Copyright@2001 David White/Industrial Fire World

Process Safety Engineering:

Fires & Explosions

Dr. Motasem Saidan

m.saidan@gmail.com

Fires & Explosions

Accident Statistics

Evaluation of the largest chemical plant accidents:

- **Most of the large accidents are due to fires and explosions.**

Introduction

The distinction between *fires* and *explosions* is the rate of energy release

FIRE: release energy slowly, rapid exothermic, oxidation, with flame

EXPLOSION: higher energy release rate (mixture) pressure or shock wave

Fires can also result from explosions, and explosions can result from fires

EFFECTS

- injuries / casualties
- property losses
- process interruption

Thermal radiation, asphyxiation, toxic products, blast, fragments

REQUIRED KNOWLEDGE FOR PREVENTION

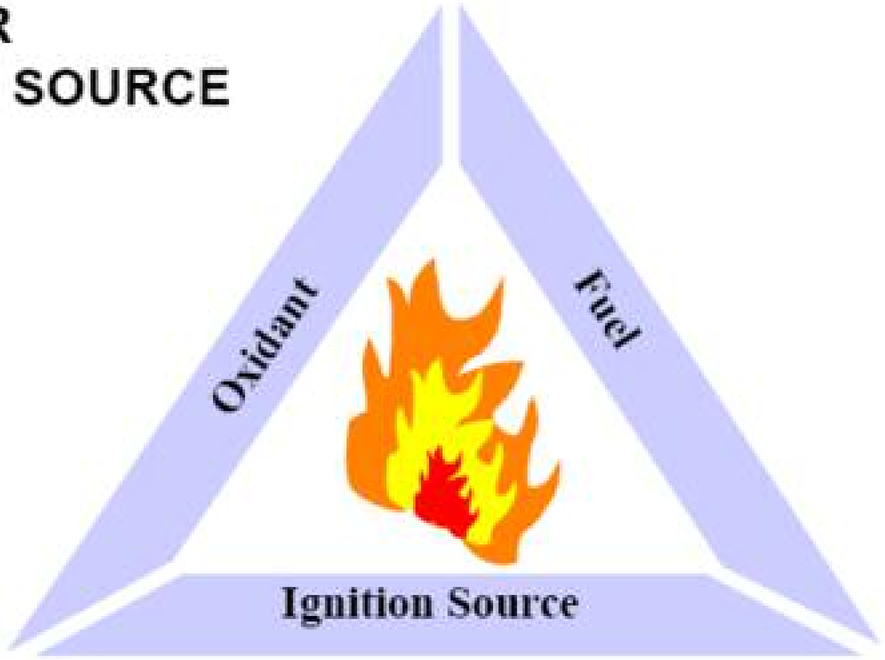
- material properties
- nature of fire and explosion process
- procedures to reduce hazards (Ch. 7)

Fire Triangle

- *Combustion or fire:* Combustion or fire is a chemical reaction.

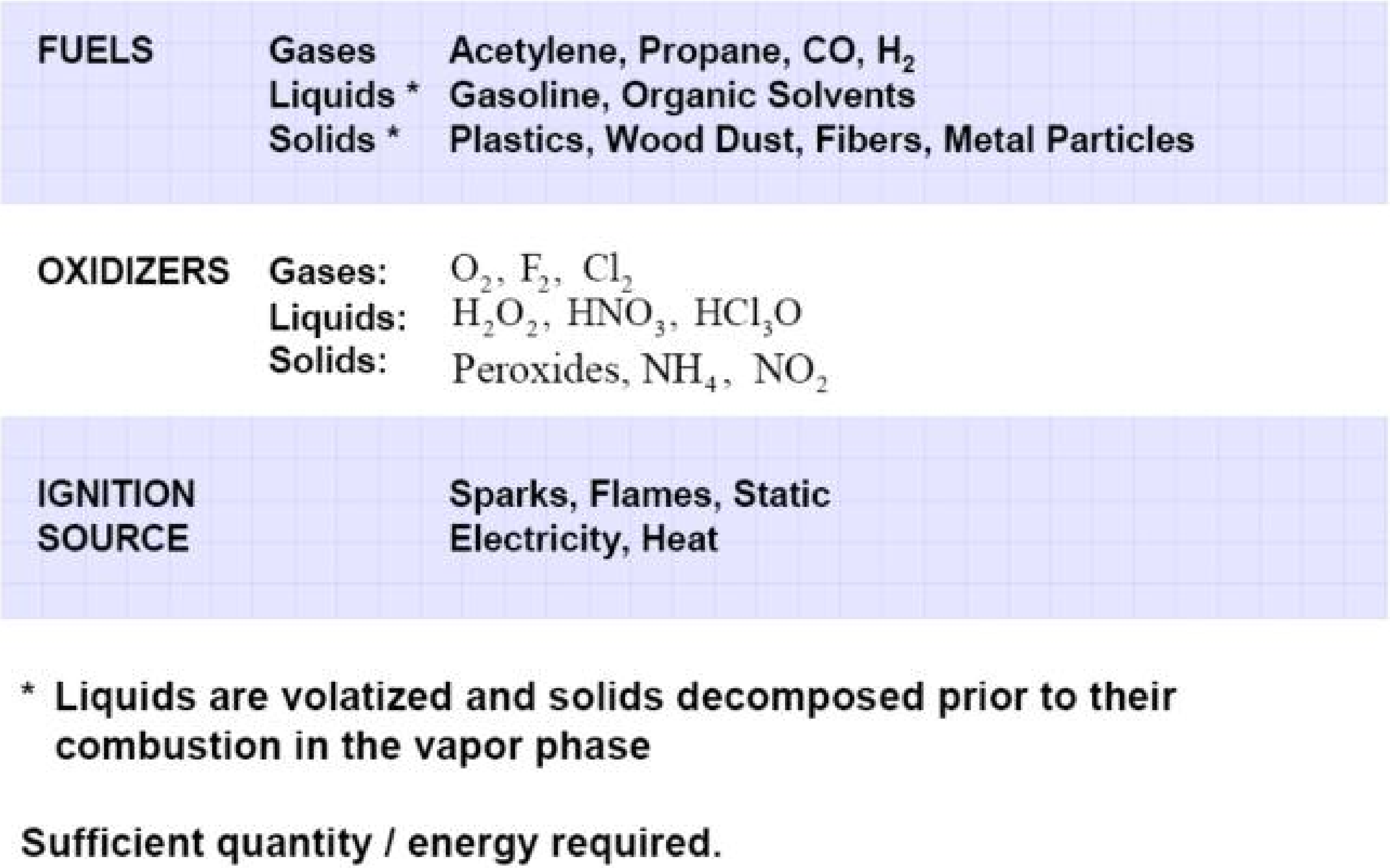
FIRE TRIANGLE

FUEL
OXIDIZER
IGNITION SOURCE



Oxidant may not be oxygen, i.e. chlorine.

Fire Triangle



FUELS	Gases	Acetylene, Propane, CO, H_2
	Liquids *	Gasoline, Organic Solvents
	Solids *	Plastics, Wood Dust, Fibers, Metal Particles
OXIDIZERS	Gases:	O_2, F_2, Cl_2
	Liquids:	H_2O_2, HNO_3, HCl_3O
	Solids:	Peroxides, NH_4, NO_2
IGNITION SOURCE		Sparks, Flames, Static Electricity, Heat

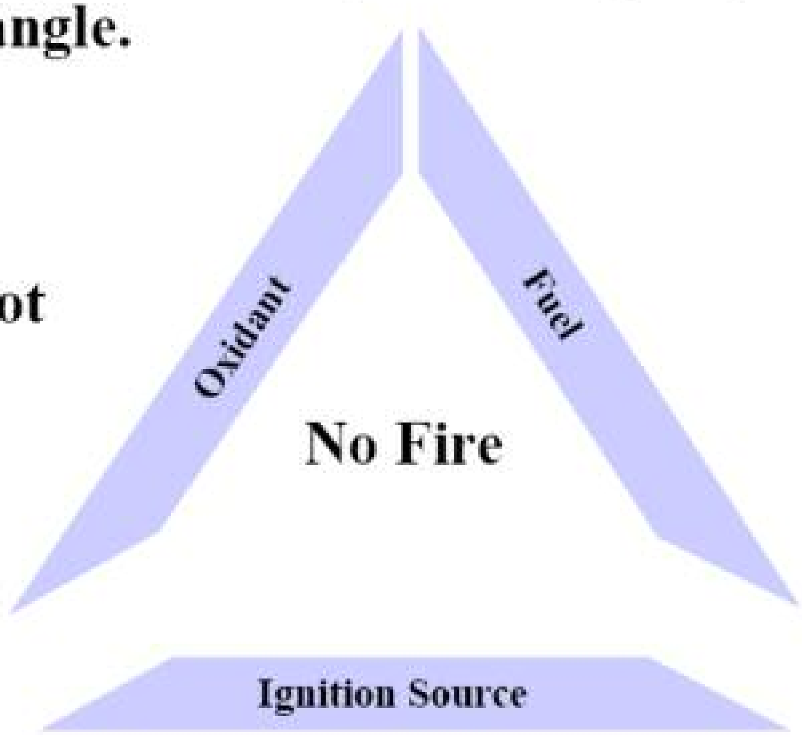
* Liquids are volatized and solids decomposed prior to their combustion in the vapor phase

Sufficient quantity / energy required.

Application of the Fire Triangle

Fires and explosions can be prevented by removing any single leg from the fire triangle.

Problem: Ignition sources are so plentiful that it is not a reliable control method.



Robust Control: Prevent existence of flammable mixtures.

Texas Fertilizer Plant Blast

“So this is what has happened, that the fire has got out of control and basically heated up the vessel. What seems to me to be wrong about this whole incident is that instead of evacuating the plant, when the fire establishment could not control it, there seemed to be brought up more and more fire people and they were putting them at risk. I don’t know, it sounds as if there have been a lot of deaths among fire people”

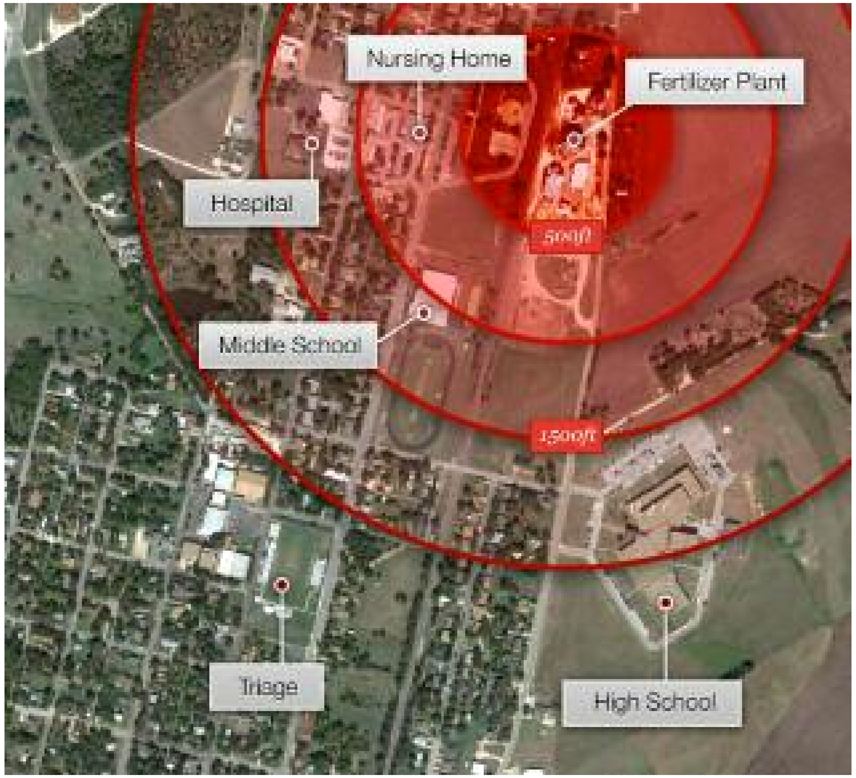
Waco, Texas early April 18, 2013

The fertilizer plant indicated the worst case scenario would be a 10-minute release of ammonia gas that would not harm anyone.
West Fertilizer told the Environmental Protection Agency that it presented no risk of fire or explosion, despite having 54,000 pounds of anhydrous ammonia

The chief safety expert at the Russia’s Nitrogen Industry Institute, Igor Solovyev, reminded that there haven’t been any serious accidents at fertilizer plants in half a century and that serious violations of safety arrangements must have led to the Texas explosion.

Texas Fertilizer Plant Blast

West Chemical and Fertilizer was fined $2,300 in March 2006 for failing to update a risk management plan and for having poor employee-training records and no formal written maintenance program, according to the EPA. The company later certified it had corrected the deficiencies, the EPA said



Combustion Behavior – Most Hydrocarbons

Smoke and fire are very visible!

Combustion Behavior – Carbon Disulfide

No smoke and fire, but heat release rate just as high.

Combustion Behavior – Methane

Methane burns mostly within vessel, flame shoots out of vessel.

Combustion Behavior – Dusts

Much of the dust burns outside of the chamber

Definitions - 1

- **LFL: Lower Flammability Limit**

  Below LFL, mixture will not burn, it is too lean.

- **UFL: Upper Flammability Limit**

  Above UFL, mixture will not burn, it is too rich.

- Defined only for gas mixtures in air.
- Both UFL and LFL defined as volume % fuel in air.

***Flammability limits:* Vapor-air mixtures will ignite and burn only over a well-specified range of compositions.**

Definitions - 2

- **Flash Point:** Temperature above which a liquid produces enough vapor to form an ignitable mixture with air.
  - Defined only for liquids at atm. Pressure.
  - The flash point generally increases with increasing pressure.

- **Auto-Ignition Temperature (AIT):** Temperature above which adequate energy is available in the environment to provide an ignition source.

Definitions - 3

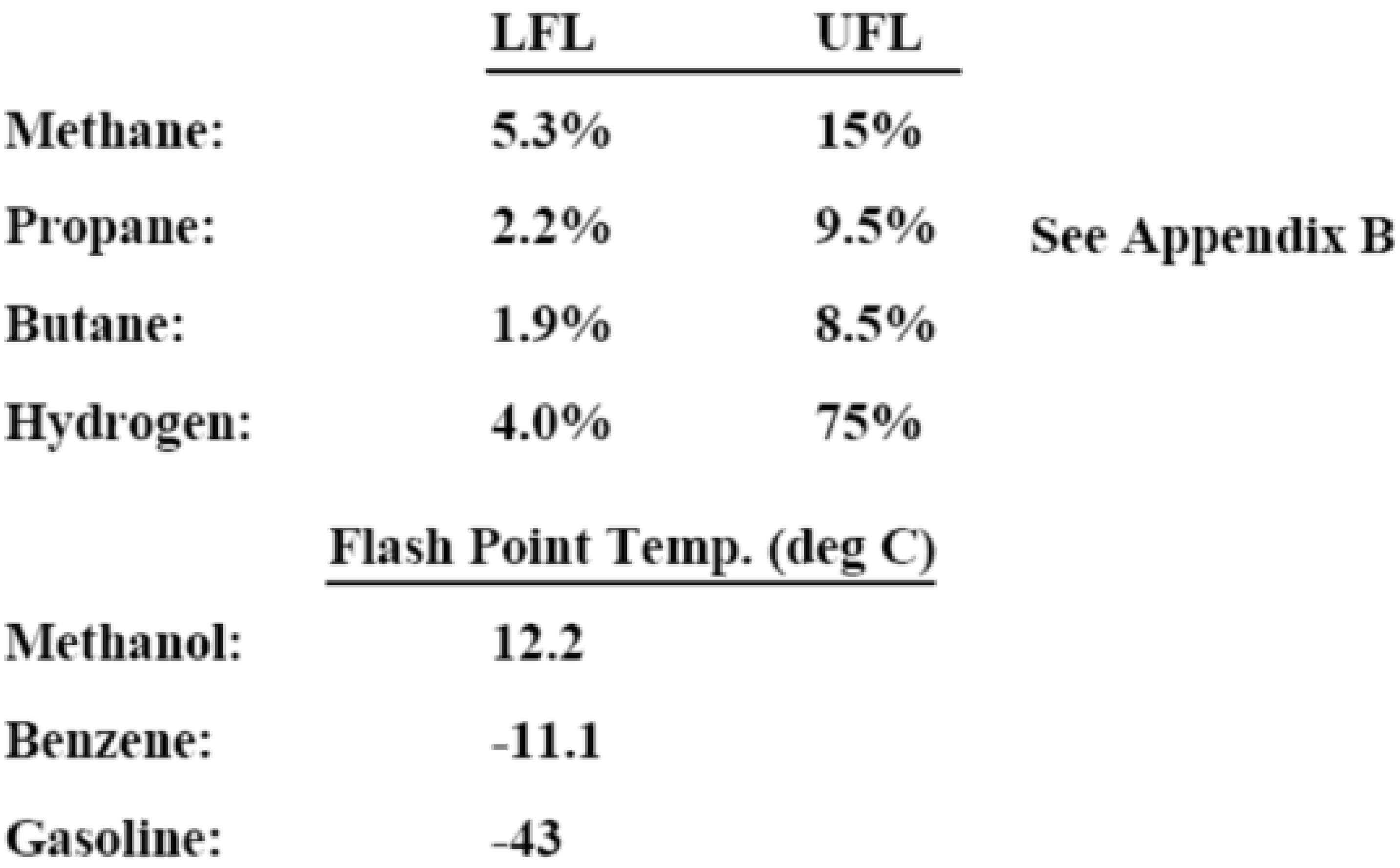
- **Limiting Oxygen Concentration (LOC):** Oxygen concentration below which combustion is not possible, with any fuel mixture.
  - Expressed as volume % oxygen.

- **Also called:** Minimum Oxygen Concentration (MOC)

  Max. Safe Oxygen Conc. (MSOC) Others

! Read the definitions at both page 227 and 228

Typical Values - 1



	LFL	UFL
Methane:	5.3%	15%
Propane:	2.2%	9.5%
Butane:	1.9%	8.5%
Hydrogen:	4.0%	75%

See Appendix B

	Flash Point Temp. (deg C)
Methanol:	12.2
Benzene:	-11.1
Gasoline:	-43

Typical Values - 2

	AIT (deg. C)
Methane:	632
Methanol:	574
Toluene:	810

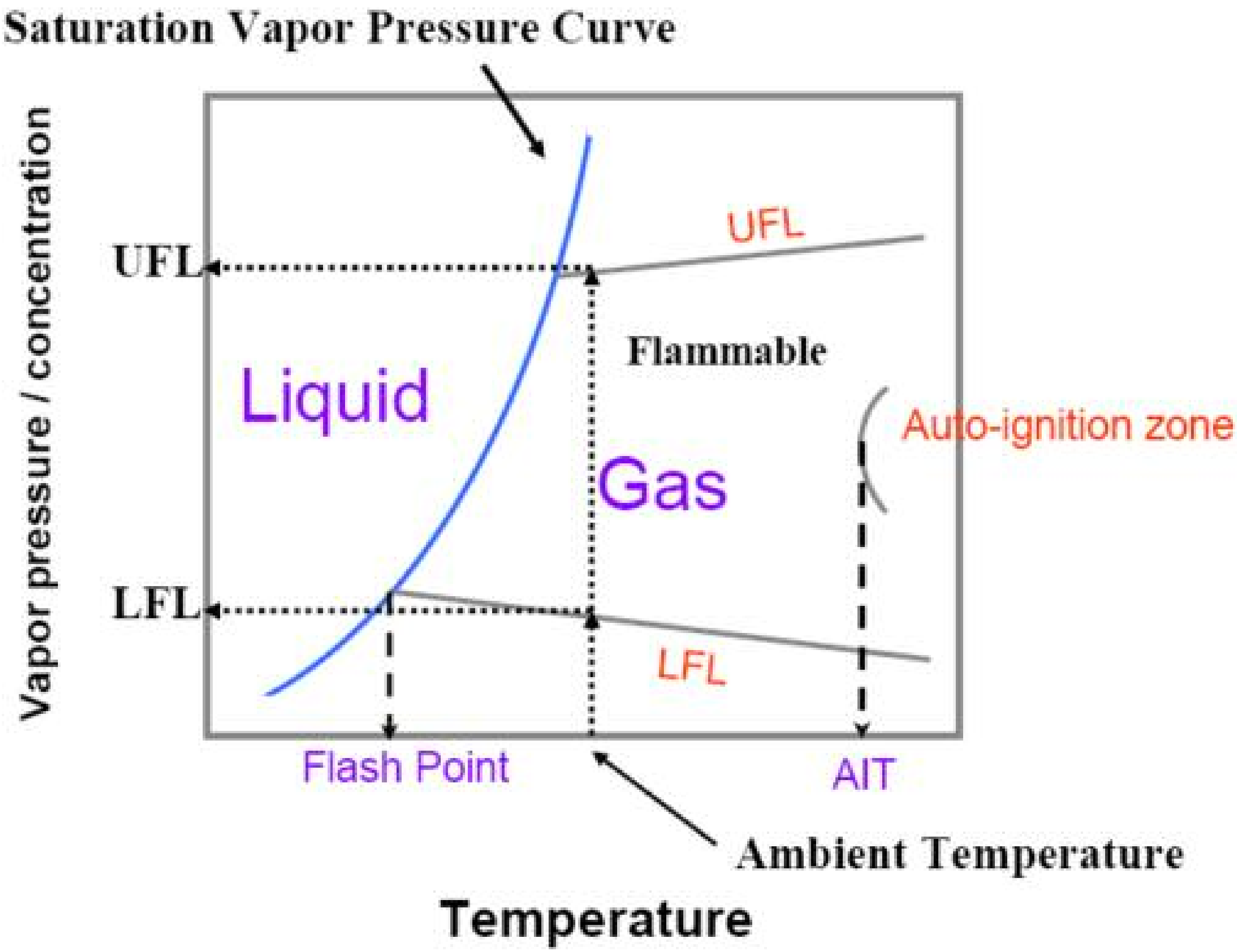
Appendix B

Great variability in reported AIT values! Use lowest value.

	LOC (Vol. % Oxygen)
Methane:	12%
Ethane:	11%
Hydrogen:	5%

Table 6-2

Flammability Relationships



Minimum Ignition Energies

What: Energy required to ignite a flammable mixture.

Typical Values: (wide variation expected)

Vapors: 0.25 mJ

Dusts: about 10 mJ

- Static spark that you can feel:

  about 20 mJ

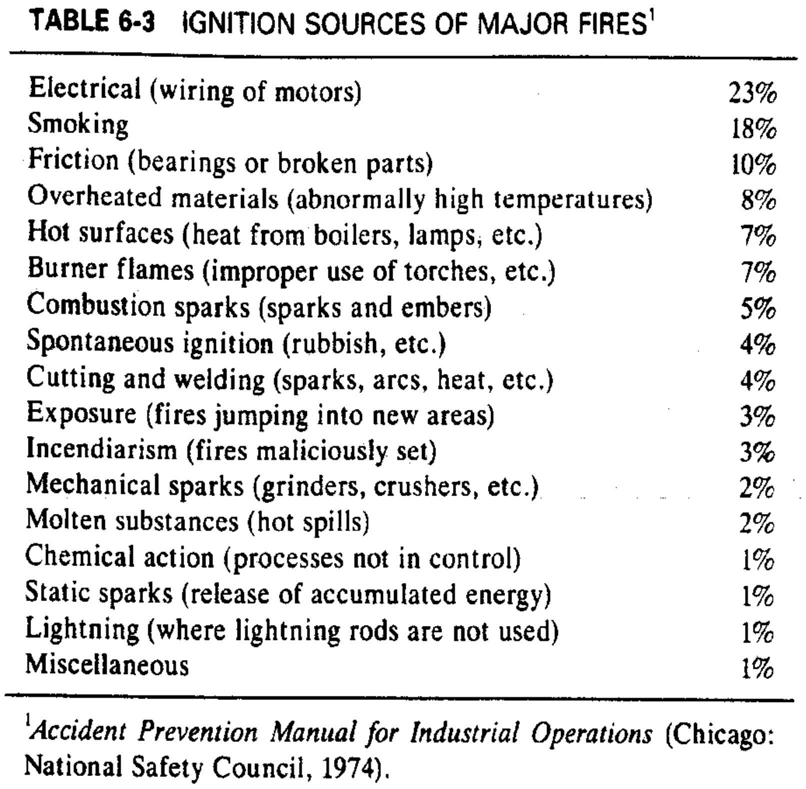
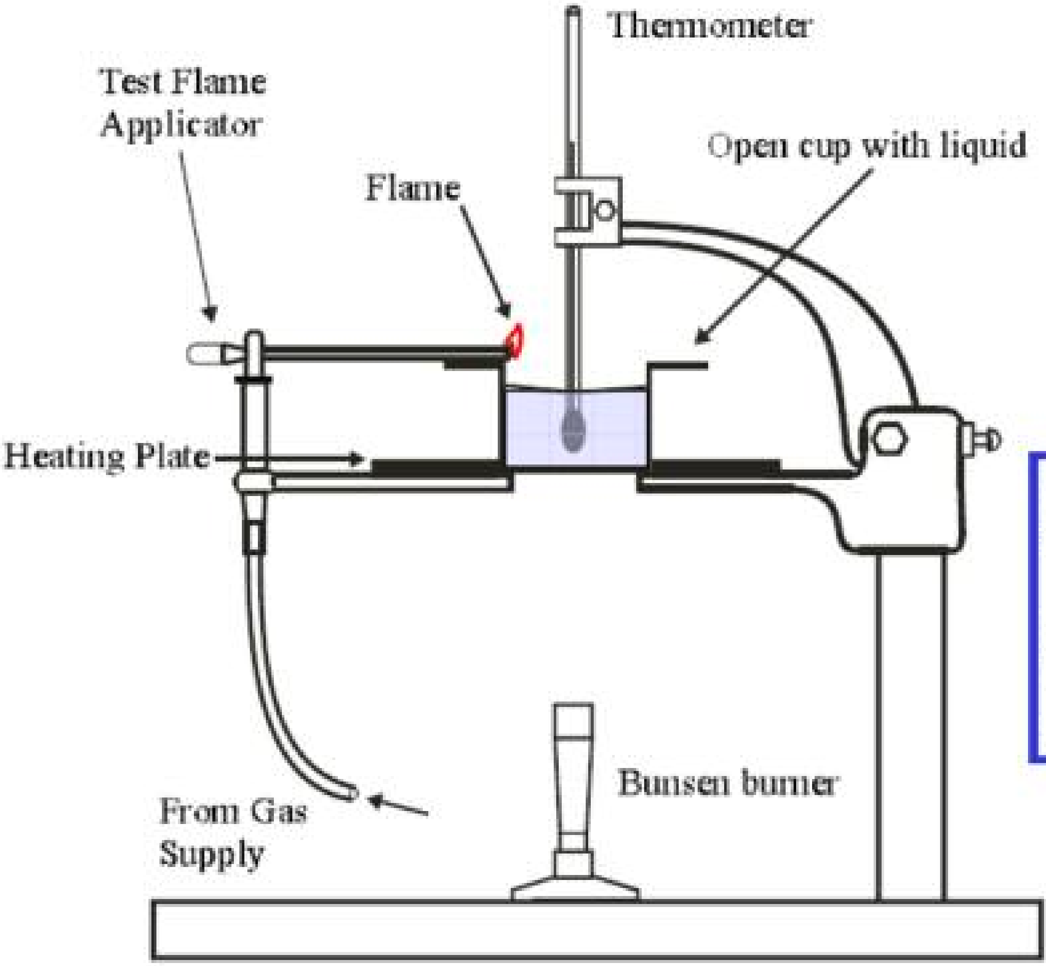


TABLE 6-3 IGNITION SOURCES OF MAJOR FIRES[1]

Electrical (wiring of motors)	23%
Smoking	18%
Friction (bearings or broken parts)	10%
Overheated materials (abnormally high temperatures)	8%
Hot surfaces (heat from boilers, lamps, etc.)	7%
Burner flames (improper use of torches, etc.)	7%
Combustion sparks (sparks and embers)	5%
Spontaneous ignition (rubbish, etc.)	4%
Cutting and welding (sparks, arcs, heat, etc.)	4%
Exposure (fires jumping into new areas)	3%
Incendiarism (fires maliciously set)	3%
Mechanical sparks (grinders, crushers, etc.)	2%
Molten substances (hot spills)	2%
Chemical action (processes not in control)	1%
Static sparks (release of accumulated energy)	1%
Lightning (where lightning rods are not used)	1%
Miscellaneous	1%

[1] *Accident Prevention Manual for Industrial Operations* (Chicago: National Safety Council, 1974).

Experimental Determination - Flashpoint



Cleveland Open Cup Method.

Closed cup produces a better result - reduces drafts across cup.

Flash point temperatures for pure materials

$$T_f = a + \frac{b(c/T_b)^2 e^{-c/T_b}}{(1 - e^{-c/T_b})^2},$$

where

T_f is the flash point temperature (K),
a, b, and c are constants provided in Table 6-1 (K), and
T_b is the boiling point temperature of the material (K).

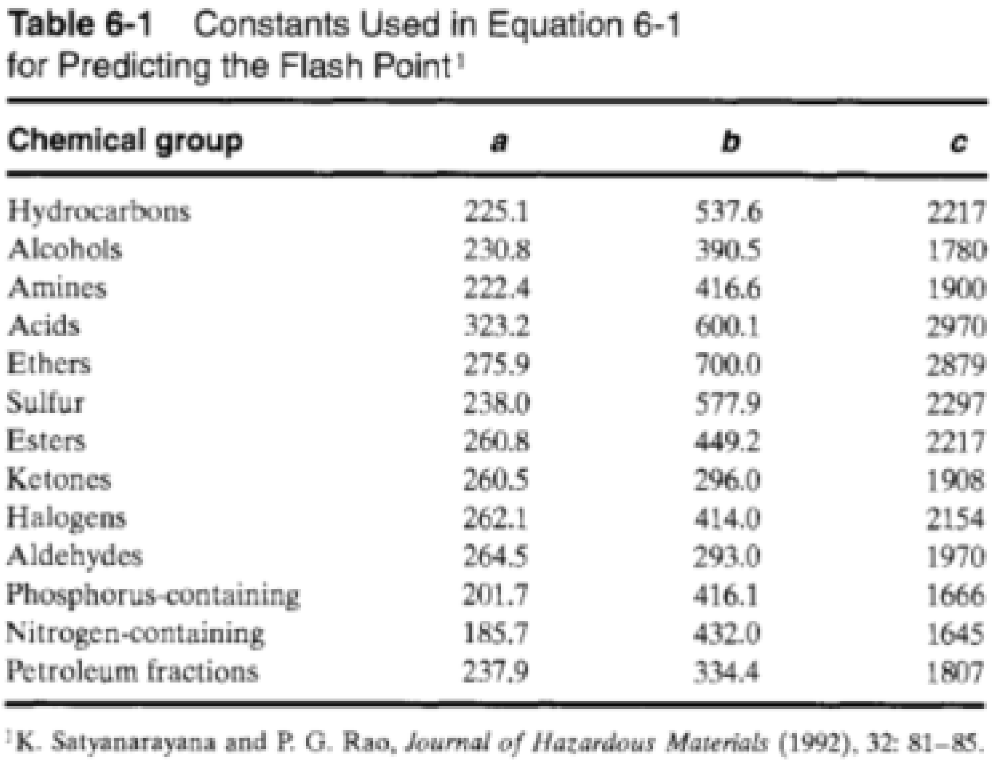
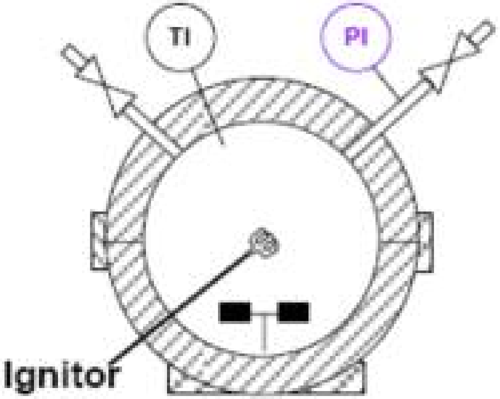


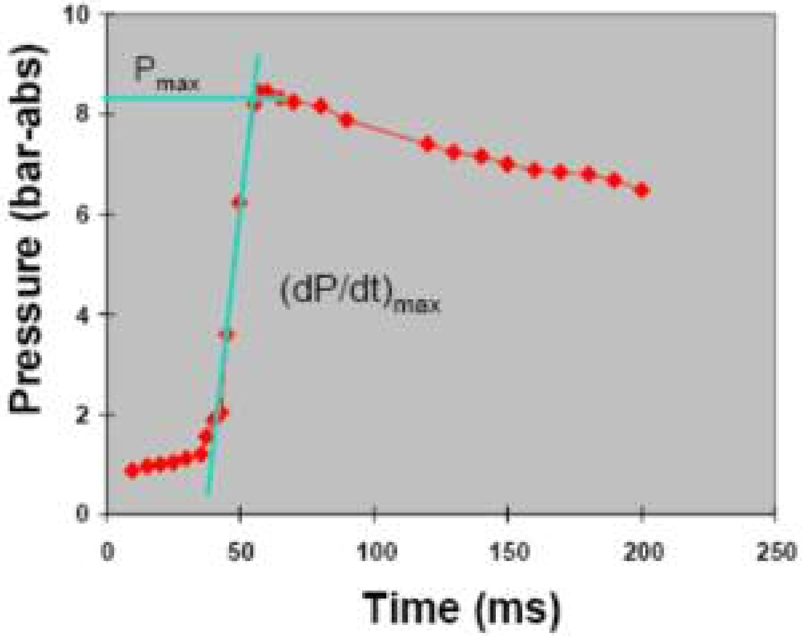
Table 6-1 Constants Used in Equation 6-1 for Predicting the Flash Point[1]

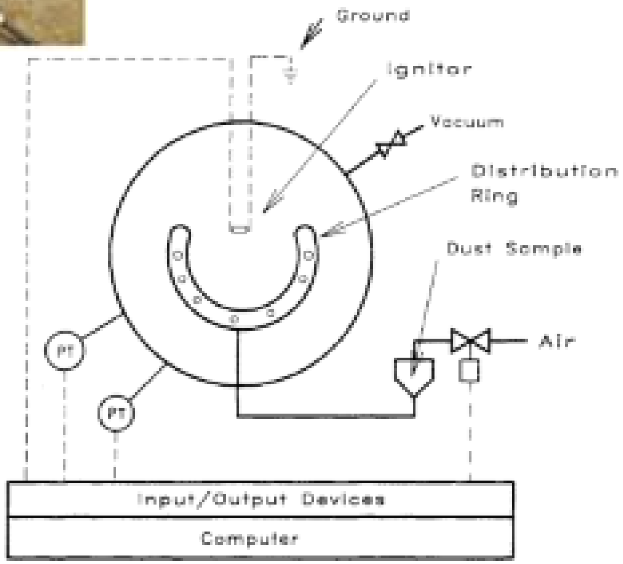
Chemical group	*a*	*b*	*c*
Hydrocarbons	225.1	537.6	2217
Alcohols	230.8	390.5	1780
Amines	222.4	416.6	1900
Acids	323.2	600.1	2970
Ethers	275.9	700.0	2879
Sulfur	238.0	577.9	2297
Esters	260.8	449.2	2217
Ketones	260.5	296.0	1908
Halogens	262.1	414.0	2154
Aldehydes	264.5	293.0	1970
Phosphorus-containing	201.7	416.1	1666
Nitrogen-containing	185.7	432.0	1645
Petroleum fractions	237.9	334.4	1807

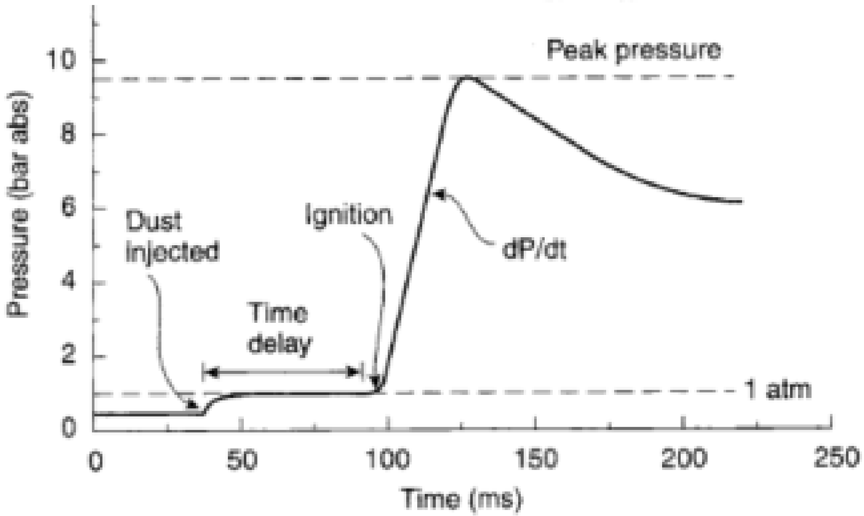
[1] K. Satyanarayana and P. G. Rao, *Journal of Hazardous Materials* (1992), 32: 81–85.

Experimental Determination: P versus t



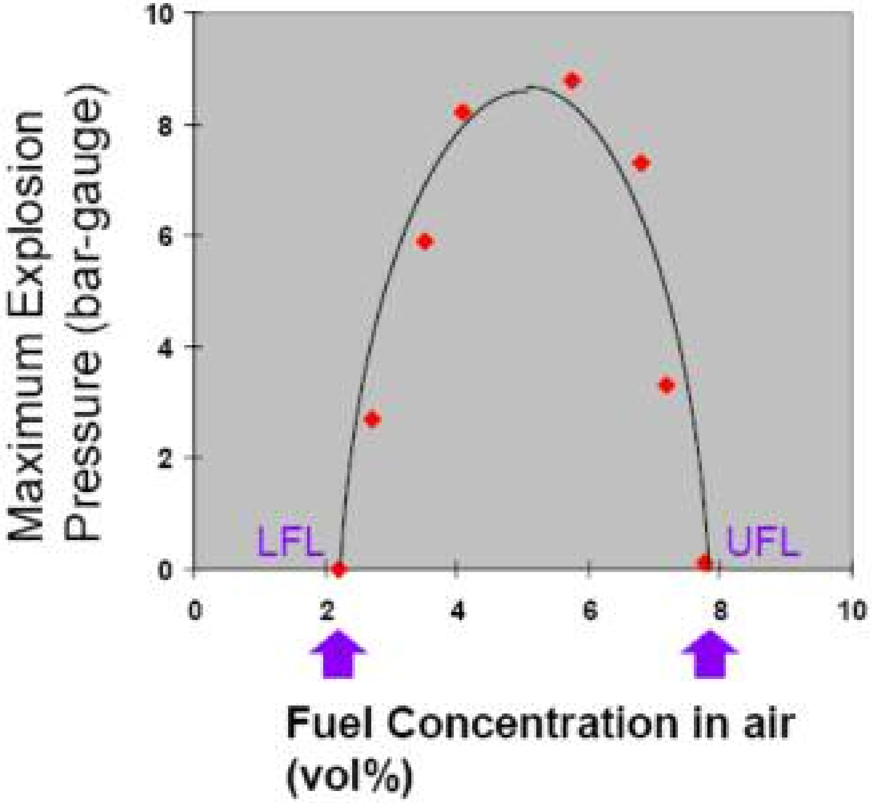






Experimental Determination - LFL, UFL

Run experiment at different fuel compositions with air:



Need a criteria to define limit - use 1 psia pressure increase. Other criteria are used - with different results!

Flammability limits are an empirical artifact of experiment!

Flammability Limits of Mixtures

Le Chatelier Rule (1891)

$$LFL_{mix} = \frac{1}{\sum_{i=1}^{n} \frac{y_i}{LFL_i}} \qquad UFL_{mix} = \frac{1}{\sum_{i=1}^{n} \frac{y_i}{UFL_i}}$$

y_i is the mole fraction of component i on a combustible basis, and n is the number of combustible species.

Assumptions:

1) Product heat capacities constant
2) No. of moles of gas constant
3) Combustion kinetics of pure species unchanged
4) Adiabatic temperature rise the same for all species

Example 6-2

What are the LFL and UFL of a gas mixture composed of 0.8% hexane, 2.0% methane, and 0.5% ethylene by volume?

Solution

The mole fractions on a fuel-only basis are calculated in the following table. The LFL and UFL data are obtained from appendix B.

	Volume %	Mole fraction on combustible basis	LFL_i (vol. %)	UFL_i (vol. %)
Hexane	0.8	0.24	1.2	7.5
Methane	2.0	0.61	5.3	15
Ethylene	0.5	0.15	3.1	32.0
Total combustibles	3.3			
Air	96.7			

Equation 6-2 is used to determine the LFL of the mixture:

$$\mathrm{LFL}_{\mathrm{mix}} = \frac{1}{\sum_{i=1}^{n} \frac{y_i}{\mathrm{LFL}_i}} = \frac{1}{\frac{0.24}{1.2} + \frac{0.61}{5.3} + \frac{0.15}{3.1}}$$

$= 1/0.363 = 2.75\%$ by volume total combustibles.

3 is used to determine the UFL of the mixture:

$$\mathrm{UFL}_{\mathrm{mix}} = \frac{1}{\sum_{i=1}^{n} \frac{y_i}{\mathrm{UFL}_i}} = \frac{1}{\frac{0.24}{7.5} + \frac{0.61}{15} + \frac{0.15}{32.0}}$$

$= 12.9\%$ by volume total combustibles.

Because the mixture contains 3.3% total combustibles, it is flammable.

Flammability Limit Dependence on Temperature

As temperature increases:

UFL increases, LFL decreases
--> Flammability range increases

$$LFL_T = LFL_{25} - \frac{0.75}{\Delta H_c}(T-25) = LFL_{25} - \frac{100C_P}{\Delta H_c}(T-25)$$

$$UFL_T = UFL_{25} + \frac{0.75}{\Delta H_c}(T-25)$$

Approx. for many hydrocarbons

$T : {}^{o}C$

ΔH_c : kcal/mole, heat of combustion

Flammability Limit Dependence on Pressure

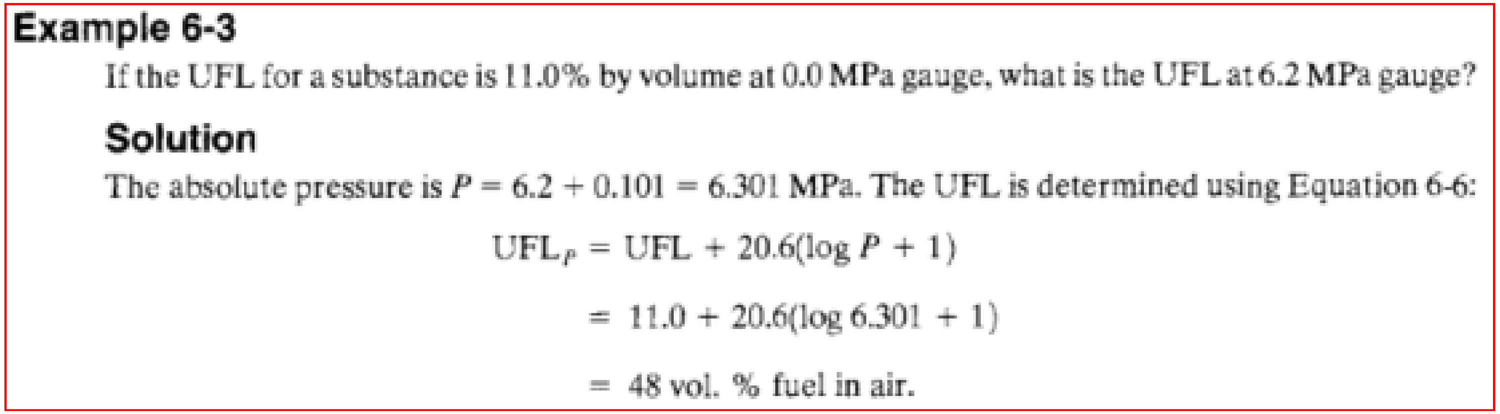
As pressure increases:

UFL increases (broadening the flammability range)
LFL mostly unaffected

$$UFL_P = UFL + 20.6 * (\log P + 1)$$

P is pressure in mega-Pascals, absolute

No theoretical basis for this yet!



Example 6-3

If the UFL for a substance is 11.0% by volume at 0.0 MPa gauge, what is the UFL at 6.2 MPa gauge?

Solution

The absolute pressure is $P = 6.2 + 0.101 = 6.301$ MPa. The UFL is determined using Equation 6-6:

$$\begin{aligned} \mathrm{UFL}_P &= \mathrm{UFL} + 20.6(\log P + 1) \\ &= 11.0 + 20.6(\log 6.301 + 1) \\ &= 48 \text{ vol. \% fuel in air.} \end{aligned}$$

In Class Problem

What is the UFL of a gas mixture composed of 1% methane, 2% ethane and 3% propane by volume at 50°C and 2 atmospheres:

Data:

Component	MW	Heat of Combustion (kcal/mol)
Methane	16.04	212.79
Ethane	30.07	372.81
Propane	44.09	526.74

Solution Procedure:

1. **Correct for temperature**
2. **Correct for pressure (only for UFL)**
3. **Find for mixture.**

Correction for Temperature : UFL from Table 6-1

$$\text{Eq. 6-4} \rightarrow \; UFL_T = UFL_{25}\left(1 + 0.75(T - 25)/\Delta H_c\right)$$

$$\text{Methane } UFL_{50} = 15\left(1 + 0.75(25)/212.79\right) = 16.32$$

$$\text{Ethane } UFL_{50} = 12.5\left(1 + 0.75(25)/372.81\right) = 13.13$$

$$\text{Propane } UFL_{50} = 9.5\left(1 + 0.75(25)/526.74\right) = 9.84$$

Correction for Pressure (UFL only)

$$\text{Eq. 6-5} \rightarrow UFL_P = UFL + 20.6(\log_{10} P + 1)$$

$$P = (2atm)\left(\frac{101kPa}{atm}\right)\left(\frac{MPa}{1000kPa}\right) = 0.202MPa$$

$$UFL_{2atm} = UFL_{1atm} + 20.6(\log_{10}(0.202MPa) + 1)$$

$$UFL_{2atm} = UFL_{1atm} + 6.290$$

$$UFL_{Methane} = 22.61$$

$$UFL_{Ethane} = 19.40$$

$$UFL_{\text{Propane}} = 16.13$$

Mixture calculation

Mixture	Vol%	Mol frac Comb
Methane	1	0.1667
Ethane	2	0.3333
Propane	3	0.5000
Combustibles	6	

Equation 6-2 for mixtures

$$UFL_{mix} = \frac{1}{\sum_{i=1}^{n} \frac{y_i}{UFL_i}}$$

$$UFL_{Mixture} = \frac{1}{\frac{0.1667}{22.61} + \frac{0.3333}{19.40} + \frac{0.5}{16.13}} = 18.0 vol\%$$

Since total combustibles in air 1+2+3=6 < 18 then the system is in the combustible range (below UFL)

Estimating Flammability Limits

- For many hydrocarbon vapors the LFL and the UFL are a function of the stoichiometric concentration (C_{st}) of fuel.

$$\boxed{LFL = 0.55 \cdot C_{st}}$$

$$\boxed{UFL = 3.5 \cdot C_{st}}$$

C_{st} **stoichiometric conc. [vol%]**

Very approximate!

Not always conservative!

where C_{st} is volume % fuel in fuel plus air.

General combustion reaction:

$$C_mH_xO_y + zO_2 \rightarrow mCO_2 + \frac{x}{2}H_2O$$

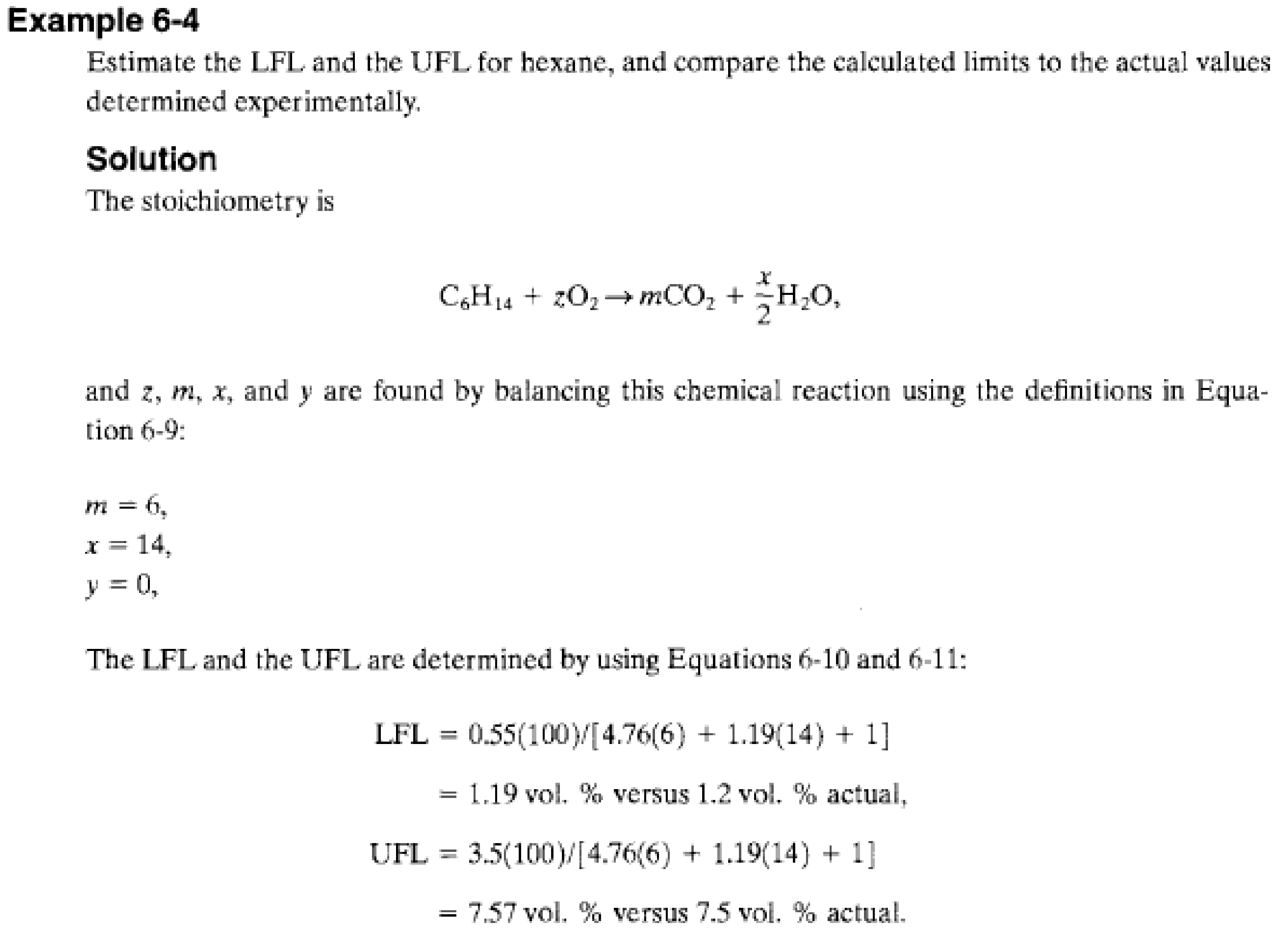
$$z = m + \tfrac{1}{4}x - \tfrac{1}{2}y$$

$$\boxed{C_{st} = \frac{100}{1 + \left(\frac{z}{0.21}\right)}.}$$

$$\boxed{C_{st} = \frac{21\%}{0.21 + z}}$$

$$\text{LFL} = \frac{0.55(100)}{4.76m + 1.19x - 2.38y + 1},$$

$$\text{UFL} = \frac{3.50(100)}{4.76m + 1.19x - 2.38y + 1}.$$



Example 6-4

Estimate the LFL and the UFL for hexane, and compare the calculated limits to the actual values determined experimentally.

Solution

The stoichiometry is

$$C_6H_{14} + zO_2 \rightarrow mCO_2 + \frac{x}{2}H_2O,$$

and z, m, x, and y are found by balancing this chemical reaction using the definitions in Equation 6-9:

$m = 6$,
$x = 14$,
$y = 0$,

The LFL and the UFL are determined by using Equations 6-10 and 6-11:

$$\begin{aligned}\text{LFL} &= 0.55(100)/[4.76(6) + 1.19(14) + 1]\\ &= 1.19 \text{ vol. \% versus } 1.2 \text{ vol. \% actual,}\\ \text{UFL} &= 3.5(100)/[4.76(6) + 1.19(14) + 1]\\ &= 7.57 \text{ vol. \% versus } 7.5 \text{ vol. \% actual.}\end{aligned}$$

Estimating LOC

$$\mathrm{LOC} = \left(\frac{\text{moles fuel}}{\text{total moles}}\right)\left(\frac{\text{moles } O_2}{\text{moles fuel}}\right) = \mathrm{LFL}\left(\frac{\text{moles } O_2}{\text{moles fuel}}\right).$$

LOC limiting oxygen conc. [vol% O_2]

(1)Fuel + (z) Oxygen --> Products

$$\boxed{LOC \cong z \cdot LFL}$$

Typically 8 - 10%

Very approximate!

Not always conservative!

Example 6-5

Estimate the LOC for butane (C_4H_{10}).

Solution

The stoichiometry for this reaction is

$$C_4H_{10} + 6.5O_2 \rightarrow 4CO_2 + 5H_2O.$$

The LFL for butane (from appendix B) is 1.9% by volume. From the stoichiometry

$$\text{LOC} = \left(\frac{\text{moles fuel}}{\text{total moles}}\right)\left(\frac{\text{moles } O_2}{\text{moles fuel}}\right) = \text{LFL}\left(\frac{\text{moles } O_2}{\text{moles fuel}}\right).$$

By substitution, we obtain

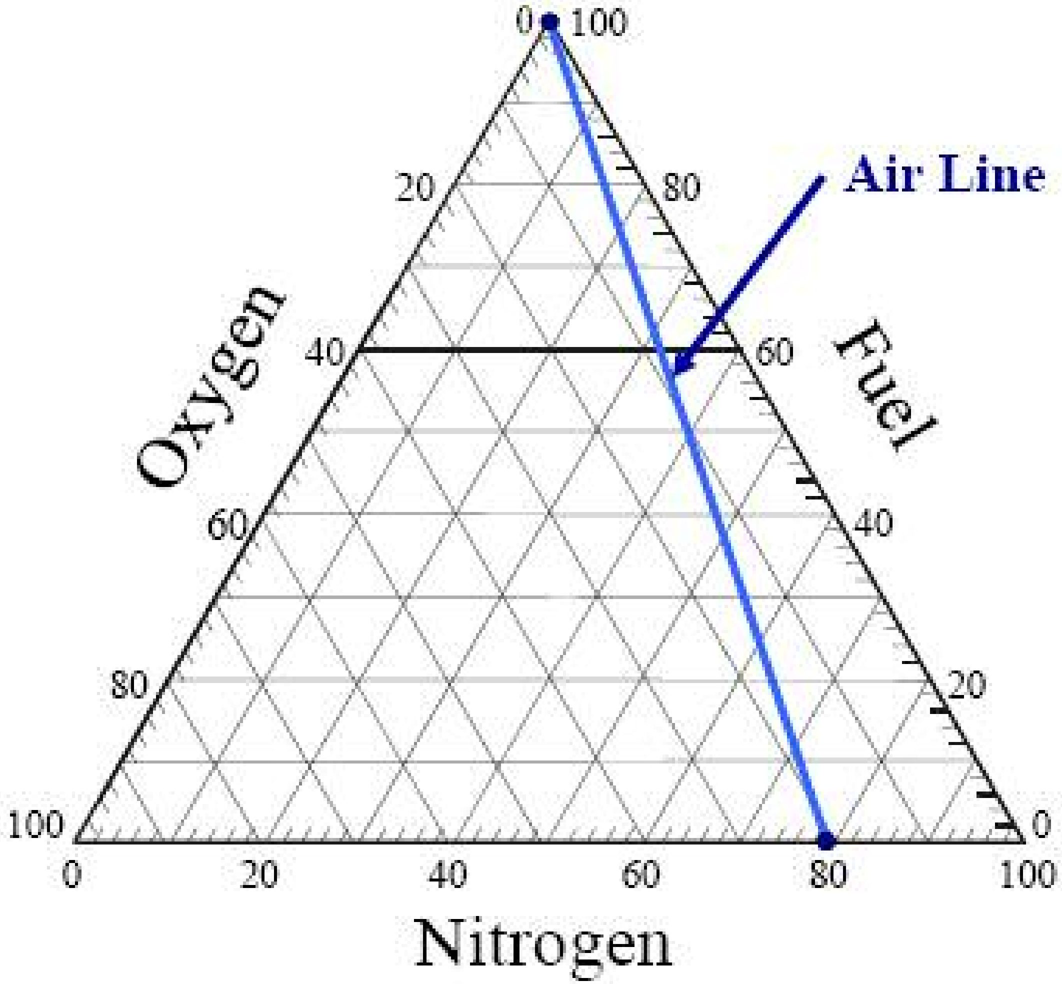
$$\text{LOC} = \left(1.9\frac{\text{moles fuel}}{\text{total moles}}\right)\left(\frac{6.5 \text{ moles } O_2}{1.0 \text{ moles fuel}}\right)$$

$$= 12.4 \text{ vol. } \% \; O_2.$$

The combustion of butane is preventable by adding nitrogen, carbon dioxide, or even water vapor until the oxygen concentration is below 12.4%. The addition of water, however, is not recommended because any condition that condenses water would move the oxygen concentration back into the flammable region.

Flammability Diagram

The Air Line is drawn as a straight line between the upper apex, representing 100% Fuel, and the point on the lower line at 79% nitrogen / 21% oxygen, Representing 100% air.

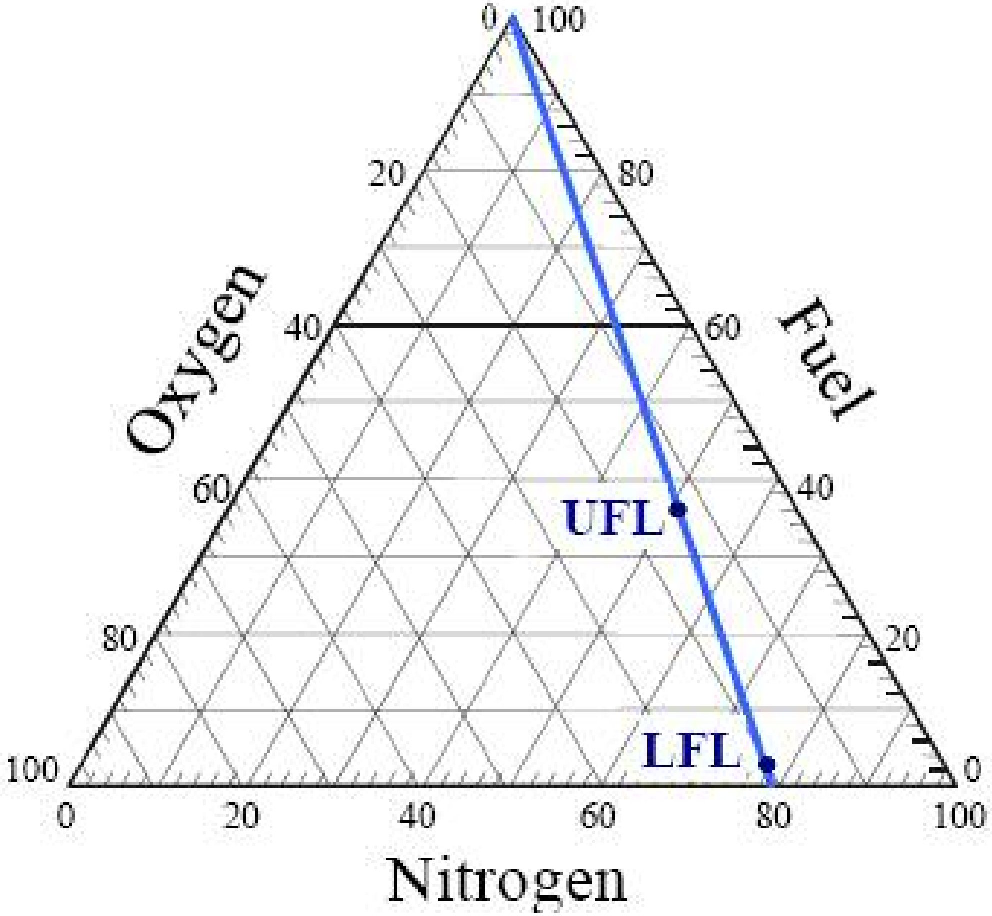


Flammability Diagram

The LFL and the UFL points

In Appendix B of the text, the LFL and UFL for ethylene are given as 2.7% and 36%, respectively.

These values are plotted on the Air Line at the corresponding Fuel percentages.



Flammability Diagram

Stoichiometric concentration

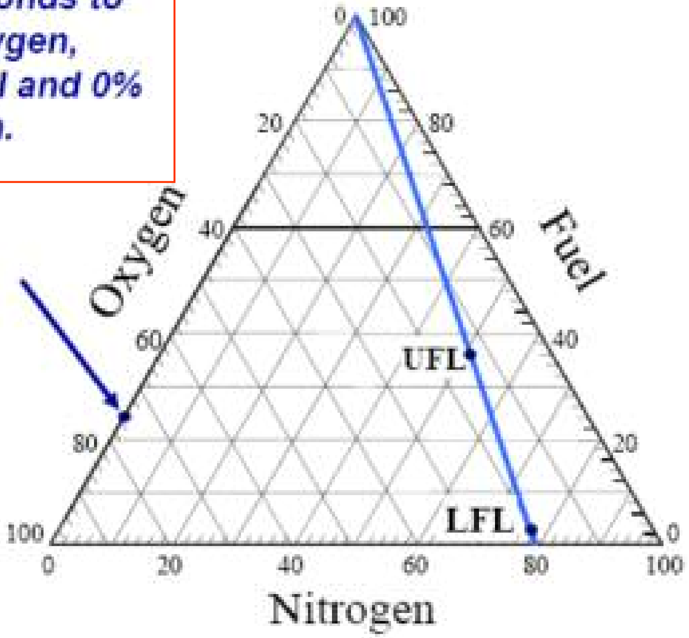
The general combustion reaction is used to determine the coefficient z, corresponding to the moles of oxygen required for complete combustion of one mole of ethylene.

$$C_mH_xO_y + zO_2 \rightarrow mCO_2 + \frac{x}{2}H_2O$$

$$z = m + \tfrac{1}{4}x - \tfrac{1}{2}y \quad = 2 + \tfrac{1}{4}(4) - \tfrac{1}{2}(0)$$

$$= 3$$

This point corresponds to 75% oxygen, 25% fuel and 0% nitrogen.



If 3 mol O_2 is required to burn 1 mol C_2H_4, the stoichiometric concentration C_{st} in pure oxygen is 75% O_2, 25% C_2H_4.

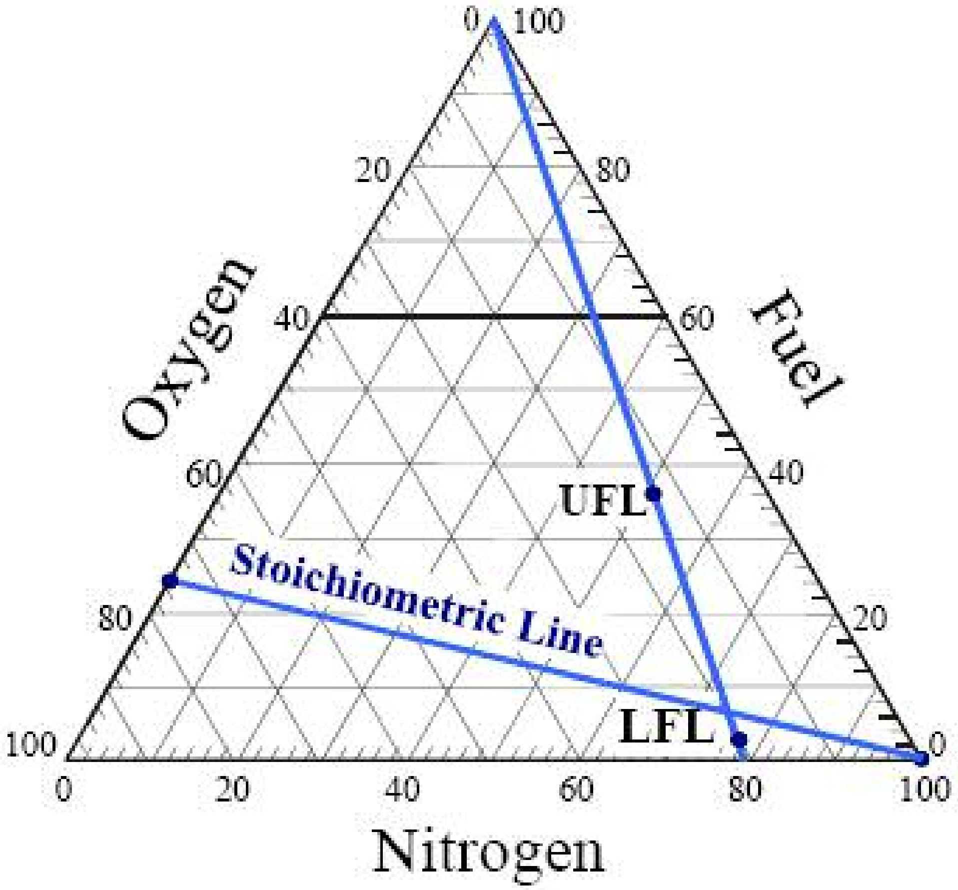
$$\left(\frac{z}{1+z}\right)*100 = \left(\frac{3}{1+3}\right)*100 = 75\%$$

Flammability Diagram

The Stoichiometric Line

The Stoichiometric Line is drawn as shown.

It represents all stoichiometric
$CH_3OH + O_2$
mixtures, with varying amounts of inert nitrogen



Flammability Diagram

Limiting or Minimum Oxygen Concentration

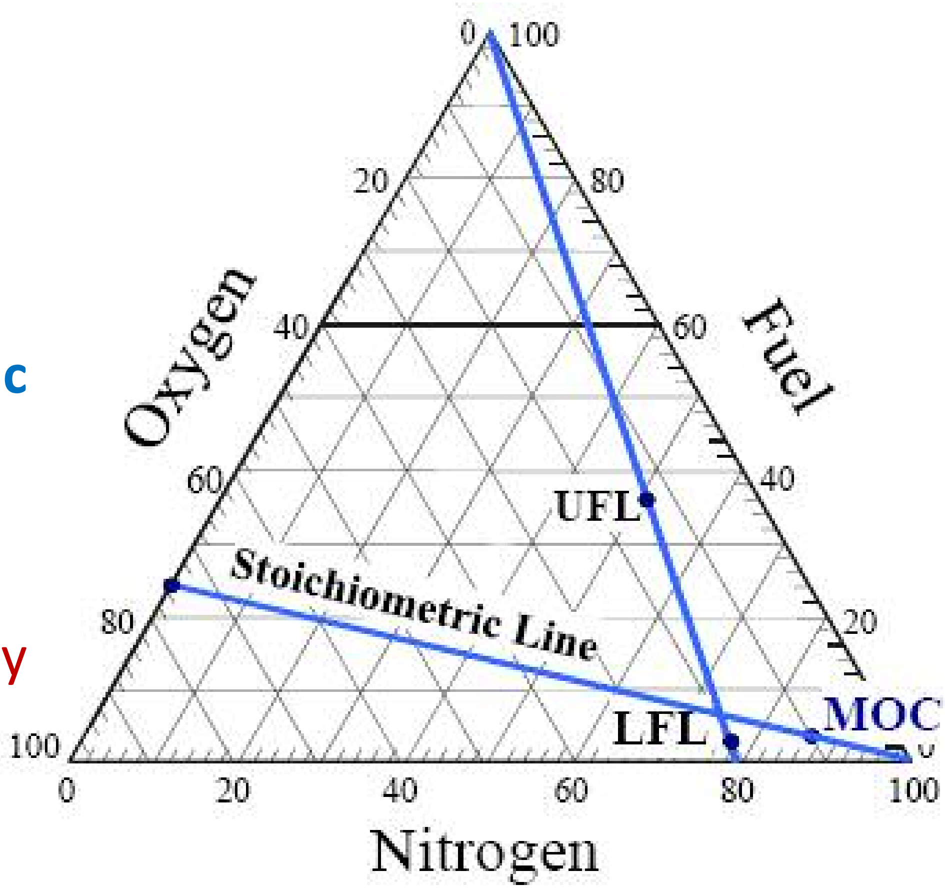
On Table 6-2 of the text, the MOC for ethylene is given as 10 vol.% oxygen.

It is plotted on the Stoichiometric Line

as shown.

Another way to estimate the LOC is by using the following approximation:

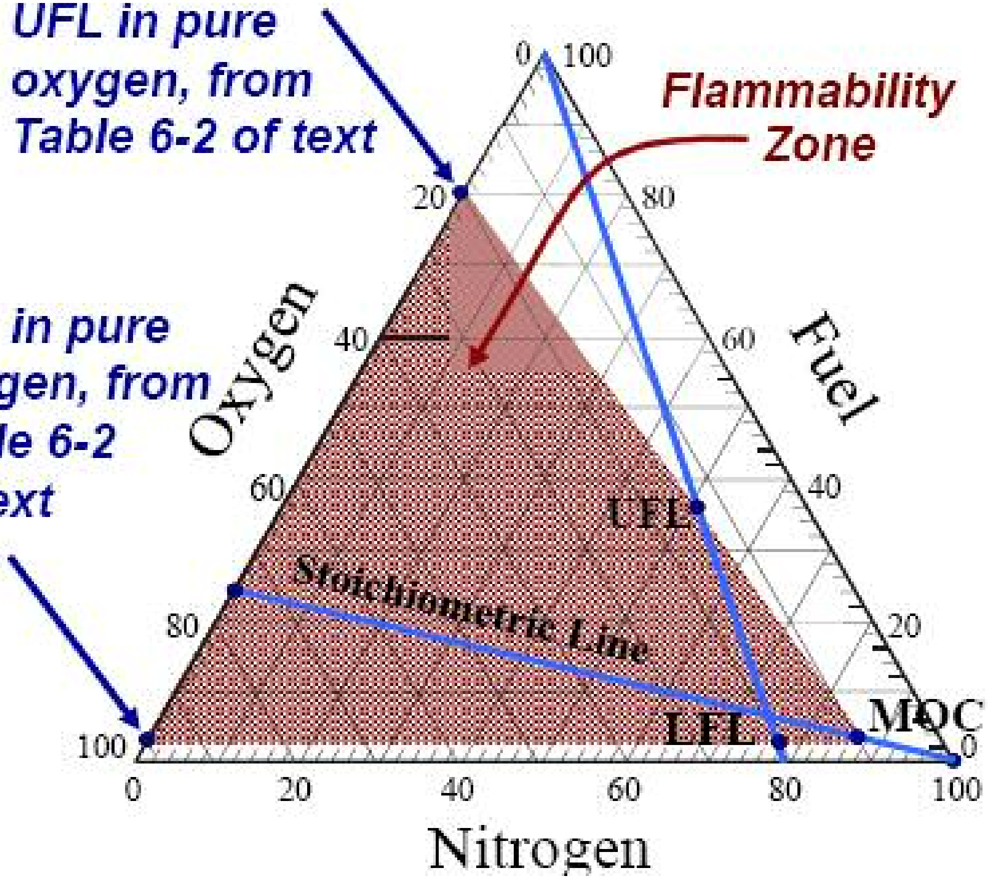
$$\mathrm{LOC} = z(\mathrm{LFL}).$$



Flammability Diagram

The general shape of the flammability boundary

This diagram reflects the fact that ethylene has relatively broad flammability limits; broader than typical alkane hydrocarbons.



UFL in pure oxygen, from Table 6-2 of text

LFL in pure oxygen, from Table 6-2 of text

Flammability Zone

Drawing an Approx. Diagram

1. Draw LFL and UFL on air line (% Fuel in air).
2. Draw stoichiometric line from combustion equation.
3. Plot intersection of LOC with stoichiometric line.
4. Draw LFL and UFL in pure oxygen, if known (% fuel in pure oxygen).
5. Connect the dots to get approximate diagram.

Example

Methane:

LFL: 5.3% fuel in air

UFL: 15% fuel in air

LOC: 12% oxygen

Pure Oxygen:

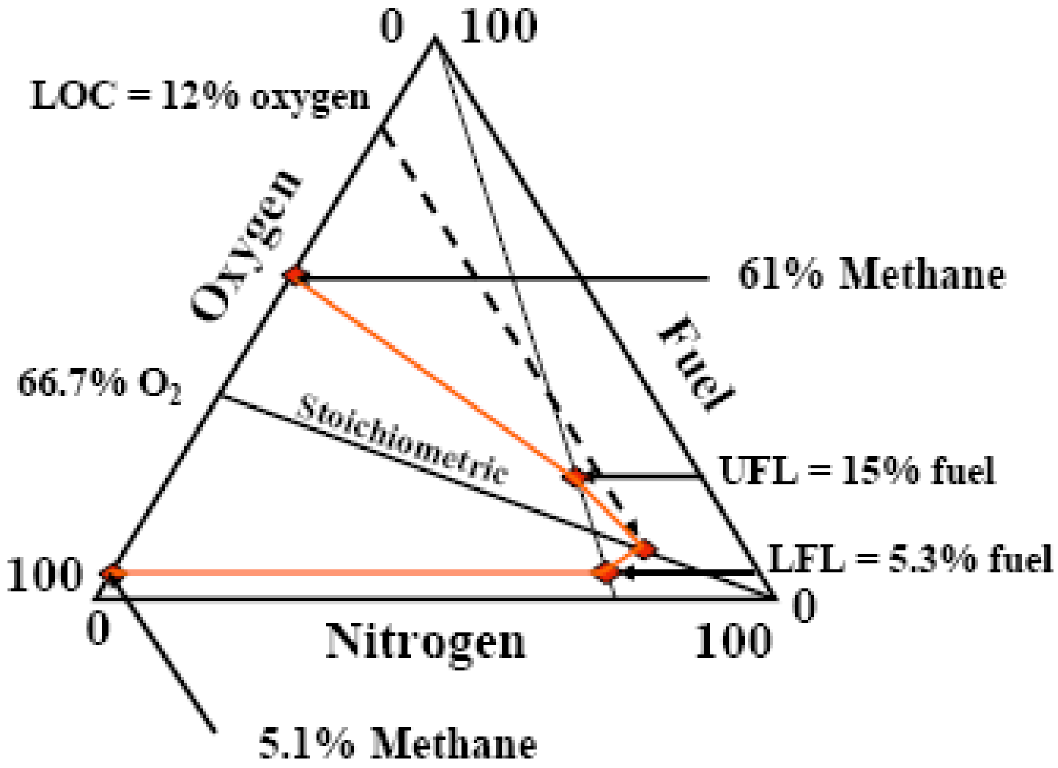
LFL: 5.1% fuel in oxygen

UFL: 61% fuel in oxygen

$CH_4 + 2\ O_2 \dashrightarrow CO_2 + 2\ H_2O$

--> $z = 2$

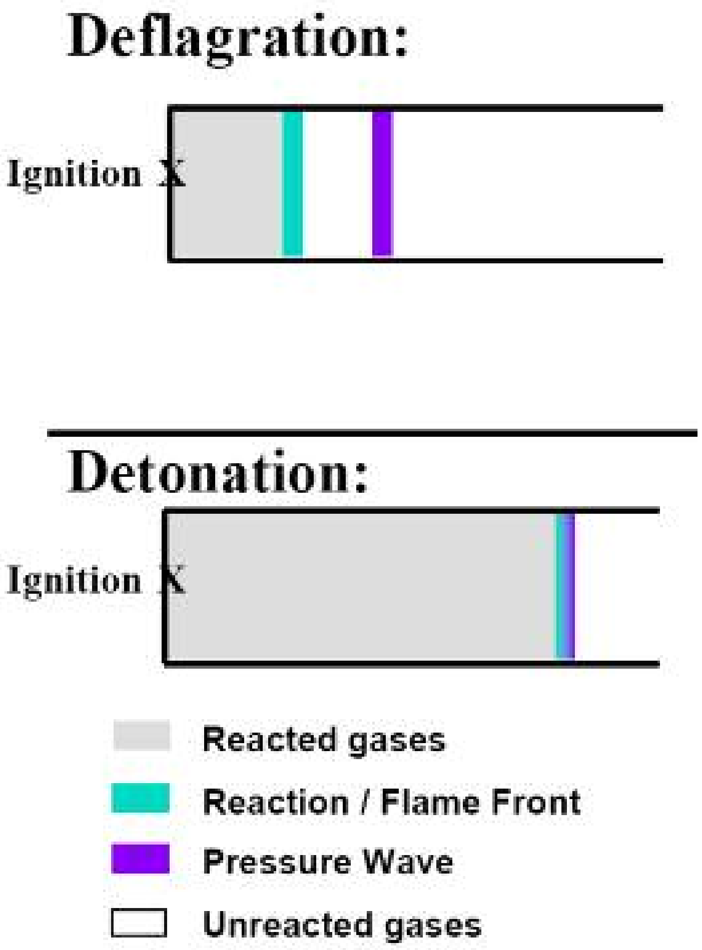
$$\left(\frac{z}{1+z}\right)*100=\left(\frac{2}{3}\right)*100=66.7$$ **% oxyge**



Explosions - Definitions

- **Explosion:** A very sudden release of energy resulting in a shock or pressure wave.
- **Shock, Blast or pressure wave:** Pressure wave that causes damage.
- **Deflagration:** Reaction wave speed < speed of sound.
- **Detonation:** Reaction wave speed > speed of sound.
- **Speed of sound in air:** 344 m/s, 1129 ft/s at ambient T, P.
- Deflagrations are the usual case with explosions involving flammable materials.

Comparison of Behavior



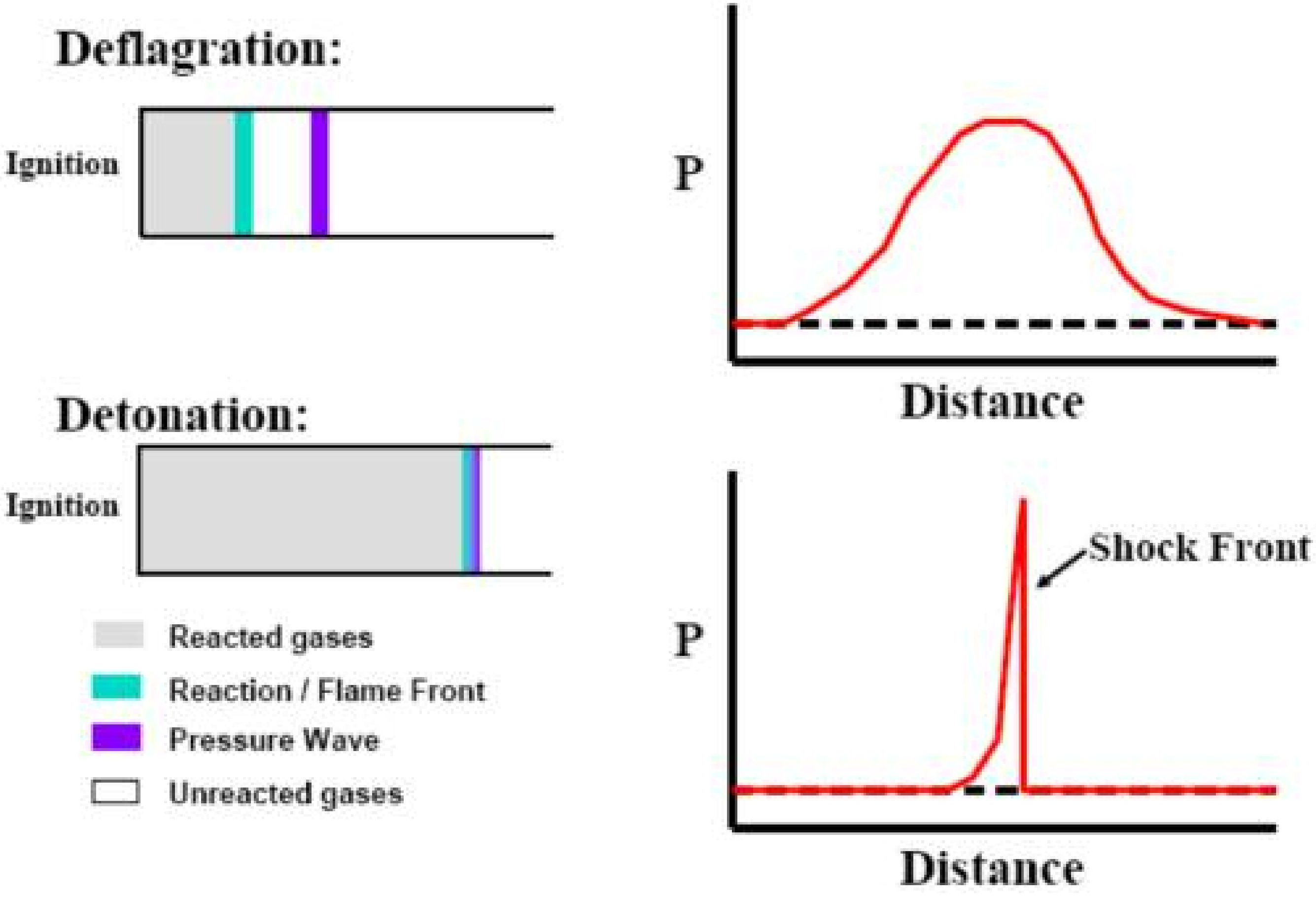
Reaction front moves at less than speed of sound.

Pressure wave moves away from reaction front at speed of sound.

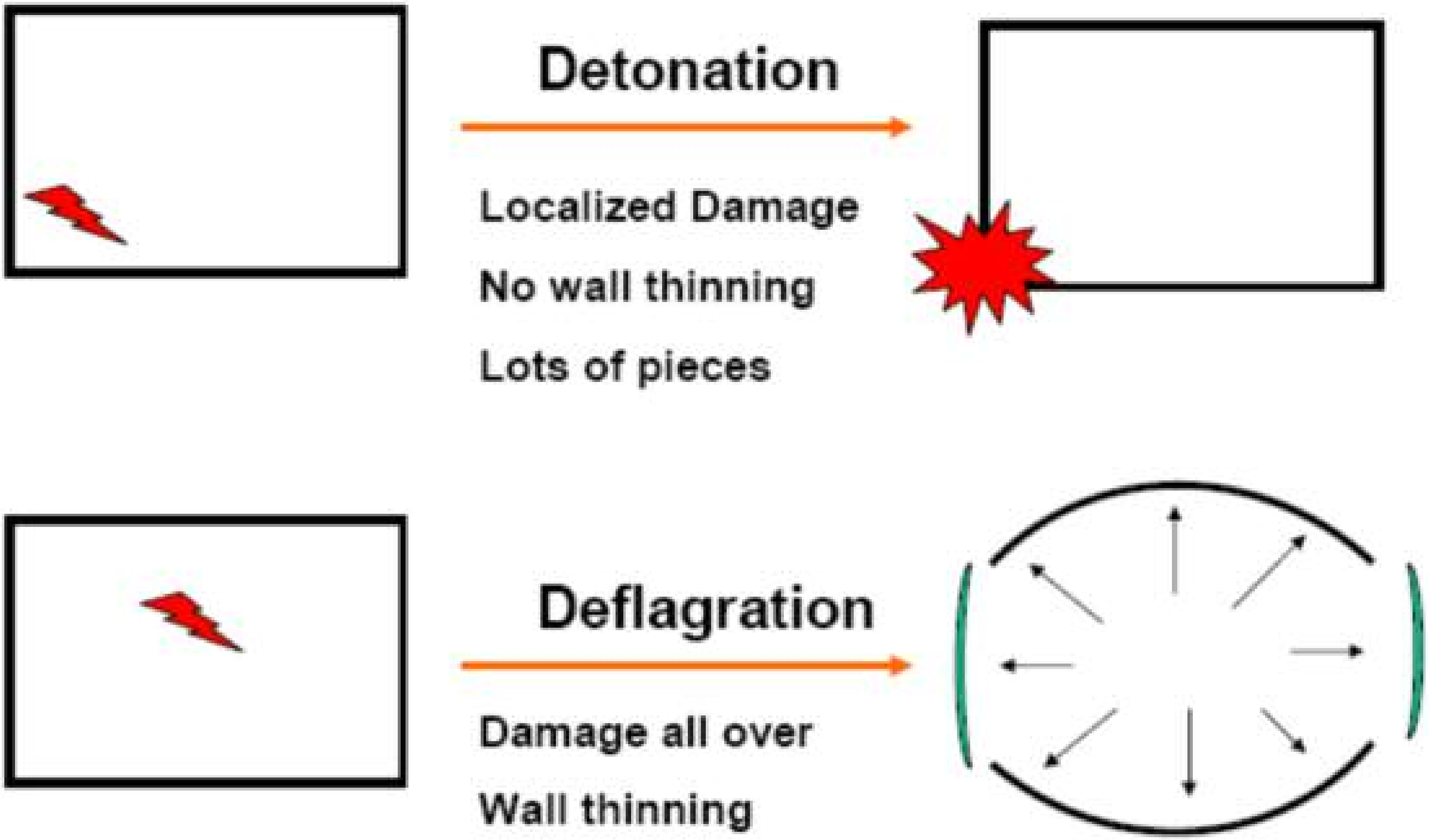
Reaction front moves greater than speed of sound.

Pressure wave is slightly ahead of reaction front moving at same speed.

Comparison of Behavior



Comparison of Behavior



Detonation

Localized Damage

No wall thinning

Lots of pieces

Deflagration

Damage all over

Wall thinning

A few pieces

Confined Explosions

Occurs in process or building. Almost all of the thermodynamic energy ends up in the pressure wave.

Cubic Law: $\left(\frac{dP}{dt}\right)_{max} V^{1/3} = K_G, K_{St}$

K Deflagration index (bar m/s)
G gas
St dust (Staub)

Deflagration index: Measure of explosion robustness, higher value means more robust.

Depends on experimental conditions
Not a fundamental property.

Unconfined Explosions

- Occurs in the open. Only 2 to 10% of thermodynamic energy ends up in pressure wave. Use 2% for this class.

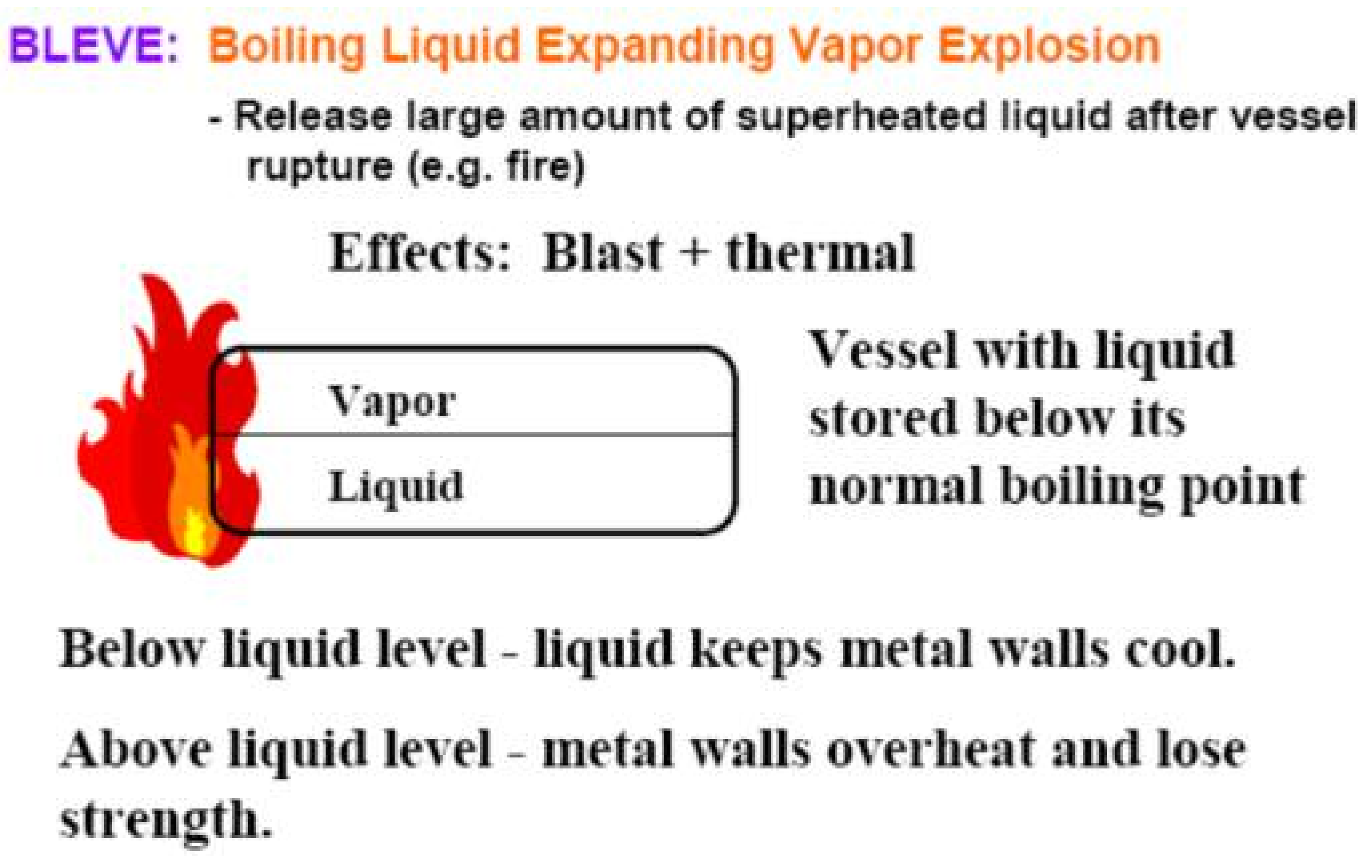
VCE: Vapor Cloud Explosion

- sudden release flammable vapor
- dispersion and mixing with air
- ignition vapor cloud

Prevention

- smaller inventories
- milder process conditions
- incipient leak detection
- automated block valves

Boiling Liquid Expanding Vapor Explosion



BLEVE: Boiling Liquid Expanding Vapor Explosion

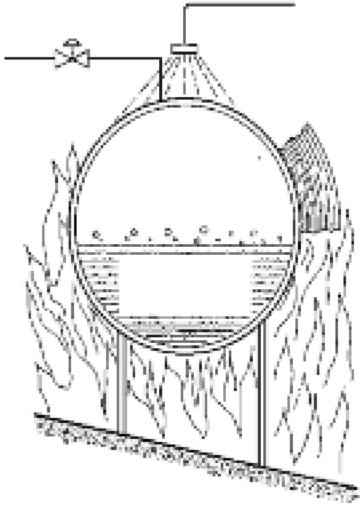
- Release large amount of superheated liquid after vessel rupture (e.g. fire)

Effects: Blast + thermal

Vessel with liquid stored below its normal boiling point

Below liquid level - liquid keeps metal walls cool.

Above liquid level - metal walls overheat and lose strength.



Overpressures

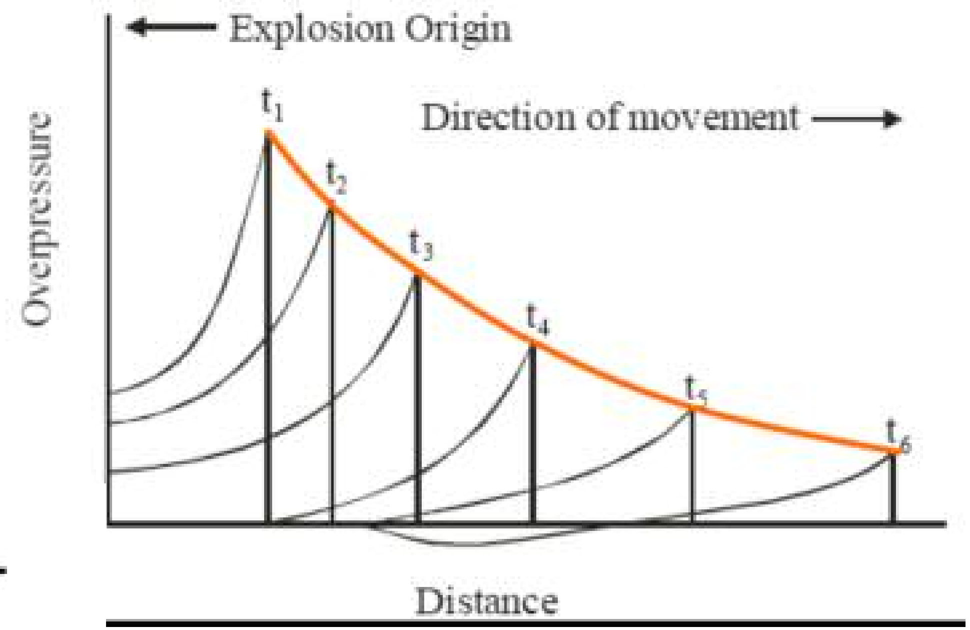
Explosions result in a blast or pressure wave moving out from the explosion center at the speed
of sound.

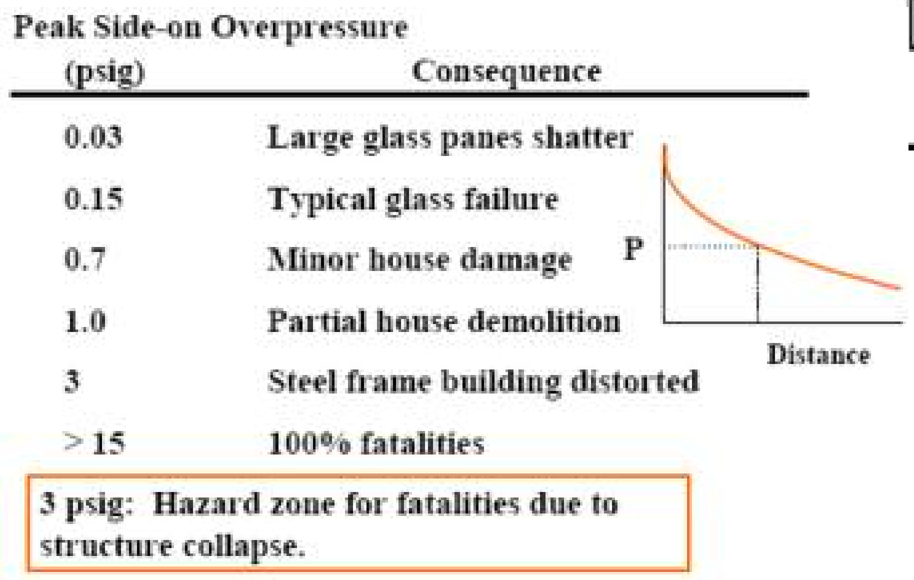
There are several ways to measure this pressure. The usual method is to measure the pressure at right angles to the pressure wave. This is called the Side-on Overpressure.

If the pressure is measured in a direction towards the blast, you get a higher value because of the deceleration of the moving gas as it impacts the pressure transducer.

Batch Reactor Explosion Consequences

Peak Side-on Overpressures





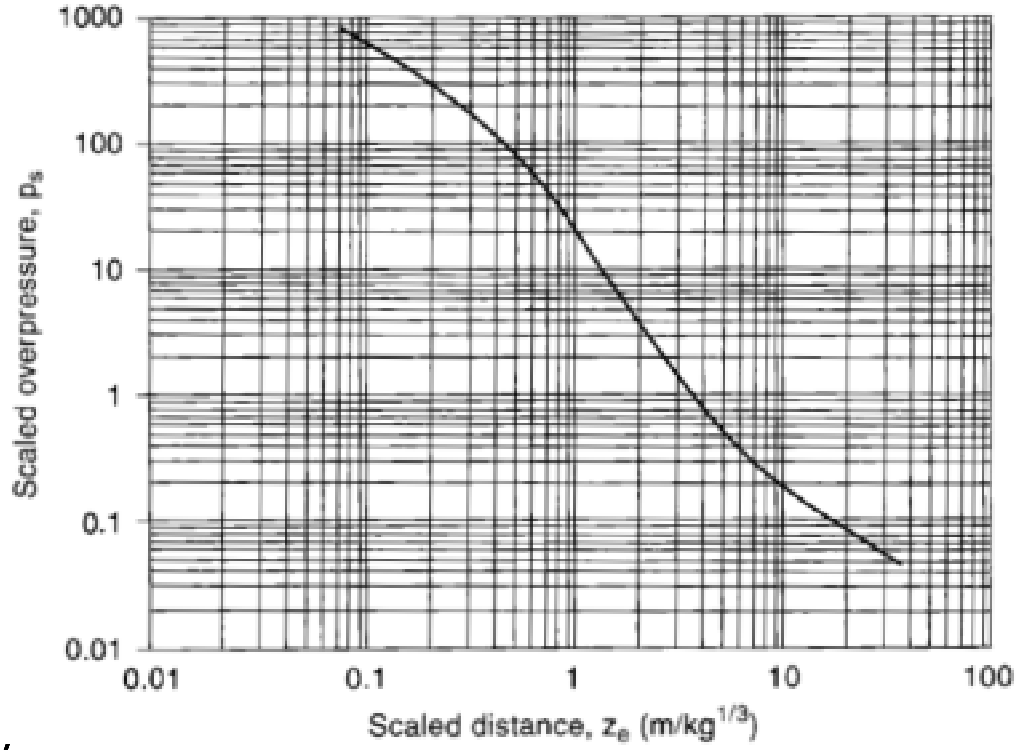
Peak Side-on Overpressure (psig)	Consequence
0.03	Large glass panes shatter
0.15	Typical glass failure
0.7	Minor house damage
1.0	Partial house demolition
3	Steel frame building distorted
> 15	100% fatalities

3 psig: Hazard zone for fatalities due to structure collapse.

Scaled overpressure versus scaled distance

The overpressure can be estimated using an equivalent mass of TNT, denoted m_{TNT}, and the distance from the ground-zero point of the explosion, denoted r.

$$z = \frac{r}{m_{TNT}^{1/3}}$$



The scaled overpressure p_s, is given by

where $$p_s = \frac{p_o}{p_a},$$

p_s is the scaled overpressure (unitless),
p_o is the peak side-on overpressure, and
p_a is the ambient pressure.

The data in Figure 6-23 are also represented by the empirical equation

$$\frac{p_o}{p_a} = \frac{1616\left[1 + \left(\frac{z_e}{4.5}\right)^2\right]}{\sqrt{1 + \left(\frac{z_e}{0.048}\right)^2}\sqrt{1 + \left(\frac{z_e}{0.32}\right)^2}\sqrt{1 + \left(\frac{z_e}{1.35}\right)^2}}.$$

Example 6-8

One kilogram of TNT is exploded. Compute the overpressure at a distance of 30 m from the explosion.

Solution

The value of the scaling parameter is determined using Equation 6-21:

$$z_e = \frac{r}{m_{\mathrm{TNT}}^{1/3}}$$

$$= \frac{30\ \mathrm{m}}{(1.0\ \mathrm{kg})^{1/3}} = 30\ \mathrm{m\ kg^{-1/3}}.$$

From Figure 6-23 the scaled overpressure is 0.055. Thus, if the ambient pressure is 1 atm, then the resulting side-on overpressure is estimated at (0.055)(101.3 kPa) = 5.6 kPa (0.81 psi). From Table 6-9 this overpressure will cause minor damage to house structures.

TNT Equivalency for VCEs

$$m_{TNT} = \frac{\eta m E_c}{E_{TNT}} = \frac{\text{Total Energy in Fuel}}{\text{Energy/mass of TNT}}$$

Where: m_{TNT} **is the equivalent mass of TNT**

η **is the explosion efficiency**

m **is the total mass of fuel**

E_c **is the energy of explosion, or heat of comb.**

E_{TNT} **is the heat of combustion for TNT**

(1120 cal/gm = 4686 kJ/kg = 2016 BTU/lb)

TNT Equiv. - Explosion Efficiency

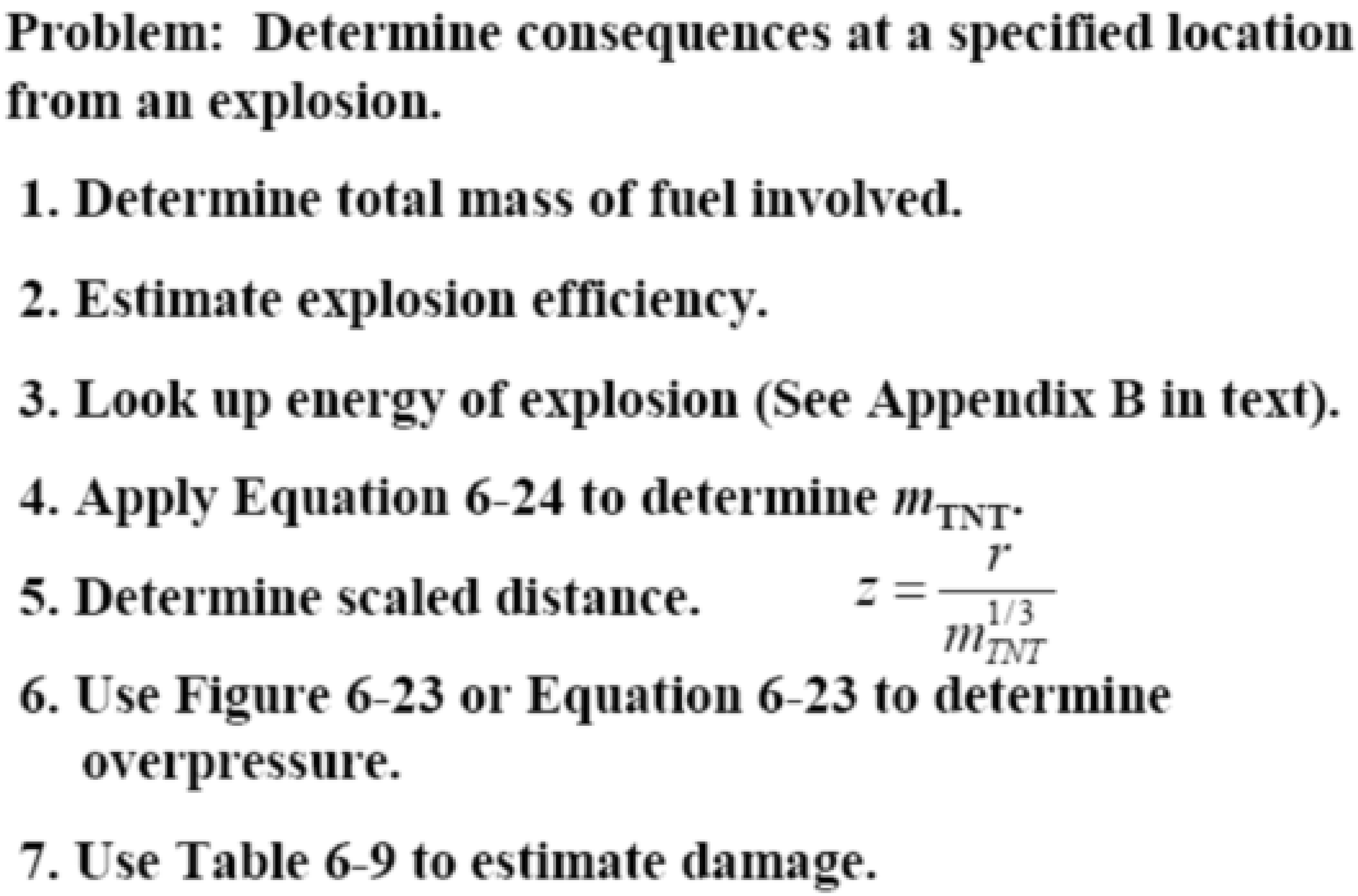
$$m_{TNT} = \frac{\eta m E_c}{E_{TNT}}$$

$\eta \rightarrow 1$ for confined explosion

$\eta \rightarrow 0.02$ to 0.10 for unconfined explosion

Use a default value of 0.02, unless other information is available.

TNT Equivalency Procedure



Problem: Determine consequences at a specified location from an explosion.

1. **Determine total mass of fuel involved.**
2. **Estimate explosion efficiency.**
3. **Look up energy of explosion (See Appendix B in text).**
4. **Apply Equation 6-24 to determine m_{TNT}.**
5. **Determine scaled distance.** $z = \frac{r}{m_{TNT}^{1/3}}$
6. **Use Figure 6-23 or Equation 6-23 to determine overpressure.**
7. **Use Table 6-9 to estimate damage.**

Example 6-9

One thousand kilograms of methane escapes from a storage vessel, mixes with air, and explodes. Determine (a) the equivalent amount of TNT and (b) the side-on peak overpressure at a distance of 50 m from the blast. Assume an explosion efficiency of 2%.

Solution

a. Equation 6-24 applies. The energy of explosion for hexane is found in appendix B. Substituting into Equation 6-24, we obtain

$$m_{\text{TNT}} = \frac{\eta m \Delta H_c}{E_{\text{TNT}}} = \frac{(0.02)(1000\text{ kg})(1\text{ mol}/0.016\text{ kg})(818.7\text{ kJ/mol})}{4686\text{ kJ/kg}} = 218\text{ kg TNT}.$$

b. Equation 6-21 is used to determine the scaled distance:

$$z_e = \frac{r}{m_{\text{TNT}}^{1/3}} = \frac{50\text{ m}}{(218\text{ kg})^{1/3}} = 8.3\text{ m/kg}^{1/3}.$$

From Figure 6-23 (or Equation 6-23), the scaled overpressure is 0.25. Thus the overpressure is

$$p_o = p_s p_a = (0.25)(101.3\text{ kPa}) = 25\text{ kPa}.$$

This overpressure will demolish steel panel buildings.

HW

6-1

6-3d

6-6

6-7

6-8

6-17