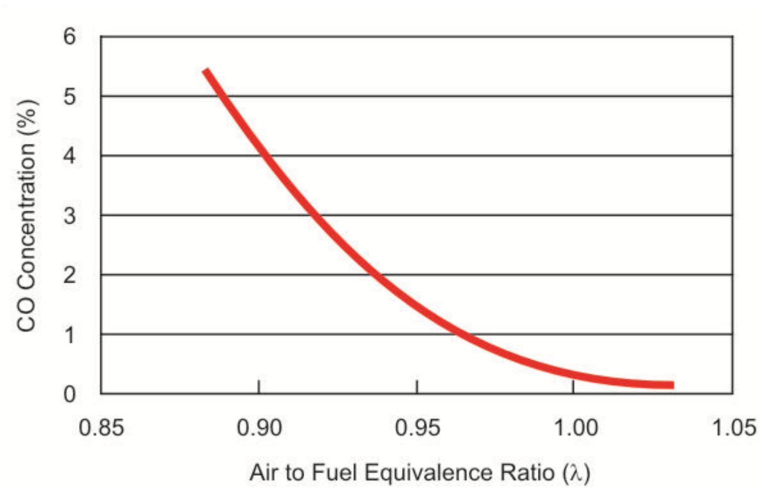

Figure 1. Sensitivity of LPG Emissions to A/F Ratio

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Are LPG Emissions Regulated?

Emissions from LPG vehicles used indoors pose a health hazard to workers. As such, they are indirectly regulated by all occupational health and safety air quality standards. There are many regulatory authorities in different jurisdictions. The Occupational Safety and Health Administration (OSHA) within the Department of Labor sets air quality standards at the federal level in the U.S. The corresponding regulatory authorities in Canada are located within provincial Ministries of Labour. Most air quality standards in North America are based on the guidelines established by the American Conference of Governmental Industrial Hygienists (ACGIH). The ACGIH Threshold Limit Values (TLV) for pollutants present in LPG exhaust are listed in Table 3. The TLVs are time-weighted averages for an 8-hour workday.

Table 3. Threshold Limit Values for LPG Exhaust Pollutants

Substance	TLV (vppm)
Carbon Monoxide	25
Nitric Oxide	25
Nitrogen Dioxide	3
Butane	800
Sulfur Dioxide	2

Most problems with indoor operation of LPG engines are related to carbon monoxide emissions. Sometimes NO_X emissions may also be an issue. TLVs for carbon monoxide vary in different jurisdictions between 25 and 50 ppm. It is recommended that ambient concentrations of carbon monoxide be monitored on a regular basis wherever LPG engines are used.

There are several misconceptions regarding the CO monitoring of LPG vehicles operating indoors. The TLVs from Table 3 refer to the ambient air and not to the tailpipe emissions. By regulating the ambient air quality, LPG emissions are regulated only in an indirect manner. The ambient levels of CO are observed after exhaust gases leave the tailpipe and are mixed with air. They depend heavily on the ventilation rate in the building.

The tailpipe emissions are not directly regulated, although they may be subject to recommendations. For example, the recommended maximum tailpipe CO level for LPG forklift trucks in Ontario is 1% (i.e. 10,000 ppm). The maximum ambient level of CO amounts to 35 ppm in the same jurisdiction. As the exact CO measuring procedures and, especially, the choice of sampling locations relative to the truck are often left to the discretion of OSHA inspectors, many areas remain open to controversy. The inspectors, however, have the upper hand in about 9 out of 10 real-life situations.

To be on the safe side, the tailpipe emissions should be kept as low as possible by combining good engine maintenance with exhaust gas after-treatment. Low tailpipe emissions also allow for lower ventilation rates (reduced heating costs) and contribute to a healthier work environment for the equipment operators.

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How Can We Reduce LPG Emissions?

Several approaches to control emissions from LPG engines operating in confined spaces are illustrated in the following chart. Usually a combination of available methods provides the optimum solution.

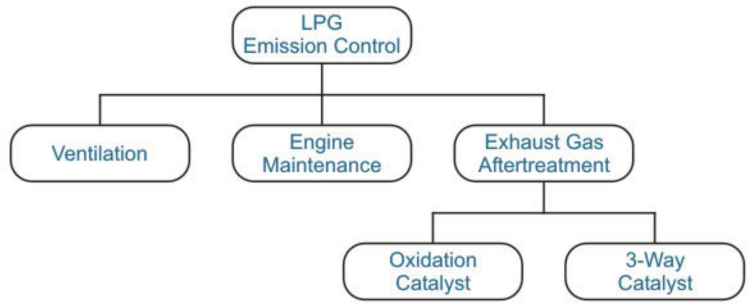

Figure 2. Methods of LPG Emission Control

Ventilation is always required in confined work environments, no matter whether engines operate in the area or not. If engines do operate, higher ventilation rates should be provided. As a guideline, each LPG forklift truck with a 60 hp engine and not equipped with an emission control catalyst requires about 2.4 m3/s (5000 cfm) of ventilation air. If electrical heating is used, this number translates to over $500.00 per month of extra heating cost during winter (heating from 0 to 18°C, 8 hrs per day, 21 days per month, energy cost 0.06 $/kWh). Another disadvantage of ventilation as a means of emission control is its uneven distribution. It is very difficult to provide perfect airflow, mixing, and distribution throughout the ventilated area. Usually certain parts of the building obtain less ventilation than others and accumulate higher concentrations of CO and other pollutants. In particular, high CO concentrations are frequently observed in proximity of operating LPG vehicles. Often LPG forklifts operate in areas with extremely poor ventilation, such as inside transport truck trailers or containers.

Engine tune-up and proper maintenance are invaluable tools in controlling carbon monoxide emissions from LPG engines. A regular maintenance program should be implemented which incorporates final engine tuning through carbon monoxide analysis of exhaust gases. A CO analyzer working on the infrared (IR) principle provides the highest accuracy and best reliability. Carbon monoxide concentrations in the exhaust gases should always be below 1% (10,000 ppm). On most engines the CO level can be kept below 0.5% (5,000 ppm) through good engine tune-up.

Catalytic exhaust gas after-treatment provides the final means of LPG emission control. Tailpipe carbon monoxide levels as low as 100 ppm can be achieved. However, this reduction is dependant upon the CO concentration of the raw exhaust. It is very important to realize that exhaust after-treatment is not a substitute for good engine maintenance and tune-up. On the contrary, exhaust gas after-treatment is complementary to engine maintenance and in itself requires that the engine be in good condition with no excessive raw emissions. Catalytic conversion of high concentrations of carbon monoxide and hydrocarbons generates large quantities of heat. As a result, the catalyst temperature would rise, leading to overheating and premature loss of activity.

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Oxidation catalyst systems are no longer commonly used for emission control of LPG forklifts and off-road vehicles. The oxidation catalyst, sometimes also called the 2-way catalyst, is effective in reducing two major exhaust pollutants, carbon monoxide and hydrocarbons. Both are removed from the exhaust through oxidation to carbon dioxide and water vapor (Figure 3)

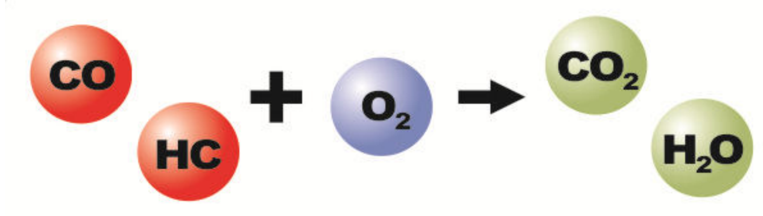
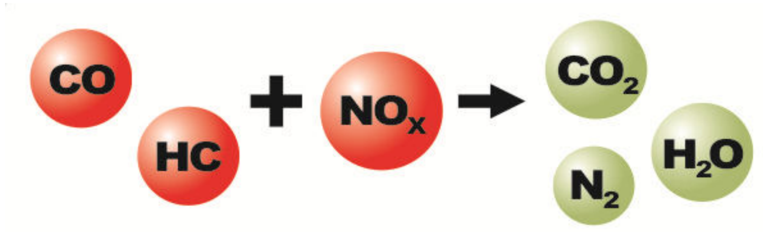


Figure 3. Chemistry in the Oxidation Catalyst

A newer catalyst technology is known as the 3-way catalyst. Three pollutants are simultaneously removed from the exhaust gas in the 3-way catalyst. They are carbon monoxide, hydrocarbons, and nitrogen oxides. The chemistry occurring in the 3-way catalyst



is schematically illustrated in Figure 4.

Figure 4. Chemistry in the 3-Way Catalyst

The fundamental reactions in the 3-way catalyst are between CO and HC on one side and NO_X on the other. To achieve high conversions of all three pollutants their concentrations must be at the stoichiometric ratio. It simply means that the amount of CO and HC should match the amount of NO_X present in the system, as reflected in the exact equations of chemical reactions which occur on the catalyst. A precise electronic engine controller maintains that ratio on a real engine, as happens in today's automobiles. 3-way catalyst systems are offered as the standard product for LPG emission control from Nett Technologies.

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How Does an Oxidation Catalyst Work?

A catalyst is a substance which promotes certain reactions but is not one of original reactants or final products. In other words, the catalyst is not consumed in the reactions it promotes. Platinum group metals (PGM) including platinum itself, palladium, and rhodium are commonly used in emission control catalysts. Modern catalytic converters utilize a monolith honeycomb substrate which is coated with the PGM metal compounds and packaged into a stainless steel container. The honeycomb is made either of ceramics or stainless steel foil. Its structure of many small parallel channels presents high catalytic contact area to the exhaust gases. As the hot gases flow through the channels and contact the catalyst, several exhaust pollutants are converted into harmless substances. The following reactions occur in the oxidation catalyst:

$$CO + \tfrac{1}{2}O_2 \rightarrow CO_2$$
$$[\text{Hydrocarbons}] + O_2 \rightarrow CO_2 + H_2O$$

The hydrocarbon emissions from LPG engines will contain a mixture of propane, butane, ethane, and other compounds. Both CO and hydrocarbons are converted in the oxidation catalyst to carbon dioxide and water vapor which are non-toxic gases. The conversion of CO and HC in the catalyst requires oxygen, as shown in the reaction equations. Usually there is not enough oxygen in the exhaust gases of LPG engines to burn all of the pollutants. Oxidation catalyst systems frequently require extra air, called secondary air, be introduced into the exhaust system in front of the catalyst.

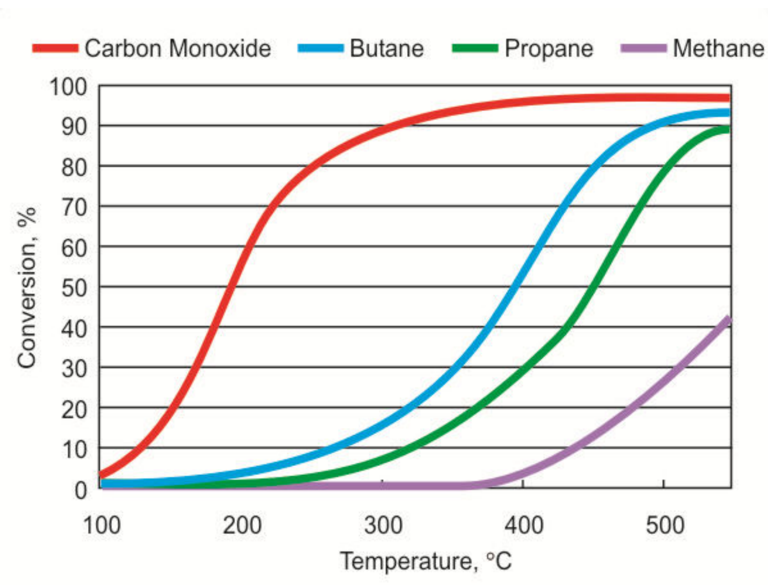

Figure 5. Conversion of CO and Hydrocarbons in Oxidation Catalyst

Typical conversion efficiencies for carbon monoxide and various hydrocarbons (butane, propane, and methane) on an oxidation catalyst are shown in Figure 5. Catalyst activity increases with temperature. A minimum exhaust temperature of about 200°C (395°F) is necessary for the catalyst to "light-off". Higher temperatures are necessary for hydrocarbon conversion. LPG exhaust contains short carbon chain hydrocarbons which are more difficult to convert in the catalyst than those found in diesel or gasoline exhaust. As illustrated in the graph, the shorter the carbon chain the higher the conversion temperature.

How Does a Three-Way Catalyst Work?

In a three-way catalyst, reactions between CO, HC, and NO_X result in the simultaneous removal of all three major exhaust pollutants. One of the fundamental chemical reactions occurring in the three-way catalyst can be written as follows:

$$CO + NO \rightarrow CO_2 + \frac{1}{2}N_2$$

Concentrations of pollutants in the exhaust gas depend on the fuel mixture composition. At lean fuel mixtures the exhaust gases contain little carbon monoxide or hydrocarbons but high concentrations of NO_X. Rich mixtures produce high concentrations of CO and HC with little NO_X. In order to achieve high simultaneous conversions of CO and NO_X, their concentrations in the exhaust must be in stoichiometric proportion, as illustrated by the above equation. If the air/fuel mixture is not stoichiometric, conversion of either NO_X or CO will deteriorate, as shown in Figure 6.

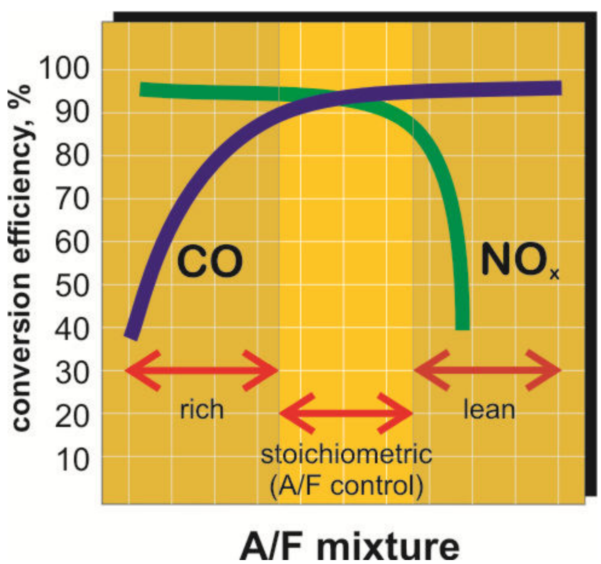

Figure 6. Three-Way Catalyst Performance

In practice, three-way catalysts are often used with air/fuel ratio controllers which maintain the mixture composition at stoichiometric. These controllers utilize a feedback signal from an oxygen sensor positioned in front of the catalyst in the exhaust system. The range of A/F ratio required for satisfactory catalyst operation is known as the "catalyst window". Precise A/F ratio control is especially important for efficient NO_X control, as the nitrogen oxides conversion drops dramatically at lean fuel mixtures.

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Three-Way Catalytic Mufflers

Nett® 3-Way catalytic mufflers have been designed to control exhaust emissions and noise from industrial forklift trucks as well as other spark ignited engines used in material handling and construction. The emission control system and the noise attenuation components are incorporated in one shell. All Nett® catalytic mufflers are designed to match the noise attenuation of the original mufflers they replace.

Three-way catalytic mufflers are the most effective way of controlling carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_X) emissions from LPG, CNG, and gasoline engines. CO and NO_X emissions can be simultaneously reduced by 90-99%. Three-way catalyst systems are available in two configurations:

Closed-Loop Control System. The complete system (see Figure 7 - Nett® system is shown in green) includes a catalytic muffler with built-in 3-way catalyst, a zirconium oxygen sensor, and an electronic control unit (ECU). The ECU receives a feedback signal from the O_2 sensor and maintains the engine air/fuel ratio at the stoichiometric point, which yields optimal catalyst performance. This system provides the best conversion of both carbon monoxide and nitrogen oxides and can improve the fuel economy of the truck. Whenever NO_X control is important, use of the closed-loop system is strongly recommended.

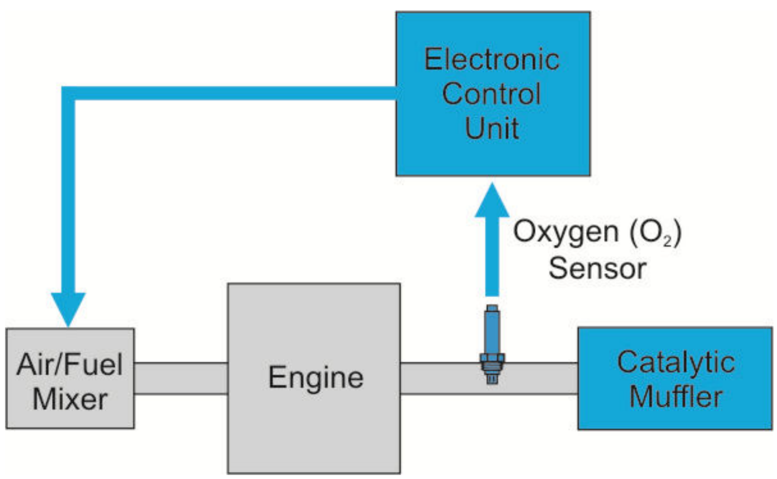

Figure 7. Closed-Loop Control System

Open-Loop Control System. The catalytic muffler with a built-in 3-way catalyst is installed directly into the existing exhaust system. This layout is recommended when CO control is required but NO_X performance can be compromised. The performance of the catalyst will vary depending on the engine A/F ratio (see performance chart above). Operating the truck at a slightly lean mixture will result in good CO abatement. The overall effect greatly depends on the engine maintenance program.

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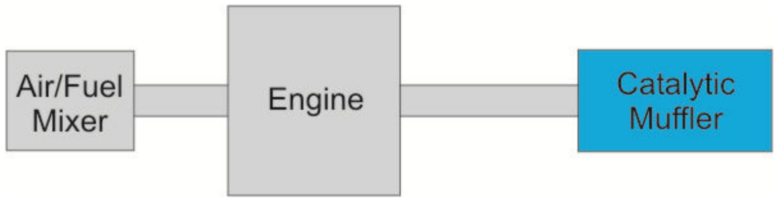

Figure 8. Open-Loop Control System

Catalyst Durability

Nett® catalysts are designed and manufactured to maintain high activity for the entire life-span of the engine. The typical catalyst life-span ranges from 5-7 years under good conditions to over 10 years under ideal conditions. There are, however, circumstances under which the catalyst life might be shortened. There are two major causes of catalyst deactivation:

- high temperature
- poisoning

Catalysts may suffer thermal degradation and loss of activity when exposed to temperatures above 650°C (1200°F) for prolonged periods of time. LPG engines have high exhaust temperatures, much higher than diesel and usually higher than gasoline, and may be close to the above limit. Catalytic combustion of carbon monoxide and hydrocarbons further increases the temperature in the catalyst. With a properly tuned engine, the temperature in the catalyst normally remains within a safe range. Good engine maintenance is very important to avoid catalyst overheating. Many engine problems might result in higher than usual exhaust temperatures. High exhaust temperatures could be a sign of either a poor engine tune-up with excessive emissions or a more serious engine problem. Engine misfire is likely to cause catalyst damage as the unburned fuel is oxidized in the catalyst with a tremendous release of heat.

Several chemical elements have the ability to selectively poison or mask the catalyst surface. Some of the substances to be avoided, such as phosphorus, may be present in the engine lube oil. Catalyst poisoning is usually not a serious problem on LPG engines but may occur as a result of excessive lube oil consumption.

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Features of Nett® Catalytic Mufflers

Nett® catalytic mufflers present a simple, practical, and cost-effective solution to the problem of carbon monoxide emissions in the workplace. Several advantages of Nett® mufflers make them the superior choice for most LPG engines:

High reduction of toxic gases

- carbon monoxide is typically reduced by over 90%.
- hydrocarbons are also substantially reduced.
- characteristic smell of propane exhaust is virtually eliminated.

Excellent noise attenuation

- Nett® mufflers match or surpass the noise attenuation performance of the original silencers.

Long life and durability

- mufflers are built entirely from corrosion resistant materials: aluminized and stainless steel.

Direct-fit design

- exact-fit replacement for the original muffler
- installation time and cost are reduced to a minimum

Direct-Fit and Universal-Fit Models

Direct-Fit Catalytic Mufflers

Nett Technologies has direct-fit catalytic mufflers available for hundreds of models of forklift trucks and other LPG powered equipment. The pre-designed models are in-stock or can be built and shipped within a few days. Catalytic mufflers are available to replace the original muffler for any LPG, CNG, gasoline or diesel application. The emission control catalyst is built into the muffler and is selected based on the size of the engine. Catalytic mufflers are guaranteed to be an exact-fit replacement for the original muffler. The emissions reduction performance of catalytic mufflers is also guaranteed provided the engine is well maintained and no excessive CO emissions are present.

Universal-Fit Catalytic Converters

For applications where a catalytic muffler is not required or desired, universal-fit catalytic converters are available. These in-stock, ready-to-ship products are available in a variety of sizes and with a range of inlet/outlet pipe diameters. Installation is not as easy as with direct-fit products but simply involves cutting-out a section of the equipment's exhaust pipe and installing the catalytic converter in its place. The section of exhaust pipe chosen must be straight with sufficient clearance on all sides and be located upstream of the muffler.

OEM Products

OEM applications are developed in co-operation with the equipment manufacturer. The catalyst specifications are optimized to meet the particular emission targets and durability requirements. As well, the design of the muffler, including the catalyst substrate selection, canning technology, and noise attenuation requirements are optimized for the application. Development of OEM exhaust systems includes the design and fabrication of prototypes which are tested for emission and noise performance. Nett also provides compliance certification with the EPA or California ARB (Air Resources Board) regardless of whether a Nett emission control device is utilized. Three emission test cells are available for exhaust analysis of LPG, gasoline, CNG or diesel engines up to 250 kW (335 hp). Contact Nett Technologies for more information.

Nett Technologies Inc. has a corporate policy of continuous product development. Specifications are subject to change without notice.

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