



A SunCam online continuing education course

Forensic Analysis Involving Fugitive Natural Gas and Propane

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I. Overview

Engineers are frequently called upon to perform forensic analyses of the origin and cause of explosions¹ and fires involving fuel gas systems that use either natural gas or propane. This course will concentrate on those cases where the natural gas or propane vapor has escaped from its normal confinement, and caused an explosion or fire or both.



Propane explosion inside house, propane tank in background at top of photo



Natural gas explosion inside house, gas meter seen at foundation wall

¹National Fire Protection Association definition of explosion, which will be used in this course: The sudden conversion of potential energy (chemical or mechanical) into kinetic energy with the production and release of gases under pressure, or the release of gas under pressure. These high-pressure gases then do mechanical work such as moving, changing, or shattering nearby materials. An ignition that produces sound alone does not qualify as an explosion in this context.



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The operations of gas-fired systems are based on the release of heat energy by the burning of either natural gas or propane. The presence of a flame or fire is, in and of itself, an integral part of such systems. However, such systems are designed to control, monitor and confine both the ignition and combustion of the fuel gases. Fuel gases are useful servants of mankind, as long as they are under control. An uncontrolled fuel gas that gets loose from its confinement is frequently referred to as a **fugitive gas**. Once a fugitive gas is ignited, the released energy may result in an explosion, a fire, or both, which can lead to great harm and damage. The two photographs above illustrate a couple of such outcomes.

When an explosion or fire occurs in or near a fuel gas system, an engineer is frequently engaged to analyze what, if any, aspect of the mechanical system failed because current fuel gas systems are designed with safeguards intended to preclude the uncontrolled release of the fuel gas. The engineer will not only be looking at the mechanics of the system, but also looking at how the system was installed, operated and maintained. While examination of the fuel-burning equipment is major part of the engineer's forensic analysis, the examination of hardware is not the subject of this course.

This is.



How does the aftermath of a gas explosion help to determine the origin and cause?



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This course will focus on two critical components of the engineer's expertise that may be brought to bear in such a forensic analysis. These concern the understanding of (1) how a fuel gas behaves when it is released from confinement, and (2) how the observed explosion damage may relate to the concentration of the fugitive gas and rate of release of the fugitive gas. Raising the understanding of these two areas of knowledge will be the focus of this course.

While technicians who install fuel gas systems may understand all aspects of the proper installation, operation and maintenance of such systems, their understanding of the behavior of a fuel gas is usually limited to their observations of gases that are always under control, and flames that are always confined to the combustion chamber. A fuller understanding of how a fugitive gas behaves both before and after an explosive ignition requires the knowledge of chemistry, combustion and fluid mechanics that is brought to the analysis by the engineer.

The two fuel gases to be discussed in this course, natural gas and propane, each has unique chemical and physical properties, which govern how each gas behaves when it becomes fugitive. Both the unique properties and the unique behaviors play critical roles in any forensic analysis of a fire or explosion involving fugitive fuels.

II. Basic Chemical and Combustion Properties of Fuel Gases

The burning or combustion of a fuel gas is a rapid, exothermic, oxidation reaction. Gas-fired systems are designed to control the **rate** at which the energy from the burning fuel is released. This is generally accomplished by controlling the rate at which fuel enters the combustion chamber and by insuring the presence of an ignition source that will ensure ignition of the fuel gas as it enters the combustion chamber. Successful operation of a fuel gas system also means all the fuel is supposed to be consumed within the combustion chamber with no unburned fuel being allowed to accumulate either inside or outside the combustion chamber.

It is important to note, however, that the simple presence of a fuel in the vicinity of a competent ignition source will not in itself guarantee combustion. A critical aspect of all such gas-fired systems is the ability to maintain a proper fuel to air ratio.

A. Flammable Range:

Each fuel gas has a specific range of fuel-to-air ratios over which ignition will occur. Outside those ranges, combustion will not be sustained, whether inside controlled equipment or in fugitive gases. That range, usually expressed as a **volume percentage of the fuel gas in a gas-**



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air mixture, is called **the flammable range**. At percentages above that range as well as percentages below that range, combustion will not be sustained.

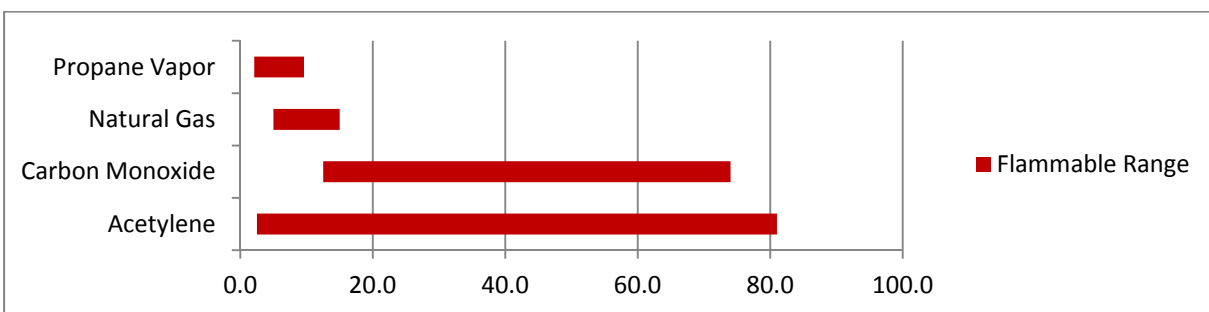
For natural gas, the flammable range is commonly stated as being between 5% and 15% of the gas-air mixture. The 5% is referred to as the Lower Flammable Limit, or LFL. The 15% is referred to as the Upper Flammable Limit, or UFL.

For propane, the flammable range of the vapor is commonly stated as being between 2.1% and 9.6% of the gas-air mixture. The 2.1% is referred to as the Lower Flammable Limit, or LFL. The 9.6% is referred to as the Upper Flammable Limit, or UFL.

Since these two flammable ranges are relatively narrow, it is worth putting these flammable range values into a context. The bar graph below shows how the flammable ranges of propane vapor and natural gas compare to the flammable ranges of two other common ignitable gases, carbon monoxide and acetylene.

While carbon monoxide is not normally thought of as an ignitable fuel, it is usually a significant part of the fuel load in most residential fires. The flames seen coming out the open windows and doors during a structure fire are frequently the result of burning carbon monoxide gases, gases that have resulted from incomplete combustion of the interior fuels. While acetylene is a fuel gas not found in most residential fires, it certainly is found in many industrial fires.

Flammable Ranges of Four Ignitable Gases



Lower Flammable Limit and Upper Flammable Limit as a Percent of the Gas-Air Mixture				
Gas	Propane Vapor	Natural Gas	Carbon Monoxide	Acetylene
LFL	2.1	5.0	12.5	2.5
UFL	9.6	15.0	74.0	81.0



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The above bar graph and table simply show that carbon monoxide and acetylene are ignitable over wider ranges of fuel-air mixtures than are natural gas and propane vapor, which makes carbon monoxide and acetylene more readily ignitable than natural gas or propane vapor when mixed with air. This bar graph in no way implies that carbon monoxide and acetylene create higher pressures or are more destructive when ignited. The amount of energy released when these four gases are ignited is dependent upon several factors, which includes the total volume of each gas involved as well as the heat of combustion of each individual gas. However, the energy release calculations are beyond the scope of this current course and will not be covered here.

B. Ignitability of a Flammable Mixture:

The fact that fuel gases have relatively narrow flammable ranges means that the presence of an ignition source in the area of a fugitive fuel gas, even if such an ignition source is an open flame, does not ensure ignition. **Ignition is only possible if the fugitive gas-air mixture in the presence of the ignition source is within the flammable range.** Gas-air mixtures outside the flammable range are not ignitable.

To put the flammable range in context, consider a leaking, fugitive gas as a spreading cloud, with gas concentrations varying from 100% gas at the leak point to near zero at the outer edge of the spreading cloud. While 100% gas is coming from the leak, the mixing with air that occurs as the gas moves outward into the cloud would result in decreasing gas concentrations the farther the gas gets from the leak.

With this model, there would be parts of the cloud near the spreading edge that are within the flammable range. Ignition sources within that area would be capable of igniting the flammable mixture explosively. While the areas of the cloud above the UFL would not immediately ignite, the explosively ignited gases within the flammable range lead to a local turbulence that speeds the mixing of the adjacent, unburned gases with the surrounding air and the subsequent ignition of those gases. The result is a growing fire ball, not further explosions. The only gases that would not be caught up in the growing fire ball would be the parts of the cloud where the gas concentrations were below the LFL. Those gases would escape ignition altogether.

C. Ignition of a Flammable Mixture:

When a flammable mixture is ignited, and the rapid, exothermic, combustion reaction occurs, the resulting products of combustion, primarily carbon dioxide and water vapor, experience a rapid increase in temperature, pressure and volume. Whether or not such an ignition results in damage is a function of two important factors. First, the volume of fugitive gas available for ignition will



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determine how much energy is available for release. Second, the degree of confinement of that available volume of fugitive gas will determine how much the products of combustion will be able to expand. Confinement of an ignited gas-air mixture will lead to a higher pressure and a higher rate of pressure increase than would be experienced in an open air, unconfined ignition.

The manual ignition of a stove top burner, or a backyard propane grill, may serve to illustrate the case where the volume of gas ignited is small and there is no confinement. In such scenarios, a lit match or other lighter is held within a few inches of a gas port. The gas leaves the burner port and travels outward in all directions. When part of this released volume reaches the ignition source, ignition occurs, and there is a characteristic “whoosh,” which is usually considered a normal part of any such ignition. When the match is held an additional inch or two from the burner port, the released gas has more time to accumulate before it reaches the match, and the “whoosh” will be louder, and may even singe the hairs on the hand holding the match. By extension, when the ignition source is located several feet away, or even a room away from the leak’s origin, the volume of the accumulated gas-air mixture may ignite with enough force to blow a house apart.

The effect of confinement can be readily seen by considering the ideal gas equation of state, $pV = nRT$. An ignition in the open will result in an expanding volume of combustion products, which may generate an outgoing pressure wave, but which will expand at a pressure only marginally greater than atmospheric. In such a case, the volume increase can be seen to be directly proportional to the absolute temperature increase. By contrast, if the ignition occurs within a fixed volume container, it can be seen from the equation of state that the increase in absolute pressure is directly proportional to the increase in absolute temperature.

The ignition of fuel gases in insulated, constant volume containers in the lab have shown that the absolute temperature increases by a multiple of about seven and one half. With such a multiple applied to the absolute pressure, theoretical pressures of 110 psia could be achieved in a closed volume. As a practical matter, such pressures could not be achieved in any structure being considered here because such normal structures would be blown apart by the time they had experienced an interior overpressure between 5 and 10 psig, and the expanding gases would no longer be confined. Nevertheless, most structures provide a degree of confinement that results in higher explosion pressure inside than outside.

D. Rate of Pressure Rise and Maximum Pressure Generated by Combustion:

While any gas concentration within the flammable range is ignitable, not every concentration in that range results in the same rate of pressure increase, or the same maximum pressure, both of



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which affect the damage to a building following the ignition of a fugitive gas inside the building. Some have characterized the range of explosion damage as from “bulging walls to fire balls.” The bulging walls occur when the ignited mixture is at or just above the LFL, and the fire balls occur when the ignited mixture is at or just below the UFL.

As discussed above, the flammable range includes all fuel-air ratios capable of sustaining combustion. The ideal fuel-air mixture, where there is not excess fuel and no excess air, is the **stoichiometric mixture**. For natural gas that gas concentration is 9.5% gas in air.² For propane vapor that gas concentration is 4.0% gas in air.³ As can be seen, these stoichiometric concentrations are close to the center of each flammable range.

For natural gas, mixtures having a gas concentration above 5% and below 9.5% are lean mixtures, with excess air. For propane vapor, mixtures having a vapor concentration above 2.1% and below 4.0% are lean mixtures, with excess air. A sizable portion of the energy released during combustion of such mixtures goes into raising the temperature of the excess air, energy which does not go into raising the pressure of the products of combustion. As a result, the closer the concentration is to the LFL, the weaker will be the explosive force. An explosion having such a lean mixture may result in the structure walls being bulged out or pushed out and laid down next to the structure, with virtually intact structural components.

For natural gas, mixtures having a gas concentration above 9.5% and below 15% are rich mixtures, with excess fuel. For propane vapor, mixtures having a vapor concentration above 4.0% and below 9.6% are rich mixtures, with excess fuel. A sizable portion of the energy released during combustion of such mixtures goes into raising the temperature of the excess fuel, energy that does not go into raising the pressure of the products of combustion. As a result, the closer the concentration is to the UFL, the weaker will be the explosive force. However, the excess fuel is still there, being mixed with and diluted by the surrounding atmosphere due to the turbulence created by the explosive ignition. Some of this fuel mixing with air will be brought down into the flammable range where it will burn, not as another explosion, but as a fire ball that will burn until all the excess fuel has been consumed.

The stoichiometric level is also where the pressure developed by the ignition of the mixture is a maximum. This is where the destructive force of a gas explosion is the greatest and where buildings show the greatest damage. Stoichiometric explosions also show minimal to no fire

² Complete combustion of methane: $\text{CH}_4 + 2(\text{O}_2 + 3.76\text{N}_2) \Rightarrow \text{CO}_2 + 2\text{H}_2\text{O} + 7.52\text{N}_2$ has $1+2(1+3.76) = 10.52$ mols of reactants for each mol of CH_4 , which makes the molar concentration of methane $1+10.52 = 9.5\%$.

³ Complete combustion of propane: $\text{C}_3\text{H}_8 + 5(\text{O}_2 + 3.76\text{N}_2) \Rightarrow 3\text{CO}_2 + 4\text{H}_2\text{O} + 18.8\text{N}_2$ has $1+5(1+3.76) = 24.8$ mols of reactants for each mol of C_3H_8 , which makes the molar concentration of propane vapor $1+24.8 = 4\%$.



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damage to building structures because all the gaseous fuel is consumed in the explosion. Such stoichiometric explosions result in short term, high heat release rates, too short in duration to ignite structural components.

While it is difficult if not impossible to determine the exact concentration level at the point of ignition, the evidence may still yield some qualitative conclusions. If a structure completely destroyed in a fuel gas explosion shows only a debris field and minimal to no burn damage to the structural components, then the concentration was most likely close to the stoichiometric on the lean side. If, however, a structure completely destroyed in fuel gas explosion shows a debris field plus charring and thermal damage to some of the structural components, then the concentration was most likely close to the stoichiometric level on the rich side.

III. Basic Physical Properties and Behavior of Fuel Gases

In order to relate gas concentration levels to observed explosion damage, the engineer must also understand how fugitive natural gas and propane vapor move and behave. Natural gas and propane differ not only in their chemistry but also in their physical properties and behavior. The primary differences between the two gases stems from their different densities.

A. Properties:

Natural gas is a naturally occurring hydrocarbon gas recovered from oil and gas wells and distributed and delivered to the end users in a gaseous state by pipelines from a utility. While natural gas contains small quantities of other hydrocarbon gases, it is predominantly methane, CH_4 . Depending upon its specific mixture of components, natural gas is about 55% the vapor density of air (i.e., a specific gravity⁴ of 0.55), so it will tend to rise when first released into the atmosphere as a fugitive gas.

Commercially available propane, labeled as LP-Gas (liquefied petroleum gas), is produced during the refining of petroleum. Although LP-Gas is most often used in a gaseous form, the bulk of propane is transported, sold and stored as a liquid. While LP-Gas contains small quantities of other products, is predominantly propane, C_3H_8 . Depending upon the specific mixture of components, commercial propane in the gaseous state is about 152% the vapor

⁴ The specific gravity of a gas is defined as the ratio of the vapor density of a gas or vapor to the vapor density of air. For most engineering purposes, vapor density of air is generally taken to be 29 g/mol.



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density of air (i.e., a specific gravity of 1.52), so it will tend to sink when first released into the atmosphere as fugitive gas.

B. Behavior:

The difference in density between a fugitive gas and the surrounding air can lead to natural gas tending to rise and propane vapor tending to sink upon initial release. This fact has frequently led investigators searching for ignition sources to limit their search to only those areas above a natural gas leak and only those areas below a propane leak. This is where an engineering analysis can show the basis for a wider ignition source search.

While natural gas may tend to rise upon its initial release and propane vapor may tend to sink upon its initial release, this tendency does not give rise to a layer of natural gas pooling at ceiling level, nor does it give rise to a layer of propane vapor pooling at floor level. Simply put, a fugitive gas, once released will disperse and dilute in the local atmosphere. However, this point does require some expansion.

C. Movement Mechanisms:

Air movement by forced convection is by far the strongest mechanism for mixing a fugitive fuel gas in air. Forced convective currents are normally thought of as arising from mechanical devices such as fans and blowers. Forced convective currents can also result from jets of escaping fuel gas.

A fuel gas released into the atmosphere is, with few exceptions, released from an area of higher pressure. Such releases, whether through leaks, breaks in pipes, or holes in containers, will usually result in a jet of fugitive gas. Such jets of fugitive gases result in gas movement away from any leak point, the entraining of air in the jet and the subsequent turbulent mixing of the fuel gas with air.

While forced convective mixing is by far the strongest means by which fugitive gases move away from any release point, two other mechanisms account for some dispersion and dilution. One such mechanism is the molecular diffusion of one gas within another. The other mechanism is the natural convective mixing that does result from the above-mentioned differences in density between the fugitive gases and the atmospheric air. These two mechanisms together are much smaller than forced convection yet both require some detailed understanding.



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D. Diffusion Mechanism:

The diffusion of gases in general as well as the diffusion of a gas in air in particular is expressed by Graham's Law of Diffusion. Named after the Scottish chemist Thomas Graham (1805 - 1869), Graham's Law states that the diffusion rate of one gas into another is inversely proportional to the square root of its molecular weight. Since the diffusion is mutual, i.e., gas 1 diffuses into gas 2 while gas 2 diffuses into gas 1, the relationship between diffusion rates and molecular weights (mw) may be stated mathematically as;

$$\frac{Rate_1}{Rate_2} = \sqrt{\frac{mw_2}{mw_1}}$$

Stated in simpler terms, lighter gases will diffuse faster than those gases with higher densities or molecular weight.

Since propane vapor is heavier than air while natural gas is lighter than air, it can be seen the natural gas diffuses into air faster than propane vapor diffuses into air. Therefore, natural gas will diffuse and move away from its leak source faster than a comparable volume of propane vapor will move away from its leak source.

It is also a basic principle of chemistry that gases once mixed, whether by diffusion or convective mixing, cannot un-mix or separate. The idea that mixtures of liquids can separate or un-mix on the basis of their liquid densities⁵ does not carry over to mixtures of gases.

This fact is demonstrated no more vividly than by the fact that our atmosphere consists of a mixture of 21% oxygen and 79% nitrogen by volume. The molecular weight of atmospheric oxygen is 32 while the molecular weight of atmospheric nitrogen is 28. If such gases could spontaneously separate due to their differing molecular weights, then people at sea level would live in a very thick layer of oxygen, above which would be a layer of nitrogen. This does not happen because gases once mixed stay mixed.

E. Natural Convection:

While the difference in density between a fuel gas and the surrounding air may give rise to mixing by natural convection, the resulting mixture of gas and air will have a specific gravity different from either the gas alone or the air alone. Since gas-air mixtures are only ignitable

⁵ In an oil-water emulsion, the lighter oil rises to the top of the water. Also, lighter cream rises to the top of milk.



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when they are in the flammable range, i.e., between the LFL and the UFL, it is essential for the engineer to determine the specific gravity of a gas-air mixture in the flammable range.

The specific gravity of a mixture is the weighted average of the specific gravities of the constituents of the mixture. An equation to determine the specific gravity of a fuel gas-air mixture is given by;

$$sg_m = (sg_f \times c_f) + (1 - c_f)$$

where sg_m is the specific gravity of the mixture, sg_f is the specific gravity of the fuel gas and c_f is the concentration of fuel gas expressed as a volume percentage of the mixture. Using the values in the table below, the specific gravities of each flammable range can be calculated.

Type of Fuel Gas	Molecule	Molecular Weight	Specific Gravity	LFL	UFL
Natural Gas	CH ₄	16	0.55	0.05 or 5%	0.15 or 15%
Propane Vapor	C ₃ H ₈	44	1.52	0.021 or 2.10%	0.096 or 9.60%

While the specific gravities are calculated below, the student is also encouraged to do the calculations in order to appreciate the changes in specific gravities that take place during the dilution of the fugitive gases compared to their specific gravities when first released.

Natural Gas:

$$sg_{LFL} = (.55 \times .05) + (1 - .05) = 0.98 = 98\% \text{ the density of air}$$

$$sg_{UFL} = (.55 \times .15) + (1 - .15) = 0.93 = 93\% \text{ the density of air}$$

Propane Vapor:

$$sg_{LFL} = (1.53 \times .021) + (1 - .021) = 1.01 = 101\% \text{ the density of air}$$

$$sg_{UFL} = (1.53 \times .096) + (1 - .096) = 1.05 = 105\% \text{ the density of air}$$



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Two observations can come out of these calculations. First, since the densities of these ignitable mixtures of the fuel gases are so close to the density of the air, the effects of natural convection on the movements of natural gas up and propane down are significantly reduced, and frequently voided by other convective currents present in most commercial and domestic settings. Second, by application of Graham's Law, it can be seen that flammable mixtures will diffuse into the adjacent air at rates higher than they did when the fugitive gas initially escaped from its confinement.

These observations can lead fire investigators to searches for ignition sources at elevations both above and below the leak points as well as ignition sources at distances beyond which there may be observable fire damage. These observations, drawn basically from a focus on the molecular level, need to be integrated into the macroscopic level, i.e., air and gas movement within a structure.

IV. Movement of Fugitive Gases in Buildings

Having an understanding of the properties and behavior of natural gas and propane vapor, the engineer investigating an explosion must attempt to correlate the a structure's observed explosive damage with the rate at which the fuel gas was released into the structure and the amount of elapsed time between the initiation of the leak and the explosion.

A. Air Movement Inside Buildings:

With the exception of rarely-encountered, hermetically sealed structures, all habitable buildings will breathe. Air is constantly entering and leaving such structures. The process is referred to as infiltration and exfiltration and is both active and passive. Active air circulation is usually accomplished by exhaust fans, while passive air circulation is the result of all the openings and cracks in a building's outer envelope. During the heating season, passive air circulation involves air leaking in across the building's sill plate, around window and door sashes and through the doors each time one is opened. The interior heated air will rise from one floor to another, then to the attic, and then out eave or roof vents. In effect, there is a constant river of air moving into, upward and then out of the average building. This has been described as the stack effect or the chimney effect because, like a chimney, air is drawn in at the bottom, rises and is exhausted out the top.



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A furnace in winter may cycle on and off two or three times an hour because the heated interior air rises, exits the home, and in so doing creates a partial vacuum inside the house, which then leads to infiltration of colder air, that again calls for heat, and the cycle starts again. To address this apparent problem, people try to reduce the infiltration by adding more weather stripping and more insulation around doors and windows. Unfortunately this has led to other problems, such as “bad house odor,” carbon monoxide buildup, aldehyde buildup, chimney downdrafts in water heaters and fire places and heavy condensation on the insides of windows.

Tight houses have led to a frequently encountered problem with a common fuel-gas-fired home appliance, the gas fireplace. Many of these fireplaces, particularly those with decorative features such as artificial logs that try to simulate a real wood fire, are sold as vent-less, which means they do not require a chimney to exhaust the combustion products, but are supposedly designed to allow the combustion products directly into the home. These appliances require a significant quantity of air, and produce not only carbon dioxide but also a large amount of water vapor. These two harmless combustion products nevertheless add gases to the home’s interior, which in turn decrease the volume percent of oxygen in the house that is necessary for complete combustion in the gas fireplace. The result is less oxygen entering the gas fireplace, which can result in incomplete combustion and the production of carbon monoxide.

The solution to the above mentioned set of problems with a tightly sealed house or structure is to allow a natural flow of air into and out of a structure, as well as to add power vents to exhaust fouled air and other collected fumes, including fugitive fuel gases, from the structure when the natural convection is inadequate. There must be a balance between the cost of heating and the cost of habitability.

B. Quantifying Air Movement Inside Buildings:

Since the flow of air through buildings has such a profound effect on heating costs, heating engineers have developed a significant body of knowledge concerning the quantification of these air flows. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has published research on the quantification of these infiltration-exfiltration air flows. The ASHRAE Fundamentals Handbook contains a chapter titled Ventilation and Infiltration, which discusses in detail how to determine infiltration rates. Rates can be determined by calculation or by actual leak tests.

While most of the ASHRAE material is aimed at the designers of structures and the designers of heating systems, the focus here will be on the determination of infiltration air flow rates. While many commercial and industrial structures have infiltration rates that vary widely, and often



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require on-site study and calculations, air flow rates through residential structures have been extensively studied and documented, and the rate of infiltration-exfiltration is expressed as “air changes per hour,” usually written as ACH or ach. If, for example, a structure having an interior volume of 8,000 cubic feet is said to have 1 ACH, then the rate of infiltration, which is also equal to the rate of exfiltration, will be 8,000 cubic feet per hour, or 8,000 cfh. For an 8,000 cubic feet house with 0.5 ACH, the infiltration rate would be 4,000 cfh, which means that it will take such a house 2 hours to completely change its air.

In the ASHRAE Fundamentals Handbook, Ventilation and Infiltration chapter, in a section titled Residential Ventilation, the wide range of ACH values is noted. Houses with very tight construction may have an ACH as low as 0.1, while old or very loosely constructed houses may have an ACH as high as 2.0. This section of the Handbook goes on to cite the results of studies in cities throughout North America. In a study of 312 newly-constructed, energy-efficient homes, the median infiltration rate was 0.5 ACH. In a study of 266 older homes, the median infiltration rate was 0.9 ACH.⁶

Unless the forensic engineer looking at the movement of air and fuel gas upward through a building can find specific data on the structure’s ACH, then an assumption must be made. Based on the above from ASHRAE, and assuming 0.5 ACH for newer, tighter buildings, and assuming 1.0 ACH for older, looser buildings, the engineer can either interpolate or extrapolate within or outside the range of 0.5 to 1.0, based on the engineer’s own observations and the known history of the building being investigated.

C. Fugitive Gas Movement Inside Buildings:

Having calculated the specific densities of ignitable mixtures of fuel gases in air, and having seen how close the densities of such mixtures are to that of the air moving through the structure, it should be clear that the movement and dispersion of such ignitable mixtures is more readily governed by the mass air movement than by the density differences between the mixtures and air.

An ignitable mixture of natural gas and air is slightly lighter than the surrounding air and would be expected to rise inside a structure. However, the engineer must consider the fact that an ignitable propane-in-air mixture may not be limited to a downward movement toward the basement or cellar. Such an ignitable propane-in-air mixture could readily be moved upward by the air rising from one floor to another and eventually out the eave or roof vents.

⁶ 2009 ASHRAE Handbook Fundamentals, page 16.17



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While such air movement is present in every structure, the case of a propane leak in a cellar or basement may prove an exception to the concept of a river of air sweeping through the entire structure. Depending upon the construction of a basement's foundation walls, a basement may be a place of stagnant air. Some older buildings may have unsealed basement walls, often referred to as dry laid stone walls. Such walls allow air in the soil to infiltrate when there is a partial vacuum created by the chimney effect.

Most basement walls are either concrete block or poured concrete, and are usually air tight. In such buildings, the air entering across the foundation sill plate enters near the basement's ceiling level and is swept upward through the structure in the rising flow of air. In such cases, the air near the floor may be unaffected by the moving air stream. If there is a propane leak in such a basement, its spread and dissipation will be driven primarily by molecular diffusion, a dispersion process much slower than the air movement associated with infiltration and exfiltration. Fugitive propane in basements and cellars are recognized as being particularly dangerous because of this fact.

Based on the above, and with the possible exception of a propane leak in a basement with sealed walls, it can be concluded that fugitive fuel gases released inside a structure will dilute and disperse as they gradually enter the upward moving air stream inside the structure, air moved upward by the stack effect, where these gases will exit the structure along with the other fouled and oxygen-depleted air that is leaving the building.

So far, in the above paragraphs, the discussion has included (1) the determination of the flammable range of each fuel gas, (2) the determination of the specific gravity of each fuel gas when it is present in its flammable range and (3) the determination of air change rates for buildings. While a structure's air exchange rates may vary slightly during the day, the air exchange rate is usually taken as a constant in an engineering calculation. By contrast, a fuel gas leak sufficient to cause a fire or explosion has a starting point in space and time, and may also have a measureable leak flow rate, all of which have an impact on how the fuel gas will spread in its immediate vicinity. Also, there is the question as to whether or not the leaking gas, which is being simultaneously diluted and being carried upward and outward, will even be around long enough to reach an ignitable mixture inside the building. The engineer is now faced with the need for a transient analysis.



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V. Gas Accumulation and Mixing as a Function of Time

Fugitive fuel gases in the open atmosphere are generally dispersed and diluted rapidly by the prevailing winds. If the ignition and combustion within such a cloud of fuel does occur, and sufficient gas remains in the area, it may result in a rising fire ball, usually with little if any blast damage. Such combustion is short lived, may be limited in size, and is usually harmful only to those who might be caught in the cloud when it is ignited.

The key element leading to damage and harm from the ignition and combustion of a fugitive fuel gas is confinement. An ignited fuel gas that is confined in a fixed volume container is capable of generating pressures in the vicinity of 110 psia and temperatures of about 7.5 times the absolute temperature of the initial reactants. Such pressures and temperatures can clearly do significant damage. However, such pressures and temperatures are not normally reached because whatever structural confinement existed at the start of combustion is usually blown away in fractions of a second. The point is that the confinement of the flammable mixture is a key element in any forensic analysis of the movement and spread of a flammable fuel gas mixture, both within the individual rooms of a building as well as through the entire structure.

Unconfined explosions of fugitive fuel gases in the atmosphere are rare, and will not be addressed any further in this course. The spread and the dispersion of fugitive fuel gases in the atmosphere is normally handled analytically using computational fluid dynamics programs. The focus in this course will be on fugitive fuel gases in confined spaces, which covers the vast majority of cases in which the forensic engineer may become involved.

A. Confinement in Buildings:

As discussed above, confinement of gases in buildings is not absolute because buildings breathe. Therefore, the discussion of rooms or compartments within a building must take into account not only the infiltration and exfiltration across the building envelope, but also the ventilation within the building, which is to say how the air moves between rooms or compartments on its way upward due to the stack effect.

The disciplines of fire protection engineering and fire science have spent much effort on determining how gases and products of combustion move through structures from room to room. The fire protection engineers use this information to improve fire safety, to provide fire control and to insure safe egress of building occupants. Fire scientists use this information in order to predict the movement of the products of combustion as well as to identify the particular gas species in the products of combustion.



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The current state of the art in analysis uses various computational fluid dynamics (CFD) models. Arguably the most widely used of such CFD software models is the Fire Dynamics Simulator, or FDS, which was produced by the National Institute of Standards and Technology (NIST)⁷, an agency within the U.S. Department of Commerce. Through the NIST technology transfer program, the FDS is available for download free of charge.

In a fashion similar to finite element analysis (FEA), where a solid material is divided into many finite elements in a three dimensional mesh network, a CFD program divides the air space within a room or structure into a three dimensional network of many small cells. While FEA allows forces and stresses to be transferred throughout the network of finite elements, CFD allows heat and mass to pass into and out of each cell, to and from its adjacent cells. Starting with initial and boundary conditions, which may also include the introduction of gases at different molecular weights and different flow rates, the CFD program keeps track of temperature changes in space and time, as well as keeping track of different species of gases and their varying concentrations as they move through the cell network under the influence of forced and natural convection. The time to construct and run such software is extensive.

It may be obvious that the greater the number of cells and the finer the mesh of cells in the room of a house, the greater would be the accuracy of the predicted air and gas properties in both space and time. The fewer the cells, the less accurate the predicted distribution of properties reported out of the program. This, of course, is because it is assumed that the properties within a single cell are constant throughout that cell. If there is a mesh of five hundred cells in a room, there would be five hundred unique temperature, pressure and species concentrations for each time step specified in the program.

Prior to the development of the FDS, NIST developed a computer program call CFAST, an acronym for Consolidated Model of Fire and Smoke Transport. CFAST is a two-zone fire model used to calculate the changing distribution of smoke, fire gas species and temperature throughout compartments of a building during a fire. The two-zone model (essentially a two-cell model) divides each room into an upper zone, which contains the hot gases produced by the fire, and a lower zone of ambient air for combustion. The two zones form because the hot products of combustion are significantly lighter than the ambient air.

As the fire in a room or compartment grows and more products of combustion move upward, the upper zone's size increases as the lower zone's size decreases. Again, as will the CFD models, the properties are assumed to be uniform throughout each zone. In other words, at any time step

⁷ Formerly the National Bureau of Standards, NBS



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through the CFAST program, there are only two temperatures and two species distributions in each room or compartment. When compared with the results of a CFD model, this may seem woefully inadequate. However, the assumption that a hot layer of combustion products banking down from the ceiling can be represented by a single value of temperature has been shown to give reasonable engineering results when the analysis is focusing on the movement of hot gases from one room to another through openings and vents.

In this present course the focus is on the movement of fugitive fuel gases prior to ignition and combustion, movement that does not usually involve significant temperature variations between the fugitive gases and air. As a result, temperature variations in a compartment in which there is a fuel gas leak can be considered negligible for the purposes of determining the changes in gas concentration as a function of time. To what extent then can an engineer assume that the fugitive gas concentration in any room of a building can be represented by a single value? To what extent can an engineer take each room of a building as a separate zone or cell that can be characterized by a single value of concentration?

B. Gas Concentration in a Compartment:

Extensive analysis and testing was conducted by British Gas to determine gas concentrations in compartments as a function of time following the initiation of a leak. They varied gas flow rates and flow directions as well as elevations within the compartments into which the gases were leaked. They also varied the sizes of air vents in each compartment, vents at both inflow and outflow locations, as well as the amount of ventilation.⁸

An important conclusion drawn from these experiments with minimally ventilated compartments was that for leaks of natural gas which occur at or near the floor level, the time required to establish a floor-to-ceiling layer of gas with a uniform gas concentration is short. In other words, it is incorrect to assume that, following the onset of leakage, a layer of high concentration is formed at the ceiling, which gradually increases in thickness, banking down as time. While a plume of a natural gas may rise to the ceiling when the gas is first released, the British Gas experiments show that when the gas is released at some point below the ceiling, a layer of essentially uniform concentration is formed between the point of leakage and the ceiling very quickly because of the dispersion due to turbulent mixing and dilution.

⁸ The research and the results were published by British Gas in a book authored by Dr. R.J. Harris titled The Investigation and Control of Gas Explosions in Buildings and Heating Plant. The book, published in 1983, is out of print, but can be found in libraries and with used book sellers.



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Harris further points out that for leaks of heavier-than-air gas, like propane, the concentration profiles within minimally ventilated compartments would be inverted, with the uniform concentrations to be found below the level of a propane leak.

The British Gas experiments that involved significant ventilation (i.e., a steady infiltration and exfiltration of air in and out of the test compartment), showed that the natural gas concentration that was uniform throughout the test compartment gradually increased with time. In fact, the tests with ventilation showed that the gas concentration eventually reached a steady state value. Such a steady state condition meant that the flow of gas into the compartment was exactly equal to the flow of gas out of the compartment, and would remain at this constant concentration as long as the leak persisted, assuming of course that there was no ignition of the mixture in the compartment.

The British Gas experiments show that gas concentrations may, depending upon leak location, be characterized by a single value throughout the gas layer, which enables the engineer to consider the use of a single zone model when calculating the spread of a fugitive gas over time. Clearly, such a single zone model will cease to be of value if and when ignition occurs and multiple gas species at high temperatures enter the compartment. Finally, the concept that the gas concentration within that single zone will increase until a steady state level is reached is a transient phenomenon that must be examined next.

C. Gas Concentration as a Function of Time:

While the FDS and other CFD programs will calculate gas concentration as a function of time and space throughout the mesh of cells, the single zone model arising out of the British Gas experiments can allow the engineer to determine the gas concentrations as a function of time with a straight forward, exponential equation and a spreadsheet like Excel.

The exponential equation is known as the **perfect mixing equation**. Perfect mixing is a concept used in computer models to predict the behavior of a mixture of vapors or gases. Perfect mixing assumes that there are no spatial gradients in a given physical envelope, such as gradients in concentration, temperature or gas species. In other words, the concentration of a gas in a compartment, the temperature of the mixture in that compartment and the percentage of each gas species present, are assumed to be uniform throughout the entire compartment. The greater the degree of natural and forced ventilation within a room, the greater the degree of mixing that will actually occur in that room, and the more reasonable the perfect mixing assumption becomes.



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When natural and forced ventilation are present, it is reasonable to assume perfect mixing in a compartment when calculating the concentration of a fugitive gas as a function of time in that compartment. With perfect mixing, the engineer only has to deal with a single gas concentration value as a function of time for each room or compartment in the building being investigated. While the gas leak may originate in one room, and increase the gas concentration in that room, the air from the first room will then move into adjacent spaces with the first room's gas concentration as an input to the adjacent spaces, which will gradually increase the gas concentration in those adjacent spaces. In effect, each room, hallway or stairway in a building can be considered as part of a network to be examined for the gas spreads.

D. The Perfect Mixing Equation:

Input parameters to the perfect mixing calculation include not only the volume flow rate of gas into the compartment and the volume of the compartment, but also the volume flow rate of the air entering the compartment. The two variables in the perfect mixing equation are the gas concentration in the compartment and time measured from the onset of the leak.

The perfect mixing equation can be stated as:

$$C = [Q_g / (Q_a + Q_g)] \cdot [1 - e^{-\frac{(Q_a + Q_g)t}{V}}]$$

where C is the concentration level of the gas in the compartment expressed as a decimal, Q_g is the volume flow rate of gas into the compartment, Q_a is the volume flow rate of air into the compartment, V is the volume of the compartment and t is the time measured from the onset of the gas flow Q_g . Since Q_g , Q_a and V are considered as constant in this equation, then it can be seen that C is a function of time from the onset of the leak. The complete derivation of the perfect mixing equation is shown in Appendix A below.

The equation as stated above consists of two terms (here bracketed) that are multiplied together. The second term, the only term in which time is found as a variable, contains an exponential term which needs to be examined more closely.

At the outset of a leak, when $t = 0$, the exponential term becomes $[1 - e^0] = [1 - 1] = 0$, which makes the concentration $C = 0$. In other words, at the start of the leak the uniform gas concentration throughout the compartment is zero.



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Again, examining the exponential term, it is clear that with the passage of time the negative exponent of e grows larger, eventually approaching infinity. As the leak time approaches infinity, the exponential term becomes:

$$\left[1 - e^{-\frac{(Q_a+Q_g)t}{V}} \right] = \left[1 - \left\{ \frac{1}{e^{\frac{(Q_a+Q_g)t}{V}}} \right\} \right] = \left[1 - \left\{ \frac{1}{e^\infty} \right\} \right] = \left[1 - \left\{ \frac{1}{\infty} \right\} \right] = [1 - 0] = 1$$

and the entire perfect mixing equation becomes:

$$C = [Q_g / (Q_a + Q_g)]$$

This first bracketed term, being a constant, can be called the steady state term because it represents the constant value of gas concentration within the chamber when the transients have passed away and the flow of gas into the chamber is exactly equal to the flow of gas out of the chamber.

When the perfect mixing equation is plotted on a concentration versus time graph, it is seen that the concentration starts at the onset of the leak with a rapid growth, but slows down as time passes, and then asymptotically approaches the steady state value of concentration. This is consistent with the British Gas experiments where the gas concentration in ventilated spaces gradually increased and approached a steady state level.

The determination of the steady state concentration depends upon determination of the rate of flow of gas into the compartment. In many cases, the engineer is able to determine the gas leak rate even after a fire or explosion has occurred. For example, the rate of gas flow through a leak in a building's gas system that has been found after a fire or explosion may be determined by reintroducing gas into the building's system and observing the movement of the gas meter.

E. The Steady State Term in the Perfect Mixing Equation:

The steady state term enables the engineer to determine whether or not a long term gas leak would even reach a flammable mixture and be capable of ignition. For example, if the natural gas flow rate into a room is 2 cubic feet per minute (cfm) and the air flow into the room is 150 cfm, the steady state concentration in that room would be:

$$C = \left[\frac{100Q_g}{(Q_a + Q_g)} \right] = \left[\frac{100 \times 2}{(150 + 2)} \right] = \frac{200}{152} = 1.32\%$$



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which is clearly below the LFL, and therefore not ignitable.

This leads to the question of how large a leak is required before a flammable mixture can be achieved. The answer is to solve for Q_g when C is known. Using the LFL for natural gas of 5%, and the same air flow rate of 150 cfm used in the above example, the steady state term is rearranged to give:

$$Q_g = Q_a \times \left[\frac{C}{(100 - C)} \right] = 150 \times \left[\frac{5}{(100 - 5)} \right] = 7.89$$

That gas flow rate 7.89 cfm is 5% of the 152 cubic feet per minute (air plus gas) that exits the compartment. The conclusion from this example is that if the gas flow rate as a percentage the air plus gas flow rate out does not exceed the LFL, a flammable mixture cannot be achieved

The steady state term can also be stated qualitatively as well as quantitatively. The gas concentration at steady state is equal to the gas flow rate as a percentage of the total outflow rate of gas plus air.

VI. Using the Perfect Mixing Equation in an Example of a Gas Leak

To demonstrate how the Perfect Mixing Equation might be used in the investigation of a gas incident, the spread of gas from a leak in a hypothetical house is analyzed. Such an analysis may help in the development of a timeline relating to when the leak started, as well as in an understanding of the size of the leak. Such information might be used in the determination of the cause of the leak.

A. Dimensions:

The structure in this example is assumed to be a single story house, having exterior dimensions of 20 feet by 30 feet, with no basement and with 8 feet high ceilings. The volume of the house is then 4,800 cubic feet. The house is assumed to have an air exchange rate of 0.5 ACH. Therefore, the air infiltration rate into the house, Q_h , will be 2,400 cubic feet per hour. The hypothesized gas leak is in the kitchen, where the gas appliances are located.

B. Infiltration Assumption:

It is further assumed that the air infiltration is evenly distributed around the entire perimeter of the house, coming in through the openings and cracks in all the exterior house walls. It is finally



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assumed that the kitchen and dining area together can be considered as a compartment having a volume one fourth the entire 4,800 cubic feet of the house, or 1,200 cubic feet, and that the exterior walls of the that compartment are one fourth the entire perimeter area. Therefore, one fourth of the entire Q_h of 2,400 cubic feet per hour entering the house, or 600 cubic feet per hour, designated as Q_a , will enter the kitchen area.

C. The Terms in the Equation:

Looking at the Perfect Mixing Equation,

$$C = [Q_g / (Q_a + Q_g)] \cdot [1 - e^{-\frac{(Q_a + Q_g)t}{V}}]$$

Q_a , the air flow rate into the compartment is 600 cubic feet per hour, V is the volume of the compartment, t is the time measured from the onset of the leak, and Q_g is the flow rate of the gas leak, also expressed in cubic feet per hour.

D. Three Leak Rates:

Using a spreadsheet, the gas concentrations as a function of time were determined for three different natural gas leak rates, and then plotted on a graph to show those concentrations over time.

The first gas leak rate is taken as 18 cubic feet per hour. Since natural gas has 1000 Btu per cubic foot, the leak is 18,000 Btu/hour. To put this leak in perspective, a single stove top burner will use 9,000 Btu/hour when fully open. A leak of 18,000 Btu/hour is therefore numerically equal to the amount of gas that could be flowing to two stove top burners.

The second gas leak rate is taken as 40 cubic feet per hour, which represents a gas leak of 40,000 Btu/hour. To put this in perspective, the normal gas input rating of a 40 gallon water heater is around 40,000 Btu/hour.

The third gas leak rate is taken as 100 cubic feet per hour, which represents a gas leak of 100,000 Btu/hour, which could be the input rating for the central furnace in a house about the size of the example house.

Other leak rates could be used, but these three were chosen to give order of magnitude perspective to leaks that might be encountered.

Extremely small leaks, such as leaks equivalent to the gas flow on a stove top pilot light, i.e., about 0.5 cubic feet per hour, will be seen for their insignificance. By contrast, extremely large



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leaks, such as those associated with an open valve directly into a gas line, or a broken joint in a gas line, can put out gas far in excess of the leak rates being considered in this example.

E. Elapsed Time:

The example will be run for a period of 390 minutes, or 6.5 hours. While this example does not involve ignition, it does show how long gas leaks can exist before an ignitable mixture is reached in the compartment, or if an ignitable mixture can be reached at all, even when the leaking gas is detected by smell.

In the spreadsheet, each cell that contains a gas concentration above the Lower Flammable Limit is highlighted in yellow.

The results of the spreadsheet calculations and the graph are seen on the next page.



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Gas Concentration Using Perfect Mixing Equation

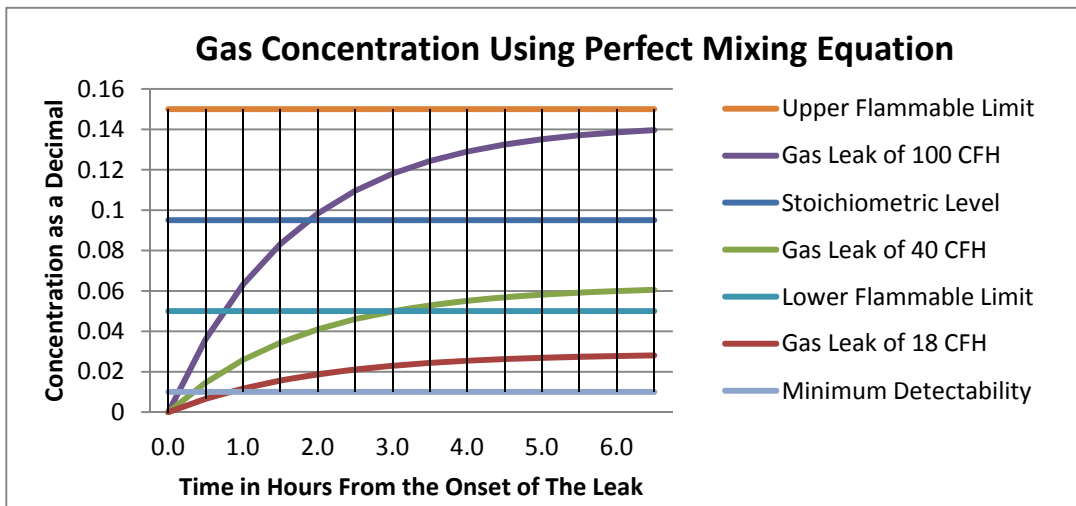
$V = 1200$	ft^3	$Q_a = 150$	ft^3/hr
$k = 0.5$	ACH	$Q_{g1} = 18$	ft^3/hr
$Q_h = 600$	ft^3/hr	$Q_{g2} = 40$	ft^3/hr
$Q_a/Q_h = 0.25$		$Q_{g3} = 100$	ft^3/hr

$$C = [Q_g / (Q_a + Q_g)] \cdot [1 - e^{-\frac{(Q_a + Q_g)t}{V}}]$$

$Q_{g1} = 18$ $Q_{g2} = 40$ $Q_{g3} = 100$

t = 0	minutes	or	0.000	hours	C = 0.000	C = 0.000	C = 0.000
t = 30	minutes	or	0.500	hours	C = 0.007	C = 0.015	C = 0.036
t = 60	minutes	or	1.000	hours	C = 0.012	C = 0.026	C = 0.063
t = 90	minutes	or	1.500	hours	C = 0.016	C = 0.034	C = 0.083
t = 120	minutes	or	2.000	hours	C = 0.019	C = 0.041	C = 0.098
t = 150	minutes	or	2.500	hours	C = 0.021	C = 0.046	C = 0.110
t = 180	minutes	or	3.000	hours	C = 0.023	C = 0.050	C = 0.118
t = 210	minutes	or	3.500	hours	C = 0.024	C = 0.053	C = 0.124
t = 240	minutes	or	4.000	hours	C = 0.025	C = 0.055	C = 0.129
t = 270	minutes	or	4.500	hours	C = 0.026	C = 0.057	C = 0.133
t = 300	minutes	or	5.000	hours	C = 0.027	C = 0.058	C = 0.135
t = 330	minutes	or	5.500	hours	C = 0.027	C = 0.059	C = 0.137
t = 360	minutes	or	6.000	hours	C = 0.028	C = 0.060	C = 0.139
t = 390	minutes	or	6.500	hours	C = 0.028	C = 0.061	C = 0.140

Steady State Concentration C = 0.029 C = 0.063 C = 0.143





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F. Four Observations from the Results:

The graph shows four straight lines, each corresponding to a known concentration. The highest line is the Upper Flammable Limit, which for natural gas is 15%. The second line from the top is the stoichiometric level, which for natural gas is 9.5% gas. The third line from the top is the Lower Flammable Limit, which for natural gas is 5%. The lowest line, labeled Minimum Detectability, represents the lowest concentration of gas in air that must have an odor detectable to the average person.⁹ This concentration for natural gas is 1% gas.

The first observation is that the gas concentration resulting for each of the three different leak rates may increase with time, but each such concentration gradually levels off as time passes, and asymptotically approaches its steady state concentration, as seen in both the graph and the spreadsheet.

The second observation is that any gas leak rate having a steady state concentration below the Lower Flammable Limit will never reach the Lower Flammable Limit, no matter how long the leak lasts. This observation also holds for any leak having a steady state concentration below the detectability level, and also means that such leak rates may be too small to even reach a detectable level in the room where the leak is taking place. Unlit pilots on a gas stove top are such leaks, and are usually only smelled by a person very close to the unlit pilot. This point cannot be overemphasized to the forensic engineer because there are still fire investigators who will maintain that such small leaks, given enough time, will reach ignitable levels.

While both the 40 CFH and the 180 CFH leak rates may reach steady state concentrations within the Flammable range, the third significant observation from both the graph and the spreadsheet is that it takes 3 hours for the 40 CFH leak rate to reach the Flammable range, while it only takes 1 hour for the 180 CFH leak rate to reach the Flammable range. Since each of the yellow cells in the spreadsheet indicates an ignitable mixture, it is clear then that the greater the leak rate, the sooner the gas-air mixture will reach ignitability.

A fourth significant observation comes from the steady state concentrations of both the 40 CFH and 180 CFH leak rates. The 40 CFH leak rate, while in the Flammable range, is below the Stoichiometric Level. Such a concentration results in a lean mixture, which can lead to an

⁹ Since both natural gas and propane vapor tend to be odorless, the law requires that an odorant be added to these fuel gases such that each is readily detectable by smell by the average person at all concentrations above 1/5 of the Lower Flammable Limit. For natural gas, that would make 1% gas the detectable limit, and for propane it would mean 0.42%. Common gas industry practice is to over-odorize, so gas is frequently detected at concentrations lower than 1/5 the LFL.



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explosion characterized by heaving walls but no follow-on fire. By contrast, the 180 CFH leak rate, also in the Flammable range, is above the Stoichiometric Level. Such a concentration results in a rich mixture, which can lead to an explosion with a follow-on fire.

While not shown in this example, a natural gas leak rate having a steady state concentration greater than the Upper Flammable Limit would show a concentration curve versus time that passes through the Flammable range to reach its steady state concentration above the Upper Flammable Limit.

G. Limitations of the Perfect Mixing Equation:

While gas concentrations above the Upper Flammable Limit as well as those below the Lower Flammable Limit will not ignite, it is essential to keep in mind that the above analyses are based on the cited assumptions, the most important being the assumption that the gas concentration is uniform throughout each compartment being modeled and examined. This analysis, while helpful in establishing average concentration levels as a function of time, does not enable the engineer to establish when or where ignition takes place. Ignition occurs when an ignitable mixture is in the presence of a competent ignition source.¹⁰

H. Perfect Mixing Equation Does Not Predict Ignition:

Gas concentrations above the Upper Flammable Limit that may escape from a compartment into the outside atmosphere can mix with air in the immediate vicinity and produce local areas within the Flammable Range. If a competent ignition source is present in that area, there can be an ignition. Likewise, at points where outside air can enter the compartment filled with gas concentrations above the Upper Flammable Limit, such air can also mix with the gas in the immediate vicinity and produce local areas within the Flammable range. If ignition sources exist in such local areas, ignition may occur.

Further, while gas concentrations below the Lower Flammable Limit will not ignite, it is important to keep in mind that the above analysis is based on the assumption that the gas concentration is uniform in any compartment, i.e., a spatial average concentration level in that compartment. While the spatial average concentration in the compartment where the gas is

¹⁰ A competent Ignition Source is defined as an ignition source that has sufficient energy and is capable of transferring that energy to the fuel long enough to raise the fuel to its ignition temperature. Not all energy sources are competent ignition sources. A lit cigarette, for example, is usually not a competent ignition source for fugitive fuel gases, while the match or lighter that provided the flame to light the cigarette invariably is competent.



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being released may be below the Lower Flammable Limit, the gas concentration at the gas release point is 100%. The concentration of the spreading, dispersing and diluting gas drops rapidly as it moves out into the compartment. However, at some point near the edge of the spreading cloud of gas-air mixture, the gas concentration will be in the flammable range. If this spreading gas finds a competent ignition source, ignition may follow, even if the average concentration in the room is below the Lower Flammable Limit.

VII. Relating Explosion Damage to Explosion Overpressure

Having now developed an understanding of how the movement, concentration and quantity of a fugitive fuel gas affect the explosion pressure and any follow-on fire in a building, it is time to see how the observed damage after a building explosion may relate to the amount and concentration of gas present.

Interior overpressure, or the interior pressure greater than atmospheric that results from an explosion inside a rigid container, can be tied theoretically to the amount of gas present in a fixed volume, as discussed earlier in this course. However, tying the overpressure to an observed level of explosive damage to a normal structure is not something that can be readily calculated. Empirical data, however, does exist that ties levels of overpressure to observed explosive damage. The test results reported over the years by various agencies is conveniently published as a table in the National Fire Protection Association's document NFPA 921, Guide to Fire and Explosion Investigations.¹¹ Below is a table of structural damage criteria reported by F. Lees.

¹¹ NFPA 921, Table 23.14.4.1.5(b) Property Damage Criteria



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Structural Damage Criteria As reported by F. Lees, Loss Prevention in the Process Industries, 1996	
Overpressure in psig	Damage
0.15	Typical pressure for glass failure
0.7	Minor damage to house structures
1.0	Partial demolition of houses, made uninhabitable
2.0	Partial collapse of walls and roofs of houses
2.5	50% destruction of brickwork of house
3.0	Steel frame building distorted, pulled away from foundations
4.0	Cladding of light industrial buildings ruptured
5.0–7.0	Nearly complete destruction of houses
10	Probable total destruction of buildings

To put these overpressure values in context, recall that the ignition of fuel gases in constant volume containers in the lab has shown that absolute pressures near 110 psia, or gauge pressures near 95 psig, could be achieved in fixed volume containers. While a building may be considered as a constant volume container, the relatively low values of overpressure simply mean that normal structures come apart long before the maximum confined pressure can be reached and that the released combustion products can now expand unconfined in the atmosphere.

This study is now completed by correlating five examples of explosion damaged buildings with their probable gas concentration levels at ignition.



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VIII. Examples of Fugitive Gas Explosions

Example 1:



The structure of this two story house was primarily intact, the exception being the first floor wall on the front of the house that has been blown outward. No other first floor walls were damaged by explosion. There was no explosion damage on the second floor. There was extensive fire damage on both first and second floor before the fire was subdued, which prevented complete destruction of the house. The fugitive fuel was natural gas, which was released into the first floor area where it reached an explosive mixture. The follow-on fire had sufficient fuel to damage the first floor area and to migrate upward as a rising fire ball to damage the second floor. The minimal explosive damage combined with the heavy burn damage on both floors indicates a rapidly released gas with a concentration at ignition near the Upper Flammable Limit. A slow gas release normally gives rise to an explosive mixture on upper floors.



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Example 2:



The structure of this two story house was completely destroyed by an explosion of propane vapor that had been released inside the house. The debris field is seen around the house. The magnitude of the pressure and, more importantly, the rate of pressure increase were great enough to blow the roofing off of the framing, which is visible in the photo. The only follow-on fire was in the vicinity of the propane leak, and that fire self-extinguished. The bulk of the structure sustained no burn damage. The high rate of pressure increase and the minimal burning indicate a propane concentration near the stoichiometric but on the lean side of the stoichiometric, except for the location of the leak. The fact that roofing and siding were blow off from all sides of the house, and not just from the area near the leak, suggests that the leak rate was approaching asymptotic, indicating that the propane had been leaking for some time.



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Example 3:



This house was completely destroyed by a propane vapor explosion originating in the basement. The debris field was far and wide. The wide-spread debris, mostly broken pieces of structure, was unburned. By contrast, the broken debris that remained within the house foundation was heavily consumed by the follow-on fire. Burn marks are also seen on the interior surface of the foundation wall. The extensive debris field, the damage to the concrete foundation walls and the heavy follow-on fire indicate that the propane concentration in the basement was near stoichiometric on the rich mixture side of stoichiometric.





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Example 4:



This house was destroyed by a natural gas explosion. The exterior walls were pushed outward and laid next to the foundation. The roof, visible on the lower left of the above photo, was also laid out intact, unlike the house in example 2 above where the roofing was blown off the framing. This house shows a lower rate of pressure increase than that seen in the house of example 2. Interior walls for the most part remained in place. There was a small area of follow-on fire in the vicinity of the gas leak, but no extensive burning. The type and level of damage indicated the ignition of a lean mixture of gas in air close to the Lower Flammable Level.





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Example 5:



One half of this house, on the left, had a basement, the other half, on the right, did not. The explosion did not create a wide debris field, but merely pushed all of the exterior walls to the ground adjacent to the edges of the house. The fire completely burned the wooden structure of the house, the burn debris falling into the basement at the left, the burn debris falling to slab level at the right. The fugitive fuel was natural gas that entered the basement from an exterior leak. The gas had to migrate up to the first floor, and then spread to the section of the house above the slab.

This damage, i.e., pushed out walls with extensive follow-on fire, indicates a rich mixture close to the Upper Flammable Level of 15% natural gas. Also, the walls were laid down all around the perimeter of the house indicating that the outward explosive force was uniform throughout, which means that the gas concentration was close to uniform throughout the house. This would indicate that the gas concentration within the structure was at or near its steady state value.

In the hypothetical spreadsheet and graph developed above for natural gas, a leak rate of 100 CFH was seen to asymptotically approach the Upper Flammable Level after about 5 to 6 hours of leakage. This time frame fit with the facts in the case, and such a high leak rate was possible in the line break that was found.



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Appendix A

Derivation of the Perfect Mixing Equation

A room of volume V has an air flow into the room due to the infiltration of outside air. The volume flow rate of this incoming air is a constant, Q_a . It is assumed that a natural gas leak begins at time $t = 0$, and that the volume flow rate of this gas is also a constant, Q_g . Assume that the total volume flow rate of air and gas into the room, i.e., $Q_a + Q_g$, is at all times equal to the volume flow rate of the gas and air mixture out of the room. Assume also that the concentration of gas in the outflowing gas-air mixture is the same as the concentration within the room.

Using C to represent the decimal concentration of the gas within the room, the total volume of gas inside the room at any point in time will be $C \cdot V$. While the flow rate of natural gas into the room is Q_g , the flow rate of natural gas out of the room is the total outflow rate times the gas concentration in the room, $C \cdot (Q_a + Q_g)$. Expressed qualitatively, the gas that enters the room either stays in the room or leaves. Clearly, at the onset of a leak, the gas is entering faster than it is leaving through ventilation to adjacent spaces. This is the mechanism that will increase the room's gas concentration as time passes after a leak is established.

Consider a small time step dt during which a small quantity of gas, $Q_g \cdot dt$, enters the room, and a small quantity of gas leaves the room, $C \cdot (Q_a + Q_g) \cdot dt$. During that same time step dt , a small change in the volume of gas in the room, $V \cdot dC$, occurs. This can be expressed as

$$V \cdot dC = Q_g \cdot dt - C \cdot (Q_a + Q_g) \cdot dt = [Q_g - C \cdot (Q_a + Q_g)] \cdot dt$$

Rearranging terms, the equation becomes

$$dC/[Q_g - C \cdot (Q_a + Q_g)] = 1/V \cdot dt$$

From a table of integrals, it is known that

$$\int dx/(ax + b) = (1/a) \cdot \ln(ax + b)$$

Using $x = C$, $a = -(Q_a + Q_g)$ and $b = Q_g$, and integrating both sides of the equation,

$$\int dC/[Q_g - C \cdot (Q_a + Q_g)] = \left[-\frac{1}{Q_a + Q_g} \right] \cdot \ln[Q_g - C \cdot (Q_a + Q_g)] = \frac{t}{V} + Constant$$



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Applying the initial condition that $C = 0$ at $t = 0$,

$$\text{Constant} = [-1/(Q_a + Q_g)] \cdot \ln[Q_g]$$

The integral then becomes

$$[-1/(Q_a + Q_g)] \cdot \ln[Q_g - C \cdot (Q_a + Q_g)] = \frac{t}{V} + [-1/(Q_a + Q_g)] \cdot \ln[Q_g]$$

Rearranging terms and consolidating the natural logarithms,

$$\left[-\frac{1}{Q_a + Q_g} \right] \cdot \{ \ln[Q_g - C \cdot (Q_a + Q_g)] - \ln[Q_g] \} = \frac{t}{V}$$

$$\left[-\frac{1}{Q_a + Q_g} \right] \cdot \ln\left[\frac{Q_g - C \cdot (Q_a + Q_g)}{Q_g} \right] = \frac{t}{V}$$

$$\ln\left[\frac{Q_g - C \cdot (Q_a + Q_g)}{Q_g} \right] = -(t/V) \cdot (Q_a + Q_g)$$

Using the relationship between natural log and e,

$$\frac{Q_g - C \cdot (Q_a + Q_g)}{Q_g} = e^{-(Q_a + Q_g)t/V}$$

Solving for C,

$$C = [Q_g/(Q_a + Q_g)] - [Q_g/(Q_a + Q_g)] e^{-(Q_a + Q_g)t/V}$$

Collecting common factors, the result is

$$C = [Q_g/(Q_a + Q_g)] \cdot \left[1 - e^{\frac{-(Q_a + Q_g)t}{V}} \right]$$