20) Correctly complete the following statement with the appropriate word provided:
_________are the upper and lower ranges of gas in the air-gas mixture that supports combustion.
    a) Limits of flammability
    b) Flammability range
    c) Flame temperatures

2. Combustion

Overview

Purpose

The gas technician/fitter must ensure safe and controlled combustion is occurring in an appliance's combustion zone. The technician's/fitter's understanding of the combustion process and the chemical reactions involved are the basis for much of the installation and service work they will perform in the gas industry.

Objectives

At the end of this Chapter, you will be able to:

- explain the requirements of combustion;
- describe the differences between complete and incomplete combustion;
- describe air supply requirements;
- describe causes of incomplete combustion; and
- describe characteristics and requirements of a stable flame.

Terminology

Term	Abbreviation (symbol)	Definition
Combustion		A chemical process in which the rapid oxidation of fuel results in the production of energy (heat)
Combustion air		The air for the satisfactory combustion of a gas
Complete combustion		All fuel is completely burned, and no harmful products of incomplete combustion are produced
Dilution air		The ambient air that is admitted to a venting system at the draft control device of the appliance

14) What is the specific gravity of liquid propane?
   a) 0.58
   b) 1.54
   c) 7.6
   d) 0.51

15) Correctly complete the following statement with the appropriate word provided:
   At atmospheric pressure, propane gas expands at the ratio of _______ when changing from a liquid to a gas.
   a) 1:270
   b) 1:300
   c) 1:600
   d) 1:670

16) What is the flame speed (inches/s) of natural gas?
   a) 11
   b) 10
   c) 12
   d) 9

17) What is the limit of flammability (%) for propane?
   a) 4–15
   b) 2.4–9.5
   c) 3.5–8.5
   d) 3–12

18) What is the maximum flame temperature in °F (and °C) for propane and natural gas?
   a) 2 600°F (1 430 °C)
   b) 1 600°F (870 °C)
   c) 3 600°F (1 980 °C)
   d) 4 600°F (2 540 °C)

19) Correctly complete the following statement with the appropriate word provided:
   ______________ is the temperature at which an air-gas mixture initiates and supports combustion. It varies according to the fuel gas used.
   a) Flame temperature
   b) Limits of flammability
   c) Ignition temperature

Term	Abbreviation (symbol)	Definition
Excess air		The air supplied to the combustion zone in excess of the required air for perfect combustion
Ventilation air		Air that is admitted to a space containing an appliance to replace air exhausted through a ventilation opening or by means of exfiltration
Flue gas condensation		Process that involves the cooling of flue gas below its water dew point and the recovery of heat released from the resulting condensation as low temperature heat
Incomplete combustion		The lack of oxygen to burn the fuel gas completely
Parts per million	ppm	Measurement of one part per 1 000 000 (10^6)
Perfect or stoichiometric combustion		Theoretical (or mathematically exact) volume of air that you must mix with fuel gas to achieve perfect combustion
Pounds per square inch absolute	psia	Pressure resulting from a force of one pound-force applied to an area of one square inch; pressure is relative to a vacuum rather than the ambient atmospheric pressure

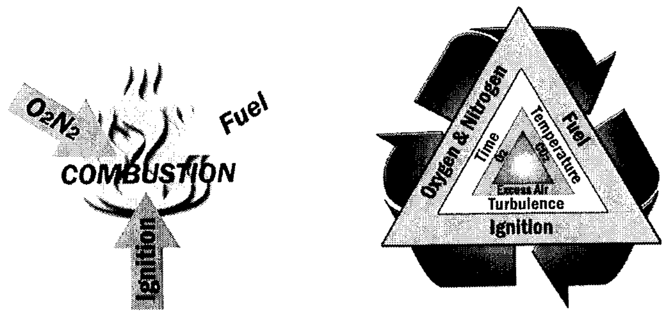
Requirements of combustion

Combustion is a chemical process in which the rapid oxidation of fuel results in the production of energy (heat). To start and sustain combustion, you must have three ingredients mixed together in the correct proportions:

- fuel, usually natural gas or liquid petroleum gases;
- oxygen, obtained from the air surrounding a burner;
- heat, enough to bring the fuel to ignition point; and
- uninhibited Chemical Chain Reaction.

If any one of these elements is absent, combustion will not take place nor will it support itself after an element is removed. This three-way relationship is commonly referred to as the combustion triangle (Figure 2-1).

Figure 2-1
The combustion triangle and advanced combustion triangle



Content on the combustion triangle and the advanced combustion triangle is excerpted from the "Combustion Analysis and Fuel Efficiency" manual courtesy of ESCO Group. For a more thorough understanding of combustion analysis, visit www.escogroup.org.

You can think of the combustion process as a living entity—it requires air to breathe, fuel as sustenance, and heat to create movement. Without one of the three, combustion ceases to exist.

The combustion triangle introduces the three basic elements required for combustion: air (O_2 and N_2), fuel (natural gas, propane), and ignition (heat). The advanced combustion triangle introduces six additional elements that aid the technician/fitter in understanding and controlling combustion, time, temperature, turbulence, oxygen, carbon dioxide, and excess air. The nine elements of the advanced combustion triangle are all related to the understanding of combustion and combustion control.

Nitrogen introduced into the combustion system is an inert gas, in that it doesn't chemically react in the combustion process. Nitrogen does absorb heat, increase flue gas volume and, at high flame temperatures, has a thermal fixation for oxygen, binding to oxygen to form nitric oxide and nitrogen dioxide commonly referred to as NO_x gasses. NO_x gases are toxic, and concentrations of 15 ppm are immediately dangerous to life and health.

> The book *Combustion Analysis & Fuel Efficiency* contains additional information on the advanced combustion triangle and combustion control.[1]

Element	Description
Fuel	Natural gas, propane, and butane are hydrocarbon fuels burned in a gaseous state.
Heat/ignition	Igniting the air gas mixture requires the supply of enough heat by a previously lit small flame such as a pilot, an ignition spark, or a hot surface igniter. Once you have provided this initial heat, the heat released from the combustion process sustains itself. Ignition temperatures vary according to the type of gas used, as Table 2-1 shows.
Oxygen	For the combustion process to consume oxygen, it must be readily available. Generally, the required oxygen supply comes from the air. Because air contains only 20% oxygen and 80% nitrogen, we must supply a much larger

Element	Description
	volume of air than the combustion process would require if the supply were pure oxygen.
Temperature	Temperature of combustion is important for efficiency and combustion control. The better the air fuel mixture, the more time the flame is given to burn, and the hotter the flame temperature. The increased flame temperature increases the radiant heat transfer to the heat exchanger.
Time	Time is an important variable for combustion control. Time relates to the air fuel mixture and how long the flame is given to burn. Time relates to temperature.
Turbulence	Turbulence relates to the air fuel mixture, flame temperature, and heat transfer. Time, temperature, and turbulence all relate to oxygen, carbon dioxide, and excess air, in that better mixing of air and fuel reduces the amount of excess air required for complete combustion. The decrease in excess air increases flame temperature and increases the percentage of carbon dioxide in the products of combustion. The decrease in excess air reduces the volume of oxygen remaining after combustion.

Table 2-1
Ignition temperatures of natural gas and propane

Gas	Chemical designation	Ignition temperature
Natural gas	CH_4	1 300°F (700 °C)
Propane	C_3H_8	920°F (495 °C)

The chemistry of combustion

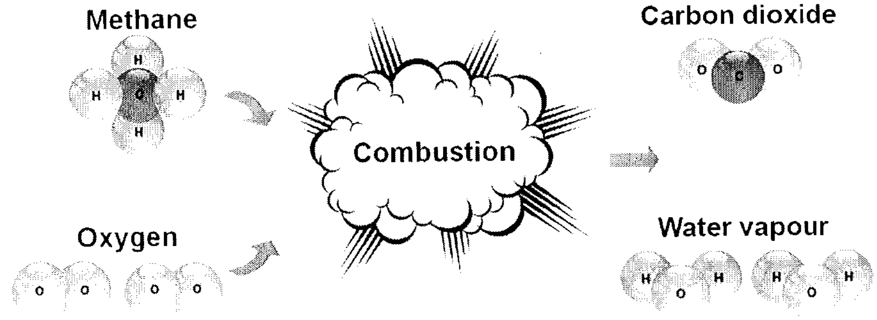
The chemistry of combustion is the reaction which takes place between fuel gas and oxygen when heated to ignition temperature. Mixing the elements of hydrocarbons with enough oxygen to support combustion leads to the formation of carbon dioxide (CO_2), water vapour (H_2O), and heat as the products of combustion.

The chemical formula expressing the combustion reaction for natural gas and oxygen is:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{heat}$$

Figure 2-2 illustrates the chemical combustion of natural gas (methane) and oxygen.

Figure 2-2
Combustion of methane and oxygen



The chemical formula describing the combustion reaction for propane and oxygen is:

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O + \text{heat}$$

Differences between complete and incomplete combustion

This section describes the following three types of combustion, each determined by the initial air supply:

- perfect or stoichiometric combustion;
- complete combustion; and
- incomplete combustion.

Perfect or stoichiometric combustion

Perfect or *stoichiometric combustion* refers to the theoretical (or mathematically exact) volume of air that you must mix with fuel gas to achieve perfect combustion. This gas-air mixture is often called the *ideal combustion ratio*.

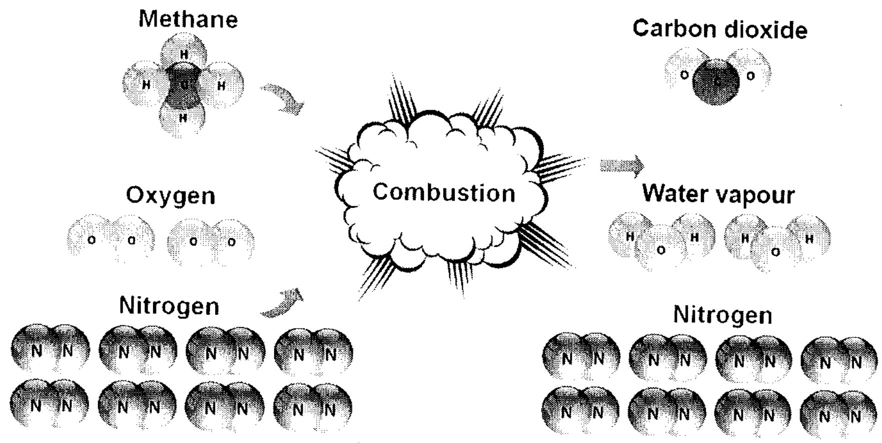
The formula for perfect combustion is used for theoretical calculations only. This is because most gas burners cannot mathematically mix exact gas and air volumes together to produce satisfactory combustion. In practice, some of the hydrogen and carbon produced will combine with oxygen, so *incomplete combustion* will occur.

Because air is 20% oxygen (O_2) and 80% nitrogen (N_2), nitrogen is included in the perfect combustion equation for natural gas. In the following formula for perfect combustion, there are 8 parts of nitrogen to two parts of oxygen. Note that nitrogen is inert and doesn't chemically react in the combustion process. As previously mentioned, nitrogen at high flame temperatures has a thermal fixation for oxygen.

$$CH_4 + 2O_2 + 8N_2 \rightarrow CO_2 + 2H_2O + 8N_2 + \text{heat}$$

Figure 2-3 illustrates the formula.

Figure 2-3
Perfect combustion of methane and air



For propane, the perfect combustion equation is

$$C_3H_8 + 5O_2 + 20N_2 \rightarrow 3CO_2 + 4H_2O + 20N_2 + \text{heat}$$

Complete combustion

Since perfect combustion is only possible in theory, you must adjust the equipment to ensure complete burning of all fuel and prevent the production of harmful products from incomplete combustion. This process is complete combustion.

Normally, to achieve complete combustion, technicians/fitters supply more air to the combustion process than perfect combustion requires to ensure that all atoms of carbon and hydrogen unite with enough atoms of oxygen to produce complete combustion.

Below is the complete combustion formula:

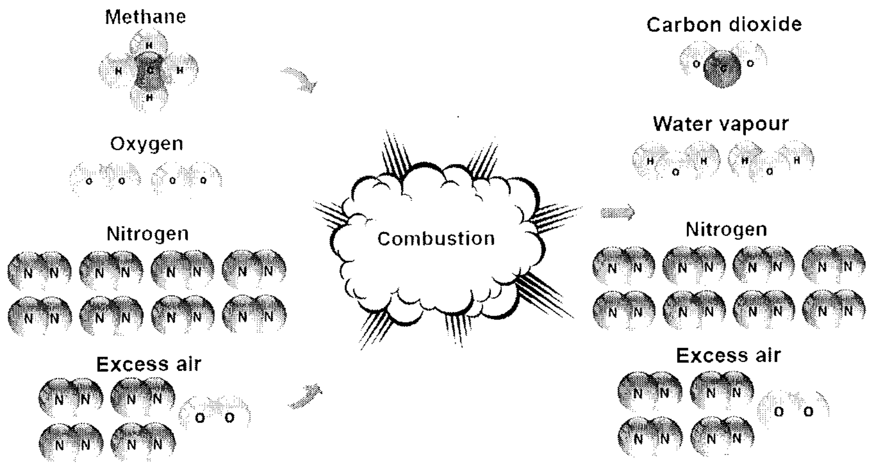
$$CH_4 + 2O_2 + 8N_2 + \text{excess air} \rightarrow CO_2 + 2H_2O + 8N_2 + \text{excess air} + \text{heat}$$

Figure 2-4 illustrates this formula.

For propane, the complete combustion formula is:

$$C_3H_8 + 5O_2 + 20N_2 + \text{excess air} \rightarrow 3CO_2 + 4H_2O + 20N_2 + \text{excess air} + \text{heat}$$

Figure 2-4
Complete combustion of methane and air



Incomplete combustion

Where there is not enough oxygen to burn the fuel gas completely, some of the fuel will not unite with its oxygen counterpart and will leave unburned fuel in the flue gas. The unburned fuel will contain carbon, hydrogen, carbon monoxide, and complex chains of alcohols called aldehydes.

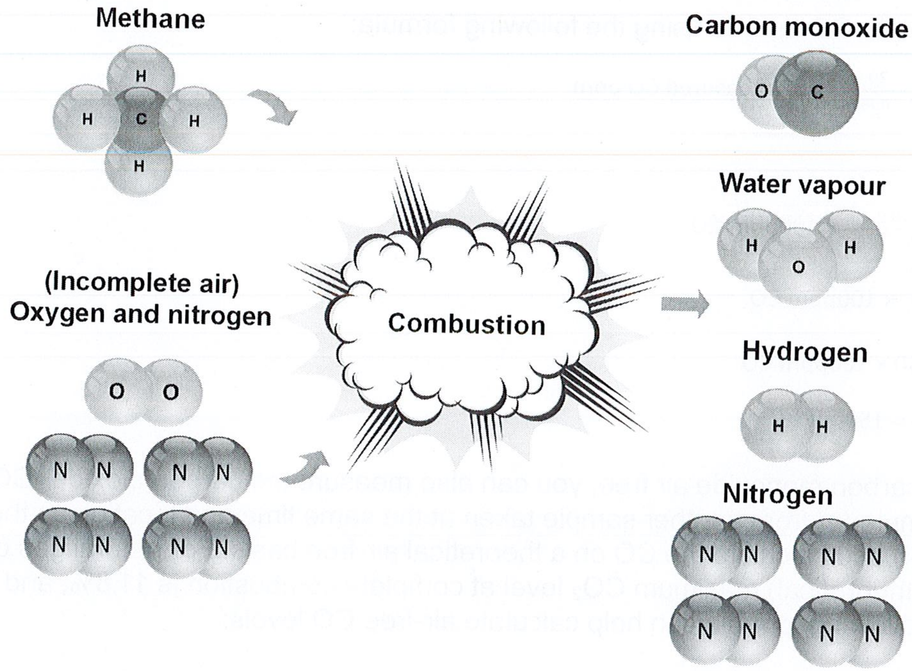
The flue gas products of incomplete combustion (particularly carbon monoxide and hydrogen) are often grouped together as combustibles. Carbon monoxide and aldehydes in any quantity are toxic and life threatening.

The following formula illustrates an example of a chemical reaction that results from the lack of air in the natural gas combustion formula. The result is incomplete combustion.

$$CH_4 + 1O_2 + 4N_2 \rightarrow CO + H_2O + H + 4N_2 + heat$$

Figure 2-5 illustrates the formula.

Figure 2-5
Incomplete combustion that has formed carbon monoxide



The following formula illustrates an example of a chemical reaction that results from the lack of air in the propane combustion formula. The result is incomplete combustion.

$$C_3H_8 + 4O_2 + 16N_2 \rightarrow CO + H_2O + H + 16N_2 + heat$$

Products of incomplete combustion

Product	Description
Carbon monoxide	Carbon monoxide is one of the most harmful products of incomplete combustion. It is toxic (i.e., it can cause death if enough is inhaled). Since it has no odour, taste, or smell, it is hard to detect without proper equipment. In higher concentrations, it is combustible.
Aldehydes	Aldehydes are a group of transparent, colourless gases with a suffocating smell, produced by the partial oxidation of fuel gas. Because of this, they are easily detected. They are toxic and irritating to the eyes, throat, and nose.

Other factors besides insufficient air can cause incomplete combustion. The *Causes of Incomplete Combustion* section describes these in more detail.

Measurement

Measured carbon monoxide levels can vary greatly depending on where they are taken. For example, measurements taken upstream of the draft hood diverter on a water heater will render higher CO levels than downstream of the draft hood, where the sample will be diluted with room air entering the draft hood relief opening. One way to compensate is to express the CO measurement on an air-free basis.

You can calculate CO air free using the following formula:

$$\text{CO air free} = \frac{20.9}{20.9 - fluegas\%O_2} \times \text{measured CO ppm}$$

Example:

$$\text{CO air free} = \frac{20.9}{20.9 - 7\%O_2} \times 100\text{ppm CO}$$

$$\text{CO air free} = \frac{20.9}{13.9} \times 100\text{ppm CO}$$

$$\text{CO air free} = 1.50 \times 100\text{ppm CO}$$

$$\text{CO air free ppm} = 150$$

To calculate carbon monoxide air free, you can also measure the carbon dioxide (CO_2) level from the same sample (or from another sample taken at the same time and location as the CO measurement) and calculate the CO on a theoretical air-free basis. For natural gas combustion, the ultimate (theoretical) maximum CO_2 level at complete combustion is 11.8%, and for propane, 13.8%. The following formula can help calculate air-free CO levels:

$$\text{CO (air-free)} = \frac{\text{CO}\left(\text{air free}\right) = \frac{\text{CO (measured)} \times CO_2\text{ (measured)}}{CO_2\text{ (measured)}}\ CO_2\text{ (ultimate)}}{CO_2\text{ (measured)}}$$

where:

CO (air-free) =	carbon monoxide expressed on an air-free basis, parts per million (ppm)
CO (measured) =	carbon monoxide measured (ppm)
CO_2 (ultimate) =	the ultimate (theoretical) maximum carbon dioxide level at complete combustion (%) – for natural gas, CO_2 (ultimate) = 11.8% – or propane, CO_2 (ultimate) = 13.8%
CO_2 (measured) =	the actual carbon dioxide level measured (%)

Air supply requirements

The efficient and safe operation of gas-fired appliances relies on an adequate supply of air. For present purposes, we divide our air supply into three main categories:

- combustion air (theoretical);
- excess air; and
- dilution air.

Combustion air

Combustion air is the air required for the satisfactory combustion of a gas. Normally, combustion air includes excess air, but here, combustion air will refer to the theoretical air discussed earlier in perfect combustion.

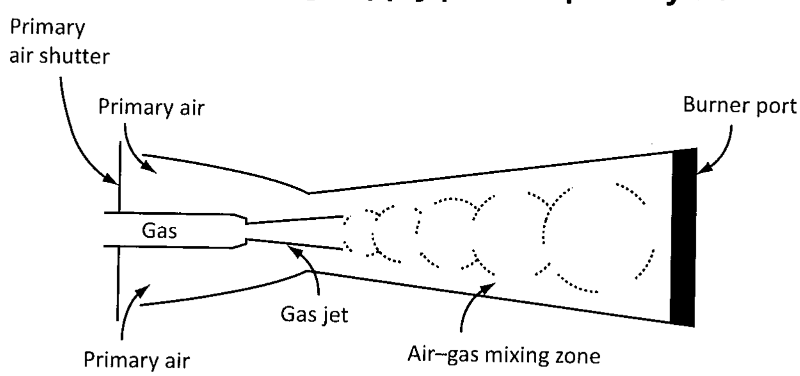
You can further classify combustion air into two:

- primary air; and
- secondary air.

Primary air

Primary air refers to the combustion air that is mixed with fuel gas before ignition (Figure 2-6). The amount of primary air is normally considered to be one-third of the theoretical amount of air used for combustion.

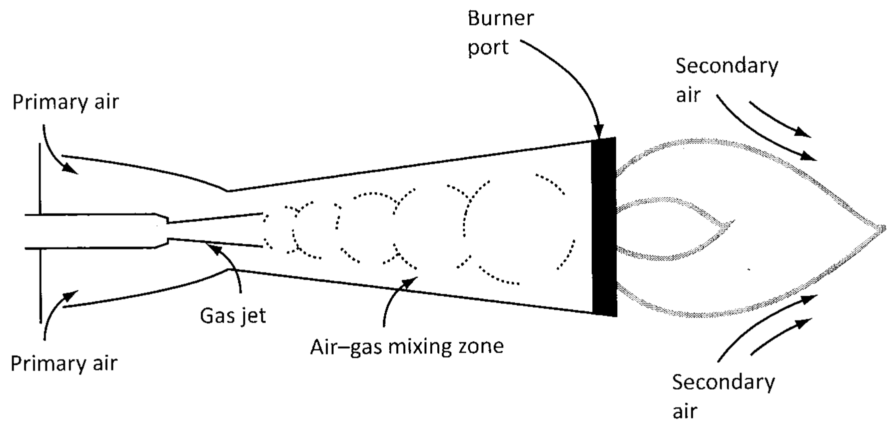
Figure 2-6
Burner showing supply point of primary air



Secondary air

The secondary air required to complete the combustion of the gas is mixed with the fuel at the point of combustion. Secondary air is supplied from around the flames (Figure 2-7) and is generally considered to be two-thirds of the theoretical air considered for perfect combustion.

Figure 2-7
Supply to burner of primary and secondary air around the flame

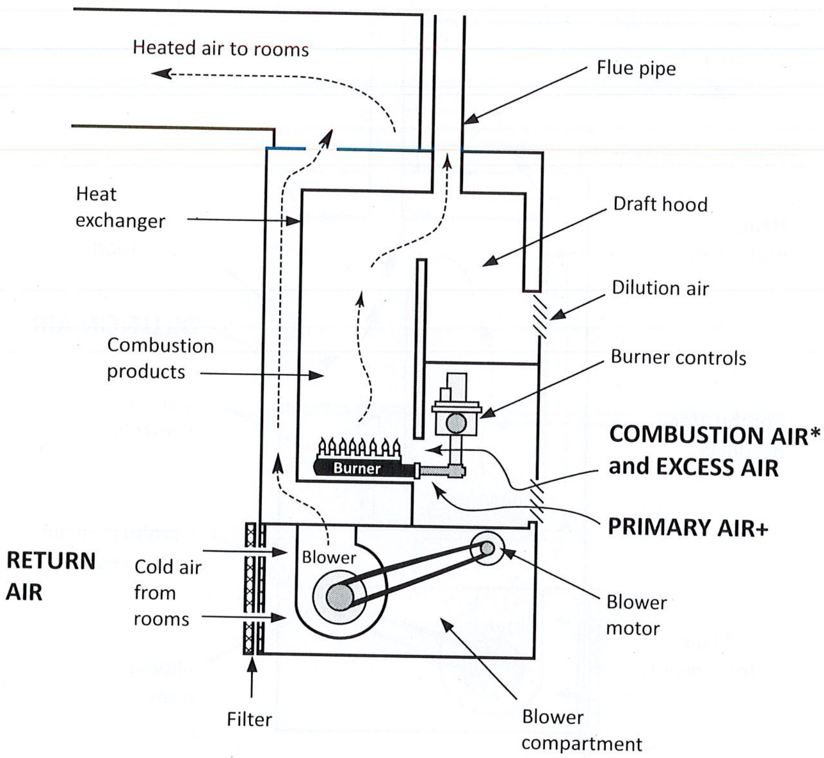


Excess air

Excess air is the air you supply to the combustion zone in excess of the required air for perfect combustion to ensure there is sufficient oxygen for complete combustion to occur. Because the excess air is over and above what is theoretically needed in the combustion process, it absorbs heat, which it carries off through the venting system. This, in turn, reduces the appliance's efficiency. So, you must keep excess air to a minimum.

Figure 2-8 shows where combustion and excess air are brought into a furnace.

Figure 2-8
Cutaway of a furnace showing combustion and excess air



* Combustion air = primary air + secondary air

Dilution air

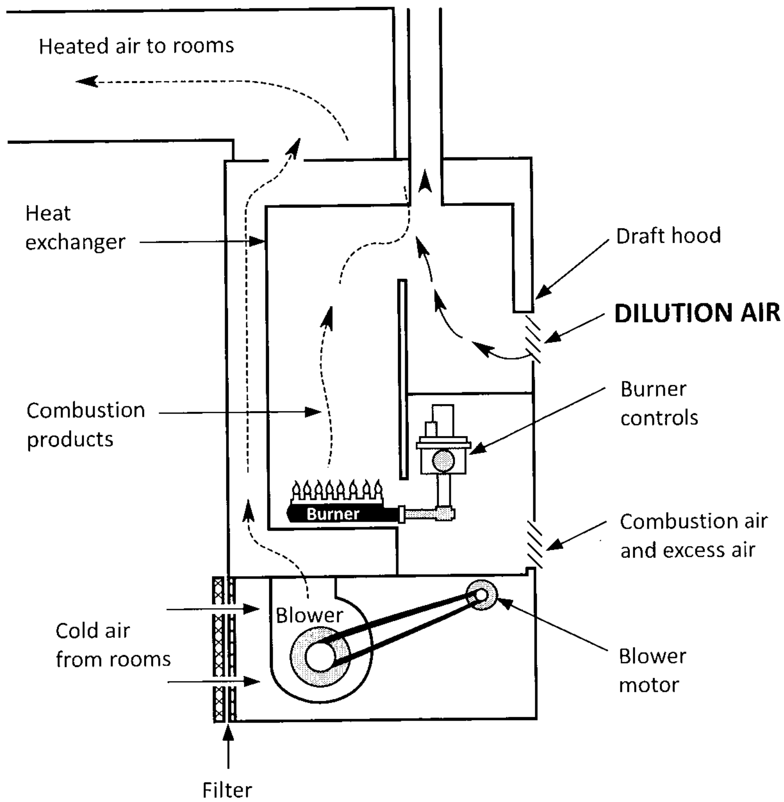
Dilution air is the ambient air that is admitted to a venting system at the draft control device of the appliance. Use it for two purposes:

- to cool the hot vent gases; and
- to provide a source of air to the draft control device (so that it can control the draft influence on the combustion chamber).

The lack of a draft control device in the equipment means no dilution air is required.

Figure 2-9 shows where a system supplies dilution air.

Figure 2-9
Cutaway of a furnace showing dilution air



Calculating the volumes of air supply

For the purpose of calculating volumes of required air, air supply has the following categories:

- combustion air supply;
- excess air supply;
- dilution air supply; and
- total air supply.

Combustion air supply volume

The natural gas industry has always used a 10: 1 ratio for the air-gas mixture required to achieve perfect combustion. This, of course, refers only to natural gas and air. The *Differences between Complete and Incomplete Combustion* section examines the chemical formula for perfect combustion. There, in terms of volume, one cubic foot (1 ft^3) of natural gas combines with 10 cubic feet (10 ft^3) of air.

$$1\ ft^3\ CH_4 + 10\ ft^3\ air = perfect\ combustion$$

As a gas technician/fitter, you will work with many types of fuel gases, and they all have something in common when it comes to perfect combustion. For each 1 000 Btu of heat that the combustion process produces, you will need 10 ft^3 of air for perfect combustion. See the following formula:

1 000 Btu of input + 10 ft^3 air = perfect combustion

You can still apply the ratio of 10: 1, but it means that you need10 ft^3 of air for each 1 000 Btu of input. Thus, you could express a new ratio, applicable to all fuel gases:

Each (1 000 Btu of input) x 10 ft^3 = perfect combustion

Example 1—Natural gas

Calculate the volume of combustion air required for an appliance with an 80 000 Btu/h input, fired on natural gas.

$\frac{80\,000 \text{ Btu/h}}{1\,000 \text{ Btu / ft}^3} \times 10 = 800\text{ft}^3\text{/h}$ combustion air

Example 2—Propane

$\frac{250000 Btu / h}{1,000 Btu / ft^3} \times 10 = 2,500\text{ft}^3\text{/h}$ combustion air

1 000 Btu of input requires 10 ft^3 of combustion air supply, whatever the type of fuel gas used.

Excess air supply volume

The excess air that you supply to a burner ensures the combination of all fuel with oxygen to produce complete combustion. A lack of excess air may cause varying degrees of incomplete combustion, while too much excess air can cool the flame and cause incomplete combustion. Too much excess air will increase the volume of gases in the heat exchanger and may cause spillage of flue gases. Too much excess air will carry off heat, reducing the efficiency of the appliance.

Modern fan-assisted burners and power burners can operate efficiently, often with as little as 20–30% excess air. For atmospheric burners, complete combustion that occurs with a volume of excess air equal to 50% of the combustion air volume is usually acceptable. A relationship between Btu of input and the volume of excess air required can be as follows:

1 000 Btu of input requires 5 ft^3 of excess air supply.

Dilution air supply volume

If an appliance comes with a draft control device, a volume of air must enter the venting system in order to cool and control the stack action. The required volume of dilution air being equal to the total of the combustion and excess air supplied to the burner is usually acceptable. The relationship between Btu of input and the volume of dilution air required is as follows:

1 000 Btu of input requires 15 ft^3 of dilution air supply.

Total air supply volume

Use the term total air to describe the volume of air required to allow the safe and efficient operation of the appliance. It is a total of combustion, excess, and dilution air requirements. The relationship between Btu of input and the volume of total air required is as follows:

1 000 Btu of input requires 30 ft^3 of total air supply.

Calculating for high altitude installations

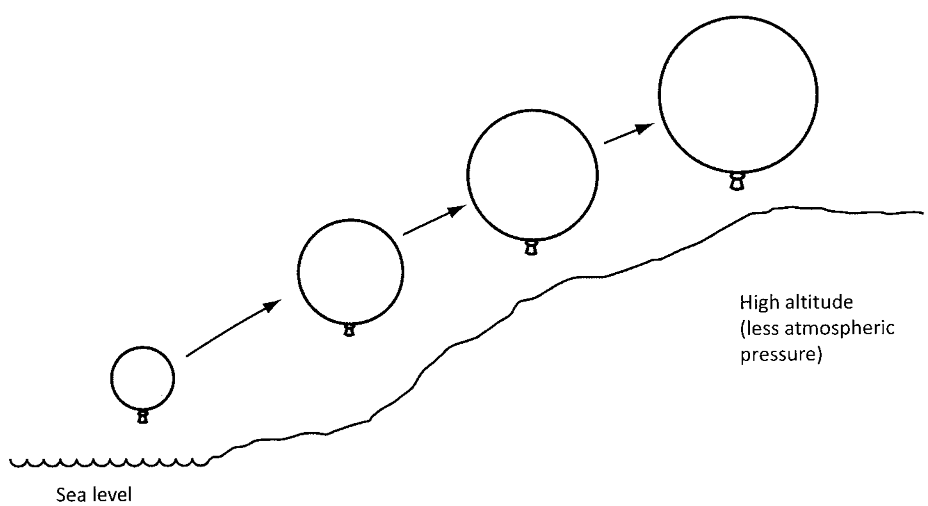
Certain areas in Canada (e.g., regions in B.C. and Alberta) are located at high altitude. It is important that you understand the effect of reduced atmospheric pressure on combustion performance.

The barometric pressure at sea level is 14.73 psia. If you visualize a balloon filled with one standard ft^3 of natural gas at sea level 14.73 psia, the balloon expands in volume to equalize against the atmospheric pressure.

For every 2 000 ft rise in elevation, the barometric pressure reduces by approximately 1 psia. For example, as the altitude increases, the pressure exerted on the sides of the balloon reduces, and the lower the pressure, the more the balloon volume expands. At a 2 000 ft rise, the volume of natural gas would expand to approximately 1.072 ft^3 and become less dense. You can calculate the amount of expansion using Boyle's Law, which states "the volume of dry gas varies inversely to the absolute pressure, providing the temperature remains constant" or $p_1V_1 = p_2V_2$.

This reduction in gas density at high altitudes changes the gas flow into the orifice. Because the gas is less dense, it flows more easily through a burner orifice, increasing the gas flow to the appliance and putting the input-to-oxygen ratio out of balance.

Figure 2-10
Effect of altitude on gas pressure inside a balloon



Summary

To determine the necessary volume of air supply, it is important that you identify the input of the appliances.

For each 1 000 Btu or 1 MBH of appliance input, the ratio of air is as follows:

- 1 000 Btu (1 MBH) of fuel × 10 = ft^3 combustion air;
- 1 000 Btu (1 MBH) of fuel × 5 = ft^3 excess air;
- 1 000 Btu (1 MBH) of fuel × 15 = ft^3 dilution air; and
- 1 000 Btu (1 MBH) of fuel × 30 = ft^3 total air.

Causes of incomplete combustion

It is important to know that incomplete combustion occurs from causes other than insufficient air. For example, the combustion process must maintain a minimum temperature. If at any time the flame is quenched below that temperature, then you may have incomplete combustion that produces toxic products.

Cause	Description
Flame temperature	The combustion process must maintain a temperature of approximately 1 300°F (649 °C) for natural gas or 920°F (495 °C) for propane. If at any time the flame is quenched below that temperature, you may have incomplete combustion and toxic products. Conditions that cause the temperature to drop below the ignition point may have this effect. These conditions include impingement on the cold metal surface of a heat exchanger or excessive cold air that chills the flame front.
Cracked heat exchanger	A heat exchanger is the component of a gas appliance that takes the heat from the hot flue gases and transfers it to the supply air that helps heat the building. On occasion, this component will develop a crack that allows the supply air to come into contact with the hot flue gases. This can cause excessive air movement in the combustion chamber and adversely affect the flame, causing incomplete combustion. If the flame characteristics change as soon as the supply air blower comes on, or if there is a change in CO_2 or O_2 levels in the flue gases when the blower starts, you may have a heat exchanger problem. On an induced draft appliance, a crack will result in less air for the combustion process and increased CO.
Blocked venting Natural draft appliance	If the venting on a gas appliance becomes blocked, the flue gases will not be able to reach the outdoors and will spill out of the draft hood and remain in the room. If the products of combustion are not leaving the room, then combustion air is not entering. In time, this lack of combustion air will cause incomplete combustion and a carbon monoxide condition.

Cause	Description
	You can check spillage at the draft hood with a smoke stick to see if there is positive or negative pressure.
Induced draft appliance	If an appliance has a fan-assisted or induced-draft combustion chamber, it has sensing devices that will shut down the burner if the venting becomes blocked.
Negative air pressure	Many venting systems rely on natural draft to move the products of combustion outdoors. Room pressure can affect this draft. If excessive air exhausted from the building produces a negative pressure in the room, the pressure will affect the combustion process and could cause incomplete combustion.

Condensation of products of combustion

Flue gas condensation

Flue gas condensation is a process that involves the cooling of flue gas below its water dew point and the recovery of heat released from the resulting condensation as low temperature heat.

When fuel is burned and the hot gases produced are exhausting through a heat exchanger, much of the heat is transferred to the medium passing through the heat exchanger, thus raising the temperature of the medium. One of the hot gases produced in the combustion process is water vapour (steam), which arises from burning the hydrogen content of the fuel. A condensing appliance extracts additional heat from the flue gases by condensing this water vapour to liquid water, thus recovering its latent heat. A typical increase of efficiency in the appliance can be as much as 10–20% of gain over a non-condensing appliance.

The condensate produced is slightly acidic, 3–5 pH, so the choice of materials used in the wetted areas must be suitable. In high temperature areas, most commonly used materials are aluminum alloys and stainless steel; in the low temperature areas, plastics, e.g., UPVC and polypropylene, are most cost effective. The production of condensate also requires the installation of a secondary heat exchanger to remove the heat from the condensate and a condensate drainage system.

Since the final exhaust from a condensing appliance has a lower temperature than the flue gas from a conventional non-condensing appliance, you must use an approved BH venting system.

Characteristics and requirements of a stable flame

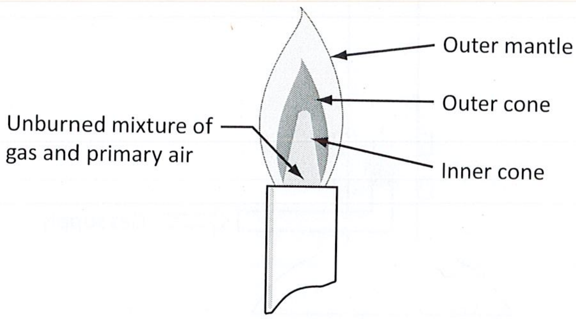
A stable flame is a flame that does not waver, lift off the burner, or flash back into the mixing tube.

Flame colour and shape are characteristics of the flame and as such can only give an indication of flame quality. You must perform a combustion analysis to accurately test flame quality and completeness of combustion, as well as for presence of toxic gases, i.e., carbon monoxide (CO).

Qualities of a stable flame

A stable atmospheric Bunsen burner flame has several colour zones. Each of these zones marks a stage in the burning of gas (Figure 2-11).

Figure 2-11
Stable Bunsen flame

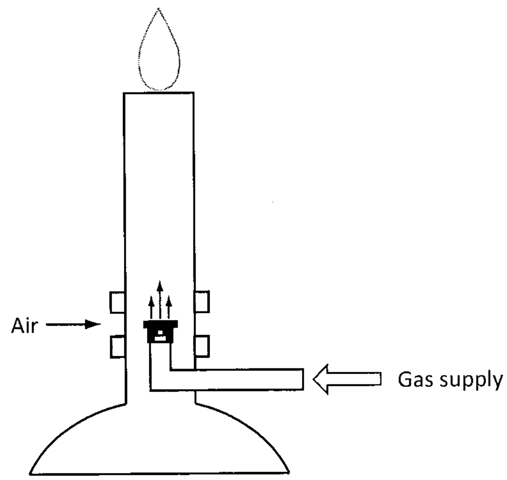


Color Zone	Description
Inner cone	The inner cone is a thin blue cone on the burner tip. The inner cone marks the first step in the burning process where burning of gas happens to form products such as aldehydes, alcohols, carbon monoxide, and hydrogen. The velocity of the unburned gas-air mixture forms the shape of the inner cone.
Outer cone	The outer cone is a darker, outer cone that surrounds the inner cone. This is where the secondary air diffuses into the flame. If enough secondary air is present, and other conditions are favourable, the complete burning of products from the inner cone happens here, yielding the final products, carbon dioxide and water vapour.
Outer mantle	The outer mantle is a colourless mantle that surrounds the outer cone. Since complete burning usually happens at the outer cone, there are almost no unburned gases at the outer mantle. This nearly invisible mantle only glows because of the combustion products' high temperature.

Requirements of a stable flame

To achieve a stable flame on an atmospheric burner, you need to maintain a fine balance between the flame speed and the flow velocity. Adjusting the primary air supply or the gas flow rates will change the flame speed and flow velocities. A properly adjusted Bunsen-type burner flame is predominantly blue when you properly adjust the primary air (Figure 2-12).

Figure 2-12
Bunsen flame



Primary air supply

The primary air supply sets the flame characteristics. If premixing of the proper amount of primary air with the gas happens, the burner will provide a stable blue flame. Adjustments to the air supply will cause the flame to change shape and colour.

Adjustment	Description
Air increase	As the percentage of primary air increases, the flame sharpens and the inner cone gets smaller. When adjustment of the primary air creates a 10% gas-air mixture for natural gas (or a 6% propane-air mixture), the flame reaches its maximum speed. Beyond this point, although adding more primary air increases flow velocity, the flame speed slows down proportionately. The flame will then start to lift off the burner port. Any further increase of primary air supply will eventually cause complete flame liftoff.
Air decrease	When the percentage of primary air decreases, the burning speed decreases since complete combustion requires more secondary air. The flame gets longer, becomes more luminous, and burning speed slows down. Further reduction of the primary air supply will result in the appearance of yellow tips in the flames and the formation of carbon. The flames will become completely yellow if all primary air is shut off.

Too little air supply

As primary or secondary air supply is decreased, the percentage of CO_2 in the flue gases increases. The theoretical maximum CO_2 produced during complete combustion is 11.8% for natural gas or 13.8% for propane. In practice, when the flue gas percentage of CO_2 reaches 10% or higher for natural gas (11.5% or higher for propane), the air being supplied becomes insufficient, and carbon monoxide may be produced.

Gas supply

The amount of gas-air mixture passing through a port—called port loading—is also important for creating a stable flame. Burner port-loading is expressed as the number of Btu/h per square inch of port-area, as the following formula shows:

$$\text{Port loading} = \frac{\text{Input rate, Btu / h (kW)}}{\text{Port area, in}^2\,(\text{mm}^2)}$$

You can change the port loading by altering either the orifice size or the gas pressure (manifold pressure). For most applications using natural gas, a port loading between 25 000 Btu/h and 30 000 Btu/h per square inch of port area provides a stable flame.

Assignment Questions – Chapter 2

1) What is the term used for the chemical process in which the rapid oxidation of fuel results in the production of heat?
   a) Ignition
   b) Explosion
   c) Combustion

2) Approximately what percentage of air is oxygen?
   a) 20%
   b) 25%
   c) 79%
   d) 1.2%

3) What are the approximate ignition temperatures in °F (and °C) for propane?
   a) 1020°F (495 °C)
   b) 1300°F (700 °C)
   c) 1000°F (538 °C)
   d) 600°F (315 °C)

4) What are the approximate ignition temperatures in °F (and °C) for natural gas?
   a) 1 000°F (538 °C)
   b) 600°F (315 °C)
   c) 1 300°F (700 °C)
   d) 1 020°F (495 °C)

5) What are the products of combustion for a hydrocarbon fuel?
   a) CO_4, H_2O, and heat
   b) CO_2, H_2O_2, and heat
   c) CO_2, H_2O, and heat
   d) $2CO_2$, H_2O, and heat

6) State the formula for perfect combustion for natural gas.
   a) $CH_4 + 2O_2 + 8N_2 > CO_2 + 2H_2O + 8N_2$ + Heat
   b) $CH_4 + 2O_2 + 8N_2 > 2CO + 2H_2O + 8N_2$ + Heat
   c) $CH_4 + 2O_2 + 8N_2 > CO_2 + 4H_2O + 8N_2$ + Heat

7) What is added to the combustion process to ensure complete combustion?
   a) Primary air
   b) Excess air
   c) Ventilation air
   d) Combustion air

8) Name two products of incomplete combustion.
   a) Water Vapour and Carbon dioxide
   b) Nitrogen and Carbon
   c) Carbon monoxide and aldehydes
   d) Nitrogen and water vapour

9) How are the three divisions of air supply categorized?
   a) Combustion air, pressurized air, dilution air
   b) Combustion air, excess air, primary air
   c) Combustion air, excess air, dilution air

10) What is the term used to describe the air that is mixed with fuel gas before the point of ignition?
   a) Primary air
   b) Excess air
   c) Dilution air

11) What is the purpose of dilution air?
   a) To remove the hot vent gases and to control the draft influence on the combustion chamber
   b) To increase the hot vent gases and to control the draft influence on the combustion chamber
   c) To cool the hot vent gases and to control the draft influence on the combustion chamber

12) What is the air-to-gas ratio that applies to all fuel gases?
   a) Each (1 000 Btu of fuel input) × 10 ft^3 air = perfect combustion
   b) Each (1 000 Btu of fuel input) × 10 ft^3 air = complete combustion
   c) Each (1 000 Btu of fuel input) × 10 ft^3 air = perfect ignition