Module 5B Explosion and Fire Protection – Flammable Gas & Vapor Explosions

Last Revised – June 2024

PS Bootcamp Modules

- ✓ **Module 1: Introduction**
- ✓ **Module 2: Hazard Identification**
- ✓ **Module 3: Risk Matrix**
- ✓ **Module 4: Safeguard Concepts**
- ✓ **Module 5: Explosion/Fire Protection**
- ❑ **Module 6: Management of Change**
- ❑ **Module 7: Incident Investigation**
- ❑ **Module 8: Facility Siting**

Module 5: Explosion and Fire Protection Agenda

- ✓ **5A – Fire, Combustion and Electrical Area Classification**
- ✓ **5B – Flammable Gas and Vapor Explosions**
- ❑ **5C - Combustible Dust Explosions**

Module 5B: Training Objectives

Gain an understanding of :

- Flammable gas and vapor explosions and their characteristics
- Conditions necessary for flammable gas or vapor explosions
- Upper and Lower Explosion Limits (UEL, LEL)
- Limiting Oxygen Concentration (LOC)
- Minimum Ignition Energy (MIE)

Be able to interpret the safety data (UEL, LEL, LOC, MIE, …) associated with flammable gases & vapors, and adjust for actual processing conditions

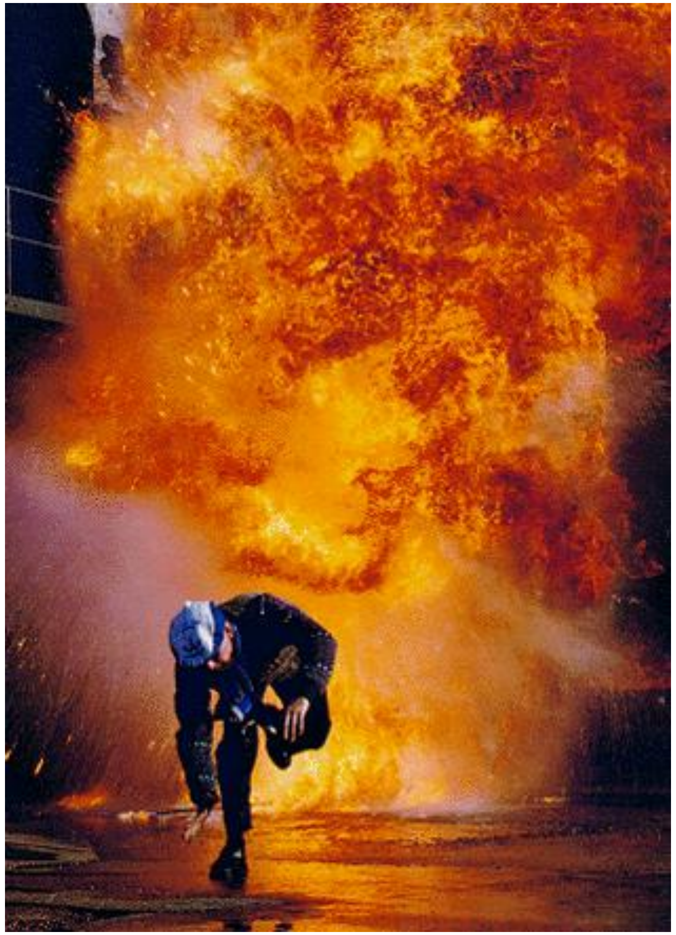
Be able to apply preventive measures to avoid the occurrence of flammable gas or vapor explosions, or prevent their propagation

Flammable Gas and Vapor Explosions

Explosions can be the result of Physical or Chemical events.

The focus here is on explosions resulting from a Chemical event

- The violent & sudden Combustion of a flammable Gas or Vapor (Explosion)



What materials are capable of forming explosive atmospheres?

Flammable Gases (CH_4, C_2H_4, NH_3,…)

Flammable Vapors (Methanol, Acetone, Toluene, …)

Fine droplets or mists of flammable liquids

Dispersed Dusts

Flammable gases or vapors that may be present in the air in quantities sufficient to ignite in the detonation range.

Definitions

Combustion

The burning of gas, liquid, or solid in which flammable material is oxidized and releases heat.

Combustion of flammable material can occur in the gas phase only and in two different modes.

- Fire
- Explosion

Definitions

Fire

- Flammable material and oxygen are mixed during the combustion process.

Definitions

Explosion

- Flammable material and oxygen are mixed before the combustion process.

Definitions

Explosion

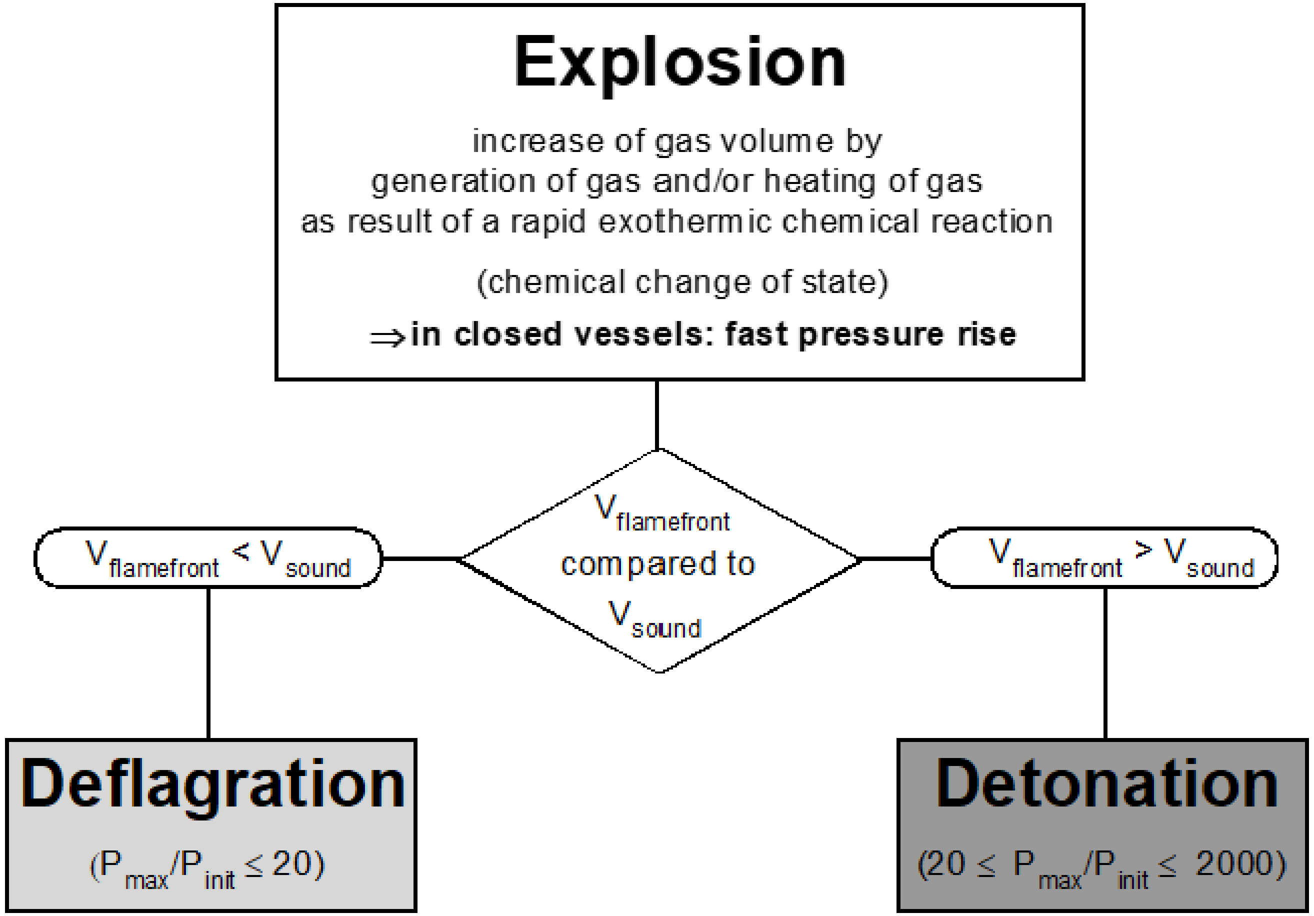
Combustion leading to a rapid increase of pressure. Explosions are either Detonations or Deflagrations. Two consequences are heat release and a pressure shock wave

- **Deflagration** – The flame front moves at a speed less than the speed of sound. A deflagration can accelerate to a detonation.
- **Detonation** – The flame front moves faster than the speed of sound in the unreacted medium

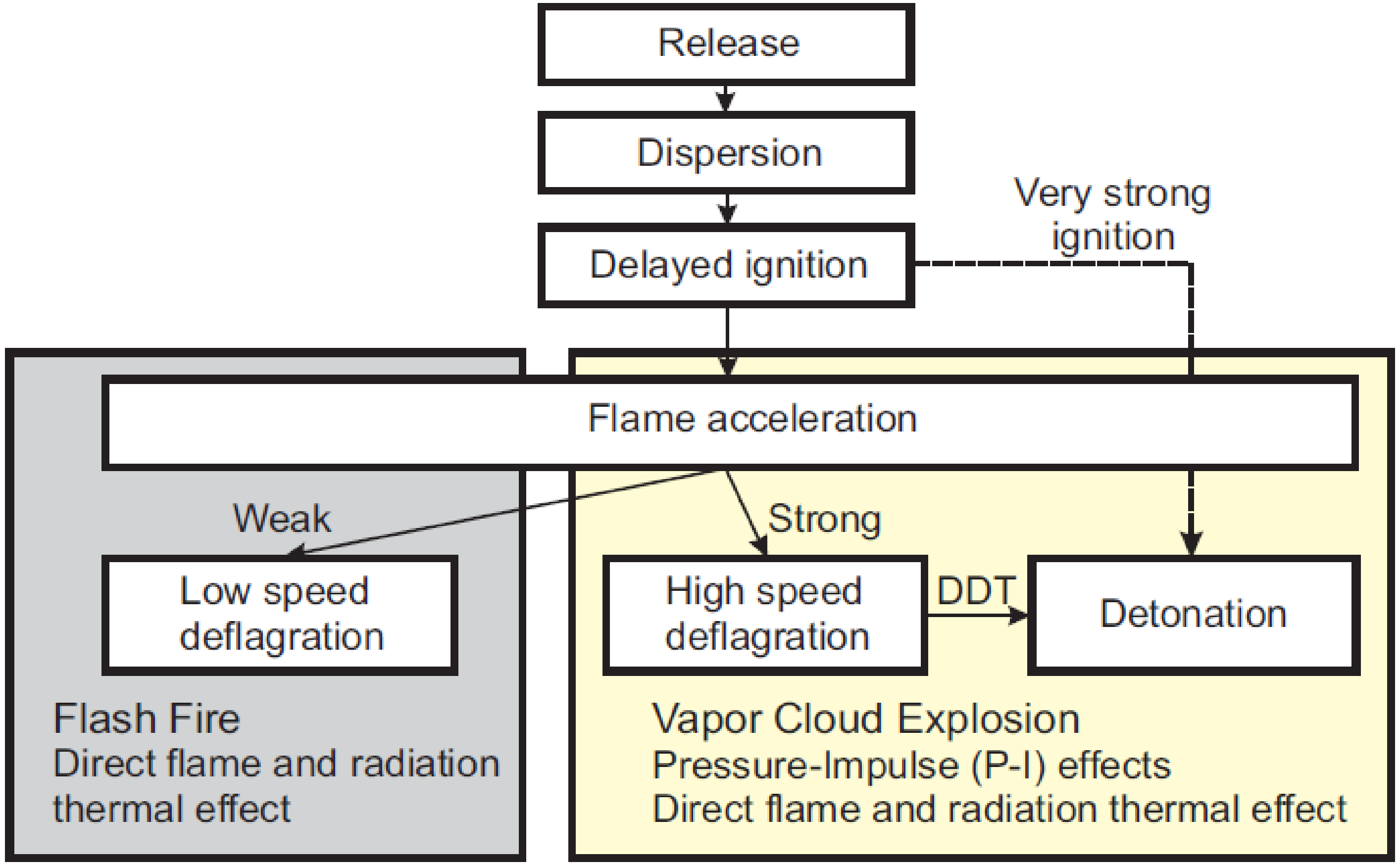
Detonations

Criteria	Type of Explosion	
	Deflagration	Detonation
Propagation speed v_f of flame	$v_f < v_{sound}$ (Typical: $0.5\ m/s \le v_f \le 10\ m/s$)	$v_f > v_{sound}$ (Typical: $2000\ m/s \le v_f \le 3000\ m/s$)
Propagation speed v_p of pressure	$v_p = v_{sound}$	$v_p > v_{sound}$
Appearance of a shock wave	No	Shock wave is coupled with the flame front
Ignition mechanism for the unburned gas	Heat transfer from the flame front to the unburned gas	Adiabatic compression by shock wave heats the unburned gas to a temperature above the ignition temperature
Explosion pressure ratio r (Pm/Pi)	$7 \le r \le 20$	$20 \le r \le 2000$
Dependence on vessel and pipe geometry	No	Yes, substantial influence of geometry
Normalized rate of pressure rise	KG ≤ 3000 bar*m/s	KG ≥ 10^6 bar*m/s

Difference between Deflagration and Detonation

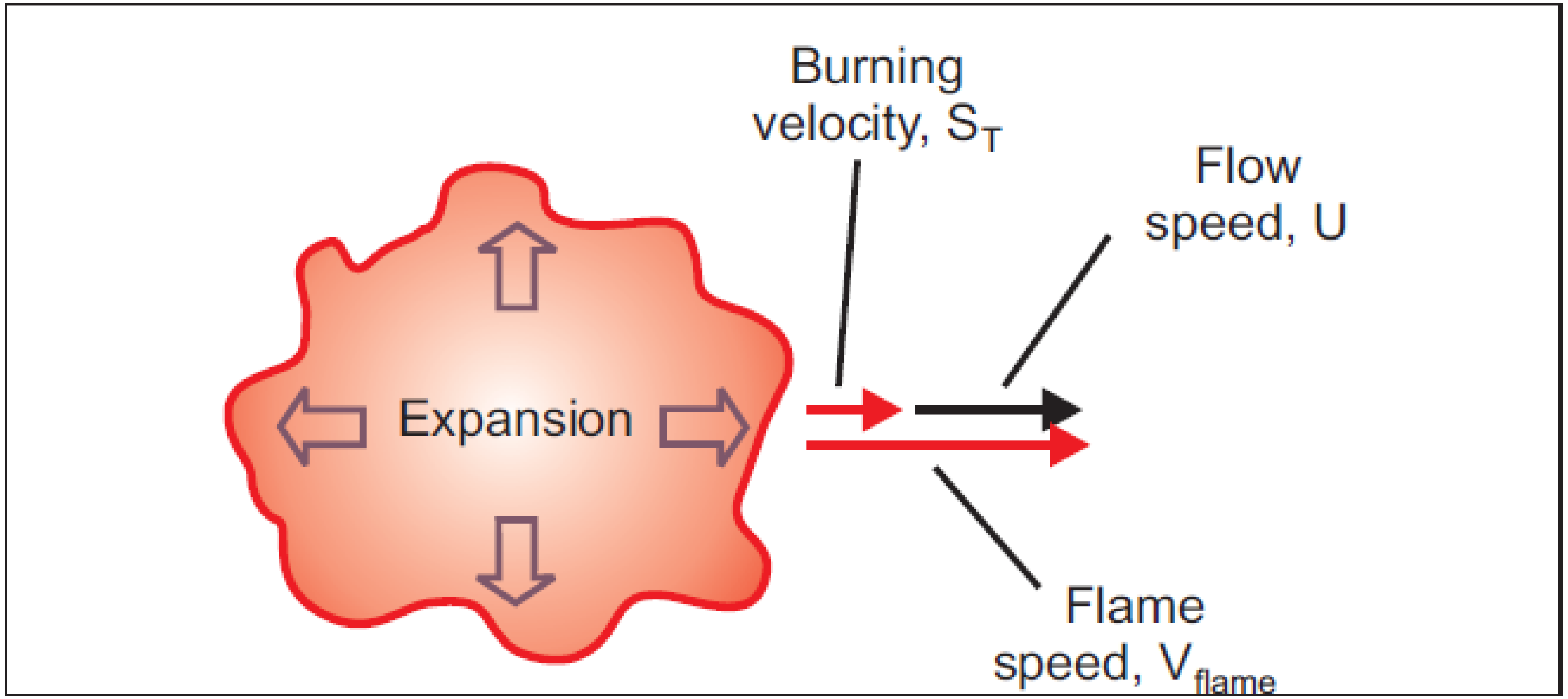


Simplified Vapor Cloud Explosion Mechanism[1]



(1) FM Global 7-42

Sketch of Flame Propagation[1]



[1] FM Global 7-42

Video of a Chemical Explosion

[China chemical explosion 2019: Jiangsu Tianjiayi Chemical plant kills 47 people - Bing video]

Video of a Chemical Explosion

[Caught On Camera: Large Explosion In Chemical Plant Fire In Hood County - Bing video]

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Video of a Chemical Explosion

[Port Neches: Chemical plant explosion rattles homes miles away - Bing video]

Factors Affecting Flame Acceleration(1)

Interactions of the flame with obstacles results in a strong increase of the flame area and acceleration of the gas flow ahead of the flame.

The upstream gas flow interacts with obstacles, generating turbulence due to shear instabilities.

Turbulence increases the burning velocity of the flame.

Any confinement that prevents the combustion products' expansion in directions other than that of the flame propagation promotes further flame acceleration.

The higher rate of fuel consumption increases the gas flow ahead of the flame, strengthening obstacle-induced turbulence as well as increasing the surface area of the flame.

This creates a positive feedback loop and results in flame acceleration and pressure rise.

(1) FM Global 7-42

Components Required for an Explosion

Fuel + oxidant + ignition source simultaneously present at same place with confinement

Mixture of fuel and oxidant is "appropriate“ i.e., mixture lies in the "flammability range"

Ignition source is sufficiently energetic

Explosion Risk

In theory, if only one of the three components is removed the Explosion can be avoided

Fuel + oxidant + ignition source simultaneously present at same place with confinement

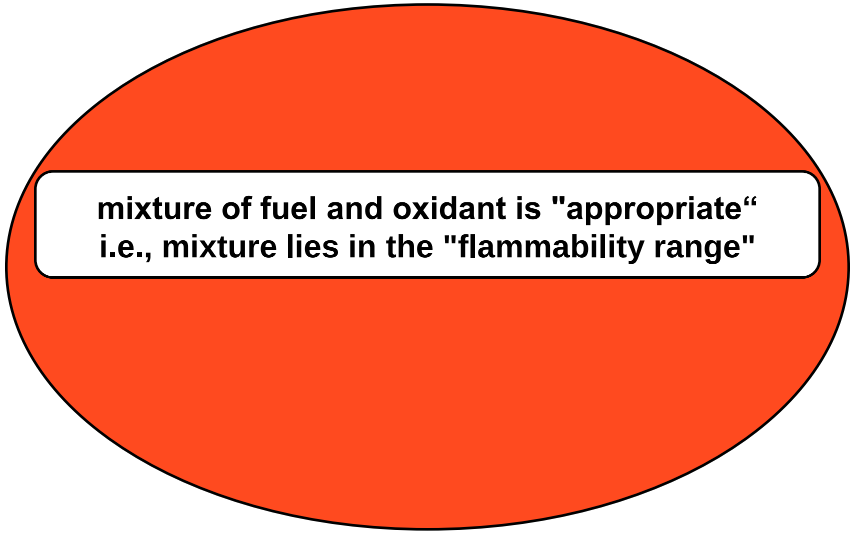
Theory is splendid but until put into practice, it is valueless.

- James Cash Penney

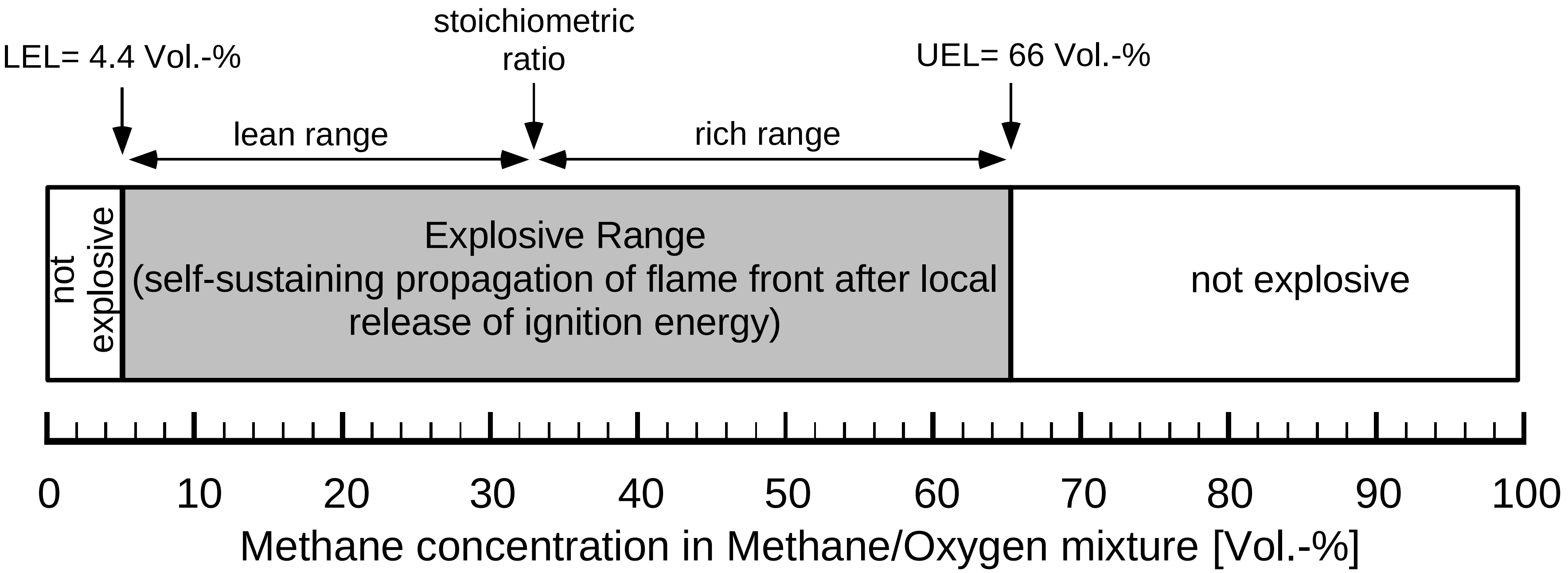
Explosion Risk

Fortunately, the appropriate mixture of flammable material and oxidant have easily measurable limits

It is often feasible to move the mixture out of the “Explosive Range” to minimize the Explosion Risk

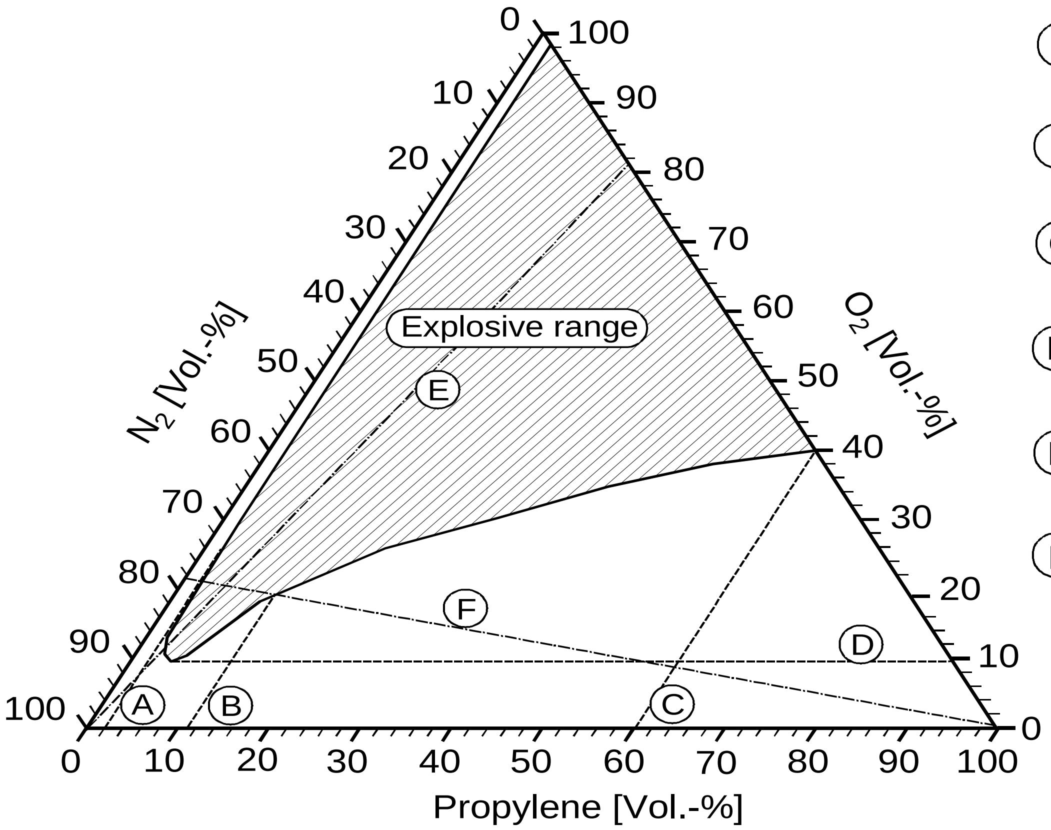


Explosive Limits



Explosivity Diagram

Explosivity diagram for the three-component system propylene/O2/N2 at P = 1 bar and T = 180°C, represented as explosion triangle.



(A) Lower Explosion Limit (LEL), relatively independent of O_2-conc.*

(B) Upper Explosion Limit (UEL) for Propylene in Air (O_2 : N_2 = 21 : 79)

(C) Upper Explosion Limit for Propylene in Oxygen

(D) Limiting Oxygen Concentration (LOC)

(E) Line of Stoichiometric Compositions, Propylene: O_2 = 1 : 4.5

(F) Propylene/Air Line, i.e. O_2 : N_2 = 21 : 79

* : if c_p-values of O_2 and inert gas are close to each other

Explosive Limits

<u>Explosive Limits</u> (LEL, UEL) limiting oxygen concentrations and explosion characteristics of a selected set of explosive systems.

Do we want to include CPET chemicals?

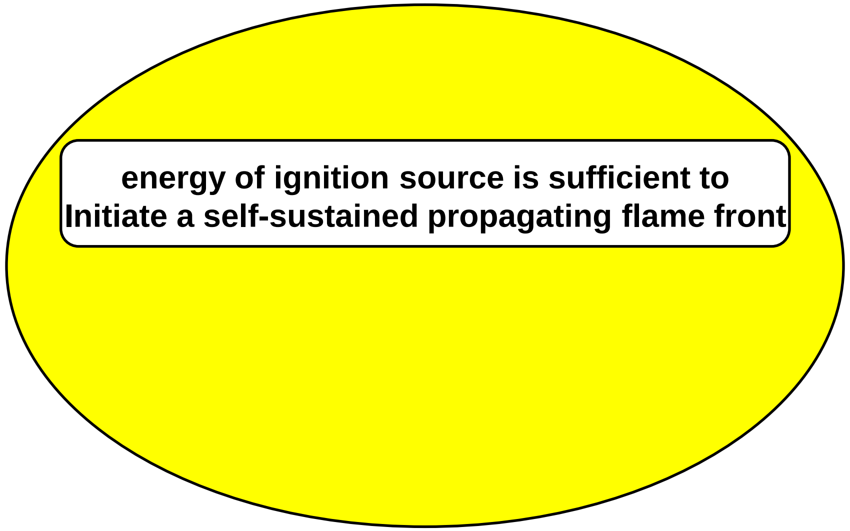
Fuel	$H_{combustion}$ [illegible]	[illegible]	[illegible]	UEL [vol. %]		LOC [vol. %]		Max. explosion pressure ratio		K_G	Ref.
	[kJ/m[illegible]	[illegible]	[illegible]	Air	O_2	N_2	CO_2	Air	O_2	[bar•m/s]	
H_2	[illegible]	[illegible]	[illegible]	[illegible]	94	4.8	4.8	8.4	9.2	550	3,8,B
CO	[illegible]	[illegible]	[illegible]	[illegible]		5.0	5.0	8.3	9.5		3
CS_2	[illegible]	[illegible]	[illegible]	60		6 (60°C) 4 (180°C)		8.8		105	4,8,B
[illegible]	[illegible]	[illegible]	1.5	100	100	0	0		14.4	1400	2,8
[illegible]	[illegible]	[illegible]	7.0	73		5 (150°C)					3,B
[illegible]	[illegible]	-50.03	4.4	16.5	66	11.6	14.1	8.2	15.4	55	3,8,B
[illegible]	[illegible]	-47.51	2.7	14.7	55	11.0	13.3		15.3	106	2,8
[illegible]	-1323	-50.88	2.3	32.4	81			8.0		171	2, 16,B
[illegible]	-1235	-26.8	3.5	15				7.0		78	2,16
[illegible]	-2043	-46.33	2.1	9.5	56	11.8	14.2	9.6		100	2,8,B
[illegible]	-1925	-45.74	2.0	11.7	59	11.5	14.1	9.6			2
n-Butane	-2657	-45.71	1.4	9.3	56	12.1	14.5	9.6			2,B
1,3-Butadiene	-2409	-44.6	1.4	16.3		10.8	13.0	8			3
n-Pentane	-3244	-44.97	1.4	7.8		11.7	14.4	9.7		104	3,8
n-Hexane	-3886	-45.10	1.0	8.1		12.1	14.5	9.7			2
Toluene	-3733	-40.56	1.2	7		9 (80°C)		7.8			4,B
o-Xylene	-4332	-40.8	1.0	7.6		8.5 (200°C)	14.5	8.8			4,B
Dimethyl ether	-1328	-28.8	2.7	32				7.9	18.8	108	3,4,16
Diethyl ether	-2503	-33.8	1.7	36				10.2	15.4	115	3,4,8

Minimum Ignition Energy (MIE)

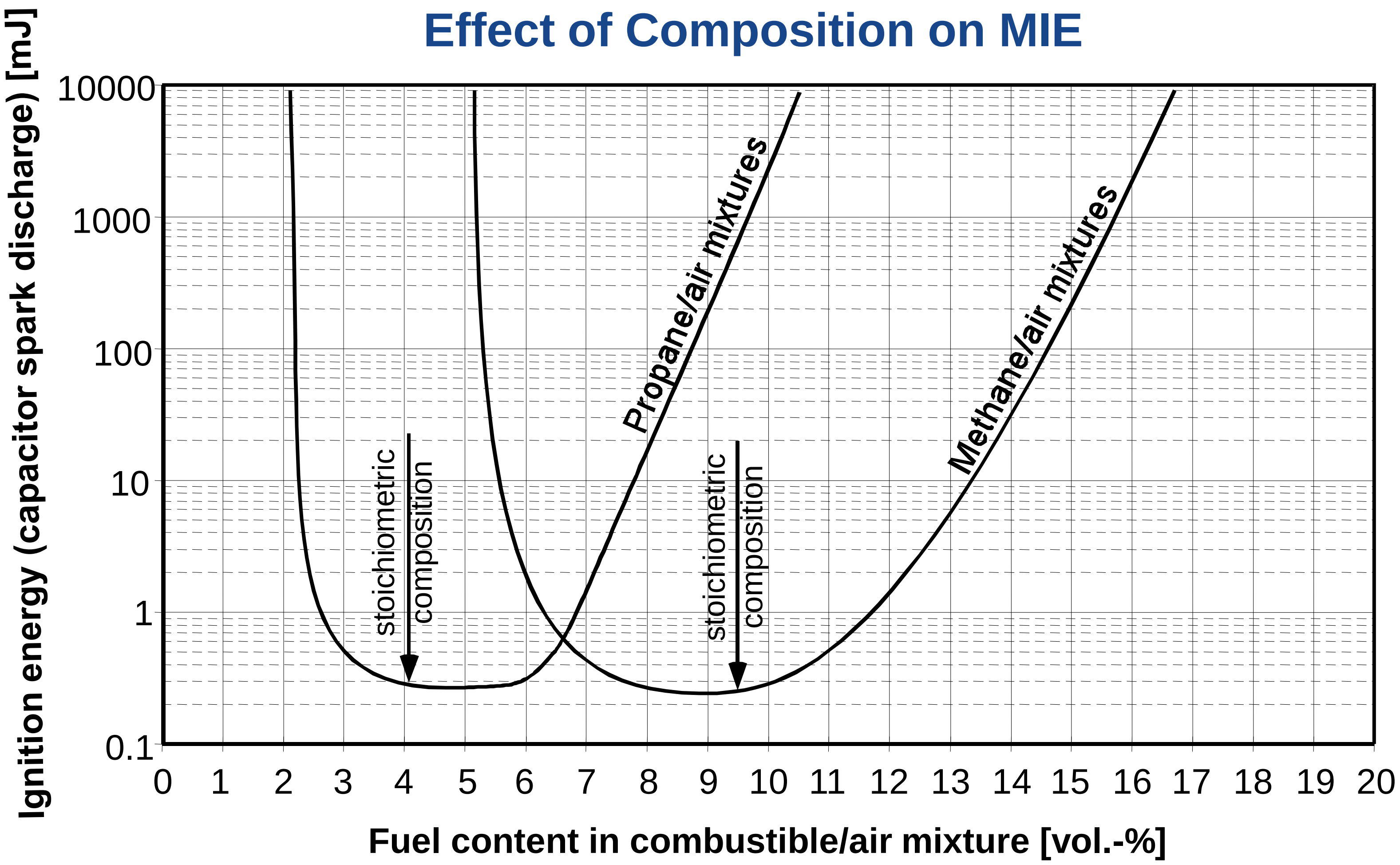
In practice, it is difficult to reliably eliminate all ignition sources.

In order to minimize the Explosion Risk, we should:

1. **Measure the MIE of the system**
2. **Identify and eliminate/control possible Ignition sources and energy**
3. **Avoid simultaneous appearance of the three components.**

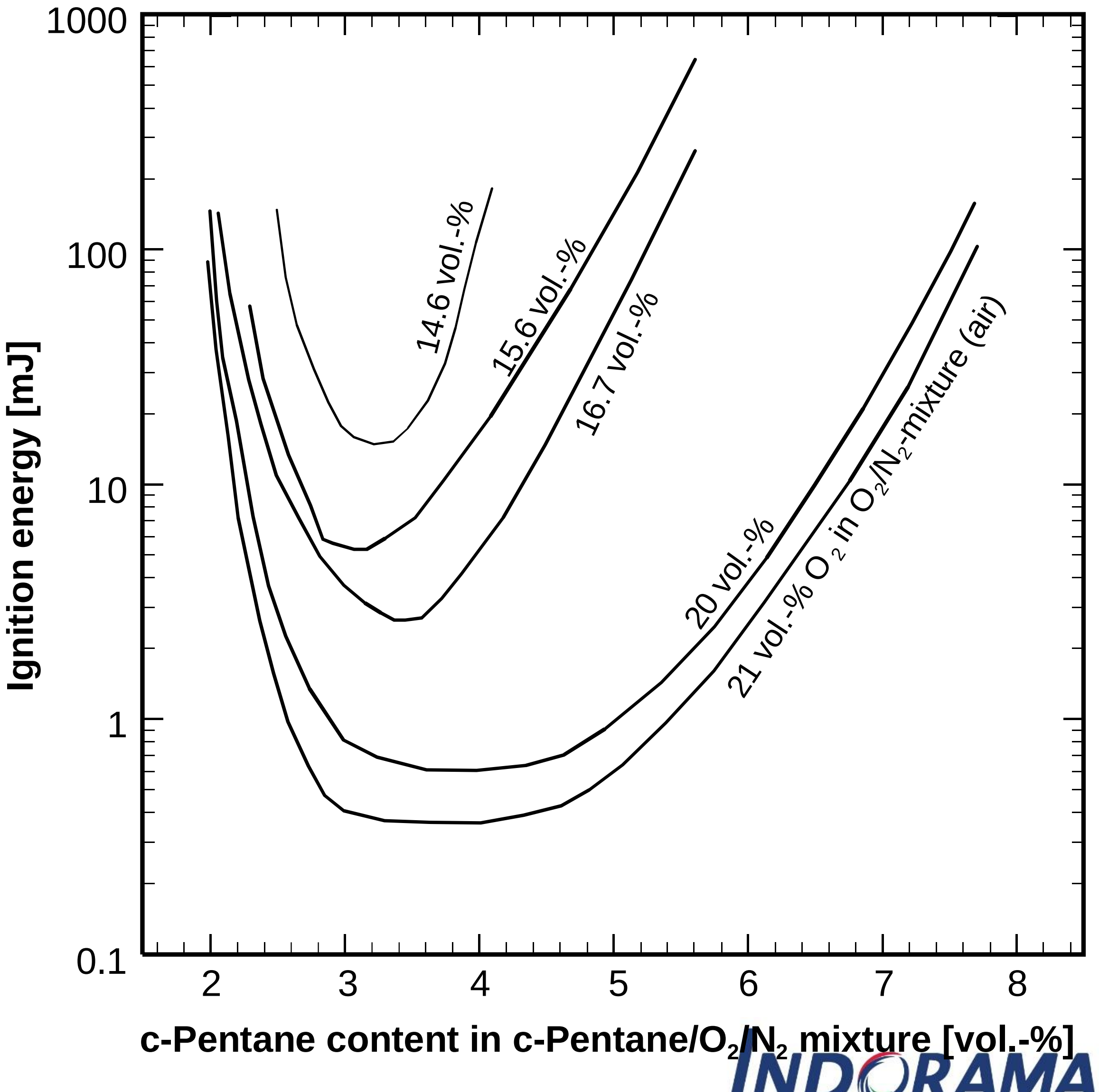


Minimum Ignition Energy (MIE)



Minimum Ignition Energy (MIE)

Ignition Energies as a function of oxygen content.



Minimum Ignition Energies

Selected gases and vapors in mixture with air

Fuel		MIE [mJ]
carbon disulfide	CS_2	0.009
hydrogen	H_2	0.016
acetylene	C_2H_2	[illegible]
ethylene oxide	C_2H_4O	[illegible]
ethylene	[illegible]	[illegible]
propine	[illegible]	[illegible]
propylene oxide	[illegible]	[illegible]
carbon mono[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
meth[illegible]	[illegible]	0.28
[illegible]	[illegible]	0.25
p[illegible]	[illegible]	0.26
cy[illegible]	C_3H_6	0.17
n-bu[illegible]	C_4H_{10}	0.25
n-pent[illegible]	C_5H_{12}	0.28
cyclohexane	C_6H_{12}	0.22
n-heptane	C_7H_{16}	0.24

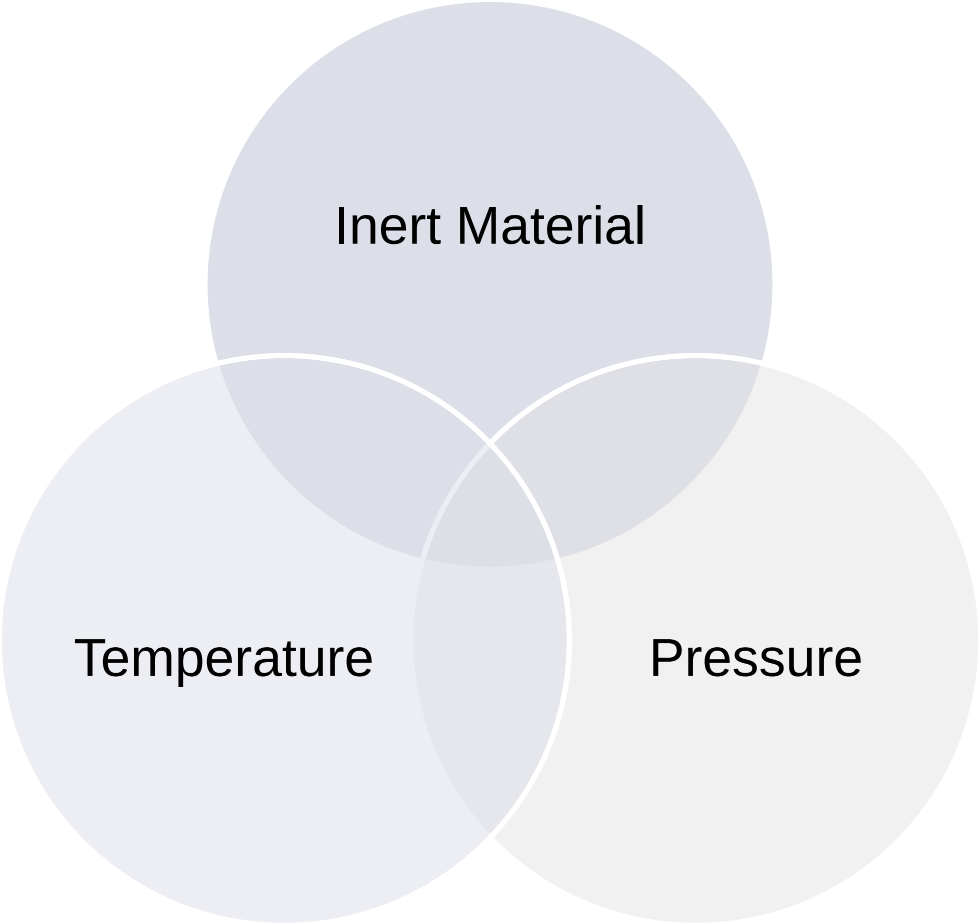
Fuel		MIE [mJ]
[illegible]	C_8H_{18}	1.35
[illegible]	$C_4H_{10}O$	0.19
[illegible]	CH_3OH	0.14
[illegible]	C_3H_7OH	0.65
[illegible]	C_3H_6O	0.55
[illegible]yl acetate	$C_4H_8O_2$	1.42
ammonia	NH_3	14
trichloroethylene	CCl_2CClH	510

Do we want to include CPET chemicals?

at P = 1 bar abs and T = 20 C - except for those substances that need to be heated to reach sufficient vapor pressure).

Factors Affecting Explosive Limits

Factors Effecting Explosive Limits



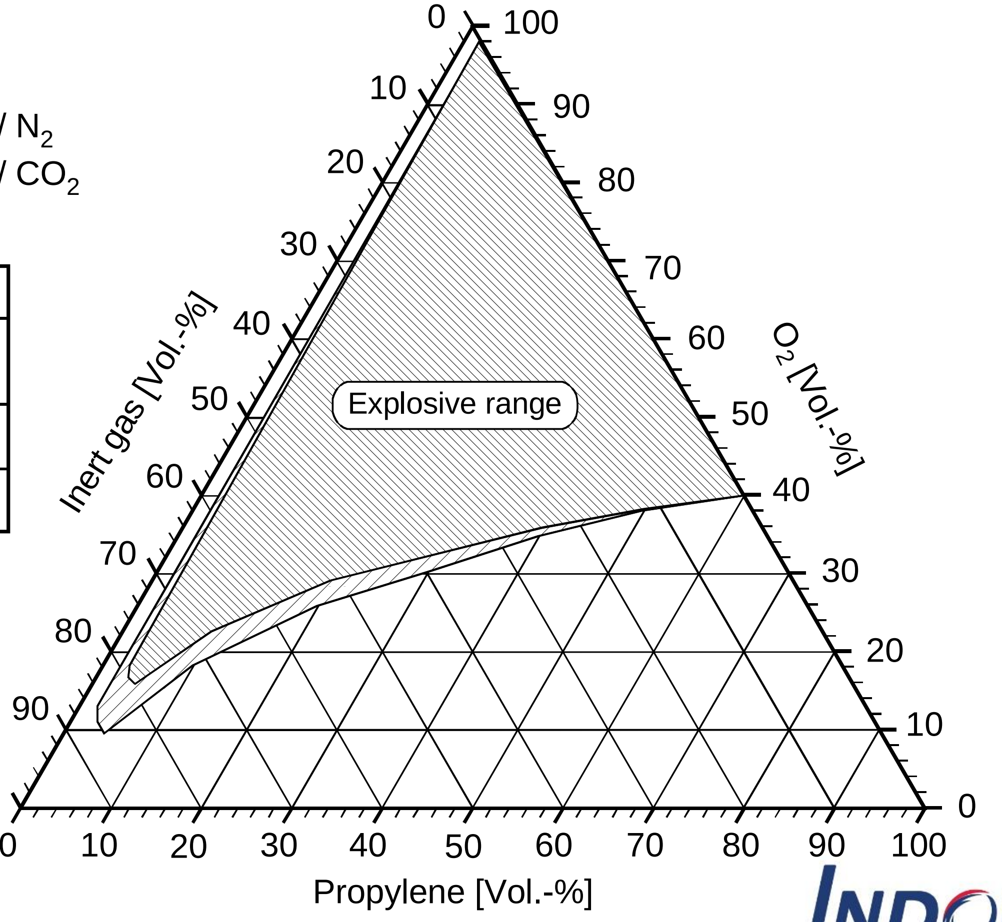
Factors Affecting Explosive Limits

1. Type of Inert Material

- Explosion triangle for the system Propylene/O2/N2 and Propylene/O2/CO2 at P = 1 bar and T = 180C.

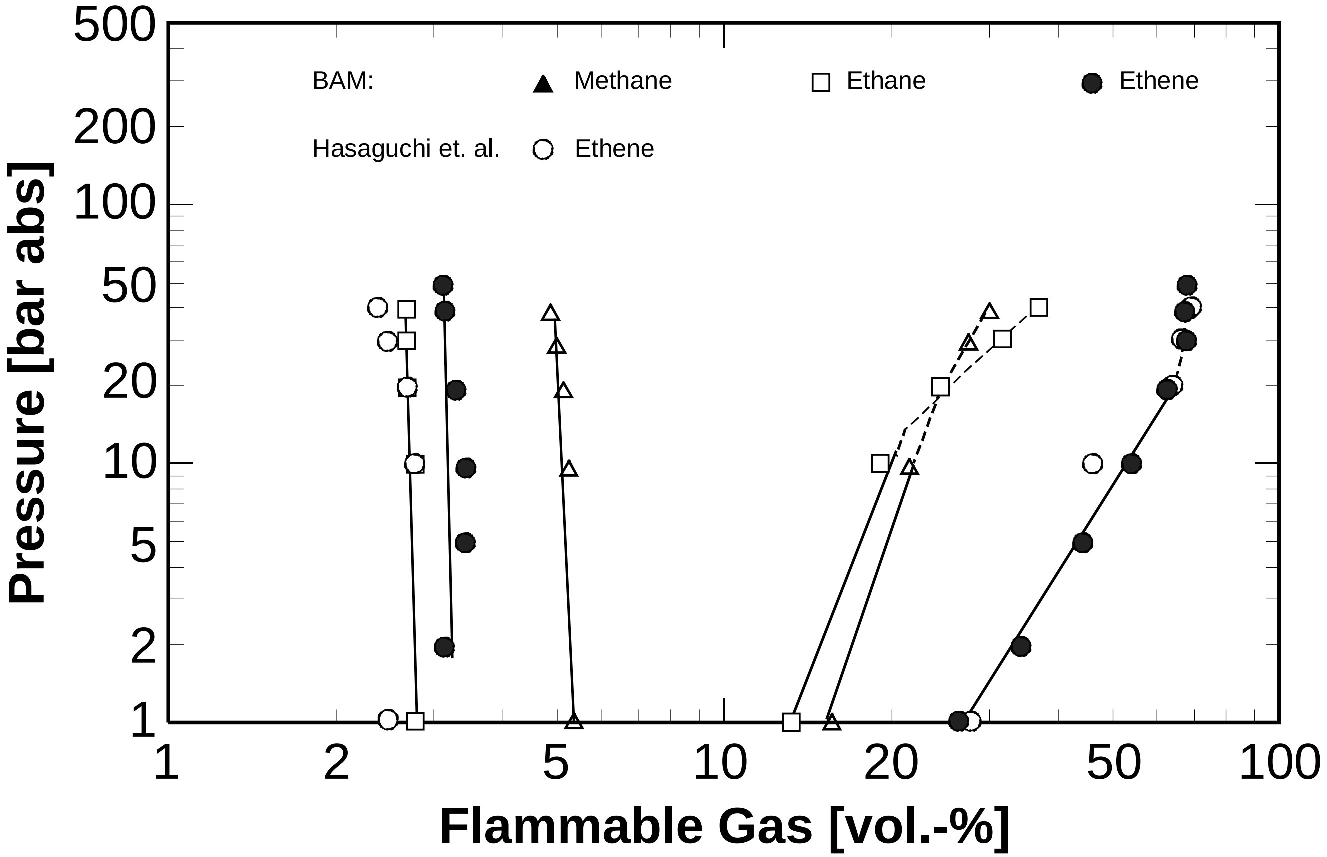
Propylene / O_2 / N_2
Propylene / O_2 / CO_2

Inert gas	c_p [J/ (mol*K)]	
	20°C (68°F)	1000°C (1832°F)
N_2	29	34
CO_2	37	57



Factors Affecting Explosive Limits

2. Pressure - LEL and UEL are pressure dependent



LEL and UEL for Methane/Air, Ethane/Air and Ethene/Air systems in the range of 1 to 50 bar.

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Factors Affecting Explosive Limits

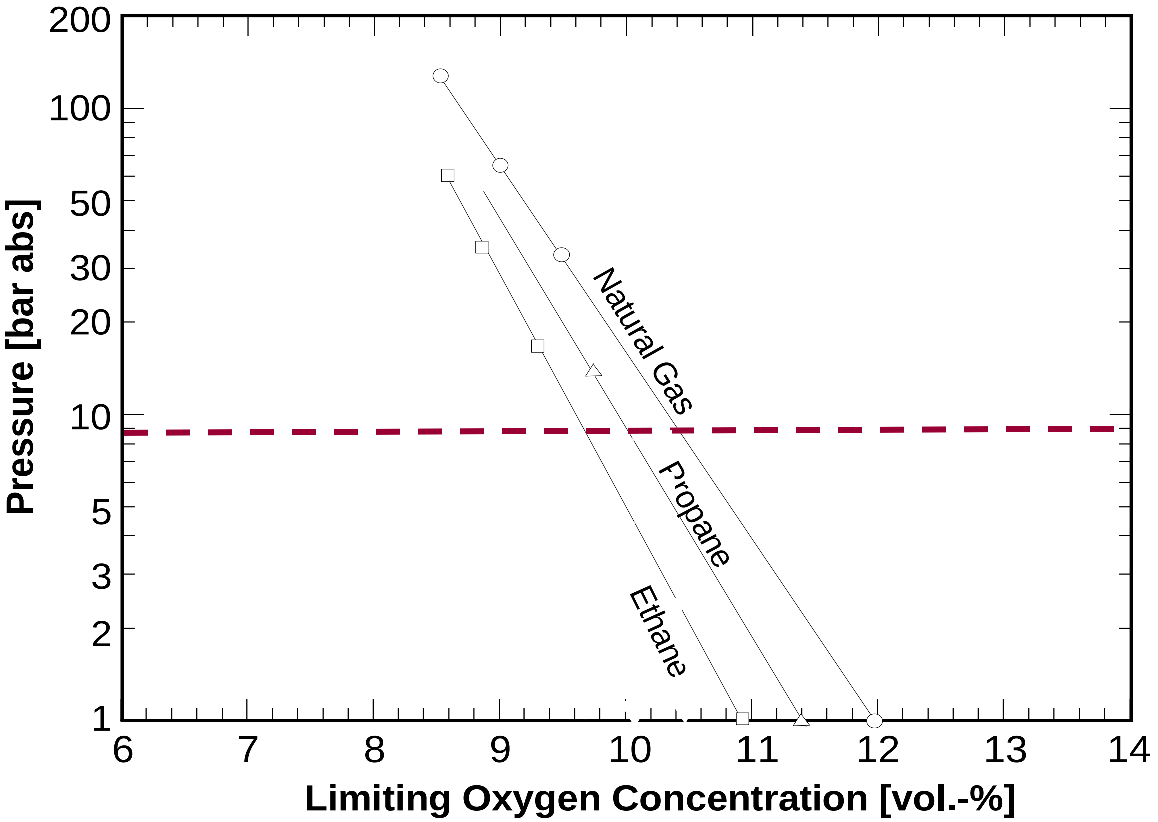
2. Pressure - UEL of Propane in O2 at T = 200 C

Initial Pressure [bar abs]	Initial Temperature [°C]	UEL [vol.-%]	Source of measurement
1	200	55	J. Stickling, University of Paderborn, 1998
2	180	64	ZAT-report no. 195.0810.3N
2	223	65.5	ZAT-report no. 196.0303.3N
6	200	79	ZAT-report no. 197.0635.3N
10	200	88	ZAT-report no. 197.0635.3N
20	200	90	ZAT-report no. 198.0534.3N
30	200	90	ZAT-report no. 198.0534.3N

*Measurements conducted by J. Stickling at University of Paderborn were performed in an open glass tube according to DIN 51649. The measurements cited in the ZAT-reports were conducted in a 5 l sphere by the safety engineering group of BASF.

Factors Affecting Explosive Limits

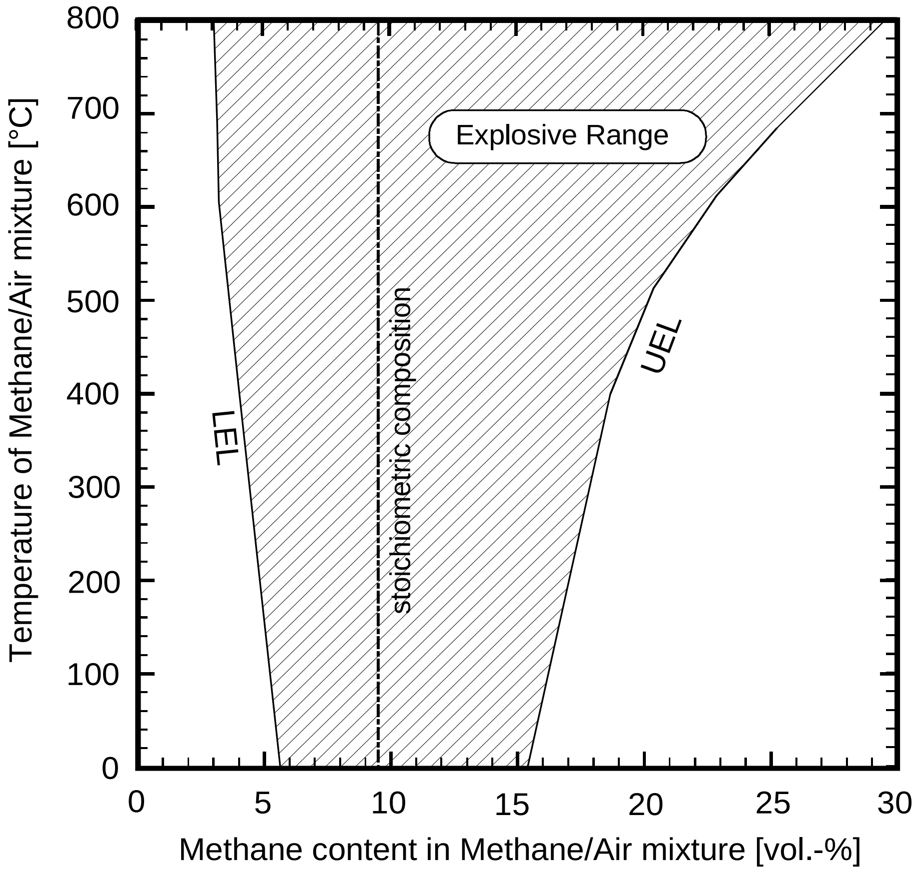
2. Pressure - LOC Pressure dependence

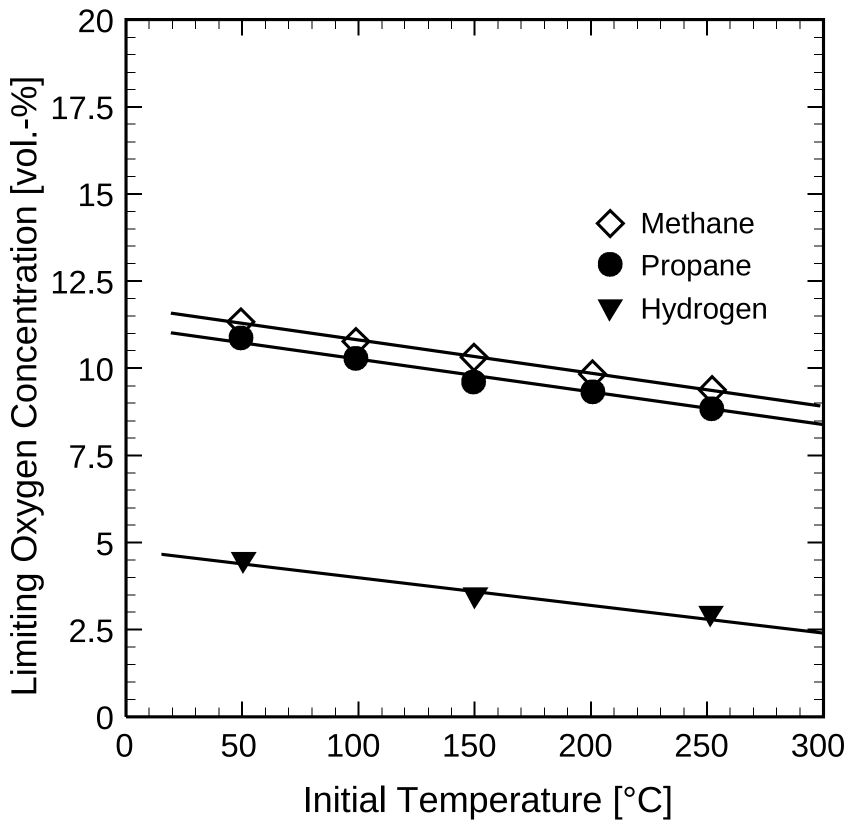


LOCs of the three-component Propane/O2/N2, Natural Gas/O2/N2 and Ethane/O2/N2 systems at 26 C.

Factors Affecting Explosive Limits

3. Temperature - LEL, UEL and LOC Dependence





Explosion avoidance

Two Methods for Explosion Prevention

- Control of flammable / oxidizer ratio.
- Isolation and control of ignition sources.

Explosion Avoidance

Control of Flammable / Oxidizer Ratio

Normally achieved by

- Addition of an Inert Gas
- Evacuation of the Oxidizer

Final Oxygen %	Initial Oxygen %	N2 available pressure	Initial Pressure (system)	Number of Cycles
6	21	1	0.2	0.8

Number of Cycles	Final Oxygen %
2	0.8

Explosion Avoidance

Isolation and control of ignition sources.

Normally achieved by

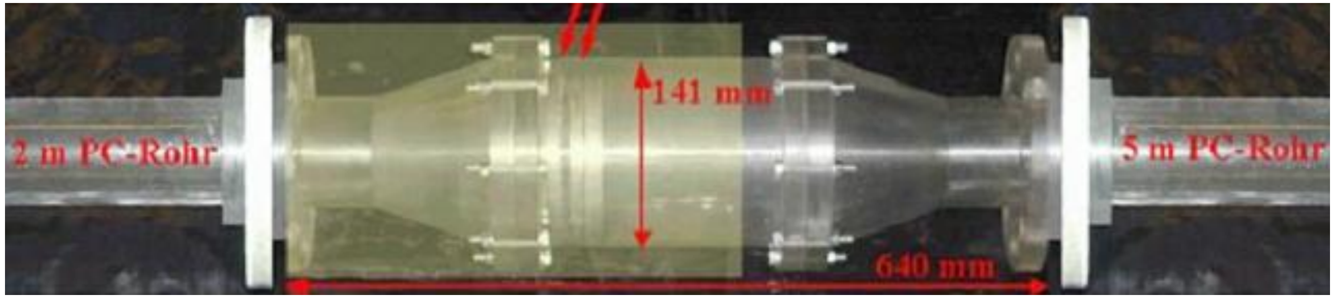
- Detection and Elimination of Ignition Sources
- Prevention of a Propagating Flame Front

Explosion Avoidance

Isolation and control of ignition sources.

Prevention of a propagating flame front

Flame arrestor



[Flame Arresters & The Deflagration To Detonation Transition (DDT) Explained - Bing video]

Summary - Takeaways

Flammable Gas & Vapor Explosions require the simultaneous occurrence of:

- An explosive mixture of gas or vapor (between the LEL and UEL)
- Enough oxygen to support sustained combustion (>MOC)
- An ignition source with energy equal to or exceeding the MIE

Eliminating one of these three conditions will prevent an explosion

Summary (continued)

LEL, UEL, MOC, and MIE are all functions of pressure & temperature.

- When using published data, be sure to know the test conditions and adjust for specific case.

It is difficult to eliminate all possible ignition sources.

- Mitigation efforts should also include preventing the occurrence of an explosive mixture (i.e. - inerting to eliminate oxygen such as EO vapor concentration in alkoxylation batch reactor headspace)

In situations where reliable explosion prevention cannot be guaranteed, preventing flame front propagation is necessary.

- Flame arrestors, detonation arrestors, or other equivalent devices will need to be incorporated into the system design.

Questions/Comments

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