CATERPILLAR®

Gas Engines Application and Installation Guide

G3600–G3300

- Fuels
- Fuel Systems

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G3600–G3300 Fuels

Fuels

Most of the fuels used in internal combustion engines today, whether liquid or gaseous, are composed primarily of hydrocarbons (hydrogen and carbon); their source is generally petroleum. Natural gas is the most popular and widely used of the petroleum gases. Digester gas (also a hydrocarbon) and some manufactured gases (from coal), which contain hydrocarbons, are also used in engines with varying degrees of success. Digester gas is the most practical of the manufactured or by-product group.

Each commercial fuel gas is a mixture of gases, some combustible and some inert. The different mixtures have extremely wide variations in composition. Consequently, it is necessary to closely examine the characteristics and behavior of an individual gas.

Fuel Characteristics

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}

Most of the important fuel gases used in engines today are of the Paraffin series. This includes both natural gas and digester gas. This series starts with methane (CH_4); each succeeding member of the series has one more carbon (C) atom and the corresponding number of hydrogen (H) atoms, etc. The normal Paraffin hydrocarbons are said to have *straight chain* molecular structures, having one bond between each atom. The first four of the Paraffin series would have structures as follows:

H	H H	H H H	H H H H
H-C-H	H-C-C-H	H-C-C-C-H	H-C-C-C-C-H
H	H H	H H H	H H H H
Methane	Ethane	Propane	Butane
CH_4	C_2H_6	C_3H_8	C_4H_{10}

As the number of atoms increases, the molecular weight of the molecule increases and the hydrocarbons are said to become heavier. Their physical characteristics change with each change in molecular structure. Only the first four of the Paraffin series are considered gases at standard conditions of 101.31 kPa (14.696 psia) and 15.55°C (60°F). Several of the others can be easily converted to gas by applying a small amount of heat.

Standard Condition of a Gas

It is important to note that when standard conditions are referenced, it means 101.31 kPa (14.696 psia) and 15.55°C (60°F). When a gaseous fuel flow is stated in SCF, it means standard cubic feet (or standard cubic meters - SCM) and is referenced to a gas at standard conditions. In some places, Europe for example, gas is referenced to 101.31 kPa (14.696 psia) and 0°C (32°F). When gases are referenced to 0°C (32°F), the units are called normal cubic meters (NM^3) or normal cubic feet (NF^3).

Heat Value

Heat value is defined as the amount of energy (heat) released during the combustion of a fuel with the correct amount of oxygen (air). It is determined with a device called a calorimeter. A known quantity of fuel and oxygen are combined in a calorimeter and burned. Heat is generated and, the water produced (from the combustion of fuels containing Hydrogen; either C_x H_y or H_2) is condensed. The heat measured by the calorimeter is called the high heat value of the fuel (also referred to as the gross heat value).

It is important to understand the difference between high and low heat value since engine manufacturers typically use low heat value when discussing fuels and engine data. A discussion of heat value as it relates to the internal combustion engine may help provide a better understanding of the difference between high and low heat value.

When any hydrocarbon is used as fuel in an internal combustion engine, one of the products of combustion is water. The amount of water formed during combustion varies for the different hydrocarbon fuels. This will be illustrated later. The water formed is converted into steam by the combustion heat before leaving the engine, and carries with it the quantity of heat used to convert the water into steam. This quantity of heat absorbed in changing water, at a given temperature to steam or vapor, is known as the *latent heat of vaporization*. The latent heat of vaporization is lost to the engine, since the exhaust temperature is always above the dew point. The engine has no opportunity to convert this heat into work. The amount of heat that is left over for the engine to convert to work is called the *low heat value* of the fuel (also referred to as the net heat value). Low heat value can be calculated as the high heat value minus the latent heat of vaporization.

Methane Number

Many gases, including natural gas, landfill gas, digester gas, propane, etc. can be effectively used in Caterpillar Gas Engines. Different gas compositions require different compression ratios and ignition timings, or may require that the engine be derated. Some fuels may not be usable at all.

Caterpillar, over the years, has used a number of approaches to analyze gaseous fuels to determine their suitability for combustion in reciprocating engines. One of the first methods used was the *Octane Rating* method, which indicates the knock resistance of a gaseous fuel. This was adapted by the gas engine industry from petroleum reciprocating engine technology and compared unknown gaseous fuels with liquid reference fuels.

The methodology multiplies the percentage mole volume of each constituent in a gas by its *Octane Rating* number and then sums these values, (obtained from comparing the individual component gases to octane). It incorrectly assumes the octane contribution for the constituents is linear. This method also does not take into account constituents with knock resistance characteristics, such as carbon dioxide.

In the past, the *Octane Rating* method has been an acceptable fuel analysis when applied to pipeline and similar gases. With today's growing market opportunities and wider range of gases available, it has limited uses and restricts the engines to known gases. Some gas engine manufacturers still use the *Octane Rating* method to analyze gaseous fuels despite these shortcomings. A more reliable method was needed to evaluate gaseous fuels.

In the mid 1980s, Caterpillar adopted the *Methane Number* approach for analyzing gases in research and development work. We found good results and consistent engine performance on a much broader range of gases than the Octane Rating method.

The *Methane Number* analogy was developed in Austria in the mid 1960s. It compares the unknown resistance to knock of gaseous fuel with the knock resistance of gaseous reference fuel. Using two reference gases, methane with greatest resistance to knock characteristics and hydrogen as the knock-prone component, a methane number can be assigned to any gaseous fuel. This is achieved by matching the knock characteristics of the unknown gaseous mixture to the knock characteristics of a blend of the two reference gases. The percentage of methane in the reference gas mixture is the methane number of the unknown gas.

After extensive research and testing on field gases to landfill gases, Caterpillar has found the *Methane Number* analogy to be an accurate and reliable assessment when analyzing fuels. Caterpillar considers it the most advanced technology in this field. It has proven to be a clear competitive advantage.

Calculation of the *Methane Number* is difficult and time consuming. An approximation method was developed called the *Caterpillar Gas Value* number. The method was developed only for the G3408 and G3412 Engines. It was limited to certain gases and similar to the *Octane Rating* method, did not take into account fuels that have knock resistance constituents. In 1989 Caterpillar developed a computer program to perform the calculations and allow field determination of the *Methane Number.* The program inputs gaseous constituents from the sample taken from the supply gas for the engine, and calculates the methane number, the LHV, the wobbe index, and the relative power capability compared to 35.6 MJ/Nm^3 (905 Btu/ft^3) fuel.

Methane numbers of some individual component gases are:

Methane	CH_4	100
Ethane	C_2H_6	44
Propane	C_3H_8	32
Butane	(commercial)	15
n-Butane	C_4H_{10}	10
Hydrogen	H_2	0

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.

Air Required for Combustion

As indicated by Figure 1, each combustible gas requires a definite volume of air for complete combustion of a given volume of the gas. This exact amount of air combined with a given amount of gas is called the stoichemetric air-fuel ratio (or chemically correct air-fuel ratio). There is a chemically correct air-fuel ratio for each gas. This ratio varies for the different gases. An understanding and working knowledge of this part of the chemistry of combustion is as important to the application engineer as to the design engineer. This will become evident later in the discussion.

To determine the minimum amount of air required for complete combustion, refer to the combustion equation for methane:

$$CH_4 + 2\ O_2 = 2\ H_2O + CO_2.$$

We are interested in the *volume* of O_2 and, in turn, the volume of air the required O_2 represents. The coefficients in the combustion equation (the number of molecules) give the combining *volumes* of the gaseous components. Thus, one Ft^3 ($0.0283m^3$) of CH_4 requires two Ft^3 ($0.0566m^3$) of O_2. Since air is 20.99% of O_2 by volume, the 2 Ft^3 ($0.0566m^3$) of O_2 represents:

$$\frac{2}{0.2099} = 9.52F^3 \text{ of air}; \qquad \frac{0.0566}{0.2099} = 0.269m^3 \text{ of air}$$

This is the air required theoretically for complete combustion of one Ft^3 ($0.0283m^3$) of CH_4. A little excess air is usually provided for most gases to ensure complete combustion.

The same results derived here can also be determined using the molecular weights to first determine the weight of air required, then converting the weight of air to volume of air. The *volume* method is less complex.

As stated earlier, most fuel gases are mixtures of several gases. Each component gas *has* different characteristics. Determination of the amount of air required per unit volume of a mixture of gases requires that the different characteristics of components be recognized. For example, assume that a given fuel gas has the following analysis by volume:

Methane (CH_4)	=	90%
Ethane (C_2H_6)	=	5%
Propane (C_3H_8)	=	3%
Carbon Dioxide (CO_2)	=	2%

The air required for one Ft^3 ($0.0283m^3$) of the gas can be calculated as follows (using data from Figure 1):

CH_4 0.90 x 9.53	=	8.5770
C_2H_6 0.05 x 16.67	=	0.8335
C_3H_8 0.03 x 23.82	=	0.7146
Total cu ft Air Required	=	10.1251

The value and use of air-fuel ratio data will be illustrated in a later paragraph dealing with heat values of chemically correct air-fuel mixtures and the relation of heat value to engine output.

Physical Properties of Gases

					Gas Density, 60°F, 14.696 psia		Heat Value: At 60°F						
Gas	Formula	Boiling Point at 14.696 psia	Specific Gravity (Air = 1)	cu ft Gas/lb	cu ft Gas/gal Liquid	lb/gal Liquid	Btu/cu ft Vapor at 14.696 psia (LHV)	Btu/cu ft Vapor at 14.696 psia (HHV)	Btu/lb Liquid (LHV)	Btu/gal Liquid (LHV)	Air Required For 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	999.40	1,010.0	21,511.0	53,778	9.53	5.00	15.00
Ethane	C_2H_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_3H_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_4H_{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_4H_{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_5H_{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_5H_{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_6H_{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_7H_{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_8H_{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_2S	–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	—	—	—	—	—	—	—

*Approximate Value

Figure 1a.

Physical Properties of Gases (Metric Values)

Gas Specific Volume													
Gas	Formula	Boiling Pt at 101.3 kPa` deg C	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_2H_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_3H_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_4H_{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_4H_{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_5H_{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_5H_{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_6H_{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_7H_{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_8H_{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_2S	–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

Figure 1b.

Composition of Natural Gases

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_2H_6	12.56	6.40	4.61	5.50
Propane C_3H_8	7.11	3.50	2.04	0.30
Butane C_4H_{10}	3.38	0.67	0.89	—
Pentane C_5H_{12}	0.69	0.30	0.26	—
Hexane C_6H_{14}	0.40	—	0.21	—
Heptane C_7H_{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	1,333.00	1,010.00	1,096.00	1,041.00
LHV (Low heat value) Btu/SCF	1,202.00	909.00	986.00	937.00
Methane Number	42.20	66.70	69.00	82.80

Figure 2.

Common Fuels

Natural Gas

The composition of natural gas as it leaves the well head varies from one area, or gas field, to another. In each instance, it is a mixture of gases composed mostly of methane (CH_4) with varying percentages of ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and usually small amounts of helium (He), carbon dioxide (CO_2), nitrogen (N_2), and in some fields hydrogen sulfide (H_2S). Natural gas in its original state is often referred to as *field* gas, *well* head 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 energy content of pipeline natural gas is determined by the molar or volume percentages of methane, ethane, and propane in the mixture.

To obtain better understanding of natural gas, it is necessary to review the physical characteristics of the individual gases usually found in natural gas. Figure 1 shows some of the more important physical constants of component gases which are often found in gaseous fuel mixtures, including natural gas.

Figure 2 illustrates the variation in composition of natural gases from different fields. An analysis of a typical *dry* pipeline gas is also represented in Figure 2. These gas analyses will have more meaning after a more thorough study of the heat value and combustion characteristics of the various gases.

Low heat value (LHV) of a gas is the high heat value less the heat used to vaporize the water formed by combustion. This applies whether the gas is a single hydrocarbon (or any other gas which forms water as a product of combustion) or a mixture of hydrocarbons.

The amount of heat (per unit volume) lost in vaporizing the water is different for different gases. This variable must be eliminated if the engine manufacturer is to provide reliable fuel consumption data. This explains why all engine manufacturers use low heat value for gaseous fuels. Contrary to the common misconception that low heat value is used merely to make the fuel consumption data appear more favorable, the practice universally used by engine manufacturers does have a very sound engineering basis.

A brief examination of the combustion equation using pure methane (CH_4), the main constituent of natural gas, will illustrate this point further. The equation for combustion of methane is as follows:

$$CH_4 + 2\,O_2 = 2\,H_2O + CO_2$$

To determine the amount of water formed, first determine the molecular weight of each gas as noted here:

$$\begin{array}{ccccccc} CH_4 & + & 2\,O_2 & = & 2\,H_2O & + & CO_2 \\ 16 & & 64 & = & 36 & & 44 \end{array}$$

The molecular weight of a substance expressed in kilograms (pounds) is known as a mol. Thus, 1 mol of methane (16 kg or 16 lb) when combined during combustion with 2 mols of oxygen (64 kg or 64 lb), will form 2 mols of water (36 kg or 36 lb) plus 1 mol of CO_2 (44 kg or 44 lb). Therefore, for each unit mass of CH_4 burned:

$$\frac{36}{16} = 2.25 \text{ kg (lb) of water are formed per kg (lb) of } CH_4.$$

To determine the amount of water formed per SCM (SCF) of CH_4 burned, divide 2.25 kg (lb) by the specific volume (m^3/kg or Ft^3/lb) of gas at standard conditions of temperature and pressure. For methane,

1kg = 1.4738 SCM (1 lb = 23.61 SCF). Therefore,

$$\frac{2.25}{23.61} = 0.09529 \ \frac{(\text{lb } H_2O)}{(\text{SCF } CH_4)}; \quad \frac{2.25}{1.4738} = \frac{1.526 \text{ kg } H_2O}{\text{SCM } CH_4}$$

of water formed per SCM (SCF) of methane burned. The difference between high and low heat value for CH_4 is the heat required to convert 1.526kg (0.09529 lb) 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. Therefore, the difference between HHV and LHV of CH_4 is: 0.09529 x 1059.9 = 101 Btu/SCF (3.763 MJ/SCM). Note that Figure 1 reflects this difference in HHV and LHV for CH_4.

As an example of the variation in the amount of water formed during the process of combustion for different hydrocarbons , compare the results of burning propane (C_3H_8) with the results just calculated for methane:

$$\underset{44}{C_3H_8} + \underset{160}{5\,O_2} = \underset{132}{3\,CO_2} + \underset{72}{4\,H_2O}$$

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

$$\frac{72}{44} = 1.6363 \text{ lb (kg) } H_2O \text{ / kg (lb) Propane}$$

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

$$\frac{1.636 \text{ lb } H_2O \text{ / lb } C_3H_8}{8.471 \text{ SCF/lb } C_3H_8} = \frac{1.1931 \text{ lb } H_2O}{\text{SCF } C_3H_8}$$

$$\frac{1.636 \text{ kg } H2O \text{ / kg } C_3H_8}{0.5288 \text{ SCM/kg } C_3H_8} = \frac{3.0937 \text{ kg } H_2O}{\text{SCM } C_3H_8}$$

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

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

Energy lost per SCM (SCF) C_3H_8 burned
= 0.1931 x 1059.9 = 204 Btu/SCF C_3H_8
(7.6 MJ/SCM C_3H_8)

Examination of Figure 1 will confirm that this is the difference between HHV and LHV for propane. Comparing again to methane, the heat lost to the engine per SCM (SCF) of gas burned is higher for propane, 204 Btu/SCF versus 101 Btu/SCF CH_4 (7.6 MJ/SCM C_3H_8 versus 3.76 MJ/SCM CH_4).

Sour Gas

Sour gas generally refers to fuels containing a high concentration of sulfur compounds (above 10 ppm), primarily hydrogen sulfide (H_2S). Fuels such as field, digester, bio-mass, or landfill gas generally fall in this category. Sweet gases are fuels with low concentrations of sulfur compounds (below 10 ppm).

Sweet gases can be used in an engine without any additional treatment or changes to the engine. However, sour gases require the appropriate operation parameters and maintenance schedule, outlined below. The maximum level of H_2S allowed under any circumstances is given by Figure 3.

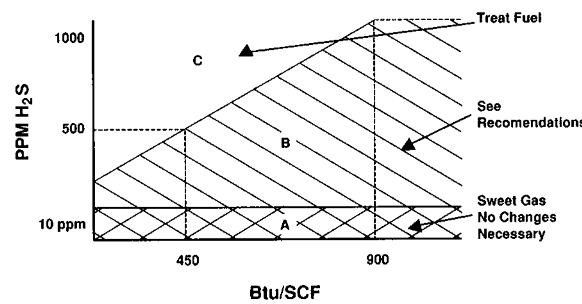

Figure 3.

Any fuel in the section "C" of the graph must be treated to remove the excess H_2S.

If gas with excessive sulfur levels is used as a fuel, sulfur compounds could be dissolved in the oil from blow-by gas and cause corrosive attack on internal engine components. The corrosion usually is caused by a direct H_2S attack of the bright metals within the engine, such as the oil cooler and bronze/brass bushings or bearings. This direct H_2S attack cannot be deterred by high TBN oils or controlled by oil analysis. There are various devices available to reduce H_2S in the fuel gas such as chemically active filters, reactive beds, and solutions. The performance of most of these devices deteriorates as the reactive chemicals are depleted. The device then requires servicing or replacing to maintain an effective level of H_2S removal. It is recommended that even though a fuel gas is scrubbed to pipeline level of H_2S, the precautions listed below should be taken for high sulfur fuels to protect against those intervals when the chemical scrubbers deteriorate and require servicing. Even brief intervals of operation with high sulfur fuel without precautions can damage the engine.

- Maintain the coolant outlet temperature between 96°C and 102°C (205°F and 215°F). Temperature rise across the engine should be no more than 15°F, and a 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 temperature will minimize the amount of condensation. Engines equipped with inlet control cooling systems will maintain outlet temperatures in the 96°C and 102°C (205°F and 215°F) range. Engines with outlet control cooling systems may require additional external controls to maintain 96°C and 102°C (205° to 215°F) outlet temperatures.

- Maintain the temperature of the oil in the sump high enough to prevent water from condensing in the oil. Normally, maintaining the jacket water outlet temperature at a minimum of 93°C (200°F) will accomplish this.

- Establish an oil analysis program to assure oil change periods are not extended beyond safe limits and that other problems are not overlooked. Caterpillar Dealers are capable of establishing and conducting such programs.

- A CD grade oil with less than 1% sulfated ash can be used instead of oils normally used in natural gas engines. CD oil has a higher TBN (which indicates its ability to neutralize acids formed from products of combustion of sulfur compounds) than normal gas engine oil.

- 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.

- There is no known oil additive that can protect the internal bright metal engine components from H_2S attack. A positive crankcase ventilation has proven to successfully reduce the H_2S 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 H_2S. Guidelines for installing and sizing a system are given in the section on “Low Btu Engines”.

Propane

Propane must meet HD-5 specification. It must be 95% pure, with no more than 5% propylene and the remaining 5% not heavier than butane, for the guidelines given in this publication to apply.

Propane is transported and stored in a liquid state. It is converted to a vapor at location. Many states prohibit the use of liquid propane within the confines of a building. It is recommended that local building codes be consulted prior to finalizing plans for propane systems. Propane is heavier than air, so engine room ventilation is a concern.

Propane is frequently used as a secondary or back-up fuel for natural gas. Low compression ratio (LCR) engines must be used for this type application in order to prevent detonation. When switching to propane, the engine timing must be retarded to prevent detonation. When switching fuels, some engines may require deration . Check the Fuel Usage Guide for the correct timing and rating.

Propane-Butane Mixtures

These are commercial mixtures of propane. The butane content usually exceeds 5% by volume.

Propane-Air

A mixture of vaporized propane and air has the same heating value per unit volume as natural gas. It is normally used as a standby fuel or peaking fuel for natural gas systems.

The same pressure regulating equipment can be used for both fuels. The propane-air mixture has the ignition qualities or methane number of propane, and the timing must be set to the propane specification.

Propane Fuel Consumption Calculations

To calculate the fuel consumption of propane, the heat rate of the engine on natural gas at the propane rating is first calculated in MJ/hr (Btu/hr). The heat rate can be calculated by multiplying the fuel rate in SCMM (SCFM) by the energy content of the fuel in Btu/MJ/SCM or by multiplying the brake specific fuel consumption in MJ/BkW-hr (Btu/Bhp-hr) by the engine power. Either method is acceptable. The heat rate is then divided by the MJ/L (Btu/gal) of propane to obtain fuel consumption in L/hr (gal/hr). If data is not published for propane fuel, the fuel rate or brake specific fuel consumption of natural gas can be used at the propane power rating. Fuel rate for natural gas and propane is usually not identical but still within the tolerance band of ± 3%.

Example:

G3516 LE 8:1 Compression Ratio, 90°F A/C, 735 ekW, 60 Hz, 1200 rpm, 1033 bhp

Brake Specific Fuel Consumption = BSFC = 7527 Btu/hp-h

Fuel Consumption = 8592 SCFH

LHV of Fuel = 905 Btu/SCF

Heat Rate = Fuel Consumption x LHV = 8592 x 905 = 7,775,391 Btu/hr

Heat Rate = BSFC x hp = 7527 x 1033 = 7,775,391 Btu/hr

Propane Data from Table I

Heat/gal = 84,194 Btu/gal

Calculated propane fuel consumption in gal/hr

$$\frac{\text{Heat Rate x Load Factor}}{\text{Heat/gal}} = \text{Fuel Consumption in gal/hr}$$

$$\frac{7{,}775{,}391 \text{ Btu hr} \times 1.00}{84{,}194 \text{ Btu/gal}} = 92.35 \text{ gal/hr}$$

To obtain metric results convert to L/hr

92.35 gal/hr x 3.79 L/gal = 350 L/hr

Digester Gas

This is one of the more widely available by-product low energy gases.

Liquid effluent is pumped into digester tanks where biodegrading takes place. As a result, the gas produced is a mixture of methane and carbon dioxide. There are a variety of products that can be digested, such as sewage, animal waste, liquid effluent from vegetable oil mills and alcohol mills.

One volume of material (waste) will produce 0.5 to 1.0 volume of gas in a 24-hour period. Volume of gas produced depends on material (vegetable waste produces less gas than animal waste). Digestion temperatures range from 35°C to 57°C (95°F to 135°F).

A typical digester gas analysis is:

Methane, CH_4	66%
Carbon Dioxide, CO_2	31%
Nitrogen, N_2	2%
Other	1%
Methane Number	132

Typical Low Heat Value:

450-650 Btu/SCF
17.69-25.55 MJ/Nm^3

Air Requirement for Combustion:
5–7 Volumes of Air per Volume of Gas

Sanitary Landfill Gas

Sanitary landfills produce large quantities of methane due to the biological degradation of the many types of organic materials incorporated in the landfill. This methane is often a nuisance emission which in many cases, is flared off to prevent it from migrating underground to nearby residential areas. Landfills are also subject to emission controls by the Environmental Protection Agency.

The gas can be recovered by drilling wells and installing perforated piping. It can then be pumped out, filtered, and used commercially.

A landfill must fulfill certain minimum requirements before a commercial scale recovery operation can even be considered*:

- Must be relatively large - minimum of one million ton of refuse in place.
- Must be deep - 30 m (100 ft) or more thickness of buried refuse. Although some landfills are recovering gas, with only 122 m (40 ft) of material.
- Must be primarily mixed municipal refuse, with minimum amounts of inert materials such as demolition rubble.

*Source: John O'Connor - *"American City and County Magazine"*

A typical landfill gas analysis is:

Methane, CH_4	55%
Carbon Dioxide, CO_2	35%
Nitrogen, N_2	10%
Other	<1%
Methane Number	130

Typical Low Heat Value:

400-600 Btu/cu ft
15.72 - 23.58 MJ/Nm^3

Air requirements for Combustion:
4–6.5 Volumes of Air Per Volume of Gas

Note: *Filtration/treatment of landfill gas is essential to obtain acceptable service life from the engine. Landfill gas is drawn from the ground and generally contains a significant amount of abrasive material. Use a filter capable of removing 99.5% A.C. fine dust (same as engine air cleaner) in the fuel line. See the section on "Air Intake Systems" for a definition of A.C. fine dust. Landfill gas may also contain significant quantities of corrosive elements. A fuel gas analysis is required to determine what type of fuel treatment is required. As a minimum, always treat the fuel as if it were sour gas and follow the precautions outlined for sour gas. For further information, see the section on "Landfill Gas Applications".*

Manufactured Gases

Our reason for discussing these gases, which are undesirable fuels, is that in some areas manufactured gas is mixed with natural gas to supplement the supply during periods of high demand. In operations where gas is a by-product, there is usually a desire to use the gas to produce power, especially in internal combustion engines. It is important for anyone engaged in the sale of gas engines to have knowledge of these gases and of their behavior.

There are several gases made from either coal, wood products, or oil which are classified loosely as *manufactured* gas. All are similar in composition and generally have two features in common.

- They have a low heat value.
- Most manufactured gases contain a high percentage of free hydrogen resulting in a low methane number.

Some of these gases are by-products of other processes. Others are produced purely for the gas and are hold-overs from a period prior to the availability of natural gas. There are a few remaining places where natural gas is not yet available; some type of manufactured gas is still used. The gas is usually too expensive to be used as fuel for gas engines.

Constituents of Gas by Volume — Percent

Figure 4 shows the average composition and characteristics of some of the more frequently encountered manufactured gases. The composition of each type of manufactured gas can vary significantly. This variability must be

Properties of Manufactured Gases

Constituents of Gas by Volume — Percent											
	Hydrogen H_2	Carbon Monoxide CO	Methane CH_4	Ethene (Ethylene) C_2H_4	Oxygen O_2	Carbon Dioxide CO_2	Nitrogen N_2	Btu/SCF LHV @ 60°F 14.696 psi	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	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

Figure 4.

taken into account when deciding on using a particular manufactured gas for an internal combustion engine.

Producer Gas

This gas is made by flowing air, or air and steam, through a thick bed of coal or coke. The temperature ranges from red hot on the lower section of the bed to low temperature on top of the bed. The oxygen in the air burns the carbon resulting in the formation of CO_2, which is reduced to CO by contacting the hot carbon above the combustion zone. The steam is dissociated which introduces H_2, and freed O_2. The free O_2 combines, as does the O_2 from the air, with hot carbon to form more CO. As shown by Figure 4, producer gas has a relatively low heat value and a high hydrogen content.

Illuminating Gas

This classification includes gases made by a number of processes. *Blue Water Gas* is made by passing steam only through a hot bed of coal or Coke to form CO and H_2. *Carbureted water gas* is formed by spraying oil into a carburetor filled with hot brick through which the gases pass. *Coal and oil gas* are formed by applying heat to coal and oil to drive off the hydrogen, methane, carbon monoxide, and ethene (C_2H_4). In gas analysis, the ethene (or ethylene) content is often listed simply as *illuminants.*

Coke-Oven Gas

This gas is similar to the coal gas previously described, but is obtained as a by-product from a process designed to produce coke. The composition of coke oven gas varies appreciably, depending on the type of coal used in the process. The volatile portion of the coal is driven off by the application of heat, and the heavier hydrocarbons are cracked. This results in a gas high in hydrogen and methane content.

Blast Furnace Gas

This gas is a by-product of the steel mills. It is formed by blowing air through cupolas containing alternate layers of hot coke and pig iron. It is similar to producer gas, consisting principally of carbon monoxide and nitrogen.

Wood Gas

Wood gasification technology has existed since World War II. The rise of oil prices in the past years has renewed interest in this low energy fuel.

The gas is manufactured in a reaction vessel at high temperature and low pressure. The gas produced is then fed through a complex cleaning and cooling train consisting of scrubbers and cycloidal cleaners. There are some companies specialized in this field throughout the United States. Initial investments costs are relatively high for this type of application.

Approximately 1.36 kg/kW (3 lb/kW) dry wood chips at 17,420-19.750 kJ/kg (7,500–8,500 Btu/lb) high heat value, are required for this type of operation. Some systems may also operate on sawdust or wet bark.

A typical wood gas analysis is:

Carbon Monoxide, CO	26%
Hydrogen, H_2	10%
Methane, CH_4	2%
Nitrogen, N_2	50%
Other	12%
Methane Number	42.9
Low Heat Value	80-200 Btu/cu ft 3.14-7.86 MJ/Nm^3

Air requirement for combustion:
0.7-2.1 volumes of air per volume of gas.

Cleaning

All manufactured gases must be cleaned to minimize dust and solid impurities. Tar and ammonia must be removed by washing or scrubbing the gases. Sulfur is usually present, and is sometimes removed by passing the gases through iron oxide beds.

Fuel Effects on Engine Performance

Heat Value of the Air-Fuel Mixture

It has been established earlier that:

- Fuel gases are always mixtures composed of a number of component gases.
- Each component gas requires a specific amount of air for complete combustion.
- Each component gas when ignited and burned in the presence of adequate oxygen, generates a specific amount of heat.

Gas engines produce power only in proportion to the low heat value of the combustible mixture of gas and air, which is supplied to the combustion chamber. If a gas is to be appraised on the basis of its power-producing qualities, first determine the low heat value of the correct air-fuel mixture of the gas. Having a volumetric analysis of a given fuel gas and access to the data provided in Figure 1, this becomes a relatively simple calculation. Using a typical landfill gas and referring to Figure 1 for heat values of the various component gases, the low heat value can be determined as follows:

CH_4	0.55 x 911 =	501 (19.69 MJ/Nm^3)
CO_2	0.35 x 0 =	0
N_2	0.10 x 0 =	0
Btu/SCF		501 (19.69 MJ/Nm^3)

This is the heat value of the gas only. The next step is to determine the quantity of air required per volume of Gas. This may be calculated as follows, using again data from Figure 1:

CH_4	0.55 x 9.53 =	5.24
CO_2	0.35 x 0 =	0
N_2	0.10 x 0 =	0
Total vol air required/vol gas		5.24

Having established the low heat value of the gas, together with the proper amount of air per volume of gas required to support complete combustion, it is only a matter of arithmetic to determine the low heat value of correct air-fuel mixture:

$$\text{LHV of air-fuel mixture } \frac{19.69}{\underset{(Gas)}{1} + \underset{(Air)}{5.24}} = 3.16 \text{ MJ/Nm}^3$$

$$\text{LHV of air-fuel mixture } \frac{501}{\underset{(Gas)}{1} + \underset{(Air)}{5.24}} = 80.29 \text{ Btu/cu ft}$$

For naturally aspirated engines, the low heat value of the air-fuel mixture is of particular significance because engine output for this engine type is directly proportional to the low heat value of the air fuel mixture. Determine engine rating for a naturally aspirated engine, the low heat value of the given air-fuel mixture is compared to the low heat value of the fuel used by the engine manufacturer when establishing the engine rating. If the given air-fuel mixture has a low heat value less than that used to establish the rating, the naturally aspirated engine will be decreased. For example, a G3516 Naturally Aspirated, 9:1 compression ratio engine has a rating of 492 BkW (660 bhp) at 1200 rpm, based upon test data when using a fuel having a low heat value of 35.57 MJ/Nm^3 (905 Btu/SCF). Assuming an air-fuel ratio of 9.5:1, which is accurate enough for such calculations, the low heat value of the air-fuel mixture used to establish the 492 BkW (660 bhp) rating would be:

$$\frac{35.57}{1 + 9.5} = 3.39 \text{ MJ/Nm}^3; \quad \frac{905}{1 + 9.5} = 86.19 \text{ Btu/SCF}$$

The output of the G3516 NA when operated on landfill gas would be:

Output =

$$\frac{429 \text{ BkW} \times 3.16}{3.39} = 459 \text{ BkW}; \frac{660 \text{ hp} \times 80.29}{86.19} = 615 \text{ bhp}$$

Dramatic comparisons for the heat value of the correct air-fuel mixture for some of the lesser used gases are found in Figure 3. Note the producer gas made from coke. This gas has a low heat value of only 4.74 MJ/Nm^3 (120 Btu/SCF) as it comes from the gas producer. Only 0.90 volume of air is required per volume of gas. (This would call for a special carburetor.) The low heat value of the correct air-fuel mixture is 2.49 MJ/Nm^3 (63.15 Btu/SCF) — surprisingly high considering the 4.74 MJ/Nm^3 (120 Btu/SCF) low heat value of the fuel. The G3516 NA 9:1 compression ratio output when operating on this gas would be:

Output =

$$492 \text{ BkW} \times \frac{2.49}{3.39} = 361 \text{ BkW}; \quad 660 \text{ bhp} \times \frac{63.15}{86.19} = 483 \text{ bhp}$$

Also consider the sewage gas previously discussed. The only combustible component present, in any appreciable quantity in sewage gas is methane (CH_4). We need only be concerned with this one component when calculating the air required and the heat value of the mixture. For the subject sewage gas, the calculations are as follow for 66% methane:

LHV of subject sewage gas = 0.66 x 911 = 23.62 MJ/Nm^3 (601 Btu/SCF)

Air required per volume of gas = 0.66 x 9.53 = 6.29 SCF

$$\text{LHV of correct air-fuel mixture} = \frac{23.62}{1 + 6.29} = 3.24 \text{ MJ/Nm}^3$$

$$\frac{601}{1 + 6.29} = 82.44 \text{ Btu/SCF}$$

$$\text{Output of G3516} = \frac{492 \text{ BkW} \times 3.24}{3.39} = 470 \text{ BkW}$$

$$\frac{660 \text{ bhp} \times 82.44}{86.19} = 631 \text{ bhp};$$

Turbocharged Engines

The heat value of the air-fuel mixture for turbocharged engines is not quite so critical within certain limits. The density of the mixture can be increased by increasing the turbocharger *boost.* This provides a higher energy air-fuel mixture than originally used to determine the engine rating. This procedure increases fuel consumption. However, when the turbocharger reaches its ambient temperature, it can no longer provide the necessary boost needed to increase the density of the air-fuel mixture. The result is that the low heat value of the air-fuel mixture of a low energy fuel may not be high enough to provide full engine rating.

The extent to which we can take advantage of this feature depends on the capability of the turbocharger available for the specific engine involved. One equation is not necessarily applicable to all occasions. Each case involving the operation of a Caterpillar Turbocharged Gas Engine on low heat value fuel should be referred to the Gas Engine Product Group for rating recommendations.

Methane Number Program Calculations

The Methane Number Program performs many calculations. Some of the values discussed in the above sections are calculated by the Methane Number Program. The manual method for calculating these values has been discussed here for reference purposes. In actual practice, the Methane Number Program would be used to calculate these values. Some values calculated by the Methane Number Program are:

- Methane number of the fuel
- Energy content of the fuel, "Lower Heating Value".
- Volume of air required per volume of fuel, "Stoichemetric air fuel ration V/V".
- Deration for low energy gases, "Relative Power Capability".

Fuel Consumption

The approach represented by the preceding calculations will serve to indicate the output which may be expected from engines when operating on low energy fuel gases. It should also be recognized that the brake specific fuel consumption in MJ/BkW-hr (Btu/bhp-hr) will be higher when operating on low energy fuels as compared to commercial pipeline gas. This results from the fact that the inert gases in low energy fuels not only do not contribute heat to the combustion process; they absorb heat which is later discharged with the exhaust and is lost to the engine. Such heat loss can be calculated for each gas. However, for fuels such as sewage gas, it is generally accurate enough to assume a loss equivalent to approximately 1.5% thermal efficiency. The fuel consumption should be adjusted accordingly.

$$E = \text{Thermal efficiency} = \frac{\text{Work out}}{\text{Heat input}}$$

Where 1 hp = 1kW = 3.6 MJ/hr (2545 Btu/hr) this equation simplifies to:

$$E = \frac{3.6}{BSFC\ metric}; \qquad E = \frac{2545}{BSFC}$$

If the sewage gas referred to in the previous example is used with a naturally aspirated G3516, the specific fuel consumption for this combination, when operating at 1200 rpm and 631 bhp, may be determined as follows:

Specific Fuel Consumption Using Natural Gas at 631 bhp = 11.24 MJ/bkW - hr (7950 Btu/bhp-hr)

$$E = \frac{3.6}{11.24} = 0.32; \qquad E = \frac{2545}{7950} = 0.32$$

E, when operating on sewage gas, is:
E = 0.32 - .015 = 0.305

Then solving for the specific fuel consumption:

$$\frac{2545}{\text{Specific Fuel}} = 0.305$$

Or, specific fuel: $\frac{3.6}{0.305}$ = 11.80 MJ/bkW-hr

$\frac{2545}{0.305}$ = 8340 Btu/bhp-hr;

When operating on sewage gas, the specific fuel consumption in this instance is 11.80 MJ/bkW-hr (8340 Btu/bhp-hr) as compared to the 11.24 MJ/bkW-hr (7950 Btu/bhp-hr) for natural gas.

Detonation

Combustion knock is also referred to as detonation. It is a combustion phenomenon which can shorten engine life due to excessive mechanical and thermal stresses. Do not confuse knock with preignition. Knock occurs when combustion is initiated in localized zones away from the combustion flame front. This localized combustion occurs after the spark plug fires and initiates combustion. Preignition refers to ignition of the air-fuel mix by a source other than the spark, and prior to the spark plug firing. Preignition can lead to combustion knock because it has the same effect as advancing the ignition timing.

This discussion will not attempt to explain knock, but only recognize that it can occur and discuss some of the many factors influencing knock. It is this combustion problem which must be considered and avoided when deciding what engine configuration to use for a specific fuel.

Methane Number

As mentioned earlier, the tendency of a given fuel to knock can be measured by its methane number. In laboratory tests, it has been found that the knock tendency for hydrocarbon molecules increases with the number of carbon atoms. A high methane number indicates high resistance to knock.

Compression Ratio

Different fuels can accept different compression ratios before they self-ignite and produce audible knock for a given operating condition. This compression ratio is called the critical compression. Figure 5 shows the critical compression ratio for some of the most common gases. The data was gathered in laboratory tests under controlled conditions and, therefore, will differ somewhat from compression ratios used in actual practice. It explains, however, that different fuel compositions can have completely different knock characteristics.

Critical Compression Ratio	
Fuel Gas	Critical Compression Ratio
Methane (CH_4)	15.0:1
Ethane (C_2H_6)	14.0:1
Propane (C_3H_8)	12.0:1
Iso-Butane (C_4H_{10})	8.0:1
n-Butane (C_4H_{10})	6.4:1

Figure 5.

Ignition Timing

Peak pressure increases as the spark timing is advanced. The tendency to knock is promoted by this increase in pressure which increases temperature levels. Ignition timing data is published in the service manuals and the performance and technical information books. Consult these publications for the correct ignition timing for a given engine and fuel.

Load
When an engine is operating at low load (low cylinder pressure), temperatures produced by compression of the charge are lower, which increases resistance to knock. Conversely, high load conditions increase the knock tendency.

Inlet Air Temperature
Combustion knock occurs when the temperature of the air-fuel mix exceeds the auto-ignition temperature of the fuel. Increasing the inlet air temperature increases the possibility of exceeding the knock producing temperature. This explains why an engine may perform satisfactorily on a fuel during winter months but encounter combustion problems during summer months. For this reason, a given engine will be derated as inlet temperatures rise. Consult the fuel usage guides found in the performance and technical information books.

Air-Fuel Ratio
Optimum combustion conditions (maximum power) are obtained when the air-fuel ratio is close to stoichiometry (chemically correct ratio of oxygen and fuel). With a leaner or richer mixture, the tendency to knock decreases. It is preferred to run leaner on natural gas engines since the excess air ensures complete combustion of the fuel giving optimum fuel consumption. This also reduces the thermal load on the engine, and increases our knock safety margin.

Emissions
Caterpillar's method to limit emissions on our gas engines is called *lean burn*. A very lean air-fuel mixture is used in the combustion chamber. The excess air cools the combustion gas temperature. The cooler combustion gas temperatures in turn restrict the formation of NO_x, reducing emissions. It is critical to maintain a nearly constant air-fuel ratio in order to maintain emission levels of an engine. A complete discussion on emissions can be found in the *Emissions* section of this guide.

Generally, the type or quality of a fuel does not have an effect on the exhaust emission of an engine. Variations in the heating value of a fuel or in the temperature of the incoming fuel can significantly affect levels of exhaust emissions on engines that do not have air-fuel ratio control. Changes in heating value are generally not a problem with commercially available natural gas or propane. Digester gases, manufactured gases, and field gases can be subject to large variations in heating value if strict controls are not placed on the process by which the gas is produced.

Variations in Heating Value
A change in the heating value of a fuel will change the air-fuel ratio required to maintain a certain emission level. Since carburetors are designed to maintain a constant air-fuel ratio (on a volume-to-volume basis) for a given engine load, any change in the heating value of the fuel will result in an incorrect air-fuel ratio for the desired emissions.

Fuel Temperature
Changes in fuel temperature can change the emission levels of a given engine. This is because the carburetors used in Caterpillar Gas Engines meter fuel into the incoming air on a volume-to-volume basis. Changes in fuel temperature will change the density of the fuel and result in a different air-fuel ratio on a mass-to-mass basis. For example, if the incoming fuel is cooled, the density of the fuel will increase. The increase in density actually means that there is more fuel (mass) present in a given volume. Since the carburetor will continue to deliver the same volume of fuel for a given volume of air, the increased mass flow of the fuel will result in a richer air-fuel ratio.

Recommendations
In order to maintain a nearly constant emission level for an engine, without the use of an air-fuel ratio control system, these guidelines should be followed:

	Emission Level		
	2.0 g NO_x/ bhp-hr	1.5 g NO_x/ bhp-hr	1.0 g NO_x/ bhp-hr
Fuel temp. to carburetor	5.6°C(±10°F)	5.6°C(±10°F)	2.8°C(±5°F)
Fuel LHV	0.43 MJ/Nm^3 (±11 Btu/SCF)	0.28 MJ/Nm^3 (±7 Btu/SCF)	0.28 MJ/Nm^3 (±7 Btu/SCF)

Fuel Requirements

Pressure	Minimum kPa (psig)	Maximum kPa (psig)
G3300		
Low Pressure Gas	1.5 (10)	10 (69)
High Pressure Gas	12 (83)	25 (172)
G3400		
Low Pressure Gas	1.5 (10)	5 (35)
High Pressure Gas	20 (138)	25 (172)
G3500		
Low Pressure Gas, Impco	1.5 (10)	5 (35)
Low Pressure Gas, Deltec	6 (41)	12 (83)
High Pressure Gas Low Emission 11:1 C/R Low Emission 8:1 C/R Standard TA Naturally Aspirated	 30 (207) 35 (241) 25 (172) 2 (14)	 40 (276) 40 (276) 30 (207) 10 (69)
G3600	43 (296)	150 (1034)

Maximum Contaminants and Conditions. Unless otherwise noted, Contaminant and Condition limits apply to fuel and combustion air. See footnote (1) on page 22.

		Standard Engine	Low Energy Fuel Engine
Sulfur Compounds as H_2S See footnotes (1, 2)*	mg H_2S/MJ ug H_2S/Btu	0.43 0.45	57 60
Halide Compounds as Cl See footnotes (1, 3)*	mg Cl/MJ ug Cl/Btu	0 0	19 20
Ammonia	mg NH_3 /MJ ug NH_3/Btu	0 0	2.81 2.96
Oil Content	mg/MJ ug/Btu	1.19 1.25	1.19 1.25
Particulates in Fuel See footnotes (1, 4)*	mg/MJ ug/Btu	0.80 0.84	0.80 0.84
Particulate Size in Fuel:	microns	1	1
Silicon in Fuel See footnotes (1, 4)*	mg Si/MJ ug Si/Btu	0.1 0.1	0.56 0.60
Maximum Temperature	°C °F	60 140	60 140
Minimum Temperature	°C °F	10 50	10 50
Fuel Pressure Fluctuation	kPa ± psig ±	1.7 0.25	1.7 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 are located on pages 22 and 23.

Heating Value

Engines are configured specifically to operate on various fuels. Consult the price list to determine the correct engine configuration for the fuel to be used. The ranges given below indicate the range of heating values for which Caterpillar provides fuel systems. For heating values outside this range, please contact the factory. Below are the typical heating value ranges of various gases. Each requires different carburetion. See also the Fuel Systems guide.

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)

Footnotes

(1) 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 ug 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 ug/Btu) (456 Btu/scf)= 9120 ug 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 ug 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 ug/Btu) (456 Btu/scf fuel)=1000 ug 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 ug 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 ug Cl/scf air.

(2) Sulfur compounds are those which contain sulfur. Total sulfur level should account for all sulfur and be expressed as hydrogen sulfide (H_2S). 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.

(3) Halide compounds are those which contain chlorine, fluorine, iodide, or bromine. Total halide level should account for all halides and be expressed as chlorine. See conversion below. Consult Lubrication section of the A&I Guide for information on proper lubrication and oil sampling when fuel or air contain halide compounds.

(4) Total particulate level must include inorganic silicon. Limit shown for silicon must account for the total organic (siloxanes, etc) and inorganic silicon content.

(5) 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.

Useful Conversions

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

% Cl= (MW of Cl) (number Cl atoms in compound) (100) / (MW of compound)

ug Cl/L= (concentration of compound ug/L) (% Cl) / 100

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

To show the level of one contaminant as another, such as ug F as ug Cl, (for use with Total Halogen levels),

ug F as Cl = (ug F/L) (MW of Cl) / (MW of F)

To convert ug/Btu to ug/L,

(ug/Btu) (LHV Btu/scf) / (28.3 L/scf)=ug/L

To convert ug/L to ppmv,

ppmv = (ug/L) (23.67) / (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 ft^3 = 28.3 L

1 m^3 = 35.31 ft^3

CATERPILLAR®

G3600 Fuel System

Facility Fuel System Design

- Basic Operating Parameters
- Fuel Filters
- Fuel Filter Installation Instructions
- Gas Pressure Regulator
- Gas Pressure Regulator Installation Instructions
- Flexible Connection

Engine Fuel Descriptions

- Shutoff Valve
- Control Valve
- Fuel Manifold
- Precombustion Chamber

Fuel System Options

- Low Btu Fuel System
- Ferrous Fuel System
- Fuel Heaters

G3600 Fuel System

Facility Fuel System Design

There are several factors that will affect the operational success of the G3600 fuel system. Proper installation will allow the engine to operate at optimum performance on a wide range of natural gas fuels.

All pressure and temperature values in this publication are gauge values unless otherwise specified. All units are in Metric convention with English equivalents next to them in parenthesis, i.e. meter (feet).

Basic Operating Parameters

The fuel system components are designed to provide the engine with a maximum fuel pressure of 325 kPa (47 psi). The limiting capabilities of Caterpillar supplied fuel system components are:

Fuel Filter	
Max. Pressure	1590 kPa (230 psi)
Max. Temperature	66°C (150°F)
Gas Pressure Regulator	
Max. Inlet Pressure	2420 kPa (350 psi)
Max. Outlet Pressure	689 kPa (100 psi)
Min. ΔP	21 kPa (3 psi)
Max. Temperature	66°C (150°F)
Min. Temperature	-29°C (-20°F)
Gas Shutoff Valve	
Max. Pressure	325 kPa (47 psi)
Max. Temperature	60°C (140°F)
Min. Temperature	-30°C (-22°F)
G3600 Engine	
Max Pressure	325 kPa (47 psi)
Max Temperature	93°C (200°F)

Fuel Filters

It is the customer's responsibility to provide clean, dry fuel to the engine. Gas pipe lines may contain varying amounts of scale and rust. In addition, new pipeline construction or pipeline repair upstream of the engine can introduce substantial amount of debris, such as dirt, weld slag, and metal shavings. Any of these foreign materials can cause poor engine performance or damage to the internal components of the engine. For this reason, fuel filters in the supply lines are required. Abrasives must be removed from the fuel to avoid reduced service life. *Caterpillar supplied fuel filters are designed to remove abrasives in the fuel system. The filter will remove 99% of all the particles larger than 1 micron in diameter.* Expenses for damage caused by debris and abrasives in the fuel system are not warrantable. A 0.01 micron filter is offered for sites that have particles smaller than 1 micron in their gas.

Fuel taken directly from a gas well may have abrasive and liquid (water and hydrocarbons) entrains in the gas, such as sulfur (H_2S). Hydrocarbon liquids must not be allowed to enter the engine fuel system to avoid combustion problems like detonation. If an engine is allowed to detonate, severe damage can result in a relatively short time period. If any liquids are suspected in the fuel, use a separate coalescing filter. The coalescing filter needs to have an automatic drain with a collection tank which prevents the liquid filtered out from entering the engine or being disposed of onto the ground.

Fuel Filters Installation Instructions

Before installing the filter, clean all piping during installation. When installing the filter, observe the flow direction indicated on the filter cap. Flow in the wrong direction will cause a higher pressure drop across the filter and cause improper operation. Mount the filter vertically and as close to the engine as possible. Position it so that there is adequate room to check and service it. Two pressure tap locations need to be added to the lines. The upstream tap should be a minimum of 5 pipe diameters and the downstream tap location should be a minimum of 10 pipe diameters from the filter. Pipe unions can be installed to allow removal of the filter housing to swing outward, but they should not be located between the pressure measuring points. The taps are used to measure the pressure difference across the filter. *The filter should be changed out when there is a 34 kPa (5 psi) pressure drop across the filter while the engine is running at the rated speed, load, and operating temperature.* Install a 1/2 inch NPT valve and pipe to blow down the filter for maintenance. This line should be vented per local codes for venting unburned gas. *The maximum inlet fuel pressure and temperature to the filter can not exceed 1590 kPa (230 psi) and 66°C (150°F) due to the limiting value of the filter element.* If a pressure higher than 1590 kPa (230 psig) is expected, a second regulator needs to be used upstream from the fuel filter. As a result of using another regulator, a second fuel filter with higher pressure capabilities is recommended upstream from the second regulator to prevent the gas regulator from being damaged by debris and abrasives.

Before starting the engine after installation of the filter, check the filter system for leaks. If leaks are found, shut off the main gas valve and open the blow down valve to release the pressure in the filter bowl and perform proper maintenance or replace filter. The vent line from the filter should be piped away from the engine.

Caution: *Do not vent gas into a room or near an ignition source.*

The pressure drop across the fuel filter needs to be checked frequently to prevent using filters that have become blocked. Figure 1 gives a schematic of how the filter should be installed.

Non-Caterpillar fuel filters need to be able to remove 99% of all the particles larger than 1 micron in diameter. The same installation procedures apply to non-Caterpillar fuel filters.

For more specific special instructions on the Caterpillar supplied filter, refer to SEHS9298 (Caterpillar's Special Instructions on Installation and Maintenance of Gaseous Fuel Filters).

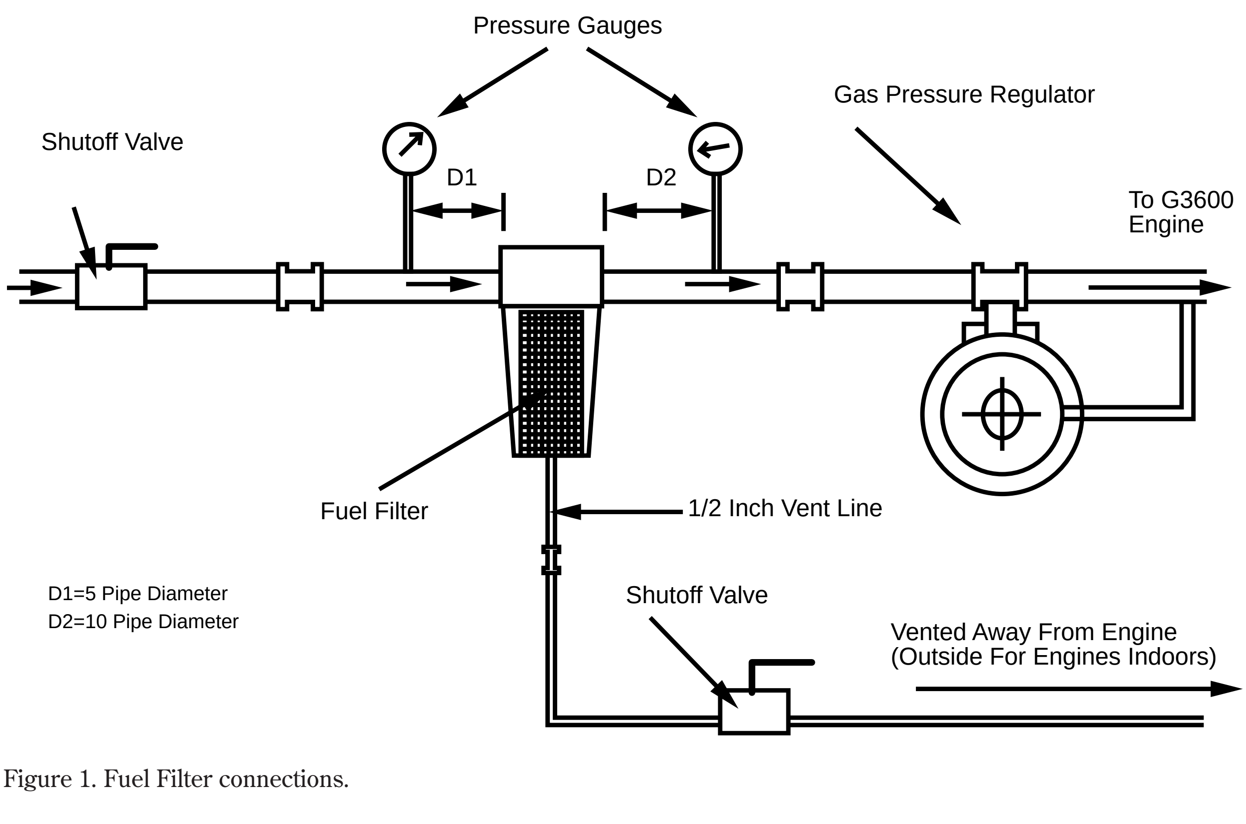

Figure 1. Fuel Filter connections.

Gas Pressure Regulator

The regulator maintains constant pressure to downstream equipment by controlling the fuel pressure at varying flow rates and supply pressures. Large fluctuations in the supply pressure can cause the gas regulator to fluctuate. This fluctuation can cause engine surge. For sites that expect to see more than a 10% fluctuation in the gas lines upstream from the regulator, a second regulator upstream from the first is required. Operation with supply gas pressures below the minimum values may prevent an engine from delivering rated power or maximum load acceptance. Pressure above the maximum may cause unstable engine operation and damage the gas shutoff valve. Supply pressure to the pilot is supplied by the customer directly from the inlet side of the main regulator body, thus requiring no upstream pilot supply line on installations.

If more than one engine is operating at a site, each engine is required to have their own fuel filter and gas regulator. The gas regulator has a female 2 inch NPT thread connection. *For engines that are located indoors, the vent line should be piped outside according to local codes.* A summary is given in Table 1.

GAS PRESSURE REGULATOR PERFORMANCE SUMMARY		
Max Inlet Pressure	2420 kPa	350 psi
Max Outlet Pressure	689 kPa	100 psi
Max Δp	1725 kPa	250 psi
Min Δp	21 kPa	3 psi
Max Temperature	66°C	150°F
Min Temperature	-29°C	-20°F

Table 1: Gas Pressure Regulator summary

Gas Pressure Regulator Installation Instructions

Clean all piping during installation. Install the regulator in the correct gas flow direction and downstream of the fuel filter. The regulator and pilot valve can be mounted in any position relative to the body, the normal installation is with the body in a horizontal run of pipe and the pilot hanging vertically from the bottom of the actuator. Good piping connection will require that outlet piping be oriented upwards and the piping size greater than the body size to prevent excessive pressure drop along the outlet line The pipe diameter should be expanded as close to the regulator as possible. The regulator should be piped so that there is a length equivalent to three pipe diameters of straight pipe upstream and downstream from it. Piping to the gas regulator must be at least as large as the regulator inlet/outlet ports.

The pressure regulator must be adjusted at the engine installation site. It is required that a pressure gauge be installed in the fuel lines between the regulator and the engine. This pressure gauge is to ensure that proper fuel pressure is going to the engine. A temperature gauge is recommended between the regulator and the engine.

Some customers use a relief valve between the regulator and the engine to protect from over pressuring the fuel system. *Due to the maximum inlet pressure of the regulator, sites that have fuel pressure that exceeds 2420 kPa (350 psi) must use more than one regulator.* Figure 2 displays how the regulator operates.

If a regulator is used that is not supplied by Caterpillar, some minimum conditions must be met. No bleed should occur when the regulator is shutoff. *The regulator must be able to deliver 310 kPa (45 psi ± 2 psi) fuel pressure to the engine.* The minimum temperature range of the regulator has to be between -29°C to 66°C (-20°F to 150°F). It should be able to maintain 310 kPa ± 15 kPa (45 psi ± 2 psi) with a 10% fluctuation in the supply fuel pressure.

Flexible Connections

The connection between the engine and the fixed fuel lines should be a stainless steel, single braided, annular corrugated flexible metal hose. The flexible hose will isolate the fuel lines from any vibration and movement produced by the engine and the driven equipment. The factory provided flexible

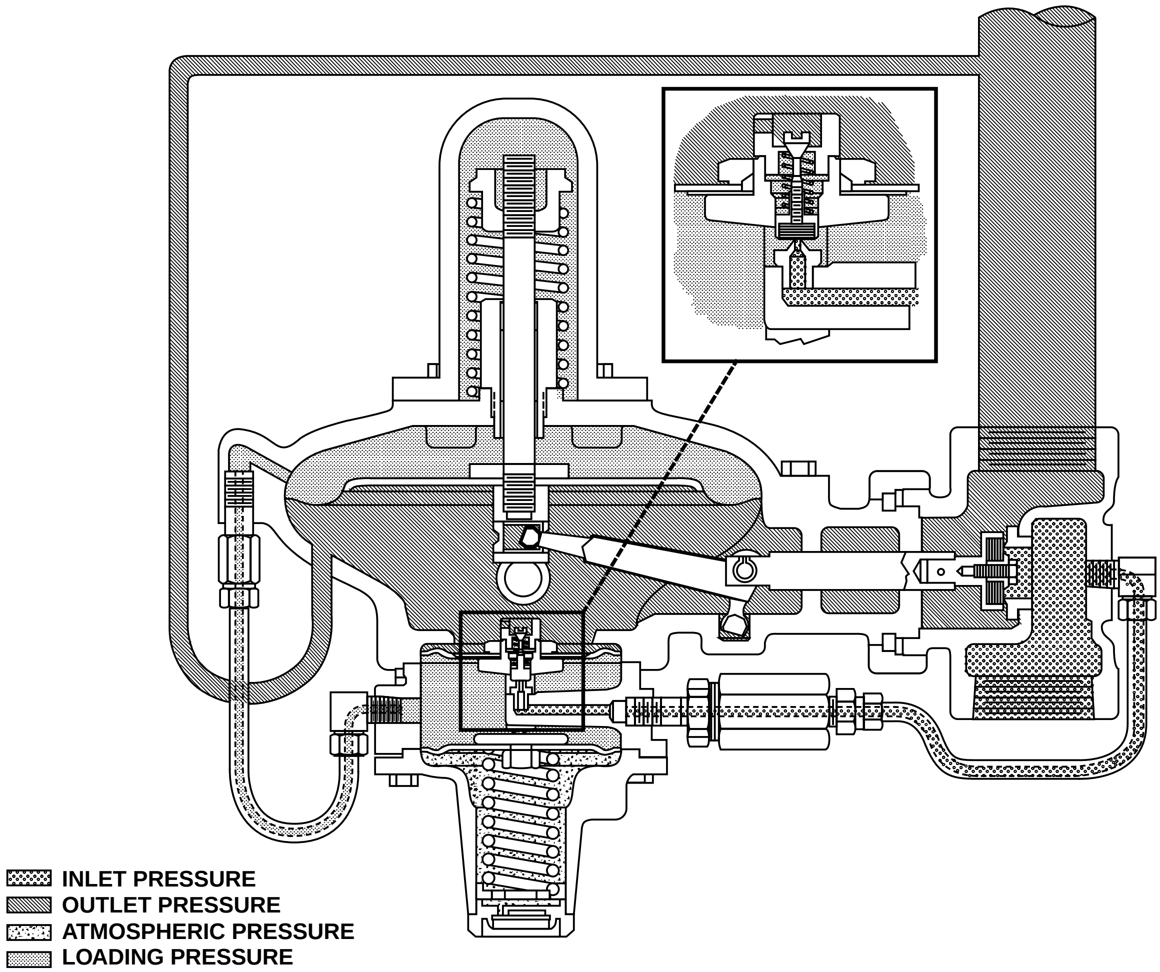

Figure 2. Regulator Schematic.

connections are designed for multiple direction flexing.

If factory supplied flexible hose is not used, the flexible connections must be compatible with the operational gas pressures and temperatures. *Any flexible hose not supplied by Caterpillar, needs to be rated for pressures up to 345 kPa (50 psi) and temperatures between -14°C and 72°C (-25°F and 160°F).*

Engine Fuel System Descriptions

Figure 3 is a schematic of the G3600 fuel delivery system. The fuel supplied to the engine passed through the filter, gas pressure regulator, shutoff valve, control valve, and gas manifold when the flow is then divided between the gas admission valves and the prechamber lines. The fuel to the main chamber flows into the head where the gas admission valve controls the flow and mixes it with the inlet air charge. The mixture that results is delivered into the combustion chamber through the intake valves.

The fuel that is delivered to the prechamber is controlled by a metering valve and flows into the head, through a check valve and enters the prechamber. The fuel in the prechamber is mixed with the fuel/air mixture from the main chamber during the compression stroke. This results in a richer air/fuel ratio in the prechamber. The gas in the prechamber is ignited by the spark plug. The burned charge is projected out through the prechamber nozzles and into the main combustion chamber igniting the leaner main chamber mixture.

Shutoff Valve

The electric shutoff valve's purpose is to prevent fuel from entering the engine when the engine is not running or has been

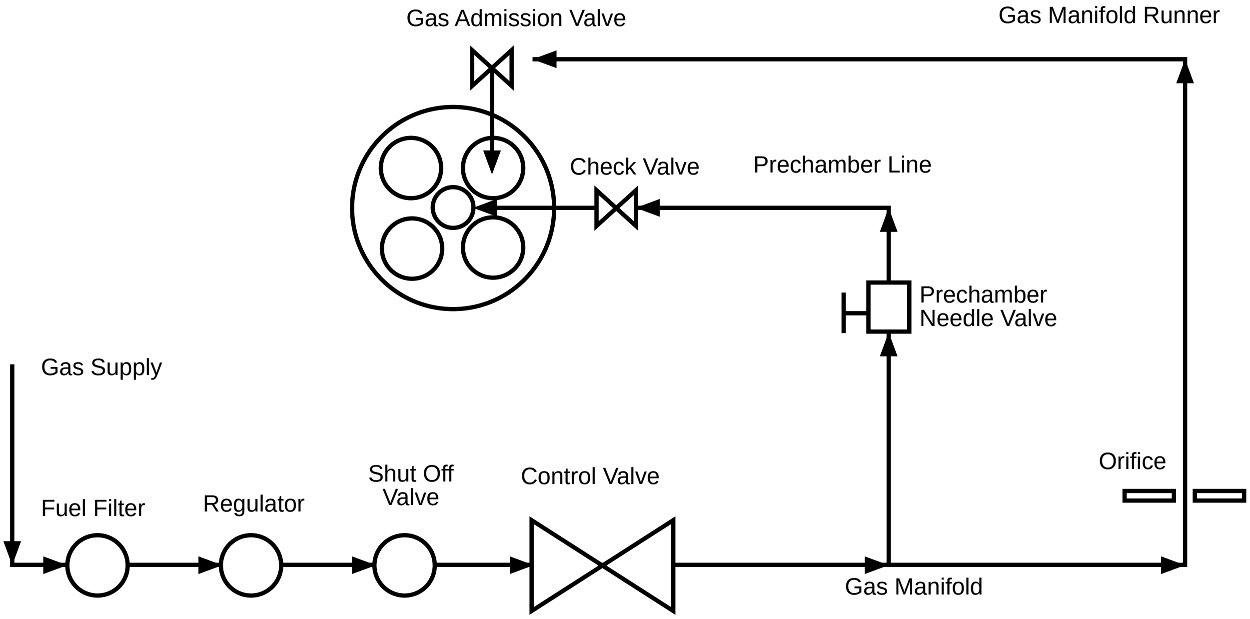

Figure 3. Fuel System Schematic.

requested to shutdown. The inlet pressure supplied to the shutoff valve is critical for engine operation. Pressure that is too low can starve the engine and prevent full load operations. *The maximum inlet pressure is 325 kPa (47 psi) due to the pressure limits of the shutoff valve.* A plug is installed in the upstream side of the shutoff valve to prevent debris from getting into the fuel system during shipping. This plug must be removed before attaching the customer's connection.

If the Caterpillar supplied shutoff valve is not used, the customer supplied shutoff valve that is used must be able to shut off the fuel immediately after the signal is given. Non-Caterpillar shutoff valves need to operate using the same operating parameters as the standard shutoff valve.

Control Valve

The fuel control valve is used to govern the fuel flow by regulating the gas manifold fuel pressure. An actuator is attached through linkages to the valve for the purpose of varying the fuel flow in the manifold. The actuator mechanically opens and closes the control valve in response to an electric signal from the engine control based on the difference between actual and desired engine speed.

The location of the actuator is such that the external temperatures must maintain ambient temperatures of less than 85°C (182°F). Internal temperature must be less than 105°C (220°F).

Fuel Manifold

Fuel is supplied to the engine by a multi-cylinder fuel manifold. Gas is delivered to each cylinder from a runner off the main manifold. A small fuel line also comes off the main manifold and feeds to the prechambers. Orifices are placed just upstream of each individual runner to prevent pressure pulsations from entering the manifold runner

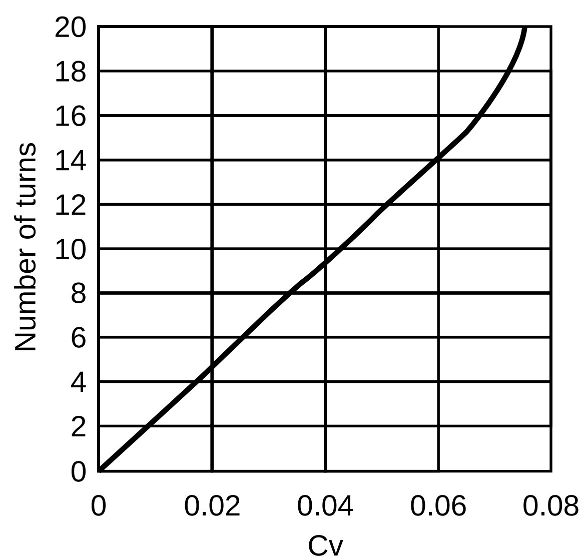

Figure 4. Flow vs. Number of turns.

causing engine instability. It is important to keep foreign material out of the fuel lines. Blockage in the gas admission valve, variable metering valve, or the check valve will result in misfires or engine instability. Examples of items which could get stuck in the check valves, metering valve, and the Gas Admission Valves are packaging material, rust, weld slag, and other debris that are located downstream of the fuel filter.

A variable metering valve is used to control the flow into the prechamber. The valve has a 20 turn stem displacement for fine metering of the gas flow. Figure 4 illustrates the flow vs. the number of turns.

Precombustion Chamber

The G3600 uses an auxiliary combustion chamber called a prechamber. Fuel flows from the main fuel manifold, through a variable metering valve, into the head passage. It then passes through the ignition body, through a check valve, and into the precombustion chamber. Each prechamber has 8 nozzles that are positioned to provide uniform ignition of the main chamber mixture. Fuel is supplied to the prechamber where it is blended with the air/ fuel mixture resulting from the compression stroke in the main cylinder. A spark plug located in the side of the prechamber ignites the mixture. A flame develops and the pressure rises forcing the burning gas out of the nozzles as 8 turbulent burning jets. These burning jets propagate into the main chamber igniting the lean mixture.

Fuel System Options

Low Btu Fuel System

The fuel system for an engine running on digester or landfill gas needs more fuel flow to compensate for the reduced volumetric energy content. Landfill and digester fuels have lower energy content than pipeline natural gas. The shutoff valve, control valve, fuel manifold orifice, gas admission valve, and variable metering valve in the prechamber lines are all modified to allow more fuel flow when operating on low energy content fuels. Table 3 defines the lower heating value fuel ranges of landfill, digester, and pipeline natural gas. For more information on the low Btu fuel system, consult the *Low Btu section of the Application and Installation Guide.*

Lower Heating Values		
	MJ/Nm^3	Btu/scf
Natural Pipeline Gas	30.7–44.7	825–1200
Digester Gas	22.4–30.7	600–825
Landfill Gas	16.8–22.4	450–600

Table 3: Summary of different gas values

Ferrous Fuel System

An all ferrous fuel system is available which, eliminates all bright metal parts from the fuel system. All components that are in contact with the fuel are made of a ferrous material. A different shutoff valve and variable metering valve are needed.

Fuel Heaters

Natural gas at some sites contains liquid hydrocarbons which tend to cause detonation and combustion instability. Heaters should be considered when the total amount of hydrocarbons larger than C_4H_{10} are greater than 3% by volume. Some hydrocarbons that are considered heavies:

Butanes	
Isobutanes	C_4H_{10}
Norbutanes	C_4H_{10}
Pentanes	
Isopentanes	C_5H_{12}
Norpentane	C_5H_{12}
Neopentane	C_5H_{12}
Hexane	C_6H_{14}
Heptane	C_7H_{16}
Octane	C_8H_{18}
Nonane	C_9H_{20}
Heavier:	C_{10+}

To prevent this, the temperature of fuel provided to the engine should be at least 40°C (104°F) during engine operation. Caterpillar has ASME certified fuel heaters available for G3600 engines, which can heat fuel from 10°C (50°F) to 60°C (140°F) using engine jacket water as the heating media. The fuel heater should be mounted as close to the engine as possible and upstream of the gas pressure regulator. The fuel lines between the fuel heater and the engine, need to be insulated.

The water for heating the fuel is taken from the engine jacket water cooling circuit. The temperature of water is 83°C (182°F) for engines that have a 9:1 compression ratio, 93°C (200°F) for engines that have a 11:1 compression ratio, and 130°C (266°F) for Cogeneration engines. The temperature of the fuel should be maintained below 60°C (140°F) to prevent damage to the gas shutoff valve seals. The customer needs to supply a control device which regulates the water flow to prevent overheating of the fuel during part load operation.

G3500-G3300 Fuel Systems

G3500-G3300 Fuel Systems

Caterpillar's gas engines contain either a mechanical carbureted fuel system or an electronic air/fuel ratio control system. G3500, G3400, and G3300 engines have standard carbureted systems with the G3500 having an option for air/fuel ratio control. The G3600 features an air/fuel ratio control system and is described in a separate module.

There are two types of carbureted fuel systems; high pressure gas fuel systems and low pressure gas fuel systems. High pressure gas fuel systems operate on gas supply pressure ranging from 137.8 kPa (20 psig) to 275.6 kPa (40 psig) depending on engine model. In high pressure gas fuel systems, the gas pressure must be higher than the boost pressure from the turbocharger compressor in order for the gas to flow into the carburetor and mix with the air.

Low pressure gas fuel systems operate on gas supply pressure ranging from 6.9 kPa (1 psig) to 68.9 kPa (10 psig) depending on engine model. In this type of fuel system, the fuel and air are mixed upstream of the turbocharger compressor. Many times gas supply pressure in a building is limited and, for this reason, low pressure gas fuel systems may be required.

Electronic air/fuel ratio control systems also have high and low pressure gas options. Air/fuel ratio control offers the ability to maintain a specific level of NO_x emissions even when there are changes in load, fuel heating value, or ambient conditions. G3500 air/fuel ratio control is described later in this manual.

High and low pressure carbureted fuel systems contain the same basic components that will be described in the following sections.

Standard Natural Gas System
(Turbocharged-Aftercooled or Naturally Aspirated)

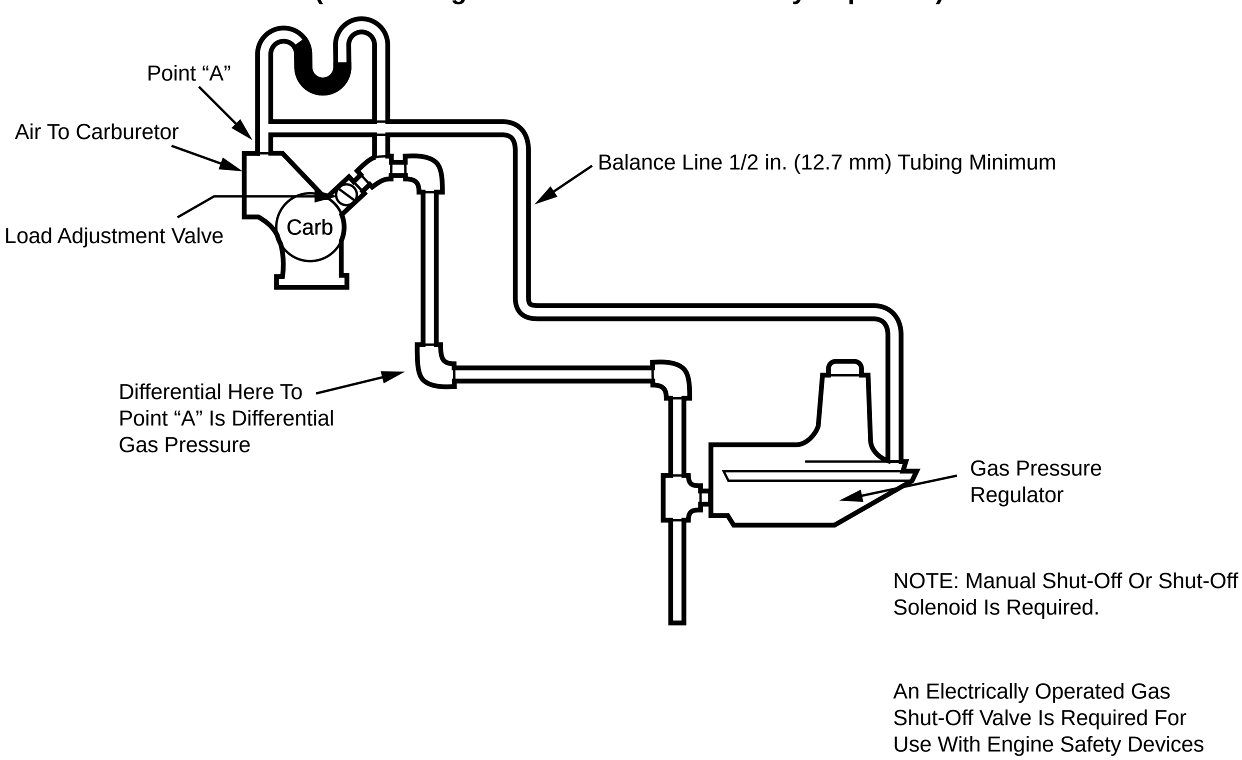

Figure 1.

Carbureted Fuel System

The following sections describe the main components of the carbureted fuel system. Figure 1 shows the layout of a typical carbureted system.

Gas Shut-off Valve

Most engine models are shipped with a gas shut-off valve. However a few models require a customer supplied gas shut-off valve. Optional shut-off valves can be found in the price list. These shut-off valves are tied into the engine start/stop logic and safety system and are an integral part of the fuel system. There are two types of gas shut-off valves; self-powered (powered by magneto voltage) and powered (usually with 24 volt supply). If power is not available at the site, the self-powered shut-off valve must be used. The self-powered shut-off valves require voltage to shut off (energized to shutdown) and are reset manually. Powered shut-off valves require power to stay open (energized to run).

In normal operation, gas shut-off valves open and close when starting and stopping the engine with the start/stop switch. When the valves are closed due to a normal shutdown, the ignition system is still active and fires the spark plugs. This allows all the fuel left in the fuel lines downstream of the shut-off valve to be burned and therefore, prevent raw fuel from being pumped into the exhaust system. In an emergency shutdown, the shut-off valve is closed and the ignition system is grounded immediately. This can leave unburned fuel in the engine and exhaust system.

Caution: *Always purge the exhaust system after an emergency shut-down to avoid potential exhaust system explosions due to unburned fuel in the exhaust stack. This can be done by cranking the engine while keeping the gas shut-off valve closed and ignition system inactive.*

Gas shut-off valve type and size can be found in the product consist or attachment section of the gas engine price list. The mounting location of the shut-off valves can be found on the general dimension drawings in the Gas Engine Installation Drawings book (LEBQ7140). Additional information can be found in the Protection Systems module of the Application and Installation Guide.

Gas Differential Pressure Regulator

The gas differential pressure regulator maintains the proper gas pressure to the carburetor-mixer relative to the air supply pressure. As air pressure to the carburetor increases, fuel pressure is maintained equal to air pressure plus the gas differential pressure. The gas differential pressure is typically set to 1.0-1.3 kPa (4-5 inches of water) by adjustment of the spring force. Gas differential pressure regulators have six basic items common to all models - the body, internal orifice, spring, balance line, sensing line and diaphragms. See Figure 2.

Basic operation is as follows. Fuel passes through the inlet (12), main orifice (6), valve disc (5), and the outlet (4). Fuel outlet pressure is felt in the chamber (8) on the lever side of diaphragm (7). This model regulator has internal sensing. Some models have an external line to connect the outlet pressure to the diaphragm cavity. Carburetor air pressure is sensed in chamber (1) via the balance line (14).

As gas pressure in chamber (8) becomes higher than the force of the spring (3) plus air pressure in chamber (1) (pressure to the carburetor-mixer), the diaphragm is pushed against the spring. This rotates the lever (9) at pin (10) and causes the valve stem (11) to close the inlet orifice.

With the inlet orifice closed, gas is pulled by the carburetor-mixer from the lever side of chamber (8) through the outlet (4). This reduces the pressure in the chamber (8) below that of chamber (1). As a result, the force of the spring and air pressure in the chamber on the spring side moves the diaphragm toward the lever. This pivots the lever and opens the valve stem, permitting additional gas flow to the carburetor-mixer.

When the forces on both sides of the diaphragm are the same, the regulator sends gas to the carburetor at a constant rate. The balance line between the regulator and carburetor must be in place to maintain the proper force balance. A turbocharged engine

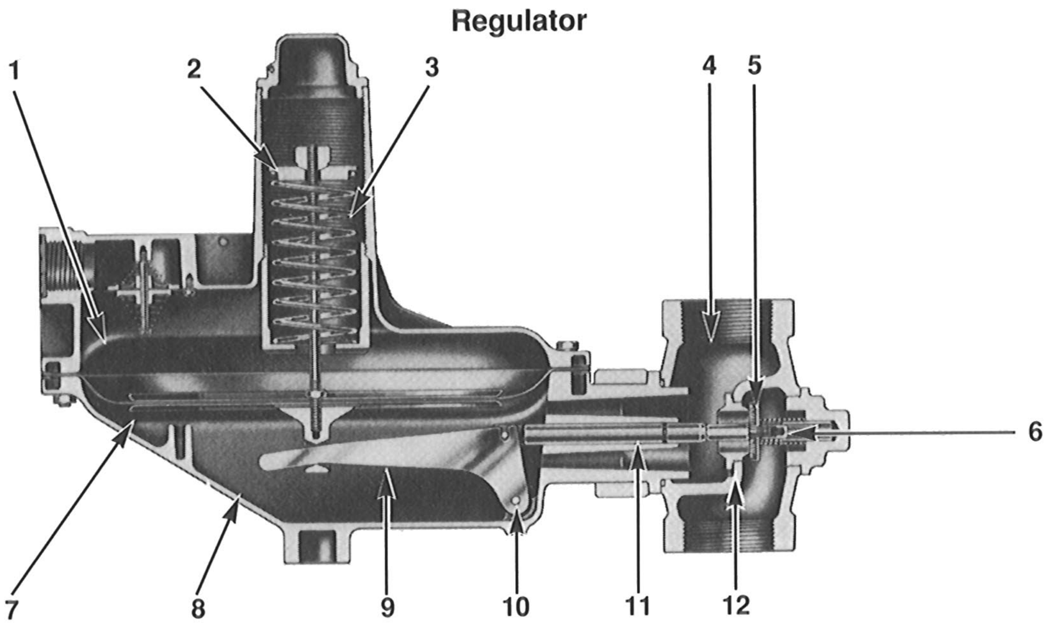

Figure 2. (1) Spring side chamber, (2) Adjustment screw, (3) Spring, (4) Outlet, (5) Valve disc, (6) Main orifice, (7) Main diaphragm, (8) Lever side chamber, (9) Lever, (10) Pin, (11) Valve stem, (12) Inlet (13) Regulator body, (14) Balance line.

will not develop full power with the balance line disconnected.

With proper adjustment of the spring pressure, gas pressure to the carburetor will always be greater than carburetor inlet air pressure, regardless of load conditions or turbocharger boost pressure.

Gas differential pressure regulators have flow capacities based on the supply pressure to the regulator, the body size and the internal orifice size (see Table 1). The gas supply pressure requirements for each engine family are shown in the section on Fuel System Considerations.

Load Adjustment Valve

The load adjustment valve is a variable orifice in the fuel line between the carburetor-mixer and the differential pressure regulator (see Figure 2). The function of the load adjustment valve is to make the air-fuel ratio non-linear; that is to lean the air-fuel ratio as the load increases. The gas differential pressure regulator is used in combination with the load adjustment valve to adjust the air-fuel ratio. The gas differential pressure effects the air-fuel ratio at lower load ranges. Raising the gas differential pressure richens the air-fuel ratio, while reducing the gas differential pressure leans the air-fuel ratio. The load adjustment valve effects the air-fuel ratio near full load operation. Opening the load screw richens the air-fuel ratio and closing the load screw leans the air-fuel ratio. Larger changes in air-fuel ratio are accomplished by changing the gas jets in the Impco carburetor-mixer or the venturi in the Deltec carburetor-mixer.

Carburetor-mixer

The carburetor-mixer's main function is metering and mixing the fuel and air prior to entering the combustion chamber. This can be done in one of two ways:

Figure 1 is a schematic of a fuel system using an Impco carburetor. Figure 3 is a cross section of a typical Impco carburetor. This system is used on all high pressure carbureted gas applications and some low pressure carbureted gas applications. As air flows past the carburetor diaphragm vacuum port, a vacuum is created. This vacuum is sensed by the air valve diaphragm which in turn raises or lowers the gas valve as the air flow increases or decreases accordingly. This allows the carburetor to adjust the fuel flow in proportion to air flow. The gas valve and jet are sized for specific fuel and operating condition ranges. For example, a carburetor containing a gas valve and jet sized for natural

Regulator Model	Body Size NPT	Orifice Size Inches	Cat Part Number	Engine Model	Differential Pressure Range In H_2O	Flow In SCFH For Varying Net Effective Supply Pressures				
						.5 psi	.75 psi	1.0 psi	2.0 psi	5.0 psi
Y600	1	1/2	7L6766	G3300	3.5-6	510	1120	1425		
Y600	1 1/4	9/16	2W6022	G3300	3.5-3	750	950	1160	1500	1800
S301	1 1/2	3/4 x 7/8	7C9735	G3406 LOSPD	3.5-6.5	700	1050	1410	2000	2800
Y610	11/2	3/4	3N4630	G3408 & G3412 LP	1-3 Neg					
Y610	1 1/2	3/4	5Z4017	SER	3-8 Neg					
Y610	1 1/2	3/4	4P2866	G3406 LP	1-3 Neg					
S201	1 1/2	3/4	6L4104	G300 Series	3.5-6.5	1400	1750	2100	2800	4500
S201	1 1/2	1	7W2363	G3408/12	3.5-6.5	1600	2050	2500	3500	5300
S201	1 1/2	1 3/16			3.5-6.5	1800	2250	2700	3800	6000
S201	2	1	2W7978	G3500	3.5-6.5	2200	2700	3200	5500	9500
S201	2	1 3/16	9Z5301	SER	3.5-6.5	2400	3100	3800	6400	10000
L34CSE-40	2	7/8 x 1	7E3407	G3500 LE	1-6	2100	3000	3700	5600	9000
4.11.0065	Flange	2.56	7E8190	G3500 LOPR COSA	0-1					
133L	2	2	7C5001	G3516 LNDFL	3.5-6.5	7000	10000	13000	20000	30000
99-903	2	7/8 -1/2	6I1946	G3600	10-65 psi					7200
99-903	2	1 1/8	4P2124	G3600	10-65 psi					1200

Table 1.

600 Series Varifuel Mixer (Cut-Away)

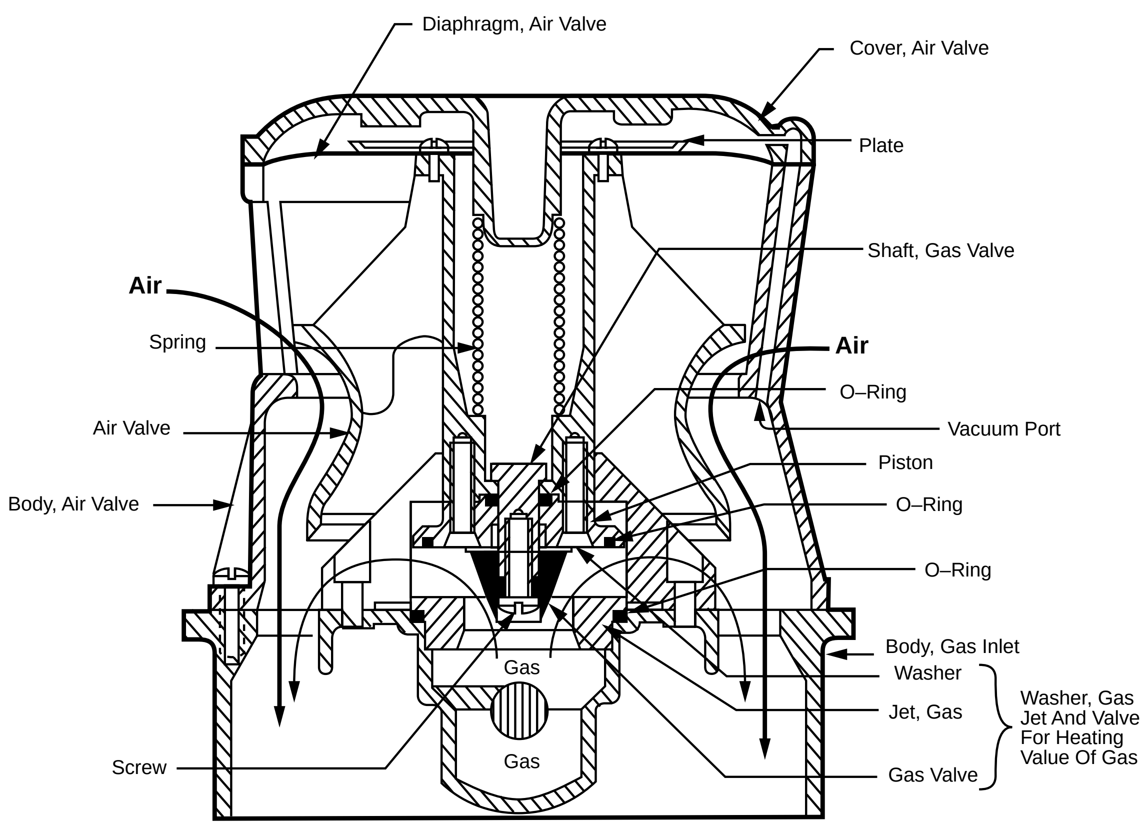

Figure 3.

gas, would not operate properly on landfill gas. Likewise, operation with a 3-way catalyst requires a different valve and jet than operation with no catalyst. A list of available gas valves and jets are shown in Table 2. It is very important that your engine contains the proper valve and jet.

***Note:** for proper application of these valves and jet, please contact the Caterpillar factory.*

The air-fuel ratio is adjusted by setting the regulator differential pressure and the load adjustment valve. Instructions for correctly adjusting the air-fuel ratio can be found in the service manuals.

The second type of carbureted system used on Caterpillar gas engines is a venturi type carburetor as shown in Figure 4. The venturi carburetors are manufactured by Deltec and are used on some low pressure gas engines. Venturi carburetors operate on the venturi effect which, simply stated, says that as air flows through a venturi its pressure is lower in the venturi (P2) than it is upstream (P1). The higher the air flow, the greater the differential pressure will be. If, at the same time, the gas pressure to the carburetor (P3) is held constant with respect to P1, the pressure differential P3-P2 will increase as air flow increases. Any increase or decrease in this differential pressure will cause a corresponding change in fuel flow. The gas pressure regulator is used to keep the pressure difference between P3 and P1 constant.

Engine power and emissions setting are determined by the mass air-fuel ratio entering the combustion chamber. A carbureted system can only maintain a fixed volume ratio of air and fuel. Therefore, as air temperature, fuel temperature, and heading value of the fuel change, so will the mass air-fuel ratio entering the engine. This is particularly important in applications where low exhaust emissions are a necessity since emissions will change with changes in mass air-fuel ratio. Depending on carburetor design, emissions can vary throughout the load range.

***Note:** Most engines come standard with natural gas carburetors which are designed for fuels with lower heating value ranges from 31.4-55.0 MJ/Nm^3 (800-1400 Btu/scf). The price list also defines the heating values ranges for optional carburetors. If the fuel to be used does not fall within the heating value ranges specified, consult the factory for assistance in carburetor sizing.*

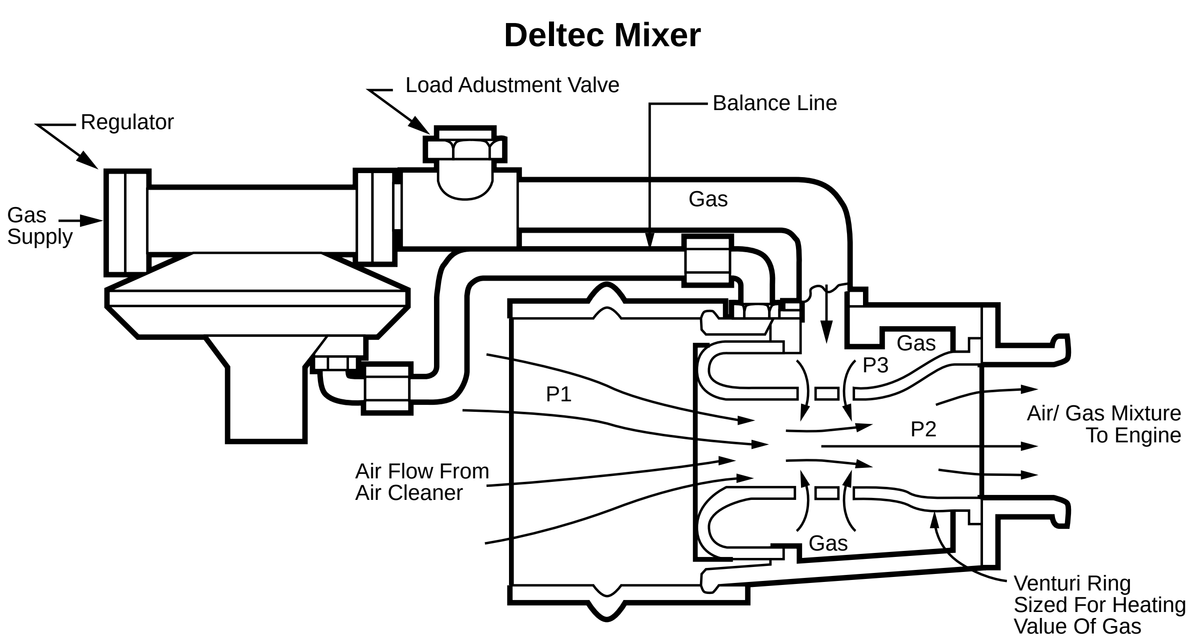

Figure 4.

Throttle Body

The throttle body is an adjustable orifice, typically a movable plate, in the air-fuel intake passage. The movable plate regulates the pressure of the air-fuel mixture in the intake manifold and ultimately the cylinders. The pressure in the cylinders has a direct relationship to the engine power. The movable plate is controlled by the governor. On high pressure gas arrangements, the throttle body is physically bolted to the carburetor-mixer and both are located downstream of the turbocharger. On low pressure gas arrangements, the carburetor-mixer is located upstream of the turbocharger and the throttle body is located downstream of the turbocharger.

Air-Fuel Ratio Control

Air-fuel ratio controlled devices seek to maintain a desired air/fuel ratio as operating conditions change. This is done by either measuring and/or calculating the actual air-fuel ratio and then adjusting either the air flow or the fuel flow to maintain the desired air-fuel ratio. These devices are closed-loop and typically measure the amount of free oxygen in the exhaust, which is proportional to the actual air/fuel ratio.

Figure 5 shows a basic air/fuel ratio control system. An oxygen sensor is used to measure the excess oxygen in the exhaust. This information is used to determine if the air-fuel ratio is correct for the desired emissions. If it is incorrect, an appropriate correction can be made to the fuel flow by an actuator controlled butterfly valve.

Air-fuel ratio controlled engines provide several advantages over engines without air-fuel ratio control. One of the primary functions of air-fuel ratio control is to maintain constant emissions for varying conditions of ambient air temperature, fuel quality, speed and load. In addition, when using air-fuel ratio control, engines can operate at leaner air-fuel ratio settings without misfire problems. This is due to the precise control that eliminates the small air-fuel ratio fluctuations present in all carbureted systems. Some high compression ratio, lean burn engines operate in a vary narrow air-fuel ratio band between lean misfire and detonation. The air-fuel ratio control system helps these engines stay within this operating band.

Air-fuel ratio control is not only used for lean burn engines. It is also necessary when using a three-way catalytic converters. In three-way catalyst applications, the NO_x and CO

Simplified Example of an Air/ Fuel Ratio Control

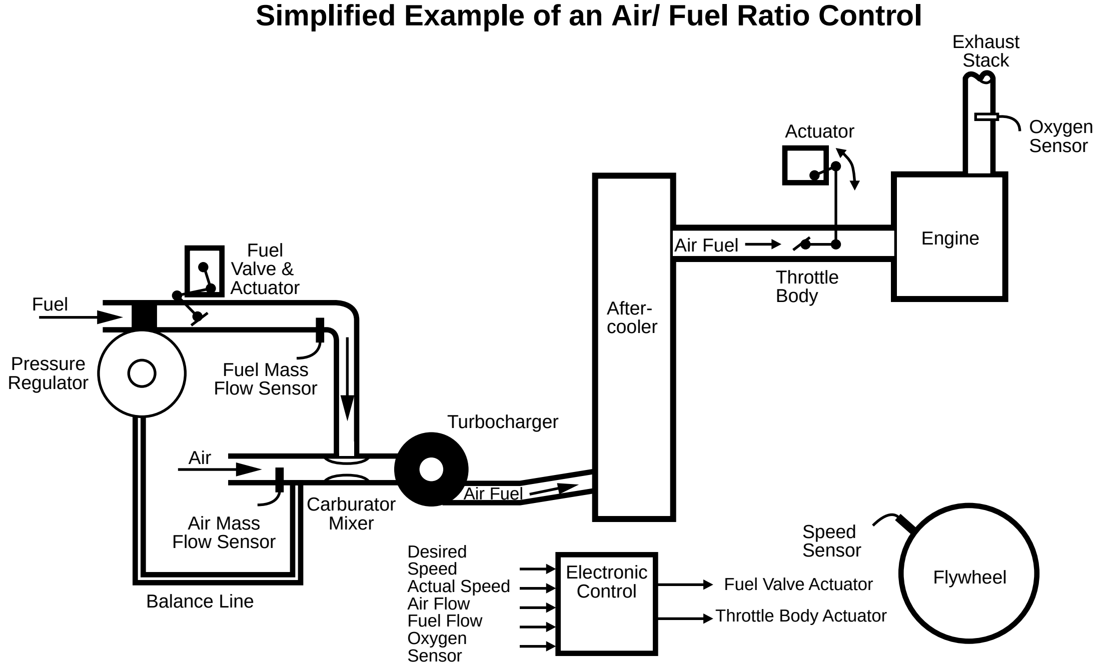

Figure 5.

emissions must be approximately equal in order for the catalyst to operate as designed. This emissions setting is achieved by operating the engine at a stoichiometric air-fuel ratio which results in about 0.5% oxygen in the exhaust. The air-fuel ratio control will adjust air flow or fuel flow to maintain this exhaust oxygen level and therefore, allow the catalyst to provide optimum emissions reduction. Caterpillar does not offer air-fuel ratio control systems for use with stoichiometric engines operating with a three-way catalytic converters, however these control systems are widely available. Note that when using a 3-way catalyst with the Impco fuel systems, the carburetor valve and jet must be changed to match the type of air/fuel ratio control device you have selected. Consult Table 2 for the available options.

G3500 Air-Fuel Ratio Control

A Caterpillar designed air-fuel ratio control system is available as an option for the G3500 engines. This system is compatible with EIS, low emission, high pressure gas engines (industrial or gen set) operating on natural gas in the range of 33.41–50.12 MJ/Nm^3 (850–1275 Btu/scf). The system is also for use with EIS, low emission, low pressure gas engines operating on natural gas, digester gas, or landfill gas. It provides constant emissions from 100% load down to 50% load throughout the turndown speed range of the engine (or Lug Range as shown in the price list ratings section).

In addition to providing air-fuel ratio control, this system also provides engine speed governing, start-stop logic, safeties and diagnostics. Since the system provides speed governing, no other governor is required. The engine control module, which is housed within a remote panel contains the hardware and software necessary to process data from various engine sensors, switches and service tools. The information is used to control the electrically driven fuel and throttle actuators. It also provides diagnostic information and safety shutdown when necessary. The components that make up the air-fuel ratio control system include a remote panel connected to the engine mounted junction box by a 6.1 m (20 ft) interconnect harness. Optional length harnesses are available from 3 m (10 ft) up to 24.4 m (80 ft) lengths. Harness length is limited to a maximum of 24.4 m (80 ft) to avoid communication problems between the remote panel and engine mounted sensors that may occur with longer harnesses. Mount the panel in order to avoid excessive vibration. Do not mount the remote panel on the engine.

The air-fuel ratio control system is compatible with the customer communication module (CCM, gas engine version), the Woodward load share interface module (pwm version), Woodward digital synchronizer and load control (DSLC), and Fisher suction pressure controllers (4-20 mA or 0-15 psi output).

For more information on the G3500 air-fuel ratio control system, consult the G3500 Air-Fuel Ratio Control Electronic Troubleshooting Guide (SENR6517) and the air-fuel ratio control system wiring diagram (114-8162).

Kit Number	Gas Valve	Gas Jet	Gas	Btu/ft^3 (1)	Application
CDV2-21-3	V2-21-3	J1-23	Natural Gas	800-1000	Non-emmissions Stoichiometric
CDV2-63	V2-63	J1-23	Natural Gas	800-1000	Ultralean (λ = 1.4 – 1.6)
CDV2-64	V2-64	J1-25	Digester Gas	540-660	Stoichiometric(2)
CDV2-65	V2-65	J1-25	Landfill Gas	420-540	Stoichiometric(2)
CDV2-94	V2-94	J1-24	Natural Gas	800-1000	Throttling Feedback (λ = 0.85 – 0.98)
CDV2-62	V2-64	J1-22	Natural Gas	800-1000	Enrichment Feedback (λ = 1.1 – 1.3)

(1) Lower heating value.
(2) Must also include J1-33 Power Jet ordered separately.

Table 2.

Fuel System Considerations

There are several factors that will affect the operational success of a fuel system. These factors include fuel pressure and fuel system components that are upstream of the engine fuel system that need to be supplied by the customer.

Fuel Pressure Requirements

It is important to supply the proper gas pressure to the engine. Table 3 outlines the gas pressures that are required at the gas pressure regulator inlet. Naturally aspirated engines follow the low pressure gas guidelines unless specifically listed.

	Minimum		Maximum	
	kPa	Psig	kPa	Psig
G3300				
Low Pressure Gas	10	1.5	69	10
High Pressure Gas	83	12	172	25
G3400				
Low Pressure Gas	10	1.5	35	5
High Pressure Gas	138	20	172	25
G3500				
Low Pressure Gas	8	1.5	35	5
Low Pressure Gas Landfill	69	1.0	35	5
High Pressure Gas				
Low Emission 11:1 C/R	207	30	276	40
Low Emission 8:1 C/R	241	35	276	40
Standard TA	172	25	207	30
Naturally Aspirated	14	2	69	10

Table 3.

Operation with supply gas pressures below the minimum values may prevent an engine from obtaining full load. Pressures above the maximum may cause unstable engine operation, difficulty in starting the engine, or could cause the gas regulator to fail.

Note: *For best engine stability, it is recommended to maintain a constant supply pressure to the regulator. For high pressure gas fuel systems, supply pressure to the regulator should not vary more than ±6.9 kPa (±1 psig). For low pressure gas fuel systems, supply pressure to the regulator should not vary more than ±1.7 kPa (±0.25 psig).*

Fuel piping to the gas pressure regulator must be as large as the gas pressure regulator body size. Any regulators used to reduce supply gas pressure to the maximum allowed in Table 3, should be able to respond faster than the engine. This ensures that supply pressure does not fall below the minimum pressure during sudden load changes, causing poor engine response. An accumulator tank located upstream of the regulator will help maintain supply gas pressure when the load changes rapidly. Suggested tank volume is equal to the gas consumed in 15 seconds of full load operation.

If the fuel pressure to the gas pressure regulator is below published limits, a gas compressor can be used. A heat exchanger may be required to cool the compressed gas. Gas pressure regulators are not designed to operate with fuel temperatures above 65.5°C (150°F).

Gas Differential Pressure Regulators

Gas pressure regulators are designed for fuel temperatures in the range of 150 to -20°F. Operation outside this range will lead to regulator failure. The pressure limits for a given regulator may be different than those listed as engine fuel supply pressure requirements (Table 3). A regulator may be capable of safely operating with a higher inlet fuel pressure than Table 3 permits, however, engine stability and startability will be adversely affected.

Fuel Filters

Gas pipe lines can contain varying amounts of scale and rust. In addition, new pipeline construction or pipeline repair upstream of the engine can introduce substantial amounts of debris such as dirt, weld slag, and metal shavings. Any of these foreign materials can severely damage the regulator, carburetor, or internal engine components. Expenses for these repairs are not warrantable. For this reason, fuel filters are required. Caterpillar offers fuel filters for all gas engine models. These filters remove 99% of all particles larger than 1 micron in diameter. It is the customer's responsibility to provide clean fuel to the engine.

In addition to abrasive debris, fuel directly from a gas well (well head gas) may have liquids such as water and hydrocarbons entrained in the gas. There may also be undesirable contaminants like hydrogen sulfide (H_2S). **Hydrocarbon liquids must not be allowed to enter the engine fuel system.** Detonation in the cylinders will result which will severely damage the engine in a short time period. If any liquids are suspected in the fuel, use a coalescing filter. The coalescing filter should have an automatic drain and collection tank to prevents the filtered liquid from entering the engine or from being disposed of onto the ground.

Fuel filters are a restriction in the fuel supply line. The fuel pressure supply requirements to the pressure regulator of Table 3 must be met, even if a fuel filter is used. Hence, the fuel pressure supplied to the fuel filter must be equal to the requirement at the pressure regulator plus the maximum restriction of the fuel filter.

Consult the price list for fuel filters for specific engine models. When using non-Caterpillar fuel filters, always size the filter based on the minimum fuel line pressure and highest expected flow. Fuel flow for each engine model can be determined from TMI data and should be adjusted for fuel consumption tolerance and to account for changes in the energy content of the fuel.

Example: Determine the fuel flow of G3516 LE 8:1 C/R Engine rated at 943 BkW (1265 bhp) at 1400 rpm, 54°C (130°F) scac when operating on 33.4 MJ/Nm^3 (850 btu/ft^3) LHV fuel.

Fuel flow from TMI data = 291.5 Nm^3/hr @ 35.57MJ/Nm^3
or 10,863 ft^3/hr @ 905 Btu/ft^3 LHV fuel

Determine Energy Flow Rate:

Energy Flow Rate = 291.5 Nm^3/hr x 35.57MJ/Nm^3 = 10,369 MJ/hr
or 10,863 ft^3/hr x 905 Btu/ft^3 = 9,831,015 Btu/hr

Determine Fuel Flow at 33.4 MJ/Nm^3 (850 Btu/ft^3):

Fuel Flow at

$$33.4 \text{ MJ/Nm}^3 = \frac{10{,}369 \text{ MJ/hr}}{33.4 \text{ MJ/Nm}^3} = 310.4 \text{ Nm}^3\text{/hr}$$

Fuel Flow at

$$850 \text{ Btu/ft}^3 = \frac{9{,}831{,}015 \text{ btu/hr}}{850 \text{ btu/ft}^3} = 11{,}566\text{ft}^3\text{/hr}$$

Determine Fuel Flow for Sizing Filter with 5% Tolerance on Fuel Flow:

Fuel Flow for Filter Sizing = 310.4 Nm^3/hr x 1.05 = 325.9 Nm^3 or 11,566 ft^3/hr x 1.05 = 12,144 ft^3/hr

Clean all piping before installing the filter. When installing the filter, observe the flow direction indicated on the filter cap. Flow in the wrong direction will cause a higher pressure drop across the filter and result in improper operation. Mount the filter vertically and as close to the engine as possible. Position the filter so there is adequate room for servicing. Two pressure tap locations need to be added to the fuel lines. The upstream tap should be a minimum of 5 pipe diameters from the filter inlet and the downstream tap should be a minimum of 10 pipe diameters from the filter outlet. Pipe unions can be installed to allow removal of the filter housing, but they should not be located between the pressure measuring points. The taps are used to measure the pressure difference across the filter. *The filter should be changed when the pressure drop across the filter reaches 34 kPa (5 psig) while the engine is running at rated speed, load and operating temperature*. Install a 1/2 inch NPT valve and pipe to vent the filter for maintenance. This line should be vented per local codes for venting unburned gas. *The maximum inlet fuel pressure and temperature to the filter cannot exceed 1590 kPa (230 psig) and 66°C (150°F) due to the limiting value of the filter element.*

Check the filter system for leaks before starting the engine. If leaks are found, shut off the main gas valve, open the vent valve to release the pressure in the filter bowl, and perform proper maintenance. The vent line from the filter should be piped away from the engine.

CAUTION: Do not vent gas into a room or near an ignition source.

The pressure drop across the fuel filter needs to be checked frequently to prevent using filters that have become blocked. Excessive pressure drop can restrict flow and may limit engine power.

Non-Caterpillar fuel filters need to be able to remove 99% of all particles larger than 1 micron in diameter. The same installation procedures apply to non-Caterpillar fuel filters.

Connections

The connection between the engine gas shut-off valve and the upstream portion of the fuel system should be made with a flexible connection. This will isolate the fuel line from the vibrations and movements of the engine. The flexible connection must be compatible with the operational fuel pressures and temperatures, and the type of gas being used.

Optional Fuel Systems

As mentioned previously, all Caterpillar gas engines come standard with a fuel system designed for natural gas. Some models offer optional fuel systems for different fuel types or combination of fuels. If a desired fuel system is not available for a given model in the price list, the factory may be able to offer some special systems. Table 4 summarizes what is offered in the price list and what might be available with an SER.

	Natural Gas	Propane	Landfill	Digester	Dual Gas Fuels
G3516	S	O (high press)	S	SER	SER
G3512	S	SER	S (50 Hz)	SER	SER
G3508	S	SER	NA	SER	SER
G3412	S	SER	NA	O	O (natural gas/propane or natural gas/digester)
G3408	S	SER	NA	O	O (natural gas/propane or natural gas/digester)
G3406	S	O (low press)	NA	SER	O (natural gas/propane)
G3306	S	SER	NA	SER	NA
G3304	S	SER	NA	SER	NA

S = Standard offering in price list
O = Option in price list
SER = Special Engineering Request
NA = Not Available

Table 4.

Vaporized Propane System

Vaporized propane is a gaseous fuel and is used with the engine similar to natural gas. Appropriate changes must be made to the carburetor-mixer or the gas differential pressure regulator to obtain the correct air-fuel ratio for propane. Two methods are applied to obtain the correct air-fuel ratio.

For most fuel systems operating on propane and using an Impco 600 VF carburetor, the correct air-fuel ratio is achieved by selecting the proper valve and jet for installation in the 600 VF (Table 2). The pressure regulator used in the system will be identical to that of a natural gas system. For systems with other Impco carburetors, the valve and jet cannot be changed, therefore the gas pressure regulator is changed to a negative pressure style. For Deltec systems, the venturi and mixing valve must be sized for propane and used in conjunction with the standard regulator.

Vaporized propane systems will usually have the propane fuel stored outside the facility as a liquid. The liquid propane must be vaporized by a heat source before being sent to the engine. Propane requires 189 Btu per pound of propane to vaporize the fuel. Most applications will use a commercial propane vaporizer to avoid freezing the storage tank or fuel lines and shutting down the engine.

Engine mounted propane vaporizers use jacket water as a heat source. At this time, Caterpillar is not offering vaporizer-regulators because they are primarily designed for the mobile market and are only offered in limited sizes and flow rates. Those sizes generally are too small for industrial applications. For higher flow applications multiple vaporizer-regulators are needed in parallel. The vaporizer-regulators have fixed orifices and the pressures are not adjustable. These limitations result in no adjustment of the differential pressure, difficulty in obtaining the correct air fuel ratio, and difficulty during start. In addition, full load operation may not be possible until jacket water temperature reaches a high enough level to vaporize the propane required.

Landfill Gas and Digester Gas

The fuel systems used with landfill and digester gas needs to account for the reduced fuel heating value compared to natural gas. With Impco systems, the carburetor valve and jet must be replaced. For Deltec systems, the proper venturi insert is sized and provided from Deltec. From Table 4, if you select a product that is standard or optional, your engine fuel system will come with everything required for operation on that fuel. If you select a product that is SER, the factory will assist you in preparing a quotation with the proper hardware.

Dual Gases Fuel Systems

Dual gaseous fuel arrangements are available for some engine models. The arrangements will have two gas differential pressure regulators as shown in Figure 6 or have two complete and separate fuel systems. Dual regulator systems for digester-propane are not recommended. The engine will be difficult to start due to the negative pressure required to obtain the correct air fuel ratio on propane.

The dual gas differential pressure regulator system has a high Btu adjustment valve between the high Btu gas differential pressure regulator and the carburetor-mixer. The air-fuel ratio for the high Btu fuel is adjusted at this valve. Air-fuel ratio for the low Btu gas is adjusted at the carburetor.

Ignition timing for the high and low Btu fuels may be significantly different and a dual timing magneto or Caterpillar's Electronic Ignition System (EIS) will be required. A dual timing magneto is available in price list for most models.

The following guidelines are given for automatic switching between the primary and secondary fuels for the following combinations:

Primary Fuel	Secondary Fuel
• Digester	• Natural Gas
• Natural Gas	• Propane

Dual Fuel Turbocharged or Naturally Aspirated Engines

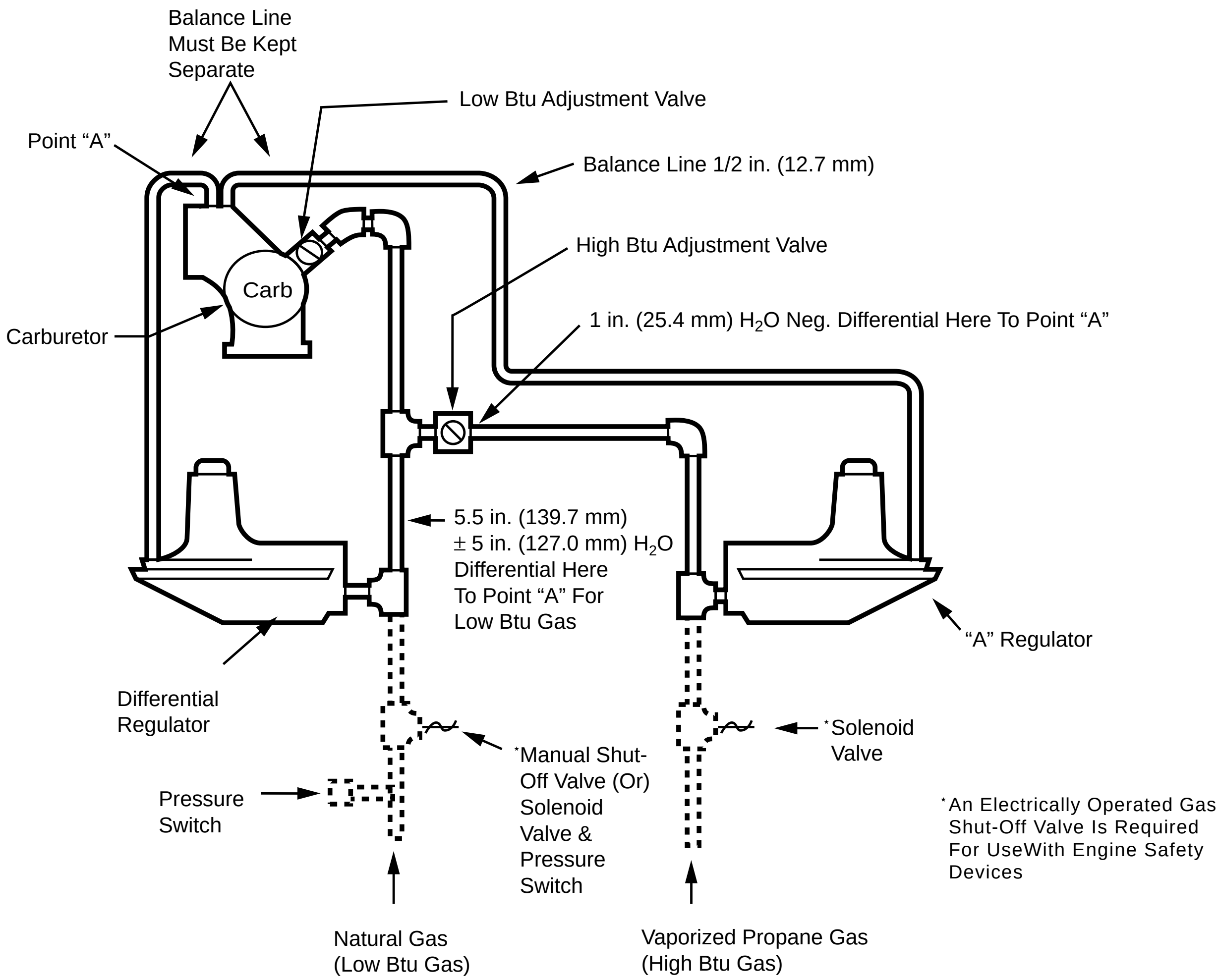

Figure 6.

In each of these systems, the primary fuel is the low Btu fuel and the secondary fuel is the high Btu fuel. Dual regulator systems can transfer between the primary and secondary fuel while under load. It is recommended that the fuel regulators not be moved from the factory mounting. Any increase in fuel line length can cause problems with smooth transfer between the primary and secondary fuel. The solenoid operated shut-off valves should be energized to run, and be mounted as close to the fuel regulators as possible. During normal operation on the primary fuel, both solenoid valves should be engaged. The primary fuel gas, supplied by low Btu regulator, is always at a greater pressure than the secondary fuel supplied by high Btu regulator. Therefore, any time the primary fuel is present, the secondary regulator will shut off the secondary fuel, even though the solenoid valve is energized. To transfer to the secondary fuel, de-energize the low Btu solenoid valve. As the primary fuel is used in the fuel line between the low Btu pressure regulator and the carburetor-mixer, the pressure in the line will drop. As this gas pressure goes negative, the secondary regulator will sense the drop and open to supply secondary fuel to the carburetor. Circuits that attempt to switch from primary to secondary fuel by flip-flopping the solenoid valves usually are not successful and are not recommended.

Dual fuel systems with regulators and mixers for each fuel can be automatically switched, but the engine must be at no load. These systems will require a flip-flop solenoid arrangement. For generator engines, it is suggested to temporarily override the reverse power relay during changeover. If switching fuel supplies under load is a requirement, a programmable controller is required to control switching from one fuel to another. The time delays for the solenoid values will need to be determined at the site for changeover.

For automatic switching between primary and secondary fuel, a dual timing magneto or EIS is required. Place the activation switch for the dual timing between the primary fuel solenoid and the primary fuel regulator. As long as primary fuel pressure is supplied to the engine, the timing will be in the advanced position. Once the primary fuel pressure is lost, the ignition will index for operation on the secondary fuel.

Materials and specifications are
subject to change without notice.

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