

Gaseous Fuels

Application & Installation Guide

LEBW4977-12

Caterpillar: Confidential Green



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Table of Contents

1	Introduction	5
1.1	References.....	5
1.2	Changes since last revision.....	5
2	Gaseous Fuels.....	6
2.1	Hydrocarbons.....	6
2.2	Standard condition of a gas.....	9
2.2.1	Temperature, pressure, and volume.....	9
2.2.2	Converting reference conditions	10
2.2.3	Standardized reference conditions	10
2.3	Physical properties.....	11
2.3.1	Specific gravity relative to air (SG)	11
2.3.2	Density	11
2.3.3	Moles and Molecular Weight	12
2.3.4	Dew Point.....	12
2.4	Properties of Gas Mixtures.....	13
3	Combustion characteristics and engine design	14
3.1	Stoichiometry	14
3.2	Heating value	17
3.2.1	Air and fuel system design	18
3.2.2	Air or fuel system limitations.....	20
3.3	Methane number	23
3.3.1	Detonation and Preignition	23
3.3.2	Caterpillar Methane Number	28
3.4	Evaluation of combustion properties	29
4	Common natural gas types and sources	31
4.1	Pipeline quality natural gas	31
4.2	Field gas	32
4.2.1	Wellhead gas	32

4.2.2	Associated gas	32
4.2.3	Sour gas	32
4.2.4	Dry gas	33
4.3	Propane	33
4.4	Biogas	34
4.4.1	Digester gas	34
4.4.2	Landfill gas	35
4.5	Coal bed methane	36
4.6	Manufactured gases	36
4.6.1	Producer and pyrolysis gases	36
4.6.2	Syngas	37
4.7	Hydrogen	37
5	Fuel gas conditions and contaminants	39
5.1	Fuel gas conditions	39
5.2	Solid contaminants	40
5.3	Liquid contaminants	41
5.4	Gaseous contaminants	42
5.4.1	Sulfur compounds	45
5.4.2	Halide compounds	48
5.4.3	Nitrogen compounds (ammonia)	51
5.4.4	Silicon compounds	52
5.5	Operation on corrosive fuel gas	54
Appendix A – Physical properties of gases		56
.....		57
Appendix B – Miscellaneous references		58
B.1	The “blue” table	58
B.2	Laboratory services	59

1 Introduction

This guide describes gaseous fuels and their attributes as they pertain to use in Cat® gas engines. Information presented in this guide is current to the date of publication.

Systems and components described in this guide are specific to the engine models mentioned regarding those components. Such equipment may not be available for or applicable to other engine models.

1.1 References

The following information is provided as an additional reference to subjects discussed in this guide. Please note the information in these publications is subject to change without notice.

- Gas Engine Rating Pro (GERP) – <https://gerp.cat.com>
- LEBW5336 – Gaseous Fuel Systems
- LEKQ7260 – Low Energy Fuels
- LEKQ9085 – G3600 Engine Basics
- LEKQ7518 – G3500 Engine Basics
- LEKQ7511 – G3400 Engine Basics
- SENR6517 – Troubleshooting, G3500 Air/Fuel Ratio Control
- KENR5186 – Systems Operation, Air/Fuel Ratio Control
- REHS8184 – Special Instruction, Installation and Maintenance of Fuel System for Certain Gas Engines
- SEBU6400 – Operation and Maintenance, Cat Gas Engine Lubricant, Fuel, and Coolant Recommendations
- Heywood, John B. *Internal Combustion Engine Fundamentals*. McGraw-Hill Education, 1988.

1.2 Changes since last revision

- Updated guide to new format
- Updated order of topics to achieve better flow
- Section 5.4.1: Corrected/updated H₂S limits charts and tables

2 Gaseous Fuels

As of this writing of this guide, most internal combustion engines use fuels that are based on hydrocarbon compounds derived from petroleum. Perhaps the most commonly seen hydrocarbon fuels are those that exist in a liquid state until they are burned (e.g., gasoline, diesel fuel, and kerosene). However, another class of hydrocarbon fuels exists in gaseous form under normal conditions. The most common examples of these gaseous fuels are natural gas, propane and butane.

While the most commonly seen examples of gaseous fuels come from petroleum, such gases may also be obtained from other less typical sources. Hydrocarbon gases are a naturally occurring byproduct of landfills and organic digester processes, but they may also be manufactured through the conversion of carbon-bearing materials such as coal, wood, or rubber. Each of these gaseous hydrocarbon fuels has unique characteristics that affect their performance as an internal combustion engine fuel. This guide provides an understanding of what gaseous fuels are and how they behave when used as fuel for an engine.

2.1 Hydrocarbons

Hydrocarbons are compounds whose molecules consist only of carbon and hydrogen atoms. Two general descriptions indicate the nature of the source of these compounds: *aliphatic*, indicating compounds derived from fats or oils; and *aromatic*, indicating compounds derived from plant extracts.

Aliphatic hydrocarbons are represented by three groups according to the bonds present in the molecules: *alkanes*, with only single bonds; *alkenes*, with a double bond between carbon atoms; and *alkynes*, with a triple bond between carbon atoms. Aromatic hydrocarbons take different forms from the aliphatic varieties, in many cases centered on the ring-shaped core structure of benzene. These categories are not absolute, as compounds may exhibit the core traits assigned to more than one of them.

The hydrocarbons most commonly used as engine fuel are alkanes (sometimes also referred to as “paraffins”), which have the general chemical formula of C_nH_{2n+2} . This family of compounds has molecules that form as chains of carbon atoms with hydrogen atoms attached at the remaining bond sites, forming a series of similar structures each with a different number of carbon atoms at its core. The series begins with methane (CH₄), with each succeeding member adding another carbon (C) atom along with the corresponding

number of hydrogen (H) atoms. Shown graphically, the first four members of the alkane series are seen below.

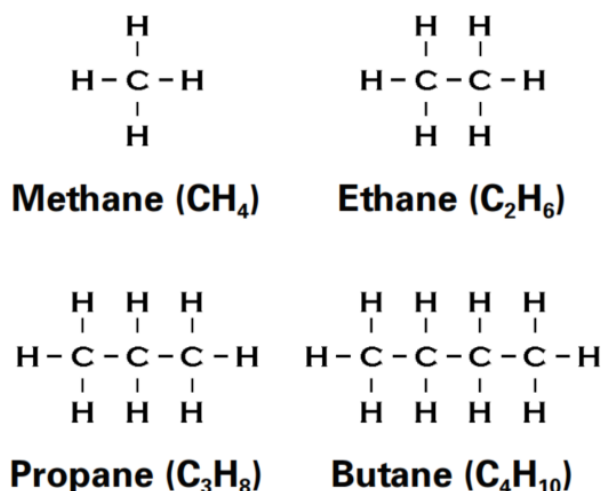


Figure 2.1

Examples of alkane hydrocarbons

This core carbon “chain” lends a similarity from compound to compound where the shorter chain molecules appear as if they are portions of the longer chains, perhaps giving rise to the term “hydrocarbon fractions” that one may hear used when discussing groups of these molecules. A common shorthand notation for these compounds is to refer to them by their number of carbon atoms, thus CH₄ becomes “C1”, C₂H₆ becomes “C2”, C₃H₈ becomes “C3”, and so on.

It is important to note that this carbon backbone is not limited to this “straight chain” shape. Beginning with C₄H₁₀ it is possible for the fourth carbon atom to attach to the center carbon atom in the chain, instead of at the end, leading to a “bent” molecular structure. These arrangements, with the same chemical formula but different molecular shapes, are known in chemistry as *structural isomers*, and their treatment in the hydrocarbon fuels space is odd but pragmatic. It is common to see a gas analysis detail the amount of each isomer present for C₄ (butanes) and C₅ (pentanes), but then to revert to grouping all isomers present under a single header for C₆ (hexanes) and larger molecules. This is largely because of the tremendous numbers of variant isomers that are possible on the longer chain molecules, so while it is reasonable to separate the two isomers of butane and the three isomers of pentane, it becomes unwieldy to document all the isomers of the longer chains separately.

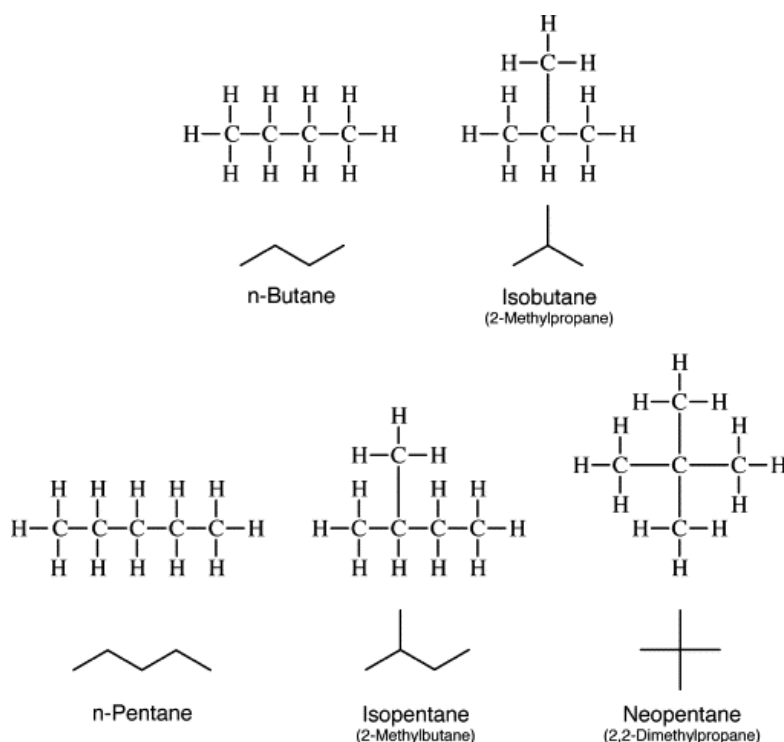


Figure 2.2

Isomers of butane and pentane

The naming of these molecules also may vary, with examples of each seen in the image above. The straight-chain versions of each compound adopt the isomer name “normal”, as in “normal butane” or “normal pentane” and seen above in their abbreviated form as “n-butane” and “n-pentane”. The common terminology used for butanes and pentanes then distinguishes the first branched isomer (only one carbon atom is linked to three other carbon atoms) with the prefix “iso”, as in “iso-butane” or “iso-pentane” and often shortened to “i-butane” or “i-pentane”. The next possibility for pentane has one carbon atom bonded to all four other carbon atoms, and this variant is commonly called “neo-pentane”. At this point this terminology begins to get complicated, as the number of prefix names will multiply rapidly if continued for hexane, heptane, and so on.

The International Union of Pure and Applied Chemists (IUPAC) addressed this difficulty in their naming strategy. In the IUPAC naming, the longest straight-chain carbon backbone found in the molecule becomes the “parent” compound, and the location and nature of the carbon branches is indicated with numbers representing their points of attachment and group names indicating the type of carbon chain found there. Using the examples in the

figure above, isobutane would be termed “2-methylpropane” because a CH₃ methyl group is attached to the second carbon in the core chain of three carbon atoms (C3 = propane). Similarly, the IUPAC name for isopentane would be “2-methylbutane” because in it a CH₃ methyl group is attached to the second carbon atom in the core chain of 4 carbon atoms (C4 = butane). Looking at the more complex case of neopentane, the same rules apply; its IUPAC name is “2,2-dimethylpropane” because there are two CH₃ methyl groups attached to the second carbon atom in the core chain of 3 carbon atoms (C3 = propane).

As the number of atoms in each molecule increases with the carbon chain length, the molecular mass increases. For this reason, longer-chain hydrocarbons are often referred to as being “heavier” than the shorter chain fractions. However, the differences between longer and shorter chain molecules are not limited to weight. They also exhibit differences in physical behavior (variations in dewpoint) and combustion characteristics (heating value and burn rate) that are significant to their use in piping systems and as engine fuel. There are tables at the end of this guide that present information about these variations among alkane hydrocarbon fractions.

2.2 Standard condition of a gas

2.2.1 Temperature, pressure, and volume

When dealing with gaseous fuels it's important to be able to gauge the amount of gas present in each sample. The number of atoms in each molecule and the number of molecules present determines the mass of the sample, but it can be difficult to weigh a gas sample to determine its mass. Volume is a more practical measurement of a gas sample, but the volume occupied by a given amount of a gas is dependent upon its temperature and pressure. Higher temperatures and lower pressures each tend to cause a gas to occupy a greater amount of space (greater volume).

These relationships are captured in the basic chemistry rules of Boyle's Law and Charles' Law.

$$\text{Boyle's Law: } P_1 V_1 = P_2 V_2, \text{ thus } V_2 = V_1 * \frac{P_1}{P_2}$$

$$\text{Charles' Law: } \frac{V_1}{T_1} = \frac{V_2}{T_2}, \text{ thus } V_2 = V_1 * \frac{T_2}{T_1}$$

It is important to notice the inverse relationships of temperature and pressure to the resulting volume – increases in temperature increase the volume occupied by the gas, while increases in pressure decrease the gas volume. Boyle's Law and Charles' Law together

are key components of a broader equation known as the Ideal Gas Law. Because these effects are functionally independent, the two laws can be combined into a single equation:

$$V_2 = V_1 * \frac{P_1}{P_2} * \frac{T_2}{T_1}$$

It is also important to note that any calculations using these relationships must start with the temperature and pressure expressed in absolute units. This is particularly important because absolute units are often not the units used in on-site measurements.

2.2.2 Converting reference conditions

These relationships are useful because they enable “conversion” of the measured volume of a gas to its equivalent under different temperature and/or pressure conditions. As noted above, the key is to represent the temperature and pressure measurements in absolute units. Those conversions look like this:

Temperature:	Fahrenheit to Rankine	$R = ^\circ F + 459.67$
	Celsius to Kelvin	$K = ^\circ C + 273.15$

Pressure:	pounds per square inch	$psia = psig + 14.696$
	kilopascals	$kPaa = kPag + 101.325$

You may notice the notations for each, where temperatures are represented by different units (the Rankine or Kelvin temperature scales) while the pressure units gain a suffix letter: “a” for “absolute” or “g” for “gauge”. It is pretty simple to see whether your temperatures have been provided in Fahrenheit versus Rankine, or Kelvin versus Celsius, but a little more attention should be paid to the pressure measurements. Measurement equipment may be configured to measure in either gauge or absolute units, and it must be clear which units have been provided for any conversion of the volume measurement to be successful.

2.2.3 Standardized reference conditions

To allow for consistent comparisons of gas samples, reference conditions of temperature and pressure have been established, termed “standard” or “normal” conditions depending on the source. The definitions for “standard” and “normal” used in Caterpillar published documentation are as follows:

For English units, standard conditions are 14.696 psia and 60°F

For metric units, normal conditions are 101.325 kPaa and 0°C

Volume measurements corrected to these reference conditions can then have the reference label added to the units, thus cubic feet would become standard cubic feet or cubic meters would become normal cubic meters. Abbreviations for these units can vary but are commonly written by Cat as “scf” or “Nm³” respectively.

As an example, consider a gas flow measured at 255 m³/hr. If the conditions at the time of measurement were 152 kPaa and 35°C, the flow can be corrected to normal conditions in this way:

$$V_2 = (255 \text{ m}^3/\text{hr}) * \frac{(152 \text{ kPaa})}{(101.325 \text{ kPaa})} * \frac{(0+273.15 \text{ K})}{(35+273.12 \text{ K})} = 339 \text{ Nm}^3/\text{hr}$$

Duplicating this calculation in English units would result in this:

$$V_2 = (150 \text{ ft}^3/\text{min}) * \frac{(22 \text{ psia})}{(14.696 \text{ psia})} * \frac{(60+460.67 \text{ R})}{(95+460.67 \text{ R})} = 210 \text{ scfm}$$

In this correction exercise, the values for T₁ and P₁ were those measured and the values for T₂ and P₂ were those for “normal conditions” as noted above.

2.3 Physical properties

2.3.1 Specific gravity relative to air (SG)

Specific gravity is the ratio of the molecular weight of a gas to the molecular weight of air. It is useful for converting between units of mass and volume. Specific gravity values of common gases can be found in a variety of engineering reference books. Tables of gas properties are included in the appendix of this guide.

2.3.2 Density

Multiplying the specific gravity of a gas by the density of air at a given set of conditions (temperature and pressure) yields the density of the gas at the same conditions.

Example

Given the following values, calculate the density of methane at normal conditions.

Specific gravity of methane = 0.5539

Density of air at normal conditions (0°C, 101.31 kPa) = 1.290 kg/Nm³

Density of methane = (specific gravity of methane) x (density of air)
 = 0.5539 x 1.290 kg/Nm³
 = 0.7145 kg/Nm³

2.3.3 Moles and Molecular Weight

A mole is a measure of the number of molecules of a substance, which is a useful way to measure how much of that substance is present when the volume it occupies is dependent upon the temperature and pressure at the time of the measurement. It provides a reference quantity to use as a starting point for discussions involving measured amounts of substances, such as the amounts of each hydrocarbon fraction that make up a gaseous fuel mixture.

It is a useful property that one mole of any ideal gas occupies essentially the same volume as one mole of any other ideal gas under the same temperature and pressure conditions. This makes it very simple to go from “how much” of a substance is present (in moles) to how much we can measure (in volume). In fact, the term “mole fraction” is commonly used for the proportionate measure of the parts that make up a gas sample. Mole fraction amounts are equivalent to volume percent values divided by 100. The sum of the mole fractions for substances in a given gas mixture added together will equal 1, just as the sum of the volume percent measurements added together will equal 100%.

The molecular weight of a substance gives the relationship between the number of molecules in a sample and the mass of that sample. Given equal amounts of two substances, a sample of a substance with a molecular weight of 12 will have twice as much mass as an equal-sized sample of another substance with a molecular weight of 6. This, together with the Ideal Gas Law described above, means the molecular weight gives us the tool to convert directly from volume measurement to mass measurement for any ideal gas.

2.3.4 Dew Point

In dealing with gases as compressible fluids it is also important to maintain an awareness of dew point, the temperature/pressure condition at which each constituent gas changes state from a gas to a liquid. While it is relatively common to think of water vapor condensing into water in this manner, it is true that with the right circumstances many of the compounds present could transition to the liquid state. Gas engines are designed to manage gaseous fuels, so liquids in the fuel can cause many problems when introduced into the engine. Liquids formed in the supply system should be addressed through the use of scrubbers or coalescers to separate the liquids from the gases. However, there will be additional restrictions found in the on-engine fuel system piping that could potentially trigger liquids drop-out. The best protection starts with an awareness of those constituents that may be close to their dew points to manage the gas flow appropriately. If needed, a fuel heater may be used to manage the dew point of the gas flow to the engine.

2.4 Properties of Gas Mixtures

Most natural gas engine fuels are a mixture of hydrocarbons and inert gases. The properties of each component must be weighted when determining the properties of the mixture. This weighting is done on a volume basis.

For example, to find the specific gravity of a mixture that is 80% methane, 15% ethane and 5% carbon dioxide, you would multiply the properties of each constituent gas by the decimal equivalent of its volume % (its “mole fraction”) then sum the results to find the aggregate value. Selected physical properties of common constituent gas compounds may be found in tables presented at the end of this guide.

For this example:

Constituent gas	Specific gravity	Volume % in mixture
Methane (CH ₄)	0.5539	80%
Ethane (C ₂ H ₆)	1.0382	15%
Carbon Dioxide (CO ₂)	1.5196	5%

$$\begin{aligned}\text{SG for the mixture} &= (0.5539 \times 0.80) + (1.0382 \times 0.15) + (1.5196 \times 0.05) \\ &= 0.6748\end{aligned}$$

Because SG is a relative measure (relative to air) the resulting value is dimensionless. This same process of proportioning the contributions of constituent gases to their mole percent (volume percent) in the mixture works for a number of different properties, many of which will be detailed in the next section of this guide.

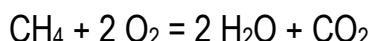
3 Combustion characteristics and engine design

The basic physical properties and their evaluation in gas mixtures from the previous section set the stage for the evaluation of that as mixture as fuel for an engine. Fuel is a key component in the selection and application of a gas engine to a particular use, so understanding the steps in the evaluation of the gas mixture is important to ensuring the best match possible between engine and fuel.

3.1 Stoichiometry

An Internet source defines stoichiometry (pronounced “sto-ee-kee-ah-muh-tree”) as “the relationship between the relative quantities of substances taking part in a reaction or forming a compound”. Stoichiometry for a gas engine is based on the chemical reaction equations for the constituent gases in the fuel, with the key consideration being the relative amounts of gas and oxygen present for the complete combustion reaction (no oxygen or gas left over).

The stoichiometric combustion equation for methane looks like this:



This equation tells us that methane and oxygen combine to form water and carbon dioxide. It also tells us that it takes two oxygen molecules to convert each methane molecule. We can use this information to determine how much air will be needed to completely burn a given amount of gas; this is important information when setting up an engine to use gas as fuel.

By the previous equation, one volume of methane requires two times that volume of oxygen to burn completely. Knowing that air is only 21% oxygen, we can work our way to the proportionate amount of air this way:

$$2 / 0.21 = 9.53$$

Thus, it takes 9.53 volumes of air to completely burn one volume of methane. This ratio of volumes, 9.53:1, is a characteristic of methane known as its stoichiometric air/fuel ratio. The stoichiometric combustion equations for the rest of the hydrocarbon fuel fractions balance differently, so the stoichiometric air/fuel ratio for each will be different. These air/fuel ratios are shown in tables presented as a reference at the end of this guide.

Most gaseous fuels don't exist as a single compound but instead as a mixture of several compounds. A typical pipeline quality natural gas will be predominantly methane but will

also contain much smaller amounts of other hydrocarbon fractions and other compounds like nitrogen or carbon dioxide. The amount of air required to burn such a gas mixture will be determined by a summing the amount required for each component of the mixture weighted for the percentage each represents in the overall mixture, similar the approach shown earlier.

Such a weighted sum might look like this:

Constituent gas	Stoichiometric air/fuel ratio	Volume % in mixture
Methane (CH ₄)	9.53	90%
Ethane (C ₂ H ₆)	16.67	5%
Propane (C ₃ H ₈)	23.83	3%
Carbon Dioxide (CO ₂)	--	2%

Following the approach outlined above, the weighted sum for this mixture would be calculated like this:

$$\begin{array}{rcl}
 \text{CH}_4: & 0.90 \times 9.53 = & 8.58 \\
 \text{C}_2\text{H}_6: & 0.05 \times 16.67 = & 0.83 \\
 \text{C}_3\text{H}_8: & 0.03 \times 23.82 = & 0.71 \\
 \text{CO}_2: & 0.02 \times 0.0 = & 0.00 \\
 \text{Total volume of air required} = & & 10.12
 \end{array}$$

Thus, the stoichiometric air/fuel ratio for this gas mixture is 10.12:1, meaning 10.12 volumes of air are required to completely burn one volume of this gas mixture. As noted earlier, this weighted sum technique is useful in determining “mixed gas” value for several of the characteristic gas properties.

At this point it is important to realize the stoichiometric air/fuel ratio may not be the operating air/fuel ratio for your engine; it is simply an important reference value. So called “rich burn” gas engines operate based on the stoichiometric air/fuel ratio, but their actual operating ratio must typically include a small amount of excess air to compensate for imperfect mixing of air and fuel. “Lean burn” gas engines include larger quantities of excess air to manipulate combustion conditions to achieved reduced emissions of oxides of nitrogen (NO_x) – however this will not be discussed further in this guide. This note is simply to raise

Gaseous Fuels A&I Guide

awareness that your actual operating air/fuel ratio will need to be established based on the instructions provided for setup of your specific engine model.

To better understand these two operating regimes, it is helpful to use the concept of lambda (λ), also known as the air-fuel equivalence ratio. It is defined as the ratio of the actual air/fuel ratio to the stoichiometric air/fuel ratio for the fuel in use.

$$\lambda = \frac{(\text{air/fuel})_{\text{actual}}}{(\text{air/fuel})_{\text{stoichiometric}}}$$

This variable simplifies evaluation of the operating condition relative to the theoretical “ideal” because the stoichiometric ratio thus becomes $\lambda=1$. Viewed in this way, lower values for lambda are said to be “rich” (more fuel than stoichiometric) and higher lambda values are “lean” (more air than stoichiometric).

The figure below presents the typical proportionate emissions from a natural gas engine based on its air/fuel ratio tuning (expressed as lambda). Here you can see the relative operating ranges for a rich burn (stoichiometric) engine, in the red zone near $\lambda=1.0$, and for a lean burn engine, in the blue zone further to the right on this scale.

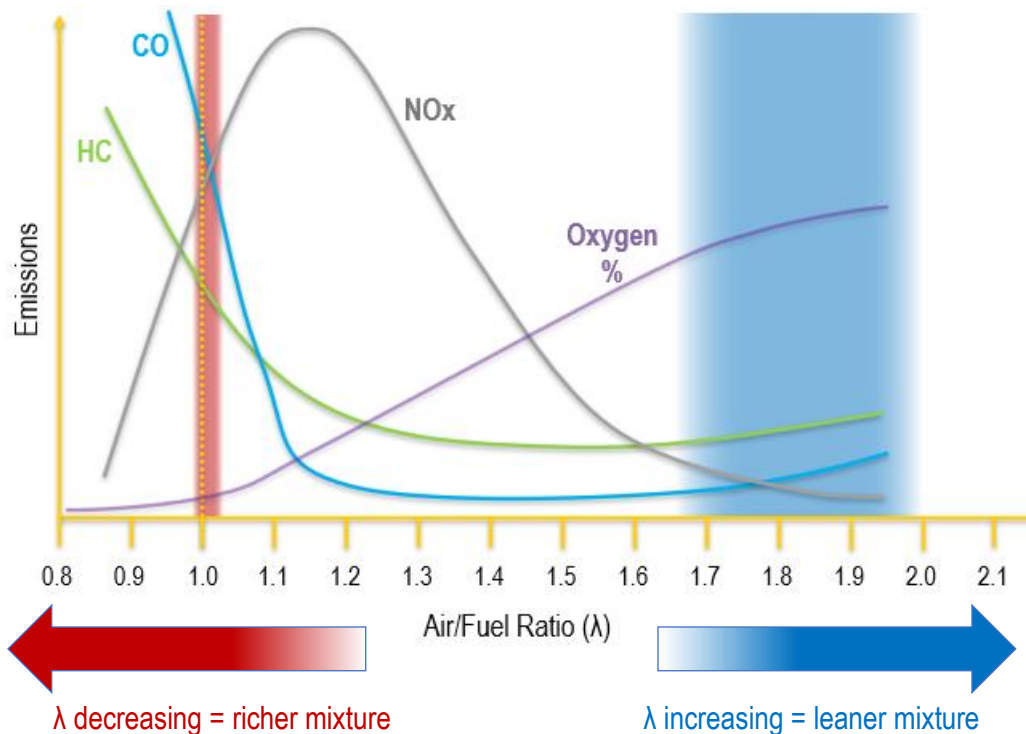


Figure 3.1

Rich and Lean operation expressed as Lambda

3.2 Heating value

Heating value is, put simply, the theoretical amount of chemical energy stored in a compound that can be released through combustion (also called “calorific value”). It can be measured using a calorimeter, a device that measures the heat released during a chemical reaction such as combustion. It is also one of those properties that can be established for a gas mixture using the weighted sum approach shown above.

The combustion of hydrocarbons consistently involves conversion of carbon, hydrogen, and oxygen into carbon dioxide and water, even though the ratios involved will vary with the specific hydrocarbon being evaluated. Given the high temperatures involved in hydrocarbon combustion reactions, the water produced by these reactions will emerge as a gas and the user really has no control over this outcome. This point is raised to explain why the energy content that is useful to the engine is less than the total energy content for the fuel gas. There is energy lost to this conversion of water from a liquid to a gas, referred to as the *latent heat of vaporization*. Because this energy expenditure is inherent to the hydrocarbon combustion process, it is not available for conversion by the engine into useful work. Thus, there are two heating value quantities that are defined for a given gas mixture:

- The higher heating value, or HHV, which is the total theoretical energy content, and
- The lower heating value, or LHV, which is the total energy content minus the latent heat of vaporization for the gas mixture.

Care should be exercised to be clear that the correct heating value is used in engine evaluations. Keep in mind that those engaged in the sale or delivery of natural gas are in the business of selling energy, thus they speak in terms of HHV. Engine people must be certain to do their work in terms of LHV since it is the useful energy available to the engine. Expressed in equation form, this relationship looks like this:

$$HHV = LHV + H_v \times \frac{n_{H_2O} \times M_{H_2O}}{n_{fuel} \times M_{fuel}}$$

This energy difference can be calculated as seen here, by applying the heat of vaporization of water (H_v in this equation) to the amount of water produced. The ratio of water to fuel seen here is used to scale the resulting energy quantity to the amount of burned. This ratio may be seen both with and without the molar masses (“M”) included. This version shown with M values included will produce results of energy per unit mass of the input fuel, while without the M values present the ratio will produce results of energy per unit volume of the input fuel.

A key consideration is what value to use for H_v , since it is a property that varies with temperature. A common choice for purposes of illustration is at standard temperature and pressure (STP), so for our purposes we will assume the standardized reference conditions noted in section 2.2.3 earlier.

Those values are: $H_v = 45.054 \text{ kJ/mol}$ at 0°C and 101.325 kPaa

$H_v = 42.07 \text{ Btu/mol}$ at 60°F and 14.696 psia

Since the heating values for gaseous fuels are typically presented in terms of volume, we would use the equation above without the molar masses included, but with a factor included to convert moles to volume. Thus, the resulting energies lost to vaporization are:

$$45.054 \text{ kJ/mol} \times (2/1) / 0.0224 \text{ Nm}^3/\text{mol} = 4022.7 \text{ kJ/Nm}^3$$

$$42.07 \text{ Btu/mol} \times (2/1) \times (453.6 \text{ mol/lbmol}) / 379.4 \text{ scf/lbmol} = 100.6 \text{ Btu/scf}$$

3.2.1 Air and fuel system design

Viewed in its simplest form, an engine is an energy conversion device, taking in chemical energy stored in the fuel and releasing it as useful mechanical work. As with any such conversion machine, the designer's challenge is to make it both as efficient and as practical as possible. Efficiency maximizes the output work relative to the input energy needed to produce it. Practicality requires that the engine be capable of operating under a range of conditions that may reasonably be encountered in the applications into which the engine is expected to be placed. In many ways, these goals are at odds with one another, challenging the designer to make choices to achieve the best combination of attributes possible for each intended use.

One task the engine must perform is to deliver air and fuel to the cylinders, mixed in the correct ratio for that engine's combustion strategy, and with sufficient fuel energy present to reach the design's target power output. The design of the air and fuel piping systems, and the technology used to precisely mix them together, are critical steps in moving from concept to actual product.

The most basic engine configuration relies on the vacuum drawn by the piston moving down in the cylinder to draw air and fuel in. This design is referred to as "naturally aspirated" and is often abbreviated "NA". An NA engine will be sensitive to any factors that restrict air flow, with a key consideration being the altitude and ambient air temperature experienced at the site where the engine operates. Increases in site altitude and air temperature both cause the air density to decrease, reducing the amount of air that can be drawn in by the vacuum of the pistons alone. With the ratio of air to fuel established by the engine's design, this

limitation on air drawn in results in a related limitation on fuel brought into the cylinders. Less fuel energy present consequently results in less power produced.

A design strategy used to overcome this limitation is supercharging, which is the additional of a mechanical device that can force more air (and consequently more fuel too) into the cylinders. The most basic form of supercharging uses a mechanically driven pump to increase the air mass flow to the cylinders. While effective, mechanically driven superchargers consume power to produce the increased performance they provide.

A variation on supercharging that doesn't consume mechanical work is turbocharging. Instead of using a mechanical drive, the turbocharger captures energy from the engine's exhaust stream to drive an air compressor. This approach has the net benefit of increasing engine performance using energy that would otherwise be exhausted to the surroundings, but the design of a turbocharging system requires a careful balance between the restrictions imposed on the exhaust path by the turbine with the air delivery performance of the compressor.

A key consideration for supercharged engines is the compression work performed on the intake air. This compression of the air causes a related increase in temperature, which adversely affects both the air density and the temperature of the intake charge (the mixture of air and fuel) at the start of the combustion process. Lowered air density limits the amount of fuel present, thereby limiting power. Increased charge temperature reduces detonation margin, also a limiting factor on power production. The solution to both problems is the aftercooler (also called an intercooler), a heat exchanger that pulls heat from the compressed air stream to lower temperature and increase air density. Nearly all turbocharged gas engines include an aftercooler; Caterpillar engines that use a turbocharger and aftercooler together often carry the notation "TA" to refer to the presence of both on the engine.

The engine's fuel system is yet another factor in the engine's ability to efficiently produce power. Like the air system, the fuel's movement into the engine is heavily influenced by the pressure available at the fuel's source and the design of the path it must follow. Design choices such as mixing the fuel with air upstream or downstream of the turbocharger enable the engine to be adapted to fuel supplies that with widely varied supply pressures. For either design the air-to-fuel mixing equipment has an important job to perform and is significantly affected by the LHV of the fuel gas. Like any mechanical device, the mixer will have practical limits to the LHVs it can support. Older carbureted engines may require modifications to the mixer to enable the engine to operate with either high or low LHV fuels. Newer designs have successfully used electronics to enable "smart" mixing valves to deliver

extended LHV range to the engine, with the fuel's LHV and SG characteristics programmed into the engine's controls on site.

Bringing this discussion back to the topic of gaseous fuels, it's important to understand that gaseous fluid flow through these systems can be a factor to consider. This is particularly true when conditions push one or both systems toward their flow capacity limit. When air flow or fuel flow is restricted in their flow paths, the direct result will be a limitation on the engine's ability to produce power.

3.2.2 Air or fuel system limitations

Because flow restriction in either the air or fuel system can occur, two calculated parameters were devised to help quantify the impact of such restriction limitations.

3.2.2.1 Relative power capability (RPC)

The relative power capability of a fuel gas is the ratio of the LHV of the fuel-air mixture for the gas being considered relative to that of the fuel-air mixture used to develop the engine rating. When the fuel-air mixture contains less energy than the developmental fuel-air mixture the relative power capability drops below 100%, representing the theoretical restriction on power production capability of the engine.

To determine relative power capability for a fuel, start by calculating the LHV of the fuel-air mixture. For this example, we will use a gas mixture high in inerts to produce a low LHV fuel that is likely to trigger an RPC-related derate. Consider this gas:

Constituent gas	Volume % in mixture
Methane (CH ₄)	55%
Carbon Dioxide (CO ₂)	35%
Nitrogen (N ₂)	10%

Analysis of this gas produces LHV values of 19.69 MJ/Nm³ or 501 Btu/scf, with a stoichiometric air/fuel ratio of 5.24:1. To determine the LHV of the air-fuel mixture we must divide the total energy content (fuel plus air) by the total volume of the fuel and air mixed at this ratio. This calculation looks like this:

$$(19.69 \text{ MJ/Nm}^3 + 0 \text{ MJ/Nm}^3) / (1 + 5.24) = 3.16 \text{ MJ/Nm}^3$$

$$(501 \text{ Btu/scf} + 0 \text{ Btu/scf}) / (1 + 5.24) = 80.3 \text{ Btu/scf}$$

The LHV for the reference fuel-air mixture is calculated in the same manner:

$$(35.64 \text{ MJ/Nm}^3 + 0 \text{ MJ/Nm}^3) / (1 + 5.24) = 3.41 \text{ MJ/Nm}^3$$

$$(905 \text{ Btu/scf} + 0 \text{ Btu/scf}) / (1 + 5.24) = 86.6 \text{ Btu/scf}$$

Dividing the LHV of the current gas with that of the reference gas gives the RPC ratio:

$$3.16/3.14 = 0.93 \quad \text{or} \quad 80.3/86.6 = 0.93$$

This RPC value indicates a stoichiometric mixture of this gas will deliver to the engine only 93% of the energy that would be present in a stoichiometric mixture of the pipeline-quality natural gas used during rating development. This factor comes into play:

- On an NA engine. The NA engine, with no turbocharger, has no means to boost air density to overcome intake restriction issues. Thus, at a specified air/fuel ratio the energy delivery to the cylinders will be limited as seen in the RPC, and thus RPC dictates the maximum site rating for the engine.
- On a TA engine only when the specified site conditions place the operating point at or past the point where the engine must derate. Up to the turbocharger's limit the engine has reserve ability available to increase compression of the intake air, thereby compensating for this intake restriction issue. However, once the site conditions reach the turbocharger and aftercooler, this intake restriction issue comes into play in the same manner as on the NA engine. With the added consideration that the site conditions are also indicating a derate, the derating of the TA engine is the combined effect of the site derate factor and the RPC.

As an example of this use of RPC on a TA engine, consider the case of a G3516 LE rated for 809 kW (1085 bhp) at 1200 rpm, located at a site of 2000 meters and 30°C (6560 feet and 90°F). As determined from the standard technical data sheet for this rating:

Altitude/ambient derate factor = 0.92

Relative Power Capability factor = 0.93

The total derate is simply the sum of these individual derates:

$$\begin{aligned} \text{Total air system derate} &= (1 - 0.92) + (1 - 0.93) \\ &= 0.8 + 0.7 \\ &= 0.15 \end{aligned}$$

Please note that this can be kept in terms of derate factor by multiplying the two individual derate factors together:

$$\text{Total air system derate factor} = (0.92)(0.93) = 0.85$$

Applying the total derate factor to determine site power available:

$$\text{Site power} = (809 \text{ kW})(0.85) = 688 \text{ kW}$$

3.2.2.2 Wobbe Index

The discussion of Relative Power Capability illustrates how energy content of the fuel can affect the achievable site rating of the engine. However, there is another gas property that is typically affected by a change in the gas composition: specific gravity (SG). Specific gravity influences the ability of the gas to flow through piping systems such as the fuel system found on the engine, with higher SG gases having greater restriction to flow than is found for lower SG gases. Because fuel flow equates to energy flow, if fuel flow becomes restricted the energy flow to the cylinders may also become limited as compared to the energy flow that is necessary to enable the engine to reach full rated power.

The Wobbe Index accounts for both the energy content of the fuel and the fuel's ability to flow through the fuel system. The volume flow equation for gases reveals that flow is proportional to 1 divided by the square root of SG, and the Wobbe Index applies this relationship to LHV to create a fuel-specific value that represents the ability of that fuel's energy to flow to the cylinders.

Expressed as a formula: $\text{Wobbe Index} = \text{LHV} \div \sqrt{\text{SG}}$

Note that the square root of SG is dimensionless, so the units for Wobbe Index will be the same as for the LHV value used in the calculation. Wobbe Index is another property that is calculated by the Fuel Analysis calculator, and some engine ratings may express fuel system limits in terms of this Wobbe Index value.

Figure 3.2

Example of Fuel Usage Guide showing Wobbe Index limits

FUEL USAGE GUIDE																	
CAT METHANE NUMBER	<10	10	15	20	25	30	35	40	45	55	60	65	70	75	80	85	100
SET POINT TIMING	-	16	16	16	16	16	16	16	16	17	17	17	17	18	18	18	18
DERATION FACTOR	0	0.50	0.62	0.75	0.87	1	1	1	1	1	1	1	1	1	1	1	1
WOBBE INDEX(Btu/scf)	700	850	1550	1870													
DERATION FACTOR	0.77	1	1	0.85													

3.3 Methane number

Gas engines can often be operated on gaseous fuel from a wide range of sources, with examples being raw field gas, processed pipeline natural gas, or gas from landfill/digester processes. The combustion qualities of these gases vary along with their compositions and can affect engine settings such as ignition timing or even limit the power which the engine may produce on that fuel. The key property involved is the ability of the fuel gas to resist detonation, an uncontrolled secondary burning of the gas in the engine. Left unchecked, detonation has the potential to cause significant engine damage. For this reason, having a scale through which to measure this detonation resistance property provides a valuable tool for assessing the usefulness of a gas as engine fuel.

3.3.1 Detonation and Preignition

Detonation and preignition are two forms of abnormal combustion that are not governed by the ignition spark. While somewhat similar in nature, they differ in their relationship to the spark. Preignition is premature combustion, burning that occurs before the spark plug has fired. Detonation occurs as a secondary combustion that is not initiated by the spark plug. Both are localized phenomena, creating sharp increases in temperature and pressure in a focused area of the combustion chamber. These effects carry a significant risk of damage to the engine.

Pre-ignition is typically the result of a “hot spot” in the combustion chamber, locations that have retained enough heat from one combustion cycle to the next to ignite the fuel-air charge by themselves before the spark occurs. Such hot spots may occur at sharp edges on the engine parts (such as valves or spark plugs), or from carbon deposits in the combustion chamber. Possible sources for these deposits include high oil consumption, poor fuel-air mixture tuning, or fuel contaminants, to name just a few. Logically, managing these forms of pre-ignition involve design work that ensures proper cooling of surfaces within the combustion chamber and effective management of oil to limit deposit formation.

Detonation is driven by a more complex mechanism influenced by a number of choices in both the design of the engine and its actual use in operation. The primary cause of detonation is compression-ignition, in which compression of the fuel-air charge causes its temperature to rise beyond the autoignition temperature of the mixture, the temperature at which it will spontaneously begin to burn. The interaction of this localized secondary burning with the primary combustion initiated by the spark produces a sharp metallic “ping” sound that is the audible evidence of detonation. This phenomenon is also referred to as “knocking”, an issue also well-documented on automotive gasoline engines.

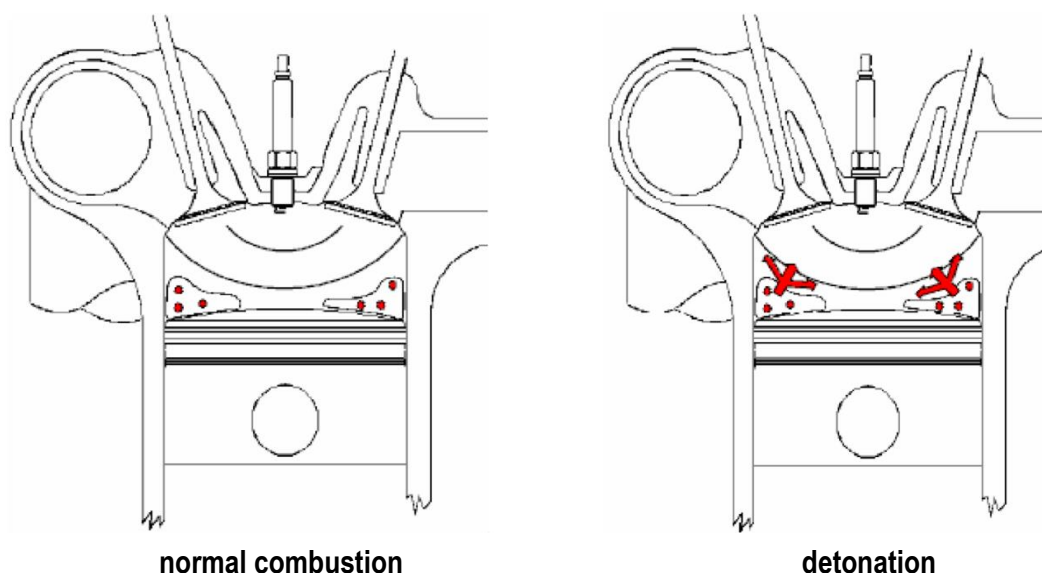


Figure 3.3

Models of normal combustion and detonation

Figure 3.1 presents a simplified two-dimensional model of a reciprocating engine combustion chamber. In the normal combustion model on the left, the center-mounted spark plug ignites a flame that rapidly sweeps across the entire combustion chamber. This flame front represents a wall of combustion-induced temperature and pressure rise that separates the burning air-fuel mixture from the mixture that has yet to burn. This burning sweeps across the combustion chamber in milliseconds, progressing to involve the entire fuel-air charge, and the pressure rise works to push the piston down in the cylinder. This is the core concept by which the piston engine converts the fuel's chemical energy to useful work. By slowing this process down, we can see that this flame front represents a pressure wave that also compresses the portion of the fuel-air charge that has not yet burned, causing it to increase in temperature before it actually ignites from contact with the flame front. With the inputs carefully controlled, this effect is simply part of the combustion process, with no adverse consequences.

In the detonation scenario on the right, everything takes place in the same sequence as in the normal combustion example, except in this instance the starting condition of the fuel-air mixture was different than in the normal case. As the flame front advances, the compression heating of the unburned gas reaches the autoignition temperature of the fuel-air mixture and the unburned gas spontaneously ignites as a second combustion event in the cylinder. This starting condition is basically established when the intake valve closes,

setting the starting temperature and pressure onto which the compression heating of the flame front is imposed, and there are factors that alter the relationship of the flame front to the unburned gas, increasing its susceptibility to autoignition. The list of contributing factors is lengthy:

Starting temperature and pressure of the fuel-air mixture must be controlled by design. On turbocharged engines this typically takes the form of a wastegate to manage boost pressure from the turbocharger, and an aftercooler to manage the temperature of the mixture. Both require the active participation of those applying the engine, as the wastegate must be set properly to do its job well and the radiator extracting heat from the aftercooler must be sized adequately for its role.

Ignition timing is another direct factor that affects the change in cylinder pressure during the combustion event. Figure 3.2 shows an example of three cylinder-pressure traces (pressure over crank angle) that differ only in the ignition timing used. The contour of the traces at the left side of the graph reflects the pressure rise of the piston moving up in the cylinder during the compression stroke. At the marks shown on each trace, the spark is fired to start combustion. The relatively late spark of “case 3” leads to a slower build-up of pressure and a late pressure peak. The earlier spark in “case 2” results in a more rapid pressure rise and higher peak pressure than for “case 3”, and the even earlier spark of “case 1” increases this effect, with a very rapid rise to an even higher peak pressure.

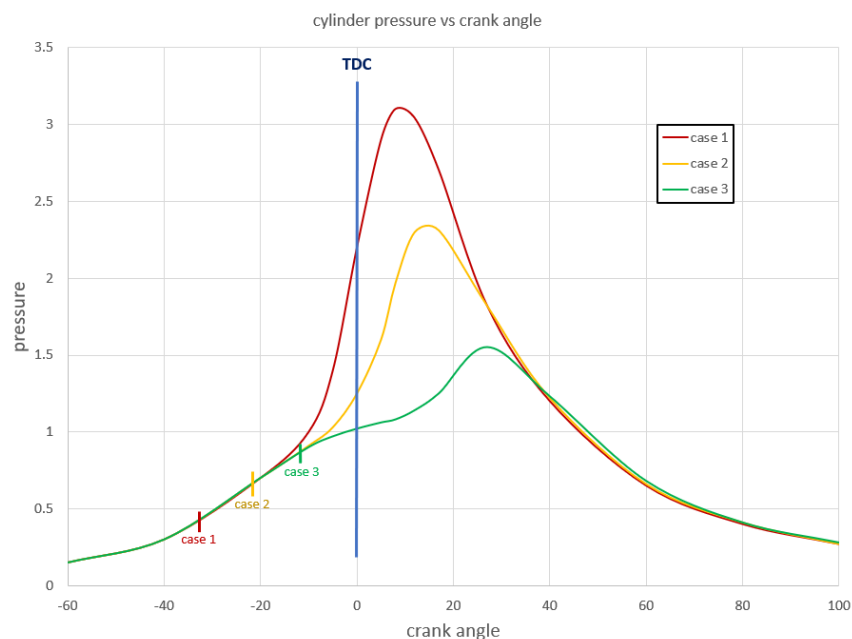


Figure 3.4

Effects of ignition timing on cylinder pressure

These effects are part of the engine designer's challenge, that they must understand the target fuel well enough to incorporate the burn rate into their design. The timing of the spark (in degrees before top dead center) must account for the burn rate to place the pressure peak at an optimal angle after TDC to make best use of applying that force to the crankshaft. A peak too late misses out of some of the power available, yet too soon risks damage to the engine's internal parts. This pressure rise rate relates to detonation in that a rapid pressure rise to a higher peak induces a similar effect on temperature of the unburned mixture, thereby directly increasing the risk of detonation.

It's relatively easy to see from this point that the burn rate of the fuel is a key factor in selection of the ignition timing. This detail is, in fact, incorporated into the setup of an engine for a particular site fuel, and is shown as a general trend versus the fuel's MN in a table titled the "Fuel Usage Guide" that is found on the documentation of each gas engine rating. This documentation is there to ensure those selecting, installing, and commissioning the engine select the proper ignition timing to ensure risk of detonation is properly managed.

Figure 3.5 Example of Fuel Usage Guide showing ignition set point timing

CAT METHANE NUMBER	<14	14	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85
SET POINT TIMING	-	27	27	27	27	27	27	27	28	28	28	28	30	30	30	30	30
DERATION FACTOR	0	0.50	0.52	0.65	0.77	0.90	0.92	0.97	1	1	1	1	1	1	1	1	1

Engine loading affects the risk by an indirect means, as a result of the normal function of another of the engine's systems. With no other changes made, adding load on the engine should cause the engine's speed to decrease. This is a normal reaction, the relationship between the amount of fuel entering the cylinders and the power being drawn by the driven equipment. In order to return to the original speed, the engine must respond by adding more fuel to make more power. This reaction is managed by the speed governor, which reads changes in speed and instructs the fuel system on how to react to return to the speed set by the operator. However, this richer fuel-air mixture also carries an increased risk of detonation. To manage this risk factor, the site conditions, fuel quality, and even the load profile must be reviewed to ensure safe operation within the engine's capabilities.

Air/fuel ratio is thus another factor to address during engine selection and application. Air/fuel ratios close to stoichiometric produce a hotter, faster burn, increasing the risk of detonation. The engine designer does their part by incorporating an appropriate design margin against the onset of detonation into the engine's setup. Use of an active air/fuel

ratio control helps to keep the engine at this optimal tune point, and thus can enable some of that design margin to be re-applied to other practical enhancements to the site rating. The user's obligation here is to select the engine with an appropriate awareness of the limits for fuel quality and loading, helping to ensure the fuel-air mixing system is set to work within the detonation limits.

Compression ratio is managed in the same manner as the previous discussion on air/fuel ratio. Compression ratio contributes directly to the pressure rise in the cylinder after the closing of the intake valve, so compression ratio has an inverse relationship to fuel MN with regard to avoiding detonation. Gaseous fuels with higher concentrations of heavy hydrocarbons will show lower MN values, making them more suited to engines with a lower compression ratio. Fuel gases with a higher concentration of methane will have higher MN values, enabling the use of higher compression ratio engines.

Inert gases in the fuel, especially carbon dioxide (CO_2), can actually enhance the MN value for a predominantly methane-based gas. CO_2 is a sufficiently heavy molecule that it can absorb a large amount of heat energy during combustion. While the heavier hydrocarbons release too much energy to be significantly affected by this, the combustion of methane is actually slowed by this "heat buffer" effect of the inert gases. This slowing of combustion has the effect of adding to the margin against detonation, thus gases with large amounts of inerts in combination with only methane can exhibit MN properties significantly above 100. Biogas, from biological sources such as landfill or digester applications, are perhaps the peak example of this.

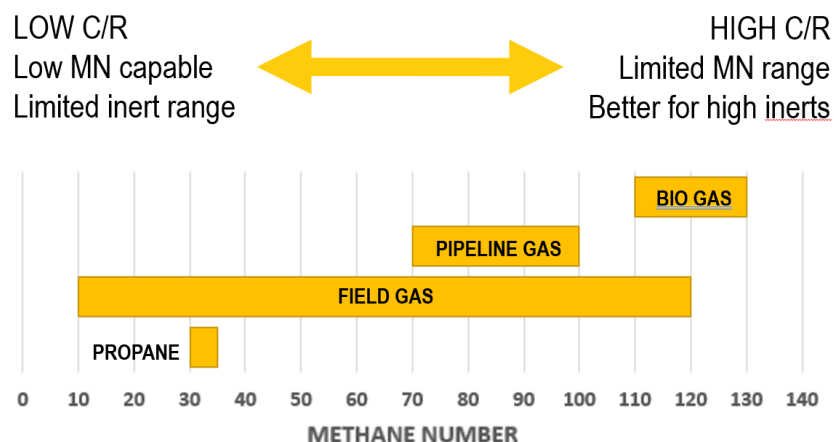


Figure 3.6

Relationship of compression ratio to MN

Just as with air/fuel ratio, compression ratio is a factor that must be addressed at the time of engine selection. This is yet another reason the fuel quality should be understood prior to settling on an engine arrangement, to ensure the engine selected is a good match to that fuel.

Other fuel characteristics: How the engine achieves its effective compression ratio can impact the match for certain fuels. In particular, this combustion buffering effect of CO₂ on methane can become a challenge when the fuel gas contains significant amounts of both CO₂ and heavy hydrocarbons. The faster burn rate of the heavy hydrocarbons will require some delay in the ignition timing (referred to as “timing retard”) to ensure the pressure peak does not occur too soon. However, a sizeable amount of CO₂ in that mixture will still slow the burning of methane, contributing to a longer burning duration of the charge. This longer burn, when combined with the later start of ignition, results in late burning that can increase exhaust temperatures, possibly putting exhaust valves or other exhaust components at risk. In situations where late burning is a possibility, high compression ratio or cam events that emphasize a longer power stroke can help. In both cases the relatively longer power stroke will extract more work from the burning charge resulting in lower final temperatures.

3.3.2 Caterpillar Methane Number

Caterpillar's earliest work on documenting a detonation resistance scale involved the octane rating method, a tool long established for use with gasoline engines. Octane rating evaluations use a special test engine with variable compression ratio to establish the critical compression ratio (the compression ratio at which detonation occurs) for the test fuel.

Unknown fuels are tested in this engine and their results are compared to a baseline set of results for blends of iso-octane and n-heptane. The octane rating number represents the percent of iso-octane in the baseline blend that best matches the performance documented during the test of the unknown fuel.

To allow for evaluation of gases of differing compositions, each hydrocarbon fraction must be tested individually to establish constituent octane values that can then be used to compute a weighted sum result for the mixture. This approach does run into problems in that it simplifies the contributions of the individual constituents into a linear pattern from one constituent to the next. Experience over time showed that not to be the case, that the heavier fractions had more influence on the result than was represented in the linear model. Another detail that did not work well in this approach was the effects of inert gases such as nitrogen or carbon dioxide. In this initial model it was assumed these inerts simply displaced energy-bearing gases in the volume mixture, requiring a different volumetric mixture to achieve the proper air/fuel ratio for the combustible portions of the fuel. However,

experience eventually showed the inerts were capable of absorbing heat energy during combustion, dissipating that energy over a larger volume of gas than would be the case for a similar fuel with no inerts. That reduction in combustion temperature was found to have a measurable impact on the onset of detonation, an attribute not represented in the simple linear model.

Regardless, the biggest problem with using the octane rating is that octane is not an effective reference point for natural gas. Natural gas typically contains a high percentage of methane, the smallest, lightest alkane fraction. Octane is a much heavier alkane fraction with very different combustion properties, and it tends to exist as a liquid under normal conditions. These details work well for gasoline engines, but not so well for natural gas engines. This led researchers to work to develop a rating scale better suited to the constituents present in gaseous fuels.

The pioneering work on development of a methane number rating scale took place in Austria in the mid-1960s. This concept used methane as the characteristic fuel component instead of octane; methane would now represent the standard value for detonation resistance. For the contrasting component (i.e., low resistance to detonation), the researchers selected hydrogen as a very fast-burning gas. Values were assigned to each, a value of 100 for methane and 0 for hydrogen, and testing was conducted to determine the appropriate values to assign to each of the alkane fractions that would commonly be encountered in gases used as engine fuel. Caterpillar adopted this methane number (MN) scale in the 1980s, then continued to refine its calculations based on research results as well as experience with various gases in actual field applications.

Over time this basis for MN calculation showed itself to carry limitations that were not easily overcome. In 2012, a project was launched to develop a new methodology for calculating methane number. Two years of conceptual work combined with exhaustive testing produced a new algorithm that was shown to work extremely well with literally hundreds of gas compositions. This new Caterpillar Methane Number (Cat MN) calculation replaced the old method and is now in use as the sole MN calculation for Cat gas engines.

3.4 Evaluation of combustion properties

Calculating the numerous combustion characteristics of fuel mixtures can be very time consuming and tedious – ideal work for a computer. The Caterpillar Fuel Analysis tool fills this role, taking the volumetric proportions (mole percent values) as inputs and quickly calculating a whole range of useful properties, including HHV, LHV, MN, Wobbe Index, specific gravity, stoichiometric air/fuel ratio, and more. The use of a consistent and reliable

calculator for these properties is important because they form an important basis for the selection and proper application of gas engines to specific fuels.

Note that it is important to enter the constituent gas values into the Fuel Analysis tool in volume percent or “mole percent”. Many analysis labs will also provide mass percent values, which will produce erroneous results with the Fuel Analysis calculator. Another common error occurs when the lab composition analysis results are presented not as mole percent but instead as mole fraction. Using mole fraction values, the sum total of the constituents will add up to “1.00”, while using mole percent they will add up to “100%”. This is a simple difference of 2 decimal places in the values displayed, but the Fuel Analysis calculator will only understand the entered values to be in mole percent and never mole fraction. When mole fraction values are entered, they are normalized to enable the calculations, but when the results are generated the Fuel Analysis tool will issue an error warning because it will only register that 1% of the total gas constituents have been entered (1.00 mole fraction equals 1% when typed into a mole percent entry field).

4 Common natural gas types and sources

As a general categorization, the term “natural gas” covers the broad range of naturally occurring combustible gases. As a specific term it is typically used to indicate the fossil fuel retrieved from geologic formations within the Earth and consisting of primarily alkane hydrocarbons. However, combustible gases can originate from many sources, each of which carry certain similarities to gases from other sources and traits characteristic of that particular source.

4.1 Pipeline quality natural gas

While often referred to simply as “natural gas”, the term “pipeline quality” helps to emphasize a gas that has been processed for general sale into a commercial distribution system. In spite of the “pipeline” moniker, such gas does not have to be transported via pipeline to qualify as such. This “pipeline” distinction is applied to characterize such gas as meeting the generalized standards of composition (and thus properties) established for commercial natural gas. You may also hear this gas referred to as “dry” or “consumer grade” natural gas. In most cases, pipeline natural gas is the result of gas processing, the act of separating raw gas components to arrive at a generally accepted composition. This composition is not absolute because the key commercial traits of the gas are in its resulting energy content and specific gravity, and because processing to exacting standard would add production cost without benefitting the market in a significant way. Looking through a number of pipeline requirements one can arrive at this representation of a pipeline gas in the United States:

Figure 4.1

Approximate composition of pipeline gas

constituent gas	mole percent	
	minimum	maximum
Methane	75	--
Ethane	--	10
Propane	--	5
Butanes	--	2
Pentanes and heavier hydrocarbons	--	0.5
Carbon Dioxide	--	3-4
Nitrogen and other misc. inerts	--	3-4

This formulation for natural gas must commonly achieve gross heating values (HHV) of between 950 and 1150 Btu/scf, while also being free from liquids, solid particles, and other contaminants. The reference to “in the United States” is important in that it reminds us that accepted gas quality can vary for other regions of the world. As the transport of liquified natural gas (LNG) enables a more global market for gas, the interchangeability of this gas with the formulation in other market areas becomes a trait that must be watched. The focus on energy content and specific gravity are rooted in tangible commercial concerns: specific gravity affects the ability of the gas to flow through piping systems, and heating value affects the combustion performance at the point of use.

4.2 Field gas

By contrast, the term “field gas” represents the broad range of raw gas compositions that may originate from a gas well. The relative concentrations of constituents in this raw gas vary widely, not only from well field to well field, but also across wells within a particular geologic formation. From a regulatory perspective, the legal definition for field gas as found in the Code of Federal Regulations (of the United States) is “Field gas means gas extracted from a production well before the gas enters a natural gas processing plant.”

Some terms that serve as subsets of field gas include the following.

4.2.1 Wellhead gas

In the practical sense, the term wellhead gas is synonymous with field gas. It is, as the name suggests, gas as extracted directly from the well.

4.2.2 Associated gas

Associated gas refers to the subset of field gas that is extracted from a formation that is also producing liquid petroleum. This distinction is made to convey the fact that gas from such sources tends to have a pronounced presence of heavier hydrocarbons and may include significant amounts of inerts, specifically carbon dioxide or nitrogen.

4.2.3 Sour gas

The term “sour” is used to indicate gas with a presence of corrosive compounds in the mixture. The most common naturally occurring corrosive constituent in natural gas is hydrogen sulfide (H_2S). While H_2S is a combustible material, presenting very minor contributions to the properties of the overall gas mixture, it is most importantly recognized as an aggressive corrosive agent and a potent neurotoxin. For this reason, the concentration of H_2S in a sour gas is one of its important attributes as it can affect whether

the gas can be used as engine fuel without treatment or if treatment to remove the H₂S will be required.

4.2.4 Dry gas

When a gas is deemed “dry” it refers not just to an absence of water, but to the fact that all liquids have been removed from the gas. Most commonly, dry gas indicates a gas that has been through processing to remove the liquids, but there are wells that produce truly “dry” gas directly from the well.

4.3 Propane

The term “propane” is a common abbreviation for commercially available propane. Similar to what was described for pipeline natural gas, propane is a processed gas, but its actual composition will depend on the market into which it is being sold. When marketed, it is also common to see the terms “LP gas” or “LPG”, both of which are abbreviations for “liquified petroleum gas”. While these terms are often synonymous with commercial propane, they also encompass propane-butane blends.

The marketable distinction for propane or LPG is the relative ease with which it can be converted to a liquid and then back into a gas, making it easy to transport larger quantities of fuel in a relatively company container. As a gas, 1 kg of pure propane occupies 540 L (0.540 m³) at standard conditions. Converted to a liquid that 1 kg occupies just 1.96 L, a volume reduction of 275:1. Combine that with the fact that propane and butane have significantly higher heating values than methane and one can easily see the appeal of LPG as a commercial fuel, because as liquids they present the ability to easily carry significant quantities of energy in a compact space, and will remain in liquid form when contained at relatively modest storage pressures. For use, they are returned to vapor form by simply releasing them from that storage pressure to atmospheric pressure.

In North America the predominant purity standard is HD-5, considered to be “consumer grade” propane. The HD-5 standard requires at least 90% propane and a maximum of 5% propylene, with the remaining portions being similar lighter fractions such ethane or butanes. Another common grade of propane is HD-10, sometimes called “commercial propane”. While both HD-5 and HD-10 require a minimum of 90% propane, HD-10 allows a maximum of 10% propylene, more than in HD-5. Propylene’s different attributes make it a useful feedstock in the manufacture of certain plastics, but for some applications as a fuel it is limited by the propensity of propylene to leave gummy residues that can foul engine systems. HD-10 is considered acceptable in burner-type applications where the propylene residues do not have adverse effects.

Standards in use elsewhere in the world allow much greater concentrations of butane, perhaps pointing back to the distinction between “propane” and “LPG”. Various markets around the world offer LPG in mixtures ranging from 100% propane-0% butanes to 20% propane-80% butanes. This blend ratio can be important due to the differences in properties between propane and butane. Increased proportions of butane will produce an LPG with greater energy density, but that increase comes with an impact on the transition from liquid back to gas. The boiling temperature of propane is -42°C , while for butane it is -0.4°C and for isobutane it is -11.7°C . In practical terms this means that for most climates the vaporization of liquid propane remains unaffected by the local temperature. Butanes, however, can become more difficult to vaporize when certain climates turn colder, and for this reason some cold-weather markets have provisions for the LPG blend ratio (propane:butane) to change with the seasons.

Another consideration that arises when discussing LPG is the fact that it is heavier than air. By contrast methane, the major component of natural gas, is lighter than air. This can have implications when considering safety in an installation where either gas is used. Methane may dissipate upward into the air, while LPG will fall downward and potentially “pool” near the ground if obstacles are present that limit its travel.

4.4 Biogas

Biogas is the broad term used to indicate gas produced from the decomposition of organic materials. More specifically, it is the result of anaerobic digestion of those organic materials, and is commonly the produced by animal waste, plant/food waste, municipal waste, sewage, or other similar sources. Due to its origins, it is considered a renewable energy source or “green” energy.

Biogas is primarily found as a mixture of methane and carbon dioxide, with the ratio between them being a function of the biogas source. Because the proportion of carbon dioxide is relatively high, biogas is also referred to as a “low energy fuel”, since the mixture carries a much lower heating value than natural gas. Biogas may also contain small amounts of other gases, including hydrogen sulfide (H_2S) – the same H_2S that was mentioned earlier in the discussion regarding sour gas. This fact means it is also subject to the same concerns and considerations as before in dealing with its corrosive and toxic tendencies. Being from a biological process, water is also a common presence in biogas.

4.4.1 Digester gas

Digester gas is produced in an anaerobic digester, an enclosure that promotes the biochemical conversion of organic wastes to combustible gas. Perhaps the most common

use of digesters is to exploit the large volume of animal waste produced at large-scale dairy and livestock operations for energy production. This is considered a “green” process because it diverts the methane produced by the animal waste to uses where it can displace other fuels, while at the same time preventing the direct release of the methane into the atmosphere. The gas produced in the treatment of wastewater also falls in the category of digester gas.

As an engine fuel, digester gas is considered to be a moderately low-energy gas. The LHVs for digester gas tend to be in the range of 21.65-25.59 MJ/Nm³ (550-650 Btu/scf), with methane numbers around 139 to 129. Note the inverse relationship between LHV and MN is intact here; as energy content falls methane number rises. In fact, these methane number ratings illustrate the combustion buffering effect of CO₂ on methane that was described in the section 3.3.2 discussion on compression ratio. Because CO₂ can absorb enough energy to slow the burn rate of methane the effective methane number of these methane-CO₂ gases registers above the “100MN” value designated for methane alone.

Digester gas can present a presence of H₂S, which must be taken into account in planning to use the gas as fuel. Digester gas from a wastewater source can also bring with it other compounds from industrial waste, including siloxanes, which are gaseous organic silicone compounds. During combustion these siloxanes are dissociated, or broken into their constituent atoms, leaving the silicon atoms available to deposit on the walls of the combustion chamber. The resulting silicate deposits typically must be cleaned out during servicing of the engine as left unchecked their accumulation can produce an incremental change in compression ratio and can also place the valves at risk of damage or failure.

4.4.2 Landfill gas

Anaerobic digestion processes also occur within landfills, where the organic portions of the solid wastes are converted into biogas. Landfill gases carry traits similar to the wastewater digester gases described above, except with even lower ratios of methane to carbon dioxide. Thus, the LHVs for landfill gas fall even lower, in the range of 17.71-23.62 MJ/Nm³ (450-600 Btu/scf), with methane numbers around 150 to 134.

Due to an even more varied presence of industrial and post-consumer waste products, landfill gas can also present siloxanes and H₂S, and numerous other compounds bearing sulfur, chlorine, and fluorine in their makeup. These sulfur, chlorine, and fluorine atoms are also dissociated during combustion, producing ions that readily combine with the ample amounts of water vapor present to produce acids in the exhaust and blowby gases.

4.5 Coal bed methane

The methane gas presence in coal deposits is well known to miners as it represents one of the ever-present safety risks in underground mining of coal. Several names have been attached to this gas: coal bed methane (CBM), coal bed gas, coal seam gas (CSG), and coal mine methane (CMM) are among the most common.

The processes that lead to the creation and capture of this gas within the coal tend to dictate the composition of the resulting gas. CBM is primarily methane, with small amounts of carbon dioxide and trace amounts of ethane and nitrogen. This “sweet” nature extends to contaminants as well, as CBM does not characteristically include hydrogen sulfide.

4.6 Manufactured gases

Combustible gases that can serve as engine fuel can also be produced by processing non-gaseous materials. Efforts have been documented as far back as the 1700s involving the manufacture of gas, and by the 1800s such processes were in regular use to generate fuel for public lighting systems.

4.6.1 Producer and pyrolysis gases

Numerous processes were developed in the early days of gas manufacture, varying in the details of their execution but all relying on the conversion of a carbon-based feedstock into a combustible gas. Examples include:

Coal gas: An early pyrolysis process in which the coal is heated in the absence of oxygen. This “manufactured gas” or “town gas” could contain proportions of methane, hydrogen, carbon monoxide, ethylene, and acetylene, in addition to aromatic gases from coal tars, ammonia, and hydrogen sulfide.

Wood gas: Another pyrolysis process, this time using wood as the feedstock. The resulting gas was a very low energy content mixture of methane, hydrogen, carbon monoxide, and organic compounds such as turpentine.

Oil gas by pyrolysis: Pyrolysis of petroleum feedstock, producing a mixture of methane, propane, hydrogen, ethylene, acetylene, and carbon monoxide.

Oil gas by catalysis: Partial reaction of petroleum feedstock with steam and a catalyst. Produced gas largely composed of hydrogen and methane, with much smaller amounts of longer chain hydrocarbons and carbon monoxide.

Producer gas: Coal gas produced by partial combustion at very high temperatures with limited oxygen present. Resulted in a weak gas, high in nitrogen and carbon monoxide but with enough hydrogen and methane to be combustible.

Water gas: Coal feedstock is heated to high temperatures then reacted with steam in the absence of oxygen. Produced a gas high in carbon monoxide and hydrogen. The process was later augmented by reacting the superheated water gas with coal tar to produce methane other fractional hydrocarbon gases.

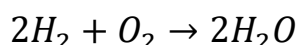
4.6.2 Syngas

“Syngas” (short for “synthesis gas”) is a mixture of hydrogen, carbon monoxide, and some carbon dioxide that serves not only as a combustible gas itself, but also as an important intermediate product in the production of synthetic natural gas, ammonia, or methanol. Syngas production involves the processing of a carbon feedstock to produce the gas, with a common source being coal gasification.

4.7 Hydrogen

Hydrogen is perhaps the simplest of gaseous fuels. It is the most basic of elements, with atoms consisting of just one proton and one electron, while at standard conditions it forms a gas of simple diatomic molecules (H_2).

Hydrogen combustion is also quite simple:



As with other gaseous fuels this combustion equation represents just the underlying reaction. In the real-world the oxygen would be supplied by air and the high temperature of combustion would produce some nitrogen oxides (NO_x) from the nitrogen in the air. But the lack of carbon dioxide and other hydrocarbons as byproducts make it a very attractive option as a fuel. It also can be used without combustion, as hydrogen is readily usable in a fuel cell to directly produce electricity.

It is important to realize gaseous hydrogen is not readily obtained from the natural world. Instead, some process must be applied to produce hydrogen gas, and typically those processes require energy to proceed. For these reasons it can be appropriate to view hydrogen as a means of transporting energy. Energy from one source may be used to generate hydrogen, which then can be converted back to another useful form – as power from an engine or as electricity from a fuel cell. Steam reforming of methane is a common method for mass-producing hydrogen, but because the input gas is a hydrocarbon there are still carbon byproducts (CO and CO_2) that must be managed to eliminate greenhouse gas

emissions. Electrolysis of water is another simple process available to capture hydrogen, but it requires a significant energy input.

These aspects of hydrogen production, the inputs in materials and energy, form the basis for categorizing produced hydrogen. A color code system has been adopted for these categories to specify the method and the energy source involved.

Figure 4.2

Hydrogen gas color codes

color	input	energy	process	byproducts
brown / black	coal	conventional	reformer	CO ₂ released
white	--	--	--	--
gray	natural gas	conventional	reformer	CO ₂ released
blue	natural gas	conventional	reformer	CO ₂ captured+stored
turquoise	natural gas	conventional	pyrolysis	C captured as a solid
red	water	nuclear	catalytic	O ₂
purple / pink	water	nuclear	electrolysis	O ₂
yellow	water	solar	electrolysis	O ₂
green	water	renewable	electrolysis	O ₂

At the time of this writing, hydrogen as a global energy source is still in its infancy. Current uses for hydrogen are in industry (petroleum, steel, ammonia, and methanol production) and in transportation, where infrastructure availability is a limiting factor. Much of the currently available hydrogen is produced from natural gas, coal, and oil, in the upper portion of this color table, while the biggest environmental gains are realized in the codes in the lower portion of the table. Advocates for hydrogen are pushing for developments on multiple fronts to advance its use: advancements in regulations, production methods, and delivery infrastructure are all necessary to achieve significant environmental gains.

An intermediate step for hydrogen use is also in its early stages. Blending natural gas with hydrogen effectively displaces some of the hydrocarbon consumption of existing natural gas engines, proportionately lowering the carbon emissions from those sources. As a near term activity this approach is promising because it doesn't require large-scale replacement of drivers (engines) to realize – assuming those engines are capable of adapting to the blended gas with minimal modifications. Research on this is advancing rapidly and is best followed through the announcements regarding the engines themselves.

5 Fuel gas conditions and contaminants

The conditions of the fuel gas as it is presented to the engine can make a difference, in both the performance and longevity of the engine. Excessively high or low gas temperatures or pressures can affect the engine in various ways, as can fluctuations in supply pressure. Managing each of these fuel attributes is important to the success of each installation.

Fuel contaminants are substances that don't assist in the engine's task of converting fuel energy to mechanical power. They take the form of gases, liquids, and solids, and thus can damage the engine through a broad range of attacks, including corrosion, abrasion, and deposit formation. The best means of limiting the risk of damage from fuel contaminants is to eliminate them altogether. However, for many applications that approach may be impractical due to costs or logistics.

This section of the Guide presents information on limits pertaining to fuel conditions and common fuel contaminants, as they relate to various engine models.

5.1 Fuel gas conditions

The temperature and pressure conditions allowed at the inlet of a gas engine form the most basic of guidelines for the engine's fuel supply, and yet they are not represented as a single set of numbers that apply to all gas engine models. Design choices made for each engine can create circumstances that drive limits particular to that engine (or engine family).

The most generally applicable guideline for fuel gas condition is for temperature. Standard Cat guidelines require fuel gas temperature at the engine's inlet to be within the following limits:

Figure 5.1

Fuel gas general temperature limits

Gas temperature at engine inlet	°C	°F
minimum	10	50
maximum	60	140

These limits consider the simultaneous effects of temperature on the materials found in the on-engine fuel systems and on the physical properties of the fuel as it travels through those fuel system components. Extremes in temperature may impact the service life of certain materials, while the fuel density resulting from those temperatures may impact the

performance of the fuel-air mixing components. The temperature-pressure conditions of the fuel may even raise the possibility of phase change (condensation) occurring as the fuel moves through the system.

The pressure condition required at the engine inlet is fundamentally tied to the design of the engine's fuel system. The presence or absence of a turbocharger is one such design issue; another is whether the fuel and air are mixed upstream or downstream of the turbocharger. These details create a basic separation of gas engines into "low pressure gas" and "high pressure gas" designs. The turbocharged gas engines in which the fuel and air are mixed downstream of the turbo represent the high pressure gas engine group, where higher fuel pressures are necessary to allow the fuel to be introduced into the pressure-boosted air flow from the turbo. The non-turbocharged (or "naturally aspirated") gas engines, along with the turbocharged engines in which fuel and air are mixed upstream of the turbo, form the low pressure gas contingent where lower gauge pressures are permissible because of the absence of turbocharger boost. The particulars of each engine dictate the pressure requirements that apply to each; thus, the allowable fuel inlet pressure range must be obtained from the specifications for each engine individually. A more generally applicable fuel pressure characteristic is the pressure stability or fluctuation allowed in the fuel gas supply. The general guideline for allowable fuel gas pressure fluctuation is:

Figure 5.2

Fuel gas pressure fluctuation limit

Gas pressure fluctuation at engine inlet	kPag	psig
maximum	±1.7	±0.25

Additional detail on fuel system designs may be found in the Gaseous Fuel Systems A&I Guide, publication number LEBW5336. Please note that any specifications published for particular engine models will supersede these general requirements.

5.2 Solid contaminants

Solid particles entrained in the fuel gas flow are easily understood as contaminants, as their effects on the system are straightforward. Particles in the fuel may inhibit the operation of moving parts or contribute to reduced service life through abrasive wear. Limiting particulates from affecting engine performance requires that they not be allowed to enter the engine to begin with. This is the role of the fuel filter. Particulate limits are established for both particle size and for quantity admitted:

Figure 5.3

Fuel gas particulate limits

Particulates at engine fuel inlet		
Maximum mass concentration allowed	0.80 mg/MJ	0.84 µg/Btu
Maximum particle size	1 micron	

Filtration techniques for particulates in the gas stream may involve centrifuges or filtration media, with canister-style filters being common.

Under specific circumstances it is possible for solid particles to be formed from gaseous compounds in the fuel. While the formation of hydrates is an issue commonly addressed in pipeline management, hydrates are rarely an issue to be dealt with in the scope of the fuel supply to the engine. Water content in the fuel can become a solid particle concern if the temperature drop in the fuel flow is sufficiently large as to cause the water to freeze into ice crystals. As an uncommon example of a solid contaminant, elimination of ice crystals would differ from the filtration strategy used for conventional particulates; ice crystal solutions would typically involve addressing the conditions that led to their formation, often through the use of a fuel heater upstream of the engine inlet.

5.3 Liquid contaminants

Liquids also are to be viewed as contaminants in gaseous fuels. This perspective relates both to what each liquid compound is and for the fact that they are present in a liquid state. Liquids present a challenge a bit different from particulates due to the fact that liquids are more readily derived from the compounds that make up the fuel gas stream. As pressure management is a normal requirement for a fuel supply system, changes in the temperature and pressure of the fuel gas flow are also common, and such changes in temperature and/or pressure can be the cause for parts of the gas stream to change into liquids.

Water is a common, naturally occurring component of raw field gas, making “de-watering” of the gas a common step soon after the gas leaves the wellhead. However, even if the liquid water is removed at this early step, it is possible for water vapor to condense into liquid further down the fuel piping system. Water that enters the engine poses a threat of corrosion if it reaches bare metal surfaces, or of emulsification into the lubricating oil if it reaches the oil sump.

It is also possible for alkane hydrocarbons to condense into liquids due to temperature-pressure changes in the gas stream. While relatively uncommon, raw gas sources with very high starting pressures that are then throttled down to the levels required by the individual engine can potentially lead to the formation of hydrocarbon liquids. Droplets of liquid hydrocarbons represent localized concentrations of fuel energy that can re-vaporize in the cylinder to create “hot spots” (a detonation risk due to localized richening of air/fuel ratio) and carbon deposits.

Similar to solid particles, the state difference between liquid and gas makes separation and removal relatively straightforward. Liquids may also be separated using centrifuges or physical media, the media involved is commonly a *coalescer*. Coalescing is the process of accumulating many tiny droplets into larger drops that are more easily separated from the gas stream. Standard and custom designs are available from many vendors, although the techniques used often involve the same strategies: centrifuging, impingement, mesh pads, and coalescing filters that repel both liquids and solids.

5.4 Gaseous contaminants

Gaseous fuels may also contain substances in gaseous form that can have detrimental effects on the engine. Compounds such as carbon dioxide or nitrogen do not contribute to combustion but are chemically inert, meaning “non-reactive”, and thus aside from taking up space in the combustion chamber are largely benign to the engine’s operation. Other compounds, however, may be corrosive, toxic, or highly reactive and thus must be limited in the concentration in the fuel gas.

Corrosive compounds in the fuel gas can attack components made of susceptible metals. Such metals include copper and aluminum, and for that reason are often referred to as “bright” metals. Susceptible components include aftercooler cores and fuel train components that are not manufactured with corrosion-resistant materials. Engines may be configured to improve their resistance to corrosive gases by using corrosion-resistant materials where contact with gas is to be expected. Engines configured in this manner may carry higher limits for exposure to corrosive gases.

Following combustion, the characteristic elements of these compounds (sulfur, chlorine, fluorine, etc.) become dissociated from their original molecules, leaving free radical ions available to recombine. In this high temperature, high moisture environment, the result is often acids that carry the opportunity for corrosive attack to other areas of the engine. While components of the exhaust system are often less susceptible to corrosion than those found in a standard engine intake, these combustion gases also escape into the crankcase in the

blowby gas. Condensation of these acids in the oil sump allows them to travel to other susceptible components, such as oil coolers, bronze or brass bearings or bushings, and any other internal engine component constructed of bright metals.

The following sections discuss these various contaminant groups based on the element present that creates the risk to the engine. The fact that these contaminant compounds are present as gases drives how the allowable limits for each are expressed, as well as how they may be measured on an actual site. Due to the compressible nature of gases, it is most convenient to express the limits in terms of mass as it is a property that is directly linked to the quantity of the substance that is present. However, direct measurement of the concentration of a substance in a gas stream is most commonly achieved in terms of volume fraction, the proportion of the volume that is the measured substance. Fortunately, some identities from basic chemistry enable conversion from volume to mass relatively easily, making it possible to convert on-site volume fraction measurements into mass concentrations that can be directly compared to the published limits.

The key piece in this conversion is the Ideal Gas Law. Under this law many gases may be accurately approximated using a single set of equations due to its underlying assumption that molecular size and molecular interactions may be neglected. Accepting those conditions allows the use of an identity that states an Ideal Gas occupies 22.41 L/mol at standard temperature and pressure conditions of 0°C and 1 atmosphere. This identity may be used in conjunction with the molar mass of the substance in question to arrive at an accurate approximation of the mass of the substance present for a given volume measurement.

The final piece needed for this limit construct is an understanding of how much of the contaminant the engine will ingest. There are many factors that establish the fuel consumption rate of the engine, but because energy content of the fuel plays a direct role in consumption rate, it is useful to express the limit as “quantity of contaminant compound per unit of fuel energy”. In this form, limits expressed as the mass of the contaminant per unit of energy in the input fuel provide the most adaptable measure, able to accommodate many of the variables that exist among engine designs and their real-world applications. Put simply, combinations of engines and applications that require more fuel to operate will ingest more of the contaminant as well, and this increased intake is addressed by these sorts of limits.

Putting all these pieces together, on-site measurements of volume fraction concentrations of a specific compound may be compared against the mass per energy limits by calculating the mass contribution of each contaminant present.

This volume to mass conversion will look like this:

$$\frac{\text{volume fraction} \times \text{atoms per molecule} \times \text{mass per mole of atoms}}{\text{volume of one mole} \times \text{LHV of the fuel gas}}$$

with the result being the mass per unit energy concentration of the measured compound. It is important in such a calculation to be certain all the appropriate units are in place on each value. Apply unit conversions where needed to get to the proper results.

It is common to see field measurements on of a substance in a gas stream as a proportionate measure: say, parts per million by volume (ppmv), or for even smaller concentrations parts per billion by volume (ppbv). Like percent by volume, these measurements greatly simplify discussing very small concentration levels by disposing of the many decimal places that may be present if they were expressed just as a decimal fraction. For reference, here are these common units expressed as decimal values:

- 1% by volume = 0.01
- 1 ppmv = 0.000001
- 1 ppbv = 0.000000001

From this comparison it should be easy to see that any conversions from or among these units will require adjusting for the decimal place differences.

To illustrate this approach in use, consider these examples:

Hydrogen sulfide (H₂S) concentration of 200 ppmv in a fuel gas of LHV = 1100 Btu/scf.

$$\frac{(0.000200) \times (1) \times (32.065 \text{ g/mol}) \times (10^6 \mu\text{g/g})}{(22.41 \text{ L/mol}) \times (1100 \text{ Btu/scf}) \times (\text{scf}/28.32 \text{ L})} = 7.37 \mu\text{g/Btu of S}$$

Carbon tetrachloride (CCl₄) concentration of 66 ppbv in a fuel gas of LHV = 19.68 MJ/Nm³:

$$\frac{(0.000000066) \times (4) \times (35.453 \text{ g/mol}) \times (10^6 \mu\text{g/g})}{(22.41 \text{ L/mol}) \times (19.68 \text{ MJ/Nm}^3) \times (\text{m}^3/10^3 \text{ L})} = 21.22 \mu\text{g/MJ of CCl}_4$$

The method easily adapts to different contaminant compounds and fuel energy values. The keys are in having the correct values for molar mass and LHV to use in the calculation.

Note the conversion factor used on units of volume in each example. Such information is typically easy to find from sources on the Internet or in other references.

5.4.1 Sulfur compounds

Sulfur compounds may be naturally occurring, the result of decomposition of organic materials. They do appear in some field gases (such fields are termed “sour gas”) and also are common in biogas. The most frequently encountered sulfur compound is hydrogen sulfide (H_2S , spelled “sulphide” in some regions of the world). It is a mildly flammable gas that is corrosive and highly toxic.

Other sulfur compounds are also possible, particularly in landfill gas where the compounds may result from both organic decomposition and from industrial/consumer wastes. The table below lists some of the more commonly encountered sulfur compounds that may be found in fuel gases. The chemical formulas presented for each reveal another consideration for these compounds – some of them have more than one sulfur atom per molecule. This means those compounds introduce twice the sulfur than do the compounds with just one atom per molecule.

Figure 5.4

Some sulfur compounds found in fuel gases

Compound name	Chemical formula	Atoms in molecule
carbon disulfide	CS_2	2
carbonyl sulfide	COS	1
dimethyl disulfide	$(\text{CH}_3)_2\text{S}_2$	2
dimethyl sulfide	$(\text{CH}_3)_2\text{S}$	1
ethyl mercaptan	$\text{CH}_3\text{CH}_2\text{SH}$	1
methyl mercaptan	CH_3SH	1
hydrogen sulfide	H_2S	1

As noted in the general description of gaseous contaminants, a greater concentration of sulfur in the fuel gas results in a higher rate of sulfur introduced into the engine. This principle underlies limits established for each engine model or family, that the sulfur concentration per unit of energy is the core limit.

Figure 5.5

Sulfur concentration limits expressed as ppmv

engine series	aspiration	configuration	standard hardware	special hardware
G3300/G3300B	NA	LPG	0-50	--
G3300/G3300B	TA	LPG	0-10	0-50
G3300/G3300B	TA	HPG	0-10	0-50
G3400	NA	LPG	0-50	--
G3400/CG137	TA	LPG	0-10	0-50
G3400	TA	HPG	0-50	--
G3500 ("A" series)	NA	LPG	0-50	--
G3500 ("A" series)	TA	LPG	0-10	0-50
G3500 ("A" series)	TA	HPG	0-50	--
G3516 ("A" series)	TA	Landfill	60 µg/Btu	
G3500B/G3500J	TA	Petro	0-50	0-500
G3500B	TA	EP gen set	0-3	0-20
G3500C	TA	EP gen set	0-3	0-20
G3520C	TA	Landfill	60 µg/Btu	
G3500E	TA	EP gen set	0-3	0-20
G3500H	TA	EP gen set	0-3	0-20
G3600	TA	A3 models	0-10	0-1300
G3600	TA	A4 models	0-10	0-1000

NOTE: "LPG" = low pressure gas fuel system "HPG" = high pressure gas fuel system

The table above provides helpful reference values for the sulfur limits expressed as ppmv of H₂S. However, the chart on the following page displays the underlying core limits for sulfur concentration in the fuel gas, expressed as "mass per energy" units. It is important to understand the mass per energy limit values are the rule, while the ppmv concentrations are approximations of those mass per energy values. This chart illustrates the key relationship for using ppmv as a proxy for the actual mass per energy limit value, in that there is a characteristic LHV indicated for each limit. Above the characteristic LHV the ppmv concentration is held constant, while below that LHV the ppmv value declines on a "sliding scale" slope. This sliding scale once again reflects the increased ingestion of contaminants resulting from low fuel energy content.

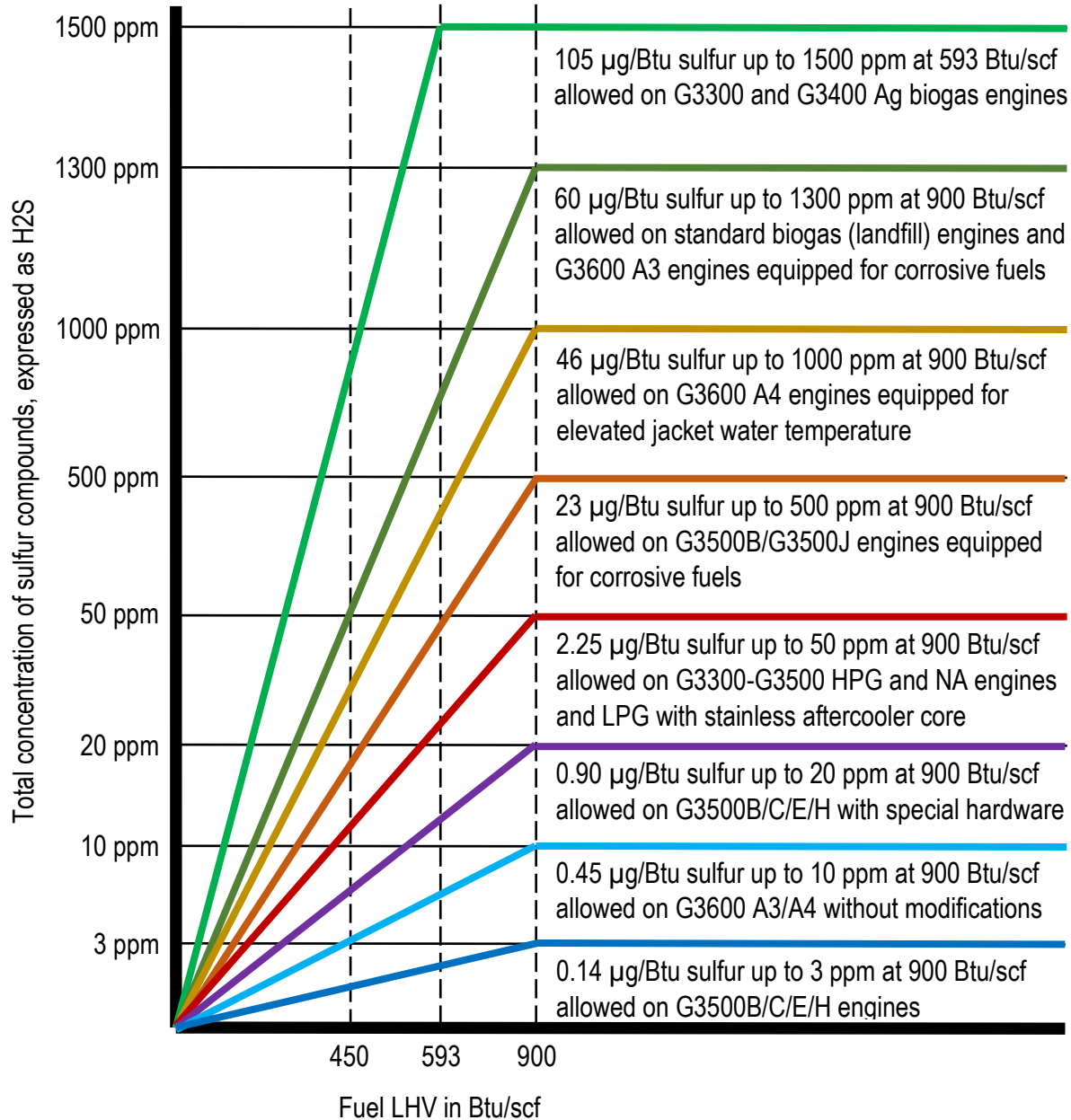


Figure 5.6

Maximum levels of sulfur compounds in fuel gas

This chart shows the expressed concentration limits for sulfur in fuel gas for many engine groups. For each concentration limit, the mass per energy value is stated at a characteristic LHV value and is charted as its equivalent ppmv limit at that LHV value. Following the protocol explained earlier, that ppmv value is held constant for LHV values greater than the characteristic and declines on a sliding scale for LHV values less than the characteristic. If there are questions regarding the compliance of a particular fuel to a particular engine, consult with Caterpillar for a specific recommendation. Graphed relationships are not to scale.

Mass per energy unit conversion: To get mg/MJ, multiply μg/Btu times 0.9478

5.4.2 Halide compounds

Halide compounds form from the negative ion form of halogen atoms. More common examples of these halide anions are fluoride, chloride, bromide, and iodide. They each form binary acids when the halide ions combine with hydrogen ions. Dissolved in water they all dissociate into ionic form, realizing their potential as corrosive agents that can damage the engine. Engines exposed to higher concentrations of hydrochloric acid (HCl) or hydrofluoric acid (HF) have shown accelerated degradation of piston rings, cylinder liners, valve stems, and valve guides.

Halide compounds have common uses in industry and thus are often found in landfill gas. As an example, chlorofluorocarbons (CFCs) have been widely used as solvents and refrigerants and thus may be present in paint thinner and degreasing compounds as well as refrigerators or air conditioners. Because they are significant greenhouse gases, CFCs are being managed more closely than in the past but still may be present in landfill gas. CFCs subjected to combustion within the engine tend to release both chlorine and fluorine ions for recombination into acids.

Many standard engine configurations are not equipped to tolerate the acids formed from halides and tolerance limits for standard configurations are considered to be zero. Special fuel system configurations have been developed for landfill applications to provide some protection from halide attack. Even so, the halide limit for these special configurations is low: 20 µg/Btu (19 mg/MJ) for total halide content represented as chlorine (Cl).

This last statement, “represented as chlorine”, illustrates a challenge posed by halides, that there may be different ionic elements present (fluorine, chlorine, bromine, iodine). The conversion to their equivalent mass represented “as chlorine” is important to enabling a single limit value, without which assessing the limit would be even more complicated.

Consider just two example CFC compounds: dichlorodifluoromethane (CCl_2F_2) and vinyl chloride ($\text{C}_2\text{H}_3\text{Cl}$). As shown earlier, the number of halide atoms in the molecule of each compound must be considered when applying this limit. To simplify things, each of the halides will be considered to contribute an equal potential for acid attack. In this way, the number of atoms found in each compound may be added to the total with only the need for evaluating each using its own molar mass. Looking at these example compounds, the vinyl chloride requires only the evaluation of the single chlorine atom, while the dichlorodifluoromethane requires two evaluations, one for the two chlorine atoms and another for the two fluorine atoms. Given the dissimilar molar mass of chlorine and fluorine, these evaluations are simplified by simply counting the atoms, in effect treating each halide ion as being equal to each other halide ion.

As an example, a gas sample is measured to contain 10 ppm C_2H_3Cl and 20 ppm CCl_2F_2 . The concentration calculation would account for the single halide atom in the first compound and for the four halide atoms in the second compound:

$$(1 \times 10 \text{ ppmv } C_2H_3Cl) + (4 \times 20 \text{ ppmv } CCl_2F_2) = 90 \text{ ppmv equivalent total halides}$$

This effective ppmv can then be converted to a mass equivalent “as chlorine” using the same calculation presented earlier:

$$\frac{(0.000090) \times (1) \times (35.453 \text{ g/mol}) \times (10^6 \mu\text{g/g})}{(22.41 \text{ L/mol}) \times (550 \text{ Btu/scf}) \times (\text{scf}/28.32 \text{ L})} = 7.33 \mu\text{g/Btu of Cl}$$

By this approach the relationship between ppmv and the core mass per energy limit of 20 $\mu\text{g/Btu}$ (19 mg/MJ) as chlorine is made simple, enough so that a simple sliding scale chart may be constructed.

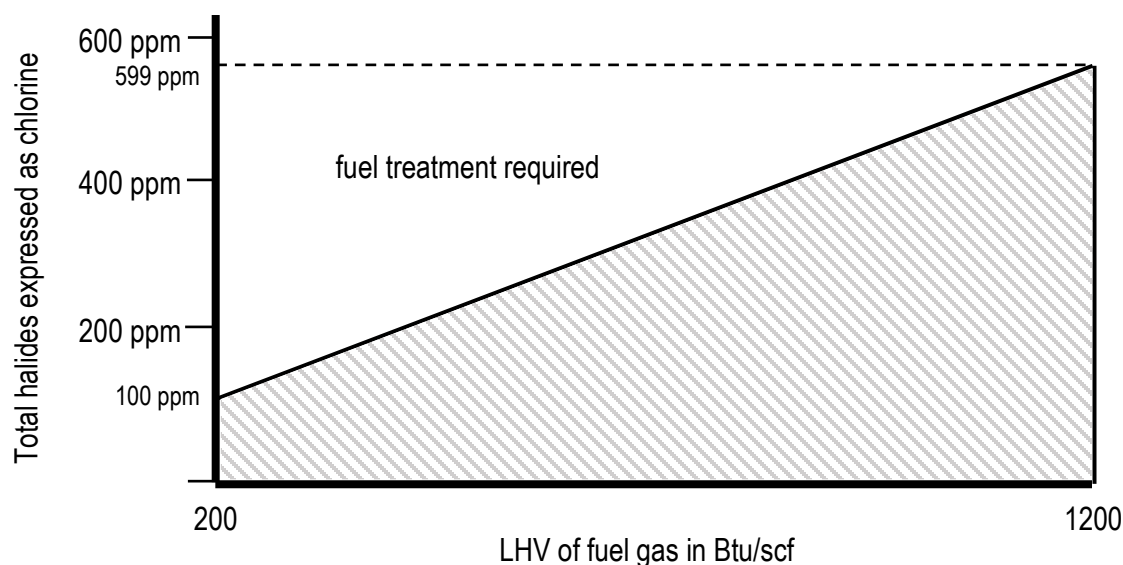


Figure 5.7

Maximum levels of halide compounds in fuel gas

While this chart won't serve as a replacement for the actual calculations, it does serve to highlight how this concentration limit varies with fuel LHV. Halide concentrations below the line (the shaded area) are considered acceptable while levels above the line should be treated to reduce the concentration to an acceptable level.

Figure 5.8

Halide compounds and their multiplier factors

compound	chemical formula	total atoms Cl, F, Br
1,1,1-trichloroethane	C ₂ H ₃ Cl ₃	3
1,1,1-trichloropropane	C ₃ H ₅ Cl ₃	3
1,1,1,2-tetrachloroethane	C ₂ H ₂ Cl ₄	4
1,1-dichloroethane	C ₂ H ₄ Cl ₂	2
1,1-dichloroethene	C ₂ H ₂ Cl ₂	2
1,2-dichloropropane	C ₃ H ₆ Cl ₂	2
1,2,3-trichloropropane	C ₃ H ₅ Cl ₃	3
2-chloroethylvinylether (chloroethoxyethanol)	C ₄ H ₉ ClO ₂	1
Bromodichloromethane	CHBrCl ₂	3
Bromodifluorobenzene	C ₆ H ₄ BrF	2
Bromoform (tribromomethane)	CHBr ₃	3
Bromomethane (methyl bromide)	CH ₃ Br	1
Carbon Tetrachloride	CCl ₄	4
Chlorobenzene (phenyl chloride)	C ₆ H ₅ Cl	1
Chlorodifluoromethane (Freon-22)	CHClF ₂	3
Chloromethane (methyl chloride)	CH ₃ Cl	1
Chloropropane (n-propyl chloride)	C ₃ H ₇ Cl	1
Chlorotoluene (benzyl chloride)	C ₇ H ₇ Cl	1
cis-1,3-dichloropropane	C ₃ H ₆ Cl ₂	2
Dibromochloromethane	CHBr ₂ Cl	3
Dichlorodifluoromethane (Freon-12)	CCl ₂ F ₂	4
Dichloromethane (methylene chloride)	CH ₂ Cl ₂	2
Pentachloroethane	C ₂ HCl ₅	5
Tetrachloroethene (tetrachloroethylene)	C ₂ Cl ₄	4
trans-1,3-dichloropropane	C ₃ H ₆ Cl ₂	2
Trichlorobenzene	C ₆ H ₃ Cl ₃	3
Trichloroethene (trichloroethylene)	C ₂ HCl ₃	3
Trichlorofluoromethane (Freon-11)	CCl ₃ F	4
Vinyl Chloride (chloroethene)	C ₂ H ₃ Cl	1

Chlorinated hydrocarbon and chlorofluorocarbon gases are in relatively low concentrations within landfill gas; however, their affect can be great. The most widely used test to determine gas concentration is the EPA624 test for volatile hydrocarbons. This EPA water standards test has been adapted for measuring gases. The EPA624 test is acceptable for determining the chlorine level provided the minimum threshold of detectability is 5 ppmv. This test has shown variability from laboratory to laboratory.

Caterpillar has developed a laboratory test for measuring the levels of halogens within a sample of landfill gas. The sample, including the halogenated organic compounds, is oxidized in a CO₂ and O₂ atmosphere. The hydrogen halide by-product of the pyrolysis is measured electrically using microcoulometric titration. The accuracy of this equipment is $\pm 0.002\%$, not including inaccuracy introduced at the sample withdrawing and depositing.

If the chlorine, fluorine, or bromine level exceeds the maximum shown in Figure 5.8, fuel treatment is required. Chlorine and fluorine are water soluble and are frequently carried into the engine by water vapor. Removing the water vapor by drying the fuel will reduce halogen levels. For more information, see the section on fuel system design in this manual.

5.4.3 Nitrogen compounds (ammonia)

Natural gas fuel may contain nitrogen compounds that can combine to form base (alkaline) compounds in the presence of hydrogen. The two compounds of greatest concern are ammonia (NH₃) and acrylonitrile (C₃H₃N). Acrylonitrile can easily be converted into ammonia in a gaseous fuel.

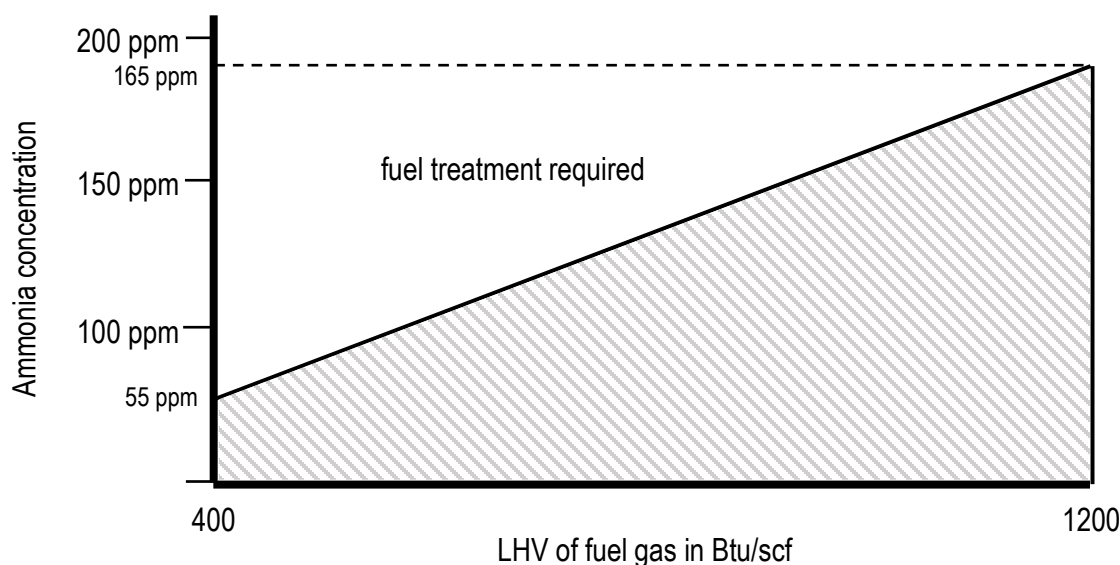


Figure 5.8

Maximum levels of ammonia in fuel gas

A standard engine configuration cannot tolerate ammonia at any concentration; it can cause serious damage to the engine. Special fuel system configurations were developed for landfill applications that provide some protection from ammonia. These special configurations have a concentration limit of 2.96 µg/Btu (2.81 mg/MJ) of NH₃. For purposes of calculations the molar mass of NH₃ is 17.031 g/mol. Using this mass, a ppmv equivalence chart can be constructed for nitrogen compound concentrations expressed as ammonia.

5.4.4 Silicon compounds

Silicon is commonly associated with solid materials. As the second most abundant element on earth it is commonly found in hard mineral form: sand, quartz, flint, granite, glass, clay, and mica are all silicon-bearing substances. If such materials enter the engine they can cause abrasive wear, as explained in the earlier section regarding solid contaminants. While most of these materials that originate in the environment around the installation will be addressed in the filtration described in the section on solid contaminants, landfill gas in particular can carry sub-micron sized silicate particles in through the fuel system. These particles start small enough to pose little risk of contributing to abrasive wear, but they are capable of combining with other elements to form larger particles that may be of concern. This is particularly true of some components of the oil additives; thus, oil sampling should include measurement of the level of silicon in the oil.

Silicon compounds can also exist in gaseous form, with perhaps the most common example being siloxanes. Siloxanes are organic compounds composed of silicon, oxygen, and methyl groups with structural units of $-(CH_3)_2SiO-$ and molecular weights typically in the range of 150 to 600. Solubility decreases as the molecular weight increases. Siloxanes may be volatile or nonvolatile. They are not regulated by the U.S. Environmental Protection Agency (US EPA) as a volatile organic compound (VOC) because siloxanes have been shown not to contribute to the formation of ground level ozone. Siloxanes are common components in products such as shampoos, cosmetics, detergents, pharmaceuticals, ink, lubricants and adhesives. A solid antiperspirant may contain 50% siloxanes. Siloxanes are found wherever consumer waste and sewage sludge are discharged, and hence are common in landfill gas or sewage treatment plant digester gas.

During combustion, the siloxane molecules break down, freeing the silicon and oxygen molecules to combine with various other elements present in the cylinder during combustion. Such combinations will often form deposits inside the volumes exposed to combustion gases, mostly as amorphous compositions of silica (SiO₂) and silicates. Analysis has shown these deposits have a high level of silicon plus elements commonly

found in oil additives and wear metals from the engine: calcium, sodium, sulfur, zinc, iron, copper, and others. Deposits caused by siloxanes will tend to be white to tan or gray in color, granular or flaky in nature, and can become thick. The deposits are extremely hard and cannot be easily removed by chemical or physical means.

Deposits can appear in the combustion chamber, exhaust manifold, turbine, exhaust stack, and even catalyst equipment. Deposits can form on the valve faces, which can result in excessive valve recession due to the grinding action of the silica on the valve and valve seat. Such deposits may also lead to valve guttering if a portion of thick deposit on the valve face chips away, leaving a leak path for the combustion gases. At very high temperature and pressure, the combustion gases become a torch that erodes (literally melts) away a portion of the valve face, leaving a permanent gap that disables the valve from sealing. It has been shown that guttering occurrences on engines with deposits can be decreased by loading the engine slowly over a 20- to 30-minute period. This allows time for the temperature of the deposits to increase, changing their consistency from brittle to plastic, lowering the risk of chipping. Deposits on the turbocharger turbine wheel can also chip or flake, and the resulting imbalance can cause bearing failure. Even if deposits on the turbine wheel remain intact, they can lead to erosion as the clearance gap between the wheel and housing is filled with silicate materials. Deposits may also mask catalyst or heat recovery equipment located in the exhaust stream.

The maximum amount of silicon permitted in the fuel gas is shown in the table below.

Figure 5.9

Maximum levels of silicon in fuel gas

Silicon in fuel gas	mg/MJ	µg/Btu
Standard configuration engines	0.1	0.1
Special configuration engines	0.58	0.60

For gaseous silicon contaminants, the “special configuration” engine noted above are functionally restricted to engines designed for landfill gas use. Silicon levels in landfill gas vary throughout the landfill’s useful life, thus testing is recommended at the beginning of the project and subsequently at 6-month intervals until the silicon level is stabilized. After the silicon level stabilizes, testing is recommended if any deposits accumulate in the exhaust or combustion chamber.

Testing for silicon compounds requires specialized equipment. Collection of gas samples for trace silicon analysis must be done with great care due to the common presence of silicon in the environment. The sample should be taken immediately before the gas delivery to the engine. During sampling a fixed amount of gas is passed through an absorption agent (typically mineral oil), which is then sent to a lab to measure the total amount of siloxane compounds.

Caterpillar has developed gas sampling equipment for siloxane and halogen measurements. It may be used to accurately collect and meter gas for the mineral oil sampling method. The kit contains three containers of mineral oil and a system to pass a fixed amount of gas through the mineral oil. The exposed mineral oil is then sent to a laboratory for testing. This kit will also gather gas in a bag for halogen and hydrogen sulfide content tests.

If the total silicon level in the sample exceeds the limit shown in the table above, gas treatment is required. Conventional filtering systems will not remove siloxane from the landfill gas. Siloxanes are solvent soluble but are only water soluble to a limited extent. It is for this reason that drying the gas of water will only remove a portion of the siloxane that may be present in a gas stream. However, refrigeration of the gas will reduce the level of siloxanes in the gas. For the most common siloxanes, D4 and D5, reduction of the gas temperature from 43.3°C (110°F) to 4.4°C (40°F) should result in an approximate 95% reduction in siloxane level. A limited number of sites have employed refrigeration as a means to control siloxanes and this technique appears to be effective.

On G3500 engines, use of “water wash”, or water injection into the engine, has been shown to reduce silicate deposit buildups. Water sprayed into the intake vaporizes in the combustion process, cleaning deposits from the combustion chamber. Water injection has been used to clean existing buildups as well as to control additional buildups. Injection rates vary from 4 to 16 liters (1 to 4 gallons) of water per hour of engine operation. A spray mist of water is injected downstream of the turbocharger. The water must be clarified by reverse osmosis as raw water can result in mineral deposits throughout the engine. Caution must be used if water injection is used to clean existing buildups as pieces of a deposit may break loose, and damage valves or turbochargers. Use low water injection rates until deposits are removed. The factory can provide further guidelines regarding water wash.

5.5 Operation on corrosive fuel gas

Operation of a gas engine on fuel that contains corrosive compounds must be managed carefully to minimize the impact of the fuel on service intervals and service life. The best

option is to utilize an engine configured for such fuels: landfill or low energy fuel generator sets or corrosive-fuel-configured petroleum/industrial gas engines provide this capability. These corrosive-tolerant engine configurations rely on modifications to area on the engine that will be exposed to the corrosive gas or its combustion byproducts. Fuel systems that mix the fuel and air upstream of the aftercooler will use a stainless-steel aftercooler core to provide resistance to corrosive attack.

Some engine models can operate with an elevated jacket water temperature (this capability is not available to all engine families). Maintaining the jacket water coolant at a higher temperature increases the temperature in the block and thus around the oil sump, both critical areas where corrosive compounds can condense into acids if the standard cooling temperature were used. The elevated temperatures help to limit such condensation and thus prevent acids from being circulated through the lubricating oil system where they can reach and attack sensitive internal components.

This same mechanism of condensation in the crankcase while temperatures are lower also points to start-up and shutdown as engine operation phases of particular concern. During start-up the engine will not have reached its operating temperature and thus will present an increased opportunity for condensation in the crankcase. Similarly, shutdown represents a phase when the gases enter the crankcase that will remain there during the engine's down time. One strategy to help limit acid exposure is to use sweet gas during start-up and shutdown, switching to the primary fuel in between for normal operation. The absence of the corrosive components in the fuel during those two critical phases can be very beneficial in limiting exposure to acids.

Crankcase ventilation is also a key component in managing the fumes present in the crankcase. Forced or "positive" crankcase ventilation ensures the vapor volume above the oil fill is exchanged in regular intervals to limit the resident time of the corrosive vapors. Similarly, the lubricating oil itself should be selected for its formulation for corrosive gas applications. Such oils may be labeled for landfill or other similar applications but will have a focus in the additives toward managing the added acid presence of such fuels. While there is no additive that can prevent acid attack, the ability to neutralize the acids does help to limit exposure time inside the engine.

Appendix A – Physical properties of gases

Table A: Physical Properties of Gases (English Units)

Gas Density, 60°F, 14.696 psia Heat Value: At 60°F													
Gas	Formula	Boiling Point at 14.696 psia	Specific Gravity (Air = 1)	SCF Gas/lb	SCF Gas/gal Liquid	lb/gal Liquid	Btu/SCF Vapor at 14.696 psia (LHV)	Btu/SCF Vapor at 14.696 psia (HHV)	Btu/lb Liquid (LHV)	Btu/gal Liquid (LHV)	Air Required For Stoichiometric Combustion (cu ft/cu ft)	Flammability Limits Volume Percent In Air Mixture	
												Lower	Higher
Methane	CH ₄	-258.72	0.5539	23.6541	59.135	2.5000	909.40	1,010.0	21,511.0	53,778	9.53	5.00	15.00
Ethane	C ₂ H ₆	-127.46	1.0382	12.6200	37.476	2.9696	1,618.70	1,769.6	20,429.0	60,666	16.67	2.90	13.00
Propane	C ₃ H ₈	-43.73	1.5226	8.6505	36.375	4.2268	2,314.90	2,516.1	19,922.0	84,206	23.82	2.00	9.50
iButane	C ₄ H ₁₀	+10.78	2.0068	6.5291	30.639	4.6927	3,000.40	3,251.9	19,590.0	91,930	30.97	1.80	8.50
nButane	C ₄ H ₁₀	+31.08	2.0068	6.5291	30.639	4.8691	3,010.80	3,262.3	19,658.0	95,717	30.97	1.50	9.00
iPentane	C ₅ H ₁₂	+82.09	2.4912	5.2596	27.380	5.2058	3,699.00	4,000.9	19,456.0	101,284	38.11	1.30	8.00
nPentane	C ₅ H ₁₂	+96.89	2.4912	5.2596	27.673	5.2614	3,703.90	4,008.9	19,481.0	102,497	38.11	1.40	8.30
Hexane	C ₆ H ₁₄	+155.70	2.9755	4.4035	24.379	5.5363	4,403.90	4,755.9	19,393.0	107,365	45.26	1.10	7.70
Heptane	C ₇ H ₁₆	+209.17	3.4598	3.7872	21.725	5.7364	5,100.30	5,502.5	19,315.0	110,799	52.41	1.00	7.00
Octane	C ₈ H ₁₈	+258.17	3.9441	3.3220	19.575	5.8926	5,796.20	6,248.9	19,256.0	113,468	59.55	0.80	6.50
Carbon Monoxide	CO	-313.60	0.9670	13.5500	-	--	320.50	320.5	4,342.2	-	2.39	12.50	74.20
Carbon Dioxide	CO ₂	-109.24	1.5196	8.6229	58.807	6.8199	-	-	-	-	-	-	-
Hydrogen	H	-422.90	0.0696	188.6790	-	-	273.93	342.2	51,566.0	-	2.39	4.00	74.20
Hydrogen Sulphide	H ₂ S	-76.49	1.1767	11.1351	74.401	6.6817	586.80	637.1	6,534.0	43,658	7.20	4.30	45.50
Oxygen	O ₂	-297.32	1.1048	11.8593	112.930	9.5221	-	-	-	-	-	-	-
Nitrogen	N ₂	-320.44	0.9672	13.5465	91.413	6.7481	-	-	-	-	-	-	-
Air		-317.81	1.0000	13.1026	95.557	7.2930	-	-	-	-	-	-	-

Table B: Physical Properties of Gases (Metric Units)

Gas Density, 0°C, 101.31 kPa Heat Value: At 0°C													
Gas	Formula	Boiling Pt at 101.3 kPa	Specific Gravity (Air = 1)	Nm³ Gas/kg	Nm³ Gas/L Liquid	kg/L Liquid	MJ/Nm³ Vapor (LHV)	MJ/Nm³ Vapor (HHV)	MJ/kg Liquid (LHV)	MJ/L Liquid (LHV)	Air Required For Combustion (Vol/Vol)	Flammability Limits Volume Percent In Air Mixture	
												Lower	Higher
Methane	CH ₄	-161.51	0.5539	1.3997	0.4190*	0.2994*	35.746	39.700	50.034	14.980*	9.53	5.00	15.00
Ethane	C ₂ H ₆	-88.59	1.0382	0.7468	0.2656	0.3556	63.626	69.558	47.516	16.897	16.67	2.90	13.00
Propane	C ₃ H ₈	-42.07	1.5226	0.5119	0.2578	0.5062	90.992	98.900	46.579	23.578	23.82	2.00	9.50
iButane	C ₄ H ₁₀	-11.79	2.0068	0.3864	0.2171	0.5619	117.937	127.823	45.571	25.606	30.97	1.80	8.50
nButane	C ₄ H ₁₀	-0.51	2.0068	0.3864	0.2253	0.5831	118.346	128.231	45.729	26.665	30.97	1.50	9.00
iPentane	C ₅ H ₁₂	+27.83	2.4912	0.3112	0.1940	0.6234	145.397	157.264	45.248	28.208	38.11	1.30	8.00
nPentane	C ₅ H ₁₂	+36.05	2.4912	0.3112	0.1961	0.6301	145.589	157.578	45.307	28.548	38.11	1.40	8.30
Hexane	C ₆ H ₁₄	+68.72	2.9755	0.2606	0.1728	0.6630	173.104	186.940	45.111	29.909	45.26	1.10	7.70
Heptane	C ₇ H ₁₆	+98.37	3.4598	0.2241	0.1539	0.6869	200.478	216.287	44.927	30.860	52.41	1.00	7.00
Octane	C ₈ H ₁₈	+125.65	3.9441	0.1966	0.1387	0.7056	227.831	245.626	44.792	31.605	59.55	0.80	6.50
Carbon Monoxide	CO	+156.44	0.9670	0.8018	+	+	12.598	12.598	10.101	+	2.39	12.50	74.20
Carbon Dioxide	CO ₂	+42.91	1.5196	0.5103	0.4167	0.8167	0	0	0	0	+	+	+
Hydrogen	H	+217.17	0.0696	11.1651	+	+	10.766	13.451	120.203	+	2.39	4.00	74.20
Hydrogen Sulphide	H ₂ S	-60.27	1.1767	0.6589	0.5272	0.8001	23.065	25.043	15.198	12.160	7.20	4.30	45.50
Oxygen	O ₂	-182.95	1.1048	0.7018	0.8002	1.1403	0	0	0	0	+	+	+
Nitrogen	N ₂	-195.80	0.9672	0.8016	0.6478	0.8081	0	0	0	0	+	+	+
Air		-194.34	1.0000	0.7754	0.6771	0.8733	0	0	0	0	+	+	+

*Approximate Value

Appendix B – Miscellaneous references

B.1 The “blue” table

This table served as the original source for limit information for gaseous fuels, remaining through numerous updates. In this revision of this Guide, elements of this table have been separated out by category into different sections of the guide, and some have been expanded in ways that the original single value could not adequately express.

This table is being included here only as a reference, to aid in transition to this new format. The information in the preceding guide should now serve as the primary references.

		Standard Engine	G33/3400NA Low Energy / Ag Biogas Fuel Engine	G3500 Low Energy Fuel Engine
Sulfur Compounds as H ₂ S	mg H ₂ S/MJ	0.43	100	57
See footnote (1,2)*	ug H ₂ S/Btu	0.45	105	60
Halide Compounds as Cl	mg Cl/MJ	0	0	19
See footnote (1,3)*	ug Cl/Btu	0	0	20
Ammonia	mg NH ₃ /MJ	0	0	2.81
	ug NH ₃ /Btu	0	0	2.96
Silicon in Fuel	mg Si/MJ	0.1	0.1	0.56
See footnote (1,4)*	ug Si/Btu	0.1	0.1	0.6
Oil Content	mg/MJ	1.19	1.19	1.19
	ug/Btu	1.25	1.25	1.25
Particulates in Fuel	mg/MJ	0.80	0.80	0.80
See footnote (1,4)*	ug/Btu	0.84	0.84	0.84
Particulate Size in Fuel	microns	1	1	1
Maximum Temperature	°C	60	60	60
	°F	140	140	140
Minimum Temperature	°C	10	10	10
	°F	50	50	50
Fuel Pressure Fluctuation	kPa +/-	1.7	1.7	1.7
	psig +/-	0.25	0.25	0.25
Water Content	Saturated fuel or air is acceptable. Water condensation in the fuel lines or engine is not acceptable. It is recommended to limit the relative humidity to 80% at the minimum fuel operating temperature.			

Footnotes

- Note carefully that the limits given also cover contaminants that may be ingested by the combustion air supply. For example, if chlorine is being ingested to the engine in the fuel and in the air, the total amount may not exceed 20.0 µg Cl/Btu of fuel on a Low Energy Fuel equipped engine. If the fuel is: 50% methane, 40% carbon dioxide, 8% nitrogen, and 2% oxygen, the Lower Heating Value (LHV) is 456 Btu/SCF and the stoichiometric air/fuel ratio is 4.76:1, as calculated by the Caterpillar methane number Program. Now the maximum amount of chlorine is: (limit for Cl)(LHV) = amount of Cl in fuel, in this example (20 µg/Btu)(456 Btu/SCF) = 9120 µg Cl/SCF of fuel, assuming there is no chlorine in the air. If chlorine is present in the air, the following example is instructive. Assume that the fuel has 2.2 µg Cl/Btu and that the engine is operating at a lambda of 1.5. What is the maximum allowable chlorine in the air? For every one standard cubic foot of fuel burned there is: Stoichiometric air/fuel ratio (lambda), in this example: (4.76)(1.5) = 7.14 SCF of air per SCF of fuel. Chlorine present in the fuel is: (Cl concentration)(LHV) = Cl in fuel, in this example (2.2 µg/Btu)(456 Btu/SCF fuel) = 1000 µg Cl/ SCF fuel and then maximum allowable chlorine in the air is: (maximum permitted Cl - Cl in fuel)/(SCF of air burned per SCF of fuel), (9120-1000)/(7.14) =1137 µg Cl/SCF air. If there was no chlorine in the fuel, the maximum amount of chlorine allowable in the air would be: (9120-0)/(7.14)=1277 µg Cl/SCF air.
- Sulfur compounds are those which contain sulfur. Total sulfur level should account for all sulfur and be expressed as hydrogen sulfide (H₂S). See conversion below. Consult Lubrication section of the A&I Guide for information on proper lubrication and oil sampling when fuel or air contain sulfur compounds.
- Halide compounds are those which contain chlorine, fluorine, iodide, or bromine. Total halide level should account for all halides and be expressed as chlorine. Refer to the following conversions below. Consult Lubrication section of the Application and Installation Guide for information on proper lubrication and oil sampling when fuel or air contains halide compounds.
- Total particulate level must include inorganic silicon. Limit shown for silicon must account for the total organic (siloxanes, etc) and inorganic silicon content.
- At low temperatures, hydrocarbon fuels may condense and enter the engine. Liquids are never permitted in the fuel. If liquids are present, the customer must remove them by increasing the fuel temperature or by a coalescing filter, or by means. Serious engine damage will result if liquids are allowed into the engine.

B.2 Laboratory services

In the previous version of this Guide, references appeared for laboratories that would provide specific services for analysis of gases. Those laboratory services were established years ago and may not be available through those sources at the time of publication for this revision to this Guide. It may also be the case that the laboratory entity listed does still exist but may not be reached at the address or phone information presented.

These details are copied here only as a reference for those who wish to track down currently available services such as those mentioned in the previous edition of this Guide.

Halide sampling (from section 5.4.2):

Caterpillar recommends the following laboratory for halogen and hydrogen sulfide testing:

Core Laboratories- Houston

Attention: Gas Analysis Chemist

phone: (713)690-4444

6310 Rothway Drive

fax: (713)690-5646

Houston, TX 77040

Silicon sampling (from section 5.4.4):

Silicon sampling kits are available through the following companies.

SiTest Landfill 1 Program

Bio-Engineering Services

36 Virginia Street

Southport, PR8 6RU England

44 (0) 1704 539094 phone

44 (0) 1704 501660 fax

Jet Care Silicon Analysis Sampling Kit

Jet-Care International Inc.

3 Saddle Road

Cedar Knoll, NJ 07927-1902

(201)-292-9597 phone

(201)-292-3030 fax

Spectro / Jet-Care

Hatchwood Place, Farnham Road,

Odiham, Hampshire, RG29 1AB, UK

44 (0) 1256 704000 phone

44 (0) 1256 704006 fax

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