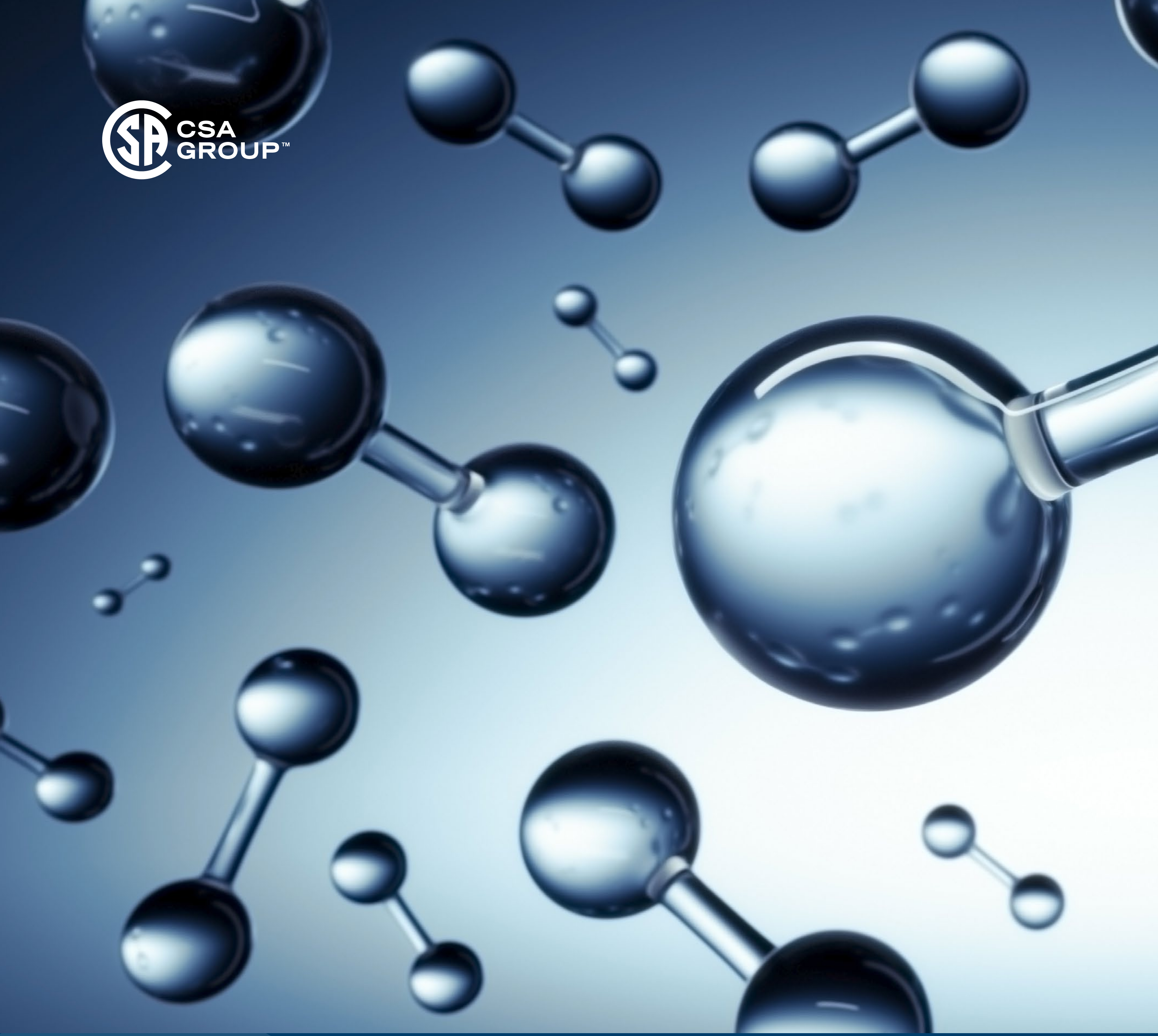

STANDARDS RESEARCH

# Appliance and Equipment Performance with Hydrogen-Enriched Natural Gases

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# Executive Summary

Mixing of hydrogen into natural gas, as a means of mitigating environmental concerns associated with the use of fossil fuels, poses a question of performance of appliances designed for use with natural gas, when fuelled by blends of hydrogen and natural gas. This study examines the performance of space and water heating appliances fuelled by methane as a natural gas proxy, and methane/hydrogen blends containing up to 15% hydrogen. The appliances were tested for input rate, ignition and burner operating characteristics, combustion products properties, and gas leakage, using three gas mixtures (pure methane, 5% hydrogen/methane blend, and 15% hydrogen/methane blend mixtures) per applicable CSA/ANSI Z21 series Standards. Effects of gas composition on furnaces were also tested for temperature rise and heating tube temperatures. Condensing appliances were additionally assessed for dew point temperatures and acidity. Overall, appliances showed no major operable issues and consistent trends of decreased heat output and $CO_2$ emissions with increase of hydrogen content in methane/hydrogen blends. Consequently, to meet the same heat demand, the appliances would need to operate for longer periods which would result in additional carbon dioxide emissions. However, the overall $CO_2$ emissions for the same heat output are still expected to be lower with the use of blends compared to natural gas. Carbon monoxide and nitrogen oxide measurements were in the acceptable ranges regardless of the type of fuel used. No consistent trends were observed for other measured properties, indicating that hydrogen mixtures up to 15% do not significantly affect these parameters. Future testing of gas blends containing 5% and 15% of hydrogen as examined herein, as well as higher hydrogen amounts, ought to incorporate natural gases to determine more representative results.

"As the amount of hydrogen determines both physical and chemical properties of hydrogen-enriched natural gases (HENG), the safety and suitability of different mixture compositions in residential applications are becoming a focus of interest."

## 1 Introduction

Natural gas is overall the most common energy source for space heating and water heating in the United States and a dominant source of heating energy in colder regions, according to the U.S. Energy Information Administration [1]. Natural gas consists mainly of methane and is considered the cleanest fuel fossil energy source, due to lower carbon dioxide per unit of energy released. To further reduce the environmental impact of natural gas, North American natural gas utilities are envisioning the introduction of renewable natural gas (RNG) into the North American natural gas system. RNG, also referred to as biomethane, is considered a carbon-neutral energy source since it captures methane emitted from the decaying organic waste that would otherwise escape into the atmosphere. RNG by most traditional definitions is a methane-rich gas obtained via upgrade or purification of biogas, i.e., gas derived from biomass [2].

In addition to RNG, the gas industry is further considering the addition of green hydrogen ($H_2$), produced from renewable sources, to natural gas to generate hydrogen-enriched natural gases (HENG), or blends of natural gas and hydrogen. Natural gas/hydrogen blending is considered by its proponents as a means of reducing carbon-containing air emissions, principally carbon dioxide ($CO_2$), as hydrogen, during combustion in oxygen, produces water vapor. Although HENG as a term implies that the two gases are mixed in any proportion, the mixture containing 10 to 20% hydrogen by volume represents the most promising near-term option for reducing the overall "carbon footprint" from the burning of natural gas [3].

Implicit in natural gas/hydrogen blending is the trade-off between reducing the carbon footprint and the interchangeability of these gas blends with natural gas. Potential issues of pipeline and end-use system and equipment durability associated with hydrogen introduction in the natural gas, including HENG, embrace the potential for corrosive effects of molecular hydrogen. As the amount of hydrogen determines both physical and chemical properties of the HENG, the safety and suitability of different mixture compositions in residential applications are becoming a focus of interest. Contemporary studies of HENG compatibility with traditional natural gas systems are, therefore, receiving renewed examination since first studied on a major scale in the "hydrogen economy" of the 1970s.

The references to hydrogen levels that are safe for North American appliances are still scarce, but it was concluded that "hydrogen concentrations up to 28% may safely be used with properly serviced existing domestic appliances" [4], although this conclusion is tentative and needs to be confirmed through continuing research and analysis. North American natural gas utilities have articulated future targets for blending are up to 15% of hydrogen. Specific commitments and timetables for blending have identified 5% blending as the near-term target. In Canada, for example, the energy delivery company Enbridge is already blending 2% of hydrogen into the natural gas delivery system to the City of Markham.

An Alberta energy company, ATCO, has announced its plans to build Alberta's first natural gas/hydrogen blending project, injecting up to 5% of hydrogen into Fort Saskatchewan's natural gas distribution network. Even more advanced efforts are underway in Europe, East Asia, and Oceania.

Performance and operational safety of natural gas residential appliances are tested according to the North American CSA/ANSI Z21 series of Standards. Performance testing to CSA/ANSI Z21 Standards requirements of appliances operated on HENG has been largely unstudied. The objective of this research was to conduct an exploratory study on performance of gas appliances fuelled by mixtures of natural gases containing up to 15% hydrogen. It is anticipated that this exploratory testing will identify future standards development activities and appliance testing needs and policy development towards better-informed decision-making.

## 1.1 Background and Literature Review

### 1.1.1 Interchangeability of Gases

Design and performance of residential appliances are dictated by combustion energy output (heating value) of fuel gases, currently including conventional natural gases and variants to conventional natural gases. Using gases that are not compatible with appliances' design can cause many issues, such as incomplete combustion and, therefore, increased level of emissions of carbon monoxide, decreased efficiency and lifetime of the appliances. For example, in the UK, the incompatibility between natural gas and appliances designed for use with a gas manufactured from coal and oil (town gas) required a costly £500-million conversion of all UK gas appliances upon its mains-distributed fuel change in 1966 [5].

The compatibility between the gases, i.e., their interchangeability in appliance applications, is nowadays most commonly determined by an empirical value called the Wobbe index. Two gases that produce the same energy and density when applied at the same supply pressure have a similar Wobbe index ($I_W$), which is calculated as a ratio of gas higher heating value (HHV) and square root of gas specific gravity *(sp)* of the fuel gas to air under standard conditions.

$$I_w = \frac{HHV}{\sqrt{sp}}$$

Minimum and maximum Wobbe index requirements, along with HHV requirements, have been used as specifications for gases traded in the United States, as laid out in the Federal Energy Regulatory Commission's (FERC) Policy Statement on Natural Gas Interchangeability [6]. FERC further defines interchangeability as "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". Trade with Canada under TransCanada General Terms and Conditions of the Transportation Tariff also specifies minimum and maximum Wobbe values as natural gas interchangeability indices [7].

When compared to natural gas, hydrogen has lower specific gravity and lower heating value by volume that overall results in a lower HENG Wobbe index than that of natural gas. Although the Wobbe index is determined to be the best single-parameter measure of gas interchangeability, a simple comparison of the Wobbe index of HENG to the natural gas is not a reliable predictor for HENG uses in residential appliances for three reasons: (i) the Wobbe index of HENG non-linearly changes with the hydrogen content [8]; (ii) the Wobbe index cannot completely predict gas interchangeability as it does not account for all combustion phenomena [9]; and (iii) the Wobbe index and HHV generally refer to burner performance but not appliance operation per se. The most comprehensive and accurate information on compatibility of a gas with a given design of appliances is therefore obtained by testing the performance parameters of the appliances in laboratory settings through standard testing procedures. In North America, testing of space heating and water heating appliances subject to this research is performed through methods outlined in the binational CSA/ANSI Z21 series of Standards.

### 1.1.2 Heating Appliances Combustion Process

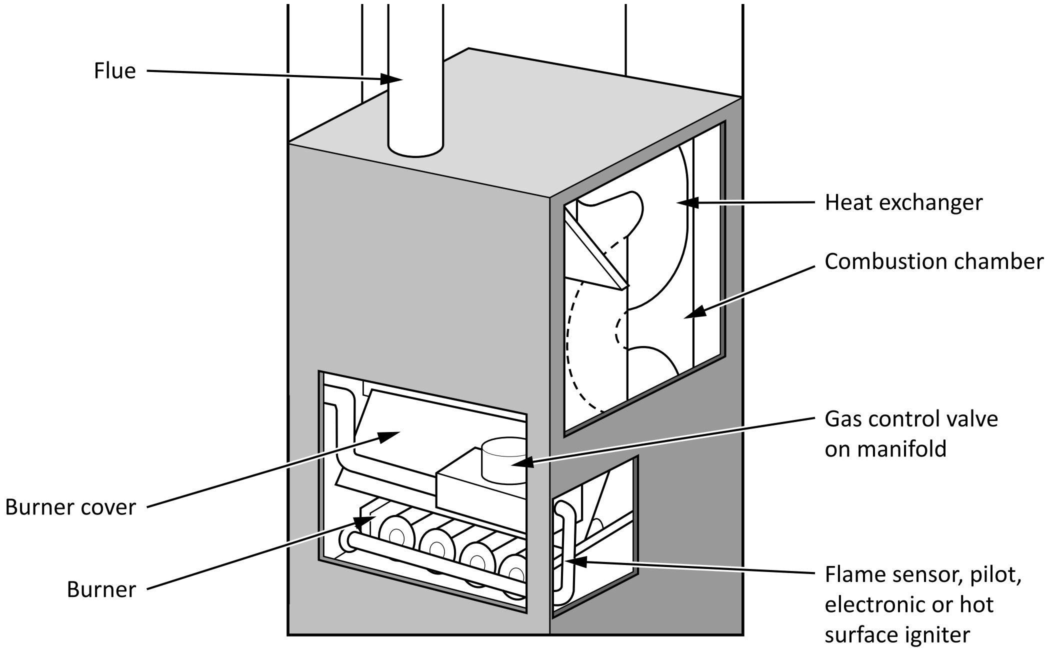
To understand the effects HENG can have on performance of heating appliances, it is important to understand the combustion process and components of the appliances. Fuel gases (usually natural gas or liquid propane) are supplied to the appliance at a given pressure that is controlled by an external delivery line pressure regulator followed by an internal appliance "step down" pressure regulator. The pressures of natural gas in the line are typically at least 1 in wc (inches of water column) higher than the manifold (i.e., operating) pressures of the appliance burner, although in many distribution systems and for many appliances, this pressure differential must be higher to ensure proper functioning of the appliance regulation.

The reduction from line to manifold pressure is set and maintained by a manifold serving the burners. In some appliances, manifold pressure is adjustable to compensate for local supplier gas compositional characteristics. In other and more modern appliances, manifold pressure is not generally adjustable and other means are used to control gas flow to appliance burners. A manifold is, simply speaking, a gas distribution apparatus serving the appliance burners that consists of pipes, connectors, valves, and various instruments for measuring and controlling the gas flow, as shown in an example of warm air residential furnace in Figure 1. Manifold pressure adjustment may be used to adjust fuel gas supply, as the appliances are designed to operate at specific heat input rates, i.e., amount of heat transferred to the burner over a period of time.

When the system calls for heat, the control valve upstream of the manifold opens and the ignition device ignites the gas inside the burner, which is a set of tubes through which gas is directed and burned. Different appliances and designs within appliance categories have different ignition devices, but they can be broadly divided into standing pilots (continuously burning flames) and electronic ignition systems. The ignition and gas combustion is monitored by a flame sensor that acts as a safeguard and shuts off the incoming gas if a flame is not detected.

Manifolds, burners, and other described devices directly associated with the combustion process are located inside a combustion chamber surrounded by a heat exchanger in the case of appliances that transfer heat energy from combustion to a circulating medium. The flames heat up a heat exchanger that then transfers energy to the heating medium – air in the

**Figure 1:** Main components of a gas heating appliance, depicted in a furnace example



case of furnaces and water in the case of boilers and water heaters. Unvented appliances, such as unvented space heaters examined in this study, do not have heat exchangers and instead transfer heat energy directly to the occupancy air. In the case of vented appliances (furnaces, boilers, and water heaters) gases formed during the combustion in the chamber are exhausted out through an appliance passageway or flue. The appliances' flue, which is an external but integral part of appliances in most cases, is connected to a venting system. The distinction of appliance "flues" from "vents" or "venting systems" is important, the latter being a structural component of the building.

The composition of the exhaust gases is determined by the gas burning process. In the case of complete combustion, which happens when the air and gas mix in optimal (stoichiometric) ratio or in excess air amounts, natural gas is ultimately converted to carbon dioxide and water, yielding blue-coloured flame and highest heat output. In cases of incomplete combustion, the efficiencies of the appliances are lower and carbon monoxide, water, and carbon are present in the flue emissions. Incomplete combustion can also result in buildup of soot and is characterized by an orange flame.

### 1.1.3 Appliance Design and Categories

Appliances examined in this study include four residential service gas-fired product categories, among which there are several classes[1]:

- Residential warm air furnaces (four units tested)
- Residential hot water boilers (four units tested)
- Residential service storage water heaters (two units tested)
- Residential unvented space heaters (two units tested)

Most homes in North America are heated with gas central heating systems, i.e., furnaces and boilers. While furnaces heat air directly and distribute hot air via ducts, boilers heat water and produce either steam or hot water, that further transfer heat to air mainly via radiators and radiant floor systems. Hot water boilers are closed loop systems, returning water to the boiler for reheating once space heating circulation is performed. Water heaters, on other hand, heat water for domestic purposes (cooking, cleaning, and bathing) that can be used as a potable (safe-for-drinking) warm water.

Among furnaces, boilers, and some water heaters, there are several distinct designs for **combustion control**, including *single-stage*, *two-stage and modulating* input rate controllers. A single-stage appliance operates at only one input rate and provides one heat output. Two-stage and modulating input rate heating systems are designed towards higher efficiencies of natural gas use. The two-stage heating means the heating system can operate at two heat output levels to satisfy two ranges of heat demand. On cold winter days, they provide high heat output by consuming more gas, i.e., they operate at a high input rate. During milder days, which account for 80% of a heating season, they operate at a lower input rate. The gas input to the appliance and the circulating air and water distribution speed are adjusted to a lower rate by furnace fans and boiler water pump control systems, respectively, thus improving not only gas but electrical energy efficiency as well.

Residential modulating appliances differ from two-stage appliances by providing continuous adjustment of gas input and fan/water pump speeds across the operating spectrum. Typically, modulating appliances provide approximately 70 discrete combinations of gas inputs adjusted for approximately 1°F difference in heat demand.

Most modulating appliances use a two-heat **exchanger configuration** to transfer heat to circulating heating medium. The first heat exchanger transfers heat in a manner comparable to the single- and two-stage appliance design discussed above. Cooled combustion gases approaching the dew point, i.e., temperature of condensation, are then passed through the second exchanger in which they are condensed and the heat of condensation collected is used for heating. This additional heat capture is formally distinguished as latent heat of condensation. Appliances of this type are referred to as *condensing combustion appliances.*

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[1] Product classes are defined by the U.S. Department of Energy to delineate residential gas-fired products according to similarity of energy services provided. Within each product class, technology and designs can vary significantly in providing their common energy service functions.

> "Overall, appliance designs that employ the condensing approach boost the overall operating efficiency of the appliance operating on natural gas by 10 to 18%, depending upon the design and rated efficiency performance."

Theoretically, latent heat of methane combustion increases recoverable heat by approximately 12% over one heat exchange. Overall, appliance designs that employ the condensing approach boost the overall operating efficiency of the appliance operating on natural gas by 10 to 18%, depending upon the design and rated efficiency performance.

Condensing appliances must dispose condensed water to a safe location outside of the furnace, typically a floor drain or outdoor condensate line. The acidity of condensed water in non-condensing appliances, measured as a pH value, should be relatively neutral (pH ~7) to avoid issues of corrosion and deposition of solids dissolved in the condensate. Non-condensing appliances are not designed for managing high acidity condensate (for example, less than pH 5) as water vapor is vented with other combustion products through the flue and house venting system, carrying with it gases and solids that can alter pH when in condensed form. In contrast, condensing appliances are designed to withstand acidities in the pH range of 2 to 5 without incurring internal corrosion damage. Condensate disposal to floor drains and other external plumbing used for condensate removal must be, therefore, able to withstand these corrosive environments.

Besides the differences in combustion control and heat exchanger configuration, venting appliances differ in **venting systems**. Classic systems rely on *natural draft* to vent combustion products outside. Newer appliances use fans in so-called *power vented draft* systems that either push (forced draft systems) or pull (induced draft systems) air out of the occupancy during operation of the appliance. The two-stage heat recovery approach, in contrast to the one-stage, requires power venting to successfully vent the combustion products to the outdoors.

In natural draft appliances, some heat from the occupancy when the appliance is not operating is lost through the venting system. This issue is overcome with an automatic device, a vent damper, that shuts off the flue pipe when the burner is not running and is most commonly used in some boiler designs. Use of vent dampers improves efficiency on the order of 1 to 3%. Besides the *vent damper,* combustion gases can be vented to the outdoors without the addition of room air for dilution via *direct venting*. In direct venting appliances, outside air is used both as a combustion supply for stoichiometric combustion and dilution air, which is not used in combustion but assists in venting of combustion gases. This is typically done using an annular, “pipe-within-a pipe” venting system design where an inner pipe vents combustion products, while a surrounding outer pipe brings in outside air for combustion. This direct vent design and combustion air supply typically boosts overall boiler efficiency by over 10% in rated performance.

As already stated, unvented gas space heaters combust gas and release heat and combustion products directly to the occupied space. These appliances do not use heat exchangers or flue systems to separate combustion from occupancy air.

Combustion gases are exchanged with occupancy air via convection or in some designs with the use of a small blower to promote heated air distribution. Unvented space heaters may be either “blue flame” designs or radiant burner designs (Figure 2). “Blue flame” unvented space heaters use a conventional burner tube with ports that support a conventional diffusion flame similar to a cook top burner, but usually configured as a tube to enhance heat transfer to the room air. Radiant space heaters, often referred to as infrared space heaters, generate infrared radiation through tile or metal matrix structures, thus transferring heat to the room air both by convection and radiation.

In some North American jurisdictions, most notably in Canada and in some states of the US, unvented heaters are not permitted because of concerns of combustion products accumulation in occupancies and potential health, safety, and building durability issues associated with CO, $NO_2$, and water vapor accumulation. In response to these concerns, the CSA/ANSI Z21.11.2 Standard, *Gas-fired Room Heaters, Volume II, Unvented Room Heaters,* covering unvented space heaters, requires demonstration of $NO_2$ air-free emission rates below 20 ppm, CO air-free emission rates below 200 ppm, and installation of an oxygen depletion sensor (ODS), which controls the main gas value and shuts down the appliance when oxygen levels drop below 18%. The oxygen level drop is highly correlated to hazardous CO level build up so that it serves as a proxy for avoiding CO accumulation that would present occupant safety issues.

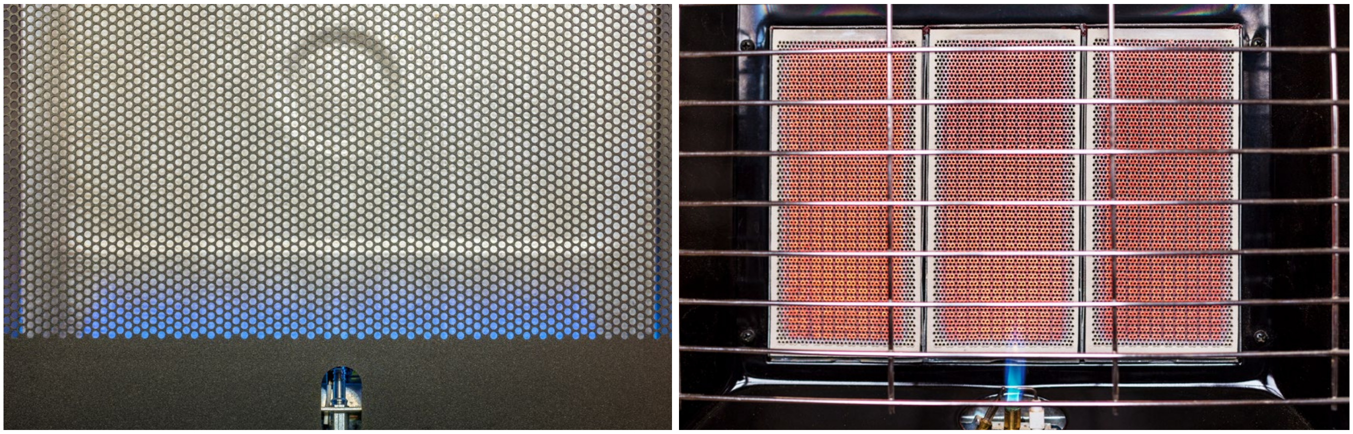
Besides being unvented, the space heaters differ from the vented appliances by not requiring electrical supply, except in designs that utilize a blower for air circulation. Likewise, many designs of storage water heaters operate without electrical supply, although higher efficiency units use electric power for power venting and various controls. Furnaces and boilers, on the other hand, all require an electrical supply.

### 1.1.4 Performance Parameter (Tests) Indicators of Interchangeability

Performance of residential North American gas-fuelled space and water heating appliances and their certification is performed according to the binational CSA/ANSI Z21 series of Standards [10]–[13].

Major performance parameters tested across the appliance categories are similar. Before the actual performance testing is performed, the manifold pressures are adjusted within the manufacturer-set limits and the input rate (energy transferred to the burner) is measured to ensure that the appliance is operated as intended. Depending on the appliance type, testing is performed at higher and lower input rates as specified in the applicable standard. The subsequent performance test measurements at manufacturer-set input rate are performed under a steady-state operation,

**Figure 2:** Blue Flame Space Heater Flame Section (left) and Infrared Gas Ceramic Tile Space Heater Closeup (Right)



i.e., at constant temperatures, combustion conditions, and emissions. To test for interchangeability of gases, the following major tests need to be performed to ensure proper operations and safety.

#### 1.1.4.1 Ignition

Initially, a successful ignition of the main appliance burner(s) per attempt is evaluated on a “pass/fail” basis under pressures and voltages within the range of operation limits. Any changes in ignition performance due to operation on HENG is of principal interest.

It has been shown that at low concentrations of hydrogen in air, the energy required to initiate combustion is similar to that of other fuels. However, at concentrations of 29% hydrogen-to-air volume ratio, the ignition energy is ten times lower than that required for natural gas [14]. In case of HENG uses in appliances, hydrogen ignition over a wide range of concentrations in air could cause inconsistent performance of appliance ignition systems, requiring the system to constantly reset and restart.

#### 1.1.4.2 Burner Operating Characteristics (BOC)

For the appliances to operate at the design process flowrate, the burners need to provide the heat necessary to maintain heating medium temperature and meet flame and vaporization requirements to maximize heat exchange. The production of the heat depends on combustion of the air and gas mixture. Under complete combustion, the flame is substantially blue and stable and of a given geometry – without floating around the edges, drifting out or lifting off the burner, or burning back into burner ports. In the case of improper burner operation however, a set of undesired observations serve as indicators for failed operation:

- Flash back (or flashback) is the burning of gases back into the burner ports and within the manifold system, rather than inside the burner. In cases of an incompatible fuel use, it can be caused by an excess amount of air in the system, or too low input rate, affecting the burner stability, efficiency, and potentially safety associated with changes in appliance emissions characteristics.
- Flame lifting off the burner is the ignition of fuel gas and air mixtures above the appliance burner port(s) during operation. This phenomenon can affect stability and efficiency of the appliance and potentially safety associated with improper heat transfer and changes in appliance emissions characteristics. Flame lifting off the burner is usually caused by an excessive amount of air or too high input rate (overfiring), resulting in operations at too high temperatures, incomplete combustion, and reduced burner efficiency.
- Higher flow rates and lowered flow resistance of hydrogen may cause flame lifting and consequently, temperature distance from the heating surface may differ depending on hydrogen content (e.g., a pot being heated on the sides instead of on the bottom).
- Delayed ignition, similar to the flashback, represents the ignition of fuel/air gas mixture outside the burner and within the combustion chamber due to failure of immediate ignition of the burner as designed for the appliance, potentially affecting safety.
- Excess noise from combustion is usually due to an excessive flow of fuel gas, and air, or fuel gas and air mixtures.
- Overpressure upon ignition is the development of impulse pressure (explosion) outside of the burner, most commonly resulting from delayed ignition.

BOC behaviours are observed during combustion performance tests. They are not tested independently or quantitatively evaluated. The results are evaluated on a qualitative pass/fail basis.

#### 1.1.4.3 Temperature Rise Test

Temperature rise measures a difference in the temperature of the heating medium before and after heating. It is assessed during the stabilization phase of appliance operation over a standard-prescribed test duration period. Temperature rises prior to achieving steady-state temperatures may alter combustion behaviour and emissions characteristics. It is expected that at a set pressure of applied gas, hydrogen could lower the temperature rise of appliances fuelled by HENG due to its lower heating value.

### 1.1.4.4 Combustion Tests

A complete combustion of gases is important not only for the performance of the appliances and efficient use of the fuel but also for safe operations, i.e., emissions of nitrogen and carbon monoxide formed during combustion that must remain at levels deemed safe for humans and the environment in the limits guided by regional regulations. The combustion tests are performed for concentrations of $NO_x$ and $CO_x$ in flue gases.

**Nitrogen oxides ($NO_x$)**, which are atmospheric ozone creation precursors, are produced in appliances mainly by thermal reactions in high temperature flame zones near the burners [15]. The flame temperature of the HENG might be different in the presence of hydrogen fractions due to the higher flame temperature of hydrogen gas as compared to methane flame temperatures, possibly resulting in higher $NO_x$ concentrations. $NO_x$ concentrations for combustion analysis, that include all forms of nitrogen oxides, are reported and limited to a concentration of air-free $NO_x$ ($NO_x$ AF). Air-free concentration of any gas is a corrected value of a gas concentration to simulated air-free conditions in the combustion gases. The air-free concentration calculation is based on theoretical complete combustion that yields either zero oxygen or "ultimate $CO_2$" amounts, i.e., total conversion of carbon to $CO_2$. Adjusting combustion gas measurements to air-free measurements using either oxygen or $CO_2$ allows for consistent combustion performance measurements across appliances by removing the contribution of air not directly involved in the combustion process (i.e., excess air).

To perform the calculation based on oxygen-free calculations, the oxygen amount in a combustion gas is measured along with the emission gas of interest and a ratio of the measured oxygen concentration to theoretical 20.9% maximum concentration of oxygen in natural gas is used as a correction factor using the following calculation:

$$NO_x\, AF(ppm) = \frac{20.9\%}{20.9 - O_2(\%)} \cdot NO_x(ppm)$$

where:

$NO_x$ AF – calculated air-free $NO_x$ concentration (ppm),

$O_2$ – measured percentage of oxygen in combustion gas, and

$NO_x$ – measured concentration of $NO_x$ in combustion gas (ppm).

If the calculation is based on $CO_2$ measurements, then the following equation is used:

$$NO_x\, AF(ppm) = \frac{12.2\%}{CO_2(\%)} \cdot NO_x(ppm)$$

where 12.2% represents the maximum concentration of $CO_2$ in natural gas (ultimate $CO_2$) and $CO_2$ is a measured concentration of $CO_2$ in flue gases.

$NO_x$ AF maximum thresholds are set under jurisdictional requirements, most notably limits set by the California South Coast Air Quality Management District (SCAQMD) in the US [16]. Although most gas appliance standards used in this study do not set emission thresholds for $NO_x$ AF, the CSA/ANSI Z21.11.2 Standard covering unvented space heaters limits $NO_2$ AF concentrations to 20 ppm, since $NO_2$ is associated with the health effects of building occupants when breathing concentrations exceeding health-based guidelines and standards.

**Carbon oxide ($CO_x$)** concentrations, are also important parameters of complete and incomplete combustion process. $CO_2$, a product of complete combustion, is usually reported as measured in samples for the purpose of calculating air-free concentrations of other gases ($NO_x$, $NO_2$, and CO), while CO is reported as air-free (CO AF) calculated value, using similar equations as those shown above. The limited amount of CO AF resulting from combustion of natural gas is limited to 400 ppm in most CSA/ANSI Z21 series of Standards.

The addition of hydrogen to HENG is expected to ultimately lower $CO_x$ emissions since carbon levels are reduced in the fuel gas used in combustion. However, considering the lower HHV of hydrogen, it is plausible that higher amounts of HENG are likely to be needed to achieve the equivalent energy output obtained with the lower amounts of natural gas. This could in turn mean that overall carbon reduction proportional to the hydrogen added may not be achieved.

> "The addition of hydrogen to HENG is expected to ultimately lower $CO_x$ emissions since carbon levels are reduced in the fuel gas used in combustion."

#### 1.1.4.5 Flue Loss

Flue loss is heat contained in flue gases above room temperature that leaves the appliance. It is used to approximate combustion and heat transfer efficiency of the appliance. Regulatory-prescribed efficiency testing is used to demonstrate compliance with minimum efficiency requirements, account for factors such as seasonal usage patterns, consumer-specific usage patterns, and other variables that approximate annual efficiency performance. However, as these testing methods and metrics differ across appliances, flue loss measurements provide a more consistent means of determining efficiency for comparison purposes.

#### 1.1.4.6 Condensing Appliances Condensate Measurements

Condensing appliances are additionally assessed for dew point temperatures and acidity. Dew point represents the temperature at which moisture in combustion gases condense into liquid water. Most condensate from natural gas appliances will have a pH of between 2 and 4, according to the chemical composition of the used fuel. Condensate acidity is affected by the generation of carbon, nitrogen, and other elemental solutes, which originate from combustion products, dilution air, and trace sources.

# 2 Methodology

## 2.1 Appliances and Verification Testing

Appliances used in this study were donated by the Air-Conditioning, Heating and Refridgeration Institute (AHRI) and previously tested for other purposes. The study included a variety of appliance categories and classes as listed in Table 1 and detailed more fully in the tables in Appendix A.

Before the actual performance test for different gas mixtures was performed, the appliances were tested to confirm satisfactory performance using service “line gas”, i.e., natural gas provided by an energy company. The testing verified the burner input rate based on gas consumption at input rating settings and, $CO_2$ and CO AF emissions. In the case of furnaces, tests were performed under normal and high external (in ducts) static pressures and additionally included a temperature rise test. Verification testing also included visual assessment of ignition and BOC that were performed on appliances operating under reduced, normal, and increased inlet test pressures (3.5, 7.0, and 10.5 in wc) with the supply voltage adjusted to 85% and 110%, as well as at appliance rating plate voltage (102, 120, and 132 V). Unvented space heaters were tested only under three line-pressures, as their operation does not require electricity input.

Issues raised during the verification tests included:

- FURN1 could not be ignited at 102 V current – the tests requiring this voltage were therefore performed at 105 V;
- WH2 design prohibited visual observation of the burner port, therefore the ignition test was assessed via successful ignition and the absence of noise during ignition and shutoff; and

**Table 1:** Classes and Descriptions of Appliance Studied for Use of Methane/Hydrogen Blends

| Appliance Category | Appliance Class | Designation |
|---|---|---|
| **Residential furnaces** | 2-stage, non-condensing, induced draft | FURN1 |
| | 2-stage, non-condensing, induced draft | FURN2 |
| | 2-stage, condensing, induced draft | FURN3 |
| | Modulating, condensing, forced draft | FURN4 |
| **Residential boilers** | 1-stage, non-condensing, draft hood | BLR1 |
| | 1-stage, non-condensing, vent damper | BLR2 |
| | Modulating, condensing, direct vent | BLR3 |
| | Modulating, condensing, direct vent | BLR4 |
| **Residential water heaters** | 1-stage, non-condensing, induced draft venting | WH1 |
| | 1-stage, non-condensing, draft hood | WH2 |
| **Residential unvented space heaters** | Blue flame | SP1 |
| | Infrared | SP2 |

- SP1 showed limited operations at lower manifold pressures. Therefore, ignition and BOC tests specific for the space heater of this design, specified in the CSA/ANSI Z21.11.2 Standard that requires testing under 50% manifold pressures and 87% minimum input rate, could not be performed.

Despite these observations, the appliances were used within their limits and these limitations were noted under applicable results as the intent of this study was to compare performance of appliances fuelled by different gas mixtures under the same conditions. As the appliances were previously used for testing at other labs, a test failure doesn't necessarily mean that a new unit from the manufacturer would also fail.

## 2.2 Materials

Pure methane and hydrogen were purchased from Airgas. Pure methane gas was used in the performance tests as a baseline for performance and as a proxy for natural gas. Pure methane was used in all gas blend tests to avoid artifacts that might be introduced by irregularities in composition of line natural gas over the course of the testing. Table 2 includes properties of pure methane and hydrogen/methane blended gases calculated using an unpublished American Gas Association (AGA) calculation procedure adopted by the AGA Gas Interchangeability Program [17]. Table 3 includes actual (measured) concentrations of methane and hydrogen gas in the blends used in this study, as provided by Airgas.

## 2.3 Testing

The appliances were tested for input rate, ignition and burner operating characteristics, combustion products properties, and gas leakage, using three gas mixtures (pure methane, 5% hydrogen/methane blend, and 15% hydrogen/methane blend mixtures) per applicable CSA/ANSI Z21 series Standards. Furnace testing also included the assessment of temperature rise and tube surface temperature measurements. A gas supply manifold, designed and manufactured for the purpose of this test, allowed for rapid changes in gases introduced to the appliance during the various tests. Adjustments in appliance setting such as manifold pressure and ignition voltage, were carried out manually. The manifold was purged every time before a new gas mixture was used.

Combustion products testing included $CO_2$ measurements, CO AF and $NO_x$ AF calculations ($NO_2$ AF in case of unvented space heaters) and for vented appliances also encompassed flue temperature measurements and flue loss and dew point calculations. Acidity of the condensate was assessed through pH values for appliances classified

**Table 2:** Properties of Test Gases Calculated Using an Unpublished American Gas Association Calculation Procedure

| Gas Property | Pure $CH_4$ | 5% $H_2$ / 95% $CH_4$ | 15% $H_2$ / 85% $CH_4$ |
|---|---|---|---|
| Higher heating value (HHV), dry, standard conditions (Btu/ft$^3$) | 1012 | 977.6 | 908.9 |
| Specific gravity relative to air, standard conditions (dimensionless) | 0.5539 | 0.5296 | 0.4812 |
| Wobbe number (dimensionless) | 1359.8 | 1343.3 | 1310.2 |
| Air required for stoichiometric combustion per cubic foot of gas (ft$^3$) | 9.53 | 9.17 | 8.46 |
| Ultimate $CO_2$ produced from complete combustion (ft$^3$) | 11.73 | 11.59 | 11.28 |

**Table 3:** Actual Concentration of Mixed Gas Components Used in the Study as Reported by Airgas

| Nominal Mixture Composition | 5% $H_2$ / 95% $CH_4$ | | 15% $H_2$ / 85% $CH_4$ | |
|---|---|---|---|---|
| Gas component | $H_2$ | $CH_4$ | $H_2$ | $CH_4$ |
| Minimum | 5.148 | 94.776 | 14.90 | 84.88 |
| Maximum | 5.224 | 94.875 | 15.12 | 85.10 |
| Average | 5.188 | 94.816 | 15.00 | 85.00 |

as condensing appliances. The measurements were performed once, unless there was a need for repetition caused by erroneous testing, due to limitations of testing resources and the need to cover all appliance categories and classes with the various performance tests relevant to the standards.

In addition, heat exchanger tube temperature profiles of one furnace were created for all gases, and surface temperatures of unvented space heaters' IR burner and metal guard were measured.

The tests were performed according to applicable tests of the CSA/ANSI Z21 series Standards and briefly described as follows:

**Manifold pressure** was measured by in-line pressure meter or U-tube manometer.

**Input rate** was measured by the Elster American Meter Company DTM-200 flowmeter, after 15 minutes of operation and upon reaching a steady-state input rate in boilers and water heaters, as specified in applicable CSA/ANSI Z21 series Standards.

**Ignition and BOC assessment** was performed by visualization of ignition success, flame extinguishment, flame geometry, and excessive noise, at minimum and maximum input rates and at cold and high temperature operations, according to CSA/ANSI Z21 series Standards. Space heater ignition and BOC behaviours were also evaluated at 87% of minimal input rate and 123% of manufacturers' declared input rate, as per requirements of the CSA/ANSI Z21.11.2 Standard.

**Combustion products testing:**

**Concentrations of $CO_2$ and CO** were measured by the Siemens Ultramat 23 gas analyzer following procedures of CSA/ANSI Z21 series Standards.

**Concentrations of $NO_x$ and $NO_2$** (for space heaters only) were measured by the Thermo Scientific™ 42i-LS NO-$NO_2$-$NO_x$ Analyzer, on an air-free basis. Space heater $NO_2$ testing was performed according to the CSA/ANSI Z21.11.2 Standard. The instrument was calibrated according to the SCAQMD protocol [16].

**Dew point** was computed according to Brokaw [18].

**Flue loss** was determined according to equations given in Annex I of the ANSI Z21.47/CSA 2.3 Standard. The calculations were based on flue temperatures measured by Fluke 52 connected to Cleveland Electric Labs ITW-J-24-2-304-0-C or Omega PR-J-SLE-1000 thermocouples.

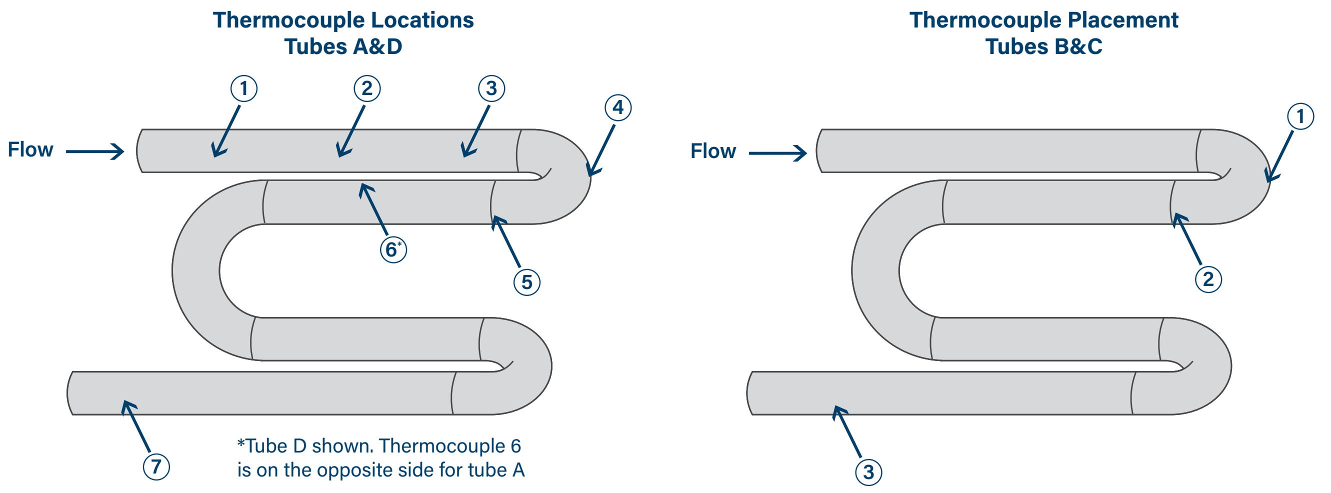


**Figure 3:** Placement of Thermocouples on Heat Exchange Tubes of the Furnace Selected for Examination (FURN1)

**Thermocouple Locations Tubes A&D**

**Thermocouple Placement Tubes B&C**

*Tube D shown. Thermocouple 6 is on the opposite side for tube A

**Condensate pH values** were assessed for condensing type furnaces and boilers. The condensate was collected during flue loss testing and the pH measured using the Hanna Instruments HI98103 pH meter.

**Leakage testing:**

Assessment of leakage, which is not a part of the CSA/ANSI Z21 series Standards testing, involved pressurizing manifold gas lines from one of each of the four appliance categories to 10.5 in wc (0.4 psi) test gas and measuring pressure decay over time. The gas lines were completely closed using orifice blanks and filled with gas, leaving no air in the system. Every 30 minutes over a two-hour period, line pressure was recorded and leaks in the joints examined using both a gas sniffer and soap and water test. The gas sniffer, Inficon GAS-Mate®, had a sensitivity of 5 ppm for both $CH_4$ and $H_2$.

In addition to the manifold gas line, leak testing was also performed on piping connected to the appliances. Four piping materials were tested: steel pipe with threaded joints sealed with Rectorseal Tplus2TM pipe thread sealant, press connect copper, 45-degree flare connect copper, and corrugated stainless-steel tubing (CSST) with mechanical joints. Each piping assembly included a tee connection with 1 ft. piping terminated with a cap and 4 ft. piping terminated with a manual valve. The purpose of the manual valve is to purge the assembly of previous test gas when adding the next test gas.

Initially, quality of connections was verified using pressurized air at 20 psi. The verification included pressure loss monitoring at the 5-minute period and subsequent bubble appearance upon immersion in water. Upon satisfactory connection confirmation, three test gases at the pressures of 5 psi and 20 psi were examined for leakage under the same tests – pressure loss and bubbles visualization.

**Temperature rise in furnaces** was assessed as a difference between the temperatures of air entering the furnace and heated air in the furnaces ducts. The temperatures were measured by Fluke 52 using Omega PR-J-SLE-1000 thermocouples placed according to ANSI Z21.47/CSA 2.3 requirements based on furnaces properties.

**Surface temperatures** of the heat exchanger tubes of one two-stage, non-condensing furnace (FURN1) were measured using Cleveland Electric Labs ITW-J-24-2-304-0-C thermocouples connected to IOtech Personal Daq/56 USB data acquisition system. Position of the thermocouples on the furnace tubes is shown in Figure 3. Space heater metal guard temperatures were measured by Fluke 52 II and J-type thermocouples. Infrared tile temperatures, also recorded at multiple locations, were measured using Omegascope® OS523-3 infrared thermocouples assuming emissivity of 0.8 at normal manifold pressure.

Influence of hydrogen gas addition to methane on the performance of appliances was determined via examination of observable trends in measured values with hydrogen content increase. No statistical analysis was performed due to an insufficient number of replicates. Only patterns of consistent change due to hydrogen gas increase are reported here.

# 3 Results and Discussion

## 3.1 Residential Furnaces

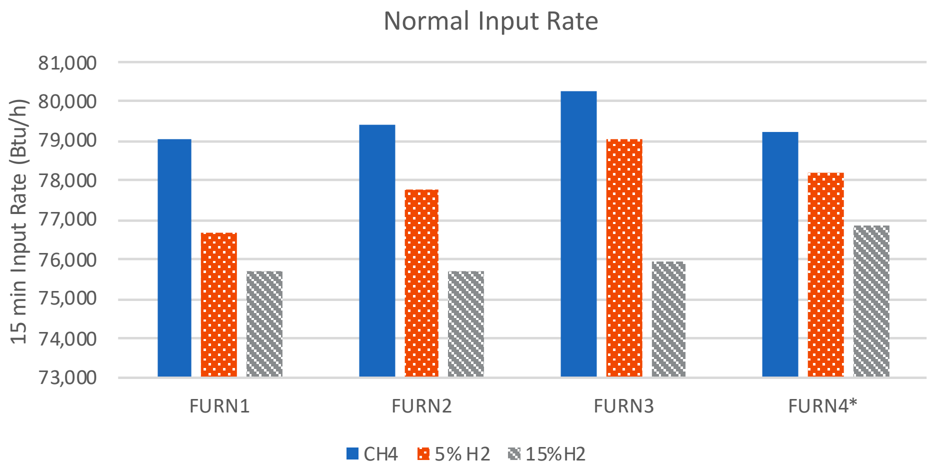
All furnaces passed ignition and BOC performance tests, regardless of the fuel used. Detailed results of performed tests are shown in Appendix B.

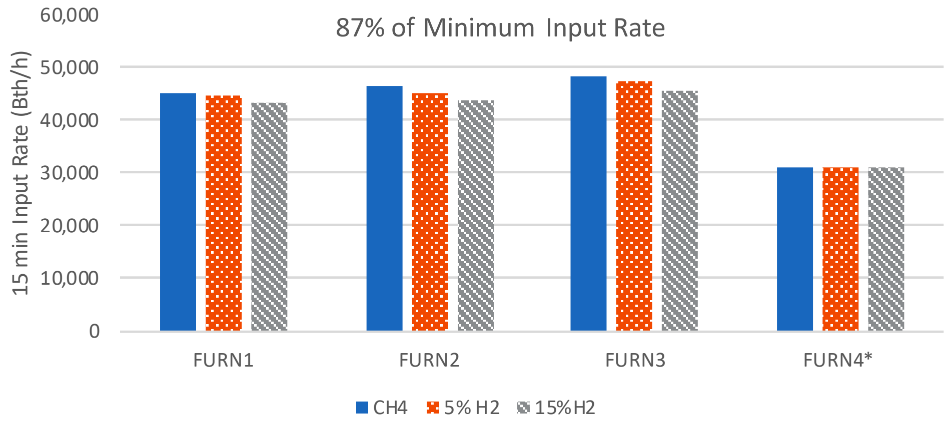
Consistent trends of hydrogen content increase were observed on the 15-minute input rate, $CO_2$ measured amounts, and the heat exchanger tube temperatures.

The most conspicuous effect of hydrogen content increase in gas mixtures on all furnaces was observed on the 15-minute input rate measurements for furnaces operated both at manufacturer-prescribed normal and 87% of minimum input rate at normal external static pressure, as shown in Figure 4. The only exception to this observation was a uniform 15-minute input rate of condensing furnaces operated under 87% minimum input rate. At equal manifold pressures, 5% gas blend-fired furnaces showed approximately 2% and 1.3% lower input rate for normal and 87% minimum input rate, respectively, when compared to the inputs of furnaces fuelled by methane. An additional drop in input rate was observed with the use of 15% gas-blend, displaying an overall decrease of approximately 4% from methane-fuelled furnaces.

**Figure 4:** Influence of Hydrogen Content on Input Rate of Furnaces Measured at Normal Input Rate (Top) and 87% of Minimum Input Rate (Bottom) at Normal External Static Pressures

Note that manifold pressures were set at normal and 87% minimum input rates for natural gas (control). The input rates of the test gases were then measured at these manifold pressures.





Similarly, at equal manifold pressures, changing gas from pure methane to a 5% hydrogen/methane blend lowered $CO_2$ content of combustion gases by 3 to 4% and 15% hydrogen further decreased $CO_2$ content by 10%. There was no apparent difference in $NO_x$ AF and CO AF measured concentrations among the gas blends, recorded in the range of 77–87 ppm and 10–29 ppm, respectively. No consistent change with increase of hydrogen content was seen in these combustion gas levels. Dew point appeared also to be unaffected by hydrogen content in gas mixtures in all furnaces, while the flue loss did not exhibit a consistent change pattern. Differences in temperature rise were also inconsistent with the hydrogen amount increase.

Condensate pH of condensing furnaces was in the range of 3.7–3.8 for all measurements. No leakage of any gas was detected.

At constant manifold pressures, the lowest heat exchanger tube temperatures overall were measured in furnaces fuelled by 15% hydrogen/methane blends and the highest with the use of methane, with a few exceptions at the points closest to the gas entries (A1/D1 and A2/D2, see Figure 3), as shown in Table 4. On average, temperature drop roughly doubled with an increase of hydrogen from 5 to 15% (see average values in Table 4). Measurement of the temperatures at the constant input rates were suggesting the opposite effect, i.e., highest temperatures in the case of 15% hydrogen and lowest in the case of methane, although the trend was not as clear as in the case of constant manifold pressure.

## 3.2 Residential Boilers

All boilers exhibited similar ignition and BOC performance regardless of gas, except the one equipped with a draft hood, when fuelled by 15% hydrogen at inlet test pressure of 3.5 in wc of pressure. This testing condition frequently caused either continuous ignition spark after the flame was lit or loss of flames.

Boilers operated at the same manifold pressure, similar to furnaces, showed a consistent decrease in 15-minute and steady-state input rate with higher amounts of hydrogen. The same was observed for $CO_2$ emissions. See Appendix B for more detail. The introduction of 5% hydrogen caused a decrease in input rate at an average of 1.3% and 15% hydrogen content further decreased input rate to 3.7 to 3.8% for both 15-minute and steady-state input rates. $CO_2$ concentration in flue products decreased 5% and 10% with 5% and 15% hydrogen content, respectively, as was the case for furnaces. CO AF and $NO_x$ AF in condensing boilers also showed a decline with increased hydrogen content (Figure 5), but non-condensing boilers deviated from this trend. The decrease in condensing boiler CO AF emissions was on average 18% and 41% and $NO_x$ AF emissions were 15% and 30%, with the increase to 5% and 15% hydrogen, respectively. The overall measured values of CO AF were in the range of 9–150 ppm and 21–140 ppm for $NO_x$ AF for condensing and non-condensing boilers. Like furnaces, differences in dew point temperatures were comparable. Acidity of condensate was similar across all four units and for all test gases, with the pH value in the range of 2.4–3.0. No leakage of any gas was detected.

## 3.3 Residential Storage Water Heaters

Water heaters also passed ignition and BOC testing regardless of the gases used and similar to furnaces and boilers, showed a decrease in input rates and $CO_2$ emissions with an increase in hydrogen amounts. At 5% hydrogen, the 15-minute and steady-state input rate decreased approximately 1 to 1.8%, and at 15% hydrogen, the 15-minute input rate decreased on average 4% and the steady-state input rate decreased approximately 4.3% when compared to their respective inputs when methane was used (see Appendix B). Also in agreement with furnaces and boilers, $CO_2$ emissions decreased 5% and 11% with the use of 5% and 15% hydrogen/methane blends, respectively. CO AF was in the range of 2–21 ppm and 11–108 ppm for $NO_x$ AF, without any obvious effect of hydrogen amount increases. The same independence was observed for other measured flue properties. No leakage of any gas was detected.

## 3.4 Residential Unvented Space Heaters

Change of test gases did not affect ignition performance and BOC performance was similar for all test gases on both space heaters. However, unvented space heaters exhibited several nonconformities when using methane/hydrogen blend with 15% hydrogen content:

- The blue flame space heater using 15% hydrogen consistently extinguished in less than one hour of continuous operation due to instability of the igniter flame.

- At 123% of high input rate and 15% hydrogen, flame tips of the blue flame unit appeared to reach the top of the porcelainized area, which was not the case when tested with pure methane or 5% hydrogen/methane blend.
- The 15% gas mixture extinguished the flame earlier than for the other test gases for the blue flame space heater when operating the gas valve for lower input.
- The emission test requiring the use of a hood introduced too much dilution air to permit reliable air-free calculations for determining the effect of hydrogen mixtures.

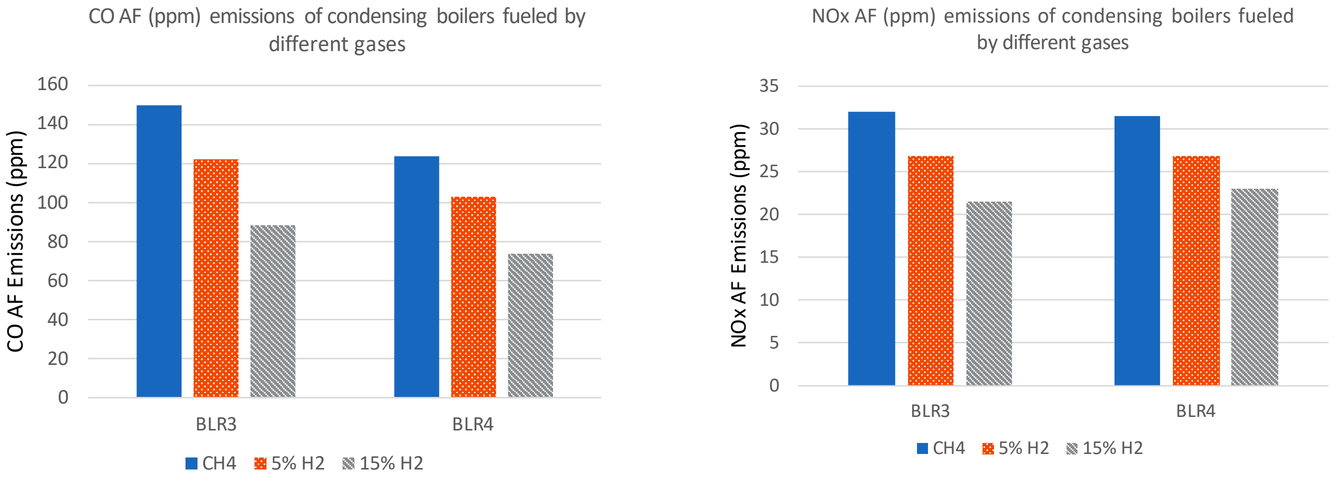
Despite these observations, unvented space heaters also showed a decrease in the 15-minute input rate with an increase in hydrogen gas when tested under the same manifold pressures, with decreases up to

**Table 4:** Average temperatures of four furnace heat exchange tubes taken along several points (tubes A and D temperatures measured at 7 locations; tubes B and C temperatures measured at 3 locations) as affected by gases at constant manifold pressure. The cells with the highest temperature among the three gases, measured at the same point, are shaded in dark gray and cells with the minimum temperature are shown in white

| **Test Gas** | **Input Rate** (Btu/h) | **Thermocouple Locations Temperature** (°F) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Tube A** | | **A1** | **A2** | **A3** | **A4** | **A5** | **A6** | **A7** | **Average** |
| $CH_4$ | 77,730 | 255 | 387 | 389 | 584 | 682 | 394 | 295 | |
| 5% $H_2$ | 75,840 | 260 | 388 | 385 | 571 | 668 | 387 | 292 | |
| 15% $H_2$ | 74,130 | 263 | 387 | 376 | 554 | 649 | 376 | 287 | |
| Temp decrease using 5% $H_2$/methane blend | | | | 1.0% | 2.2% | 2.1% | 1.8% | 1.0% | 1.6% |
| Temp decrease using 15% $H_2$/methane blend | | | | 3.3% | 5.1% | 4.8% | 4.6% | 2.7% | 4.1% |
| **Tube D** | | **D1** | **D2** | **D3** | **D4** | **D5** | **D6** | **D7** | **Average** |
| $CH_4$ | 77,730 | 192 | 421 | 461 | 528 | 689 | 476 | 304 | |
| 5% $H_2$ | 75,840 | 194 | 418 | 451 | 521 | 675 | 467 | 300 | |
| 15% $H_2$ | 74,130 | 201 | 413 | 440 | 514 | 660 | 453 | 293 | |
| Temp decrease using 5% $H_2$/methane blend | | | 0.7% | 2.2% | 1.3% | 2.0% | 1.9% | 1.3% | 1.7% |
| Temp decrease using 15% $H_2$/methane blend | | | 1.9% | 4.6% | 2.7% | 4.2% | 4.8% | 3.6% | 4.0% |

| **Test Gas** | **Input Rate** (Btu/h) | **Thermocouple Locations Temperature** (°F) | | | |
|---|---|---|---|---|---|
| **TUBE B** | | **B1** | **B2** | **B3** | **Average** |
| $CH_4$ | 77,730 | 580 | 755 | 277 | |
| 5% $H_2$ | 75,840 | 555 | 716 | 274 | |
| 15% $H_2$ | 74,130 | 534 | 683 | 269 | |
| Temp decrease using 5% $H_2$/methane blend | | 4.3% | 5.2% | 1.1% | 3.5% |
| Temp decrease using 15% $H_2$/methane blend | | 7.9% | 9.5% | 2.9% | 6.8% |
| **Tube C** | | **C1** | **C2** | **C3** | **Average** |
| $CH_4$ | 77,730 | 542 | 696 | 289 | |
| 5% $H_2$ | 75,840 | 519 | 663 | 287 | |
| 15% $H_2$ | 74,130 | 503 | 641 | 280 | |
| Temp decrease using 5% $H_2$/methane blend | | 4.2% | 4.7% | 0.7% | 3.2% |
| Temp decrease using 15% $H_2$/methane blend | | 7.2% | 7.9% | 3.1% | 6.1% |

**Figure 5:** Change in CO AF and NOx AF Emissions (ppm) of Condensing Boilers (BLR3 and BLR4) with Changes in Hydrogen Content



1.5% using 5% hydrogen/methane blend for blue flame heaters and 5% using 15% hydrogen content blend in infrared heaters. $CO_2$ emissions showed a decreasing trend with increased hydrogen amounts only in the infrared unit, with simultaneous increases in CO AF and $NO_2$ AF concentrations. The overall measured values of CO AF and $NO_2$ AF were in the range of 12–68 ppm and 9–12.5 ppm, respectively. No leakage of any gas was detected. Detailed results of performed tests are shown in Appendix B.

Temperatures measured at various positions of IR burner and metal guard surface temperatures also did not show any consistent difference between the gases.

### 3.5 Gas Leakage in Pipes

Similar to the absence of leakage in appliance manifolds, all of the piping assemblies passed pressure loss or bubble tests, regardless of the test gas and pressures used, or piping type. Therefore, the test results indicate that the addition of hydrogen up to 15% shouldn't introduce a leak concern in indoor piping.

## 4 Discussion and Other Considerations

The results generally demonstrated that the mixtures of methane and hydrogen up to 15% do not present operability challenges and no critical issues were identified for operating appliances tested using CSA/ANSI Z21 standard test protocols. In addition, CO and $NO_x$ emissions of all appliances remained below acceptable levels. The physical properties of the gas blends, such as reduced gas density, did not appear to negatively affect appliance controls or leakage from connected supply tubing. One exception in appliance control operation might be inferred from the inability of one space heater to maintain stable pilot behaviour and presumably going into shutdown by the ODS as a result. This behaviour may represent issues for other pilot ignition and pilot-related safety devices, the latter including atmospheric burner storage water heaters and unvented space heaters, both of which use pilot stability in shutoff safety devices. In unvented space heaters, the safety function shuts off the main burner in response to oxygen depletion and correlated accumulation of CO.

The addition of hydrogen to the gas supply was expected to lower input rates due to a lower hydrogen heating value, but not affect the operation of the system. The results proved the expectations to be valid for all appliances. This measured reduction in input rate consequently led to lower heat output, as indicated by the decreased temperatures of heat exchange tubes when using higher hydrogen fractions. This would suggest that higher amounts of hydrogen-blended gas are required to provide equivalent heat of pure methane and by inference, natural gas. The results also consistently showed a decrease in $CO_2$ emission with

"The addition of hydrogen to the gas supply was expected to lower input rates due to a lower hydrogen heating value, but not affect the operation of the system. The results proved the expectations to be valid for all appliances."

with the increase of hydrogen content across the tested appliances. The observed hydrogen effects of a decreased input rate and postulated increased use of HENG on one hand, and the decreased $CO_2$ emissions on the other hand, naturally raise the question of the levels of $CO_2$ emissions decrease at equivalent rates of heat output.

In an attempt to provide some insight to this question, we further compared the percent decrease in released $CO_2$ to the percent decrease in temperatures of heat exchange tubes of the examined furnace. For the two-stage, non-condensing furnace (FURN1), the 5% hydrogen/methane gas blend yielded a 2.6% $CO_2$ decrease and 2.5% decrease in tube temperatures and the 15% hydrogen/methane blend showed a 9.9% decrease of $CO_2$ and overall 5.2% tube temperature decrease. These extremely simplified comparisons indicate that there are overall potential benefits in using higher hydrogen content gas blends in terms of $CO_2$ emissions versus heat output, but only a full-cycle analysis of hydrogen production and use as a supplement for natural gas, with a detailed examination of the heat output requirements, could give complete insight into the overall advantage of HENG applications.

The insignificant change in CO AF, despite decreased $CO_2$ emissions with the use of hydrogen/methane blends versus methane, was also expected, considering the differences in the ultimate $CO_2$ factor for these two gases. No pattern in $NO_x$ emissions can further be explained by trace amounts of nitrogen in the test gases.

The steady flue loss and dew points across different gases in all appliances can also be explained by insignificant differences in the tested range of gas mixtures to show an effect.

In the residential furnaces tested, the effect on modulating condensing furnaces was expected to push operation modulation into higher input rates and fan speeds to compensate for reduced heating value of the gas mixture. As a practical response to these differences, manifold pressure may need to be adjusted by a service person if HENG blending is stable as received by appliances and equipment to maintain acceptable performance. For some important end-use technologies, adjustment of manifold pressures cannot be performed to respond to these changes.

However, it is important to note that for both the two-stage furnaces and the modulating furnace, only full heating mode (full input) was used for testing so that switching of modes for the two-stage furnace and modulating mode for the modulating furnace were not directly tested or represented in the test results. In the case of the modulating furnace though, the modulating function might be expected to contribute to more precise matching of burner input to fan speed and result in differences in combustion performance. Nevertheless, condensing combustion from differences in combustion product composition might alter flue loss efficiency under the actual operating conditions, which was used as a proxy of rated performance efficiency.

Appliances with adjustments for manifold pressure might be optimized for operation on HENG blends to maintain input and acceptable flame behaviours. However, such adjustments would only be justified if gas supplies to accommodate HENG blends were consistent over time. As a practical matter, adjusting appliance manifold pressures for HENG blends that might revert to more traditional natural gas compositions might result in overfiring and problematic flame behaviours, including overproduction of CO. More modern, non-modulating appliances that do not have adjustable manifold pressures do not raise this concern, but changes in appliance performance from varying gas compositions, such as between HENG blends and traditional natural gases, would need to be anticipated and accounted for in evaluating appliances in the field, such as during combustion efficiency and emissions tests.

It is important to point out that the testing of baseline gas and HENG blends formulated from pure methane provided a measure of consistency across the tests by avoiding the introduction of variability in natural gas compositions that might have influenced results had the baseline gas and HENG blends been formulated from distribution system-supplied natural gas. Additionally, HENG blends used in the testing appear to be within the ranges of applicability of standard natural gas interchangeability criteria such as HHV and Wobbe number limits used in gas supply contracts and tariffs. However, the extension of these criteria to higher percentages of hydrogen may be unjustified, just as extrapolation of these test results to these higher percentages would be unjustified.

Common diluents of natural gas including nitrogen and higher order hydrocarbons such as ethane and propane may have produced different results since these potential natural gas constituents alter gross properties of natural gas such as HHV and Wobbe number. Since HENG might be inconsistently provided to end use appliances due to differences in blending practices and pipeline network delivery, adjustment of appliances to a HENG may not be a practical alternative since the delivered gases (HENG and conventional natural gases) may be highly transient in composition. As a consequence, future testing of even the HENG blend rate of hydrogen (5% and 15%) ought to incorporate more realistic natural gases to determine more representative results.

# 5 Conclusions

The significance of this study is in addressing the question of whether hydrogen gas blends of up to 15% would affect the operability of space and water-heating appliances in the context of North American standards. Testing demonstrated a consistent decrease in $CO_2$ emissions and heat outputs. No other obvious trends were noted in regard to other behaviours. The study indicated the need for continued examination of the use of hydrogen with natural gas and possible increased amounts of gas mixtures to achieve the same heat demands. Further validation of the results would require a larger sample size, other types and capacities of appliances, and additional test conditions.

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# Appendix A: Tested Appliances Specifications

## Residential Furnaces

**Table A1:** Specifications of Tested Residential Furnaces

| | FURN1 | FURN2 | FURN3 | FURN4 |
|---|---|---|---|---|
| **Combustion control** | 2-stage | 2-stage | 2-stage | Modulating |
| **Heat exchanger** | Non-condensing | Non-condensing | Condensing | Condensing |
| **Venting type** | Induced draft | Induced draft | Induced draft | Forced draft |
| **Ignition type** | Electric | Electric | Electric | Electric |
| **Gas manifold pressure (in wc)** | 3.5 | 3.5 | 3.5 | 3.5 |
| **Max input rate (Btu/h)** | 80,000 | 80,000 | 80,000 | 80,000 |
| **Temp rise range (°F)** | 30–60 | 30–60 | 45–75 | 40–70 |
| **Min static pressure** | 0.15 | 0.15 | 0.2 | 0.2 |
| **Max static pressure** | 0.5 | 0.5 | 0.5 | 0.5 |
| **Min input rate (Btu/h)** | 52,000 | 52,000 | 56,000 | 28,000 |
| **Temp rise range (°F)** | 20-50 | 20-50 | 20-50 | 20-50 |
| **Annual Fuel Utilization Efficiency (AFUE)** | 80% | 80% | 96% | 97.5% |

## Residential Boilers

**Table A2:** Specifications of Tested Residential Boilers

| | BLR1 | BLR2 | BLR3 | BLR4 |
|---|---|---|---|---|
| **Combustion control** | 1-stage | 1-stage | Modulating | Modulating |
| **Heat exchanger** | Non-condensing | Non-condensing | Condensing | Condensing |
| **Venting type** | Draft hood | Vent damper | Direct vent | Direct vent |
| **Ignition type** | Electric spark to pilot | Electric | Electric | Electric |
| **Gas manifold pressure (in wc)** | 3.5 | 4 | Not applicable | Not applicable |
| **Max input rate (Btu/h)** | 96,000 | 100,000 | 100,000 | 120,000 |
| **Min input rate (Btu/h)** | Not applicable | Not applicable | 10,000 | 13,200 |
| **Annual Fuel Utilization Efficiency (AFUE)** | 82% | 85% | 95% | 95% |

## Residential Water Heaters

**Table A3:** Specifications of Tested Residential Water Heaters

| | WH1 | WH2 |
|---|---|---|
| **Combustion control** | 1-stage | 1-stage |
| **Heat exchanger** | Non-condensing | Non-condensing |
| **Venting type** | Power | Draft hood |
| **Ignition type** | Electric | Electric |
| **Gas manifold pressure (in wc)** | 4 | 5 |
| **Max input rate (Btu/h)** | 40,000 | 40,000 |
| **Min input rate (Btu/h)** | Not applicable | Not applicable |
| **Tank capacity** | 50 gallon | 40 gallon |
| **Amount of heated water produced per hour (Recovery)** | 37.8 gallon | 43.1 gallon |
| **Other description** | Energy star | Ultra-low NOx |

## Residential Unvented Space Heaters

**Table A4:** Specifications of Tested Unvented Space Heaters

| | SP1 | SP2 |
|---|---|---|
| **Combustion control** | Manual gas valve | Manual gas valve |
| **Heat exchanger** | Not applicable | Not applicable |
| **Burner type** | Blue Flame – no electric | Infrared – no electric |
| **Venting type** | Unvented | Unvented |
| **Ignition type** | Pilot ignition | Pilot ignition |
| **Gas manifold pressure (in wc)** | 3.5 | 6.0 |
| **Max input rate (Btu/h)** | 30,000 | 30,000 |
| **Min input rate (Btu/h)** | 8,500 | 8,000 |

# Appendix B: Detailed Results

## Residential Furnaces

**Table B1:** Input Rate of Residential Furnaces Measured at Normal and 87% of Minimum Input Rate Under Normal External Static Pressure

| | | Normal Input Rate | | | 87% of Minimum Input Rate | | |
|---|---|---|---|---|---|---|---|
| | **Test Gas** | **Manifold Pressure** (in wc) | **15-min Input Rate** (Btu/h) | **Temp Rise** (°F) | **Manifold Pressure** (in wc) | **15-min Input Rate** (Btu/h) | **Temp Rise** (°F) |
| **FURN1** | $CH_4$ | 3.8 | 79,050 | 42.0 | 1.3 | 44,920 | 28.1 |
| | 5% $H_2$ | 3.8 | 76,670 | 39.6 | 1.3 | 44,580 | 27.6 |
| | 15% $H_2$ | 3.8 | 75,730 | 39.2 | 1.3 | 43,360 | 25.3 |
| **FURN2** | $CH_4$ | 3.9 | 79,420 | 42.7 | 1.4 | 46,450 | 34.4 |
| | 5% $H_2$ | 3.9 | 77,760 | 42.7 | 1.4 | 44,890 | 32.8 |
| | 15% $H_2$ | 3.9 | 75,710 | 43.6 | 1.4 | 43,470 | 32.2 |
| **FURN3** | $CH_4$ | 3.7 | 80,290 | 59.9 | 1.4 | 48,010 | 47.2 |
| | 5% $H_2$ | 3.7 | 79,030 | 58.8 | 1.4 | 47,510 | 46.5 |
| | 15% $H_2$ | 3.7 | 75,920 | 56.7 | 1.4 | 45,600 | 45.0 |
| **FURN4*** | $CH_4$ | 3.9 | 79,220 | 58.1 | 0.65 | 30,920 | 44.7 |
| | 5% $H_2$ | 3.9 | 78,210 | 59.2 | 0.65 | 30,920 | 45.0 |
| | 15% $H_2$ | 3.9 | 76,880 | 59.2 | 0.65 | 31,050 | 44.6 |

***FURN4 is a modulating furnace. Internal control function maintains temperature rise with changes in input rate.**

**Table B2:** Combustion Gas Properties of Residential Furnaces Under High Input Rate

| **Furnace** | **Test Gas** | **$CO_2$%** | **CO AF** (ppm) | **Flue Temp** (°F) | **Flue Loss** (%) | **Dew Point** (°F) | **Condensate pH** | **$NO_x$ AF at Steady-state** (ppm) |
|---|---|---|---|---|---|---|---|---|
| **FURN1** | $CH_4$ | 4.55 | 24 | 336.8 | 21.9 | 110.4 | NA | 79.1 |
| | 5% $H_2$ | 4.43 | 23 | 331.0 | 21.9 | 110.3 | NA | 77.8 |
| | 15% $H_2$ | 4.10 | 25 | 328.1 | 22.4 | 109.4 | NA | 80.6 |
| **FURN2** | $CH_4$ | 7.48 | 28 | 400.2 | 19.6 | 125.1 | NA | 80.5 |
| | 5% $H_2$ | 7.26 | 24 | 394.7 | 19.6 | 124.8 | NA | 80.4 |
| | 15% $H_2$ | 6.76 | 20 | 385.4 | 19.9 | 124.2 | NA | 78.9 |
| **FURN3** | $CH_4$ | 8.47 | 18 | 104.6 | 4.2 | 128.5 | 3.83 | 84.8 |
| | 5% $H_2$ | 8.16 | 17 | 104.4 | 4.2 | 128.1 | 3.67 | 86.0 |
| | 15% $H_2$ | 7.64 | 10 | 103.2 | 4.0 | 127.9 | 3.63 | 80.9 |
| **FURN4** | $CH_4$ | 8.12 | 25 | 104.9 | 4.8 | 126.4 | 3.73 | 77.3 |
| | 5% $H_2$ | 7.77 | 29 | 104.3 | 4.6 | 126.6 | 3.73 | 87.4 |
| | 15% $H_2$ | 7.32 | 20 | 104.3 | 4.8 | 126.4 | 3.73 | 84.5 |

**NA – not applicable.**

## Residential Boilers

**Table B3:** Input Rates of Residential Boilers Measured at High Manifold Pressures

| | **Test Gas** | **Manifold Pressure** (in wc) | **15-min Input Rate** (Btu/h) | **Steady-state Input Rate** (Btu/h) |
|---|---|---|---|---|
| **BLR1** | $CH_4$ | 3.7 | 95,100 | 95,200 |
| | 5% $H_2$ | 3.7 | 92,920 | 92,950 |
| | 15% $H_2$ | 3.7 | 90,490 | 90,200 |
| **BLR2** | $CH_4$ | 4.5 | 99,560 | 99,890 |
| | 5% $H_2$ | 4.5 | 98,150 | 98,080 |
| | 15% $H_2$ | 4.5 | 96,630 | 96,267 |
| **BLR3** | $CH_4$ | NA | 96,010 | 93,720 |
| | 5% $H_2$ | NA | 95,710 | 94,160 |
| | 15% $H_2$ | NA | 92,020 | 91,000 |
| **BLR4** | $CH_4$ | NA | 116,100 | 117,300 |
| | 5% $H_2$ | NA | 114,700 | 116,500 |
| | 15% $H_2$ | NA | 112,600 | 113,200 |

**NA – not applicable.**

**Table B4:** Combustion Gas Properties of Tested Residential Boilers at High Input Rate

| **Boiler** | **Test Gas** | **$CO_2$%** | **CO AF** (ppm) | **Flue Temp** (°F) | **Flue Loss** (%) | **Dew Point** (°F) | **Condensate pH** | **$NO_x$ AF at Steady-state** (ppm) |
|---|---|---|---|---|---|---|---|---|
| **BLR1** | $CH_4$ | 4.20 | 17 | 269 | 19.6 | 107.9 | NA | 137.3 |
| | 5% $H_2$ | 3.74 | 9 | 269 | 20.6 | 105.3 | NA | 130.9 |
| | 15% $H_2$ | 3.45 | 10 | 266 | 21.1 | 104.6 | NA | 132.0 |
| **BLR2** | $CH_4$ | 5.33 | 70 | 243 | 16.8 | 115.0 | NA | 115.5 |
| | 5% $H_2$ | 5.15 | 79 | 236.5 | 16.7 | 114.7 | NA | 117.0 |
| | 15% $H_2$ | 4.79 | 35 | 237.7 | 17.1 | 114.6 | NA | 108.3 |
| **BLR3** | $CH_4$ | 9.00 | 150 | 126.7 | 8.1 | 130.6 | 2.56 | 32.1 |
| | 5% $H_2$ | 8.76 | 122 | 126.9 | 8.4 | 130.6 | 2.53 | 26.9 |
| | 15% $H_2$ | 8.26 | 88 | 128 | 9.2 | 130.6 | 2.40 | 21.5 |
| **BLR4** | $CH_4$ | 9.15 | 124 | 122.3 | 5.9 | 131.0 | 2.73 | 31.5 |
| | 5% $H_2$ | 8.89 | 103 | 121.6 | 5.9 | 130.9 | 2.93 | 26.9 |
| | 15% $H_2$ | 8.58 | 74 | 122.8 | 6.4 | 132.0 | 3.00 | 23.0 |

**NA – not applicable.**

## Residential Water Heaters

**Table B5:** Input Rates of Residential Water Heaters at High Manifold Pressures

| | Test Gas | Manifold Pressure (in wc) | 15-min Input Rate (Btu/h) | Steady-state Input Rate (Btu/h) |
|---|---|---|---|---|
| **WH1** | $CH_4$ | 4.5 | 39,900 | 39,600 |
| | 5% $H_2$ | 4.5 | 39,500 | 39,200 |
| | 15% $H_2$ | 4.5 | 38,100 | 37,800 |
| **WH2** | $CH_4$ | 4.5 | 39,600 | 39,700 |
| | 5% $H_2$ | 4.5 | 38,900 | 39,000 |
| | 15% $H_2$ | 4.5 | 38,200 | 38,100 |

**Table B6:** Combustion Gas Properties of Tested Residential Water Heaters Under High Input Rate

| | Test Gas | $CO_2$% | CO AF (ppm) | Flue Temp (°F) | Flue Loss (%) | Dew Point (°F) | Condensate pH | NOx AF at Steady-state (ppm) |
|---|---|---|---|---|---|---|---|---|
| **WH1** | $CH_4$ | 1.91 | 8 | 161.2 | 19.3 | 85.6 | NA | 107.3 |
| | 5% $H_2$ | 1.82 | 2 | 160.0 | 19.6 | 84.3 | NA | 108.2 |
| | 15% $H_2$ | 1.80 | 8 | 160.3 | 19.6 | 86.3 | NA | 103.8 |
| **WH2** | $CH_4$ | 5.77 | 12 | 314.0 | 18.9 | 117.3 | NA | 16.45 |
| | 5% $H_2$ | 5.44 | 21 | 315.5 | 19.4 | 115.9 | NA | 14.8 |
| | 15% $H_2$ | 5.00 | 16 | 311.0 | 19.8 | 114.7 | NA | 11.05 |

**NA – not applicable.**
**Note: $CO_2$ levels of WH1 measured in the combustion gas were mixed with dilution air drawn into the vent from outside the water heater.**

## Residential Unvented Space Heaters

**Table B7:** Input Rates of Residential Unvented Space Heaters Measured at High Input rates

| | Test Gas | Manifold Pressure (in wc) | 15-min Input Rate (Btu/h) |
|---|---|---|---|
| **SP1** | $CH_4$ | 3.5 | 29,930 |
| | 5% $H_2$ | 3.5 | 29,490 |
| | 15% $H_2$ | 3.8 | 29,800 |
| **SP2** | $CH_4$ | 6.2 | 29,400 |
| | 5% $H_2$ | 6.2 | 29,260 |
| | 15% $H_2$ | 6.2 | 27,890 |

**Table B8:** Combustion Gas Properties of Tested Residential Unvented Space Heaters

| | Test Gas | $CO_2$% | CO AF (ppm) | $NO_2$ AF (ppm) |
|---|---|---|---|---|
| **SP1** | $CH_4$ | 0.94 | 12 | 10.3 |
| | 5% $H_2$ | 1.04 | 56 | 11.4 |
| | 15% $H_2$ | 1.02 | 33 | 8.8 |
| **SP2** | $CH_4$ | 1.08 | 65 | 10.2 |
| | 5% $H_2$ | 0.88 | 66 | 10.6 |
| | 15% $H_2$ | 0.83 | 68 | 12.5 |

**Table B9:** Metal Guard High Temperature (°F) of Tested Blue Flame Residential Unvented Space Heaters at Various Positions

| Test Gas | Position | Left | Middle | Right |
|---|---|---|---|---|
| **$CH_4$** | Top | 187 | 265 | 175 |
| | Bottom | 112 | 181 | 116 |
| **5% $H_2$** | Top | 206 | 380 | 184 |
| | Bottom | 126 | 149 | 136 |
| **15% $H_2$*** | | - | - | - |

***Main and pilot flame extinguished after 30 minutes; therefore, test not completed.**

**Table B10:** Metal Guard High Temperature (°F) of Tested Infrared Residential Unvented Space Heaters at Various Positions

| Test Gas | Position | Left | Middle | Right |
|---|---|---|---|---|
| **$CH_4$** | Top | 180 | 340 | 187 |
| | Middle | 191 | 306 | 182 |
| | Low | 195 | 320 | 187 |
| **5% $H_2$** | Top | 200 | 319 | 190 |
| | Middle | 188 | 316 | 201 |
| | Low | 176 | 357 | 185 |
| **15% $H_2$** | Top | 199 | 371 | 195 |
| | Middle | 201 | 327 | 193 |
| | Low | 194 | 312 | 192 |

**Table B11:** Infrared Burner Surface High Temperature (°F) of Tested Infrared Residential Unvented Space Heaters at Various Positions

| Test Gas | Positions Along the Width of the Space Heaters at Equal Distances from Left to Right | | | | |
|---|---|---|---|---|---|
| **$CH_4$** | 1120 | 1180 | 1195 | 1165 | 1120 |
| **5% $H_2$** | 1100 | 1121 | 1131 | 1114 | 1047 |
| **15% $H_2$** | 1023 | 1110 | 1200 | 1130 | 1060 |

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