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Air Drilling in the Presence of Hydrocarbons: A Time for Pause

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Abstract

Drilling with compressed air continues to enjoy vast popularity. It is often the application of choice in dry, hard rock because the drilling fluid medium is inexpensive and, compared to water or weighted drilling mud, respectable rates of penetration can be achieved. In terms of economic considerations with respect to drilling fluid expenditures, air drilling has virtually no equal. However air drilling is not without its impediments; not the least of which is its reactivity with hydrocarbons.

Historical Perspective

The first recorded use of drilling with compressed air is in the early 1860’s where a piston-type compressed air mechanical drill bit bored an 8-mile long Mount Cenis Tunnel in the Alps. In the late 1940’s and early 1950’s, air drilling became a popular departure from standard rotary drilling operations.

Safety Considerations

The application of drilling with compressed air provides many benefits, but misapplication of this technology has led to losses that include equipment both on the surface and downhole. More seriously, the most devastating of these losses are injuries to rig personnel and many times those injuries are fatal.

Is air drilling safe? Yes, as long as the laws of nature are not violated. For too long, some operators, drilling contractors, rig and service personnel have been under the mistaken impression that air drilling is somehow an inherently safer operation than conventional drilling over a broad range of applications. While that can be true, the basic fundamental chemical concept of the classical fire triangle (Figure 1) has often been ignored, discarded, neglected, or forgotten.

The fourth edition of flammability studies performed jointly in the 1920’s by the US Department of Interior, Bureau of Mines and the Safety in Mines Research Board of Great Britain was published in 1952. These classical studies describe the hazards of working in an oxygen-rich environment in the presence of hydrocarbons. As long as hydrocarbons are not encountered, air drilling can be just as safe as drilling with non-reactive liquid fluid media common to drilling operations, such as water, water base mud, oil base mud, or synthetic base mud, etc.

Fire is an oxidative process. Combustion can only occur when the three legs of the classical combustion triangle (Figure 1) are present.

Chemistry

Air is mixture of many gases as described in .Table 1. Within that mixture there is 21% of oxygen by volume to sustain life. However, the minimum oxygen concentration needed for combustion of methane is only 12% by volume at sea level (Figure 2).

The primary constituent of natural gas is methane (CH_4). In the presence of an ignition source the balanced stoichiometric chemical reactions are described below.

Where the oxidizing agent (oxygen) is in excess…

$$CH_4\ (\text{gas}) + 2O_2\ (\text{gas}) \longrightarrow CO_2\ (\text{gas}) + 2H_2O\ (\text{liq}) + \text{Heat} \quad \ldots\ldots (1)$$

In the presence of sufficient oxygen complete combustion of hydrocarbons occurs to create carbon dioxide, water, and heat.

Where the fuel (methane) is in excess…

$$CH_4\ (\text{gas}) + O_2\ (\text{gas}) \longrightarrow C\ (\text{solid}) + 2H_2O\ (\text{liq}) + \text{Heat} \quad \ldots\ldots (2)$$

When there is too much fuel or not enough oxygen, the chemical reaction cannot oxidize the hydrocarbons completely to carbon dioxide and water. The reaction yields carbon black, commonly known as soot, as a solid carbon product along with water and heat.

Reliability

When we turn on the gas to heat food on our reliable natural gas stove, we witness a controlled reaction between methane and oxygen in the presence of an ignition source that does not present an overt danger under normal use and operating conditions. The natural gas utility provider regulates the flow and pressure of the methane going into the residence. While the valve on the stove regulates on/off and gross flow, an orifice between the valve and burner also regulates the amount of methane to be combusted. Virtually every common purposeful combustion mechanism is strictly metered in some manner to exert control. Usually, it is the hydrocarbons that are restricted. Examples include not only burner tip, but carburetion and fuel injection.

Surface Release of Hydrocarbons

A release of natural gas from the wellbore, whether by accident or design, into the open atmosphere provides two of the three requirements of the combustion triangle for an explosion or fire. Ignition could come from virtually any energized source capable of creating a spark, including static electricity. The potential for a catastrophic incident increases because this type of reaction is uncontrolled. There is an unknown concentration of methane and other hydrocarbons in the wellbore, the pressure is not often known, the released amount of hydrocarbons escaped from the wellbore is not known or controlled to any degree, the rig is almost always open-air, and despite our Herculean efforts a potential ignition source always seems to be present.

If the methane released locally from the wellbore is a high concentration, too rich for immediate ignition, eventually it will be diluted in air and dispersed to become a potentially volatile, explosive, and combustible material. In the presence of an ignition source, the explosive nature of this chemical reaction will be uncontrolled until the fuel is completely combusted (Equation 1) (Figure 3). Air-Hydrocarbon mixtures have a maximum burning velocity when the concentration of fuel is slightly above stoichiometric.

Downhole Fires

Most downhole fires and explosions probably result from downhole detonations. When compressed air expands, the adiabatic expansion to the atmosphere creates a localized cooling effect. Conversely, when atmospheric air is compressed, the local temperature increases because of the compression of the air molecules in a confined space. This is known as adiabatic compression (Figure 4).

A typical mechanism proceeds as follows: compressed air exits the bit or downhole hammer, a productive pay is exposed usually producing condensate, a mud ring forms uphole creating an annular packoff. The air compresses in that space below the annular pack-off increasing the partial pressure of the oxygen content and supplementing the heat already in the confined space; add fuel from the condensate, and maybe a friction spark from the drill bit or downhole hammer – the result is a downhole detonation, very similar to that created in a diesel engine.

The overpressure created during an explosion depends on the ability for the flame front to accelerate and achieve high speeds. Obstacles and equipment within the wellbore are the chief contributors to flame acceleration. The turbulence induced by obstacles in the flame path actually increases the flame speed, creating a situation where the increased flame speed intensifies the turbulence. The high burning velocities create high overpressures. In some cases, that explosion is so violent and intense that it can collapse (actually flatten) and twist drilling tubulars. Often times there is little need to run a junk basket after a downhole detonation because the bottomhole assembly and bit disintegrate downhole due to the explosive overpressure and heat intensity.

The downhole detonation seems to occur more frequently in the presence of condensates, also known as “wet” gas. Figure 5 illustrates the autoignition temperatures for aliphatic hydrocarbons commonly produced. The ignition temperature tends to decrease with the number of carbons in the chain. An increase in pressure typically reduces the spontaneous ignition temperature.

Discussion

Numerous authors contend that it is acceptable practice to drill in the presence of “dry” gas. Figure 6 would seem to support that initial assertion as long as the combined adiabatic compression temperature <u>and</u> the Bottom Hole Static Temperature does not exceed 1000^{o}F <u>and</u> there is not another source for ignition, for example, friction. Friction ignition may come from any number of sources. Metal to metal friction of the drill bit and/or air hammer or metal to formation friction are some obvious examples. How many of us would bet our lives that the gas in the exposed wellbore during air drilling operations is absolutely dry? How do we assure ourselves that the gas-air mixture concentration is either above the Upper Explosive Limit (UEL) or below the Lower Explosive Limit (LEL) (Figure 7) (Table 2)? What kind of safety factors do we assign to compensate for any margin of error? What actions do we take to mitigate that risk?

An uncontrolled, accidental release of hydrocarbons into the atmosphere at a petrochemical refinery is a very serious safety incident and is not tolerated by management, by the public, and by regulatory bodies. It is not acceptable practice because tragic things tend to happen as a result. Is an accidental release of hydrocarbons on a drilling rig less dangerous than at a refinery? Operations cannot be considered safe just because generally recognized ignition sources have been eliminated. If air and fuel are permitted to mix in flammable proportions, it should be assumed that a source of ignition will somehow be provided. There is a high probability that escaped gas on a drilling site and in the presence of drilling equipment will come into contact with an ignition source. At least in a refinery environment, internal and regulatory statutes require Class I, Division 1 provisions for electrical safety. Class 1 Division 1 regulations are strictly adhered to on drilling rigs operating in offshore state or federal waters. The same fire zone classification exists over the wellhead on land rigs, but adherence to these regulations is typically more lenient.

The International Association of Drilling Contractors (IADC) has published a Well Classification System for Underbalanced Operations and Managed Pressure Drilling. On a Risk Level criteria from 0 – 5, air drilling for performance (rate of penetration) enhancement where no hydrocarbons are present is assigned the Level 0. Thereafter, the risk levels increase with operational complexity and potential well productivity. Those utilizing air drilling should keep in mind that even though air drilling is only specifically listed in the IADC document as an example under Risk Level 0, when hydrocarbons are present in an air drilling environment the Risk Level will be significantly higher (Table 3).

Conclusion

Drilling with air continues to be a very popular method of drilling. There are many advantages to drilling with air, especially in hard rock, non-hydrocarbon bearing and non water producing lithology. The question for every prudent engineer, operator, and contractor should be, “Is it technically appropriate to continue to drill with air when hydrocarbons are suspected of being present in the open wellbore?” There are many other underbalanced and managed pressure drilling techniques along with other fluid media that could be applied to mitigate the fire and explosive potential of mixing air and hydrocarbons in an uncontrolled manner.

From 1994-2003, the upstream oil and gas sector has had the dubious distinction of having a fatality rate 8.5 times higher than the average for all industries within the United States. There were 8 very specific recommended strategies described in SPE 94416 to modify our existing safety track record, of which seven are directly related to the theme of this discussion. As a reminder, they are listed below.

1. Get the Word Out
2. Develop Specific Training and Awareness Tools
3. Improve Accessibility
4. Partner Up
5. Apply Appropriate Technologies
6. Assess and Manage Risks
7. Drive Safely
8. Establish a New Culture

In an attempt to establish a new culture, the authors recommend that drilling operations and engineering assess and manage the risks associated with air drilling by applying the appropriate technologies for the prospective application. We recommend that air drilling be used for performance enhancement purposes in only non-hydrocarbon bearing lithology. Ideally, air drilling should cease just prior to exposing any hydrocarbon production zones.

Once a hydrocarbon zone is penetrated or suspected of being penetrated, air drilling should cease and another drilling fluid should be used. Alternates may include natural gas or nitrogen. Misting of the air is not a good option because it may contribute to the formation of mud rings downhole (Figures 8a and 8b). Changing the drilling fluid to natural gas or nitrogen will mitigate the occurrence of a downhole detonation, but will not necessarily diminish the explosion or fire potential from a release of commingled gaseous fluids at the surface from exposure to atmospheric oxygen.

In organizations that apply air drilling techniques, engineering and safety departments should make special efforts to frequently inform, educate, and train personnel on safe air drilling operations and make that information available to them on a continuing basis.

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SI Metric Conversion Factors

ft	x	3.048		E-01	=	m
in	x	25.4		E+00	=	mm
psi	x	6.894		E+03	=	N/m^2
^oF	-	32	x	5/9	=	^oC
Vol-%	x	1.0		E-02	=	m^3/m^3

Glossary

Autoignition Temperature	The lowest temperature at which a combustible material ignites in air without a spark or flame. Spontaneous Ignition Temperature.
Blast Pressure Front	The expanding leading edge of an explosion reaction that separates a major difference in pressure between normal ambient pressure ahead of the front and potentially damaging high pressure at and behind the front.
Boiling Point	The temperature at which the vapor pressure of a liquid equals atmospheric pressure or at which the liquid changes to a vapor. If a flammable material has a low boiling point, it indicates a special fire hazard.
Burning Velocity	Rate at which a flame from moves through a stationary flammable mixture.
Condensate	A low-density, high-API gravity liquid hydrocarbon phase that generally occurs in association with natural gas. Its presence as a liquid phase depends on temperature and pressure conditions in the reservoir allowing condensation of liquid from vapor. The production of condensate reservoirs can be complicated because of the pressure sensitivity of some condensates: During production, there is a risk of the condensate changing from gas to liquid if the reservoir pressure drops below the dew point during production. Reservoir pressure can be maintained by fluid injection if gas production is preferable to liquid production. Gas produced in association with condensate is called wet gas. The API gravity of condensate is typically 50 degrees to 120 degrees.
Deflagration	Propagation of a combustion zone at a velocity that is less than the speed of sound in the unreacted medium.
Detonation	Propagation of a combustion zone at a velocity that is greater than the speed of sound in the unreacted medium.
Dry Gas	Natural gas that does not have a significant content of liquid hydrocarbons or water vapor. Natural gas that occurs in the absence of condensate or liquid hydrocarbons, or gas that has had condensable hydrocarbons removed. Dry gas typically has a gas-to-oil ratio exceeding 100,000 scf/STB.
Explosion	The sudden conversion of potential energy (chemical or mechanical) into kinetic energy with the production and release of gas(es) under pressure. These high-pressure gases then do mechanical work such as moving, changing, or shattering nearby materials.
Fire	A rapid oxidation process, which is a chemical reaction resulting in the evolution of light and heat in varying intensities.
Flame Front	The leading edge of burning gases of a combustion reaction.
Flammable Limit	The upper or lower concentration limit at a specified temperature and pressure of a flammable gas or a vapor of an ignitable liquid and air, expressed as a percentage of fuel by volume that can be ignited.
Flash Point	The lowest temperature of a liquid, as determined by specific laboratory tests, at which the liquid gives off vapors at a sufficient rate to support a momentary flame across its surface. The lower the flash point the more volatile the substance.
Lower Explosive Limit	The terms lower flammable limit (LFL) and lower explosive limit (LEL) are used interchangeably in fire science literature. CFR 29, Section 1915.11(b). The lowest concentration of a gas or vapor that will support propagation of flame away from a pilot ignition source. The LEL is commonly measured in volume percent. By convention LFL values are reported for normal atmosphere of 21% by volume oxygen, at 25°C (77°F),

	and a pressure of 1 atmosphere (760 mm Hg) unless specified otherwise. The limit below which, the concentration of hydrocarbon gas in the air mixture is considered to be "too lean" i.e. insufficient hydrocarbon to support and propagate combustion.
Minimum Oxygen Concentration	Minimum oxygen concentration in air necessary to sustain flame propagation.
Stoichiometric	The quantitative relationship between reactants and products in a chemical reaction.
Upper Explosive Limit	The terms upper flammable limit (UFL) and upper explosive limit (UEL) are used interchangeably in fire science literature. CFR 29, Section 1915.11(b). The highest concentration of a vapor or gas that will ignite and burn with a flame in a given atmosphere, expressed in percent of vapor or gas in the air by volume. Above this limit the mixture is said to be too "rich" to support combustion. Above the UEL there is too little oxygen to sustain a flammable mixture.
Wet Gas	Natural gas containing significant amounts of liquefiable hydrocarbons. Natural gas that contains less methane (typically less than 85% methane) and more ethane and other more complex hydrocarbons.

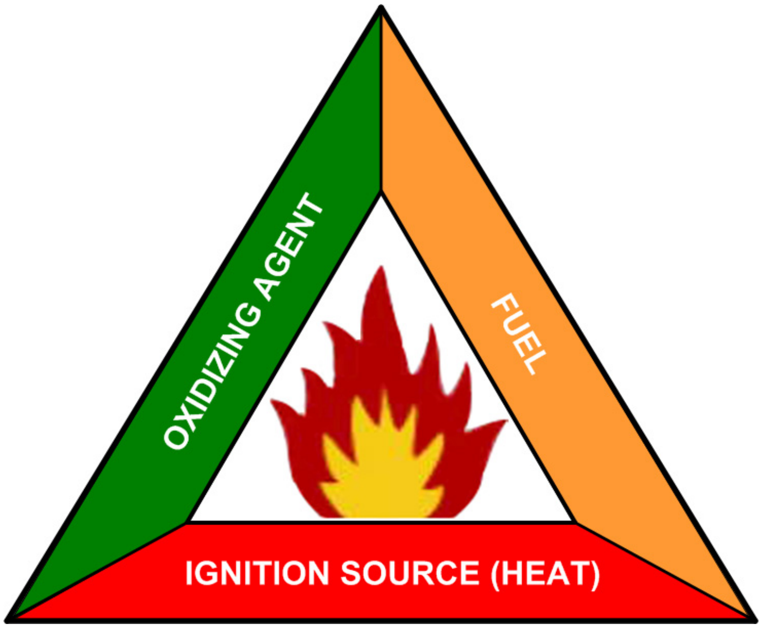
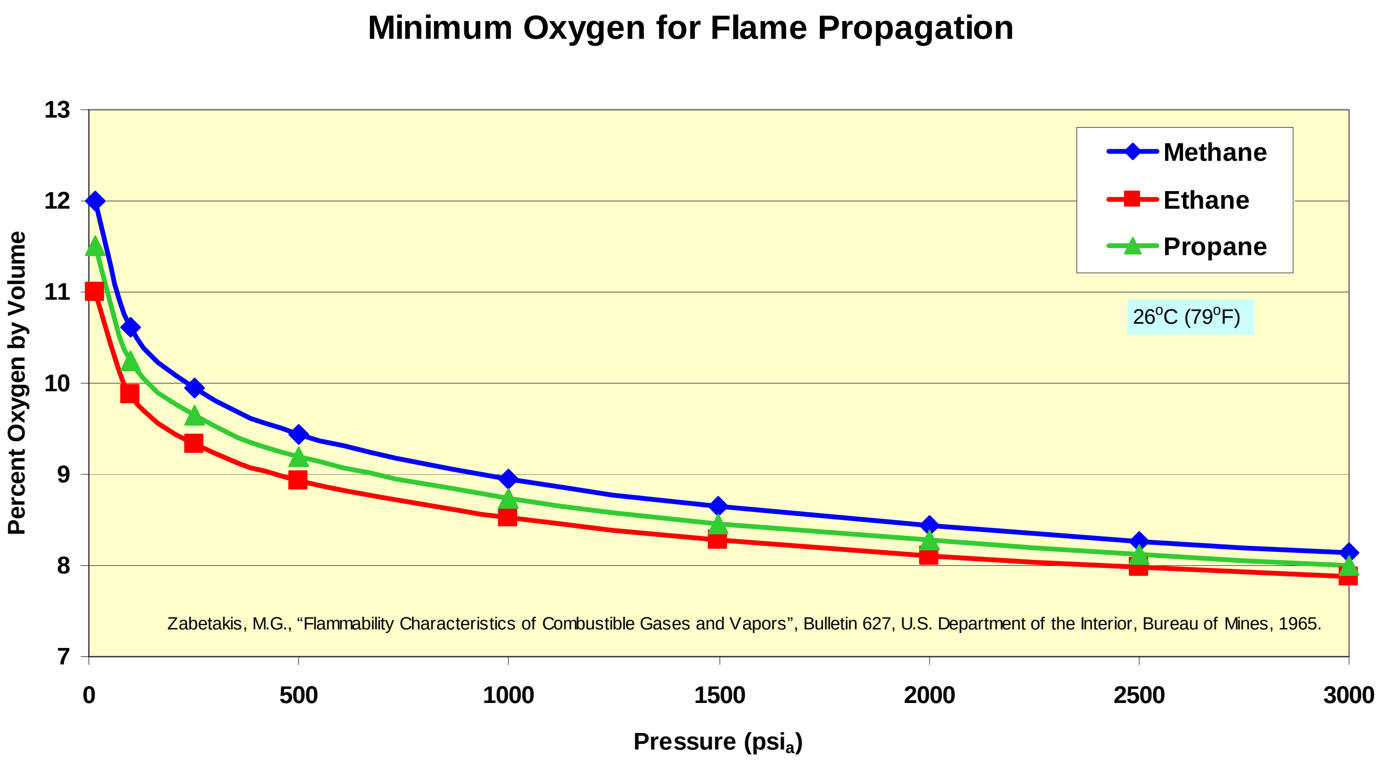


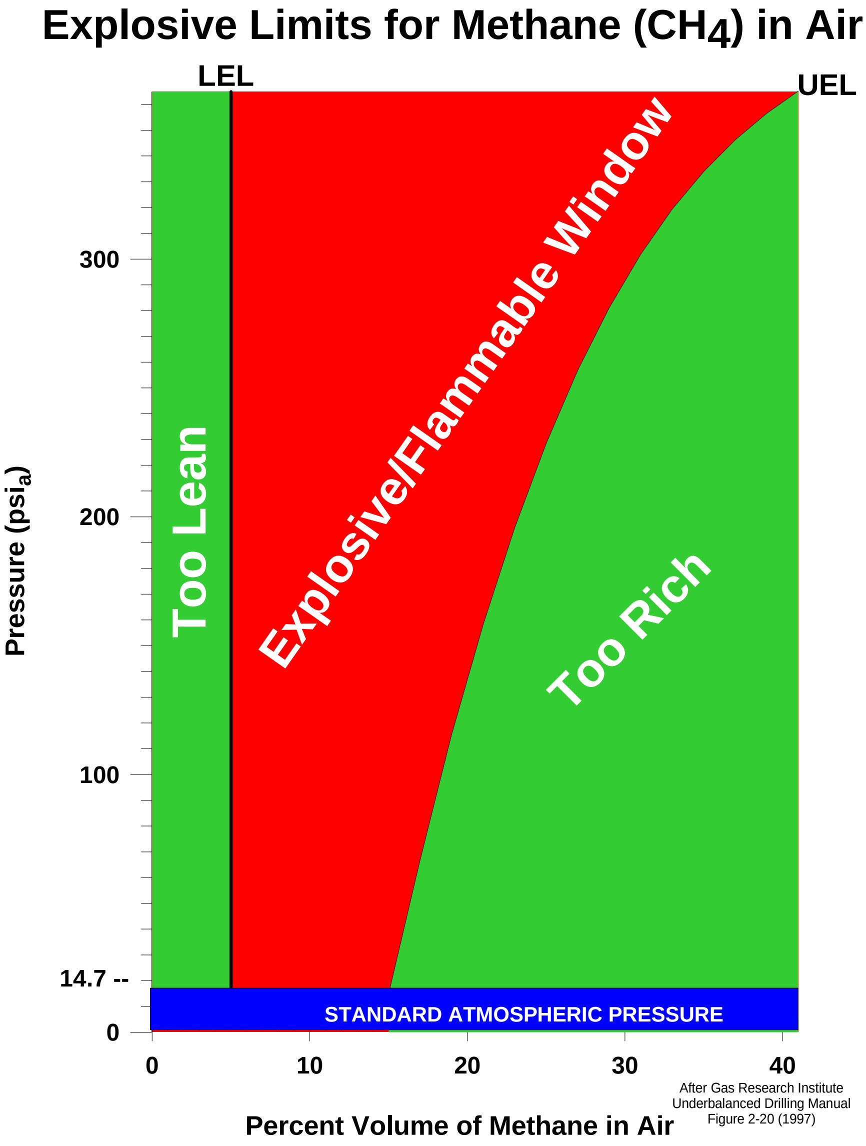
Figure1. Classical Combustion Triangle



26^{o}C (79^{o}F)

Zabetakis, M.G., “Flammability Characteristics of Combustible Gases and Vapors”, Bulletin 627, U.S. Department of the Interior, Bureau of Mines, 1965.

Figure 2. Minimum Oxygen Required for Flame Propagation of Methane, Ethane, and Propane at Pressure and 26^{o}C.



After Gas Research Institute
Underbalanced Drilling Manual
Figure 2-20 (1997)

Figure 3. Explosive Limits for Methane in Air

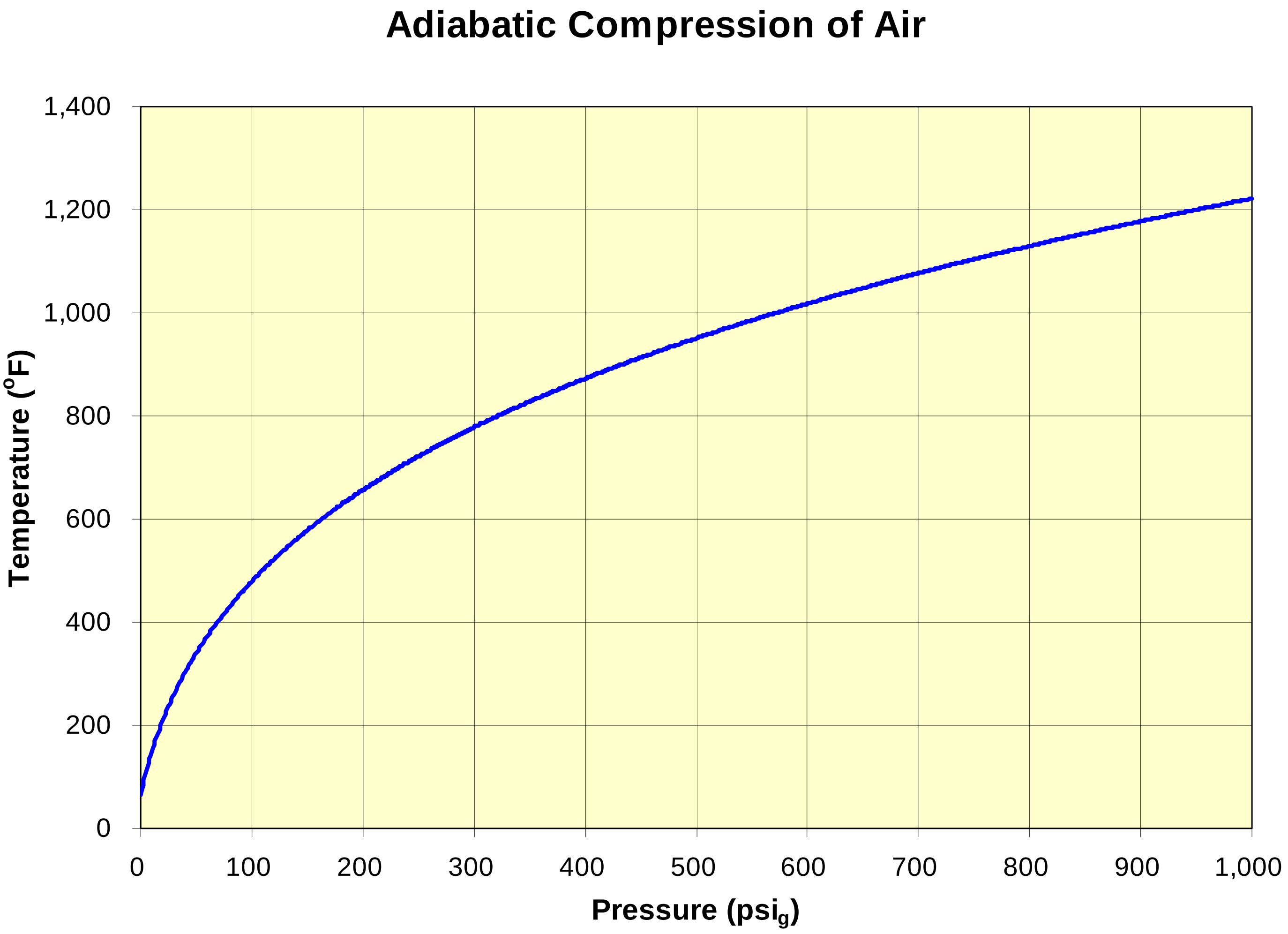


Figure 4. Temperature Increase Due to Adiabatic Compression of Air

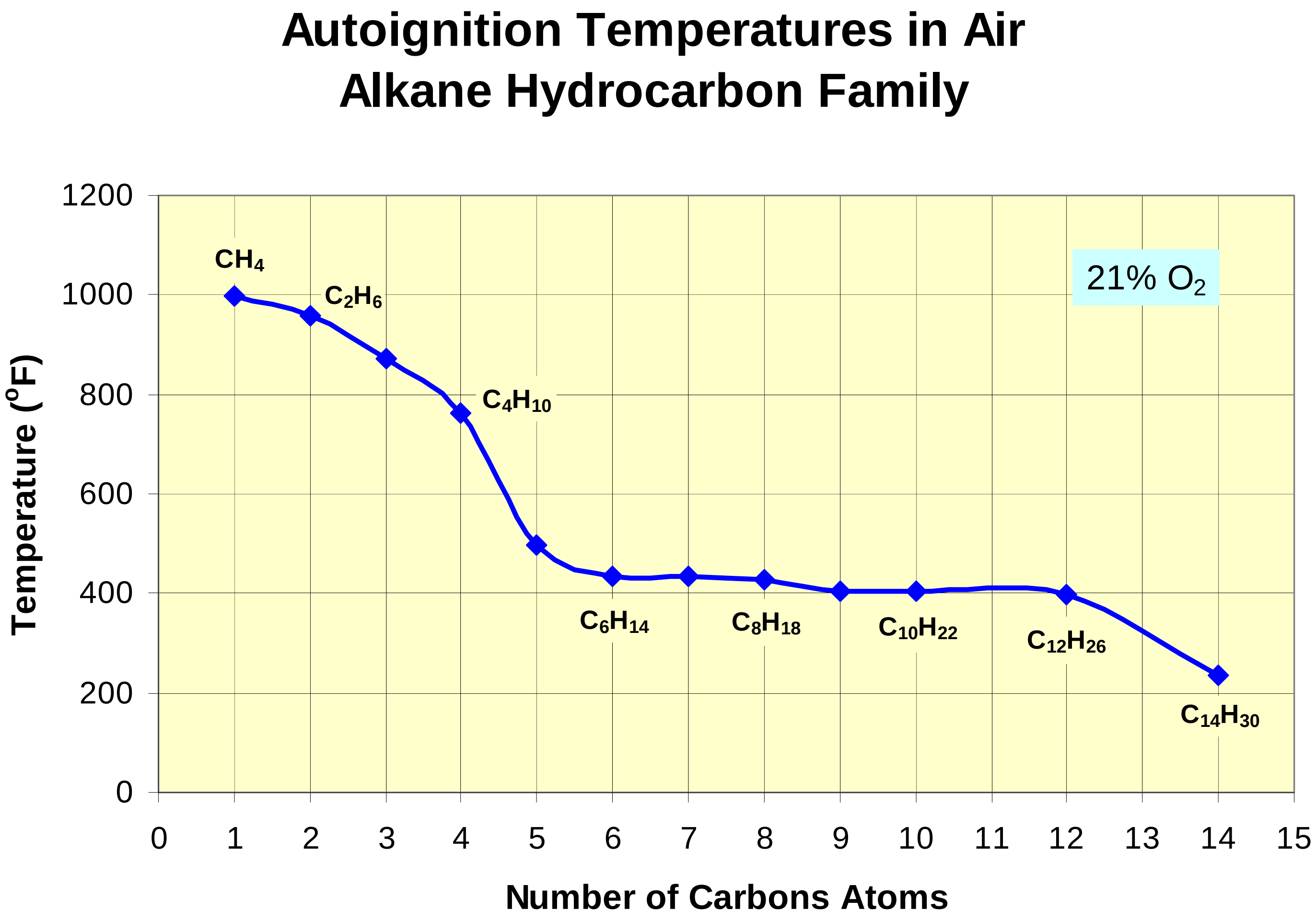


Figure 5. Autoignition Temperatures of Alkane Hydrocarbons Declines with Chain Length.

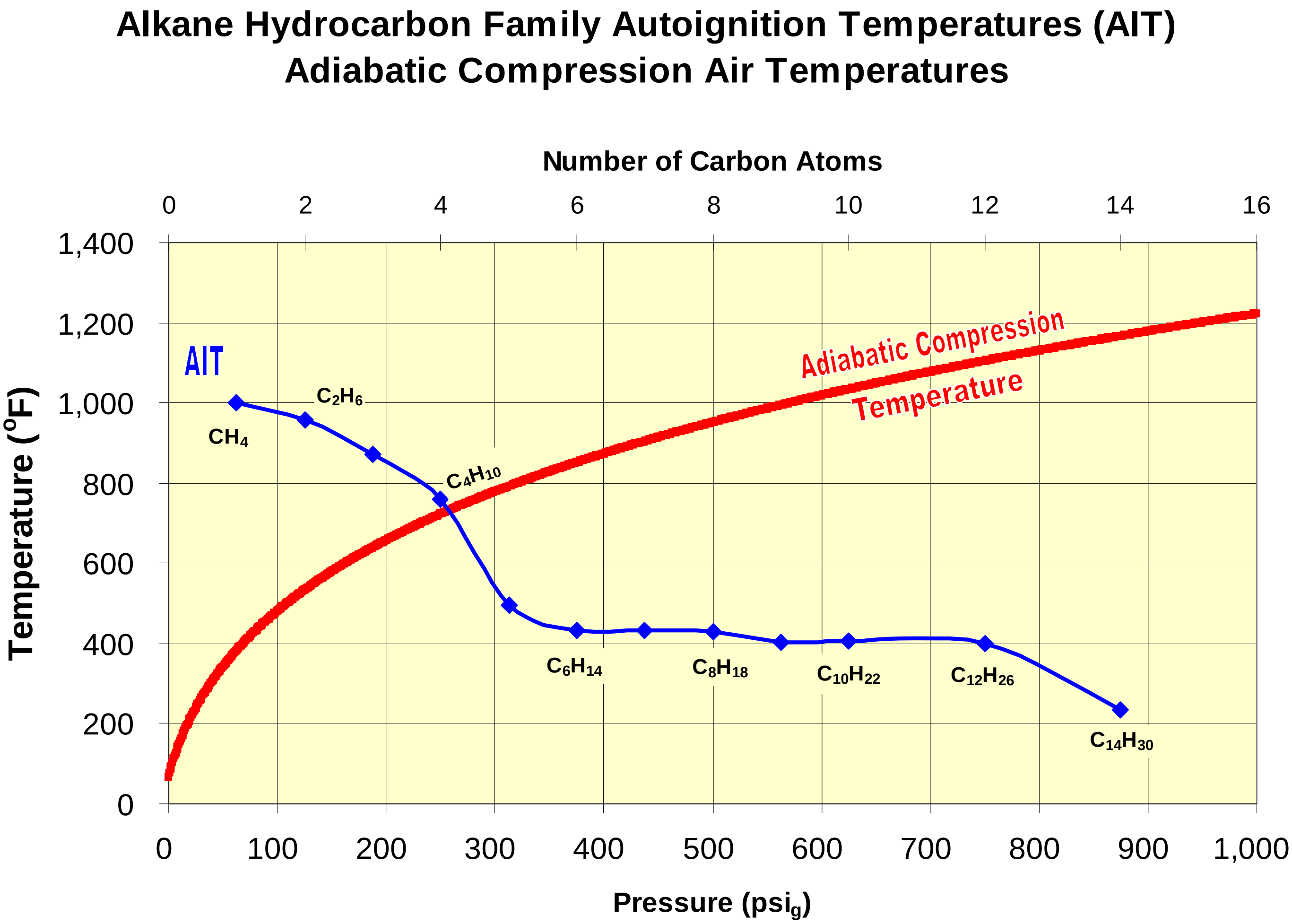


Figure 6. Autoignition Temperatures of Alkane Hydrocarbons Superimposed with Temperature due to Adiabatic Compression of Air.

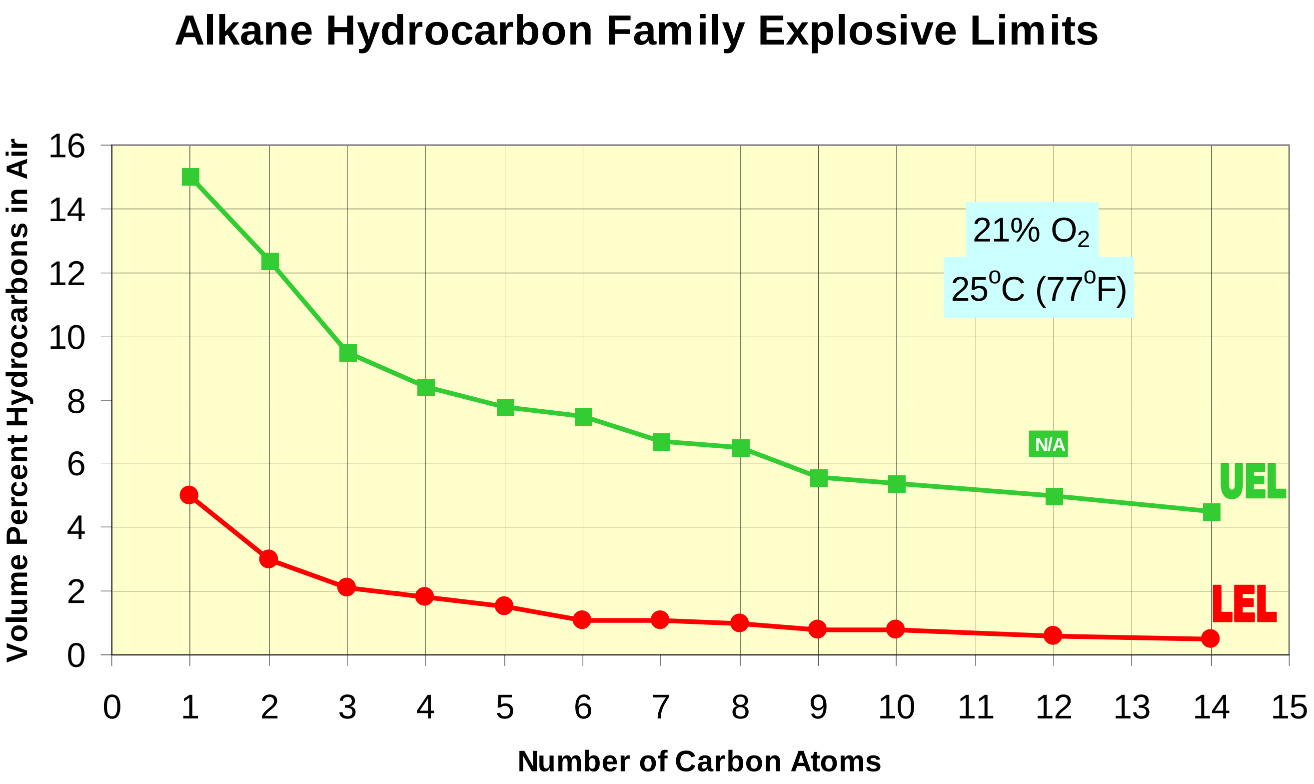


Figure 7. Upper and Lower Explosive Limits of Alkane Hydrocarbon Family decline with chain length. The range between UEL and LEL narrows with chain length.

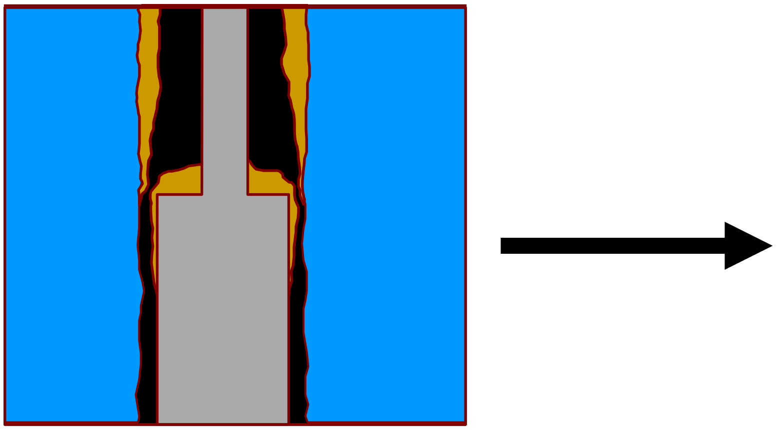


Figure 8a. Mud Ring Formation

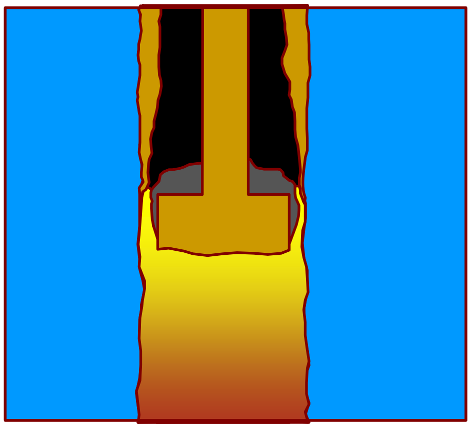


Figure 8b. Mud Ring Contribution to Downhole Detonation and Fire

Component		Molecular Mass (gm)	Volume Percent	Partial Pressure (mmHg)
Nitrogen	N_2	28.013	78.06	593.4
Oxygen	O_2	31.998	20.95	159.2
Argon	Ar	39.948	0.93	7.1
Carbon Dioxide	CO_2	43.999	0.03	0.2
		28.95 (avg)	99.99%	759.9

Table 1. Constituents of Air

Compound	Chemical Formula	AIT (^{o}F)	Flash Point (^{o}F)	Boiling Point (^{o}F)	LEL(%) in Air 21% O_2	UEL(%) in Air 21% O_2	Minimum Oxygen Concentration %
Methane	CH_4	999	-306.4	-258.7	5.0	15.0	12.0
Ethane	C_2H_6	959	-211.0	-127.8	3.0	12.4	11.0
Propane	C_3H_8	871	-155.2	43.8	2.1	9.5	11.5
n-Butane	C_4H_{10}	761	-101.2	31.1	1.8	8.4	11.5
n-Pentane	C_5H_{12}	496	-56.2	97.0	1.5	7.8	12.0
n-Hexane	C_6H_{14}	433	-9.4	155.7	1.1	7.5	12.0
n-Heptane	C_7H_{16}	433	26.6	209.1	1.1	6.7	11.5
n-Octane	C_8H_{18}	428	57.2	257.0	1.0	6.5	N/A
n-Nonane	C_9H_{20}	403	87.8	303.4	0.8	5.6	N/A
n-Decane	$C_{10}H_{22}$	406	114.8	345.4	0.8	5.4	N/A
n-Dodecane	$C_{12}H_{26}$	399	165.2	421.2	0.6	N/A	N/A
n-Tetradecane	$C_{14}H_{30}$	235	210.2	485.7	0.5	4.5	N/A

Table 2. Physical Properties of Alkane Family Compounds

Level	Description
0	Performance enhancement only; no hydrocarbon containing zones. • Air drilling for ROP enhancement
1	Well incapable of natural flow to surface. Well is inherently stable and is a low risk from a well control point of view. • Sub-normally pressured oil wells
2	Well is capable of natural flow to surface, but can be controlled using conventional well kill methods. Catastrophic equipment failure may have limited consequences. • Abnormally-pressured water zones • Low flow rate oil or gas wells • Depleted gas wells
3	Geothermal and non-hydrocarbon bearing formations. Maximum anticipated shut-in pressure (MASP) is less than UBO/MPD equipment pressure rating. • Includes geothermal wells with H_2S present.
4	Hydrocarbon bearing formation. Maximum anticipated shut-in pressure is less than UBO/MPD equipment operating pressure rating. Catastrophic equipment failure will likely have immediate serious consequences. • High pressure and/or high flow potential reservoir • Sour oil and gas wells • Offshore environments • Simultaneous drilling and production operations
5	Maximum anticipated surface pressure exceeds UBO/MPD equipment operating pressure rating. Catastrophic equipment failure will likely have immediate serious consequences. • Any well where Maximum Anticipated Surface Pressure (MASP) is greater than UBO/MPD equipment pressure rating

Table 3. International Association of Drilling Contractors Underbalanced Operations and Managed Pressure Drilling Committee Risk Level Classification. Generally, risk increases with operational complexity and potential well productivity. The examples provided are for guidance only.