GAS TECHNOLOGY INSTITUTE

Natural Gas Composition and Fuel Quality

Information Report

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Outline

Natural Gas Composition and Quality

SUMMARY

There are renewed questions in California and elsewhere regarding natural gas composition and quality -- spurred in part by issues surrounding growing use of imported LNG. In the U.S., the Natural Gas Council (NGC) has formed an Interchangeability Work Group to help address this subject. There is a long and rich history of work on natural gas composition to draw upon. Our review of the current situation supports the following:

- Gas composition or quality limits should mainly be based on use of the Wobbe Number, perhaps with complementary combustion indices.
- Variability in natural gas composition regionally and seasonally are not uncommon occurrence. Few end users are aware of such variations and the emission impacts are generally modest, especially when monitoring and controls systems are used.
- Based on conventional practice and draft recommendations of the NGC work group, Wobbe Number ranges of about +/- 4 to 5 percent from prevailing regional averages will likely be recommended.
- Coupled with elements of existing natural gas tariffs (e.g., Southern California Gas' Rule 30), the NGC work group findings should provide a sound foundation for California rulemaking on this topic.
- Overly restrictive composition limits and use of niche measurements (e.g., Methane Number) should be avoided to the maximum extent possible.
- Future energy requirements are likely to necessitate continued flexibility in natural gas composition and property limits, considering issues such as bio-energy resources, gasification, and hydrogen.

I. INTRODUCTION

Natural gas is a naturally occurring hydrocarbon mixture found throughout the world. Natural gas contains methane (typically 90% or more by volume) along with other hydrocarbons, inert gaseous components, water vapor, and trace compounds. Natural gas is derived from thousands of separate reservoirs throughout North America and is produced alone or along with crude oil (this co-production is sometimes referred to as "associated gas"). When co-produced with oil, non-methane hydrocarbons levels such as ethane and propane are often greater than when natural gas exists alone (e.g., in coalbed methane). When natural gas has with higher levels of ethane and propane, it is often called a "rich" gas; when the methane content is very high, it is sometime referred to as a "lean" gas.

Prior to transporting to end-use markets, natural gas is processed to meet pipeline-quality standards or conventional practice. Natural gas processing techniques vary considerably. In some cases, these practices differ due to regional circumstances or prevailing economics. Before delivery to customers, local distribution companies (LDCs) add sulfur-based odorants for leak detection and safety.

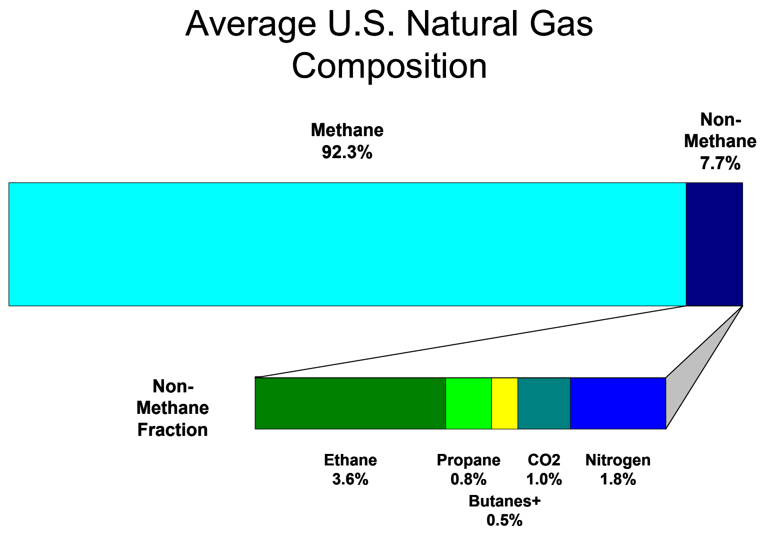
Natural Gas Quality Measurements

There are a variety of measurements (or metrics) and measurement techniques that can be use to quantify or qualify the composition or "quality" of natural gas. Most broadly, these fall into two categories:

- Chemical composition (including bulk and trace components)
- Physical properties and indices

Natural Gas Chemical Composition

The chief component in natural gas is methane. Most natural gas contains about 90-95 percent methane by volume after processing, with the balance including decreasing amounts of heavier hydrocarbons (e.g., ethane, propane, butanes, etc.) and inert gas such as nitrogen, carbon dioxide, and water.
Figure **1** shows results from a comprehensive natural gas composition survey performed by Gas Research Institute (GRI-92/0123) – a predecessor to Gas Technology Institute. These data are based on nearly 7000 gas samples in twenty six different cities around the U.S.



Source: Gas Technology Institute

Figure 1: Average Natural Gas Composition

These survey results showed regional variability in the amount of non-methane compounds present in natural gas (Figure 2). For example, two cities (#6 and #13) showed somewhat higher non-methane content. These were regions that were close to natural gas production areas and where co-production of oil was also ongoing. One city (#21), located in the Rocky Mountain region, had much higher levels of ethane and inert gases. This situation exists due to the challenges in finding local markets for ethane gases in this region. Instances of unique regional natural gas situations exist in the US and throughout the world.

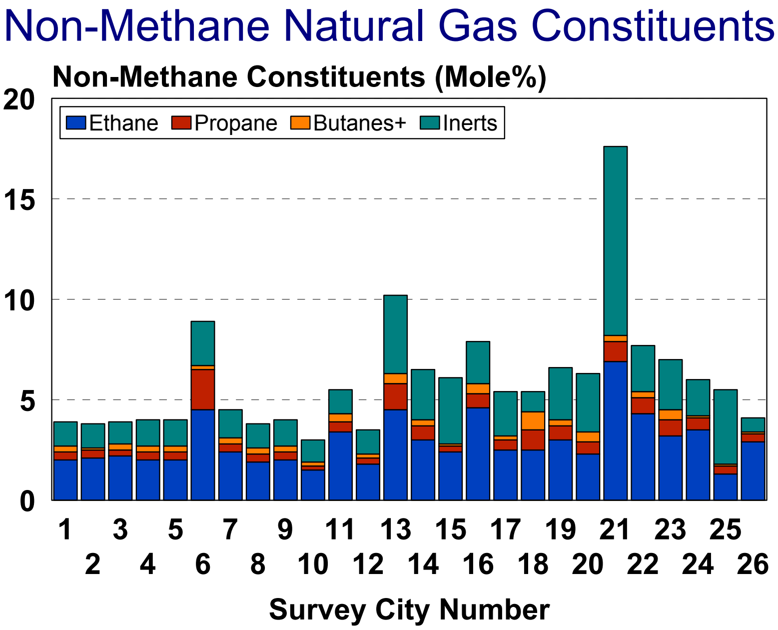


Figure 2: Average Natural Gas Composition in Twenty Six Cities

The national natural gas pipeline network is highly integrated, allowing gas to flow from supply centers to consumption centers. The composition of natural gas arriving at a specific area depends on many factors, including proximity to supply, number of different pipelines serving the city, producing gas field characteristics, and the techniques used for gas processing and clean up. As a result, gas transported to a particular utility or customer can vary with time and location.

Table 1 shows a summary of the prior natural gas composition survey, including statistics including the 10th and 90th percentile as well as minimum and maximum values for key compounds present in natural gas. Note that the minimum and maximum values are more extreme in cases where propane-air peakshaving is included. The 10th and 90th percentile define points in the database where 10 percent and 90 percent of samples are above or below that value.

Table 1: US Natural Gas Composition Statistics (Mole %, excluding peakshaving)

	Minimum	10th Percentile	Mean	90th Percentile	Maximum
Methane	74.5	89.6	93.9	96.5	98.1
Ethane	0.5	1.5	3.2	4.8	13.3
Propane	0.0	0.2	0.7	1.2	2.6
C_4 and higher	0.0	0.1	0.4	0.6	2.1
$N_2 + CO_2$	0.0	1.0	2.6	4.3	10.0

Table 2 shows the data collected in this survey for twelve different locations within California. Generally, these data show somewhat more lean natural gas mixtures in Northern California and richer natural gas mixtures in Southern California. These data represent end use natural gas composition measured at various locations in natural gas utility service regions. In certain portions of the state where natural gas composition can vary more than this – particularly in areas close to in-state natural gas production regions.

Table 2: California Fuel Survey (1226 samples, 8/89-8/91)

	SITE	METHANE (mole %)	HEATING VALUE (Btu/scf)	WOBBE NUMBER (Btu/scf)
Northern California	1	93.92	1033	1340
	2	94.33	995	1301
	3	95.53	1017	1326
	4	96.64	1011	1336
	5	94.94	1026	1340
Southern California/San Diego Region	6	93.10	1039	1341
	7	93.73	1028	1335
Southern California/LA Region	8	93.60	1030	1335
	9	92.25	1040	1335
	10	91.19	1048	1337
	11	93.48	1029	1333
	12	92.34	1042	1340
Summary				
Average		93.09	1035	1337
Minimum		90.31	986	1290
Maximum		96.88	1060	1358

The current natural gas supply mix in the US (and California) is diversified. This situation will continue to evolve over the coming decades as other natural gas supply resources within North America and other trans-ocean LNG imports take on a more prominent role in the domestic natural gas supply and demand portfolio. Over the next 25 years, according to a recent National Petroleum Council study, increasing amounts of natural gas will come from Canada, Alaska and deep off-shore Gulf of Mexico resources. These will be complemented by steady growth in Rocky Mountain natural gas production as well as LNG imports. California should be a direct beneficiary of upper North America production supply expansion and, with possible West Coast LNG import facilities, international LNG imports.

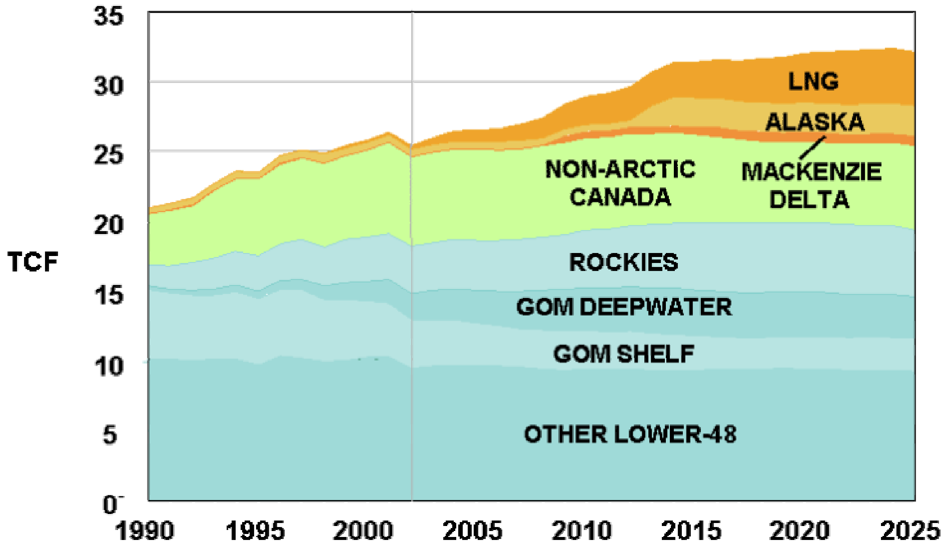


Figure 3: US Natural Gas Supply Mix Projection

Natural gas composition can also be impacted by natural gas utility peakshaving practices. In the U.S., periods of peak natural gas demand are addressed by using different peakshaving methods: underground gas storage, propane/air injections, LNG vaporization, and curtailment. Propane/air and LNG have potential natural gas composition implications.

Propane/air is used in some parts of the US—mainly the Midwest and East Coast. This process stores propane (or liquefied petroleum gas or LPG) that is vaporized during cold periods and mixed with roughly equal parts of air. This mixture is injected into the natural gas pipeline and commingles with conventional natural gas, yielding a gas mixture that depends on injection rates. Propane values as high as 23 percent have been documented in extreme cases.

Vaporized LNG is used by many US utilities for peakshaving. The methane content of the LNG varies depending on supply. LNG may be produced domestically in a peakshaving liquefaction plant or imported. Figure 4 shows typical LNG compositions from different international sources. Most LNG has higher levels of ethane and propane (a “rich” LNG product). International LNG exports show gas compositions with higher levels of ethane due to the cost associated with natural gas liquids (NGL, comprising mainly ethane, propane, and butanes) removal equipment and, as importantly, the lack of a domestic demand for ethane in the chemicals industry. This LNG quality that is similar to certain regions of the US – and California – where above average levels of ethane are found. Some international LNG plants have natural gas liquids removal capabilities.

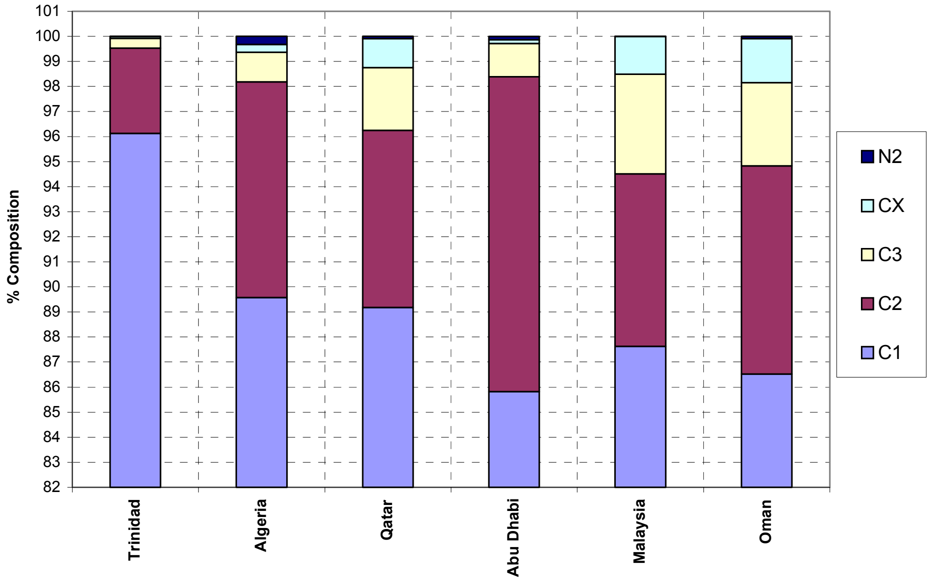


Figure 4: Representative Imported LNG Composition

In addition to bulk natural gas constituents, several trace compounds can often be found in natural gas at trace levels (often referred to as parts per million, ppm, or as parts per billion, ppb). For example, natural gas will often contain very low levels of heavy hydrocarbons containing more than six carbon atoms – so called C_6+ compounds.

Natural Gas Physical Property Measurements

Measuring individual natural gas constituents is commonly in the natural gas industry, using analytical instruments such as a gas chromatograph. Gas composition can be segmented between major constituents – typically methane, ethane, propane, butanes plus heavier hydrocarbons, and inert gases. Even with this simplification, the industry primarily uses physical property measurements or indices to quantify and characterize natural gas rather than gas composition.

The most popular of these include: **heating value (also called calorific value)**, **specific gravity**, and **Wobbe Number** (also known as Wobbe Index). These are the primary natural gas “figures of merit.” In addition, there are many secondary physical property measurements or indices. In some cases, these factors are derived from empirical tests, often related to fuel combustion characteristics. Example secondary factors include: Yellow Tipping, Flashback, Lifting, Weaver Index, Motor Octane Number, Research Octane Number, Methane Number, hydrocarbon dewpoint, water dewpoint, etc.

Heating Value

Heating value, or calorific value, is a measure of the gross or useful heat generated through the combustion of natural gas. The heating value can be reported as the higher heating value (or gross heating value) or the lower heating value (or net heating value). Higher heating value (HHV) includes the fuel’s latent heat of vaporization–the energy recoverable by condensing water vapor from the combustion products. Lower heating value (LHV) excludes the latent heat of vaporization of moisture from exhaust gases. Heating values can be reported in many different units, such as BTU/scf (British Thermal Units per standard cubic foot), MJ/m^3 (megajoules per cubic meter), and others.

The following table shows US statistics for higher heating values for natural gas. These data show a range of -6 percent and +9 percent around the mean.

	Minimum	**10th Percentile**	**Mean**	**90th Percentile**	**Maximum**
Higher Heating Value (BTU/scf)	970	1006	1033	1048	1127

Specific Gravity

As applied to gases, specific gravity is the ratio of the density of the gas to air at standard conditions of temperature and pressure. Specific gravity values are usually derived from chemical composition analyses, but can also be estimated through the use of specialized analytical instruments. As a physical property measure, specific gravity provides a first order estimate of certain aspects of gas flow through a meter or orifice.

The following data summarize US statistics on specific gravity. These data show a range of -6 percent and +17 percent around the mean. Higher levels of specific gravity result from the presence of larger or heavier compounds such as ethane, propane, nitrogen, and carbon dioxide. Specific gravity is directly correlated to natural gas' molecular weight. For reference, the specific gravity and molecular weight of pure methane are 0.5543 and 16.041.

	Minimum	**10th Percentile**	**Mean**	**90th Percentile**	**Maximum**
Specific Gravity	0.563	0.576	0.598	0.623	0.698
Molecular Weight	16.4	16.7	17.3	18.0	20.2

Wobbe Number

The Wobbe Number is not a measured value, but instead is calculated by dividing the heating value by the square root of the specific gravity. The usefulness of the Wobbe Number stems from being a very good measure of the amount of chemical energy of gaseous fuel that can flow through an orifice of fixed size at a constant pressure drop. Since many natural gas appliances and other combustion devices have a fixed orifice, changes – upwards or downwards – in Wobbe Number give a direct correlation to changes in the amount of heat generated per unit of time.

In addition, the power of the Wobbe Number is related to its ability to directly predict the change in phi, ϕ, or equivalence ratio. The equivalence ratio is defined as the actual fuel/air ratio of a combustible mixture of fuel and air divided by the stoichiometric fuel/air ratio. A first order approximation of the impact of fuel composition on equivalence ratio is obtained by:

$$\phi_2 = \phi_1 * (WN_2 / WN_1)$$

That is, the equivalence ratio of changing from one equivalence ratio point (ϕ_1) using a fuel with a certain Wobbe Number (WN_1) can be approximated by taking the ratio of the second Wobbe Number to the first. This insight is particularly effective since many emission-related changes are strongly correlated with equivalence ratio (or its corresponding metric, Air/Fuel Ratio).

The following data summarize US statistics on Wobbe Number. These data show a range of -10 percent and +6 percent around the mean.

	Minimum	**10th Percentile**	**Mean**	**90th Percentile**	**Maximum**
Wobbe Number (BTU/scf)	1201	1331	1336	1357	1418

International LNG Fuel Properties

Table 3 shows a comparison between average natural gas physical properties with various international LNG sources. These data indicate that many international LNG resources on the world transport have natural gas properties higher than typical for the US – that is, most international LNG can be characterized as "rich" natural gas.

Table 3: US Average and LNG Import Natural Gas Properties

	Higher Heating Value (BTU/scf)	Specific Gravity	Wobbe Number
US Average	1033	0.598	1336
Trinidad	1042	0.576	1372
Algeria	1096	0.614	1398
Qatar	1126	0.631	1417
Abu Dhabi	1126	0.632	1417
Malaysia	1155	0.649	1434
Oman	1162	0.654	1437

Methane Number

The Methane Number (MN) is a measure of knock resistance of a gaseous fuel, similar to how Octane Number is used for gasoline. The Methane Number is a derived by running specialized tests using different reference fuels and a sample gas on a unique single-cylinder engine. Methods have been developed to estimate the Methane Number by calculation. The higher the Methane Number, the greater its resistance to engine knocking.

The following data summarize US statistics on Methane Number. These data show a range of -10 percent and +6 percent around the mean.

	Minimum	10th Percentile	Mean	90th Percentile	Maximum
Methane Number	73.1	84.9	90	93.5	96.2

It is important to put the Methane Number into context. GRI-sponsored testing shows that most natural gases have Motor Octane Numbers (MONs) in the range of 115-130 – much higher than conventional gasoline. This means that even gaseous fuels with higher levels of ethane and propane still have much greater knock resistance than conventional gasoline. Figure 5 shows a graphical relationship between Methane Number and Motor Octane Number. This figure also shows where most natural gas compositions reside relative to conventional gasoline.

Natural gas with a Methane Number of 73 is equal to a Motor Octane Number of over 121. This is considerably higher than conventional gasoline. Based on this, even a very rich natural gas – that is, one with high levels and ethane and propane – still has astronomically higher knock resistance than conventional gasoline. For this reason, there are really no meaningful concerns about using this type of fuel in typical light-duty spark-ignited gasoline engines.

There are generally greater concerns about fuel quality when natural gas is used in medium and heavy-duty trucks and buses. The natural gas engines in these vehicles, in some cases, are highly turbocharged and have a higher compression ratio than do light-duty vehicles. These factors combine to make these engines more sensitive to engine knock.

One engine manufacturer, Cummins Engine Co., previously issued a minimum Methane Number for their early generation natural gas engines at MN=80 or higher. In more recent years, they have introduced more modern engines with improved control systems that have a minimum MN=65 or higher. This is below the lowest MN measured in the GRI gas quality survey (excluding propane-air peakshaving gases).

Detroit Diesel has issued natural gas engine specifications that include a Motor Octane Number of greater than 115. This equates to a Methane Number in the low 60's.

One unique area of consideration is heavy-duty diesel engines that operate in "dual fuel" modes, using for example 5-10 percent diesel fuel along with a balance of natural gas. Since these engines tend to retain their diesel engine capability, they feature turbocharging along with very high compression ratios (greater than advanced technology spark-ignited engines). While this population of engines is rather small, this may be an area of concern with respect to engine knock.

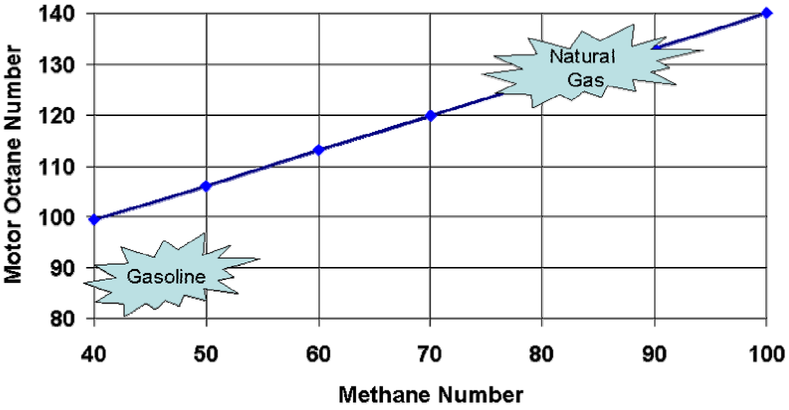


Figure 5: Natural Gas Knock Resistance (Methane Number and Motor Octane Number Relationship)

Hydrocarbon Dewpoint

Hydrocarbon dewpoint, or what is sometimes called pressure hydrocarbon dew point temperature, is the temperature, referenced to a specific pressure, at which gaseous hydrocarbon components begin to condense into liquids. Figure 6 shows an example dew point curve, illustrating the combined impact of temperature and pressure. The dewpoint temperature of a natural gas gives an indication of the temperature at which some hydrocarbon condensates form. The amount of condensates will vary, being very slight if the gas is close to the dewpoint curve and being more significant the greater it lies within the green liquid and gas region shown in this figure.

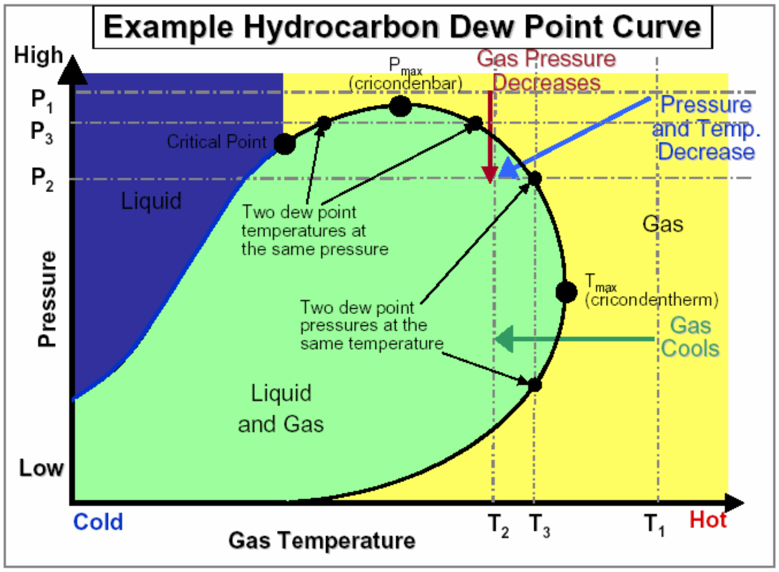


Figure 6: Hydrocarbon Dewpoint (Source: NGT+)

The primary concern with the hydrocarbon dewpoint is related to assurances of gas flow, avoidance of hydrates, and potential need for recovery and disposal of liquids. Beyond the operational issues, natural gas producers also view the issue of heavier hydrocarbons (and the derivative issue of hydrocarbon dewpoint) from an economic vantage point. There often needs to be a compelling economic driver – that is, a market – to justify removing non-methane hydrocarbons. Typically, this means a producer must have a high-volume market outlet for selling these products such as ethane, propane, and butanes into the Natural Gas Liquids market. Typically, a market outlet exists for selling propane and butane for LPG. In some cases, the lack of regional ethane consumers can result in situational challenges that make it economically impractical to remove ethane.

Other Physical Property and Interchangeability Indices

There are several other physical property measurements as well as indices, some that fall under the overarching banner of "natural gas interchangeability." Interchangeability has been used in the natural gas industry as an empirical means of evaluating the effects of natural gas. Typically, this involves using a specific combustion device and visually characterizing the flame characteristics. Two different gases would be considered "interchangeable" if their combustion attributes were comparable.

Early work by the American Gas Association used comparative measurements of yellow tipping, flashback, and lifting on specific gas appliances. Other factors have been developed over the years, often looking at combustion-related phenomenon such as firing rate, temperature, flame stability, incomplete combustion, emission levels, etc. Combustion emissions have mostly focused on carbon monoxide (CO) levels, due to safety considerations.

Importantly, in some cases, it is possible for these physical properties, interchangeability indices, and other factors to identify different impacts in natural gas equipment that are not otherwise known or perceptible to the end user. For example, a measurement that indicates changes in yellow tipping may actually result in no discernable impact to a residential customer's furnace operation. Further, the growing use of sensors and feedback controls can often mitigate the potential impacts of gas composition changes on equipment performance, emissions, etc. This situation makes it difficult to universally apply empirical indices or to draw conclusions regarding potential real-world impacts from different gas compositions.

Role of Gas Quality Requirements, Standards, and Practices

There has been a long history of largely voluntary industry practices that guide participants in the natural gas industry. The purpose of gas quality requirements, contract limits, conventional practices, voluntary standards, and formal standards are to avoid issues amongst the various participants in the natural gas value chain: gas producers, gas processors, pipeline operators, storage operators, gas marketers, local distribution companies, natural gas equipment manufacturers, and end use customers. There is a long history of interactive efforts amongst different natural gas industry stakeholders to address issues and concerns regarding natural gas composition and quality.

As noted, much of the natural gas industry operates on an informal set of standard practices. In some instances, this becomes more formalized. For example, Table 4 shows a listing of some common contract limits for natural gas. These limits, or a subset of these, may be used in custody transfer agreements and contracts between market participants (e.g., for gas custody transfer between a producer and pipeline operator or a pipeline operator and a LDC). Several items are focused on operational and corrosion concerns, providing pipeline owners and operators with assurance that they should not encounter excess levels of compounds such as hydrogen sulfide or carbon dioxide that could cause internal pipe corrosion, embrittlement, or other metallurgical or material integrity concerns.

Table 4: Example Contract Natural Gas Limits

Component	Typical Contract Limits*
Hydrogen sulfide	0.25–1.0 grains/100 scf
Total sulfur (including odorants)	10–20 grains/100 scf
Carbon dioxide	2% by volume, max.
Oxygen	0.2% by volume, max.
Nitrogen	3.0% by volume, max.
Total inert gases	4.0% by volume, max.
Hydrogen	400 parts per million, max.
Water	7 lb/million scf, max.
Heating value	975 Btu/scf min. (higher heating value)

* Values are typical;, however contracts seldom list all of the components shown and limits can vary.

Natural Gas Interchangeability

More significantly, issues about the equipment operation, safety, and gas composition have evolved over a long period of time. Since the early 1900s, studies on the effects of natural gas composition on the combustion characteristics of a burner have focused on development of index values and/or on experimental testing of different appliances with different fuel sources – what was referred to previously as “interchangeability.”

An index value is a quantitative comparison of the relative change of the physical characteristics of burner’s flame based upon the properties of two fuel gases. The value is calculated using gas properties such as heating value and specific gravity along with experimentally derived constants. Generally, a specific index value is calculated for certain characteristics of a flame such as lifting or yellow tipping. The value is a ratio of the properties of a baseline fuel gas (typically a pipeline natural gas) compared to another fuel source and is meant to relate how a certain flame characteristics will change when the burner is switched between these two gases.

Early work on fuel gas interchangeability led to the development of the Knoy value and Wobbe Number or Index. Wobbe Index (heating value divided by the square root of specific gravity) was shown by multiple investigators to correlate much better with interchangeable flame behavior than the fuel heating value alone. Particularly for gases with similar composition, Wobbe Index is a good indication of similar performance.

The most significant early work in this area was started by the American Gas Association (AGA) and published in a series of reports and bulletins. AGA Bulletin 10 (1940) was a study of how the design features and operation of an atmospheric gas burner affects the characteristics of its flame. Features such as fuel source, primary air, orifice sizes, surface finishes and port area, both size and location, were studied. AGA's Bulletin 36 (1946) was used for interchangeability studies and the development of AGA's gas interchangeability index values. Three indices were derived because the researchers believed the current practice at the time of using only one index did not adequately cover the full range of differences in burner flame performance. Single index values used at the time included heating value of the gas, Wobbe Index, the AGA "C" and Knoy "C" values. The new AGA indices were the Lifting Index (IL), Flash-Back Index (IF) and Yellow Tip Index (IY). For interchangeability, values for each index must fall within the numerical limits established for a specific adjustment gas.

Table 5 and Figure 7 show AGA's Bulletin 36 data and the procedure for evaluating the three interchangeability indices. Subscript "s" denotes substitute gas and subscript "a" denotes an adjust gas. Results for the index values were compared to results with a range of appliances using the same set of gases. Gases used included Adjustment Gases or typical pipeline natural gases and Supplemental Gases or gas mixtures of higher heating values than the Adjustment Gases. Appliances tested included gas range, floor furnace, water heater, radiant heater and refrigerator. Many of the test methods and basic concepts from this work were used as the basis for the study in the GTI 2003 study on gas interchangeability.

AGA expanded their interchangeability work by researching low heating value gases using more contemporary burners. Results were presented in a series of four reports and are compiled in AGA Bulletin 60 (1950) for an expanded range of appliances relative to those tested in Bulletin 36. A numerical system was developed during this work for describing burner appearance. This system could then be used to adjust a flame to a desired appearance. This method assigns a flame a value between –5 and +5 depending on characteristics of flame including softness, visibility of the inner cones, yellowing and lifting (Table 6, with representative flame pictures). A "0" flame is considered to be a properly adjusted flame based on fuel and air ratio. This method is used and discussed extensively in another section of this report.

Work discussed in Bulletin 36 recognized that a single index value could not represent the entire spectrum of changes in a flame's performance. Weaver (1951) of the U.S. Bureau of Mines derived a series of six index values to include even more characteristics of the combustion of a flame compared to the work of AGA. These included values such as flame speed and incomplete combustion. Incomplete combustion is very important for appliance operation because it relates to the formation of carbon monoxide (CO).

Table 5: AGA Bulletin 36 Interchangeability Index Values

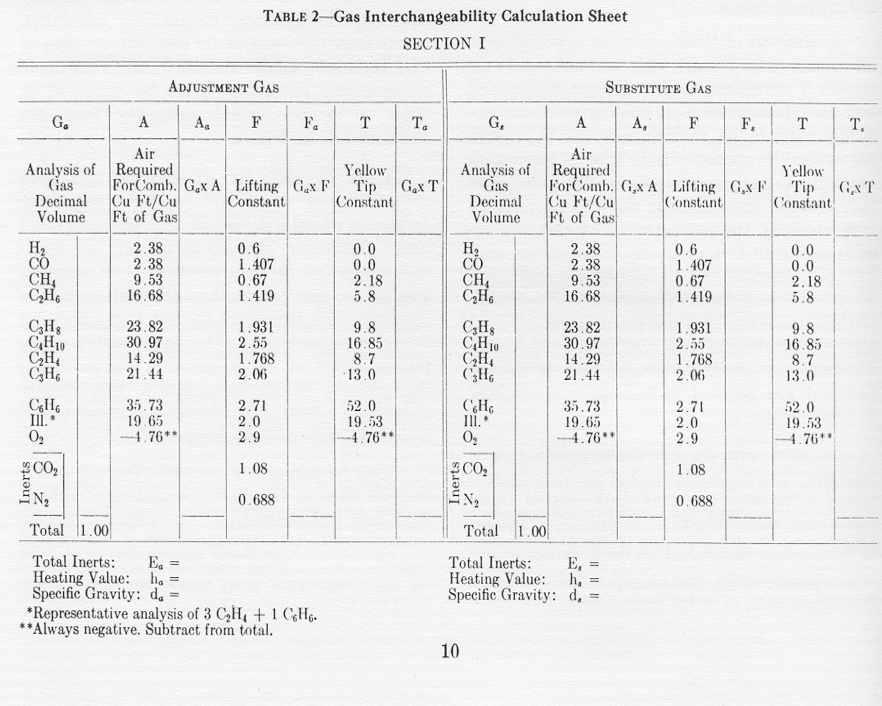


TABLE 2—Gas Interchangeability Calculation Sheet

SECTION I

ADJUSTMENT GAS

G_a Analysis of Gas Decimal Volume		A Air Required For Comb. Cu Ft/Cu Ft of Gas	A_a G_ax A	F Lifting Constant	F_a G_ax F	T Yellow Tip Constant	T_a G_ax T
H_2		2.38		0.6		0.0	
CO		2.38		1.407		0.0	
CH_4		9.53		0.67		2.18	
C_2H_6		16.68		1.419		5.8	
C_3H_8		23.82		1.931		9.8	
C_4H_{10}		30.97		2.55		16.85	
C_2H_4		14.29		1.768		8.7	
C_3H_6		21.44		2.06		13.0	
C_6H_6		35.73		2.71		52.0	
Ill.*		19.65		2.0		19.53	
O_2		—4.76**		2.9		—4.76**	
Inerts CO_2				1.08			
Inerts N_2				0.688			
Total	1.00						

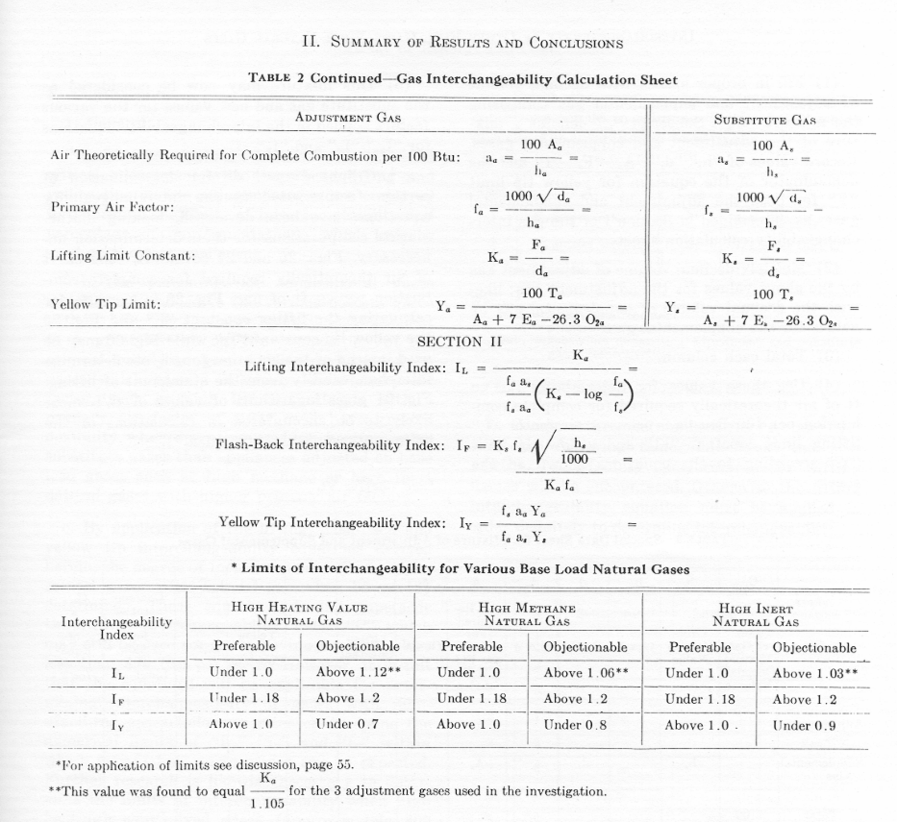
Total Inerts: E_a =
Heating Value: h_a =
Specific Gravity: d_a =

SUBSTITUTE GAS

G_s Analysis of Gas Decimal Volume		A Air Required For Comb. Cu Ft/Cu Ft of Gas	A_s G_sx A	F Lifting Constant	F_s G_sx F	T Yellow Tip Constant	T_s G_sx T
H_2		2.38		0.6		0.0	
CO		2.38		1.407		0.0	
CH_4		9.53		0.67		2.18	
C_2H_6		16.68		1.419		5.8	
C_3H_8		23.82		1.931		9.8	
C_4H_{10}		30.97		2.55		16.85	
C_2H_4		14.29		1.768		8.7	
C_3H_6		21.44		2.06		13.0	
C_6H_6		35.73		2.71		52.0	
Ill.*		19.65		2.0		19.53	
O_2		—4.76**		2.9		—4.76**	
Inerts CO_2				1.08			
Inerts N_2				0.688			
Total	1.00						

Total Inerts: E_s =
Heating Value: h_s =
Specific Gravity: d_s =

*Representative analysis of 3 C_2H_4 + 1 C_6H_6.
**Always negative. Subtract from total.



II. SUMMARY OF RESULTS AND CONCLUSIONS

TABLE 2 Continued—Gas Interchangeability Calculation Sheet

	ADJUSTMENT GAS	SUBSTITUTE GAS
Air Theoretically Required for Complete Combustion per 100 Btu:	$a_a = \frac{100\ A_a}{h_a} =$	$a_s = \frac{100\ A_s}{h_s} =$
Primary Air Factor:	$f_a = \frac{1000\sqrt{d_a}}{h_a} =$	$f_s = \frac{1000\sqrt{d_s}}{h_s} =$
Lifting Limit Constant:	$K_a = \frac{F_a}{d_a} =$	$K_s = \frac{F_s}{d_s} =$
Yellow Tip Limit:	$Y_a = \frac{100\ T_a}{A_a + 7\ E_a - 26.3\ O_{2a}} =$	$Y_s = \frac{100\ T_s}{A_s + 7\ E_s - 26.3\ O_{2s}} =$

SECTION II

Lifting Interchangeability Index: $I_L = \dfrac{K_a}{\frac{f_a\, a_s}{f_s\, a_a}\left(K_s - \log \frac{f_a}{f_s}\right)} =$

Flash-Back Interchangeability Index: $I_F = \dfrac{K_s\, f_s \sqrt{\frac{h_s}{1000}}}{K_a\, f_a} =$

Yellow Tip Interchangeability Index: $I_Y = \dfrac{f_s\, a_a\, Y_a}{f_a\, a_s\, Y_s} =$

*** Limits of Interchangeability for Various Base Load Natural Gases**

Interchangeability Index	HIGH HEATING VALUE NATURAL GAS		HIGH METHANE NATURAL GAS		HIGH INERT NATURAL GAS	
	Preferable	Objectionable	Preferable	Objectionable	Preferable	Objectionable
I_L	Under 1.0	Above 1.12**	Under 1.0	Above 1.06**	Under 1.0	Above 1.03**
I_F	Under 1.18	Above 1.2	Under 1.18	Above 1.2	Under 1.18	Above 1.2
I_Y	Above 1.0	Under 0.7	Above 1.0	Under 0.8	Above 1.0	Under 0.9

*For application of limits see discussion, page 55.
**This value was found to equal $\frac{K_a}{1.105}$ for the 3 adjustment gases used in the investigation.

Figure 7: Equations for Calculating Bulletin 36 Index Values

Table 6: AGA Flame Code for Describing Flame Characteristics and Example Flames

Code	Flame Description	
+ 5	Flames lifting from ports with no flame on 25% or more of the ports	
+ 4	Flames tend to lift from ports, but become stable after short period of operation	
+ 3	Short inner cone, flames may be noisy	
+ 2	Inner cones distinct and pointed	
+ 1	Inner cones and tips distinct	
0	Inner cones rounded, soft tips	
- 1	Inner cones visible, very soft tips	
- 2	Faint inner cones	
- 3	Inner cones broken at top, lazy wavering flames	
- 4	Slight yellow streaming in the outer mantles, or yellow fringes on tops of inner cones. Flames deposit no soot on impingement	
- 5	Distinct yellow in outer mantles or large volumes of luminous yellow tips on inner cones. Flames deposit soot on impingement	

While an index calculation approach is often used in the US, countries in Europe tend toward a graphical approach for predicting gas interchangeability. A graphical method uses plots typically with the y-axis being the Wobbe Index and the x-axis being a modified Wobbe number or other value that accounts for changes in the fuel gas composition or properties. Within the plots are limit lines for the different measures of interchangeability including incomplete combustion, flashback, yellow tipping and lifting. The space within these lines defines an area of interchangeability. An inherent advantage of the graphical approach is that it indicates the degree of potential interchangeability by referring to the location of the point for the substitute gas in relation to the limit lines.

Within Europe, different graphical values have been developed in several countries. For example, Delbourg (1951) in France uses a Wobbe number that has been modified with an orifice discharge coefficient to define an area of interchangeability. Developed in the United Kingdom, the Gilbert and Prigg (1956) method plots Wobbe number as a function of Weaver Flame Speed Factor. The graphical method used today is basically the same with modifications in the calculations of the axis values and limit lines. The values used vary depending on the gases used, the application and/or country of use. The graphical method has not been adopted in the US in part because the domestic composition of natural gas has been fairly stable.

Europe and the United States have also differed in the process of establishing standards for correlating the performance of appliances with the fuel source or gas supply. Western European countries adopted tests in the early 1970s for appliance performance based on adjust and limit gas compositions. These tests are outlined in CEN Standards. Appliances are tested with specified test gases to ensure satisfactory operation over the range of gas characteristics during normal operation. However, after years of development, a draft written in 1981 for the United States by American Society of Testing Materials (ASTM) Committee D-3 on Gaseous Fuels was prevented from becoming a standard on an ASTM Society Ballot. Another attempt to develop provisions to establish parameters for gas compositions to ensure proper appliance operation was undertaken by the American National Standards Institute (ANSI) Committee Z21. The work is chronicled in a report published by the Gas Research Institute (Griffiths et. al., 1982). The work includes a survey of natural gases in use in the United States, application of the AGA's Bulletin 36 Index Values, testing of appliances on a range of adjust and limit gases and suggestions for revisions to the ANSI standards to include appliance flexibility tests.

The approach on interchangeability index choice varies throughout the world. In the US the Wobbe Number and AGA indices are most commonly used. Other groups in the U.S. also use the Weaver indices. One LDC has developed its own graphical approach similar to the Dutton method. Europeans use many different approaches including the Delbourg method in France and the Dutton method in England. France (1970) describes these methods in some detail and presents a critical comparison of different indices and graphical approaches to interchangeability. Table 7 lists various interchangeability approaches found in the literature. Note that not all of these approaches are currently used.

Table 7: Listing of Natural Gas Interchangeability Techniques

Author	Year	Country	Technique
Wobbe	1926	--	Single Index
AGA	1933	U.S.	Single Index
Willien	1938	U.S.	Single Index
Knoy	1941	U.S.	Single Index
AGA (Bulletin 36)	1946	U.S.	Multiple indices
Weaver (USBM)	1951	U.S.	Multiple indices
Delbourg	1953	France	Diagram
Gilbert and Prigg	1956	U.K.	Diagram
Grumer, Harris, Rowe	1956	U.S.	Diagram
Holmqvist	1957	Sweden	Diagram
Shuster	1957	Germany	Single Index
Harris and Lovelace	1968	U.K.	Diagram
Van der Linden	1970	Holland	Diagram
Soomers and Jost	1973	Germany	Single Index
Harris and Wilson	1974	U.K.	Diagram
France	1976	U.K.	Diagram
Dutton	1978	U.K.	Tetrahedron

Figure 8 shows an example concept for an interchangeability operating regime or "box" based on a draft report from the NGV+ Interchangeability Work Group. A fundamental of this type of approach is to often anchor one side of the box with a Wobbe Number range. The other axis could, if desired, be constrained by a second key parameter.

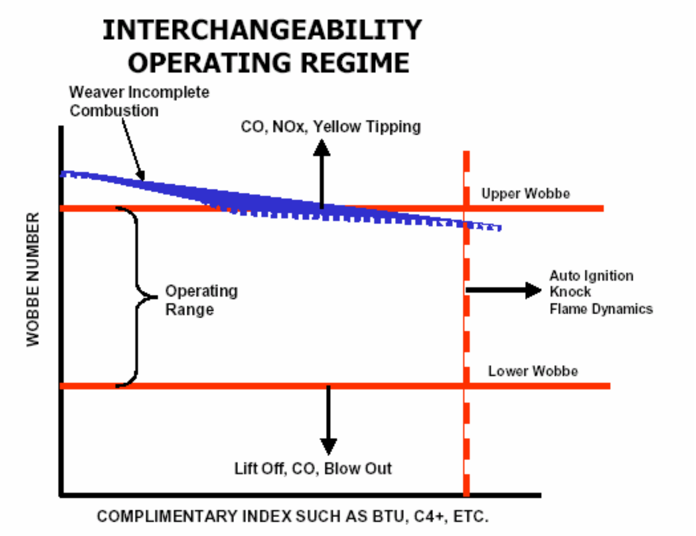
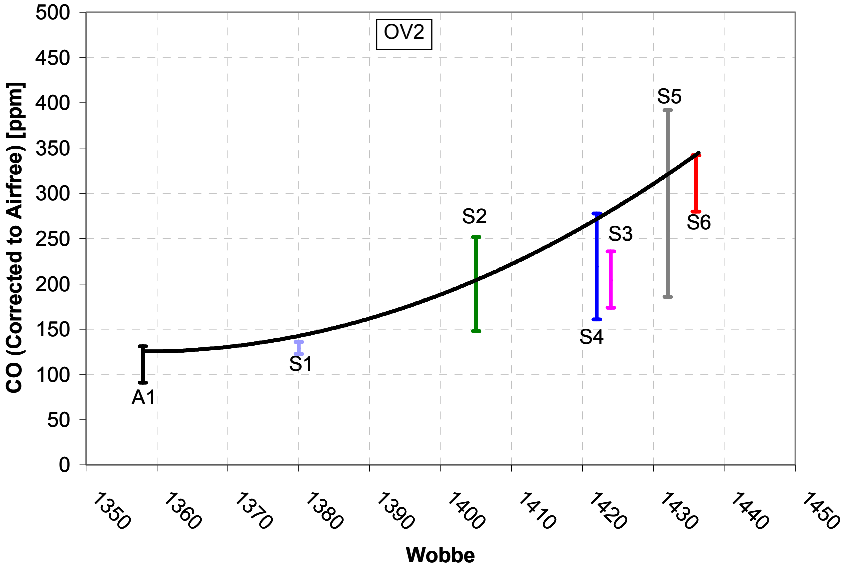


Figure 8: Example Interchangeability Operating Box (NGC+)

In practice, the situation in the market is such that there is a large degree of acceptance in the U.S. on gas composition, in part because of the history of work and methods used by equipment manufacturers to ensure their products are able to operate on a range of fuel options. For example, although ANSI standards for gas appliances call for testing on "Gas A", with a gross heating value (GHV) of 1075 Btu/scf and specific gravity of 0.65, neither ANSI nor appliance manufacturers actually use Gas A for adjustments and tests. Instead they use pipeline gas from their local distribution system. Appliance manufacturers will periodically test their natural gas composition to ensure it falls within a representative range.

Combustion technology has changed dramatically in the last several decades, and interchangeability questions and standards extend well beyond (and may supplant) the indices for lifting, flash back, and yellow tipping on residential burners that were developed by AGA Labs and the Bureau of Mines. Important interchangeability concerns that must be addressed today include fuel and oxidant (air or oxygen) supply, mixing, and ratio control equipment performance; flame safety and monitoring equipment operation; and burner emissions (CO, unburned hydrocarbons, and NO_x) for a wide range of traditional and low-NO_x burners.

Figure 9 shows results from GTI testing on different natural gas compositions covering a broad spectrum on a conventional natural gas appliance. There were identified trends on CO emission levels with changes in gas composition. As noted earlier, changes in emissions such as these CO data can often be closely related to changes in equivalence ratio (or its inverse, air/fuel ratio). The magnitude of emission changes will be dependent on many factors, including the sensitivity of combustion emission levels to changes in equivalence ratio. In this testing, while CO emission changes were noted, the equipment still safely operated within limits described by ANSI standards.



Maytag – 18,000 Btu/h (GTI, 2002)

Figure 9: Appliance Tests – CO Impacts

The potential impact of natural gas composition can be complicated in some circumstances, but in most cases the influence of composition changes can be understood –on a first order – by using the following equation (King, SAE 920593):

$$\phi_2 = \phi_1 * (WN_2/WN_1) \quad \text{Eq. 1}$$

In this equation, the symbol ϕ, phi, stands for the fuel/air equivalence ratio and WN stands for the Wobbe Number. Values of phi greater than one indicate a "rich" fuel/air mixture and values less than one indicate a "lean" or excess oxygen combustion mixture. The fuel air equivalence ratio is found by the following equation:

$$\phi = (M_f/M_a)/F_s \qquad \text{Eq. 2}$$

In this equation, M_f/M_a, are the actual mass flow rates fuel to air going to the combustion device. F_s is the stoichiometric fuel air ratio for the specific fuel.

Through a set of analyses described in the referenced Society of Automotive Engineers (SAE) paper by King, Equation 1 can derived. The power of this relationship in describing the first order impact of fuel composition changes on basic combustion emissions is obtained by understanding the emissions curve and operating point of specific equipment. Figure 10 shows a generic emissions curve, indicating the stoichiometric point (where $\phi = 1$) and rich and lean combustion impacts. Historically, equipment manufacturers select nominal operating points along the fuel-air equivalence ratio axis to achieve their emissions objective. For example, some equipment operates "lean" with high excess air ratios to lower NO_x emissions.

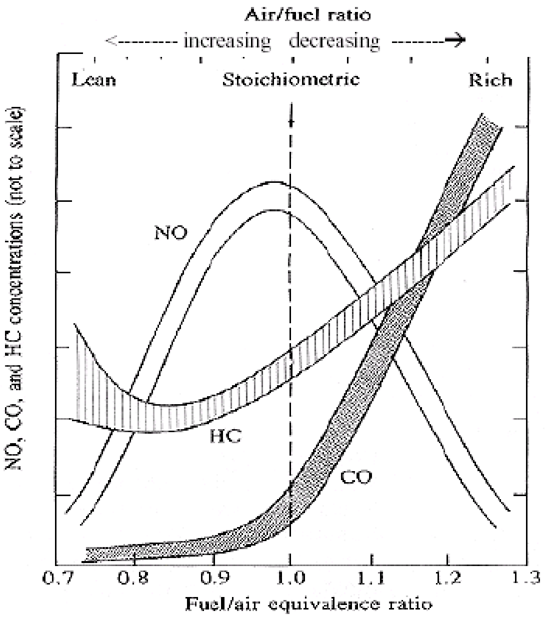


Figure 10: Representative Emissions Trade-off Curve

With Equation 1 and an emissions curve, and a known baseline or nominal operating point for a specific piece of equipment, a first order estimate of emissions impact can be derived. Depending on the slope of the NOx, CO, and hydrocarbon emissions curve at the initial point and the directional change in Wobbe Number (lower or higher), emissions may increase, decrease, or stay largely unchanged.

Importantly, more sophisticated combustion control techniques used on larger emission sources (e.g, staged combustion, split rich and lean combustion), post-combustion emission controls, and the use of closed-loop controls can result in canceling out many impacts from gas composition changes. For example, by holding exhaust oxygen levels constant (with feedback controls on fuel metering), certain state-of-the-art equipment can maintain a constant equivalence ratio even with changing fuel composition.

Figure 11 shows an example of a lean-burn natural gas engine with a nominal fuel/air equivalence ratio of 0.7. The green lines show the potential shift in equivalence ratio from a Wobbe Number (WN) change upward of 4 percent or downward of 4 percent. Using an average Wobbe Number of 1340, this would cover a broad range from as low as 1286 up to 1394 – a range that covers nearly all expected fuel compositions.

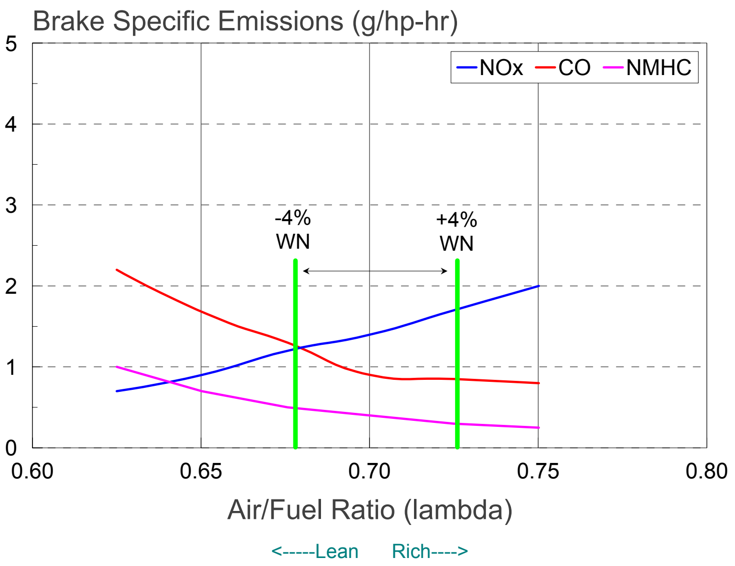


Figure 11: Example Lean Burn Gas Engine Emissions With Fuel Tolerance Window

Importantly, since the early 2000's, the latest technology low-emission heavy-duty natural gas vehicles (NGVs) now can negate this impact by using wide-range oxygen sensors. This type of control strategy enables constant adjustment of the fuel-air equivalence ratio to achieve virtually constant emissions.

Importantly, all light-duty natural gas vehicles have always required the use of closed-loop control with oxygen sensors to allow effective operation of the three-way stoichiometric catalysts. These inherent cancel the impacts of gas composition changes on emissions.

Similar closed-loop controls are used on a wide range of large stationary sources. Increasingly, these major sources require real-time emissions monitoring to ensure compliance with environmental permits. In these circumstances, such sophisticated systems largely mitigate emissions impact from changes in gas composition. Over time, the trend has been for increasingly smaller emission sources to incorporate more sophisticated control capability.

II. CALIFORNIA'S CURRENT STANDARDS

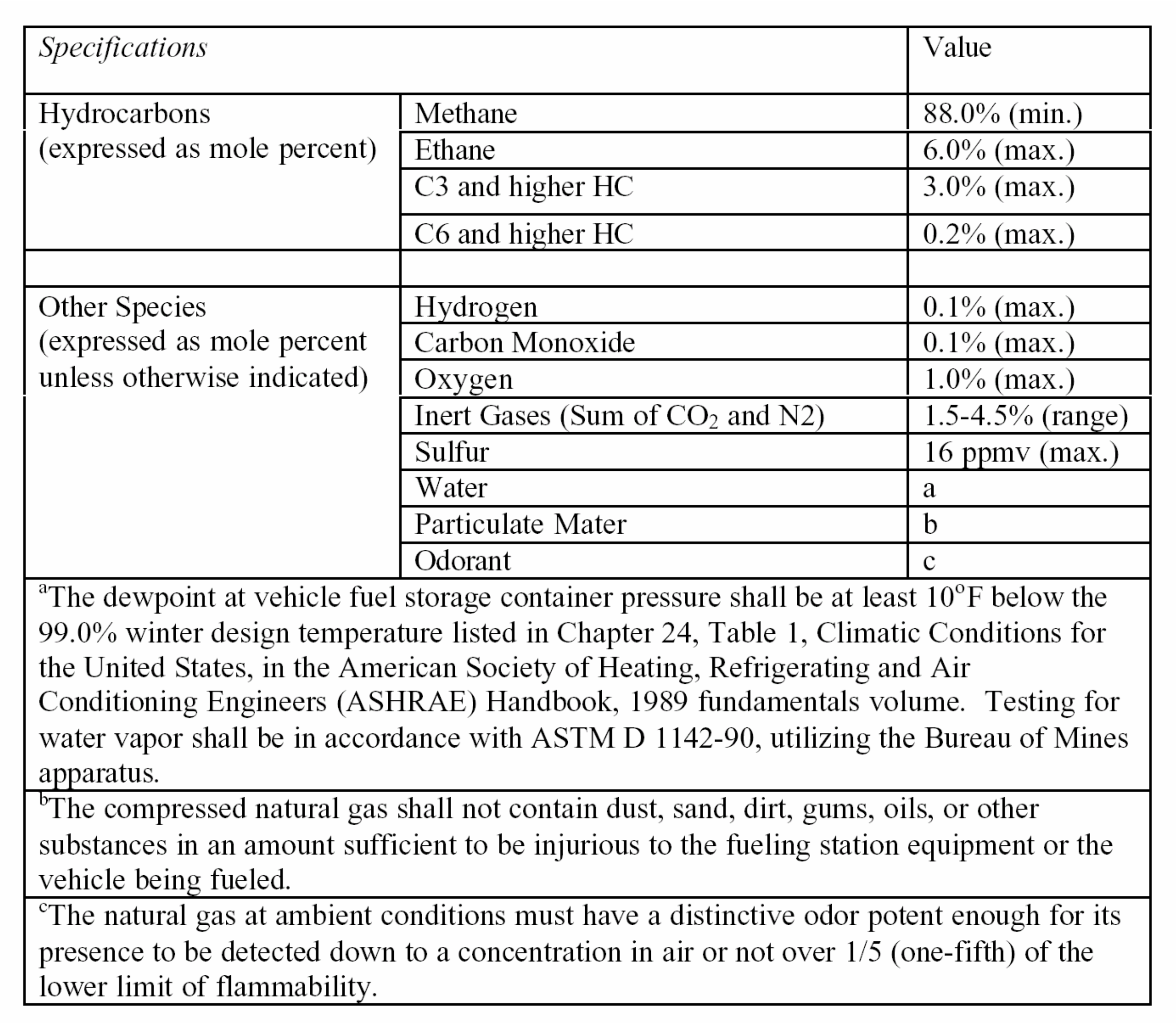
California Natural Gas Tarriffs

Gas Quality Rule 30 for Southern California Gas, entitled "Transportation of Customer-Owned Gas" contains a section discussing gas quality. This identifies a heating value range of 970 to 1150 Btu/scf (gross). Other requirements include 3% maximum for CO2 and 4% maximum for total inerts together with limits on water, hydrocarbon dewpoint, sulfur, and oxygen. There are additional limit ranges for Wobbe Number, Lifting Index (IL), Flashback Index (IF), and Yellow Tip Index (IY) – derived from prior AGA work.

CARB Fuel Specifications

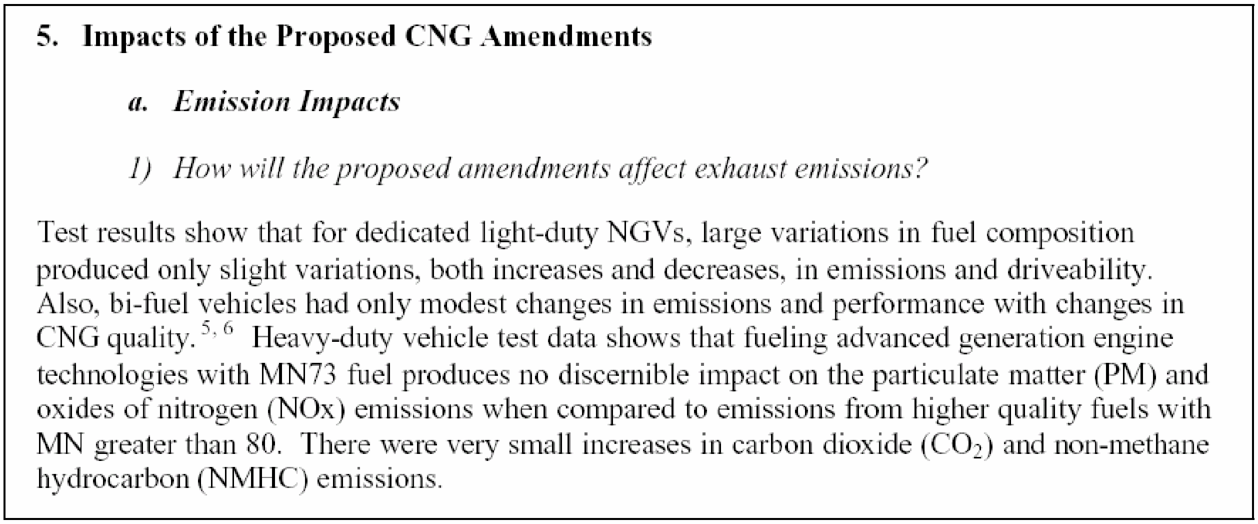
The California Air Resources Board implemented natural gas composition and property limits for use in natural gas vehicles.

Table 8: Summary of California NGV Fuel Specification



Specifications		Value
Hydrocarbons (expressed as mole percent)	Methane	88.0% (min.)
	Ethane	6.0% (max.)
	C3 and higher HC	3.0% (max.)
	C6 and higher HC	0.2% (max.)
Other Species (expressed as mole percent unless otherwise indicated)	Hydrogen	0.1% (max.)
	Carbon Monoxide	0.1% (max.)
	Oxygen	1.0% (max.)
	Inert Gases (Sum of CO_2 and N2)	1.5-4.5% (range)
	Sulfur	16 ppmv (max.)
	Water	a
	Particulate Mater	b
	Odorant	c
[a] The dewpoint at vehicle fuel storage container pressure shall be at least 10°F below the 99.0% winter design temperature listed in Chapter 24, Table 1, Climatic Conditions for the United States, in the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Handbook, 1989 fundamentals volume. Testing for water vapor shall be in accordance with ASTM D 1142-90, utilizing the Bureau of Mines apparatus.		
[b] The compressed natural gas shall not contain dust, sand, dirt, gums, oils, or other substances in an amount sufficient to be injurious to the fueling station equipment or the vehicle being fueled.		
[c] The natural gas at ambient conditions must have a distinctive odor potent enough for its presence to be detected down to a concentration in air or not over 1/5 (one-fifth) of the lower limit of flammability.		

The limits placed on natural gas for vehicles in California differ from other uses of natural gas. This is placing a burden on some in-state natural gas producers and distributors. An effort was underway in 2002 to modify natural gas vehicle fuel specifications, shifting to alternative metrics that would decrease the challenge place on certain in-state producers. This effort led to specific staff recommendations, including a shift to a Methane Number basis (and elimination of specific composition limit). The MN limits were 80, with a regional limit of 73 for certain qualifying fleets. This effort did not ultimately result in changes.



5. Impacts of the Proposed CNG Amendments

a. Emission Impacts

1) How will the proposed amendments affect exhaust emissions?

Test results show that for dedicated light-duty NGVs, large variations in fuel composition produced only slight variations, both increases and decreases, in emissions and driveability. Also, bi-fuel vehicles had only modest changes in emissions and performance with changes in CNG quality.[5, 6] Heavy-duty vehicle test data shows that fueling advanced generation engine technologies with MN73 fuel produces no discernible impact on the particulate matter (PM) and oxides of nitrogen (NOx) emissions when compared to emissions from higher quality fuels with MN greater than 80. There were very small increases in carbon dioxide (CO_2) and non-methane hydrocarbon (NMHC) emissions.

Figure 12: CARB Staff Language On Natural Gas Fuel Composition Impacts on Emissions

Potential Regulatory Impacts

Natural gas quality or composition regulations can have far reaching economic and energy efficiency impacts. The current natural gas production and delivery system is highly efficient. Data from Argonne National Lab indicate the production and delivery efficiency of natural gas (from wellhead to end user) is 93.6% -- that is, only about 6.4% of the energy value of natural gas is used for wellhead production, gas processing, gas transmission, and gas distribution. This represents a highly efficient energy delivery system, especially when compared to electricity which features a fuel cycle efficiency in the range of 25 to 30%.

In California, there is a regional concern for in-state producers on ethane levels from natural gas produced from associated resource basins. This natural gas can routinely have ethane levels of 5 to 10 percent. In other regions of the US, there may be an economic motivation to make substantial capital investment to remove this ethane for sale into chemical manufacturing. Even with this, such equipment typically entails a significant energy consumption penalty to operation refrigeration or cryogenic/low-temperature refrigeration cycles to partially liquefy and separate the ethane. This can add substantially to decreases in fuel cycle efficiency as well as emissions from electric motors driving refrigerant compressors.

The need to have flexibility on natural gas fuel specifications includes other near and long-term considerations such as the use of unconventional natural gas or gaseous-based energy resources that may become more prominent in the future:

- Biomass-based methane resources such as landfills, digesters, and wastewater treatment plants. Societal benefits are gained from using these renewable biomass resources, but they often face their own unique gas composition issues (including carbon dioxide, water, and trace contaminants).
- Synthetic natural gases or synthesis gases that can be produced through gasification of abundant solid fuels such as coal or biomass waste products[1].
- The potential future role of hydrogen in our gaseous energy distribution system. There may be a need to consider future appliances that can operate on natural gas with mixtures of hydrogen ranging as high as 10 to 20 percent.

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[1] While not commonly used today, historically natural gas was often derived through manufactured processes such as gasifying coal or liquid products such as naphtha. These practices may increase in the future as conventional naturally occurring gas resources decrease.

III. WORLDWIDE PRACTICES, CURRENT AND PROPOSED NATURAL GAS QUALITY STUDIES

Worldwide Natural Gas Practices

There are common practices and some areas of difference among international natural gas system operators. The following is a general overview of three different regions.

1. **UK and US:** distributed gas is lean, with a higher heating value usually less than 1,065 Btu/scf (42 MJ/m^3).
2. **Asia (Japan, Korea, Taiwan):** distributed gas is rich, with a higher heating value greater than 1090 Btu/scf (43 MJ/m^3).
3. **Continental Europe:** acceptable higher heating value is quite wide—about 990-1,160 Btu/scf (39-46 MJ/m^3).

In other countries, the issue of natural gas composition has evolved along different pathways depending on their historical and regional circumstances. In Asian countries for example, such as Japan and Taiwan, natural gas has always been mainly an imported LNG product. For example, Japan imports approximately 97% of its natural gas – essentially all in the form of LNG. These countries use "rich" LNG natural gas compositions.

In Europe, part of the continent has historically relied on imported LNG, others pipeline imports, and others North Sea production. This has resulted in a rather balkanized set of limits. Figure 13 shows an example based on Wobbe Number limits (in MJ/m^3 units) for different parts of Europe. In some cases, the multiplicity of supply sources in Europe has resulted in the acceptance of a wide range of natural gas composition – from lean to rich gas compositions.

E	Orange	$45.7 < W < 54.7$ MJ/m^3
H	Blue	$40.9 < W < 54.7$ MJ/m^3
L	Green	$39.1 < W < 44.8$ MJ/m^3

Cagnon, Marquer, Meunier, NGTC II (2004)

Figure 13: European Wobbe Number Limits By Region

With the US being historically mainly dependent on domestic natural gas supplies, much of the country has grown accustomed to relying on lean natural gas compositions with a higher heating value below 1050 Btu/scf and Wobbe Number in the range of 1336.

Current Natural Gas Quality Studies

As noted earlier, activity on interchangeability was high in the 1930s to 1950s as fuel gas was changed from lower-Btu content producer gases (e.g., so-called town gas or city gas) to higher-Btu naturally occurring natural gas resources. After this wave of activities, natural gas compositions and supplies were stable for many decades. Work in the 1950s to 1970s was limited to appliance tests by IGT and several local gas distribution companies (LDCs) including SoCalGas (Los Angeles) and Excel (Denver). Further developments again slowed through the 1980s and early 1990s. Activities picked up in the early 1990s as interest in North America focused on expansion of the natural gas vehicle market. Prompted by engine and vehicle manufacturers, several studies and tests were conducted to document and understand the impact of natural gas composition on engine performance, knock resistance, and emissions.

In the later 1990s a number of organizations realized that new natural gas supplies were needed to meet the expected importation of natural gas. The U.S. was moving from a net natural gas producer to a net natural gas consumer. The most likely means of meeting the expected increased demand was through LNG importation. The United States currently has four active LNG import terminals (Everett in MA, Elba Island in the mid-Atlantic, Port Charles SC, and Lake Charles LA). Currently, only 1 to 2 percent of fuel gas is supplied by LNG. The expected increase up to 10 percent of all gas supplies in the form of LNG over the next decade has prompted a number of actions.

The following is a partial list of contemporary fuel gas interchangeability projects or activities that have been conducted or are underway.

- SoCalGas, multiple combustion systems (ongoing)
- Florida Gas Transmission, appliances
- Washington Gas and Light (with TIAX), appliances for WGL service area (2003)
- GTI, appliances (2003)
- California Energy Commission PIER, catalytic combustion
- DOE NETL paper, power systems, turbines (2000)
- World Gas Conf., wide Wobbe range, 21st century appliance (2003)
- ILEX Consulting, U.K., impact of fuel gas changes in U.K. (2003)
- European study of burner control system performance (2000)
- Gaz de France, current work on French concerns
- Gas Unie, recent work related to fuel changes and H_2 use
- Natural Gas Council task forces

Suppliers, pipeline companies, and LDCs understand that world LNG compositions, heating values, and specific gravities are often similar to domestic natural gas, but can be significantly different when some LNG sources are considered. Questions have been raised regarding what properties (or calculated indices) should be used to specify acceptable LNG cargoes, what limits should be set on these properties, and what means are acceptable to bring LNG cargoes into desired specifications. This work is compounded by the range in tariffs in existence around the country on different pipeline systems. Several studies, activities, and Task Groups have begun under the auspices of the Natural Gas Council (NGC)

TIAX (a spin-off of A.D. Little) has conducted appliance interchangeability studies for Commonwealth Gas and Distrigas in the northeast and for Washington Gas and Light. These studies included new appliances and appliances in service. Only parts of the collected data are publicly available.

GTI conducted a study of ten new appliances relative to a wide range of potential LNG supplies and relative to various means of bringing hotter LNG into line with domestic natural gas (blending with nitrogen and air and blending with natural gas). The GTI study (2003) is publicly available at no cost, due to the generosity of sponsors Shell, BP, Washington Gas, Enron, El Paso Merchant Gas, and Southern LNG. The ADL, TIAX, and GTI studies found CO to be a quantitative measure of natural gas interchangeability for most appliances (though in testing the changes in CO were relatively minor and still complied with ANSI requirements). The benefit of using CO as a discriminator is that it avoids the qualitative nature of historical combustion indices.

The only active study currently underway and collecting new data (as of the end of December, 2004) is sponsored by SoCalGas. This study conducted by SoCalGas and UC Irvine involves measuring interchangeability indices and interchangeability for 14 appliances. SoCalGas has generously agreed to post findings on the INGAA website (www.ingaa,org). To date, 8 of the 14 combustion systems have been studied. Findings show that older appliances are well characterized by the interchangeability indices developed by AGA and Weaver (at USBM), but newer appliances with high efficiency and low NO_x burners behave in unique ways that depend on hardware and design components. A final report for this work is expected in the first quarter of 2005.

At least two new studies are under consideration. One study to be led by Florida Gas Transmission will focus on local combustion equipment that might be affected by LNG brought into Florida through the undersea pipeline from the Bahamas. The second proposed study is a large scale ‘gap filling’ project to address the equipment using natural gas for which incomplete information is available. The hope is to have the project funded by the U.S. Department of Energy and a consortium of pipeline, LDC, and supplier companies. The work would likely take several years to complete and would be divided among several companies that are best equipped to undertake various parts of the study. GTI is actively participating in the formulation of this activity.

The NGC Task Groups that have been formed include one on Dew Point Dropout and one on Interchangeability. The Dew Point Dropout Task Group is headed by Terry Boss of INGAA, and the Interchangeability Task Group is headed by Ted Williams of AGA. The two Task Groups were formed in 2003 to provide industry input to the Federal Energy Regulatory Commission (FERC) so appropriate properties and ranges of properties can be set in the future regarding LNG and other new gas supplies entering the pipeline system.

Both Task Groups have prepared long white papers to support their recommendations. The draft versions of these documents are available on the INGAA website. The Interchangeability Task Group has had a much more difficult time coming to a consensus. The reasons for this include lack of sufficient data for all natural gas utilization equipment, the wide range of gas utilizing equipment, and the variations that exist in different parts of the country in gas supply properties.

No final recommendations have been made by the Interchangeability Task Group, but that work is coming to completion in January, 2005. The Task Group recognizes that the tighter regulations are set, the higher the natural gas processing costs will be. Alternatively, wider limitations on acceptable natural gas compositions may increase the likelihood that some equipment will have difficulties. The most likely recommendations to FERC will be a Wobbe Number range of 1120 to 1380 or 1400 coupled with a swing range of ±3 to ±5 percent). Butane and higher hydrocarbons (C_4+) maximum value of 1.0 to 1.8 percent is likely along with recommendation of using the Weaver incomplete combustion test.

One expected outcome of the FERC process is setting of interim limits based on certain properties of the fuel gas, followed by long-term limits established in several years when more complete testing data is available. A final consideration in the establishment of acceptable limits is that certain regions of the country have unique historical and on-going situations. These areas include the Rocky Mountains (high altitude and low Btu gas), the gulf coast (with large petrochemical facilities), and California (with tight environmental regulations).

Natural Gas Quality Data Gaps

Recent interest in LNG interchangeability with natural gas warrants review of the historical approaches to fuel gas interchangeability, the approaches commonly employed, and areas in which further information is needed. Groups seeking information on the effects of changing fuel gas are also aware that combustion systems have become more complex, emissions control has become increasingly important, and efficiency demands have led to ever tighter controls. These circumstances have led to identification of information gaps that exist on performance changes for a wide range of combustion as well as non-combustion uses. These can be broken down into several broad categories.

- Appliances
- Industrial and Commercial Burners
- Turbines and Microturbines
- Stationary Engines
- Non-combustion Applications

Interchangeability concerns and available information differ in these categories. An effort has been made to outline the knowledge gaps in each category and to suggest an approach to acquiring the missing information.

Appliances

More work has been conducted on appliances, both historically and recently, than other gas utilization equipment. Gaps in information on appliance fuel gas interchangeability relate to identifying the most sensitive appliances, selecting the best indices for interchangeability, and testing of certain appliances. Future work can be divided into the following tasks:

1a	Rank appliances in terms of likely sensitivity to fuel gas changes - Some types of appliances are more sensitive to fuel gas changes than others. Creation of a comprehensive list and a ranking of the list will enable further testing to be carried out on the most sensitive appliances.
1b	Collect available interchangeability and analysis data to determine the best indicators of fuel interchangeability (such as Wobbe number, CO production, and various indices).
1c	Conduct long-term testing of sensitive appliances. The range of acceptable interchangeability can be affected by changes that occur during the operational lifetime of an appliance. Testing simulated to duplicate aging and long term performance combined with statistical analysis can reduce the testing efforts required.
1d	Test appliances in the field. A statistically relevant group of appliances with a range of types and ages can be selected and tested relative to acceptable performance and relative to changes encountered during use.

Industrial and Commercial Burners

Industrial and commercial burners are more tightly controlled than appliances and consume much more gas per burner. Some industrial burners consume more than 50,000 scf of natural gas per hour. In striving for high efficiency and low emissions, many burner styles have been developed. In general, these burners require tight fuel/ air controls and consequently the performance of some of these burners will likely be sensitive to fuel gas changes. Current data are insufficient to characterize the potential impacts on the wide range of available commercial and industrial burners. The following work will acquire needed industrial and commercial burner data relative to fuel gas interchangeability.

2a	Define major classes of burners and identify representative examples of each class. This will also include identifying dominant burners sold in each class.
2b	Rank burner types by those potentially most sensitive to fuel gas changes. Those most sensitive likely will be burners that have low emissions, that operate in processes in which flame temperature is crucial, and that operate in air to fuel ratio and flame temperature regimes close to stability limits.
2c	Prepare a list of parameters to monitor during testing. These parameters fall into three categories of 1) burner, combustion and process system operating parameters, 2) flame characteristic parameters, and 3) emissions values.
2d	Develop testing protocols. Documented, repeatable tests must measure all parameters of interest including flame temperature, flame length, emissions, air and gas rates, etc. In many cases, no standard test currently exists.
2e	Test representative examples of the most sensitive types of burners and combustion systems in the laboratory. All parameters of interest regarding fuel gas interchangeability should be monitored under controlled conditions.
2f	Burners found in laboratory testing to be most sensitive, burners unable to be tested in the laboratory, and burners expected to be sensitive to aging should be

	tested under field operating conditions. These tests could be more limited and less controlled than the laboratory tests, but the changes from laboratory to real-world applications are important to quantify.
2g	Analyze data to assess burner sensitivity and parameters best describing that sensitivity. This analysis is expected to produce guidelines to cover most types of industrial burners and their performance with changes in fuel gas.

Turbines and Microturbines

Power systems range from moderate sized microturbines to very large turbines. Combustion systems in turbines can be complex, and manufacturers go to great lengths to optimize performance and to meet strict environmental limits on emissions. The range of fuel gas composition and fuel gas heating value is always a concern because components must be changed if fuel gas composition outside the design range is used. Turbine manufacturers conduct extensive tests of their systems. These data are proprietary considering the competitive nature of the market. Conducting independent tests, particularly on larger units, is difficult because of the large volumes of gas required and because turbine operators are not comfortable with potential instabilities created by testing. Filling in fuel gas interchangeability gaps for turbines may be challenging. An approach to acquiring as much useful data as possible in a timely manner is outlined below.

3a	Review the major types of turbines and microturbines with an analysis of the relative levels of sensitivity, tolerance to fuel gas changes, and emissions for each identified turbine type.
3b	Prepare a list of turbine and microturbine manufacturers. The list will include types of turbines, turbine size ranges, and other relevant supplier information for each manufacturer.
3c	Contact turbine and microturbine manufacturers and acquire as much data as possible on 1) emissions, 2) efficiency, 3) service life, 4) combustion changes, and 5) impacts of slow and rapid fuel gas changes on turbine operation
3d	Determine testing needs after consolidating and analyzing data from turbine manufacturers and operators. Data may have to be collected on a proprietary basis and not released.
3e	Test turbines and microturbines where possible to fill in gaps concerning impacts of fuel gas changes. Some tests can be made in laboratory settings (particularly microturbines). Some tests may be conducted at turbine test facilities of specific manufacturers, if possible. If necessary, efforts can be made to conduct tests with working power turbines.

Stationary Engines

Stationary engines are operated with steady or intermittent load. The technology is robust and assumed to be able to operate satisfactorily with fuel gas compositions between those of domestic natural gases and most world LNGs. There are, however, questions remaining regarding the effect of fuel gas changes on combustion characteristics, efficiency, and emissions. Targeted work is advised to acquire these missing data. This work can include the following.

4a	Identify principal engine types and sizes for major manufacturers.
4b	Collect available information on effects of fuel changes on engine performance. These should include published papers, vendor specification sheets, and discussions with vendors and users of engines.
4c	Determine gaps most in need of attention relative to fuel gas interchangeability.
4d	Test engines and collect data. This work can be carried out in the lab and in field-installed units. Determine best interchangeability indices for engines.

Non-Combustion Applications

Natural gas is used primarily for combustion applications, but this versatile material is also used for other processes including transportation (engines), fertilizer production, ammonia production, chemical production, reforming, and fuel cells. The work outlined below addresses the gaps regarding the impacts of natural gas and LNG interchangeability in these areas.

5a	Transportation. • CNG and LNG vehicles have specific concerns, such as knock, that must be addressed. Significant work has been conducted in this area, and this work must be reviewed and summarized relative to fuel gas interchangeability.
5b	Chemical feedstock. • Users of natural gas as a feedstock in ammonia, fertilizer, reforming, and other processes must be identified and then surveyed to learn the sensitivity of their processes to changes in natural gas composition. • Summaries must be prepared showing the ranges of acceptable natural gas composition and impact of natural gas composition changes on users of natural gas as a feedstock. No testing is expected relative to natural gas to LNG change.
5c	Fuel cells. • Fuel cell types and their many variations must be listed and major developers must be identified. • Impact of changing natural gas composition on fuel cell operations such as reforming, coking, CO formation, impact of inerts, etc. must be identified and quantified wherever possible. No testing relative to natural gas to LNG composition changes is expected.

IV. POTENTIAL END USE IMPACTS

END USE NATURAL GAS COMPOSITION CONSIDERATIONS

As noted previously, the relative importance of natural gas composition to end-users will vary depending on a large number of factors. In some cases, end-use equipment will be highly resilient to changes in gas composition and exhibit no discernable effects in the eyes of the customer. In more extreme cases, certain end-use applications may prove to be highly sensitive to changes in gas composition (an issue that may potentially be addressed using equipment sensors and controls).

The complexity of this situation makes it challenging to establish gas composition or property limits that effectively balance the collective interests of the natural gas industry, its customers, and other stakeholders. For example, setting overly restrictive limits on natural gas may lead to increased costs to all end users – many of whom may not see any benefits at all. Conversely, setting broad limitations may leave certain end users vulnerable or necessitate they make site-specific investments to address their fuel quality concerns.

Historically, most efforts looking into gas composition or property impacts have focused on conventional residential natural gas products such as home furnaces, water heaters, etc. In some cases, targeted studies have been undertaken to look at impacts on a special class of natural gas customers.

NGVs represent a case study. NGVs, as noted previously, are a small portion of current US and California natural gas demand (about 0.1%). The US natural gas industry and the federal government actively supported NGV development during the 1990s. This was done to help grow a new natural gas market segment and to diversify energy use in the transportation sector. During this time period, several studies and analyses were undertaken to understand the impact of natural gas composition on NGVs – looking at issues such as drivability, engine knock resistance, and emissions.

On a national level, this resulted in the formulation of a Recommended Practice (J1616) from the Society of Automotive Engineers (SAE). The SAE J1616 document is largely informative and non-binding, lacking specific limits on natural gas composition or physical properties. This reflected in part the reality of the marketplace. That is, there is no federal natural gas composition requirement or comparable industry guidelines through organizations such as ASTM.

On a state-level, the California Air Resources Board (CARB) formulated natural gas composition requirements for NGVs as part of their charter to control vehicle tailpipe emissions. These compositional-based requirements are unique, contrasting with more conventional approaches that rely on setting range values based on certain natural gas properties (e.g., heating value or Wobbe Number). The CARB standard sets the minimum methane level at 88% while limiting ethane (6%) and propane (3%). The rationale for setting these limits is unclear, though was likely the result of a compromise among fuel providers, engine builders, customers, and regulatory authorities.

As a practical matter, many NGV equipment manufacturers have taken responsibility to assure their equipment satisfies emissions standards regardless of the specific fuel quality. They have also incorporated advanced controls that eliminate or reduce the risk for engine knock on a very wide range of fuels.

For example, the latest natural gas engine control technology developed by Cummins Engine Co. (their "Plus" technology, first introduced into the market in 2001) enables their engines to operate on natural gas fuels with Methane Numbers down to 65 (equivalent to a Motor Octane Number of about 115). By incorporating exhaust oxygen sensors that enable feedback control on the precision fuel metering injectors, these engines are also able to operate with a constant fuel/air equivalence ratio. By accomplishing this feat, Cummins' natural gas engines are able to achieve virtually constant emission levels regardless of natural gas composition. The type of technology being used in the Cummins natural gas engine product line are also being applied by other heavy-duty engine manufacturers, including John Deere and Mack Trucks.

This trend toward advanced controls will continue in the future as emissions regulations place further emphasis on lowering and maintaining emission levels over the life of the equipment. These controls are not needed solely to address fuel composition changes. Many other factors can influence the fuel/air equivalence ratio (ϕ) of equipment, including air density, fouling or plugging of air or fuel metering orifices, blockage of air filtration equipment, and equipment deterioration with time. In the future, more equipment will need improved sensors and controls to maintain emission levels – this can help enable our natural gas energy supply infrastructure to have the flexibility of supplying a range of different natural gases to consumers.

Appendix A. Glossary, Abbreviations, and Acronyms

Air-fuel ratio—the mass (or volume) ratio of air and fuel delivered to an engine's cylinders. Air-fuel ratio is commonly regarded as a measure of the richness or leanness of the combustible mixture relative to combustion requirements. However, because variations in the composition of natural gas fuel alter its combustion chemistry, the equivalence ratio is a more reliable measure of richness or leanness.

Btu—British thermal unit

City Gate—the point at which custody of pipeline gas is metered and transferred to the local distribution company

Closed loop engine controls—Engine control systems that employ an exhaust oxygen sensor to detect completeness of combustion and provide feedback to an electronic engine control module that adjusts air-fuel ratio for optimum combustion.

Dedicated NGVs—natural gas vehicles that are optimized for operation on natural gas and are unable to operate on another fuel, even for brief periods.

Dew point—the temperature at which the vapor in a given space (at a given pressure) will start to condense into a liquid.

Engine knock—in spark-ignited engines, abnormal combustion, often associated with audible sound, caused by autoignition in localized areas ahead of the spark-ignited flame front.

Equivalence ratio—the stoichiometric air-fuel ratio divided by the actual air-fuel ratio. This ratio is used to indicate a fuel-rich condition (values greater than 1.0) or fuel-lean condition (values less than 1.0).

Heating value—the energy content of natural gas stated in Btu/scf. See **higher heating value** and **lower heating value.**

Lower heating value (LHV)—the heat value of a combustion process assuming that the latent heat of combustion (i.e., condensation of water vapor) is not recovered.

Heavier hydrocarbons—see **higher hydrocarbons**

Higher heating value (HHV)—The heating value that includes the fuel's latent heat of vaporization–the energy recoverable by condensing water vapor from the combustion products. HHV is an appropriate measure for some high-efficiency combustion equipment but is less appropriate in relation to internal combustion engines, which are unable to recover energy by condensing exhaust products.

Higher hydrocarbons—hydrocarbons with molecular weights greater than methane. Higher hydrocarbons may affect NGV fueling stations and vehicles because of their propensity to form liquid deposits and alter the combustion characteristics of natural gas in internal combustion engines. The higher hydrocarbons are as follows—

Ethane, designated C_2H_6 or, simply, C_2
Propane, designated C_3H_8 or C_3
Butane, designated C_4H_{10} or C_4
Natural gasoline, C_5 and higher

Hydrates—A solid combination of water and methane that exists under certain temperature and pressure conditions (part of a class of substances called clathrates).

Hydrocarbon dewpoint temperature—see **pressure hydrocarbon dewpoint temperature**

Landfill gas—a gas predominantly methane but also containing various amounts of carbon dioxide and other gases produced by the digestion of organic matter in buried municipal solid wastes. Such gases are typically recovered and flared at large landfills; however, some is processed and used onsite as boiler fuel or sold to other parties.

Lean-burn combustion—used in some engines to reduce emissions by providing excess air to the combustion process. Because lean-burn combustion reduces power, turbocharging is often used to recover the lost power.

Liquefied natural gas (LNG)—Natural gas that has been converted to a liquid by cooling to a temperature of approximately -260^{o}F at atmospheric pressure. LNG is used to store and transport natural gas because of its reduced volume and increased energy density. A volume of LNG stores about 600 volumes of gas at atmospheric pressure; by comparison, CNG at 3000 psig stores approximately 260 volumes of gas.

Lower heating value (LHV)—the heating value of natural gas stated in Btu/scf at standard temperature and pressure, excluding the latent heat of vaporization of moisture from exhaust gases.

Methane Number–A measure of the knock resistance of natural gas. In the Methane Number scale, pure methane has a 100 rating and hydrogen, the other reference gas, has a 0 rating. The antiknock performance of natural gas decreases with additions of higher hydrocarbons such as ethane and propane.

Moisture content–natural gas absorbs water vapor much as the air does.

Mole %—measure of a gaseous component as a percentage of the overall molecular volume of a gaseous mixture.

Motor Octane Number (MON)—a measure used to describe the antiknock rating of fuels.

Open-loop engine controls—Electronic engine control systems that determine air-fuel mixture based on operational data (e.g., temperature, engine speed, load, etc.) but without feedback from an exhaust oxygen sensors. Open-loop control systems are programmed with assumptions regarding average fuel composition and thus cannot respond to variations in energy content and combustion properties.

Otto-cycle engines—internal combustion engines in which combustion is initiated by spark ignition.

Peakshaving—The practice by local distribution utilities of meeting winter peak demand for natural gas by supplementing normal pipeline deliveries of natural gas with one of various sources including gas from underground and above-ground storage, vaporization of stored LNG, and injection of interchangeable gas mixtures such as propane and air.

Pressure hydrocarbon dew point temperature–The temperature, referenced to a specific pressure, at which gaseous hydrocarbon components begin to condense into liquids.

Pressure water dew point temperature—The temperature, referenced to a specific pressure, at which water vapor begins to condense into liquid water.

psig–pounds per square inch gauge

scf—standard cubic foot of natural gas measured at 60^{o}F and atmospheric pressure (14.73 psia).

Specific gravity—As applied to gases, the ratio of the density of the gas to air at standard conditions of temperature and pressure.

Stoichiometric—The numerical relationship of chemical elements and compounds as reactants and products in chemical reactions such as the combustion process. In stoichiometric combustion, fuel and oxygen reactants are present in the exact proportions required to sustain complete combustion, leaving no unreacted elements or compounds.

Wobbe Number–a measure of the chemical energy of a gaseous fuel that can flow through an orifice of fixed size at a constant pressure drop. It is defined as the fuel's higher heating value divided by the square root of the fuel’s specific gravity. Changes in the Wobbe Number affect engines the same way as changes in the volume of a liquid fuel: an increase, due for example to the addition of ethane and propane, results in a richer air-fuel ratio; a decrease, caused by a greater proportion of inert gases, creates a leaner air-fuel ratio.