

Application & Installation Guide

Gaseous Fuels

Technical Information

G3600 • G3500

G3400 • G3300

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Foreword

This section of the Application and Installation Guide generally describes Gaseous Fuels for Cat[®] engines listed on the cover of this section. Additional engine systems, components and dynamics are addressed in other sections of this Application and Installation Guide.

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

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

Gaseous Fuels

Most internal combustion engines today use fuels that are based on hydrocarbon compounds derived from petroleum. The most commonly seen hydrocarbon fuels are those used in automotive and aerospace applications that typically exist in a liquid state until they are burned (i.e., gasoline, diesel fuel and kerosene). 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 hydrocarbon 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. They may also be manufactured through the conversion of carbon-bearing materials such as coal or wood. 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.

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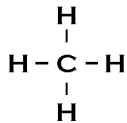
Fuel Properties

Hydrocarbons

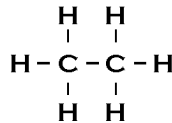
Hydrocarbons are grouped into three classifications according to their molecular structure.

- Paraffins - C_nH_{2n+2}
- Napthenes - C_nH_{2n}
- Aromatics - C_nH_{2n-6}

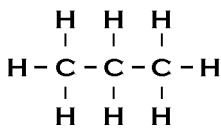
The hydrocarbon gases used as engine fuels are almost exclusively paraffins (also known as alkanes). This family of compounds has molecules formed as a chain of carbon atoms with hydrogen atoms attached at the remaining bond sites. The series begins with methane (CH_4), with each succeeding member adding another carbon (C) atom along with the corresponding number of hydrogen (H) atoms. Shown graphically, the first four members of the paraffin series look like this.



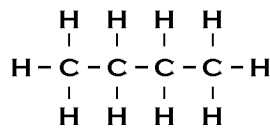
Methane (CH_4)



Ethane (C_2H_6)



Propane (C_3H_8)



Butane (C_4H_{10})

Note the similarity in how each additional set of carbon and hydrogen atoms is added to the chain. Because of the way in which the shorter chains appear as if they are portions of the longer ones, the different hydrocarbon compounds in the series are sometimes called "hydrocarbon fractions".

Once the chains become long enough they can different shapes. Some keep the "straight chain" shape shown above and some form branches. These different versions of the same molecule are known as isomers, the name for chemical compounds that have the same formula but different molecular structures. The straight chain version of these compounds is termed "normal" and is often shown with a prefix of "n-" or "nor-". The branched versions may be indicated by the prefixes "iso-" or "neo-", with the difference between them being where in the molecule the branch is found.

As the number of atoms in the molecule increases, the mass of the molecule increases. Such larger hydrocarbon fractions are said to be "heavier". The increased size of each successive molecule brings with it changes to the characteristic properties that define the behavior of each. The shape of the molecule alters these properties as well, such that the various isomers of a given fraction will also have somewhat different characteristic properties. **Tables A & B** on Pages 37 & 38 compare the physical properties of the paraffin series hydrocarbon fractions most typically found in gaseous fuels, along with some other non-hydrocarbon compounds that are also common in fuel gas.

Standard Condition of a Gas

When dealing with gaseous fuels it's important to be able to gauge the amount of gas present in a given 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 (higher volume). 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:

Standard Conditions

Typically used with English units of measure, standard conditions are defined as 14.696 psia (101.31 kPaa) and 60°F (15.55°C).

Normal Conditions

Typically used with metric units, normal conditions are defined as 101.31 kPaa (14.696 psia) and 0°C (32°F).

Note in each case that the pressure units of pounds per square inch (“psi”) or kilopascals (“kPa”) are followed by a small letter “a”. The “a” stands for “absolute”, indicating that the measurement takes into account the ambient barometric pressure. A reference measurement that does not account for this atmospheric pressure is termed “gauge” and is indicated by a small letter “g”. Similarly, the units of volume carry a special tag when they are measured at these reference conditions. Cubic feet measured at standard conditions are considered “standard cubic feet”

and are often abbreviated “SCF”. Cubic meters measured at normal conditions are termed “normal cubic meters” and are often indicated as “Nm³”. Other abbreviations or reference conditions do sometimes get used, so it is important to know the terminology and references used on each job. The abbreviations and conditions noted above are the references used throughout this guide.

Converting Reference Conditions

Because gas measurements are rarely made when the ambient temperature and pressure match the reference conditions described above, it is important to be able to convert measurements from one set of conditions to another. This is done using the Ideal Gas Law, a chemistry principle that summarizes the relationships among temperature, pressure, volume and amount of gas present into a single simple equation. Because we’re comparing a single sample under “before” and “after” conditions the equation is simplified even further to:

$$\text{Vol.2} = \text{Vol.1} \times \frac{\text{Temp2} \times \text{Press1}}{\text{Temp1} \times \text{Press2}}$$

IMPORTANT: This equation only works when the measurements for temperature and pressure are expressed on an absolute scale. For pressure, the measurements must account for atmospheric pressure and would appear as “psia” or “kPaa”. For temperature, units must be used that measure temperature relative to absolute zero. The temperature scales that do this are Rankine (R) and Kelvin (K).

Temperatures in Fahrenheit or Celsius are easily converted to Rankine or Kelvin using the following relationships:

$$R = ^\circ F + 460$$

$$K = ^\circ C + 273$$

As an example of how these equations and conversions are used, consider a gas flow measured at 255 cubic meters per hour. If the conditions at the time of measurement were 152 kPa pressure and 35°C temperature, we can convert the flow rate to normal conditions in this way:

$$\text{Vol.2} = 255 \text{ m}^3 \text{ hr} \times \frac{(0+273\text{K}) \times (152\text{kPa})}{(35+273\text{K}) \times (101.3 \text{ kPa})}$$

$$\text{Vol.2} = 339 \text{ Nm}^3 \text{ hr}$$

The same measurement expressed in English units would have a flow rate of 150 cubic feet per minute at 95°F and 22 psia. This flow rate can be converted to standard conditions thus:

$$\text{Vol.2} = 150 \text{ ft}^3 \text{ min} \times \frac{(60+460\text{R}) \times (22 \text{ psia})}{(95+460\text{R}) \times (14.696 \text{ psia})}$$

$$\text{Vol.2} = 210 \text{ scfm}$$

These types of conversions are done commonly to give information about gases in terms of reference conditions.

Specific Gravity & Density

Specific Gravity (Relative to Air)

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. A table of gas properties is included in this guide in **Table A** on Page 37.

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 at Normal conditions = specific gravity of methane) x (density of air at Normal conditions)

$$0.5539 \times 1.290 \text{ kg/Nm}^3 = 0.7145 \text{ kg/Nm}^3$$

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 mix. 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 gas by its volume % or "mole fraction" from **Table A** on Page 37.

| Gas | Formula | Specific Gravity |
|----------------|--------------------------------|------------------|
| Methane | CH ₄ | 0.5539 |
| Ethane | C ₂ H ₆ | 1.0382 |
| Carbon Dioxide | C ₇ H ₁₆ | 1.5196 |

$$\text{Specific Gravity of the fuel mixture} = (0.8 \times 0.5539) + (0.15 \times 1.0382) + (0.05 \times 1.5196) = 0.6748$$

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 chemical 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. All of the mole fractions for substances in a given gas mixture added together will equal 1, just as all 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.

Heat Value

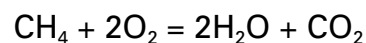
Combustion is the combination of the fuel gas with oxygen to release heat energy. Since the amount of energy released is directly tied to how much power the engine can

produce, it is important to know the potential of each fuel gas to release heat during combustion. This potential is known as the heat value (or calorific value) of the gas, and it is defined as the amount of thermal energy released during complete combustion of the gas. It can be measured using a calorimeter, a device that measures the heat released during a chemical reaction (such as combustion).

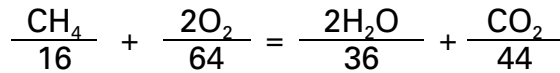
Given that combustion of hydrocarbons involves the combination of hydrogen and oxygen, one consistent byproduct of the reaction is water. Furthermore, given the high temperatures of the typical combustion reaction, the water produced during combustion comes out in a gaseous state. This change of state from a liquid to a gas consumes heat energy (known as the latent heat of vaporization), meaning a portion of the theoretical energy release of combustion is not available to the engine for use in producing mechanical power. Thus for gaseous fuels, we document two heat values:

- The higher heat value (HHV), which is the total theoretical energy potential of the gas
- The lower heat value (LHV), which is the higher heat value minus the latent heat of vaporization of the water in the exhaust.

An examination of the combustion equation using pure methane (CH₄), the main constituent of natural gas, will illustrate this point further. The equation for combustion of methane is:



To determine the amount of water formed during combustion, first identify the molecular weight of each gas.



When one mole of methane (16 kg or 16 lb) is combined during combustion with two moles of oxygen (64 kg or 64 lb), it will form two moles of water (36 kg or 36 lb) and one mole of CO₂ (44 kg or 44 lb). Therefore, for each unit mass of CH₄ burned:

$36/16 = 2.25$ kg (lb) of water are formed per kg (lb) of CH₄.

To determine the amount of water formed per SCM (SCF) of CH₄ burned, divide 2.25 kg (lb) by the specific volume (m³/kg or ft³/lb) of gas at standard conditions of temperature and pressure. Methane is:

$$1 \text{ kg} = 1.4738 \text{ SCM} \\ (1 \text{ lb} = 23.61 \text{ SCF})$$

Therefore:

$$\frac{2.25}{1.4738 \text{ SCM CH}_4} = 1.526 \text{ kg H}_2\text{O}$$

$$\frac{2.25}{23.61 \text{ SCF CH}_4} = 0.09529 \text{ lb H}_2\text{O}$$

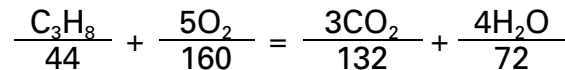
1.526 kg H₂O (0.09529 lb H₂O) is the amount of water formed per SCM (SCF) of methane burned.

The difference between high and low heat value for CH₄ is the heat required to convert 1.526 kg/SCM (0.09529 lb/SCF) of water to vapor at standard conditions. The latent heat of vaporization per kg (lb) of water at 15.55°C (60°F) from the steam tables is 2.4653 MJ/SCM (1059.9 Btu/SCF). Therefore, the difference between HHV and LHV of CH₄ is:

$$3.763 \text{ MJ/SCM} (0.09529 \times 1059.9 = 101 \text{ Btu/SCF}).$$

Note that **Tables A & B** (Page 37 & 38) reflect this difference in HHV and LHV for CH₄.

As stated previously, the amount of water formed depends on the hydrocarbons being burned. As a comparison, consider the combustion products of propane (C₃H₈).



The amount of water formed per kg (lb) of propane burned is:

$$72/44 = 1.6363 \text{ kg (lb) H}_2\text{O/kg (lb) C}_3\text{H}_8$$

And the amount of water formed per SCM (SCF) of propane burned is:

$$1.636 \text{ kg H}_2\text{O/kg C}_3\text{H}_8 = 3.0937 \text{ kg H}_2\text{O}$$

$$\frac{1.636 \text{ kg H}_2\text{O/kg C}_3\text{H}_8}{0.5288 \text{ SCM/kg C}_3\text{H}_8} = \frac{3.0937 \text{ kg H}_2\text{O}}{\text{SCM C}_3\text{H}_8}$$

$$\frac{1.636 \text{ lb H}_2\text{O/lb C}_3\text{H}_8}{8.471 \text{ SCF/lb C}_3\text{H}_8} = \frac{0.1931 \text{ lb H}_2\text{O}}{\text{SCF C}_3\text{H}_8}$$

When burning one SCM (SCF) each of methane and propane, the methane forms 1.526 kg/SCM (0.09529 lb/SCF) of water and the propane forms 3.0937 kg/SCM (0.1931 lb/SCF) of water.

To pursue this one step further, the amount of heat lost to the engine in converting this water to vapor at 15.55°C (60°F) for propane is:

Energy lost per SCM (SCF) C_3H_8 burned is 7.6 MJ/SCM C_3H_8 ($0.1931 \times 1059.9 = 204$ Btu/SCF C_3H_8)

Examination of **Tables A & B** (Page 37 & 38) will confirm that this is the difference between HHV and LHV for propane.

As stated earlier, the heat energy lost to the vaporization of water is lost to the engine for producing power as well. For this reason, LHV is the fuel property used when determining the power-producing potential of a gas when used as engine fuel.

Hydrocarbon Dew Point

The hydrocarbon dew point is the temperature (at a given pressure) at which the hydrocarbon components of any hydrocarbon-rich gas mixture, such as natural gas, will start to condense out of the gaseous phase. It is often also referred to as the HDP or the HCDP. The hydrocarbon dew point is a function of the gas composition as well as the pressure. It is typically

calculated in a laboratory during the gas sample analysis.

The hydrocarbon dew point of a gas is a different concept from the water dew point, the latter being the temperature (at a given pressure) at which water vapor present in a gas mixture will condense out of the gas.

The fuel gas temperature would need to be above both dew points to ensure there is no condensate present in the fuel. Dew point is affected by pressure and temperature, so the dew point needs to be evaluated at all temperature and pressure conditions the fuel will experience prior to combustion. This would include pressure and temperature changes at the fuel pressure regulator(s) and compression at the turbocharger.

If the fuel gas needs heated to be above the dew point, the design must ensure the gas is not heated above the maximum fuel supply temperature.

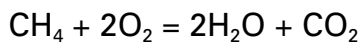
Fuel Characteristics

While discussing the makeup and structure of gaseous fuels in the previous sections, references were made to characteristic properties that vary among different gases. Understanding the properties of each gas is very important to being able to properly prepare an engine to use a particular gas as fuel.

Stoichiometry

Stoichiometry (pronounced “stoy-kee-ah-muh-tree”) simply refers to the relative quantities of elements in a molecule or the relative amounts of reactants and products in a chemical reaction. We use it in regard to the amounts of fuel and air involved in the chemical reaction that is combustion. Stoichiometric combustion takes place when the fuel and air are in the correct proportions so that there is no oxygen or fuel remaining when combustion is finished. This proportion is found by balancing the chemical equation for combustion, which is different for each gas.

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:

$$\frac{2}{0.21} = 9.53$$

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 A & B** on Page 37 & 38.

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. Such a weighted sum might look like this:

| Gas Constituent | Percent | Stoichiometric Air/Fuel Ratio |
|--|---------|-------------------------------|
| Methane CH ₄ | 90% | 9.53 |
| Ethane C ₂ H ₆ | 5% | 16.67 |
| Propane C ₃ H ₈ | 3% | 23.83 |
| Carbon Dioxide CO ₂ | 2% | 0.00 |

To find the weighted sum for this mixture, the percentages and air/fuel ratios are multiplied and summed like this:

| | | |
|--|---|-------|
| CH ₄ : 0.90 x 9.53 | = | 8.58 |
| C ₂ H ₆ : 0.05 x 16.67 | = | 0.83 |
| C ₃ H ₈ : 0.03 x 23.82 | = | 0.71 |
| CO ₂ : 0.02 x 0.0 | = | 0.00 |
| Total m ³ (ft ³) | | |
| Air Required | = | 10.12 |

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. This weighted sum technique is useful in determining "mixed gas" value for several of the characteristic gas properties.

Methane Number

Cat engines can operate on gaseous fuel from a wide range of sources, ranging from raw field gas to processed pipeline natural gas to gas from landfill/digester processes. However, the combustion qualities of gas from these sources varies a great deal, affecting engine settings such as ignition timing or even limiting the power which the engine may produce. The key property involved is the ability of the fuel gas to resist detonation, an uncontrolled burning of the gas in the engine. Left unchecked, detonation has the potential to cause significant engine damage. For this reason, having a measure of this detonation resistance property provides a valuable tool for assessing the suitability of a gas to use as engine fuel.

Caterpillar's earliest attempt at a detonation resistance scale was using the octane rating method, a

tool long established for use with gasoline engines. The octane rating method uses a special test engine with variable compression ratio to establish the critical compression ratio for a fuel, the compression ratio at which detonation occurs. 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. The 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 paraffin fraction. Octane is a much heavier paraffin series molecule with very different combustion properties, including the fact that it tends to exist as a liquid under normal conditions - good for gasoline engines, but not so good for natural gas engines.

To use the octane rating for gas engines, each hydrocarbon fraction (methane, ethane, propane, and so on) must be tested to establish its octane rating number. These values are then used to compute a weighted average octane rating for each gas mixture being evaluated. This approach has two significant drawbacks. First, it assumes a linear contribution by each fraction to the overall average result. In fact, the heavier fractions tend to have more impact than the lighter ones on the behavior of the mixed gas. Secondly, the octane rating system provides no way to take into account the beneficial effects of inert gases like carbon dioxide or nitrogen. In certain blends, these gases can help to cool combustion,

allowing a small improvement in resistance to detonation. The octane rating method was acceptable when used with processed “pipeline-quality” natural gas, but its usefulness was limited when applied to the broad range of gas compositions found at the well. These applications needed a more reliable rating method.

The methane number rating method was first developed in Austria in the mid-1960s. Instead of octane, it uses methane as the reference for establishing resistance to detonation. The methane number scale sets a value of 100 for pure methane and uses hydrogen, with a value of 0, as the reference for a very fast-burning gas prone to detonation. Caterpillar adopted this method in the 1980s, continuing to refine the system through extensive research and testing on a wide range of fuels from field gas to landfill gas.

Calculating the methane number requires a set of complicated computations; therefore, Caterpillar developed a computer program to perform these calculations and allow

field determination of the methane number. This program makes it a simple task to enter the gas composition values and have the computer deliver a full report of the expected properties of the gas, including not only the methane number but also the higher and lower heat values, the specific gravity, the stoichiometric air/fuel ratio, and other properties, such as the Wobbe Index. Methane numbers of some individual component gases are:

| | |
|--|------|
| Methane (CH ₄) | 100 |
| Ethane (C ₂ H ₆) | 52.5 |
| Propane (C ₃ H ₈) | 33 |
| n-Butane (C ₄ H ₁₀) | 8 |

After calculating the methane number and knowing the aftercooler water temperature (or air-to-air aftercooling temperature) available, the engine rating can be determined from the fuel usage guides published by Caterpillar. The guides show engine power and timing for specified ranges of methane number for each aftercooler water temperature.

Impact of Fuel Quality on Engine Performance

LHV, Air Required for Combustion & Engine Power

An engine is a conversion device. It takes in the chemical energy stored in the fuel, releases that energy as heat during combustion, and then converts the heat energy into mechanical work. Part of the engine's job, then, is to make certain enough fuel gets into the cylinder to enable it to reach its full rated power output. But, as we learned earlier, combustion requires fuel and air, so getting enough air into the cylinder is just as important as getting enough fuel.

The path the air takes, from first entering the air cleaner until it reaches the cylinder, poses a restriction to flow of the air. This is characteristic of the design of the engine, so it is a property that varies from engine model to engine model. Also characteristic of the engine design is whether or not it has a device that helps to push air into the cylinder to increase the power-producing potential of the engine. Such devices are known as superchargers, with the type most commonly seen on large engines being called turbochargers since the power used to pump the air into the engine comes from a turbine placed in the engine exhaust stream.

The most basic engine air inlet design uses no supercharger; it relies only on the vacuum drawn by the piston moving down in the cylinder to pull air in. This design is known as "naturally aspirated" (abbreviated "NA"). An NA engine will be sensitive to any factors that restrict airflow, and one such factor is the altitude and ambient temperature of the installation

where the engine is in use. Increased altitude or ambient air temperature causes the air to become less dense, making it more difficult for the engine to draw in enough air to support combustion. The fuel gas makeup comes into play in that the amount of air required to support combustion is determined by the air requirements of the fuel as shown by the stoichiometric air/fuel ratio.

Adding a turbocharger to an engine is an effective way to offset this breathing problem. The turbocharger forces air into the engine, allowing it to overcome the effects of decreased ambient air density. But, pumping up the pressure of the inlet air to increase the density also pumps up the temperature of that air, and higher temperatures mean decreased air density. For this reason, many turbocharger installations also include an intercooler or aftercooler, a heat exchanger designed to cool the inlet air, allowing it to become more dense. The turbocharged-aftercooled ("TA") engine design gives greatly expanded breathing ability to the engine, supporting the production of power.

The fuel system has a similar role in enabling the engine to produce rated power. It also poses a restriction to the flow of fuel into the engine and so is critical in the design of the engine. It is also affected by the inlet pressure of the fuel supply much like the air system is impacted by the site altitude and ambient temperature. But, unlike the air system, the fuel system may also be impacted by the LHV of the fuel gas. Too high an energy content may cause the fuel system

to be unable to mix air and fuel in the proper ratios, resulting in poor combustion and reduced power. To low an LHV results in starving the engine for the fuel energy necessary to produce power.

Relative Power Capability & Wobbe Index

Two calculated properties of a fuel gas were created to help in sizing up the concerns over air system and fuel system restriction on power production. The relative power capability documents the combined impact of the air system and fuel quality on the ability to get fuel energy into the cylinder. Wobbe Index serves as a tool to help gauge whether the fuel system will be able to flow enough fuel to put fuel energy into the cylinder.

Relative Power Capability

The relative power capability of a fuel gas is a ratio of the LHV of the fuel-air mixture for the engine installation relative to the LHV of the fuel-air mixture used to develop the engine power rating. If the fuel-air mixture contains less energy than the reference 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.

Fuel composition:

CH₄ = 55%

CO₂ = 35%

N₂ = 10%

The LHV for this mixture, calculated using the weighted sum method described earlier, is 501 Btu/SCF (19.69 MJ/Nm³). The

stoichiometric air/fuel ratio for this fuel is 5.24:1, also determined by the weighted sum method. To determine the LHV of the fuel-air mixture, we must divide the fuel content of one volume of fuel by the total volume of a stoichiometric air-fuel blend, which is the sum of 1 plus the stoichiometric ratio. This gives:

$$\frac{501}{1 + 5.24} = 80.29 \text{ Btu/SCF}$$

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

The LHV of the reference fuel-air mixture is calculated in the same way, using the LHV and air/fuel ratio information for the pipeline quality natural gas used in rating development:

$$\frac{905}{1 + 9.45} = 86.6 \text{ Btu/SCF}$$

$$\frac{35.64}{1 + 9.45} = 3.41 \text{ MJ/Nm}^3$$

The Relative Power Capability (RPC) is the ratio of the two.

RPC = 3.16/3.41 = 0.93, or using the values in English units:

$$\text{RPC} = 80.29/86.6 = 0.93$$

So the stoichiometric air-fuel mixture of this fuel would deliver to the engine only 93% of the energy that would be contained in a same volume of a stoichiometric mixture of pipeline natural gas.

This factor is particularly important when determining the rating of a naturally aspirated (NA) engine. Without a turbocharger, the engine does not have the means to increase the density of the incoming air-fuel mixture, and the fuel RPC factor will dictate the engine rating.

Even a turbocharged engine has its limits. While the turbocharger and aftercooler help to compensate for decreased air density at high site altitudes and ambient temperatures, their ability to do so has limits too. Once the turbocharger's contribution reaches its limit, the TA engine is subject to the same RPC limits that we've shown for the NA engine. Additionally, the decline in air density delivered to the cylinders creates a second source of derate that must be taken into account. To determine the limits of the air system on a TA engine, the altitude ambient derate factor (provided with the engine Technical Data Sheet) and the fuel RPC must be considered together. These derates are cumulative.

For example, consider a G3516LE engine rated at 809 bkW @ 1200 rpm in a location at 2000 meters altitude and 30°C (86°F) ambient temperature that would burn the low energy fuel used in the previous example.

Ambient/altitude derate factor = 0.92 (found on Altitude Derate Table provided with the Technical Data Sheet)

Relative Power Capability factor = 0.93

Total Air System Derate

$$= (1 - 0.92) + (1 - 0.93)$$

$$= 0.8 + 0.7$$

$$= 0.15$$

The total derate = 15%

The total derate factor may be found multiplying the two factors together:

$$(0.92)(0.93) = 0.85$$

The site rating is limited by the air system capacity (site conditions and RPC) to:

$$809 \text{ bkW} \times 0.85 = 688 \text{ bkW}$$

Wobbe Index

Changes in the fuel composition affect not only the energy content of the fuel, but its specific gravity (SG) as well. The impact of the LHV changes is clear; less energy in the fuel means potentially less energy delivered to the cylinder. The impact of the specific gravity is important in the same manner. The specific gravity of the fuel is the property that determines how well it can turn corners and squeeze through tight spaces in the fuel system. A higher specific gravity fuel gas will have more difficulty traveling through a given fuel system than will a fuel gas with a lower specific gravity. More restriction to flow through the fuel system means potentially less fuel energy flowing into the cylinder and thus less power. This flow capability of a fuel gas is measured using the Wobbe Index.

The Wobbe Index takes these two critical properties of the fuel – LHV and SG – and puts them together to create a direct measure of fuel energy flowing through the fuel system. The LHV is a measure of how much energy is in the gas. Flow of a gas through the fuel system is proportional to 1 divided by the square root of SG. Putting them together, the flow of energy through the fuel system is proportional to LHV divided by the square root of SG. This is the definition of the Wobbe Index.

Fuel System Sizing & Fuel Metering

The fuel system on any engine must be capable of delivering a fuel flow rate that enables the engine to achieve its full rated power. As shown in the discussions on

Relative Power Capability and Wobbe Index, its ability to do so is dependent upon the fuel LHV and SG, making it a challenge for a single design to successfully adapt to the broad range of gases that may be used as engine fuel. Fortunately, certain fuel system designs can be adapted relatively easily to enable them to work with different gases. As an example, consider the broad fuel gas categories described in **Table 1**. A carbureted fuel system can often be adapted to different fuel LHV ranges by changing the internal parts that establish the air/fuel ratio characteristic for the carburetor. Such fuel system changes should be considered when the standard engine fuel system cannot be made to work with a given fuel gas.

| Gas Heating Values | |
|------------------------|---|
| High Energy Gas | 55.0 –94.3 MJ/Nm ³ (1400 –2400 Btu/SCF) |
| Natural Gas | 31.4 –55.0 MJ/Nm ³ (800 –1400 Btu/SCF) |
| Low Energy Natural Gas | 23.6 –31.4 MJ/Nm ³ (600 –800 Btu/SCF) |
| Biogas | 17.7 –25.5 MJ/Nm ³ (450 –650 Btu/SCF) |
| Landfill Gas | 15.7 –23.6 MJ/Nm ³ (400 –600 Btu/SCF) |

Table 1

Methane Number, Detonation & Engine Power

Earlier we discussed the creation of a rating scale based on the detonation-resistant characteristics of methane and hydrogen. This Methane Number scale serves as a basis for rating fuel mixtures on their relative ability to resist detonation. To understand how this information is used, we start with an understanding of detonation itself.

Detonation and Pre-ignition

Detonation and pre-ignition are two forms of abnormal combustion that involve uncontrolled burning of the fuel-air mixture in the cylinder. Pre-ignition is the term used to describe premature ignition of the fuel-air mixture before the spark plug has fired. Detonation describes the scenario where the fuel-air mixture is ignited at the proper time by the spark plug and a second ignition event takes place in the unburned fuel-air mixture before the normal combustion sequence can go to completion. Both events are potentially damaging to the engine due to their potential to produce localized high temperatures and sharp rises in pressure.

Pre-ignition is typically a result of a “hot spot” in the combustion chamber. Such hot spots may occur at sharp edges on the engine parts (such as valves or spark plugs) if they get too hot, or from carbon deposits in the combustion chamber. If these hot spots cannot cool between combustion cycles, they can get hot enough to serve as an ignition source themselves and will light the fuel-air charge before the spark plug gets the chance.

Detonation is the result of a more complex set of circumstances, involving the combined influence of fuel quality, engine design, engine set-up, site construction, ambient conditions, and engine loading. If enough of these inputs stray from their proper ranges during engine operation, combustion that begins normally can suddenly see a portion of the unburned gas self-ignite before it has been met by the primary flame front. The flame fronts from these two combustion sources will eventually collide,

creating a sharp metallic “ping” sound that is the audible evidence of detonation. Detonation is the event often called “knocking” in your car’s gasoline engine.

The following descriptions illustrate normal combustion and detonation.

Normal Combustion

Burning of the fuel-air mixture is started by the spark plug. The flame front progresses uniformly across the combustion chamber until the entire fuel-air charge is burned. Heat released by combustion produces a rise in pressure that pushes the piston down in the cylinder, producing useful work at the crankshaft. Refer to **Figure 1**.

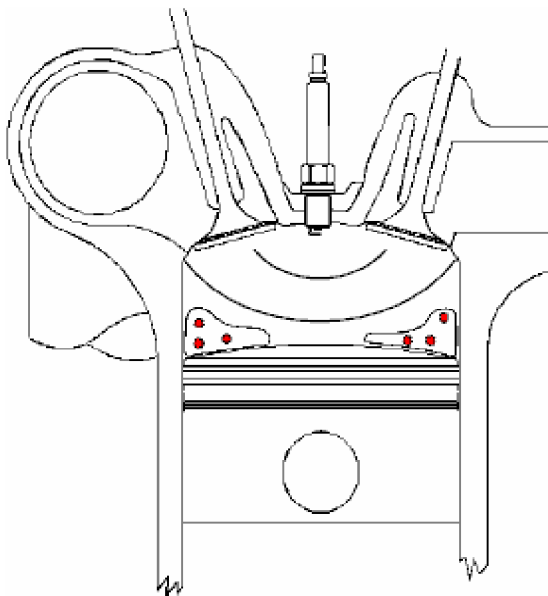


Figure 1

Detonation

The advancing flame front compresses the unburned fuel-air mixture, pushing its temperature beyond the auto-ignition point. The unburned portion of the mixture self-ignites, creating a sharp rise in pressure and localized high temperatures. Refer to **Figure 2**.

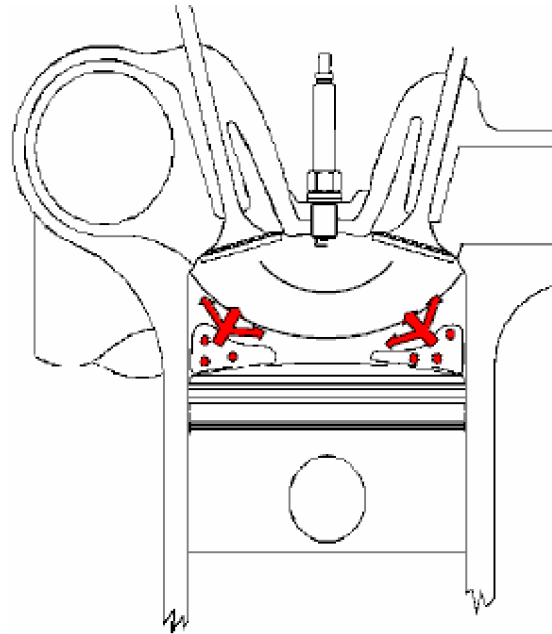


Figure 2

As described earlier, detonation results from one of several factors being out of range either at the start of, or during, the combustion sequence. The basic driver for detonation is the temperature of the unburned gas, or “end gas”, before it is ignited by the flame front. Because of this, the list of direct causes for detonation can be pretty well defined (although the root causes for those conditions can sometimes be more difficult to establish). Direct causes of detonation include:

- Fuel-air charge temperature too high: High starting temperature of the fuel-air mixture results in temperature rise in the end gas beyond the auto-ignition threshold.
- Fuel-air charge pressure too high: High starting pressure of the fuel-air mixture results in temperature rise in the end gas beyond the auto-ignition threshold.

- Low fuel MN: Fuel gas does not have sufficient resistance to detonation. The fuel auto-ignition temperature is low compared to the standard fuel resulting in auto-ignition under normal combustion pressure rise conditions.

This short list of direct causes can grow to an extremely lengthy list of root causes if we were to look at all of the design and environmental factors that can result in one of these conditions.

Focusing just on engine attributes that directly play into detonation sensitivity, four design issues come to the forefront.

- Compression Ratio
- Ignition Timing
- Aftercooler Temperature
- Power Rating.

As we examine these attributes, you should begin to notice how several of the factors are directly related to one another.

Compression Ratio

The compression ratio of the engine and the fuel MN go hand-in-hand when searching for the proper engine for a given fuel. High compression ratios tend to increase in-cylinder pressures, making factors sensitive to the pressure rise critical with regard to detonation. Low MN fuels burn faster than higher MN fuels, creating steeper pressure rise rates that are not well matched to high compression ratios. In general, low MN fuels require low compression ratio engines.

Ignition Timing

Ignition timing is also directly tied to fuel MN and pressure rise rate. Achieving peak combustion pressure at the proper time in the piston's movement in the cylinder requires that the spark plug fire at a precise moment in advance of that point. The timing of that "spark advance" depends heavily on the burning rate of the fuel, which is closely related to the fuel's MN. Lower MN fuels require the use of less spark timing advance.

Aftercooler Temperature

The aftercooler serves as the final control over the starting temperature of fuel-air charge. Because this plays directly into the risk of detonation, any design or installation issues that can compromise the aftercooler's ability to achieve the appropriate temperature in the inlet charge are critical detonation risk factors. The aftercooler can fail to provide adequate cooling of the inlet air by not being large enough to handle the heat removal demand placed on it or by being fed aftercooler water at too high a temperature. High aftercooler water temperatures can stem from improper selection of the aftercooler water thermostat set point, or an inadequately sized radiator, or by high ambient air temperatures reducing the cooling capabilities of the radiator.

Power Rating

Engine power output is the most challenging to see how it contributes to detonation because it involves the movement of the piston. Normal operation of the engine uses the pressure rise in the cylinder to push the piston and eventually drive the load attached to the crankshaft. If the driven load on

the crankshaft becomes too great it restricts the movement of the piston. With the piston movement restricted, the pressure rise in the cylinder gets steeper, eventually resulting in detonation.

Fuel Usage Guides

To successfully use fuels that are more prone to detonation, cylinder temperatures and pressures must be limited to the fuel's capabilities and ignition timing must be optimized. To match fuel capability with engine characteristics,

Caterpillar publishes a Fuel Usage Guide with each engine's technical data sheet. The Fuel Usage Guide is a table that lists a range of fuel methane number values and provides the required engine derate factor and recommended engine timing for each. The derate factor, when multiplied by the standard engine rating in the technical data, tells the maximum power that the engine should run on a fuel with the MN shown. The ignition timing is the recommended spark advance setting for that fuel.

Example of Fuel Usage Guide

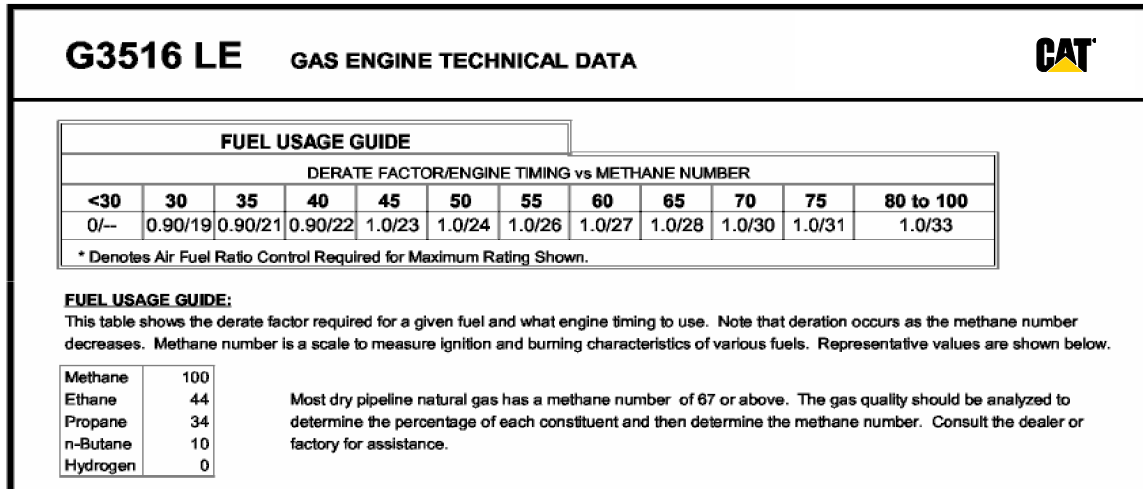


Figure 3

An example of a fuel usage guide is shown in **Figure 3**. This example guide suggests that with a fuel gas of MN=46, this engine could operate at the full published rating (derate factor = 1.0), and the recommended timing would be 23 degrees BTDC

("before top dead center"). If the fuel MN dropped to 40, however, the rating would need to be dropped to 90% of the published rating (derate factor = 0.9) and the ignition timing should be set to 22 degrees BTDC.

Contaminants

Contaminants may be introduced into the engine as chemical compounds carried in the fuel or air. These contaminants may cause damage to the engine through corrosion, abrasion, or formation of deposits. The amount of each allowed to enter the engine must be

limited to protect the engine from damage. **Table 2** below gives an overview of the general limits for fuel contaminants and conditions. The sections that follow describe the potential adverse effects of specific contaminants and may include more detailed limits for specific engine models.

Maximum Contaminants and Conditions

(Unless otherwise noted, Contaminant and Condition limits apply to fuel and combustion air. See footnote 1 below.)

| | | 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 |
| | ug H ₂ S/Btu | 0.45 | 105 | 60 |
| Halide Compounds as Cl | mg Cl/MJ | 0 | 0 | 19 |
| | 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 |
| | 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 |
| | 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.

Table 2

Sulfur Compounds

Sulfur compounds are formed during the decomposition of organic waste. The primary compound of concern is hydrogen sulfide (H_2S), although any compound containing sulfur should be considered when comparing sulfur intake to engine limits.

Table 3 provides a list of typical sulfur compounds.

Table 4 provides a summary of the sulfur tolerance limits for different gas engine models. Because the amount of fuel consumed by the engine varies with fuel heat value, these limits are indexed to lower heat value (LHV) for gas streams with LHV lower than typical pipeline natural gas (about 900 Btu/scf), as shown in Figure 4.

Sulfur compounds which condense out of the fuel gas are highly corrosive and will quickly damage and fail bright metal engine components. Condensation of the air fuel mixture in the aftercooler will lead to failure of the aftercooler core. Even more significant, sulfur compounds dissolved in the engine oil from blow-by gas will corrode the oil cooler, bronze and brass bushings and bearings and any internal engine components containing copper.

Even trace amounts of sulfur can significantly damage engine components. The high manifold pressures of high performance engines, like the G3500B, C, E, and H result in higher levels of condensation in the aftercooler. For these engines, a stainless steel aftercooler core is recommended when the fuel sulfur content is

above 0.14 ug H_2S /Btu or 3 ppm of H_2S @ 900 Btu/Scf. For all models, the gas should be treated as corrosive when sulfur content is above 0.45 ug H_2S /Btu or 10 ppm @ 900 Btu/Scf. as shown in **Figure 4**.

Special measures can be taken to make an engine more tolerant to sulfur and other corrosive compounds contained in the fuel. These measures are outlined in the Corrosive Gas guidelines discussion later in this section. When these guidelines are followed, the fuel sulfur level can be increased, depending on the fuel lower heating value (LHV). The maximum level of sulfur compounds, in terms of ppm vs. LHV.

When determining the sulfur level in a fuel, the number of sulfur atoms must be considered. As an estimate, this can be done by counting the sulfur atoms in a compound. Constituents with two sulfur elements, such as carbon disulfide (CS_2), should be counted at twice their ppm level.

For example, 20 ppm H_2S and 15 ppm CS_2 are equivalent to 50 ppm sulfur compounds:

$$1 \times 20 \text{ ppm } (H_2S) + 2 \times 15 \text{ ppm } (CS_2) = 50 \text{ ppm}$$

Refer to **Table 3** for the number of sulfur elements in a variety of sulfur compounds.

Maximum Level of Sulfur Compounds

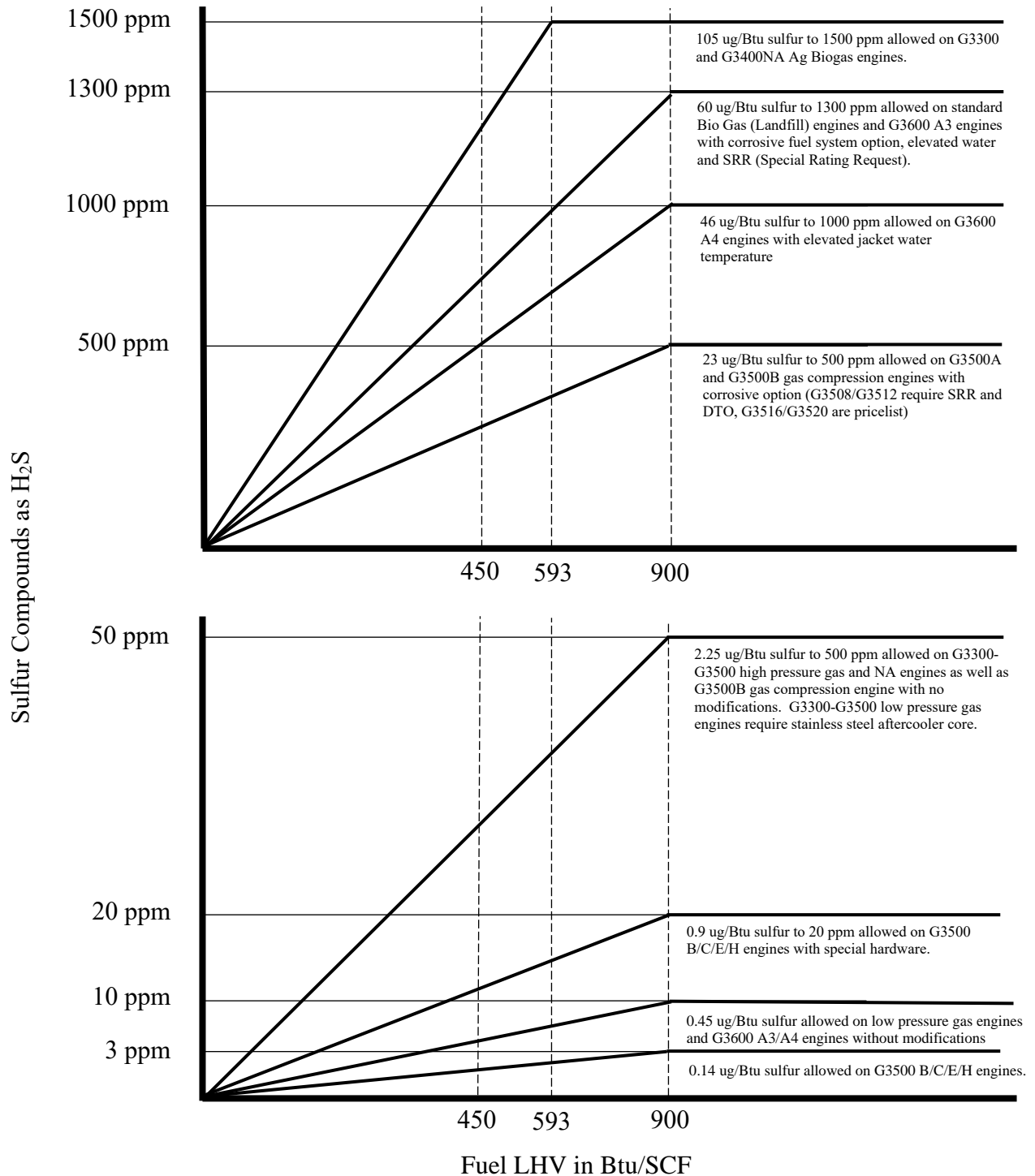


Chart showing “sliding scale” relationship of allowable sulfur levels in fuels with lower energy content. Below the reference LHVs shown above, allowable sulfur concentration decline with decreasing energy content to account for the increased amount of fuel that must be consumed to make power. Sulfur concentrations in ug/Btu (micrograms/Btu) represent the slope of the sliding scale portion of each graph line

Figure 4

| Typical Sulfur Compounds | | |
|-----------------------------------|--|--------------------------|
| Compound Name | Chemical Formula | Sulfur Atoms in compound |
| Carbon Disulfide | CS ₂ | 2 |
| Carbonyl Sulfide | COS | 1 |
| Dimethyl Disulfide | C ₂ H ₆ S ₂ | 2 |
| Dimethyl Sulfide | C ₂ H ₆ S | 1 |
| Ethyl Mercaptan (Ethanethiol) | C ₂ H ₆ S | 1 |
| Hydrogen Sulfide | H ₂ S | 1 |
| i-propyl Mercaptan (Propanethiol) | C ₃ H ₈ S | 1 |
| Methyl Ethyl Sulfide | C ₃ H ₈ S | 1 |
| Methyl Mercaptan (Methanethiol) | CH ₄ S | 1 |
| n-propyl Mercaptan (Propanethiol) | C ₃ H ₈ S | 1 |

Table 3

| H ₂ S Limits @900+Btu/scf LHV | | | | |
|--|------------|-------------------|-------------------|------------------|
| Series | Aspiration | Notes | Standard Hardware | Special Hardware |
| All H ₂ S values are ppm | | | | |
| G3300 | NA | LPG | 0-50 | N/A |
| G3300 | TA | LPG | 0-10 | 10-50 |
| G3300 | TA | HPG | 0-10 | 10-50 |
| G3400 | NA | LPG | 0-50 | N/A |
| G3400/CG137 | TA | LPG | 0-10 | 0-50 |
| G3400 | TA | HPG | 0-50 | N/A |
| G3500 | NA | LPG | 0-50 | N/A |
| G3500A | TA | LPG | 0-10 | 10-50 |
| G3500A | TA | HPG | 0-50 | N/A |
| G3516A | TA | Landfill | 60 ug/Btu | |
| G3500B | TA | Petro | 0-50 | 50-500 |
| G3500B | TA | Genset | 0-3 | 4-20 |
| G3500C | TA | Genset | 0-3 | 4-20 |
| G3520C | TA | Landfill | 60 ug/Btu | |
| G3500E | TA | Genset | 0-3 | 4-20 |
| G3500H | TA | Genset | 0-3 | 4-20 |
| G3600 TA | | A3 Control System | 0-10 | 10-1300 |
| G3600 | TA | A4 Control System | 0-10 | 10-1300 |

Table 4

LPG = low pressure gas
 HPG = high pressure gas

Halide Compounds

Landfill gas may contain halogenated hydrocarbons, which contain chlorine, fluorine, bromine or some combination of the three. The most common halogenated hydrocarbons are referred to as chlorofluorocarbons (CFC's) and have been widely used in the refrigerant industry. Refrigerant 12, the most common refrigerant, has the chemical name dichlorodifluoromethane (CCl_2F_2) and the trade name Freon-12. Refrigerant 11 and 22 are also similarly composed and have been widely used. Paint thinners, degreasers, aerosol cans, refrigerators, and air conditioners are all sources for CFC's and other hydrocarbons. Very few of the halogenated hydrocarbons are formed from the decomposition of plastics and other petroleum-based materials.

When the CFC's are burned within the engine, chlorine and fluorine are released during the combustion process, then react with water, and finally form hydrochloric acid (HCl) and hydrofluoric acid (HF). Both these acids are very corrosive to internal engine components. Excessive levels of HCl or HF acid result in accelerated piston ring, cylinder liner, exhaust valve stem, and valve guide wear.

These hydrocarbons are heavier molecules than the methane and

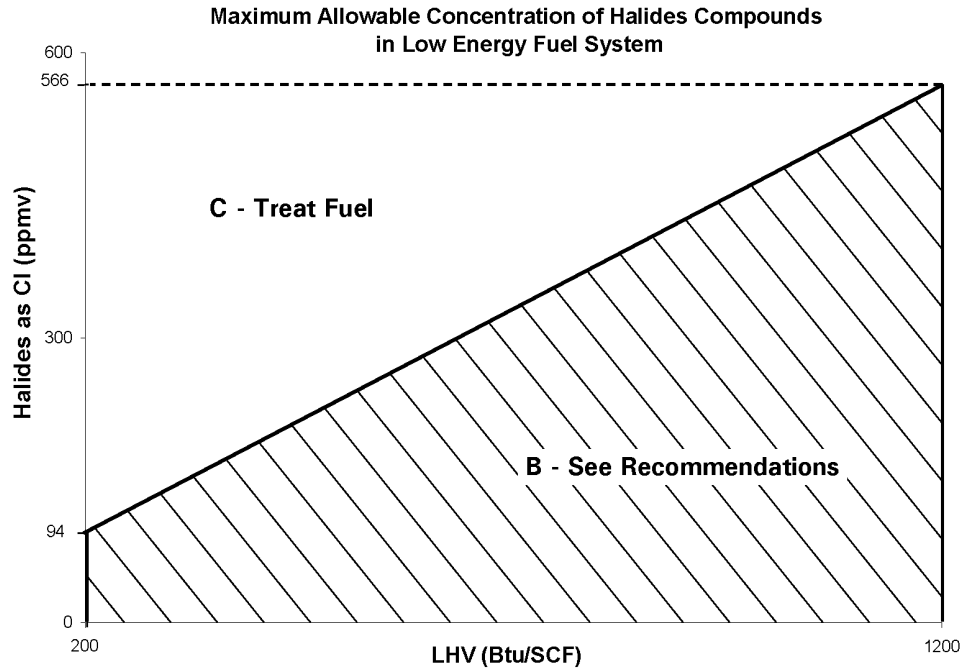
CO_2 . They tend to remain in the landfill until the landfill gas is collected. Once gas is drawn from the field, the hydrocarbons are evaporated into the moving gas stream until they are depleted. Measurements from producing landfills indicate the volatile hydrocarbons drop to 10 - 25% from their original levels after one or two years of gas production.

Note: The standard engine configuration cannot tolerate any halides; they can cause serious damage to the engine. However, special fuel system configurations were developed for landfill applications that provide **some** protection from halides.

Table 5 provides acceptable halide levels for the special configurations. These special configurations have a halide limit of 20 $\mu\text{g}/\text{Btu}$ (19 mg/MJ) of halides as Cl.

The level of halides is given in mass divided by the fuel energy content, or micrograms of chlorine and fluorine per low heating value of the gas. This is the total amount of chlorine and fluorine present in all the various compounds that may carry halides. See **Figure 5** for the maximum acceptable level.

Note: If this level is exceeded at any time through the lifetime of the project, serious damage may occur to the engine.

**Figure 5**

When determining the halide level in a fuel, the number of CL, F and Br atoms must be considered. As an estimate, this can be done by counting these atoms in a compound. Constituents with one chlorine element, such as vinyl chloride (C_2H_3Cl), should be counted once, while constituents with two chlorine and two fluorine elements, such as dichlorodifluoromethane (CCl_2F_2), should be counted four times, twice for each of the two element constituents.

Typical halide compounds are shown in **Table 5**.

For example, 10 ppm C_2H_3Cl and 20 ppm CCl_2F_2 are equivalent to 90 ppm halide compounds:

$$1 \times 10 \text{ ppm } C_2H_3Cl + 4 \times 20 \text{ ppm } CCl_2F_2 = 90 \text{ ppm}$$

Refer to **Table 5** for the number of chlorine elements in a variety of halide compounds.

| Typical Halide Compounds | | |
|--|--|------------------------------|
| Compound Name | Chemical Formula | Cl, F & Br Atoms In Compound |
| 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 |
| 1,1,2,2-Tetrachloroethane | C ₂ H ₂ Cl ₄ | 4 |
| 1,1,2-Trichloroethane | C ₂ H ₃ Cl ₃ | 3 |
| 1,1-Dichloroethane | C ₂ H ₄ Cl ₂ | 2 |
| 1,1-Dichloroethene | C ₂ H ₂ Cl ₂ | 2 |
| 1,2-Dichloroethane | C ₂ H ₄ 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 |
| Bromofluorobenzene | 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 |
| Chloroethane (Ethyl Chloride) | C ₂ H ₅ Cl | 1 |
| Chloroform (Trichloromethane) | CHCl ₃ | 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 |
| Total 1,2-Dichloroethenes cis-1,2-Dichloroethene trans-1,2-Dichloroethene | C ₂ H ₂ Cl ₂ | 2 |
| Total Dichlorobenzenes o-Dichlorobenzene m-Dichlorobenzene p-Dichlorobenzene | C ₆ H ₄ Cl ₂ | 2 |
| Total Trichlorobenzene 1,2,3-Trichlorobenzene 1,2,4-Trichlorobenzene 1,3,5-Trichlorobenzene | C ₆ H ₃ Cl ₃ | 3 |
| Trans-1,3-Dichloropropane | C ₃ H ₆ Cl ₂ | 2 |
| Trichloroethene (Trichloroethylene) | C ₂ HCl ₃ | 3 |
| Trichlorofluoromethane (Freon-11) | CCl ₃ F | 4 |
| Vinyl Chloride (Chloroethene) | C ₂ H ₃ Cl | 1 |

Table 5

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 ±0.002%, not including inaccuracy introduced at the sample withdrawing and depositing. Caterpillar recommends the follow laboratory for halogen and hydrogen sulfide testing:

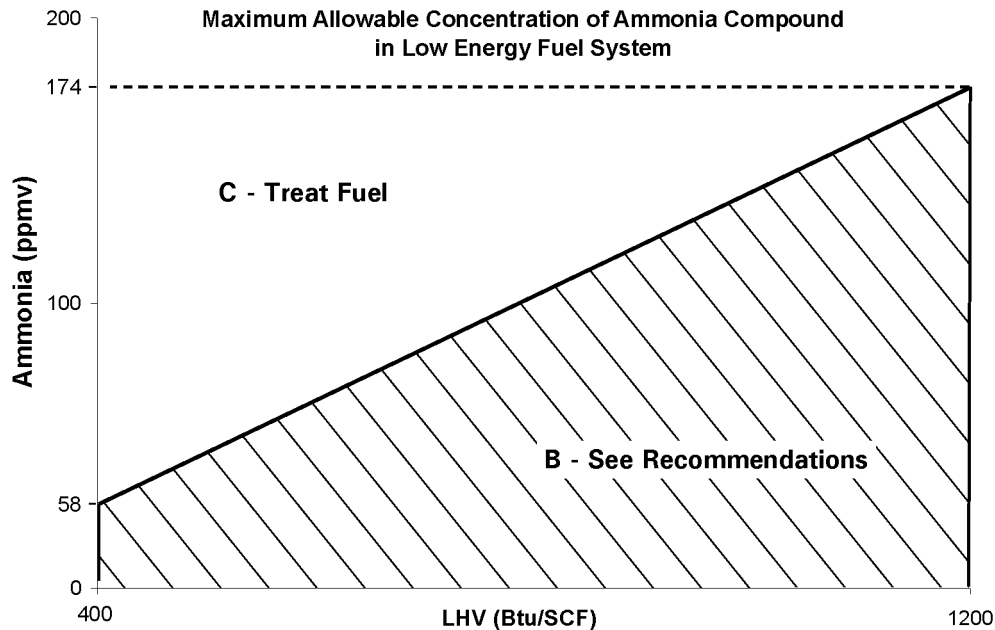
Core Laboratories- Houston
Attention: Gas Analysis Chemist
6310 Rothway Drive
Houston, TX 77040
(713)690-4444 phone
(713)690-5646 fax

If the chlorine, fluorine or bromine level exceeds the maximum shown in **Figure 5**, 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.

Ammonia Compounds

Natural gas fuel may contain nitrogen compounds, that when hydrogen is present, can combine to form base compounds. The two compounds of concern are Ammonia (NH₃) and Acrylonitrile (C₃H₃N) that can easily be converted into ammonia in gaseous fuels.

Note: The standard engine configuration cannot tolerate ammonia; it can cause serious damage to the engine. However, special fuel system configurations were developed for landfill applications that provide some protection from ammonia. These special configurations have an ammonia limit of 2.96 µg/Btu (2.81 mg/MJ) of NH₃.

**Figure 6**

The maximum level of nitrogen compounds in terms of ppm vs. LHV is given in **Figure 6**.

When determining the ammonia level in a fuel, ammonia (NH_3) and acrylonitrile ($\text{C}_3\text{H}_3\text{N}$) should both be counted only once.

For example, 50 ppm NH_3 and 10 ppm $\text{C}_3\text{H}_3\text{N}$ are equivalent to 60 ppm ammonia compounds:

$$1 \times 50 \text{ ppm } (\text{NH}_3) + 1 \times 10 \text{ ppm } (\text{C}_3\text{H}_3\text{N}) = 60 \text{ ppm}$$

Any fuel in region "C" of **Figure 6** must be treated to remove the excess Ammonia.

Water

Water can be damaging to the engine in any form - liquid or vapor. Water vapor is a very common constituent in gases and should be taken into account whenever evaluating a gas stream for its potential as engine fuel. Water vapor can combine with organic compounds or carbon dioxide form

acids that can be very corrosive to the gas handling equipment as well as to the engine.

Condensation of water is not permitted in the engine and should be avoided at all points in the fuel delivery system. If the risk of condensation is too great, the fuel must be treated to reduce its water content.

Silicon

Silicon, the second most abundant element on the earth, is commonly found in sand, quartz, flint, granite, glass, clay, and mica. If ingested into an engine, microscopic pieces of these compounds can cause abrasive wear leading to significant damage. Gaseous compounds containing silicon are man made and can form deposits in the combustion chamber and exhaust system of an engine. Both types of silicon ingestion are discussed below.

Silicon Crystals

Depending upon the landfill cover material, the climate, and the velocity of the gas within the fill, significant levels of microscopic silicon crystals can be carried with the gas. Generally, this silicon is less than one micron in size. The particles are generally too small to cause significant abrasive wear within the engine. However, if the silicon particles are in high enough density, they can combine with other elements, including elements found in oil additives, in the combustion process and form larger particles. These larger particles can result in abrasive wear of the exhaust valve face and valve seat. The compound silicon particles can also form indentations on the exhaust valve face and seat if they become trapped between those surfaces during valve closure. These indentations or pitting of the valve face and seat may result in eventual leakage or guttering of the valve. Engine oil should be analyzed for silicon.

Filtration is recommended to control the silicon. Filters with 100% effectiveness of particles 1.0 micron (1 micron equal 10^{-6} meters) and larger are recommended. Even with this filtration equipment, significant amounts of silicon can still enter the engine. The silicon will be detected in the oil analysis results. See Lubrication section of this guide for further information.

Silicon Containing Gases

The more difficult silicon to deal with enters the engine in gaseous compounds containing silicon. The most common class of gaseous silicon compounds known to exist in landfills and in landfill gas are siloxanes.

Siloxanes are organic compounds composed of silicon, oxygen, and methyl groups with structural units of $-(\text{CH}_3)_2\text{SiO}-$, and molecular weights typically in the range of 150 to 600. Solubility decreases as the molecular weight increases. Siloxanes may be volatile or non-volatile. In the US, they are not regulated by the environmental protection agency (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.

During combustion, the siloxane molecules break down, freeing the silicon and oxygen molecules to an unstable monatomic state. They can then form a deposit by combining with various other elements that may be present in the cylinder during combustion. X-ray diffraction of deposits shows a mostly amorphous composition of silica (SiO_2) and silicates. The elemental composition of a deposit has a high level of silicon plus elements commonly found in oil additives and wear metals from the engine, such as 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. In the combustion chamber, deposits can on the valve faces. This will lead to excessive valve recession due to the grinding action of the silica on the valve and valve seat. Deposits may also lead to valve guttering. This occurs when a portion of thick deposit on the valve face chips away. This leaves a path for the combustion gases to pass through when the valve is closed; creating a torch effect that literally melts a part of the valve. 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 to plastic from brittle. Deposits on the turbine can cause bearing failure due to imbalance and can cause turbine wheel erosion due to buildup between the wheel and housing. Deposits may also mask catalyst or heat recovery equipment located in the exhaust stream.

The maximum amount of silicon permitted in the gas for standard engines is shown in **Table 2**. For low energy fuel engines, the limits are 0.56 mg Si/MJ (0.60 µg Si/Btu). If the silicon level in the gas exceeds this amount, serious damage to the engine may occur. Silicon levels may vary throughout the lifetime of the landfill project. 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. The following section describes the procedure to determine the level of silicon in landfill gas.

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, mineral oil. The absorption agent is then sent to a lab for analysis to confirm 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.

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

or

Spectro / Jet-Care
Hatchwood Place, Farnham Road,
Odiham,
Hampshire, RG29 1AB, UK
44 (0) 1256 704000 Phone
44 (0) 1256 704006 Fax

If the total silicon level in the sample exceeds the limit shown in **Table 2**, 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, a water wash, or water injection into the engine, has been shown to reduce siloxane caused buildups. Water is sprayed into the intake. The added water vaporizes in the combustion process, cleaning deposits from the combustion chamber. Water injection has been used to clean existing buildups and has been used 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 the product of reverse osmosis cleaning. Raw water will lead to severe deposits of calcium throughout the engine.

Caution must be used if water injection is used to clean existing buildups. Pieces of a deposit may break loose, guttering valves and damaging the turbochargers. Use low water injection rates until deposits are removed. The factory can provide further guidelines regarding water-wash.

Corrosive Gas Guidelines

The following modifications to the operating and maintenance practices and engine hardware will significantly increase its tolerance to corrosive elements introduced in the fuel.

- Maintain the coolant outlet temperature at 110°C (230°F). Temperature rise across the engine should be no more than 8.3°C (15°F), and a 5.6°C (10°F) rise is desirable. Water and sulfur oxides are formed during combustion and will condense on cylinder walls at low temperature. The higher jacket water temperature will minimize the amount of condensation. Engines equipped with inlet control cooling systems will maintain outlet temperatures 110°C (230°F) range. Engines with outlet control cooling systems may require additional external controls to maintain 110°C (230°F) outlet temperatures. Elevating coolant temperatures may not be an option and all engine models, such as the G33/3400. Contact Caterpillar before applying such changes.
- Maintain the temperature of the oil in the sump high enough to prevent water from condensing in the oil. Maintaining the jacket water outlet temperature at a minimum of 93°C (200°F) will normally accomplish this. Elevating oil temperatures may not be an option and all engine models, such as the G33/3400. Contact Caterpillar before applying such changes.
- Where it is possible to start the engine on sweet gas, bring the engine up to operating temperature on sweet gas, then switch to sour gas; reverse the procedure when shutting the engine down.
- Establish an oil analysis program to assure oil change periods are not extended beyond safe limits and that other problems are not overlooked. Cat Dealers are capable of establishing and conducting such programs.
- Use a gas engine oil designed for landfill applications. These oils include a specialized additive package suitable for corrosive gas applications. See the Cat Fluids service publications listed in the reference material to this section for more information on Caterpillar's oil recommendations.
- There is no known oil additive that can protect the internal bright metal engine components from H₂S attack. Positive crankcase ventilation has proven to reduce the H₂S attack of internal engine components. The ventilation system should positively remove the fumes from the crankcase and allow filtered air to enter the crankcase to dilute the levels of H₂S. Guidelines for crankcase ventilation systems are provided in the Crankcase Ventilation section of the Application and Installation Guide.
- When using an engine configuration which mixes air and fuel prior to the aftercooler, a stainless steel aftercooler core must be used.

Useful Conversions

To determine the amount of a particular atom contained in a compound, such as Cl from a particular Cl bearing compound,

$$\% \text{ Cl} = (\text{MW of Cl})(\text{number Cl atoms in compound})(100)/(\text{MW of compound})$$

$$\mu\text{g Cl/L} = (\text{concentration of compound } \mu\text{g/L})(\% \text{ Cl})/100$$

The same procedure can be used for other atoms and compounds.

To show the level of one contaminant as another, such as $\mu\text{g F}$ as $\mu\text{g Cl}$, (for use with Total Halogen levels):

$$\mu\text{g F as Cl} = (\mu\text{g F/L})(\text{MW of Cl})/(\text{MW of F})$$

To convert $\mu\text{g/Btu}$ to $\mu\text{g/L}$:

$$(\mu\text{g/Btu})(\text{LHV Btu/scf})/(28.3 \text{ L/scf}) = \mu\text{g/L}$$

To convert $\mu\text{g/L}$ to ppmv:

$$\text{ppmv} = (\mu\text{g/L}) (23.67)/(\text{MW})$$

Where:

ppmv = part per million volume

1 mole of gas contains 22.4 liters at 0°C, 101.3 kPa

1 mole of gas contains 23.67 liters at 15.5°C, 101.3 kPa

MW (molecular weight):

fluorine = 19

chlorine = 35.5

bromine = 79.9

iodine = 126.9

sulfur = 32

hydrogen = 1

1 ft³ = 28.3 L

1 m³ = 35.31 ft³

Common Fuels

Natural Gas (Pipeline)

By definition, natural gas is any gas that occurs organically within the earth and often is associated with oil reserves and/or oil production. In this Application & Installation Guide, natural gas is assumed to have certain properties. In this guide, natural gas is clean, dry, pipeline quality gas or treated field gas. Treated field gas is a gas that has been treated to remove the following elements.

- Particulate Matter
- Water
- Inert gases such as Carbon Dioxide (CO₂) and Nitrogen (N₂)
- Heavier Hydrocarbons

Removal of these elements from field gas provides a consistent, high quality gas with at least a 905 BTU value and an 80MN (Methane Number). This is the gas typically associated with household heating and cooking and purchased from a utility. This is also the BTU value gas used in all Cat natural gas engine technical data and rating sheets.

Field Gas

Natural gas in its original state is often referred to as field gas, wellhead gas, or wet gas. In the gas industry, the designation wet or dry does not refer to the presence or absence of water, but to the presence or absence of liquid hydrocarbons such as butane, pentane, etc. Before being marketed through the gas distribution pipelines, the wet ends are removed to provide what we often refer to as dry pipeline gas.

The composition of natural gas as it leaves the wellhead varies from one area, or gas field, to another. In each instance, it is a mixture of gases composed mostly of methane (CH₄) with varying percentages of ethane (C₂H₆), propane (C₃H₈), butane (C₄H₁₀), and usually small amounts of helium (He), carbon dioxide (CO₂), nitrogen (N₂), and in some fields hydrogen sulfide (H₂S).

Table 6 illustrates the variation in composition of natural gases from different fields, including an analysis of a typical dry pipeline gas.

Note that the quality of field gas is never constant. Field gases will vary not only from site to site, but also from minute to minute on a single well or field. Because engine fuel-air mixing systems are typically designed for a specific input fuel, larger variations can have detrimental effects on the engine. Any application fuel gas source that has an unacceptable amount of liquids or heavy hydrocarbons, or that exhibits notable swings in fuel composition may be a candidate for fuel treatment.

Fuel Treatment

The presence of water, heavy hydrocarbons or contaminants doesn't necessarily render a gas stream unusable as engine fuel. There are many gas treatment methods available that can remedy one or more of these issues - at a cost. Some, such as coalescers and scrubbers to remove excess water, are relatively inexpensive and simple to implement. Others for addressing certain contaminant compounds can be very involved and expensive. The challenge of

reducing the content of heavy hydrocarbons in a gas stream is often inversely proportional to the pressure of the stream. Higher pressures can make simpler, less expensive solutions possible. The

proper choice in each case will depend upon the economics of the project to determine if the fuel treatment technique required is worth the investment.

| Natural Gas Analysis - Percent by Volume | | | | |
|--|--------------------------|--------------------------|--------------------------|------------------------------|
| | Example A (Field Gas) | Example B (Field Gas) | Example C (Field Gas) | Example D (Dry, Pipeline) |
| Methane, CH ₄ | 75.23 | 76.00 | 89.78 | 92.20 |
| Ethane, C ₂ H ₆ | 12.56 | 6.40 | 4.61 | 5.50 |
| Propane, C ₃ H ₈ | 7.11 | 3.50 | 2.04 | 0.30 |
| Butane, C ₄ H ₁₀ | 3.38 | 0.67 | 0.89 | – |
| Pentane, C ₅ H ₁₂ | 0.69 | 0.30 | 0.26 | – |
| Hexane, C ₆ H ₁₄ | 0.40 | – | 0.21 | – |
| Heptane, C ₇ H ₁₆ | – | – | – | – |
| Nitrogen, N ₂ | 0.43 | 12.33 | 2.13 | 1.60 |
| Carbon Dioxide, CO ₂ | 0.20 | 0.40 | – | 0.40 |
| Others | – | 0.40 | 0.08 | – |
| | 100.00 | 100.00 | 100.00 | 100.00 |
| HHV (High heat value) Btu/SCF | 1,323.00 | 1,005.00 | 1,092.00 | 1,038.00 |
| LHV (Low heat value) Btu/SCF | 1,202.00 | 909.00 | 986.00 | 936.00 |
| Methane Number | 44.20 | 65.00 | 67.90 | 83.50 |

Table 6

Reference Material

The following information is provided as an additional reference to subjects discussed in this manual.

Media Numbers

LEBW5336: Gaseous Fuel Systems

LEKQ7260: Low Energy Fuels

LEKQ7742: Detonation and Preignition

LERW4485: Gas Engine Rating Procedure (GERP)

LEKQ9085: G3600 Engine Basics

LEKQ7518: G3500 Engine Basics

LEKQ7511: G3400 Engine Basics

SENR6517: Troubleshooting - G3500 Air/Fuel Ratio Control Engines with Electro

SEBU6400: Caterpillar Gas Engine Lubricant, Fuel, and Coolant Recommendations

Internal Combustion Engine

Fundamentals: Heywood, John B., New York, 1988.

REHS8184: Installation and Maintenance of Fuel Systems for Certain Gas Engines

KERN5186: Air/Fuel Ratio Control

Definitions

| | |
|-------------------------------------|---|
| BACT = | Best Available Control Technology |
| Bar = | 14.5 psi |
| BMEP | Brake Mean Effective Pressure |
| bhp-hr = | Base Horsepower per Hour |
| Btu/SCF | British Thermal Units per Standard Cubic Foot |
| C ₃ H ₃ N = | Acrylonitrile |
| CH ₂ O = | Formaldehyde |
| CH ₄ = | Methane |
| CO = | Carbon Monoxide |
| CO ₂ = | Carbon Dioxide |
| DWC = | Dry To Wet Conversion |
| DST = | Detonation Sensitive Timing |
| EIS = | Electronic Ignition System |
| EPA = | Environmental Protection Agency (USA) |
| H ₂ O = | Water |
| H ₂ S = | Hydrogen Sulfide |
| HAP = | Hazardous Air Pollutants |
| Lambda = | Air/Fuel Ratio |
| LHV = | Lower Heating Level |
| m ³ = | Meters Cubed = 35.3147 ft ³ at equal temperatures |
| mg = | Milligrams |
| mg/Nm ³ = | Milligrams per Normal Meter Cubed |
| MJ/Nm ³ = | Mega Joules per Normal Meter Cubed |
| Mole = | Molecular Weight |
| MW = | Molecular Weight = sum of atomic weights of all atoms in the molecule |
| N ₂ = | Nitrogen |
| NH ₃ = | Ammonia |
| Nm ³ = | Normal Cubic Meters = 1 m ³ @ 0°C and 101.3 kPaa (1013 mbar) |
| NMHC = | Non Methane Hydrocarbons |
| NMNEHC = | Non Methane, Non Ethane Hydrocarbons |
| NO = | Nitric oxide |
| NO ₂ = | Nitrogen dioxide |
| NO _x = | Oxides of Nitrogen |
| O ₂ = | Oxygen |
| O ₃ = | Ozone |
| ppm = | Parts Per Million |
| ppmv = | Parts Per Million By Volume |
| ppmvd = | Parts Per Million By Volume Dry |
| PSD = | Prevention of Significant Deterioration |
| SCF = | Standard Cubic Feet = 1 ft ³ @ 60°F and 14.696 psia (760 mm Hg) |
| SCR = | Selective Catalytic Reduction |
| SiO ₂ | Silica |
| SO ₂ = | Sulfur Dioxide |
| SO _x = | Sulfur Oxide |
| Stoichiometric/ Stoichiometric = | Theoretically Complete Combustion - The objective of stoichiometric combustion is to achieve complete fuel burn, with no oxygen fuel left over, after combustion. |
| THC = | Total Hydrocarbon |

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) | Nm ³ Gas/kg | Nm ³ Gas/L Liquid | kg/L Liquid | MJ/Nm ³ Vapor (LHV) | MJ/Nm ³ 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

Table C: Constituents of Gas by Volume

| Constituents of Gas by Volume - Percent | | | | | | | | | | | | |
|---|----------------|------|-----------------|-------------------------------|----------------|-----------------|----------------|--|--|---------------------|---|-------------------|
| | H ₂ | CO | CH ₄ | C ₂ H ₆ | O ₂ | CO ₂ | N ₂ | Btu/SCF LHV @ 60°F 14.696 psi | MJ/Nm ³ LHV @ 0°C 101.31 kPa | Vol Air/ Vol Gas | Btu/SCF of Correct Mixture (LHV) | Methane Number |
| Producer Gas | | | | | | | | | | | | |
| Anthracite Coal | 20.0 | 25.0 | – | – | 0.5 | 5.0 | 49.5 | 135 | | 1.05 | 65.85 | 53.30 |
| Bituminous Coal | 10.0 | 23.0 | 3.0 | 0.5 | 0.5 | 5.0 | 58.0 | 136 | | 1.12 | 64.25 | 66.70 |
| Coke | 10.0 | 29.0 | – | – | 0.5 | 4.5 | 56.0 | 120 | 4.74 | 0.90 | 63.15 | 60.30 |
| Illuminating Gas | | | | | | | | | | | | |
| Blue Water Gas | 50.0 | 43.3 | 0.5 | – | – | 3.0 | 3.2 | 280 | | 2.27 | 85.63 | 5.20 |
| Carbureted Water Gas | 40.0 | 19.0 | 25.0 | 8.5 | 0.5 | 3.0 | 4.0 | 526 | | 4.97 | 88.10 | 2.60 |
| Coal Gas | 46.0 | 6.0 | 40.0 | 5.0 | 0.5 | 0.5 | 2.0 | 584 | | 5.74 | 86.64 | 5.20 |
| Oil Gas | 32.0 | – | 48.0 | 16.5 | 0.5 | – | 3.0 | 772 | | 7.66 | 89.14 | -1.50 |
| By-Product Gas | | | | | | | | | | | | |
| Coke Oven Gas | 53.0 | 6.0 | 35.0 | 2.0 | – | 2.0 | 2.0 | 513 | | 5.02 | 85.21 | 12.70 |
| Blast Furnace Gas | 5.2 | 26.8 | 1.6 | – | 0.2 | 8.2 | 58.0 | 115 | | 0.90 | 60.50 | 76.70 |

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