

GAS ENGINE EMISSIONS

G3600 • G3500

G3400 • G3300

CATERPILLAR[®]

Contents

Natural Gas Engine Combustion.....	2
Combustion Models	2
Rich-Burn	2
Lean-Burn.....	3
Exhaust Constituents	6
Water Vapor	6
Carbon Dioxide (CO ₂)	6
Nitrogen (N ₂).....	7
Oxides of Nitrogen (NO _x)	7
Carbon Monoxide (CO).....	8
Unburned Hydrocarbons	8
Hazardous Air Pollutants.....	9
Particulates.....	10
Sulfur Dioxide	10
Influence of Fuel Type on Emissions.....	11
Heavy Hydrocarbons	12
Inert Gas	12
Sour Gas	12
Exhaust Gas After-Treatment.....	13
Catalysts.....	13
Three-Way Catalyst	14
Oxidation Catalyst	14
Selective Catalyst Reduction	15

Engine Arrangements	16
G3600	16
G3500	16
G3400	16
G3300	16
Emission Permitting	17
USA Federal EPA Legislation	17
USA State, County and Local Legislation	18
Overseas Legislation	18
Guidelines for On-Site Permitting or Certification	19
Field Resetting	19
Measurement Location	19
Monitoring.....	19
Measurement Devices	20
Emission Units & Conversions	22
Parts Per Million (PPM)	22
Milligrams Per Normal Meter Cubed (mg/Nm ³)	23
Mass Units	24
Molecular Weight	25
Fuel Rate.....	25
Definitions.....	26

Foreword

This section of the Application and Installation Guide generally describes Gas Engine Emissions for Caterpillar® engines listed on the cover of this section. Additional engine systems, components and dynamics are addressed in other sections of this Application and Installation Guide.

Engine-specific information and data is available from a variety of sources. Refer to the Introduction section of this guide for additional references.

Systems and components described in this guide may not be available or applicable for every engine.

Some emission levels and values in this guide are generalized and are provided only for the purpose of comparison.

Information contained in this publication may be considered confidential. Discretion is recommended when distributing. Materials and specifications are subject to change without notice.

CAT, CATERPILLAR, their respective logos, "Caterpillar Yellow", and the POWER EDGE trade dress, as well as corporate and product identity used herein, are trademarks of Caterpillar and may not be used without permission.

Gas Engine Emissions

In theory, the ideal combustion of gas and air is revealed in the following equation: $\text{CH}_4 + 2\text{O}_2 + 7.52\text{N}_2 = 2\text{H}_2\text{O} + \text{CO}_2 + 7.52\text{N}_2$. Note that this equation is for pure methane and that typical gas fuels are comprised of other constituents which require different combustion equations.

Unfortunately, combustion in a real-world gas engine is far from ideal. Undesirable exhaust emissions can be formed by the interaction of a specific combustion design or the prevailing operating conditions which can cause imperfect combustion.

Small amounts of oxides of nitrogen (NO_x), carbon monoxide (CO) and unburned or partially burned hydrocarbons are emitted from the exhaust. The amounts vary greatly depending upon engine design, application, operation and maintenance.

Critical operating conditions include combustion temperature, air/fuel ratio of the inlet charge, engine load, engine design (piston crevice volume, spark plug location, charge turbulence, jacket water temperature) and control system capability (ignition timing, inlet charge, mixture control).

This guide addresses natural gas engine emissions through description and discussion of combustion, natural gas fuels, engine configuration, environmental requirements, permitting and certification.

SECTION CONTENTS

Natural Gas Combustion	2	• Overseas Legislation
• Combustion Models		
Exhaust Constituents	6	Guidelines for On-Site
Influence of Fuel Type on		Permitting or Certification
Emissions	11	• Field Resetting
• Heavy Hydrocarbons		• Measurement Location
• Inert Gas		• Monitoring
• Sour Gas		• Measurement Devices
Exhaust Gas		Emission Units &
After-Treatment	13	Conversions
• Catalysts		• Parts Per Million (PPM)
• Selective Catalyst Reduction		• Milligrams Per Normal Meter
Engine Arrangements	16	Cubed (mg/Nm^3)
• G3600, G3500, G3400 &		• Mass Units
G3300		• Molecular Weight
Emission Permitting	17	• Fuel Rate
• USA Federal EPA Legislation		Definitions
• USA State, County and		26
Local Legislation		

Natural Gas Engine Combustion

The main components of natural gas engine exhaust are nitrogen, water, carbon dioxide, and oxygen (in lean burn engines).

Critical operating conditions include combustion temperature, air/fuel ratio of the inlet charge, engine load, engine design (piston crevice volume, spark plug location, charge turbulence, jacket water temperature) and control system capability (ignition timing, inlet charge, mixture control).

The combustion chamber design affects the combustion temperature and efficiency, thereby changing the level of emissions. Changing the air/fuel ratio, timing, load and fuel type also changes the quantities of certain constituents in the exhaust stream.

This section discusses combustion methods in Caterpillar natural gas engines.

Combustion Models

Reciprocating engines are grouped into two general categories based on the combustion model used in their design: “rich-burn” and “lean-burn”.

The primary distinction between the two is the amount of excess air admitted prior to combustion.

Rich-burn engines are designed to operate with a minimum amount of air for combustion and lean-burn engines use 50% to 100% more air than is necessary for combustion.

Rich-Burn

Rich-burn engines use only enough air to burn all of the mixture in the cylinder at combustion. This condition is referred to as stoichiometric combustion or theoretical combustion.

The objective of stoichiometric combustion is to achieve complete fuel burn with no oxygen or fuel left over after combustion.

Rich-burn engines are often selected when NO_x emission requirements are very low. In these cases, an after-treatment system (such as a three-way catalyst) can be added to drop NO_x to as low as 0.15 grams per brake horsepower per hour (g/bhp-hr).

Rich-burn engines typically produce emission levels as shown in **Table 1**.

Typical Rich-Burn Emission Levels (g/bhp-hr)				
Setting	NO _x (Oxides of Nitrogen)	CO (Carbon Monoxide)	THC (Total Hydrocarbons)	NMHC (Non Methane Hydrocarbons)
10% rich (Lambda=0.9) of Stoichiometric	5.0	40.0	2.0	0.30
Stoichiometric (Lambda = 1.0)	10.0	10.0	1.5	0.20
10% lean (Lambda = 1.1) of Stoichiometric	20.0	1.0	1.0	0.15

Table 1

A rich-burn engine is typically set up to achieve minimum fuel consumption which is also the setting at which NO_x emissions are the highest. This setting is slightly leaner than the stoichiometric point, as some extra oxygen must be made available to ensure the most complete combustion possible. In terms of lambda (the air/fuel equivalence ratio = actual air/fuel ratio ÷ stoichiometric air/fuel ratio), this is about lambda = 1.05.

On a rich-burn engine, the air/fuel ratio will vary with changes in load and/or speed depending on the design of the fuel system (carburetor, etc.). In general, power-specific levels of NO_x will vary in the opposite direction of CO and THC (i.e., NO_x falls while CO and THC rise and vice versa).

If a three-way catalyst is to be used, the relative levels of NO_x, CO and THC must remain fairly constant. This is accomplished with an air/fuel ratio control, a device that

monitors combustion and adjusts the air/fuel ratio to maintain the proper balance.

Rich-burn engines are power limited due to high exhaust temperatures and in-cylinder detonation. They are most often used when fuel efficiency is not the primary requirement.

Lean-Burn

Lean-burn engines operate with large amounts of excess air, as much as 50% to 100% more air than the stoichiometric requirement.

The excess air absorbs heat during the combustion process which reduces the combustion temperature and pressure. This results in greatly reduced levels of NO_x.

There are two common types of lean-burn engines: open chamber and enriched pre-chamber.

Open-chamber

Open-chamber engines draw an air/fuel mixture into the cylinder and ignite the mixture with a spark plug.

This technology provides good efficiency and NO_x emission levels as low as 0.5 g/bhp-hr.

As the air/fuel ratio increases, combustion speed decreases. Continuing in this direction, start of combustion eventually becomes very erratic and lean misfire results. This lean limit is marked as point **C** in **Figure 1**.

Lean-burn engines are specifically designed to handle a high volume air/fuel flow with minimal pumping losses. However, adjusting a given engine leaner will increase fuel consumption due to increased pumping work.

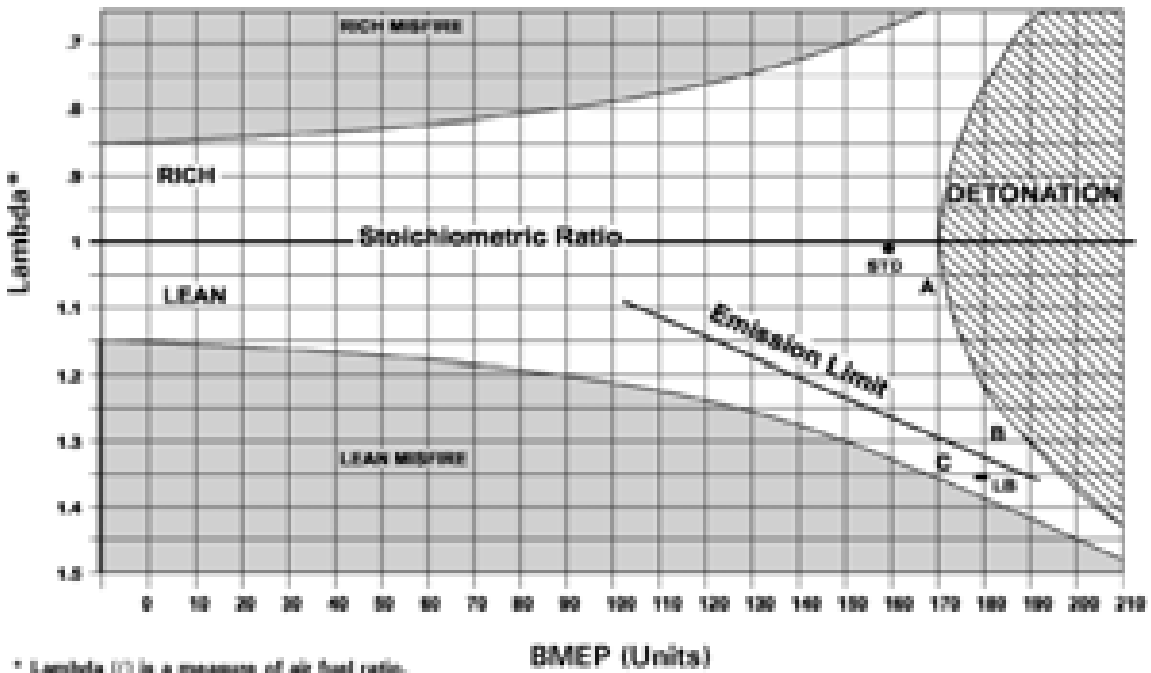
Lean-burn engines are typically more efficient than stoichiometric engines. The lower combustion temperatures raise the ratio of

specific heats which in turn causes increased expansion work, thereby providing better efficiency.

Enriched Pre-chamber

Pre-chambered engines use a small enclosure separate from the main combustion chamber to ignite the air/fuel mixture under more controlled conditions. An enriched pre-chamber provides an additional fuel feed to alter the air/fuel ratio in the pre-chamber. This allows the pre-chamber to be ignited at a near stoichiometric ratio, serving as a very high-energy ignition source for the very lean main chamber (where lambda may be 2.0 or greater). Pre-chambers are typically found in engines with bore diameters greater than 200 mm and rotating speeds less than 1200 rpm.

Air/Fuel Ratio vs. Brake Mean Effective Pressure for Rich-Burn Combustion Model



* Lambda (λ) is a measure of air fuel ratio.

$$\lambda = \frac{A/F}{A/F \text{ stoichiometric}}$$

Figure 1

Exhaust Constituents

Exhaust Gas Components				
Constituents	Rich-Burn, LAMBDA = 1.0		Lean-Burn, LAMBDA = 1.5	
	% weight	% volume	% weight	% volume
Nitrogen	72	70.7	73.3	73.1
Water	12.7	19.4	8.6	13.3
Carbon Dioxide	13.8	8.6	9.3	5.9
Oxygen	0.5	0.4	7.9	6.5
Oxides of Nitrogen	0.35	0.21	0.05	0.03
Carbon Monoxide	0.45	0.44	0.03	0.03
Unburned Hydrocarbons	0.08	0.17	0.07	0.15

Table 2

Table 2 displays typical proportions of various exhaust constituents for rich- and lean-burn configurations.

Water Vapor

Water vapor is water in its purest form and is one of the basic byproducts of ideal combustion. Although it is an exhaust constituent, it is non-polluting and thus not an emissions concern. It is, however, a concern of the exhaust system components from a serviceability and longevity standpoint. The potential for water vapor condensation must be considered in the design of the exhaust system. Stainless steel silencers, piping, expansion joints, etc, are commonly used in applications where condensation is a concern.

Carbon Dioxide (CO₂)

Carbon dioxide (CO₂), along with water and nitrogen are the main components of exhaust from all hydrocarbon combustion processes. However, CO₂ is inert and is usable by plant life as a basic component of photosynthesis.

Carbon dioxide is not regulated as a direct irritant or carcinogen, such as NO_x, but some regions are considering limits on CO₂ production.

Because CO₂ is a direct byproduct of combustion, CO₂ emissions are proportional to combustion efficiency. When compared to other carbon fuels, natural gas delivers the lowest levels of CO₂ produced per unit of energy delivered.

Nitrogen (N₂)

Nitrogen is an inert gas that exists naturally in the inlet air (and sometimes in the fuel gas). In its diatomic form, N₂, nitrogen is stable and non-reactive, thus diatomic nitrogen found in engine exhaust is not a regulated constituent. Nitrogen is not typically a concern until it is dissociated by the high temperatures of combustion, enabling the formation of oxides of nitrogen (see next section).

Oxides of Nitrogen (NO_x)

Oxides of nitrogen (NO_x) is a family of compounds, including nitric oxide (NO) and nitrogen dioxide (NO₂). These compounds are produced from combustion with air which is 79% nitrogen. Nitric oxide (NO) and nitrogen dioxide (NO₂) are typically grouped together as NO_x emissions. Nitric oxide is created from the oxidation of atmospheric nitrogen. Once NO arrives in the atmosphere, it reacts with diatomic oxygen to form NO₂.

Nitrogen dioxide is known to irritate the lungs and lower the resistance to respiratory infections in humans. It is also an important precursor to the production of ozone. In the presence of ultraviolet light and volatile organic compounds

(unburned hydrocarbons), NO₂ can promote the creation of O₃, or ozone, the primary component of photochemical smog. This ozone is present at or near ground level, in contrast with the ozone in the upper atmosphere which shields the Earth from excessive ultra-violet radiation. Ground level ozone damages lung tissue and reduces lung function.

NO_x production is heavily influenced by combustion temperature which, in turn, is affected by the amount of excess air present during combustion. As shown in **Figure 2**, NO_x emissions vary greatly with air/fuel ratio, peaking slightly lean of stoichiometry ($\lambda = 1.0$) and falling off sharply with successively leaner mixtures ($\lambda > 1.0$).

NO_x production is also strongly affected by the amount of exhaust gas in the cylinder and the ignition timing. Exhaust gas remaining in the cylinder or ingested with the intake mixture (EGR) contains inert gases. These inert gases absorb heat and reduce the combustion temperature which subsequently lowers the NO_x. Retarding the ignition timing reduces the peak cylinder pressure and temperature, again lowering the actual NO_x output.

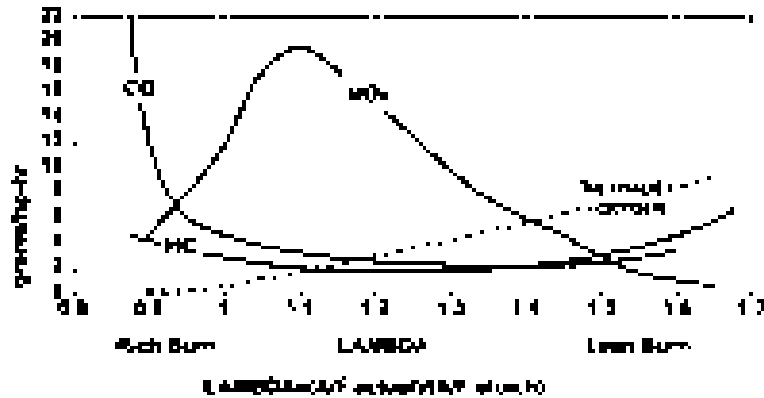


Figure 2

Carbon Monoxide (CO)

Carbon monoxide (CO) is the result of incomplete combustion of carbon and oxygen. Carbon monoxide is formed when insufficient oxygen or poor charge mixing interferes with the mechanism to produce CO₂. CO formation is greatest when the fuel mixture is rich (lambda less than 1); however, CO also forms when a very lean mixture cannot sustain complete combustion.

Carbon monoxide enters the bloodstream of humans and reduces the delivery of oxygen to the body's organs and tissues. Exposure to CO is most serious for people with cardiovascular disease, but even in healthy people, CO can impair work capacity, manual dexterity and learning ability.

Carbon monoxide emissions in gas engines are controlled primarily by the air/fuel ratio. For engine operation fuel lean of stoichiometric, excess oxygen is available to oxidize CO into CO₂. Moving fuel rich of stoichiometry, oxygen is in short supply and CO production increases

dramatically, as can be seen in **Figure 2**. Lean of stoichiometry, the CO level is fairly stable, increasing slightly at high lambda due to decreased combustion efficiency.

CO concentration is also affected by combustion chamber design. For chambers with a large crevice volume between the top piston ring and the top of the piston, CO production will be increased. Unburned fuel will emerge from the crevice during the expansion process and some will partially oxidize into CO.

CO levels increase when there is a large amount of CO₂ in the fuel, such as landfill or digester gas. Carbon dioxide will dissociate and increase CO levels by 40 to 60%.

Unburned Hydrocarbons

Hydrocarbon emissions result from incomplete combustion of hydrocarbon fuels. The composition will vary some according to the incoming composition of the fuel. The reactivity of particular hydrocarbon molecules varies considerably, some being nearly inert

physiologically and some being very reactive in the production of photochemical smog. Methane has a very low reactivity and for this reason is often excluded from hydrocarbon regulations and measurements. Heavier hydrocarbons are generally more reactive.

Unburned hydrocarbons are typically grouped into three categories:

- Total Hydrocarbons (THC)
- Non Methane Hydrocarbons (NMHC)
- Non Methane, Non Ethane Hydrocarbons (NMNEHC)

A THC measurement will include all exhaust emissions of methane, ethane, propane, butane, pentane and higher molecular weight hydrocarbons.

A NMHC measurement, sometimes referred to as volatile organic compounds (VOC), will account for all hydrocarbons except for methane.

Hydrocarbon emissions versus air/fuel ratio are shown in **Figure 2**. At rich and very lean air/fuel ratios, combustion efficiency deteriorates as THC levels increase.

Unburned hydrocarbons have four main sources:

- Flame quenching at cylinder walls, leaving a small layer of unburned air/fuel mixture (10%).
- Crevice volumes that fill with air/fuel and do not combust (65%).

- Absorption and desorption of fuel in the oil layer (25%).
- Incomplete combustion from either partial burning or complete misfire.

Since many fuels contain a majority of methane, the exhaust hydrocarbons are mostly methane. On Caterpillar engines using natural gas, the non-methane hydrocarbons generally do not exceed 15% (volume) of the total hydrocarbon level.

NMNEHCs are all unburned fuel except methane and ethane. To predict NMNEHC emission levels, the fuel composition must be known.

Hazardous Air Pollutants

The US EPA has recently recognized specific pollutants as being hazardous air pollutants (HAPs). Although numerous HAPs may be emitted from the engine combustion, only a few aldehydes account for virtually all of the mass of HAPs from a reciprocating engine. These four are:

- Formaldehyde
- Acrolein
- Methanol
- Acetaldehyde

Note: Aldehydes resulting from combustion are dependent on the type of fuel burned. For example, partially burned CH₄ results in the creation of formaldehyde and partially burned C₃H₈ creates propanaldehyde.

Of these four compounds, formaldehyde is found in greatest quantities in engine exhaust.

Formaldehyde is a human carcinogen and can cause irritation of the eyes and respiratory tract.

Acrolein is corrosive and can cause severe irritation of the eyes, nose, throat and lungs, but is not considered a carcinogen in humans.

Methanol in acute doses can cause blindness, coma and death.

Acetaldehyde can irritate the eye membranes, skin and upper respiratory tract and is a probable carcinogen in humans.

The EPA has determined which stationary engines are affected and when the rule applies, according to power, application, combustion type (rich-burn or lean-burn) and fuel type, among others. Not all stationary engines are affected by the rule. Those that are affected may require the addition of an oxidizing catalyst in the exhaust stream. This catalyst will remove the HAPs prior to reaching the atmosphere. Also, some engines will require periodic inspection and maintenance of the catalyst. We recommend that you consult with your dealer to determine if your engine is affected by this rule.

Particulates

Particulates have been linked to aggravated respiratory functions, reduction of the human body's defense against foreign materials and increased levels of cancer.

The combustion of natural gas produces virtually no particulates. However, small amounts are produced from the normal combustion of engine oil in the combustion chamber. Typical oil consumption of a modern natural gas burning engine is less than 0.24 g/bhp-hr. A majority of this oil will burn in the combustion chamber. It is conservatively estimated that less than half the oil consumed becomes particulate in the exhaust stream at a level of 0.1 g/bhp-hr. Frequently, particulate information is requested as PM-10, or particulate matter less than 10 microns in diameter.

Sulfur Dioxide

Sulfur will only be present in the exhaust of a gas engine when it is present in the fuel or oil. Most pipeline fuels contain only a trace or no sulfur compounds. Natural gas engine oils typically have very little if any sulfur. Hydrogen sulfide (H₂S) is the most common sulfur-bearing compound found in gaseous fuels, often occurring in landfill, digester and wellhead or associated gases. Caterpillar limits for sulfur bearing compounds in the fuel can be found in the Fuels Application and Installation Guide. The H₂S in the fuel will be burned in the combustion chamber to yield very low levels of sulfur dioxide and sulfuric acid.

Influence of Fuel Type on Emissions

Variations in the heating value of a fuel or in the temperature of the incoming fuel can significantly affect levels of exhaust emissions on engines that do not have air-fuel ratio control.

A change in the heating value of a fuel will change the air/fuel ratio required to maintain a certain emission level. Carburetors are designed to maintain a constant air/fuel ratio (on a volume-to-volume basis) for a given engine load. Therefore, any change in the heating value of the fuel will result in a less desirable air/fuel ratio for a specific emissions level. Changes in heating value are generally not a problem with commercially available natural gas or propane. However, digester gases, manufactured gases and field gases can be subject to large variations in heating value if strict controls are not placed on the process by which the gas is produced.

Changes in fuel temperature, assuming a constant air temperature, can also change the emission levels of a given engine. This is because the carburetors used in Caterpillar gas engines meter fuel into the incoming air on a volume-to-volume basis. Changes in fuel temperature will change the density of the fuel and result in a different air/fuel ratio on a mass-to-mass basis.

For example, if the incoming fuel is cooled, the density of the fuel will increase. The increase in fuel density

actually means that there is more fuel (mass) present in a given volume. Since the carburetor will continue to deliver the same volume of fuel for a given volume of air, the increased mass flow of the fuel will result in a richer air/fuel ratio. The hotter mixture raises NO_x emissions. Cooler combustion reduces NO_x but increases CO.

In order to maintain a nearly constant emission level for an engine without the use of an air/fuel ratio control system, the guidelines shown in **Table 3** should be followed.

Fuel Temperature to Carburetor*	± 5.5 °C (± 10 °F)
Fuel LHV	± 0.43 MJ/Nm ³ ± 11 Btu/scf

* Relative to intake air temperature.

Table 3

Emission data presented in TMI and on specification sheets is valid for a particular fuel. The emissions data given for natural gas should not be used for propane or landfill gas.

Propane fueled engines require a lower compression ratio to avoid detonation.

When burning propane, THC emissions equal NMHC emissions because there is no methane in the fuel.

THC emissions for landfill gas are comprised almost entirely of

methane because the only hydrocarbon contained in landfill gas is methane. In this case, NMHC emissions levels are nearly zero and result from oil consumption.

Heavy Hydrocarbons

Heavy hydrocarbons impact ignition timing for open-chamber engines. However, the timing is optimized for the altered burn rate to achieve similar detonation margins. NMHC and NMNEHC would be directly impacted by the change in fuel composition however.

Inert Gas

Inert gases have an apparently limited impact on performance and emissions.

N₂ does little more than occupy space in the fuel system and

combustion chamber. Consequently, its impact is limited to situations where it forces an engine to be derated due to inadequate fuel delivery capacity.

CO₂ carries a greater molecular mass which gives it the ability to absorb heat energy and thus slow the burn rate. This reduces the tendency to detonate, but increases the exhaust port temperature. The impact is largely limited to methane only. CO₂'s impact on heavier hydrocarbons has been shown to be much less.

Sour Gas

Sour gas contains a sizeable presence of H₂S, thus the emissions of SO_x will be proportionately higher.

Exhaust Gas After-Treatment

When emission level requirements are below the levels attainable by the engine, exhaust gas treatment may be applied. There are various types of after-treatment for gas engines and they are based on the use of catalysts. Three-way catalysts, oxidation catalysts and selective catalyst reduction (SCR) are the more common aftertreatment devices used. Each method has particular attributes that provides appropriate after-treatment for various gas engine fuel systems and most gaseous fuels.

Catalysts

In discussion of exhaust after-treatment, the term *catalyst* can be used to describe the after-treatment device or the noble metals used in the device.

The after-treatment device (catalyst) consists of a high temperature tolerant substrate coated with noble metals (catalyst). The devices are designed to provide a very high surface area to maximize contact between the exhaust gas and the noble metals.

Platinum, palladium and rhodium are typically the noble metals used to enable and accelerate a chemical reaction within a temperature range. The reaction combines byproducts of incomplete combustion with available oxygen, converting them to less troublesome compounds.

Catalyst efficiency is greatly affected by temperature; there is a specific temperature window for

catalyst operation. The functional minimum temperature is known as "light-off". It is the point at which the conversion efficiency becomes greater than 50%. The maximum temperature is below the point at which the noble metals begin to melt and pool on the substrate. This clumping of noble metals reduces the effective surface area and diminishes catalyst efficiency. High temperatures will occur if large amounts of unburned fuel pass into the catalyst device. The device manufacturer can provide specific minimum and maximum temperatures.

The conversion efficiency of a new catalyst device can be as high as 95%, but through normal use will continually deteriorate. Deterioration is caused by catalyst fouling and catalyst poisoning.

Catalyst fouling is usually a result of combustion byproducts, such as ash or silicon, coating the noble metals. Catalyst fouling can often be reversed by periodic cleaning.

Note: Engine applications that require high ash oil or have a fuel with contaminants should not apply catalysts. This typically includes landfill and digester gas applications.

Catalyst poisoning is a result of compounds being adsorbed into the noble metals. Catalyst poisoning permanently interferes with catalyst function. Sulfur-bearing compounds adsorbed into specific noble metals are irreversible and require the replacement of the catalyst device.

Three-Way Catalyst

Three-way catalysts use oxygen to treat exhaust emissions; however, three-way catalysts do not use unburned combustion oxygen to reduce emissions, they make use of the oxygen within the constituent compounds. Oxygen from NO_x is used to oxidize the CO and HC. This converts the three pollutants into more innocuous elements of N_2 , CO_2 and H_2O .

Catalysts may be used in series to obtain lower emission levels.

Note: Three-way catalysts are rendered ineffective by excess oxygen leftover from the combustion process. Therefore, this after-treatment is used on rich-burn engines only and requires the use of an air-fuel ratio control system.

Typically, the reduction level for NO_x is 90 to 95%, CO is 50 to 90%, and NMNEHC is 90%.

Figure 3 shows the window of operation for three-way catalysts.

Oxidation Catalyst

On lean-burn engines, oxidation catalysts using platinum and palladium are effective at lowering CO and NMHC levels in exhaust emissions.

Methane is difficult to oxidize at exhaust temperatures provided by lean-burn engines; therefore, the conversion efficiency for methane can be very low. No air-fuel ratio control system is required with this type of catalyst and it can be applied to either rich-burn or lean-burn engines.

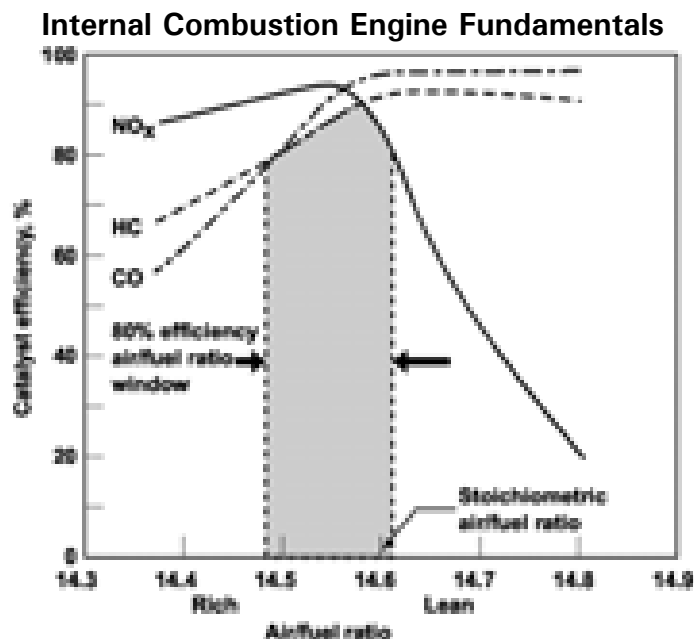


Figure 3

Selective Catalyst Reduction

Selective Catalytic Reduction (SCR) is an exhaust gas after-treatment that specifically targets the NO_x in engine exhaust and converts it to N₂ and H₂O. Unlike the three-way catalyst which uses oxygen from the exhaust stream to treat emissions, SCR injects a compound into the exhaust stream to start the reaction.

The process begins when a small amount of urea, a nontoxic and biologically harmless compound, is injected into the exhaust stream. After hydrolysis, the urea becomes ammonia and reacts with NO_x to break down into nitrogen and water.

On closed-loop control systems SCR can reduce gas engine NO_x by greater than 95%.

Although prices have declined, SCR systems are generally expensive. An SCR requires ammonia tanks and ammonia metering. Without precise control, the system may let ammonia pass through the catalyst, a phenomenon known as “ammonia slip”. Ammonia slip can be avoided if the urea injection is metered to match the NO_x that the engine is producing. This requires an air/fuel ratio control to stabilize the NO_x emissions level. In cases where the NO_x level will still vary due to external factors, the

SCR may require a closed-loop control to manage the urea injection rate. The closed-loop control measures the actual NO_x level out of the catalyst to determine if the urea injection rate is adequate.

Some of the expense of an SCR installation is in the form of an oxidation catalyst. Because SCR lowers only NO_x levels, any limits pertaining to CO or THC must be addressed by adding an oxidation catalyst to the system. Oxidation catalysts require high temperatures for optimal operation and should be placed upstream of the SCR. Note also that NO_x levels do increase a small amount across an oxidation catalyst; this effect should be taken into account when sizing the SCR.

Engine Arrangements

Figure 3 shows that emission levels are affected by the air/fuel ratio. Emission levels will also change with changes in load, speed and compression ratio. **Figure 1** shows a map of possible areas of operation for a gas engine.

The area for rich-burn operation is indicated by **point A** and the lean-burn operation by **point B**. Reduced NO_x is achieved by moving leaner. Operating with NO_x levels close to the lean limit, generally below 1.5 grams NO_x/bhp-hr, usually require the use of an air/fuel ratio control.

Engine Arrangements

G3600

All G3600 engines employ enriched pre-combustion chambers in order to get excellent efficiency and very low emissions. The G3600 engines are designed for not more than 0.7 g/bhp hr engine-out NO_x operation. The pre-chamber produces an aggressive combustion allowing excellent engine efficiency with very low NO_x levels. All G3600 engines have an air/fuel ratio control as standard equipment.

G3500

G3500 engines are all open chamber and available in both lean-burn and stoichiometric or rich-burn configurations. The lowest NO_x engine-out levels are achieved with lean-burn, high speed and high compression ratio. The minimum NO_x is 0.5 g/bhp-hr for a high compression ratio configuration and 1.5 g/bhp-hr for an 8:1 compression ratio configuration. The lowest emission levels require the use of an air/fuel ratio control.

For stationary emissions compliance of lean-burn engines within the United States, an air/fuel ratio control will be required, and oxidation catalysts may be required in some cases depending on fuel and

operating conditions. Factory emissions certification will require an oxidation catalyst.

The rich-burn (stoichiometric) engines are available in 9:1 compression ratio and are designed to operate at speeds ranging from 1000 to 1200 rpm. Engine-out NO_x emissions from the rich-burn engines are approximately 10 g/bhp-hr. Applications of these engines are for areas where emissions are not regulated or where regulations are such that a three-way catalyst must be used.

G3400

G3400 engines are all open chamber and are available in lean-burn and stoichiometric or rich-burn configurations. NO_x levels and fuel consumption levels are proportionately similar to that of the G3500 engines.

G3300

G3300 engines are all open chamber and are available in rich-burn configurations. An 8:1 and 10.5:1 compression ratio are offered with speeds ranging from 1000 to 1800 rpm. NO_x levels and fuel consumption are proportionately similar to the G3400 and G3500 stoichiometric engines.

Emission Permitting

Caterpillar published emission data for stoichiometric and G3600 products are provided at "not to exceed" levels for all exhaust constituents. NO_x levels are nominal for G3400 and G3500 low emission products since the engine can be adjusted in the field to the NO_x level.

Upon request, Caterpillar will provide a detailed emission chemistry data sheet to help in the permitting process for your engine. CO and HC emissions information provided by Caterpillar includes a margin above the nominal measurement value to account for differences in emission measurement equipment, engine-to-engine variations and fuel fluctuations.

It is the customer's responsibility to obtain the required operating permits from the appropriate regulatory agency. The process can be lengthy, so proper consideration should be given when ordering the engine. In some cases, the customer or dealer may do the permitting. There are times when a consultant should be hired to help complete the permitting process. The cost of permitting can be significant and must be quoted as part of the total job. It is essential to the success of the job that permitting is completed.

USA Federal EPA Legislation

In the USA, review of a project takes place at a federal level when one of two events takes place:

- If the site exceeds 250 tons/year of NO_x, SO₂, HC, O₃

or CO in an attainment area, a Prevention of Significant Deterioration (PSD) review is required. Attainment refers to an area in compliance with Federal guidelines for that particular constituent.

- If the site is in a non-attainment area (where Federal emissions guidelines have been exceeded), a PSD review is required.

In addition to the above site requirements, all new, remanufactured or modified natural gas engines must meet the requirements of either the Spark Ignited (SI) Nonroad Mobile rule or the SI Stationary rule. Stationary engines must also meet the requirements of the proposed Hazardous Air Pollutants (HAP) rule.

Nonroad mobile engines are engines that, among other requirements, do not remain at a single site for at least 12 months. Caterpillar currently does not offer engines larger than 25 hp certified to the SI Nonroad rule.

Stationary SI engines are engines that remain at one site for at least 12 months. The Stationary rule and the HAP rule provide limits for NO_x, CO and NMHCs. Either these engines must be factory certified, or (engines greater than 24 hp) may optionally be uncertified, but must pass a compliance demonstration test. This compliance demonstration includes 3 tests of at least 1 hour each from which data is averaged

and kept on file. Engines at 500 bhp and above require additional testing every 3 years or 8760 hours, whichever ever comes first, and test results must be reported to the EPA.

These federal rules provide minimum standards, and local regulations may be more stringent.

USA State, County and Local Legislation

Federal regulations require each state to implement a plan to bring areas of non-attainment into compliance. In addition, counties or municipalities may have their own requirements. Required emission levels and how one should achieve operating permits vary considerably.

In general, an engine or group of engines will be considered either a major or a minor source. These usually require an operation permit which can take 3 to 8 months to obtain. Many of these local legislations will have horsepower minimums. Below these horsepower levels, the engine may be fully exempt and only need to file a notice of intent.

Not only do these various entities have different emission targets, they can also determine what control technology, such as lean-burn or rich-burn with three-way catalyst, is used through application of Best Available Control Technology (BACT). Consult with your local regulatory agency to determine the current requirements.

Overseas Legislation

Regulations vary widely around the world. Consult your Caterpillar dealer for information on world-wide emissions standards.

Guidelines for On-Site Permitting or Certification

Field Resetting

When an engine leaves the factory, it has been set under factory conditions. Field conditions will vary from the factory and some adjustments will be required. The engine should be field-set to the desired nominal NO_x ppm emission level at start-up for NSPS compliant engines. Nominal NO_x levels are specified in the applicable engine performance technical data. Local permit regulations may require lower settings for NO_x, and the engine should be set accordingly. Consult your dealer for factory approval of a non-standard setting through a Special Rating Request (SRR).

Proper maintenance as specified in the O&M manual is required to maintain NSPS emissions compliance. This includes calibration of the A/F ratio control sensor at start-up and at the recommended preventative maintenance service intervals.

Measurement Location

To correlate with Caterpillar emissions reports, measurements should be made downstream of the turbocharger. Some conversion of CO to CO₂ occurs in the relatively high temperature exhaust upstream of the turbocharger. Emission levels provided by Caterpillar represent measurements at the engine exhaust, not downstream at the site stack outlet.

Monitoring

The preferred method of monitoring gas engine emissions is periodic measurement of NO_x. Some regulatory bodies may require continuous monitoring. This is generally a negotiated item in the permitting process which, if required, will add significant cost to the project. Periodic measurements can be performed at a reasonable cost using portable emissions analyzers.

Engine adjustments are also easily performed using a portable emissions analyzer to directly measure the NO_x level in the exhaust. An emissions analyzer should be used to set the NO_x ppm level during periodic A/F ratio adjustment. This includes engines using an oxygen sensor for feedback control. Changes in air/fuel ratio, timing, intake manifold temperature and fuel composition affect NO_x emissions. Properly maintained engines using air/fuel ration controlled feedback will help account for these changes with periodic adjustment.

For a lean-burn engine, it is not possible to adjust the engine to significantly change the level of carbon dioxide and hydrocarbons. After-treatment will be required if CO or HC levels exceed the regulations. Rich-burn engines should be carefully adjusted when using a catalyst, as CO levels rise quickly as the air/fuel ratio move rich of stoichiometric.

Measurement Devices

Portable emissions analyzers use electrochemical sensors to measure NO_x, and models that measure dry NO and NO₂ ppm separately may be used for adjustment of the engine during regular engine maintenance. The accuracy of the emissions analyzer used for calibration to maintain NSPS compliance must be within 10% of a standard at the desired engine NO_x emissions level. Calibrate the emissions analyzer for both NO and NO₂ as needed to maintain this accuracy level.

Measurement of NO_x during site certification tests will typically be performed by a contracted measurement service using a more sophisticated chemiluminescence meter. The meter measures the amount of light emitted by photons released when nitrogen oxide reacts with ozone. The sample passes through a catalyst to convert any NO₂ to NO and then is exposed to ozone. The intensity of the ensuing reaction is proportional to the amount of NO in the sample. This meter requires water to be removed from the sample; hence, the results will be expressed as dry. The contracted service will also typically provide the measurement of exhaust mass flow and ambient corrections needed if reporting is done on a mass basis.

Portable CO analyzers also measure CO levels using electrochemical sensors. CO₂ is rarely measured directly; values used prior to site permitting are typically calculated values.

Site certification tests for CO and CO₂ will typically be performed by a contracted measurement service using infrared analyzers to measure both CO and CO₂. An infrared light source is passed through a reference chamber and a chamber with the gas sample. The chambers absorb energy from the light source and are connected by a diaphragm that deflects proportionally to the CO or CO₂ concentration in the sample chamber. This meter requires water to be removed from the sample; hence, the results will be expressed as dry.

Hydrocarbons are typically measured using a flame ionization detector (FID). This device burns the sample in a hydrogen and air flame surrounded by an electric field. The field responds to the number of ions produced. This meter does not give information about the hydrocarbon structure but provides an indication of the total hydrocarbon content. A heated FID with a methane cutter may be used for measurement of non-methane hydrocarbons (NMHC). This equipment will capture only a portion of the formaldehyde in a sample, but does provide a proportional indicator of the actual formaldehyde levels. This method does not isolate ethane from the hydrocarbons. This may preclude the use of fuels with relatively high ethane content (above 14% on a mole basis), or may require a more expensive alternative measurement method to separate the exhaust ethane for NMNEHC specific rules.

For a specific analysis of hydrocarbon constituents, including aldehydes, a gas chromatograph is typically used. The chromatograph separates complex mixtures through selectively adsorptive compounds.

The FID uses wet samples while the chromatograph needs dry samples.

When converting hydrocarbons to mass volumes, a molecular weight of 15.84 is used in accordance with ISO8178-1 1996.

Emission Units & Conversions

When measuring and reporting emissions information, many different units are used.

Parts Per Million (PPM)

Exhaust constituents are commonly measured in volume units of parts per million (ppm) of exhaust. Since the values use the exhaust volume as a reference, it is important to note whether the exhaust volume is the full “wet” exhaust flow that could be measured, including water vapor, or if it is a comparison to a “dry” exhaust volume, without water vapor. NO_x, CO and O₂ are typically dry measurements since the equipment used to analyze these constituents require a dry exhaust sample. In contrast, HC is usually measured wet.

Since combustion exhaust gases include oxygen levels that vary significantly with engine model and configuration, an exhaust O₂ level is generally referenced with an emission measurement expressed in volume units. The reference condition for the measured ppm is the measured or “uncorrected” O₂ level.

Regulating agencies often request data reported at a specified reference exhaust level such as 0%, 3%, 5%, or 15%. The following equations can be used to convert or “correct” from one exhaust O₂% level to another. They can be applied whether the values are on a wet or dry basis.

$$\text{ppm @ } X\% \text{ O}_2 = \frac{(\text{ppm}_{(\text{measured})}) \times (20.9 - X\% \text{ O}_2)}{(20.9 - \% \text{O}_2 \text{ measured})}$$

Where:

X% = Desired oxygen level

Example:

An exhaust constituent value of 325 ppm with 8% O₂ can be converted to 5% O₂.

$$\text{ppm @ } 5\% \text{ O}_2 = \frac{325 \text{ ppm}_{\text{measured}} \times (20.9 - 5\% \text{ O}_2)}{(20.9 - 8\% \text{ O}_2 \text{ measured})}$$

$$\text{ppm @ } 5\% \text{ O}_2 = 402 \text{ ppm}$$

Similarly, to correct from one ppm level to another:

$$\text{ppm @ } X\% \text{ O}_2 = \frac{(\text{ppm}_{(\text{reported})}) \times (20.9 - X\% \text{ O}_2)}{(20.9 - \% \text{O}_2 \text{ reported})}$$

Milligrams Per Normal Meter Cubed (mg/Nm³)

Milligrams per normal meter cubed (mg/Nm³) are another common volume based unit of measure for exhaust emissions. Converting from ppm to mg/Nm³ can be done as follows:

$$\text{mg/Nm}^3 = \frac{\text{ppm} \times P \times \text{MW}}{R \times T}$$

Where:

- P = Pressure in kPa, for normal conditions, this is 101.3 kPa
- MW = Molecular weight of the exhaust constituent
- R = Universal gas constant, 8.3144 kN m / kmole K
- T = Temperature in degrees Kelvin, this is 273.15°K (0°C) for normal conditions.

Substituting these constants and the molecular weight of the various exhaust constituents into the equation, the formula can be sorted to the following.

$\text{mg/Nm}^3 = \text{ppm} \times \text{mg/Nm}^3 \text{ per ppm conversion}$
where the conversion factor is:

- 1 ppm NO_x = 2.052 mg/Nm³
- 1 ppm CO₂ = 1.963 mg/Nm³
- 1 ppm HCHO = 1.339 mg/Nm³
- 1 ppm CO = 1.249 mg/Nm³
- 1 ppm THC = 0.707 mg/Nm³

Example:

The following example converts 325 ppm NO_x from parts per million to milligrams per normal meter cubed.

$$325 \text{ ppm NO}_x \times 2.052 \text{ mg/Nm}^3 \text{ NO}_x/\text{ppm} = 667 \text{ mg/Nm}^3 \text{ NO}_x$$

mg/Nm³ units require a %O₂ reference point; this is the same requirement as ppm. The same equations apply to convert from one O₂ level to another.

Continuing with the same example: If the 325 ppm NO_x is at 8% exhaust O₂, the 667 mg/Nm³ is also at 8% exhaust O₂. To convert to 5% exhaust O₂:

$$\text{mg/Nm}^3 @ 5\% \text{O}_2 = \frac{667 \text{ mg/Nm}^3 @ 8\% \times (20.9 - 5\% \text{O}_2)}{(20.9 - 8\% \text{O}_2)}$$

$$\text{mg/Nm}^3 @ 5\% \text{O}_2 = 822$$

Mass Units

Mass flow rate units may also be used to report emissions. The typical units are:

- grams/horsepower-hour (g/hp-hr)
- tons/year
- pound/hour (lb/hr)
- pound/day

To convert from ppm to mass units, the following applies:

$$\text{grams/hr} = \frac{(\text{ppm dry}) \times (\text{exh mass rate}) \times (\text{mol wt of constituent}) \times (\text{DWC})}{1,000 \times (\text{mol wt of exh gas, wet})}$$

Where:

DWC = Dry-to-wet conversion

The dry to wet conversion is used when the emission ppm is on a dry basis and exhaust flow is on a wet basis. Exhaust mass flow can be found in the Caterpillar TMI.

Molecular Weight

Molecular weights are as follows:

NO _x (as NO ₂)	=	46.0 g/mole
CO ₂	=	44.0 g/mole
HCHO	=	30.0 g/mole
CO	=	28.0 g/mole
THC	=	15.84 g/mole

Approximations for exhaust molecular weight and DWC for the above calculation are provided in **Table 4**. For permitting processes, the exact values should be calculated for a given lambda and fuel chemistry. The following values will be within a few percent for natural gas fuels.

Model	Molecular Weight	DWC
G3600	28.36 g/mole	0.90
G3500/G3400 Lean-Burn	28.16 g/mole	0.87
Stoichiometric	27.86 g/mole	0.83

Table 4

For Landfill gases use the values from **Table 5**.

Model	Molecular Weight	DWC
G3600	30.00 g/mole	0.89
G3500	30.00 g/mole	0.86

Table 5

The dry to wet conversion is used to convert a dry ppm measurement to an equivalent wet measurement. This decrease in the parts per million of either CO or NO_x puts the measured emission data on the same terms as the wet exhaust mass flow, which includes the water of combustion. DWC values increase as lambda increases, since the amount of water from combustion stays essentially the same while excess air increases.

Fuel Rate

Fuel rate is another class of units used as a basis for comparison, such as New Jersey's pounds/million Btu of fuel consumed or, in Holland, grams/Gigajoule of energy consumed. In general, it is not a preferred unit because the engine is penalized for being more energy efficient by consuming less fuel. However, Holland's law also encourages fuel efficiency by correcting permitted NO_x based on 30% mechanical efficiency.

To express a mass based HC emission in terms of a molecular weight based on carbon: Multiply the published value by the ratio of the molecular weight of carbon divided by the molecular weight of THC in the exhaust.

$$\text{THC (mole wt 12)} = \frac{\text{THC (mole wt 15.84)} \times 12}{15.84}$$

Definitions

BACT	Best Available Control Technology
Bar =	14.5 psi
BMEP	Brake Mean Effective Pressure
bhp-hr =	Brake Horsepower Hour
Btu/SCF =	British Thermal Units per Standard Cubic Foot (14.696 psia 60°F)
HCHO =	Formaldehyde
CH ₄ =	Methane
CO =	Carbon Monoxide
CO ₂ =	Carbon Dioxide
DWC =	Dry To Wet Conversion
EPA =	Environmental Protection Agency (USA)
H ₂ O =	Water
H ₂ S =	Hydrogen Sulfide
HAPs =	Hazardous Air Pollutants
Lambda =	Air/Fuel Equivalence Ratio $\text{Lambda} = \text{A/F (actual)} \div \text{A/F (stoich)}$
LHV =	Lower Heating Level
m ³ =	Meters Cubed = 35.3147 ft ³ at equal temperatures
mg =	Milligrams
mg/Nm ³ =	Milligrams per Normal Meter Cubed (1013 mbar at 0°C)
MJ/Nm ³ =	Mega Joules per Normal Meter Cubed (1013 mbar at 0°C)
MW =	Molecular Weight (sum of atomic weights of all atoms in the molecule)
N ₂ =	Nitrogen
Nm ³ =	Normal Meter Cubed = 1 m ³ at 0°C and 1013 milliBar
NMHC =	Non Methane Hydrocarbons
NMNEHC =	Non Methane, Non Ethane Hydrocarbons
NO =	Nitrogen oxide or Nitric oxide
NO ₂ =	Nitrogen dioxide
NO _x =	Oxides of Nitrogen
O ₂ =	Oxygen
O ₃ =	Ozone
ppm =	Parts Per Million
ppmv =	Parts Per Million By Volume
ppmvd =	Parts Per Million By Volume Dry
PSD =	Prevention of Significant Deterioration
SCF =	Standard Cubic Foot = 1 ft ³ at 60°F and 760 mm Hg (14.696 psia)
SCR =	Selective Catalytic Reduction
SO ₂ =	Sulfur Dioxide
SO _x =	Sulfur Oxide
Stoichiometric =	Theoretical Combustion - The objective of stoichiometric combustion is to achieve complete fuel burn, with no air or fuel left over, after combustion.
THC =	Total Hydrocarbon

