Estimating Flammability

Estimating flammability limits for hydrocarbons JONES(1928)

$\boxed{LFL = 0.55 \cdot C_{st}}$ C_{st} stoichiometric conc. [vol%]

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

Very approximate!
Not always conservative!

General combustion reaction:

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

$z = m + ¼\ x - ½\ y$

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

Estimating LOC

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!

Flashpoints of Liquid Mixtures

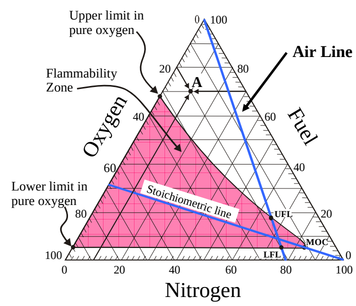
Rule: At flashpoint temperature of mixture, the partial pressure of the flammable is equal to the saturation vapor pressure of the pure component at its flash point.

P^{sat} = 100 mm Hg at flashpoint of pure

Partial pressure of flammable = 100 mm Hg at mixture flashpoint

When possible, get data as close to process conditions.

Flammability Diagram



Flammability Diagram

Useful for:

- **Determining if a mixture is flammable.**
- **Required for control and prevention of flammable mixtures**

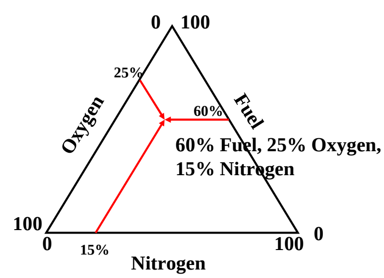
Problems:

- **Only limited experimental data available.**
- **Depends on chemical species.**
- **Function of temperature and pressure.**

Flammability diagram can be approximated.

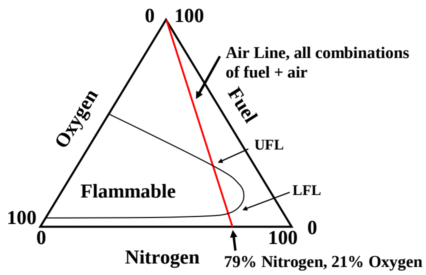
Flammability Diagram - 1

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



Flammability Diagram - 2

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



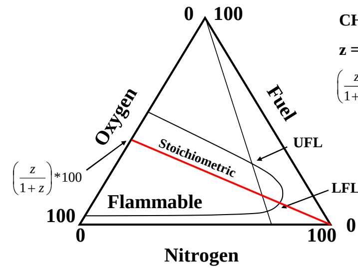
Flammability Diagram - 3

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

CH_4 + 2 O_2 --> Products

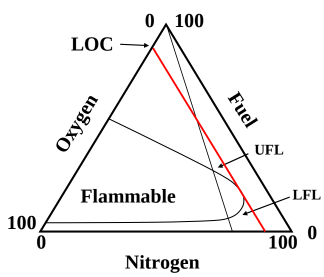
z = 2

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



Flammability Diagram - 4

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



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 <u>approximate</u> 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

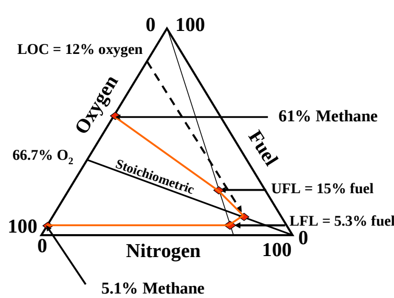
UFL: 61% fuel in oxygen

$CH_4 + 2\ O_2$ --> $CO_2 + 2\ H_2O$

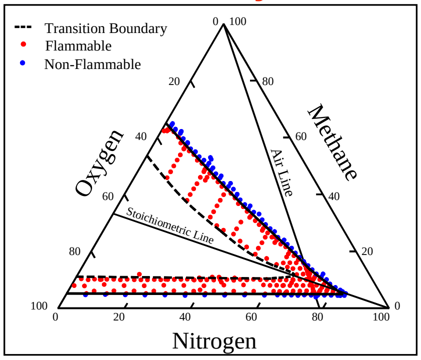
--> z = 2

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

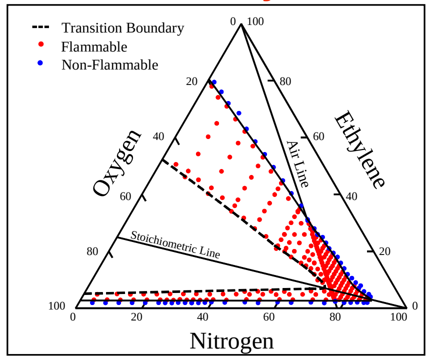
Flammability Diagram - Example



Flammability Zone

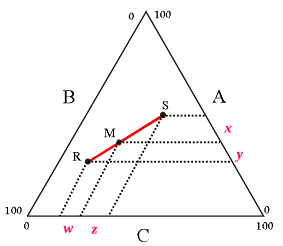


Flammability Zone



Rules for Flammability Diagrams - 1

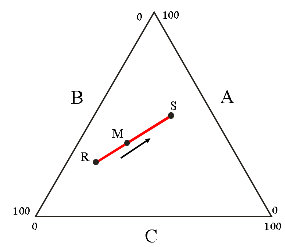
When 2 mixtures, R and S, are combined, the resulting mixture composition, M, is found on a straight line connecting the two mixtures. The location of M depends on the relative number of moles of R and S.



$y/x = w/z$

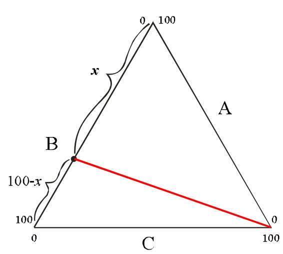
Rules for Flammability Diagrams - 2

If a mixture R is continuously diluted with mixture S, the mixture composition, M, will follow along a straight line connecting the two mixtures. As the dilution continues, the mixture composition will move closer to point S.



Rules for Flammability Diagrams - 3

For systems having composition points that fall along a straight line passing thru an apex corresponding to one component, the other two components are present in a fixed ratio along the entire line length. This ratio is A/B = x/(100-x).



Explosions - Definitions

<u>Explosion:</u> A very sudden release of energy resulting in a shock or pressure wave.

<u>Shock, Blast or pressure wave:</u> Pressure wave that causes damage.

<u>Deflagration:</u> Reaction wave speed < speed of sound.

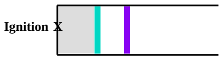
<u>Detonation:</u> Reaction wave speed > speed of sound.

<u>Speed of sound in air:</u> 344 m/s, 1129 ft/s at ambient T, P.

Deflagrations are the usual case with explosions involving flammable materials.

Comparison of Behavior

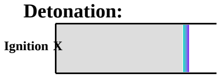
Deflagration:



Reaction front moves at less than speed of sound.

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

Detonation:



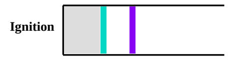
Reaction front moves greater than speed of sound.

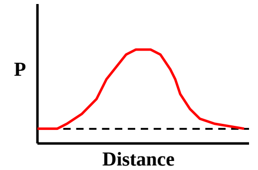
Pressure wave is slightly ahead of reaction front moving at same speed.

- Reacted gases
- Reaction / Flame Front
- Pressure Wave
- Unreacted gases

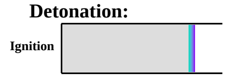
Comparison of Behavior

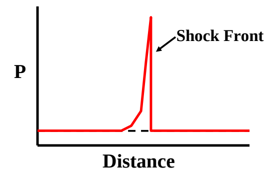
Deflagration:





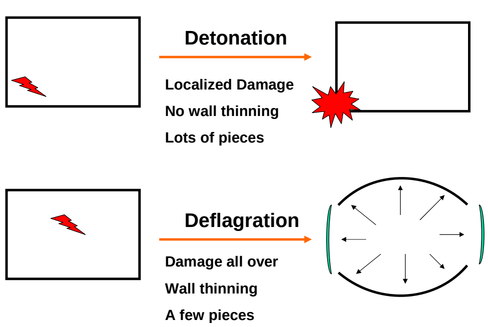
Detonation:





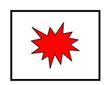
- Reacted gases
- Reaction / Flame Front
- Pressure Wave
- Unreacted gases

Comparison of Behavior



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.

Confined Explosions

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

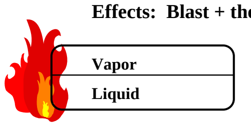
Flixborough

BLEVE

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

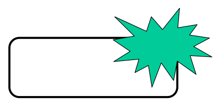
Below liquid level - liquid keeps metal walls cool.

Above liquid level - metal walls overheat and lose strength.

BLEVE

BLEVE Consequences

Mechanical Explosions



Rupture of vessel containing an inert gas at high pressure.

Eqn. 6-31

$$W_e = R_g T \left[\ln\left(\frac{P}{P_E}\right) - \left(1 - \frac{P_E}{P}\right) \right]$$

Max. Mechanical Energy

Where: W_e is the energy of explosion, P is abs. gas pressure in vessel, P_E is abs. ambient pressure, T is abs. temperature.

Batch Reactor Explosion Consequences

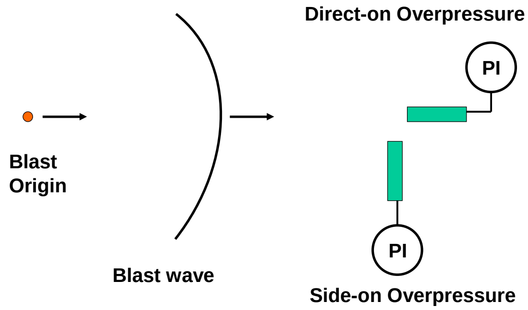
Overpressures

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

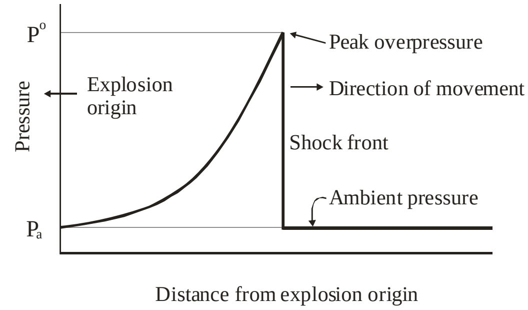
There are several ways to measure this pressure. The usual method is to measure the pressure at right angles to the pressure wave. This is called the Side-on Overpressure.

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.

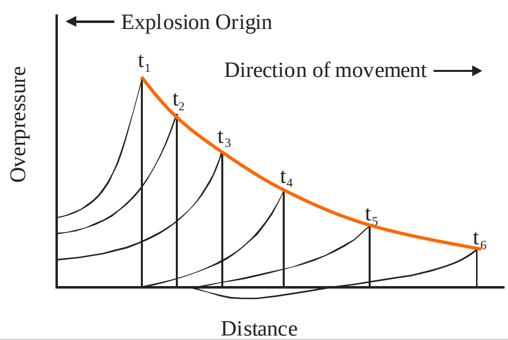
Overpressures



Peak Side-on Overpressures

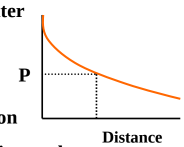


Peak Side-on Overpressures



Consequences of Explosions: Table 6-9

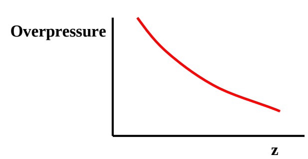
Peak Side-on Overpressure (psig)	Consequence
0.03	Large glass panes shatter
0.15	Typical glass failure
0.7	Minor house damage
1.0	Partial house demolition
3	Steel frame building distorted
> 15	100% fatalities



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

Scaled Distance, *z*

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



Where: ***z*** **is the scaled distance**

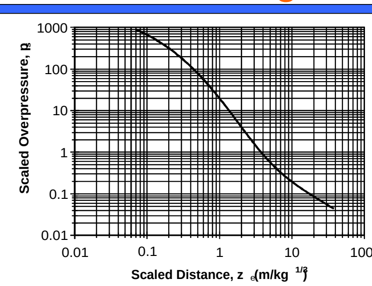
r **is the distance from the blast**

$\boldsymbol{m_{TNT}}$ **is the mass of TNT**

Valid only for point source, TNT type explosions.

See Figure 6-23 in text.

Figure 6-23



See Equation 6-23

Scaled Overpressure, $p_s = \dfrac{p_o}{p_a}$

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.

Other Methods

Other methods are based on degree of congestion or confinement. Basis is that confinement leads to turbulence which increases the burning velocity.

- **TNO Multi-Energy Model (see pages 271-274)**
- **Baker - Strehlow Model**

Both produce essentially the same answer.

Need much more information, i.e. confinement info.

TNT Equivalency Procedure

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

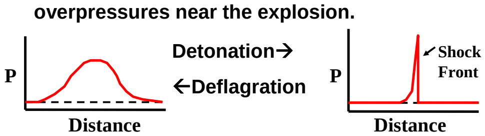
1. **Determine total mass of fuel involved.**
2. **Estimate explosion efficiency.**
3. **Look up energy of explosion (See Appendix B in text).**
4. **Apply Equation 6-24 to determine m_{TNT}.**
5. **Determine scaled distance.** $z = \frac{r}{m_{TNT}^{1/3}}$
6. **Use Figure 6-23 or Equation 6-23 to determine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

TNT Equivalency Procedure

The problem with the application of this approach to exploding vapor is that:

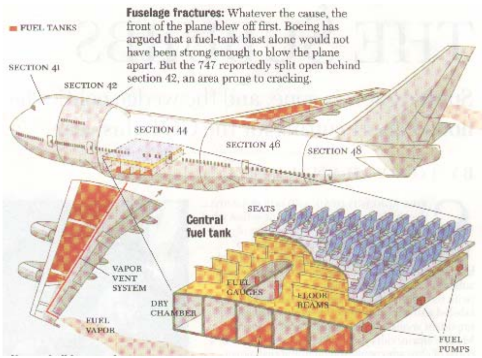
Overpressure curve developed from detonation data, i.e. TNT, and flammable vapor explodes as a deflagration.

The TNT method applied to vapor explosions tends to underpredict overpressures at some distance from the explosion, and over-predicts the overpressures near the explosion.



TWA - 800: July 17, 1996

TWA - 800: July 17, 1996



Example

Determine equivalent TNT mass for TWA 800 explosion.

Assume: 18,000 gallon fuel tank, P = 12.9 psia, T = 120 F, Concentration of fuel = 1%, Energy of explosion for jet fuel = 18,850 BTU/lb, M = 160.

Mass of fuel in vapor:

$$n_{total} = \frac{PV}{R_g T} = \frac{(12.9 \text{ psia})(18{,}000 \text{ gal})(0.1337 \text{ ft}^3/\text{gal})}{(10.731 \text{ psia ft}^3/\text{lb-mole } ^\circ\text{R})(580^\circ\text{R})}$$

$$= 4.99 \text{ lb-moles total}$$

Example

Moles of fuel = (0.01)(4.99 lb-moles) = 0.0499 lb-moles = 7.98 lb of fuel

Assume 100% efficiency (confined explosion).

$$m_{TNT} = \frac{\eta m E_c}{E_{TNT}} = \frac{(1)(7.98 \text{ lb})(18{,}850 \text{ BTU/lb})}{2076 \text{ BTU/lb TNT}}$$

$$= 74 \text{ lb of TNT}$$