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Impacts of Imported Liquefied Natural Gas on Residential Appliance Components: Literature Review

1.0 Executive Summary

An increasing share of natural gas supplies distributed to residential appliances in the U.S. may come from liquefied natural gas (LNG) imports. The imported gas will be of a higher Wobbe number than domestic gas, and there is concern that it could produce more pollutant emissions at the point of use. This report will review recently undertaken studies, some of which have observed substantial effects on various appliances when operated on different mixtures of imported LNG. While we will summarize findings of major studies, we will not try to characterize broad effects of LNG, but describe how different components of the appliance itself will be affected by imported LNG. This paper considers how the operation of each major component of the gas appliances may be impacted by a switch to LNG, and how this local impact may affect overall safety, performance and pollutant emissions. These are discussed here in terms of each affected appliance component.

- Gas supply system: There will be no effects on the gas supply system itself. However, one study found that pressure pulsations caused by a faulty gas pressure regulator caused carbon monoxide spikes at the burner head.
- Fuel-air mixing system: In properly operating appliances, LNG will have no effect on the mixing system. However, in appliances already experiencing a level of incomplete combustion, the increased oxygen requirement of imported LNG may cause a further increase in carbon monoxide emissions.
- Ignition system: In burning imported LNG, appliance pilot flames may produce more heat overall and could emit elevated levels of CO, but in no case among the studies considered here did CO emissions exceed allowable levels. There is a possibility of delayed or inhibited ignition of main burners, but current research has not observed this.
- Burner head: Possible effects of gas quality changes include soot formation, flame elongation, flame lifting, and increased emissions. However, these effects have typically been seen only on appliances performing below design standards prior to the introduction of LNG.
- Controls and safety devices: In rare cases, it is plausible that elevated temperatures may affect thermal cut-off switches, or flame lifting could incapacitate oxygen depletion sensors.
- Heat exchanger: The heat exchanger may reach a slightly higher sustained operating temperature if the imported LNG causes a hotter flame. There is a possibility of flame impingement on the heat exchanger due to elongation or flame lifting, or soot buildup on the heat exchanger due to yellow tipping.
- Vent system: Under certain scenarios, the vent system could also reach a higher sustained operating temperature. A further residual buildup of soot inside the flue is a theoretical possibility when pre-existing upstream incomplete combustion is exacerbated by the introduction of LNG.

In most cases, the most serious consequence of a switch to substitute natural gas is a rise in CO emissions. Fortunately, no studies considered here found an appliance setup that consistently breaches the acceptable limit of CO emissions. However, it should still be stated, based on the findings of this report, that a rise in CO emissions cannot be avoided with absolute certainty. The range and number of appliances in the field, the variety of the field installations and operating conditions, together with the range of effects that can cause an increase in CO emissions after a switch to substitute gas, suggests that at least a small sample of the 93 million U.S. homes that use at least one gas appliance will experience a rise in CO emissions to beyond acceptable levels.

2.0 Introduction

Faced with growing demands for natural gas , net imports of liquefied natural gas (LNG) are expected to grow to nearly 1.5 trillion cubic feet over the next decade (see Figure 2-1).[1]

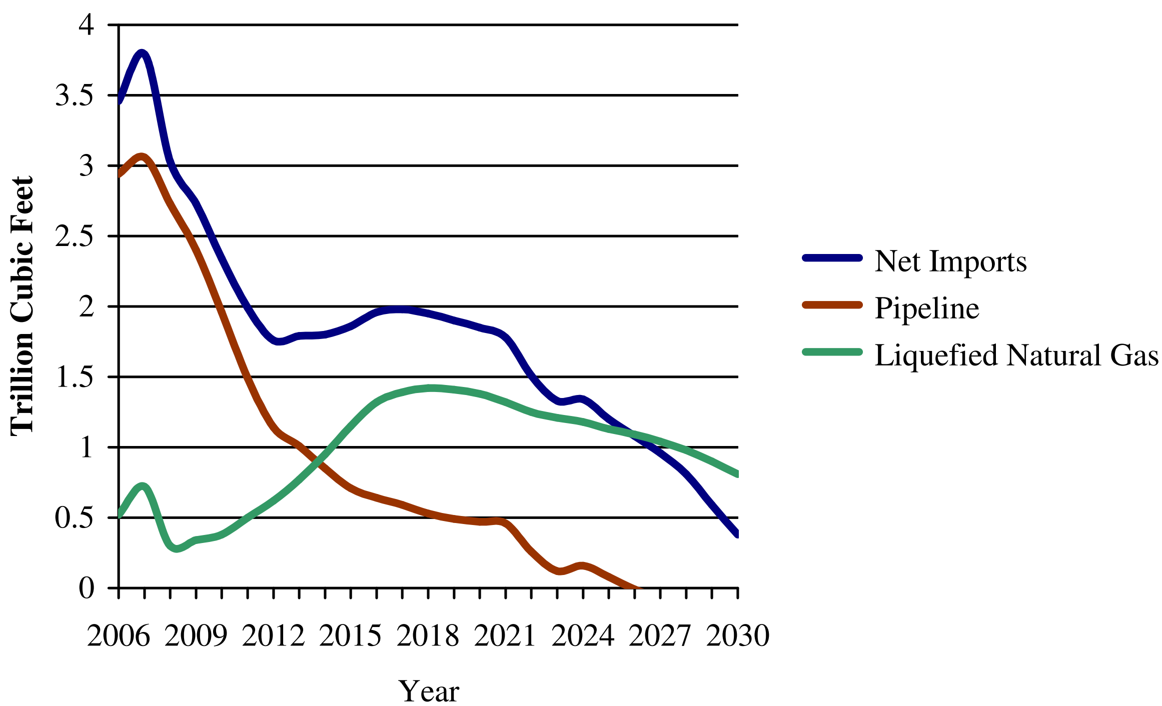

Figure 2-1 U.S. Natural Gas Imports, 2006–2030.[2]

In response to the expected influx of LNG, distributors throughout the U.S. will need to integrate this gas, which differs in chemical and physical composition (also referred to as "gas quality")[3], with the natural gas being distributed throughout the country. LNG is chemically different than the natural gas currently distributed by local utilities to U.S. residences. LNG has a higher percentage of heavy hydrocarbons (C_2–C_4), is shipped without inerts (typically N_2), and will generally have a higher Wobbe number.

Wobbe number is a relative measure of the energy delivery rate of a gas through a fixed orifice. Because this creates a need at the burner for a higher delivery rate of oxygen—which may not be available—this has lead to concern about replacing or mixing current supplies of natural gas with

LNG. Potential adverse impacts on the performance, safety, and emissions of residential gas appliances must first be understood.

Investigation of the potential adverse impacts of imported LNG is particularly important in the case of residential appliances. They are found in most households across the US, they vary widely in age, condition, and design, and most of these appliances are not regularly maintained or serviced. Studies have been conducted to measure emissions from appliances with LNG. However, there is no systematic and centralized source of information on natural gas appliance components that might be impacted by gas quality changes. Most of the studies reviewed here involved experiments on whole appliances. This paper considers the component technologies of appliances, how each component may be impacted be a fuel change, and how these localized impacts may translate to an overall change in appliance safety, performance, or emissions. Thus, in this paper we ask: What are the appliance component technologies most likely to be impacted by imported LNG?

Because imported liquefied natural gas is mostly of a higher Wobbe number (i.e. it has a higher heating value) than natural gas currently distributed to U.S. residential gas customers, this paper assumes that any gas substitution impacts on a given appliance will be caused by a move from a gas with a lower heating value to a gas with a higher heating value. With Wobbe numbers, the heating value of two dissimilar gases can be directly compared. For U.S. residential distribution, most utilities restrict their gas to be in the range of about 1331 to 1357.[4] When combined with imported LNG, a natural gas mix could reach a Wobbe number of 1385 or higher. Thus, for the remainder of this paper, we restrict our analysis to the case where a substitute gas has a higher Wobbe number than the adjust gas.

The gas industry uses the term “adjust gas” to refer to a gas to which a burner or appliance has been tuned. The term "substitute gas" is used to refer to some other fuel on which the burner or appliance is then operated. In this report, we consider appliances that have been either adjusted or designed to operate on current fuel, but which are operating on substitute gas. This terminology is less meaningful today because most residential appliances are not adjusted per se. Rather, they are designed to operate on a range of gases. However, some adjustment is possible: For example, appliances sold at high altitude are fitted with different orifices to deal with lower oxygen density.

The report is divided into two parts: In the first part, we discuss the major design components of residential gas appliances. The second part addresses ways that LNG will impact the appliance components, and ways that LNG will affect the safety, performance, and emissions of the appliance.

Cooking products, water heaters, furnaces and clothes dryers represent the vast majority of gas appliances found in US homes. This review focuses primarily on these four residential product categories. Other products play a smaller role in the U.S. gas appliance market but are not considered here.

3.0 Description of Impacted Natural Gas Appliance Components

In this section, we describe in detail the operation of any appliance component categories that may be impacted by a shift in gas quality. First we describe a typical appliance combustion system, which includes gas supply, air supply and fuel-air mixing, ignition, burner head, and controls and safety devices. Then we discuss several types of heat exchangers and the venting types used in appliance installations. Reports covered here find that the main components of a natural gas appliance that could be impacted by the shift in gas quality are the combustion system and, for those appliances so equipped, the heat exchanger, and the vent system.

3.1 Combustion System Components

A gas appliance combustion system accomplishes the following: (a) it controls and regulates the flow of gas, (b) it (pre)mixes fuel and air, and (c) it ignites the gas. It is possible to consider six separate major components of the appliance combustion systems: gas supply, air supply, ignition, burner, controls and safety devices (Figure 3-1). The technologies associated with each component are described subsequently.

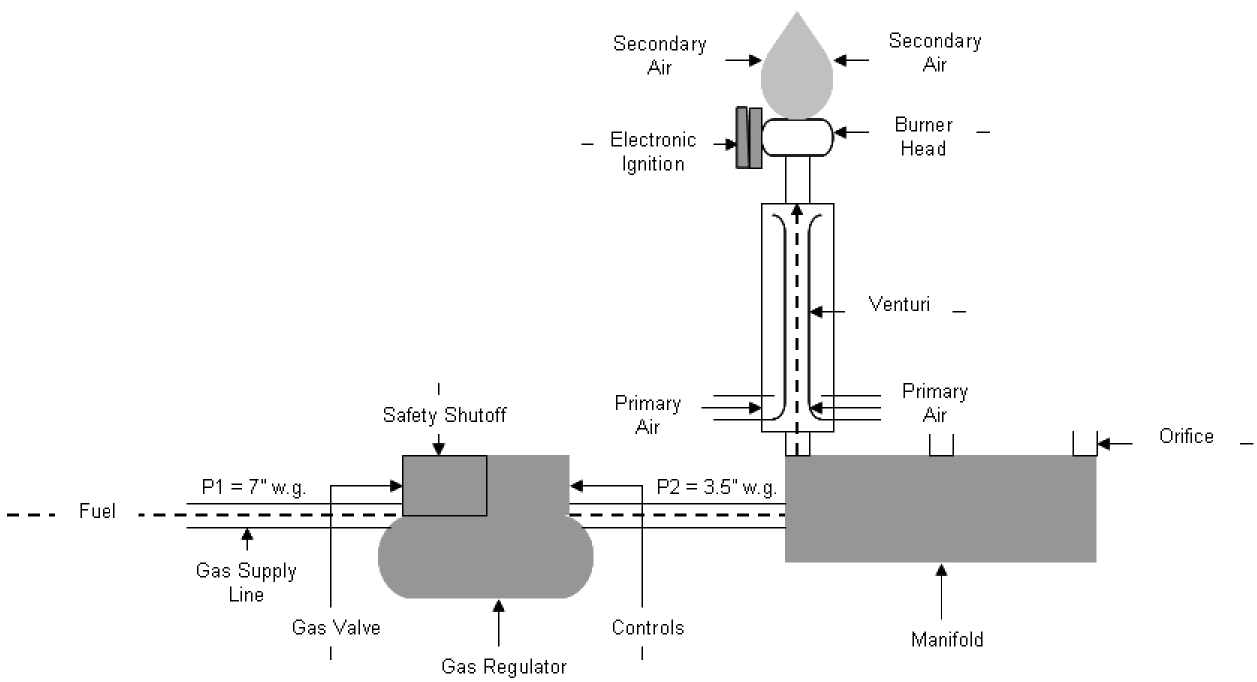

Figure 3-1 Gas Appliance Burner System Layout

3.1.1 Gas Supply

The gas supply of an appliance (Fig. 1) is commonly comprised of one or more of the following: (1) a gas supply line, (2) a gas regulator, (3) a gas valve, and (4) a burner supply line

The *gas supply line* runs from the meter outside of the home through to the gas valve within the residential gas appliance. It often includes a manual or automatic external shut-off valve located at the supply line entrance into the appliance. The U.S. standard for natural gas delivery into a home is 7" water gauge (w.g.) To account for potential variability in supply pressures encountered in practice, most residential appliances are designed and tested to operate over range of supply line pressure.

The *gas regulator* reduces the pressure of the gas being delivered from the gas supply line to the burner supply line by adjusting the gas valve. It is a device that maintains the gas pressure to the burner supply line within a narrow range of the design operating pressure over a range of gas input rates. There are three types of regulating devices: adjustable, multi-stage, and non-adjustable. As the names suggest, adjustable regulators allow external adjustment across a range of gas supply line outlet pressure settings; multistage regulators can be positioned to allow for two or more outlet pressure settings; and non-adjustable regulators are preset to a single outlet pressure.[5]

The *gas valve* controls gas flow rate. The gas valve could operate as a simple on/off device or it could modulate (gradually change) the gas flow.

The *burner supply line* runs from the gas valve to the manifold, which distributes gas to the burners. The pressure from the burner supply line through the manifold remains constant. The manifold orifices regulate the flow of gas to individual burners based on the size of the orifice opening and the pressure upstream of the orifice (typically 3" to 4" w.g., but may be higher).

3.1.2 Air Supply and Fuel-Air Mixing

Burners can be classified according to the extent to which combustion air is mixed with gas before the mixture emerges from the ports of the burner head. The mixture types most applicable to residential gas appliances are (1) partial (rich) premix, (2) full premix, and (3) non-premix (non-aeration) burners. Figure 3-2 shows a schematic of a partial-premix burner type.

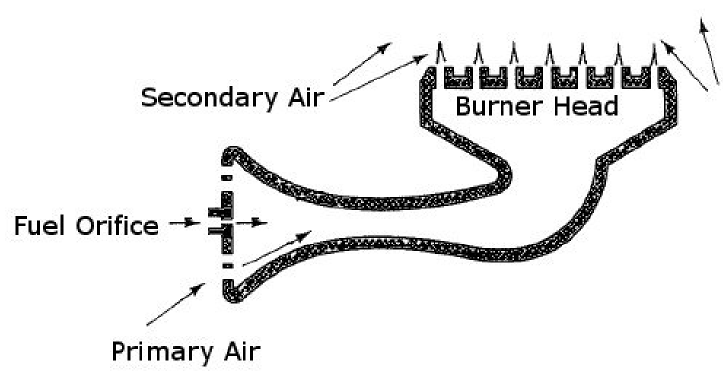

Figure 3-2 Burner design illustrating primary and secondary air flows.[6]

In *partial premix* burners a fraction of the air required for complete combustion is provided upstream of the burner head, while the remainder is drawn in from around the flame. Air added before combustion is called "primary," and air drawn in from around the flame is termed “secondary.” In conventional appliance burners, the pressurized gas flows through the orifice of a nozzle into a venturi where the primary air is pulled in. Fuel and primary air mix while accelerating through the venturi. This mixture exits the burner port(s) and combustion begins as it confronts the flame front in the primary combustion zone.

The combustion process is completed as secondary air diffuses into the flame front. In the partial premix burners used in residential appliances, primary air typically provides 20–60% of the total air required for complete combustion. Air flow depends on the geometry and size of the venture and openings. Older designs used to incorporate shutters, thus the amount of primary air available to the flame could be adjusted by tuning air shutters on the burner, which change the size of air inlet ports.

In *full premix* burners the fuel and all of the air required for combustion are mixed upstream of the combustion zone. The amount of premix excess air sets the fuel-air ratio at which primary combustion occurs, allowing for control of flame temperature, and NO_x and CO production.[7] These burner types are typically paired with blowers to control the fuel-air mixing and ensure adequate combustion.

In *non-premix* burners the gas mixes with the air only after it has passed through the burner head. This technology is used in some pilot burners to obviate the need for small air supply openings, which can become blocked with dirt, lint, cooking residues, etc. These types of burners have a characteristic hard blue flame.

3.1.3 Ignition

This report considers three types of ignitions systems commonly found in residential gas appliances: standing pilot (most storage water heaters), electronic ignition (cooking equipment, tankless water heaters), and light by hand (older fireplaces and ovens).

A *standing pilot* is a small auxiliary gas burner that provides a constant flame to ignite a larger gas burner. There are two types of pilot burners: primary-aerated and non-aerated, which correspond to main burner aeration systems described above. Primary-aerated pilots typically have a screened air supply opening that can get plugged with lint, dust and other debris and must be cleaned periodically.[8]

Electronic ignition systems are frequently used with residential gas appliances; common variations include intermittent pilot ignition, intermittent direct ignition, and hot surface ignition. *Intermittent pilot ignition* uses a spark to light a temporary pilot flame, which in turn lights the main burner. *Intermittent direct ignition*, commonly used for cooktops, lights the main burner directly by generating a spark. *Hot surface ignition*, commonly used for ovens and furnaces, lights the main burner directly from a silicon carbide element which glows red hot when an electric current is passed through it. This device typically functions as a flame detector as well.

Some older appliances may still have *light by hand* ignition. In this system, the user opens a supply valve before manually inserting a lit match into a special pilot light area. When the pilot flame is ignited, it in turn lights the main burner.

3.1.4 Burner Head

The burner (or burner head) contains ports through which the gas (for a non-aeration flame) or the primary gas-air mixture (for a premix flame) is conveyed to the combustion zone. Residential appliance burners can be classified as follows: (1) single-port (in-shot); (2) multi-port (circular, tube or other geometry), (3) radiant, and (4) ribbon.

In *single-port (in-shot)* burners, fuel and air are mixed inside of the burner tube, ignited at the outlet of the burner, then directed into a heat exchanger.

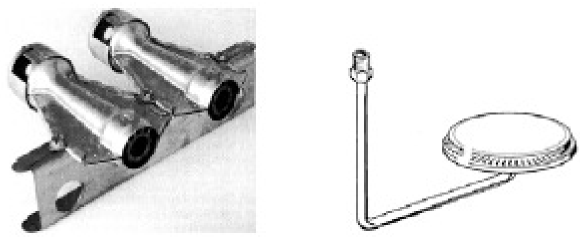

Figure 3-3 Examples of single-port (in-shot) and multi-port/circular burners.[9, 10]

Multi-port burners include the circular heads common to storage water heaters and cooktops, long tubes commonly used for ovens and grills, and blade-type burners used in boilers.

Figure 3-3 shows examples of the single-port and multi-port types of burner heads.[11]

Figure 3-4 Example of infrared burner.[12]

Radiant gas burners (sometimes called infrared burners) (see Figure 3-4) are common in heating applications and sometimes also used in cooking appliances. In a radiant burner, combustion occurs at the surface of a perforated ceramic tile or stainless steel mesh. These surfaces are designed to evenly disperse the fuel/air mixture. All required combustion air is provided through the burner; they are thus fully premixed. Heat transfer can occur through both radiant and convective energy processes. For example, a radiant cooktop burner provides radiant energy through a glass-ceramic plate overlying the ceramic tile on which combustion occurs.

Convective heat transfer occurs as the combustion products are jetted through the perforated glass-ceramic plate.

Ribbon burners are found in tankless water heaters. There is not clear consensus on whether ribbon burners are full, partial or non-premix burners.

3.1.5 Controls and Safety Devices

A *safety shutoff* device stops the gas supply to the burner(s) if the ignition source fails. This device can interrupt the flow of gas to main burner(s), pilot(s), or both.

Residential gas appliance burners have two types of burner controls: *on/off* and *modulating*.

On/Off controls are used in devices that are turned on/off manually, such as clothes dryers, or automatically, such as water heaters. The switch can be located either directly on the appliance or in a more accessible location.

Modulating controls allow variable fuel input rates. This type of control is commonly found in cooktops and occasionally in space heating appliances. Tankless water heaters have modulating controls that operate 2–3 banks of burners that can be used in various combinations.

In this study we are discussing five types of burner safety devices: (1) flammable vapor ignition resistance (FVIR) (specific to water heaters), (2) safety shutoff, (3) thermal cut-off or energy cut-off, (4) safety pilot, and (5) oxygen depletion sensor.

A *flammable vapor ignition resistance (FVIR)* device includes a sensor placed inside the combustion area to detect the ignition of a flammable vapor from outside the appliance and shut off the flow of gas to the burner and pilot light. FVIRs also include arrestor plates that prevent ignited gas from escaping the combustion area except through the appropriate venting system. To comply with American National Standards Institute (ANSI) standard Z21.10.1, first enacted in 2003, all new storage water heaters manufactured after January 1, 2004 and having an input rating of 75,000 Btu/hr or less must include FVIR devices. FVIR water heaters still comprise a minority of in-use devices, but saturation will increase steadily as old units are replaced.[13]

A *thermal cutoff fuse* (referred to as the "over-limit switch") is designed to electrically shut down the unit when it senses excessive temperatures either inside the combustion chamber or, in the case of some water heaters, inside the storage tank. The device functions as a thermal fuse (one time operation). If the temperature exceeds carefully predefined cutoff points, the temperature sensitive fuse will melt, interrupting power to the unit and stopping gas flow to the pilot and main burner.

Oxygen depletion sensors (ODS) (see Figure 3-5) are designed to prevent accidental carbon monoxide poisonings by shutting down the appliance when the oxygen concentration in air drops below a specified level. Such oxygen depletion is used as a marker of improper ventilation and a build-up of combustion exhaust. ODS systems have three main components: (1) an oxygen sensitive pilot burner; (2) a thermocouple positioned in the pilot flame; and (3) a safety shutoff valve.[14] When the pilot lifts off the burner and away from the thermocouple due to the decreased flame speed associated with an oxygen-deprived environment, the thermocouple cools and activates the safety shutoff valve, which stops the flow of gas to the pilot and to the main burner.

Figure 3-5 Oxygen Depletion Sensor unit[15]

3.2 Heat Exchangers

A heat exchanger transfers energy from hot combustion gases to water or air for various applications. In many residential appliances combustion occurs directly within the heat exchanger. There are six main types of heat exchangers: (1) individual section, (2) tubular, (3) serpentine or clamshell, (4) cylindrical, (5) central flue, and (6) finned copper/aluminum tube.

An *individual section heat exchanger* is comprised of a number of separate heat exchangers with separate burners. The sections are joined below to allow a common ignition system to light all burners and joined above where exhaust gases are directed to a common flue. The *tubular* and *serpentine heat exchangers* (found in appliances such as furnaces, boilers, and pool heaters) are variations of the individual section type that are used exclusively on gas-burning equipment. Figure 3-6 shows pictures of typical individual section, tubular, and serpentine (clamshell) heat exchangers.[16] In furnaces, tankless water heaters, and pool heaters, the heat exchanger is usually made of cold-rolled, low-carbon steel or copper, but the materials vary by application.

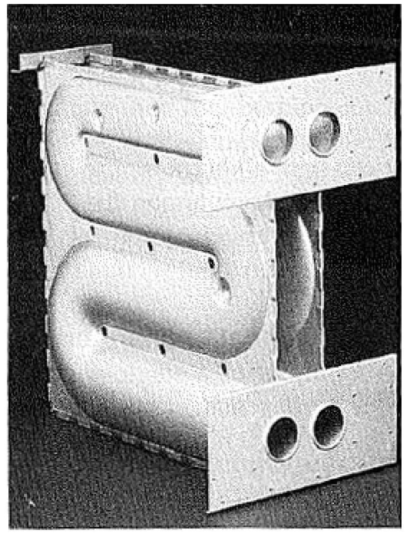

Figure 3-6 Examples of serpentine (clamshell) heat exchanger.[17]

A *cylindrical heat exchanger* has a single combustion chamber and uses a single-port burner. Cylindrical heat exchangers are used on gas and oil units. In the last 15 years, it is uncommon to find residential gas appliances with a cylindrical heat exchanger, especially in California.

A *central flue heat exchanger*, found in storage water heaters only, is a long cylindrical passage where exhaust gases pass from the combustion chamber to the draft hood inlet opening on an appliance equipped with a draft hood or to the outlet of the appliance. Figure 3-7 shows a typical central flue heat exchanger.[18] These are less efficient by design, as exhaust gases must retain enough heat to provide buoyancy for the atmospheric venting.

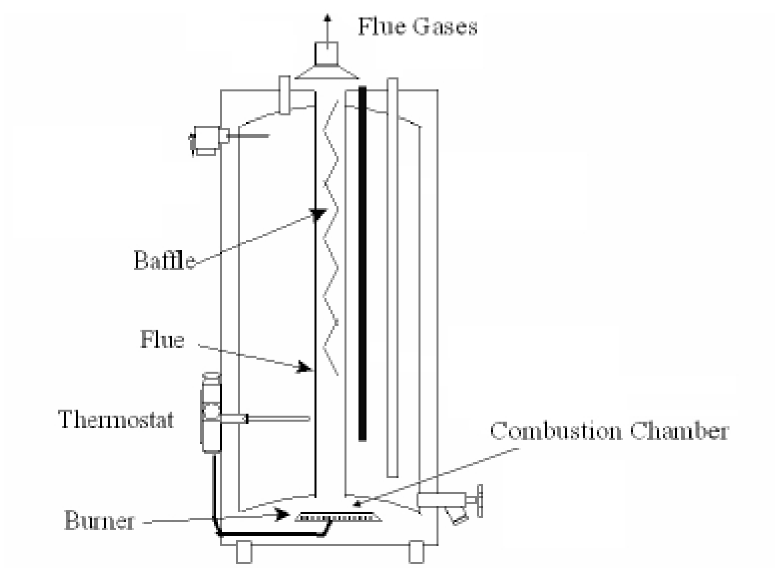

Figure 3-7 Water heater with central flue heat exchanger.[19]

A *finned copper/aluminum heat exchanger*, found in pool heaters and condensing furnaces, is a thin fin wrapped around a pipe where the cool water enters. After passing through the heat exchanger, the warmed water is delivered to the pool or home.[20]

3.3 Vent Systems

A vent system is a continuous open passageway from the flue collar or draft hood of a gas-burning appliance to the outdoors for the purpose of removing flue or vent gases. There are three main types of venting systems: natural draft, mechanical (induced, forced, or power), and ventless.

Natural draft systems depend primarily on the natural draft[a] created as hot exhaust gases rise through ducting that is open to the atmosphere. There are three main types of *mechanical draft* systems: *induced, forced,* and *power*. An *induced draft system* uses a fan (located within the appliance) to remove flue or vent gases under non-positive static vent pressure (the fan is pulling the air) whereas *forced draft systems* operate under positive static pressure (the fan is pushing the air); both of these draft systems are, in general, vented vertically. *Power draft systems* use a fan (located within the vent) to remove flue or vent gases under positive static pressure. *Ventless* burners include cooktops, some gas ovens, outdoor tankless water heaters, and certain gas fireplaces.

4.0 Impacts of Gas Substitution on Residential Appliances

In this section we describe some possible effects of operating the current population of residential appliances with fuels having compositions, heating values and Wobbe numbers associated with liquefied natural gas. For each appliance component, we outline how the substitute gas might affect that component (the local effect), as well as how it might affect the overall operation of the whole appliance (the general effect). It should be noted that most of the effects discussed throughout the remainder of this report occur very rarely in the field, and only a few have been observed as parts of the laboratory studies cited herein. Most residential appliances will perform adequately with imported LNG. However, the uncertainty involved in switching fuels deserves consideration.

To motivate a discussion of impacts of gas quality, we begin with a description of how combustion with an adjust gas may be different from combustion with a substitute gas of a higher Wobbe number. For the remainder of this report, “substitute gas” refers only to a substitute gas of a higher Wobbe number than the corresponding adjust gas, as mentioned above.

4.1 Potential Outcomes of Appliance Operation on Substitute Gas

[a] Hot gas rises which creates a negative pressure/vacuum at the lower point that sucks in the air. It is important to note the importance of providing a sufficient temperature difference to ensure adequate draft and mitigate the back draft.

The following points describe some potential negative characteristics that may arise from substitute gas operating on a certain fraction of residential gas appliances. The use of LNG in place of historically distributed fuels may lead to one or more of the following:

- Higher sensitivity to (increased) CO emissions[21, 22]
- Higher NO_X emissions[23],[24], [25]
- Higher stoichiometric oxygen requirement
- Hotter flame
- Over firing
- Yellow tipping[26, 27]
- Sooting[28]
- Flame elongation[29, 30]

In short, a natural gas appliance burning substitute gas may, under certain conditions, produce a flame outside of the design characteristics of the appliance. This could theoretically result in unsafe operation or damage to the appliance. The effects listed above are never seen together; however individually or in certain combinations they are of enough concern to merit careful consideration of the impact of substitute gas on each appliance component. The remainder of this section will discuss those effects.

4.2 Gas Supply System Impacts

Local Effect
Gas supply components (see section 3.1.1) will not see any effects of the change in gas quality. Substitute gas would be delivered from the gas supply line at the same pressure as adjust gas (7 in. H_2O), gas and it would have no effect on gas regulators, shut-off, or safety valves themselves.

General Effect
While a higher heating value gas passing through a gas regulator will not affect the regulator, it will ultimately deliver more heating power to the burner head, effectively passing on the impact of the substitute gas from the gas regulator and the supply system to the combustion point itself.

A 2005 study by the Southern California Gas Company found that pulsations caused by an upstream gas supply regulator caused noticeable spikes in carbon monoxide emissions in a particular instantaneous water heater. Under steady operation with an unstable regulator, emissions increased from about 300 ppm with the adjust gas to about 1200 ppm with a substitute gas.[31] This effect disappeared when the faulty regulator, which was part of the laboratory equipment and not part of the appliance, was replaced.

Additionally, there has been some debate about the safety of LNG in the supply line at low temperatures. Some sources warn of the possibility of hydrocarbon condensation in cold climates.[32] However, experts do not agree that this presents a legitimate threat in most areas for residential consumers, citing the low dew point of LNG (less than 10 degrees Fahrenheit) at supply line pressure. [33]

4.2.1 Fuel-Air Mixing System Impacts

Local Effect
Substitute gas will have no effect on the fuel-air mixing system.

General Effect
As the Wobbe number of a given natural gas rises, so does its oxygen requirement.[34] For a burner with any type of pre-mixing, this means that the fuel-air mixture of the substitute gas will be more rich, as the volume of supply gas remains unchanged while the oxygen requirement increases. Care may need to be taken to ensure that a substitute gas can draw enough primary air through the burner's shutters. Most modern appliances don't require manual adjustment of air shutters because burners are designed to operate over a wide range of gas qualities. However, some new appliances still come equipped with air shutters that are meant to be adjusted at the time of installation, usually to account for high altitudes. If the shutters are adjusted too low to allow enough air to pre-mix with the substitute gas, the rich gas-air mixture may lead to incomplete combustion and elevated CO emissions. The additional CO formed will typically burn to completion (that is, to CO_2) in the secondary flame but could in rare cases result in a net increase in CO exhaust emissions. However, this considers only the CO production that is associated with the primary air-fuel ratio and associated equilibrium CO concentrations.[35]

One study of a residential oven tested with domestic natural gas and several LNGs evaluated the impact of gas composition on CO emissions.[36] The study found that with air shutters open, CO emissions were low and relatively insensitive to gas composition. However, with the air shutters closed, CO emissions varied significantly with natural gas composition. Most generally, studies examined in this paper found a correlation between the introduction of substitute gas and CO emissions only when an appliance was already producing elevated CO emissions with the adjust gas.

In the case of non-aeration burners, an adjust gas will receive 100% of the needed air after passing through the burner head, ensuring proper combustion on a well-designed burner.

4.2.2 Ignition System Impacts

Ignition criteria for natural gas is well established, and all appliance manufacturers ensure that sufficient power is supplied by the ignition system to ignite a properly mixed adjust gas. However, along with the switch from an adjust gas to a substitute gas come changes in gas quality, including changes to ignition requirements. While various characteristics of substitute gas (such as ballasting with an inert gas to lower Wobbe number) may delay or inhibit ignition, no study recorded a residential appliance failing outright to ignite a burner.

Local Effects

Substitute gas will cause no local effects on any ignition system components.

General Effects

A 2007 Lawrence Berkeley National Laboratory publication which included a review of recent major studies reported no indication based on existing information that ignition problems will result from expected changes to gas quality:

> Many studies have examined ignition either ad-hoc or systematically. For example, ignition tests were performed on most appliances in the SCG (2005) study using the highest and lowest Wobbe number gases (2 and 3) in addition to baseline gas, and in some cases the test was repeated for under- and over-fired conditions or for hot and cold starts. No ignition problems were observed for the residential appliances. Ignition was similarly not found to be affected by gas quality changes in the other major studies reviewed (Johnson and Rue 2003; TIAX 2004a; Williams et al. 2004; Williams et al. 2005).[37]

Despite these findings, in the field the wide variability of residential appliances with respect to age, wear, maintenance, usage patterns, and technology merits a detailed discussion of how the ignition system may be affected by a switch to substitute gas. According to guidelines set by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE), ignition must be immediate, smooth, and complete.[38] We begin by discussing general effects without respect to specific ignition system technologies.

High-Wobbe number substitute gas which has been ballasted with elevated levels of inert gasses (which are added to lower the Wobbe number) could theoretically delay or prohibit ignition, in addition to causing flame lifting.[39] This is an issue both for pilot burners and for electric ignition systems of all types.

Substitute gas with lower heating values could also experience delayed ignition, causing poor carryover (wherein one burner acts as a pilot to an adjacent main burner), flame instability, and gas buildup outside of the appliance.[40]

In many cases, the danger of substitute gas on ignition systems comes from the pilot flame. Because the pilot flame itself may burn hotter when fueled by a substitute gas, permanent pilot flames near outer appliance surfaces may cause the surface to become dangerously hot, affecting consumer safety. This can be the case in older cooktops, in which a permanent pilot is often found directly underneath the metal cooktop surface. The safety issues arise when the surface temperatures on actual cooktops is higher than 60 degrees C (140 F), the human upper temperature limit for metal contact.[41]

Furthermore, pilot flames burning a substitute gas may become dangerously unstable due to flame lifting and higher oxygen requirements. Flame lifting or lengthening could cause a pilot light to produce excess emissions or to quench onto a nearby surface. A 1978 BG&E study observed that range pilot flame lengthening was a somewhat widespread problem in the field when LNG was distributed in the late 1970s.[42] Pilot flames burning substitute gas may need to be adjusted to avoid flame lifting or flame lengthening.

The higher oxygen requirement of a primary-aerated permanent pilot light placed deep inside an appliance without sufficient access to oxygen may cause the pilot to flame out entirely. This could be the case when permanent pilot lights draw oxygen from small orifices which may become clogged with debris. This may leave enough air supply for an adjust gas, but not for the higher oxygen requirements of a substitute gas, causing partial combustion and potentially emitting high levels of CO into the residence. In some older appliances the flameout of a permanent pilot light could be problematic because the gas supply to the pilot is designed to operate constantly (no shut off).

Any issues related to pilot lights need to be understood within the context that most gas appliances sold today have electronic ignition. For example, residential furnaces have been manufactured exclusively with electronic ignition since the 1992 efficiency standard. With typical furnace lifetime of 20 years (+/-10 years)[43] the number of remaining in-use furnaces with pilot lights is expected to be small. Similarly, the stock of many other appliances (pool heaters, cooking equipment) with pilot lights has decreased significantly over the last decade.

The safe use of an appliance depends upon that appliance's ignition system's ability to ignite any active burners under any and all field conditions. In the event of failed ignition, gas supply must be shut off by whatever safety features the appliance includes. These are described in detail below.

4.2.3 Burner Head Effects

Today's appliance burners are designed to operate on a wide range of gas qualities, and no substitute gasses considered in recent studies fall outside of these ranges. However, problems relating to emissions, flame shape, and performance could occur when using a substitute gas falling outside burner design parameters.

Local Effects
Burner heads themselves will see little or no effect of a switch from adjust gas to substitute gas.

General Effects
Generally, burners which are performing poorly with the adjust gas may also see CO sensitivity when operated on a substitute gas.[44] The most sensitive appliances are those designed or set to operate with lower primary air ratios—that is, with primary air-fuel mixtures that are more fuel rich. Lean premix burners, which are becoming more common in both residential and small commercial applications for the purpose of NO_X control, are by design sensitive to the fuel gas Wobbe number.[45, 46] An increase in Wobbe number pushes the lean primary air-to-fuel ratio towards stoichiometric conditions, resulting in higher flame temperatures and higher NO_X emissions.[47]

In a 1996 study by the Public Service Company of Colorado, field technicians found many appliances that were already over-firing on adjust gas because they had not been properly de-rated to account for the high elevation. Appliances in such cases would likely see further performance declines when operated on a substitute gas.[48]

In one high-intensity atmospheric burner (~117,000 Btu/hr max. input) used in instantaneous water heater heaters, the flame was found to lengthen as richer gases were supplied, with the potential that the flame could be quenched by the heat exchanger. Such conditions could result in higher CO emissions or damage to the heat exchanger. Also, as the flame changes, combustion equilibrium can shift, causing a parallel increase in CO and NO_X emissions.[49]

On exiting the burner head, flame temperature and flame length have been found to track to Wobbe number.[50] This merits reconsideration of burner head proximity to other appliance elements, such as the heat exchanger. A lengthened flame could impinge on other appliance components, causing further soot formation, orange tinting, or incomplete combustion.[51] In a feedback cycle, this soot formation could actually exacerbate flame lifting, which in turn causes more soot.[52]

According to a 1982 study by the Gas Research Institute, appliances that feature modulating controls (those which cycle on and off) could see higher levels of flame lifting due to the exacerbating effect on flame lifting by cold burner heads. Appliances that cycle on and off many times throughout a 24 hour period (such as a water heater) would typically start each cycle with cold burner heads, causing flame lifting and the associated rise in CO and NO_X emissions over a period of time (typically 6–14 minutes[53]) in the beginning of each cycle.[54] Offsetting this effect is the hotter temperature of burning substitute gas, which might heat the burner head more quickly, reducing the time of cold burner operation. (See Singer 2007 for a more detailed discussion of this topic.)

4.2.4 Controls and Safety Devices Impacts

Because of the uncertainty surrounding impacts of substitute gas on residential appliances, appropriate care should be taken to inspect safety features and evaluate their effectiveness in preventing appliance malfunction. Most safety features rely on chemical and temperature detection, and a change in gas quality will impact both of these.

Local Effects

Mechanical or electronic controls themselves will see little or no impact from gas quality changes, but their intended operation may be altered.

General Effects

Recent ANSI standards governing Flammable Vapor Ignition Resistance (FVIR) devices on new water heaters motivate a discussion of FVIR components and imported LNG.[55] An FVIR device typically consists of combustion air pathway originating higher off the floor to avoid the accumulation of floor-level lint, dust, and oil, and a flame arrestor with ports large enough for air but too small for flames to pass through. While not exhaustively tested in any of the studies cited in this paper, there is no reason to believe that FVIR components would cause an increased danger with the introduction of imported LNG.

Safety shut-off devices which interrupt the gas flow to main burners upon ignition failure become increasingly important as the ignition issues noted in section 4.2.2 become manifest, but a change in gas quality will have no impact on the device itself.

Among safety devices, the operation of thermal cut-off switches may be most impacted. If an appliance is designed to operate on adjust gas just below the thermal fuse temperature threshold, then substitute gas of higher heating content may cause the thermal switch to activate. This would indicate a properly functioning switch, which is part of an appliance rated to operate only below a given temperature.

Oxygen Depletion Sensors (ODS) may also be impacted by a change in gas quality. In a 2005 study, Advantica tested ODS units on several devices, and found that they did not operate as required. The report states that "the Wobbe number of the test gas can have a significant impact" on ODS operation.[56] However, for at least two devices (live fuel effect fire and back boiler unit), ODS failures were not clearly associated with gas quality changes based on the results shown. For the other two devices, it is unclear if the ODS was directly affected by gas quality or if it was just that the metrics used to gauge performance (CO and CO_2 levels) were affected by the gas quality change.[57]

ODSs may impact the operation of both the main burner and the pilot light as a result of a change in gas quality. These sensors are subject to two main vulnerabilities associated with a change in gas quality. First, the space immediately surrounding the main burners of an appliance may experience oxygen deprivation if the substitute gas causes flame lifting and increased emissions. In this case, and particularly in the case of unvented appliances, the ODS shutting off the gas supply line would constitute proper operation, a clear signal that, in the case of premix burners, the air supply is insufficient to accommodate the new gas.

Second, as discussed in section 3.1.5, the pilot flame, which would be burning the same substitute gas, could be subject to flame lifting associated with substitute gas.This would prevent it from adequately engulfing the thermocouple, which activates the gas shut-off valve. In this case, the main function of the ODS is prevented, and the ODS will stop the flow of gas.

4.3 Heat Exchanger Impacts

Firing an appliance with substitute gas may also impact appliance heat exchangers. Most generally, the heat exchanger may reach a higher sustained operating temperature. This could affect efficiency, as heat exchangers are designed to operate within a specific range of flame characteristics. One possible shift in the operation pattern of a heat exchanger is for the unit to operate at a higher sustained operating temperature over a shorter time period.

Local Effects

If the flame shape itself changes when burning substitute gas, the flame may affect the heat exchanger. Elongated flames exiting the burner head may impinge on the heat exchanger, causing uneven heating and points of intense heat.

Flame yellow-tipping or other effects of incomplete combustion may cause a soot residue to deposit on the heat exchanger, reducing its heat transfer efficiency and increasing the temperature of the flue gasses. This could also have the effect of restricting the flue gas pathway through the heat exchanger and into the flue.

Continuous over-firing of a heat exchanger due to substitute gas may cause long-term physical damage to the heat exchanger itself. Extreme heat may crack or otherwise damage the heat exchanger. Possible long-term wear issues associated with using gas of a higher heating value also include warping and oxidation. A cracked heat exchanger could, in a worst-case scenario, quickly introduce CO into the heated air, which, in the case of home heating appliances, could result in serious health risks.

General Effects
A 2005 study by the Southern California Gas Company included measurements taken from a tubular heat exchanger operated with substitute gas. The study found that the heat exchanger reached a higher temperature, but remained within safe operating conditions. [58]

4.4 Vent System Impact Issues

A change in gas quality may unevenly and differentially impact the performance and safety of venting systems.

Local Effects
Effects of substitute gas stem from the characteristics of the flue gas exhausted through the vent system. In the rare case of incomplete combustion at the burner head, (evidenced through flame lifting or yellow tipping) residual buildup of soot could deposit inside the flue, restricting air flow. This could affect appliance vents meant to carry CO away from the interior of the residence.

A higher soot content in flue gas may also affect fan motors of forced air venting system operating under negative static pressure. Failure of a fan motor could cause a backup of flue gases and release emissions into a residence. Care should be taken to ensure that fan motors are properly shielded from flue gas emissions and particulate matter.

Combustion gases may leave condensation in the flue, leading to corrosion and the escapement of dangerous gases from vented appliances into the residence.[59] Some LNGs may contain traces of sulfur, oxygen, and hydrogen, as well as heavy hydrocarbons. These constituents can mix with water vapor in the flue gas and condense, causing vent corrosion.[60]

General Effects
Appliances burning substitute natural gas could exhaust products of combustion at a higher temperature, causing the venting system to reach a higher sustained operating temperature. However, in appliance testing performed by the Southern California Gas Company with high Wobbe Number gas, elevated temperatures in the vents were generally found to stay within safe operating limits.[61]

5.0 Conclusions

The vast majority of U.S. residential gas appliances will see little or no effect from a switch to gas of a higher Wobbe number. Appliances of an older design are more likely to be impacted than newer appliances. The heat exchanger is most likely to be physically affected, due to soot deposition and flame impingement.

The most serious potential consequence of a switch to substitute natural gas will most likely be caused by 1) inadequate oxygen supply to the combustion zone of a main burner or a permanent pilot due to improper pre-mixing or closed air shutters and 2) vent blockage due to soot deposition or corrosion.

Most gas appliances currently in the field will properly combust natural gas over a wide enough range of Wobbe numbers to alleviate concern over the widespread introduction of LNG to the residential sector. Older appliances will likely be replaced as they reach the end of their useful lifetimes. A nation-wide push towards sustainability, together with a rise in energy prices, will continue to encourage the replacement of older units with newer, more efficient models, further diminishing the likelihood any possible negative impacts.

6.0 Appendix: Summary of Appliance Technologies

Table 6-1summarize important features of residential and commercial appliance technologies that could be impacted by a shift in natural gas quality.

	Burners					**Heat Exchanger**	**Venting**	**Typical Input (Btu/h)**
	Fuel/Air Mixture	Controls	Burner Head	Ignition	Safety Features			
Cooktops	Partial premix (standard) or lean premix (radiant)	On/off or modulating (manual)	Multi-port (circular) or radiant	Electronic ignition or pilot	Safety shut-off	None	None (draft hood)	9,000
Ovens	Partial premix (standard) or lean premix (radiant)	On/off or modulating (manual)	Multi-port or radiant (uncommon)	Electric ignition or pilot	Safety shut-off or thermal cut-off	None	None (draft)	11,000
Clothes Dryers	Partial premix (typical)	On/off*	Single-port	Electronic ignition or pilot	Safety shut-off or thermal cut-off	None**	Mechanic al/induce d	24,000
Storage Water Heaters	Partial premix (typical)***	On/off	Single-port mulit-port (circular)	Electronic ignition or pilot	Safety shut-off, energy cut-off, or FVIR	Central Flue	Natural, direct, or mechanic al-power	20,000–75,000
Tankless Water Heaters	Partial premix (typical)	On/off and/or modulating (automatic)	Single-port or multi-port (ribbon)	Electronic ignition	Safety shut-off or thermal cut-off	Tubular	None or Mechanic al-power	100,000 – 200,000
Central Furnaces	Partial premix (typical)	On/off or modulating	Single-port or multi-port (ribbon)	Electronic ignition or pilot	Safety shut-off or thermal cut-off	Clamshell, serpentine, or tubular	Natural, direct, or mechanic al	30,000–225,000
Hearth	Partial premix, lean premix (radiant), or	On/off or flame height adjustment	Single-port, multi-port, or radiant	Electronic ignition, pilot, or	Safety shut-off	None	None or natural	10,000–60,000

	non-aeration			light by hand					
Pool Heaters	Partial premix and lean premix (radiant)	On/off	Multi-port or radiant (rare)	Electronic ignition	Safety shut-off	Individual (finned copper tube)	Natural (direct exhaust)	250,000	

Table 6-1 Residential Gas Products

* The on/off control can be controlled by a sensor.
** Hot flue gasses are mixed with a large amount of air and are forced through the dryer tumbler.
*** In 2006 the South Coast Air Quality Management District (SCAQMD) mandated low NO_X water heater limits which will require all new water heaters to use lean premix.

7.0 Glossary

- Adjust Gas – A natural gas fuel for which an appliance has been tuned, or adjusted. This typically takes into account fuel oxygen requirements, elevation, and other factors.
- Air Shutter – An adjustable device for varying the size of the primary air inlet(s).[62]
- Automatic Gas Shutoff Device – A device constructed so that the attainment of a water temperature in a hot water supply system in excess of some predetermined limit acts in such a way as to cause the gas to the system to be shut off.[63]
- Burner – A device for the final conveyance of gas, or a mixture of gas and air, to the combustion zone.[64]
- Combustion – As used herein, the rapid oxidation of fuel gases accompanied by the production of heat, or heat and light. Complete combustion of a fuel is possible only in the presence of an adequate supply of oxygen.[65]
- Combustion Chamber – The portion of an appliance within which combustion occurs.[66]
- Combustion Products – Constituents resulting from the combustion of a fuel with the oxygen of the air, including the inert but excluding excess air.[67]
- Condensate – The liquid that separates from a gas (including flue gas) due to a reduction in temperature or an increase in pressure.[68]
- Direct Vent Appliance – Appliances that are constructed and installed so that all air for combustion is derived directly from the outdoors and all flue gases are discharged to the outdoors.[69]
- Draft Hood – A nonadjustable device built into an appliance, or made a part of the vent connector of an appliance, that is designed to (1) provide for the ready escape of flue gases from the appliance in the event of no draft, backdraft, or stoppage beyond the draft hood, (2) prevent a backdraft from entering the appliance, and (3) neutralize the effect of stack action of the chimney or gas vent upon the operation of the appliance.[70]
- Gas Supply Line – The portion of the residential gas supply system which carries natural gas from the utility-maintained gas meter to the appliance. U.S. gas supply lines are typically under 7 inches of H_2O pressure.
- Household Cooking Appliance – An appliance for domestic food preparation, providing at least one function of (1) top or surface cooking, (2) oven cooking, or (3) broiling.[71]

- Interchangeability – The ability to substitute one gaseous fuel for another in a combustion application without materially changing operational safety, efficiency, performance or materially increasing air pollutant emissions.[72]
- Mechanical Draft – Draft produced by a fan or an air stream or jet. When a fan is located so as to push the flue gas through the chimney or vent, the draft is forced. When the fan is located so as to pull the flue gases through the chimney or vent, the draft is induced.[73]
- Natural Draft – Draft produced by the difference in the weight of a column of flue gases within a chimney or vent and a corresponding column of air of equal dimension outside the chimney or vent.[74]
- Orifice – The opening in a cap, spud, or other device whereby the flow of gas is limited and through which the gas is discharged to the burner.[75]
- Power Burner – A burner in which either gas or air, or both, are supplied at a pressure exceeding, for gas, the line pressure, and for air, atmospheric pressure; this added pressure being applied at the burner. A burner for which air for combustion is supplied by a fan ahead of the appliance is commonly designed as a forced-draft burner.[76]
- Primary Air – The air introduced into a burner that mixes with the gas before it reaches the port or ports.[77]
- Residential Building – A structure used primarily as a dwelling for one or more households.[78]
- Safety Shutoff Device – A device that will shut off the gas supply to the controlled burner(s)
- Substitute Gas – A natural gas fuel which has replaced the adjust gas on a given appliance.
- Venturi – A section of tubing upstream from the burner head which, due to a decrease in pressure from increased flow velocity caused by the narrowing of the tube, draws in air to be mixed with the gas. Also called an inspirator.
- Wobbe Index – A number which indicates interchangeability of fuel gases and is obtained by dividing the heating value of a gas by the square root of its specific gravity.[79] For a given gas, if V_C is the higher heating value and G_S is the specific gravity, then Wobbe Index $I_W = V_C/\text{sqrt}(G_S)$. Since it is typically expressed as BTU/scf (standard cubic foot), the Wobbe index can be used to compare the combustion output of two different gases.

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9.0 References

1. Okaloosagas. *Annual Cost Comparisons of Using Appliances: Electricity vs. Natural Gas.* 2006. (Last accessed August 8,, 2006.) <http://www.okaloosagas.com/appliances/appliancecomparison.cfm>

2. Consumer Services Technical Education Group. *Gas Basics: Dryer and Range Burners*. 1988. Whirlpool Corporation.
3. Appliance Recycling Information Center. *INFOBulletin: Mercury in Home Appliances*. 2005.
4. U.S. Department of Energy - Office of Energy Efficiency and Renewable Energy. *Technical Support Document: Energy Conservation Standards for Consumer Products: Cooking Products.* September, 1998. U.S. Department of Energy. <http://www.eere.energy.gov/buildings/appliance_standards/residential/pdfs/genmet.pdf>
5. Enbridge Gas Distribution and Pacific Gas & Electric Company. *Commercial Cooking Appliance Technology Assessment.* 2002. Report No. 5011.02.26.

10.0 Notes

[1] Energy Information Administration (2009). Annual Energy Outlook. Report NumberDOE/EIA-0383(2009) March 2009. Page 78.

[2] Energy Information Administration (2009). Annual Energy Outlook. Report NumberDOE/EIA-0383(2009) March 2009. Report: An Updated Annual Energy Outlook 2009 Reference Case Reflecting Provisions of the American Recovery and Reinvestment Act and Recent Changes in the Economic Outlook

[3] The gross caloric value (GCV) of LNG ranges between 1075 and 1160 Btu per standard cubic foot (Btu/scf).

[4] White Paper on Natural Gas Interchangeability And Non-Combustion End Use. NGC+ Interchangeability Workgroup. February 28, 2005. Page 21.

[5] American Gas Association and National Fire Protection Association. National Fuel Gas Code 1999 Edition. 1999 ed. 1999. National Fire Protection Association: Quincy, MA.

[6] William B. Cooper, Raymond E. Lee, Raymond A. Quinlan, Martin W. Sirowatka, and Robert Featherstone. Warm Air Heating for Climate Control. 4th ed. ed. 2000. Prentice Hall: Upper Saddle River, NJ.

[7] White Paper on Natural Gas Interchangeability And Non-Combustion End Use. Appendix D. Monitoring Interchangeability and Combustion Fundamentals. Edgar Kuipers, Shell Trading. Page 2.

[8] William B. Cooper, Raymond E. Lee, Raymond A. Quinlan, Martin W. Sirowatka, and Robert Featherstone. Warm Air Heating for Climate Control. 4th ed. ed. 2000. Prentice Hall: Upper Saddle River, NJ.

[9] William B. Cooper, Raymond E. Lee, Raymond A. Quinlan, Martin W. Sirowatka, and Robert Featherstone. Warm Air Heating for Climate Control. 4th ed. ed. 2000. Prentice Hall: Upper Saddle River, NJ.

[10] Ken Smith. The Gas Fitter's Guide to Domestic Hot Water. 1993. KLS Training Corporation: Lewiston, NY.

[11] U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy. Technical Support Document: Energy Efficiency Program for Consumer Products: Energy Conservation Standards for Residential Furnaces and Boilers. July, 2004. U.S. Department of Energy.

[12] Johnson, F. and D. M. Rue (2003). Gas Interchangeability Tests: Evaluating the Range of Interchangeability of Vaporized LNG and Natural Gas. Des Plaines, IL, Gas Research Institute. Page 114.

[13] Gas Appliance Manufacturers Association (2005). "Consumer Information on New FVIR Water Heaters." Retrieved 04/17/2009, 2009, from http://www.gamanet.org/gama/inforesources.nsf/c952ec14927fc9cb85266eaf0046bdb1/43e698228eba0b7f85256e90006418cd?OpenDocument.

[14] American Gas Association. Fundamentals of Gas Combustion. 2001: Washington, DC. 131 pp.

[15] FocalPoint, Inc. http://www.focalpointfires.co.uk/images/faq/NG9090.JPG. Last accessed 22 May 2009.

[16] William B. Cooper, Raymond E. Lee, Raymond A. Quinlan, Martin W. Sirowatka, and Robert Featherstone. Warm Air Heating for Climate Control. 4th ed. ed. 2000. Prentice Hall: Upper Saddle River, NJ.

[17] William B. Cooper, Raymond E. Lee, Raymond A. Quinlan, Martin W. Sirowatka, and Robert Featherstone. Warm Air Heating for Climate Control. 4th ed. ed. 2000. Prentice Hall: Upper Saddle River, NJ.

[18] American Gas Association and National Fire Protection Association. National Fuel Gas Code 1999 Edition. 1999 ed. 1999. National Fire Protection Association: Quincy, MA.

[19] U.S. Department of Energy's Office of Energy Efficiency & Renewable Energy. Technical Support Document: Energy Efficiency Standards For Consumer Products: Room Air Conditioners, Water Heaters, Direct Heating Equipment, Mobile Home Furnaces, Kitchen Ranges and Ovens, Pool Heaters, Fluorescent Lamp Ballasts & Television Sets. Volume 2: Fluorescent Lamp Ballasts, Television Sets, Room Air Conditioners, & Kitchen Ranges and Ovens. November, 1993. U.S. Department of Energy.

[20] U.S. Department of Energy's Office of Energy Efficiency & Renewable Energy. Technical Support Document: Energy Efficiency Standards For Consumer Products: Room Air Conditioners, Water Heaters, Direct Heating Equipment, Mobile Home Furnaces, Kitchen Ranges and Ovens, Pool Heaters, Fluorescent Lamp Ballasts & Television Sets. Volume 2: Fluorescent Lamp Ballasts, Television Sets, Room Air Conditioners, & Kitchen Ranges and Ovens. November, 1993. U.S. Department of Energy.

[21] Benson, C. (2004). Modifying Imported LNGs for Interchangeability with Domestic Natural Gas. LNG and the Changing U.S. Natural Gas Supply. Dallas, TX, Tiax LLC.

[22] Rue, D. (2004). Gas Quality, Interchangeability, and LNG Utilization in the United States. LNG and Changing U.S. Natural Gas Supply. Dallas, TX, Gas Appliance Manufacturers Association.

[23] Sasaduesz, L., R. Schwedler, et al. (2005). Gas Quality and Liquefied Natural Gas Research Study. Los Angeles, CA, Southern California Gas Company. Page 21.

[24] Levinsky, H. B., 2004. Consequences of "new" gases for the behavior of gas utilization equipment. 2004 International Gas Research Conference.

[25] Rue, D. (2004). Gas Quality, Interchangeability, and LNG Utilization in the United States. LNG and Changing U.S. Natural Gas Supply. Dallas, TX, Gas Appliance Manufacturers Association.

[26] Benson, C. (2004). Modifying Imported LNGs for Interchangeability with Domestic Natural Gas. LNG and the Changing U.S. Natural Gas Supply. Dallas, TX, Tiax LLC.

[27] Rue, D. (2004). Gas Quality, Interchangeability, and LNG Utilization in the United States. LNG and Changing U.S. Natural Gas Supply. Dallas, TX, Gas Appliance Manufacturers Association.

[28] Rue, D. (2004). Gas Quality, Interchangeability, and LNG Utilization in the United States. LNG and Changing U.S. Natural Gas Supply. Dallas, TX, Gas Appliance Manufacturers Association.

[29] Benson, C. (2004). Modifying Imported LNGs for Interchangeability with Domestic Natural Gas. LNG and the Changing U.S. Natural Gas Supply. Dallas, TX, Tiax LLC.

[30] Singer, Brett C. 2007. Natural Gas Variability in California: Environmental Impacts and Device Performance: Literature Review and Evaluation for Residential Appliances. California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2006-110. Page 49.

[31] Singer, Brett C. 2007. Natural Gas Variability in California: Environmental Impacts and Device Performance: Literature Review and Evaluation for Residential Appliances. California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2006-110. Page 53, citing 2005 SGC study[31]

[32] Erickson, John: LNG: Impacts on Gas Distribution. Powerpoint presentation. Given June 2—3, 2004 in Dallas, TX (marriot Dallas Solana): LNG and Changing U.S. Natural Gas Supply: Implications for Gas Appliances and Gas Distribution Systems

[33] Kuipers, Edgar. GAMA, 2, June 2004. Shell US G&P

[34] Erickson, J. (2004). *LNG: Impacts on Gas Distribution*. LNG and Changing U.S. Natural Gas Supply: Implications for Gas Appliances and Gas Distribution Systems, Dallas, TX.

[35] Singer, Brett C. 2007. Natural Gas Variability in California: Environmental Impacts and Device Performance: Literature Review and Evaluation for Residential Appliances. California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2006-110. Page 51.

[36] Benson, C. (2004). Modifying Imported LNGs for Interchangeability with Domestic Natural Gas. LNG and the Changing U.S. Natural Gas Supply. Dallas, TX, Tiax LLC.

[37] Singer, Brett C. 2007. Natural Gas Variability in California: Environmental Impacts and Device Performance: Literature Review and Evaluation for Residential Appliances. California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2006-110. Page 30.

[38] American Society of Heating, Refrigeration, and Air-Condition Engineers, Inc. (ASHRAE). 2008 ASHRAE Handbook: HVAC Systems and Equipment. Inch-Pound Edition. Page 30.4

[39] Direct Testimony of Charles Benson For Questar Gas Company, April 15 2005, QGC Exhibit 6. Public Service Commission of Utah. Pages 16—17.

[40] Suchovsky, C. (2005). Re: Testing of Armstrong Category I Furnace on Standard and Substitute Natural Gas. C. L. Bell. Walton Hills, OH, Gas Consultants, Inc. Page 6.

[41] U.S. Department of Defense. Military Standard MIL-STD-14720. "Human Engineering Design Criteria for Military Systems, Equipment, and Facilities." 14 March 1989.

[42] Steinmetz, G. F., 1979. "Special combustion characteristics and blending problems of LNG, SNG and LPG gases." New Fuels and Advances in Combustion Technologies, New Orleans, Louisiana, March 26–30. GTI Electronic Symposium Proceedings, Gas Technology Institute, Des Plaines, Illinois.

[43] U.S. Department of Energy, Assistant Secretary, Office of Energy Efficiency and Renewable Energy. Technical Support Document: Energy Efficiency Program For Consumer Products: Energy Conservation Standards For Residential Furnaces And Boilers. September 2007. Available online: http://www1.eere.energy.gov/buildings/appliance_standards/residential/fb_tsd_0907.html [last accessed 8 October 2009.]

[44] Singer, Brett C. 2007. Natural Gas Variability in California: Environmental Impacts and Device Performance: Literature Review and Evaluation for Residential Appliances. California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2006-110. Page 30.

[45] Levinsky, H. B., 2004. Consequences of "new" gases for the behavior of gas utilization equipment. 2004 International Gas Research Conference.

[46] Singer, Brett C. 2007. Natural Gas Variability in California: Environmental Impacts and Device Performance: Literature Review and Evaluation for Residential Appliances. California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2006-110. Page 58.

[47] Singer, Brett C. 2007. Natural Gas Variability in California: Environmental Impacts and Device Performance: Literature Review and Evaluation for Residential Appliances. California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2006-110. Page 37, citing Levinsky 2004.

[48] Singer, Brett C. 2007. Natural Gas Variability in California: Environmental Impacts and Device Performance: Literature Review and Evaluation for Residential Appliances. California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2006-110. Page 27.

[49] Sasaduesz, L., R. Schwedler, et al. (2005). Gas Quality and Liquefied Natural Gas Research Study. Los Angeles, CA, Southern California Gas Company. Appendix A-3

[50] Sasaduesz, L., R. Schwedler, et al. (2005). Gas Quality and Liquefied Natural Gas Research Study. Los Angeles, CA, Southern California Gas Company. Appendix A-3

[51] Sasaduesz, L., R. Schwedler, et al. (2005). Gas Quality and Liquefied Natural Gas Research Study. Los Angeles, CA, Southern California Gas Company. Appendix B-2

[52] Johnson, F. and D. M. Rue (2003). Gas Interchangeability Tests: Evaluating the Range of Interchangeability of Vaporized LNG and Natural Gas. Des Plaines, IL, Gas Research Institute. Page 6.

[53] Rana, H. S. and Johnston, D. S., 2003. "An empirical approach to evaluating gas interchangeability." AGA Operations Conference, Orlando, Florida, April 27–29, 2003. American Gas Association.

[54] Griffiths, J. C., Connely, S. M., and DeRemer, R. B., 1982. Effect of fuel gas composition on appliance performance. GRI-82/0037, Gas Research Institute, Chicago, Illinois, December 1982. Cited from Singer's paper on page 31.

[55] American National Standards Institute ANSI Z21.10.1-2001.

[56] Williams, T., Estell, L. and Brown, M., 2005. Assessment of changes to the performance of gas appliances in relation to variations in gas quality. Advantica Report R 8527; DTI Report URN 05/1938, Prepared for Dept. of Trade and Industry, U.K., Prepared by Advantica: Loughborough, Leicestershire, U.K., October 2005. www.dti.gov.uk/energy/markets/gas-quality/phase-2/page21044.html.

[57] Singer, Brett C. 2007. Natural Gas Variability in California: Environmental Impacts and Device Performance: Literature Review and Evaluation for Residential Appliances. California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2006-110. Page 50.

[58] Sasaduesz, L., R. Schwedler, et al. (2005). Gas Quality and Liquefied Natural Gas Research Study. Los Angeles, CA, Southern California Gas Company. Appendix A-1 Executive Summary.

[59] Kawasaki, Mikio: Research in the safety of gas appliances and integration of gas groups in Japan. Power Point presentation.

[60] Williams, T. (2004). Gas Quality Standards. LNG and the Changing U.S. Natural Gas Supply. Dallas, TX, American Gas Association.

[61] Sasaduesz, L., R. Schwedler, et al. (2005). Gas Quality and Liquefied Natural Gas Research Study. Los Angeles, CA, Southern California Gas Company. Page 21.

[62] American National Standards Institute. ANSI Z223.1-2006. 3.3.4. Page Z223.1-8.

[63] American National Standards Institute. ANSI Z223.1-2006. 3.3.28.1. Page Z223.1-10.

[64] American National Standards Institute. ANSI Z223.1-2006. 3.3.16. Page Z223.1-9.

[65] American National Standards Institute. ANSI Z223.1-2006. 3.3.19. Page Z223.1-10.

[66] American National Standards Institute. ANSI Z223.1-2006. 3.3.20. Page Z223.1-10.

[67] American National Standards Institute. ANSI Z223.1-2006. 3.3.21. Page Z223.1-10.

[68] American National Standards Institute. ANSI Z223.1-2006. 3.3.22. Page Z223.1-10.

[69] American National Standards Institute. ANSI Z223.1-2006. Page Z223.1-8.

[70] American National Standards Institute. ANSI Z223.1-2006. 3.3.32. Page Z223.1-11.

[71] American National Standards Institute. ANSI Z223.1-2006. 3.3.6.7 Page Z223.1-9.

[72] NGC+ Interchangeability Work Group (2005). White Paper on Natural Gas Interchangeability and Non-Combustion End Use, NGC. Page 2.

[73] American National Standards Institute. ANSI Z223.1-2006. 3.3.31.1. Page Z223.1-11.

[74] American National Standards Institute. ANSI Z223.1-2006. 3.3.31.2. Page Z223.1-11.

[75] American National Standards Institute. ANSI Z223.1-2006. 3.3.72. Page Z223.1-14.

[76] American National Standards Institute. ANSI Z223.1-2006. 3.3.16.5. Page Z223.1-10.

[77] American National Standards Institute. ANSI Z223.1-2006. 3.3.2.4. Page Z223.1-8.

[78] Energy Information Administristration. U.S. Department of Energy. 2005 Residential Energy Consumption Survey. Released April 2008. http://www.eia.doe.gov/emeu/recs/. Last accessed 19 May 2009.

[79] American Gas Assocation. Natural Gas Glossary. http://www.aga.org/Kc/aboutnaturalgas/glossary/ Last accessed 1 May 2009.