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## **ABSTRACT**

In any process industry, good emergency response procedure must be in place to prevent incidents like gas leak from turning to major accidents. Obtaining an early reliable warning of a leak or potential fire event is very important for safety engineers working in the petrochemical industries especially oil and gas industries.

Installing flame and gas detectors at defined locations is one of the indispensable solutions of avoiding leaks from leading to major accidents. The main function of flame and gas detectors is to detect the presence of hazardous gas (flammable or toxic) and fire, while usually not every leak can be detected (because it is too small to threaten safety or result in flash fires which are can be detected and extinguished immediately) it is important to detect leaks or formation of dangerous clouds that can threaten the safety of the plant.

For a fast and reliable detection of presence of dangerous cloud, positioning of gas detector system is then very crucial, likewise the same for flame detectors. When installing and positioning of flame and gas detectors, it is important to have an optimal placement of the detectors which minimizes the amount of detectors while still maintaining a good coverage of the area.

This thesis studies the optimization of flame and gas detectors and the different factors which plays an important role when optimizing detectors. In addition, strengths and weaknesses of different detectors are studied; regulations and standards are looked into.

At the end, verification of flame detector optimisation will be studied using the technique for evaluating visibility field of flame detector in 3D developed by Lloyd's Register Consulting. Comparison between convectional 2D mapping used by many companies as of today and the emerging 3D mapping will be done.

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Emmanuel Chidiebere Obi

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## **ABBREVIATIONS**

**LFL/LEL:** lower flammable limit or lower explosive limit. Is the unit of measurement of gas concentration (Båfjord, 2011) 100% LEL is the lowest concentration at which a flammable substance can produce a fire or explosion when ignited

**UFL/UEL:** Upper flammable limit or upper explosive limit

**ATM:** atmospheric pressure

**ESD:** emergency shutdown system

**BD:** Blow down system

**ISC:** Ignition source control

**PA:** Public address

**HC:** hydrocarbon

**IR:** Infrared

**UGLD:** Ultrasonic gas detection. A technology used in gas detector

**PPM:** parts per million of combustible gas. 1ppm is one part in 1,000,000 parts. Generally ppm (parts per million) is the lowest unit of measurement 10,000ppm = 1% by Volume

**HVAC:** heating, ventilation and air conditioning

**GDS:** Gas detection system

**LOS:** line-of-sight

**ESC:** Equivalent stoichiometric cloud

## **DEFINITION OF TERMS**

**Combustion:** a chemical change that occurs when oxygen (air) reacts with fuel (gases) to produce energy (heat). In this thesis, combustibility is the ability of a material to burn when exposed to burning source.

**Flammability:** a material that is flammable ignites when there is minimal ignition source e.g propane. This should not be confused with combustible materials, the later needs more than an ignition source to burn e.g wood, but propane needs just a little ignition source to ignite.

**Dimensioning gas cloud:** smallest stoichiometry gas cloud that has the potential to cause explosion load exceeding the DAL.

**DAL:** Dimensioning/design accidental load, the most severe accidental load that the structure will be able to withstand during a required period of time, so that it can be said that it meets the required risk acceptance criteria.

**Toxic gas:** gases that can cause hazard to humans including death

**Vapour Density:** molecular weight of a gas divided by the molecular weight of air (molecular weight of air is 28.9). This helps to determine whether a gas is lighter or heavier than dry air (i.e., whether a gas will rise or settle when released).

**Filtered** – filtration is done by doing a 3D analysis and removing the regions that are smaller than Company B criteria.

**Unfiltered** – standard 2D analysis

## **CHAPTER 1.**

### **1.1. BACKGROUND**

On 6 July 1998, a gas leak occurred in the gas compression area of Piper Alpha Platform, and within seconds was ignited resulting in explosions and fire escalating because of no fire water was available. In total, 166 people lost their lives while 63 survived. Although the cause of the leak was known, it is unknown what caused the ignition of the leak (Vinnem, 2007). The scale of the disaster was enormous and in just 22 minutes the platform was destroyed.

The Piper Alpher disaster goes down as one of the major oil and gas disaster and results in one of the turning point for safety improvements in process industries especially oil and gas.

Increasingly industrial processes involve the use and manufactures of dangerous gases which are mostly flammable, toxic and oxygen gases. Time after time escape or leaks of these gases results in an unwanted situations including loss of life and loss of containment. Escape of gas or leaks are in most cases inevitable and not all gas leaks results in dangerous outcome.

Use of early-warning devices like flame and gas detectors, are part of safety measures employed by most industries to reduce the risk posed by gas leaks and fires to personnel, plant and the environment.

Fire and gas detectors are used to give early warnings of presence of dangerous gas or potential fire developing and at the same time they automatically initiate safety measures which includes emergency shut-down (ESD), Ignition Source Control (ISC), fire water, system isolation, evacuation of people and others.

### **1.2. OBJECTIVE**

Installing flame and gas detectors remains the most effective way of stopping escaped gas or developing fire from turning into measure disaster. The gas detectors detects presence of dangerous gas, alarm personnel and initiate safety actions whiles the flame detector does similar thing like the gas detector except it detects fire in this case.

In addition to alarm settings, effective positioning of the detectors is very crucial in detecting the presence of gas before it reaches dangerous condition and threaten the safety of the plant. Proper design of detector positioning should take into account uncertainties that exist in the plant, like weather conditions, leak locations, rate of leak, compositions and the plant general conditions. In many cases, these uncertainties are usually not accounted for in traditional approaches which rely mostly on heuristics, volumetric, parameter and source monitoring (Legg et al., 2013).

A better method of gas detector positioning is to model the area that needs detector coverage using Computational Fluid Dynamics (CFD). In CFD, it is possible to model the exact plant

in questions taking into account uncertainties that exist in that particular plant which we are not able to achieve in convectional or traditional method.

Also, in the case of flame detector positioning, mapping is required to show that combinations of multiple flame detectors in a layout effectively cover all areas eliminating all “blind spot” where fires can develop undetected. Until now, flame detector mapping are done by two-dimensional (2D) modelling techniques. The problem with 2D is that the effect of obstructions is not effectively shown as a result, it is not taking into account or are completely ignored by engineers. This problem is solved by using three-dimensional (3D) technique. In addition, 3D techniques has many other advantages over 2D which will be shown later in this thesis.

Lloyd's Register Consulting has recently developed a technique for evaluating the visibility field of a flame detector in 3D, taking into account the process module geometry.

Main objective in this thesis is to evaluate the optimization of detector layout and to evaluate the visibility field of flame detector in both 2D analysis and 3D analysis; this will be compared to criterion by two companies for visibility field of flame detector.

### **1.3. LIMITATIONS**

The context of this thesis is based on offshore and onshore installations mostly in the Norwegian sector, thus NORSOK regulations are mostly cited although other regulations for example Health and Safety Executive (HSE) were also cited.

There is a wide variety of fixed, portable and hand-held devices for detecting gas concentration in the market today. This thesis is limited to fixed flame and gas detectors only.

In order to verify optimization of detector layouts, simulations have been performed, while simulations was done for flame detector layouts, time did not permit to do the same for gas detector layouts, nevertheless we chose to focus our attention on flame detection optimisation rather than gas since little is done so far in this area. The simulation was focused on coverage evaluation of detector layouts in two modules, a simple module and an onshore enclosed real-world module. In the simulations, we only concentrate on evaluating the visibility field of the flame detectors, no other external, physical or environmental factors is taking into consideration.

### **1.4. THESIS STRUCTURE**

First the thesis work starts with basic introduction to industrial gases and gas combustions. Then properties of these gases and the principle of detection of the gases were introduced. In same chapter the technologies used in detection and the types of gas detectors were introduced.

In chapter three the gas detection as a system is introduced and then factors that influence gas detection is evaluated. In chapter four we introduce optical flame detectors, and flame detection technologies.

Chapter five is about how to optimise detectors, methods to achieve detector optimization. Then comes simulation part in chapter six, where we test detector optimization using both simple and complex module, followed finally by discussions on the result of the simulations in chapter seven.

## CHAPTER 2.

### 2.1. GAS HAZARDS

There are basically three main types of hazards from gases.

- **Flammable**



Risk of fire or explosion  
e.g methane, butane and propane

- **Toxic**



Risk of poisoning  
e.g carbon monoxide, chlorine

- **Asphyxiant**



Risk of suffocation  
e.g oxygen deficiency

#### 2.1.1. *Flammable gases*

Flammable gases are those ones that undergo chemical reaction with oxygen which usually produce heat and causing fire or explosion. This process is normally termed combustion. In order to have combustion, three factors are needed:



**Figure 1: Fire Triangle(Honeywell, 2013)**

- Air
- Heat
- Fuel/gas



A fire protection system is successful when it's able to remove any of these three factors. Fuel is normally industrial hydrocarbon compound and can be liquid or gas or solid. For this thesis, we will concentrate on liquid and gases since this usually the case in offshore operations.

### 2.1.2. Flammability limit

In general this is limited band of gas/air concentration which can produce a combustible mixture. The flammability limit is usually predetermined under standard (room) temperature and pressure (1 atm). A mixture of gas and air will burn if their concentration is between upper (UFL or UEL) and lower (LFL or LEL) flammability. In this thesis, we will be using LFL and UFL instead of LEL and UEL.

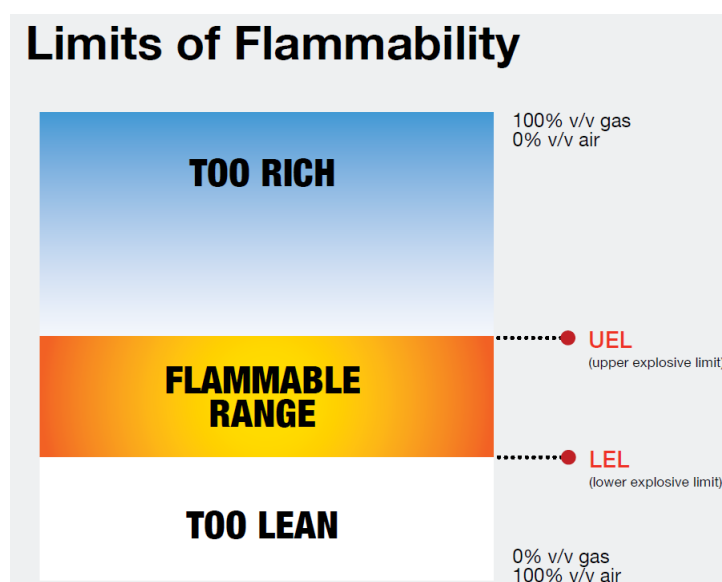


Figure 2: Flammable range (Honeywell, 2013)

Above UFL the mixture is almost gas (no oxygen and no combustion) and below LFL is almost air (insufficient gas, no combustion) therefore the combustion of mixture of fuel/air takes place within the flammability limit.

In offshore installations, flammable gases leak from time to time and since concentration of the flammable gas must be within its flammability limits for ignition and possible fire and damage, the aim here is to avoid the leaked gas from reaching its flammable limit.

It would be noted that detector systems are set up to detect leaked gases from zero percent till the LFL (since combustion can only take place after LFL is reached and within UFL).

Shutdown or emergency clearance or deluge should take place once this LFL is reached, it is highly advisable that ESS system should start once 50% or less of LFL is reached to provide adequate safety margin.

On the other hand, in some cases we may achieve excess of UFL especially in confined or enclosed facilities, for example during inspection, therefore special care should be taking

during those times to avoid ingress of air which may dilute the concentration of the gas to its flammability limit and risk of combustion.

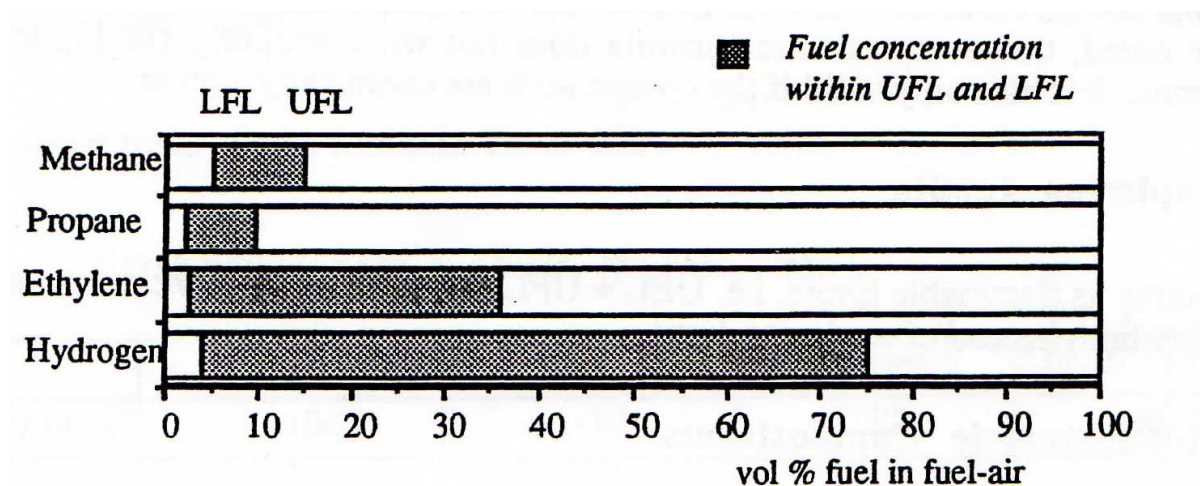


Figure 3: Flammable limit for some fuel-air mixture at 1 atm and 25°C (Bjerketvedt et al., 1993)

For a detailed list of flammability limits of most industrial gases see appendix A

## 2.2. FLAMMABLE INDUSTRIAL GASES

In order to develop good method to detect industrial gases, it will be a good practice to understand some basic properties of these gases.

### 2.2.1. Properties of Flammable Gases

Combustible gases have some interesting characteristics and here we will introduce some of them that are relevant for this thesis.

#### 2.2.1.1. Flash Point

The flash point of a liquid is the lowest temperature at which the liquid gives off enough vapour (above its surface) to form flammable or explosive mixture. (General Motors) Most industrial gases have flash point below or at room temperature (20 to 25°C).

At flash point, the liquid vapour will most likely ignite and result in explosion if the vapour comes in contact with an ignition source. Vaporization increases as temperature rises.

Table 1: Flash point of some industrial Gases/Vapours

Gas / Vapour	Flash Point °C	Ignition Temp. °C
Methane	<-188	595
Kerosene	38	210
Bitumen	270	310

### 2.2.1.2. Auto-Ignition/Ignition Temperature

Flammable gases can ignite at a certain temperature even without the presence of ignition source, this is called self-sustained ignition. This is not to confused with flash point, on table 1, we see that methane gas has flash point temperature of 188°C or less and ignition temperature when its temperature reaches 595°C. at this temperature, methane vapour will ignite on its own irrespective of the presence of outside ignition source or not.

### 2.2.1.3. Vapour Density

Vapour density of flammable gases are very important in sensor placement especially as regards to height with respect to the leak source. The vapour density of this gases are compared with that of air density, where air density = 1.0.

**Table 2: Gas/vapour Density of some industrial gases**

Gas / Vapor	Vapor density
Methane	0.55
Carbon Monoxide	0.97
Hydrogen Sulfide	1.19
Petrol Vapor	3.0 approx

Gases with Vapour density > 1.0 will fall

Gases with Vapour density < 1.0 will rise

## 2.3. PRINCIPLE OF GAS DETECTION SYSTEM

The primary reason of installing GDS is to be able to identify flammable or toxic leak that if not controlled might lead to loss of containment or eventual loss of life. GDS system consist of different types of detectors, tuned to different set points and alarm logics, thus it is important to consider many factors before installing GDS example type of detector, number of detectors, location, set points and alarm logic. We shall discuss more on GDS in chapter 3.

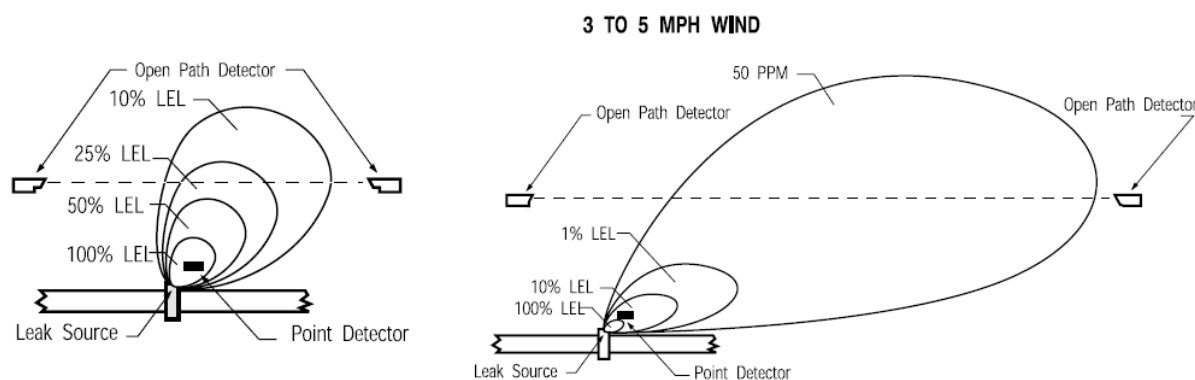
There are two basic principles used in gas detections, which are:

- Point detection
- Open path detection

When gas leaks, it can either form a stationary cloud or be dissipated depending on factors like the wind, leak rate, density of the gas and the structural environment around the leak(General Monitors, 2014d).

According to (General Monitors, 2014d), if gas leak creates gas cloud, there are three things likely to happen:

- Highest gas concentration are at the source and decrease down to the edges
- The shape of the cloud is elongated or irregular pattern, depending on the air current
- In outdoors, gas clouds dissipate faster and can have very low concentration as shown by the figure below.



**Figure 4: Cloud dispersion(General Monitors, 2014d)**

Knowledge of gas cloud behaviour during gas leaks can help in detector placement, thus like the figure shows; a good way to start is to place point detectors near the leak source as there is the highest gas concentration and open path installed on the process or plant area boundaries, where they can monitor the plant perimeter and provide over all gas movement (irrespective of the wind or air current) in and out of the plant(Opheim, 2008).

Open path detection is also known as line detection. In this section we shall introduce these two principles that form the basis of gas detection installation.

### **2.3.1. Point detection principle**

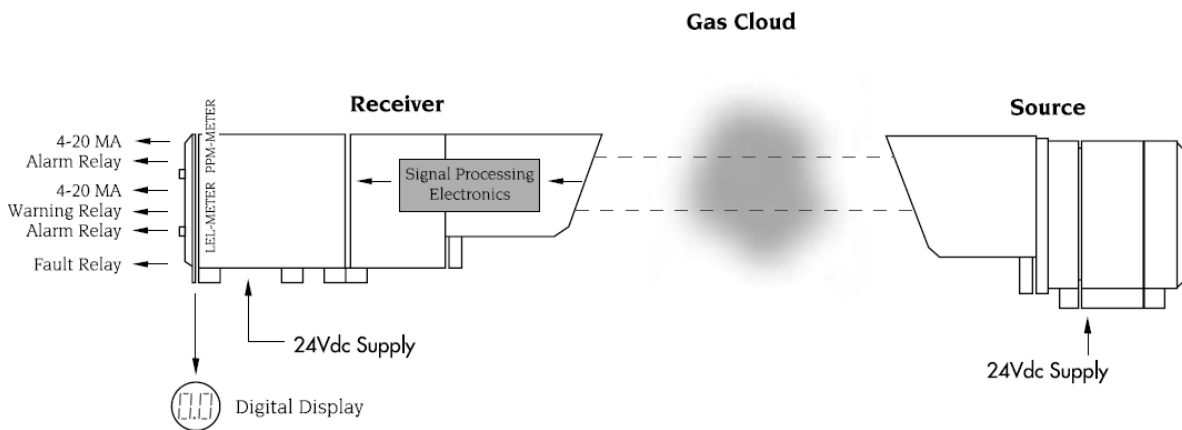
A point detector measures the concentration of interested gas at point of detection. It is based on the fact that the target gas must come in physical contact with the detector and they cover limited area. Combustible gas concentration are measured in %LFL while toxic gas in ppm or ppb(Båfjord, 2011).

Since it point detection covers limited area and gas has to be physically in contact with the detector to be sensed; it follows then that to obtain reasonable coverage of a process module, many point detectors has to be installed around the area.

Many detector types are based on this principles examples include Infrared, Catalytic, Acoustic, Semiconductor and Electrochemical detectors. Some of these technologies will be introduced in section 2.4.

### 2.3.2. Open path detection principle

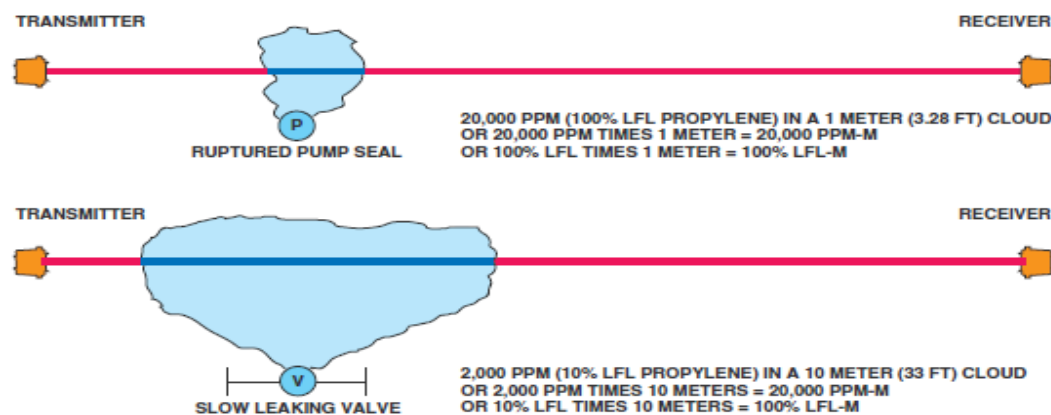
This principle of detection measures the concentration of the target gas along a beam line and Infrared technology is the only detection technology that uses this principle.



**Figure 5 Principle of Open path detection(General Monitors, 2014a)**

The concentration of the target gas passing along the beam path is measured and not that of a giving point like in point detection. The advantage is that a large area can be monitored and therefore replaces several point detectors.

The concentration is measured in LFL times the beam length; that is  $LFL * m$ , where 100%LFL over one meter equals one LFLm(DET-TRONICS, 2011). The problem with this type of measurement is that it is difficult to different a small cloud with high concentration and a large one with low concentration; thus consider a small cloud with high concentration of 100%LFL over one meter, it will give the same value as low concentrated dispersed cloud of 10%LFL over 10 meters as the figure below shows.



**Figure 6: two clouds which give the same value(DET-TRONICS, 2011)**

Also, since the open path detection can replace several point detectors, it follows that the loss of one open path system (example obstruction of beam path by equipment or personnel) might leave the facilities vulnerable unlike when several point detectors are installed.

## 2.4. GAS DETECTION TECHNOLOGY

In this section, we will examine different technologies employed in HC detection. Modern industrial site is a complex environment for safety monitoring, many factors play role in choosing the right detector for a specific site. A typical oil and gas facility install different types of detectors that use different techniques in detecting industrial gases, this we can call “*technology diversification*” (Naranjo and Neethling), meaning that combinations of different gas detection techniques reduces the risk of failure to detect loss of containment.

In order to choose good combinations, it is important to have an overview of different technologies in the market today, particular interest in their strengths and weaknesses.

Some of the gas detection technologies are:

- Catalytic
- Infrared
- Ultrasonic
- Semiconductor
- Electrochemical

### 2.4.1. *Catalytic bead*

Combustible gas detectors fall basically into two categories, the first includes varieties of passive technologies of which catalytic or electro-catalytic is one of them. Catalytic technique is one of the oldest techniques in use in many industries and usually comes as a single point detector and mainly for detecting combustible gas. It use the principle that combustible gases can be oxidised producing heat, and the accompanying change in temperature can then be converted (by the help of wheatstone bridge) to signal which is then sensed and used to activate alarms and consequent safety measures applied.

One of the problems with catalytic detectors is that of contamination and poisoning, on the other hand, they are one of the best options for arctic environment like the North Sea; they are good for extreme temperatures, both hot and cold harsh environment. According to (General Monitors, 2014a), they are the best choice for not only environments with extreme temperatures, but also humid, around hot and vibrating equipment.

## Advantages

- Robust
- Simple to operate
- Easy to install, calibrate, and use
- Long lived with a low life-cycle cost
- Can detect a variety of gases
- Wide operating temperature range
- Easily calibrated to gases such as hydrogen which cannot be detected by infrared absorption

## Disadvantages

- Passive detection – not fail to safe
- Gas must diffuse into catalytic bead in order to be detected
- Catalyst can become poisoned or inactive due to contamination
- The only means of identifying sensitivity loss due to catalytic poisons is by checking with appropriate gas regularly
- Requires oxygen for detection
- Prolonged exposure to high concentrations of combustible gas may degrade sensor performance

**Figure 7 Advantages and Disadvantages of Catalytic Gas Detector(Naranjo and Neethling)**

Catalytic bead detector is used for detecting combustible gas and readings in %LEL.

### **2.4.2. Infrared**

Infrared detection is one of the oldest technology used in gas detection, it is based on the principle of absorption of infrared radiation at specific wavelength as it passes via a volume of gas.(General Monitors, 2014a). It uses two wavelengths, one at the absorbing wavelength and the other outside the absorbing wavelength. It is made up of a light source and a detector, when gas passes between the light source and the detector, it measures the intensity of the two wavelengths and gas concentration can be measured by comparing the values of this two wavelengths.

It is believed that almost all HC absorb IR and according to (General Monitors, 2014a) at around 3.4 micrometres. So infrared detection is based on this fact that HC absorb IR radiation and therefore that combustible gases can be detected with a dedicated spectrometer operating at this absorption wavelength (3.4mm). There are two types of infrared radiation; infrared point detectors and the open path infrared detectors, we will talk more about then in section 2.4.

The main advantage of IR detectors over others is that they offer fail-to-safe operation but suffers from the fact that they can only detect gases that are absorbent in the infrared spectrum.

### Advantages

- Immunity to contamination and poisoning
- Fail-to-safe operation
- No routine calibration
- Ability to operate in the absence of oxygen or in enriched oxygen
- Ability to operate in continuous presence of gas

### Disadvantages

- Gas must cross the sampling path in order to be detected
- The gas to be measured must be infrared active, such as a hydrocarbon
- Gases that do not absorb IR energy are not detectable
- High humidity and dusty field environments can increase IR detector maintenance costs
- Routine calibration to a different gas is not practical
- A relatively large volume of gas is required for response testing
- Ambient temperature of detector use is limited to 70°C
- Does not perform well for multiple gas applications
- Cannot replace the IR source in the field – must be returned to factory for repair

**Figure 8: Advantages and Disadvantages of IR detectors (Naranjo and Neethling)**

Infrared detectors are mainly for detecting combustible gas and readings in %LEL except for open path IR which reading is in %LEL per meter.

### 2.4.3. Ultrasonic

The Ultrasonic gas detection (UGLD) technique is set to revolutionised gas detection especially in open ventilated offshore installations. Conventional techniques like Catalytic or Infrared detection relies on the bases that the escaping gas comes in contact with the detectors or pass via the infrared light source, in some case this can be problematic for example imagine ventilated offshore installations where the escaping gas can easily be drifted by the wind or diluted in air, that makes it then very hard for conventional detectors like fixed or open path detectors to detect the gas, well this can be solved by the UGLD.

UGLD responds to high pressure leaks by measuring the airborne ultrasound emitted by the leaking gas, which when detected by the detector, provides a measure that is proportional to the leak rate.(Gregory, 2010).



When gas molecules moves from a pressurized environment like gas pipe, to a lower pressurized one at the speed of sound, it produces a specific hissing acoustic sound which comprises also sound/noise in the ultrasonic (ultrasonic range are 25Khz – 10Mhz(General Monitors, 2014b)) frequency spectrum, the UGLD filters away all noise in the lower frequency range (example audible range are 20Hz – 10Mhz(General Monitors, 2014b)), while reacting instantly (by sounding an alarm) to specific ultrasonic noise above the filtered level, thus UGLD respond to high pressure leak without having to wait until the leaking gas accumulates or come in contact with the detector.(Gregory, 2007).

Acoustic detection technique uses ultrasonic sensors and is used for example to detect leaks by monitoring changes in the background noise.

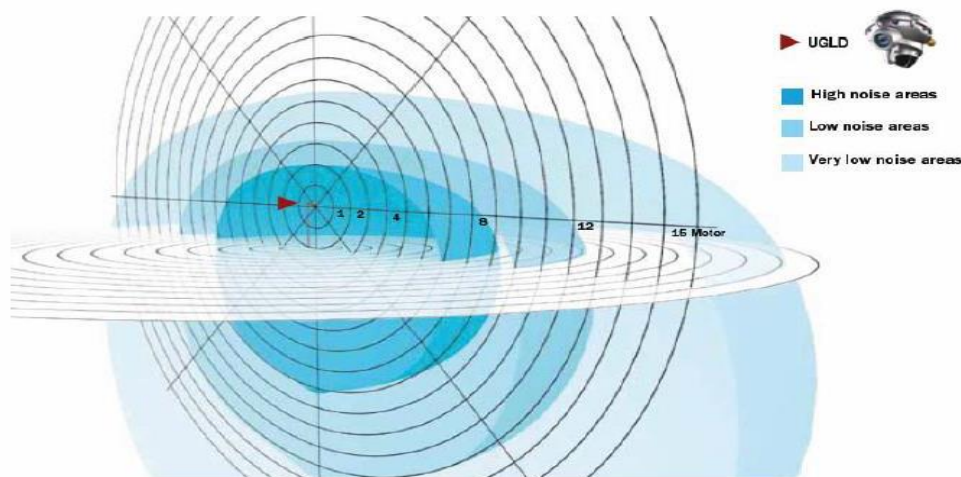
Unlike other detectors which measures gas concentration example in %LEL or ppm, it expresses gas leaks in sound pressure level (SPL), thus the greater the leak rate, the greater the SPL emitted by the escaping gas.

According to (General Monitors, 2014b), there are three leak categories basically used in the oil and gas industries to classify leak rate in terms of its potential to accumulate into an explosive concentration, the categories are presented in the table below:

**Table 3: UGLD leak categories used in the oil and gas Industries (General Monitors)**

Minor leak	< 0.1 kg/s – duration less than 1 min
Significant leak	0.1 – 1.0 kg/s – duration between 1 min and 5 min
Major leak	> 1.0 kg/s – duration over 5 min

Despite all the advantages of UGLD, there are some drawbacks example, UGLD is unable to detect low pressure leaks (example less than 10 bar) that are not within the audible and ultrasonic frequency range.



**Figure 9: UGLD detection coverage for High Noise, Low Noise and Very Low Noise Environment(Gregory, 2010)**

Leaks outside this coverage are not detected. The figure below summarizes advantages and disadvantages of UGLD.

### Advantages

- Instant detection of pressurized gas leaks
- Versatile – detects pressurized leaks regardless of type of gas
- Not influenced by fog, heavy rain, or other ambient conditions.
- Minimal maintenance and no consumable parts
- Robust, fail safe operation.
- Not sensitive to changing wind direction and gas dilution

### Disadvantages

- Not suitable for low pressure leaks
- Under certain conditions affected by man-made or natural ultrasonic sources
- Background noise levels need to be estimated prior to installation
- Unable to determine concentration of gas

**Figure 10: Advantages and Disadvantages of UGLD(Naranjo and Neethling)**

Detectors based on the ultrasonic principle can detect any high pressure leaks (combustible or toxic) and measures concentration in kg/s.

#### 2.4.4. Semiconductor (MOS)

Made of a metal oxide that changes resistance in response to the presence of a gas; this change is measured and translated into a concentration reading (MSA, 2007).

Also called solid state sensor, consist of one or more metals oxides (semiconductor oxide) from the transition metals and is deposited onto a silica or aluminium oxide substrate between two electrodes. A heating element is used to regulate the temperature of the sensor, the sensor responds differently to different gases at different ranges of temperature.

When no gas is present, oxygen is ionised (via heating of the substrate) and the sensor becomes semi-conductive, if the gas we want to sense is present, the molecules of the gas replaces the charged oxygen ions which decreases the resistance between the two electrodes, thus this change is then electrically measured and corresponds to the concentration of the gas we are measuring or sensing.

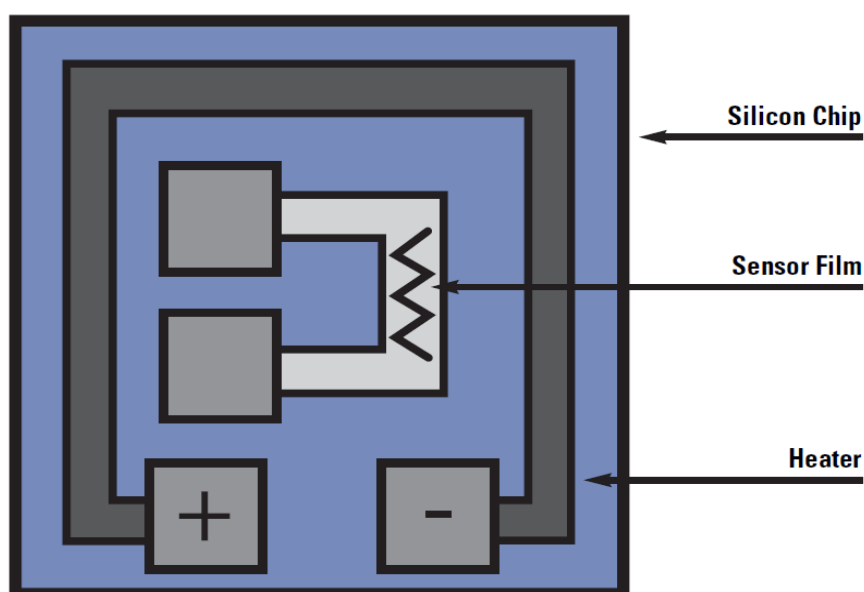
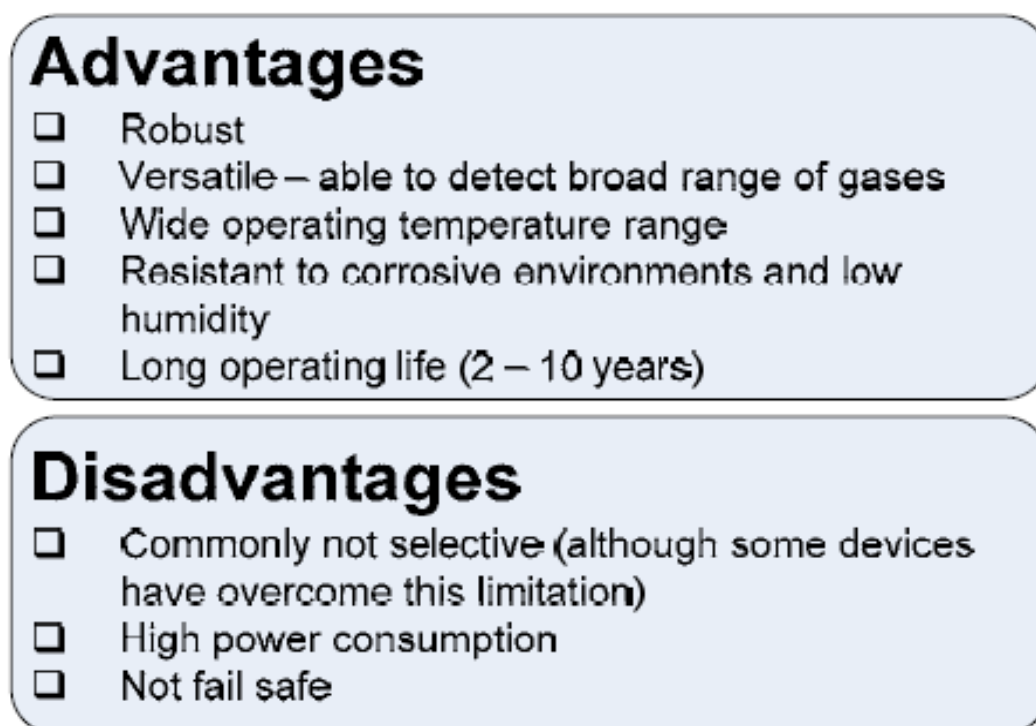


Figure 11: Typical MOS Semiconductor sensor operation (MSA, 2007)

Semiconductor or Solid state sensors have many advantages; they are long lived and can detect wide varieties of gases. The figure below shows some of the advantages and disadvantages of Semiconductor detectors.



**Figure 12: Advantages and Disadvantages of MOS Semiconductor sensor(Naranjo and Neethling)**

MOS detectors can detect both combustible and toxic gases, readings are in PPM.

#### **2.4.5. Electrochemical**

One of the oldest technologies in gas detection industries can be used to detect number of industrial gases including carbon monoxide, hydrogen sulphide and chloride. It works like a transducer converting gas concentration to electrical signal. It is made up of three electrodes – sensing, counter and reference, sealed in a container containing electrolyte. The gas to be detected reacts with the sensing electrodes generating electrical current. The amount of current generated by the detector is proportional to the amount available in the environment.

Over time, the electrodes can be poisoned by small amount of impurities example present in the gas, thereby affecting its sensing ability and detection of gas. Also, the temperature range of electrochemical detectors is very small. Therefore they are not ideal for harsh

environments like desert and arctic environment. They are not resilience, the electrolyte can evaporate in hot dry desert and humidity affects its operation.

### Advantages

- Fast response
- High accuracy
- Versatile - responds to wide range of toxic gases
- Low power consumption

### Disadvantages

- Limited at low ambient temperatures ( $\leq -40^{\circ}\text{C}$ )
- Unsuitable for use in dry environments ( $< 15\% \text{ RH}$ ) over several months
- Operates in a narrow range of pressures ( $1 \pm 0.1 \text{ atm}$ )
- Not fail safe

**Figure 13: Advantages and Disadvantages of Electrochemical detector(Naranjo and Neethling)**

Electrochemical detectors are used to detect toxic gases and readings in PPM.

## 2.5. TYPES OF DETECTORS

In section 2.3 we have introduced different technologies implied in designing gas detectors, in this section, we will be introducing few types of detectors mostly installed in the process industries today.

### 2.5.1. Point IR Detection

Infrared type of detectors is based on the principle of absorption of infrared radiation at certain wavelength as it passes through volume of gas. Devices that use this technology have two wavelengths, one at the absorption (active) wavelength and the other a reference wavelength that are outside the absorption wavelength. When the target gas pass between a light source and light detector, the amount of light that falls on the absorption wavelength is reduced while that on the reference is unchanged, and the amount of target gas is then determined by the difference between these two lights that fall on this two wavelengths.

In the case of Infrared point detectors, there is a fixed distance between the light source and the detector. The path length is fixed and only a few inches thus the target gas is assumed to be uniform across this length making is possible for the detector to make a direct measurement of the target gas in %LEL.

### 2.5.2. Open Path IR/Line Detection

In the open path infrared detectors, philosophy is the same like that of Infrared point detectors but there is a considerably distance between the light source and the detector, that is the path length is not fixed as shown by the figure below.



**Figure 14: Open path Infrared(Båfjord, 2011)**

The Infrared open path can more large area of the facility and can replace several point detectors, the problem of that as explained in section 2.3 is that any obstruction of the beam path can leave the plant vulnerable.

There are several advantages of using infrared detectors; they are immune to all chemical poisoning, does not need oxygen to or air to detect gas, and perhaps the most important is that they offer “fail-to safe” technology, that is, because optical sensing is active technology, they continuously monitor for sensor fault or failure and conveys information to the user(General Monitors, 2014b).

The recent development in optical designs means that they can be factory calibrated and needs virtually no maintenance except periodic cleaning of the optical windows and reflectors(General Monitors, 2014d), they are good for monitoring facilities located in inaccessible areas where servicing and maintenance is not easily available.

The main disadvantage of Infrared detectors is that they are not suitable for hydrogen gas detection.

### 2.5.3. Optical Gas Detector

Optical method of gas sensing is based on the principle of absorption of spectrometry, it involves techniques based on absorption and emission of spectrometry. According to law of spectrometry, excited atoms will emit photons and then go back to its ground state(Liu et al., 2012). Sensors that using this technique are relatively high cost but attain excellent sensitivity, selectivity and reliability compared to other gas sensors.

Infrared optical sensing is the most widely used of this technique. There are many advantages of using optical gas sensing including:

- Fast responds time
- Not affected by chemical poisoning

- Offer long term stability
- Not affected by temperature, humidity, dust and other environmental factors.

They are suited for harsh and hazardous environment thanks to the unique advantages that Infrared offers (Tan et al., 2013).

#### **2.5.4. Acoustic Gas Detector**

Acoustic sensors use ultrasonic techniques to monitor and detect leaks based on the background noise. The principle works on the fact that gas leaks from pressurized system or high pressure pipeline generate ultrasonic sound, which is then detected by the acoustic sensor and can be used to measure the leak rate. It provides a 360 degree coverage and does not need contact with the target gas to detect the gas. This principle has been described earlier refer to section 2.4.

## **2.6. INTEGRATION OF DETECTION TECHNOLOGIES**

The main function of gas detectors is basically to detect the presence of toxic and or combustible gas in a process facility. From what we have learnt from section 2.4 and 2.5, that different detector types using different technologies and principles thus having different advantages and disadvantages, therefore it is important to recognise that no single detector technology or type is robust enough to provide the sensitivity and fast response time required for every gas.

On the other hand, a combination of Ultrasonic, Optical and Conventional gas detectors like Infrared and Catalytic detectors can form a formidable defence against developing hazards. The key to realizing this technology “diversification (this principle was introduced area in section 2.4)” is by grasping how these detectors (operating on different technologies) complement one another. The table below summarizes the basic advantages and disadvantages of most used detectors;

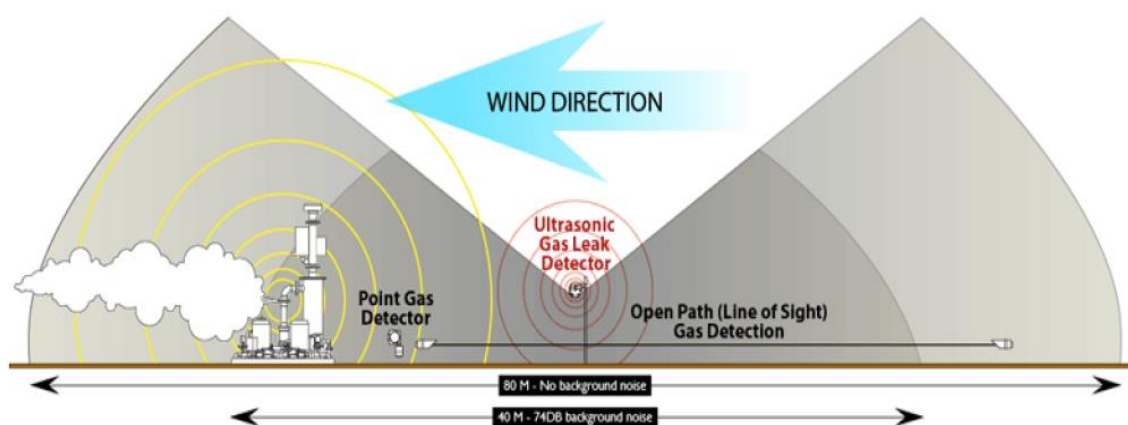
**Table 4: Advantages of Selected detector types**

<b>Detector type</b>	<b>Advantages</b>
Point Infrared	Factory calibrated, maintenance free, good for remote areas, immune to chemical poisoning, provide for fail-to-safe operation, no routine calibration
Open Path Infrared	Can monitor large areas, position not so critical, do not need oxygen or air for detection, long live and greater stability over time
Optical	Longer life time, short responds time, not affected by weather, poisoning or environment,
Acoustic	No need for physical contact, not affected by ventilation or wind, wide range of gases detected,
Point Catalytic	Proven technology, wide operating temperature range, detect wide varieties of gases, robust, low cost, easy to install, use and calibrate, long lived, can detect hydrogen

**Table 5: Disadvantages of Selected detector types**

Detector type	Disadvantages
Point Infrared	Not suitable for H <sub>2</sub> detection, physical contact with target gas needed, not good for multiple gas sensing, only infrared active gas can be monitored
Open Path Infrared	Not suitable for H <sub>2</sub> detection, problem with locating leakage source, needs physical contact with target gas, requires no obstruction of beam path
Optical	Miniaturization, high cost,
Acoustic	Prone to false alarm due to noise not coming from leak sources, only detect leaks in ultrasonic range, positioning problem, requires establishment of background noise to set alarm level
Point Catalytic	Not fail to safe, suffers from gas poisoning, requires oxygen or air for detection, prolonged use can degrade sensor sensitivity and performance

There are many factors that can lead to failure of detecting presence of toxic or combustible gas by a gas detector, for example, consider the influence on wind direction as shown by the figure below;

**Figure 15: UGLD verses point and open path detector(Båfjord, 2011)**

the presence of point and open path detectors were not able to detect the leak because the leaked gas was drifted away from these detectors, but fortunately this leak was picked up by the ultrasonic detector, thanks to its wide coverage and no need of contact with the target gas to detect it.

As evident from table 4 and 5, and figure 15, reliable application of these detector types depends on a good system that uses the advantages and limitations of them to pair them together to the target gas and environmental conditions of the area to be monitored.



## CHAPTER 3.

This chapter shall be dedicated to GDS. GDS will be introduced and various factors to consider when installing GDS and some standards and regulations concerning installing GDS will be examined also.

### 3.1. GAS DETECTION SYSTEM

A GDS is a layout of different types of detectors installed in a process facility where there is a probability of HC or toxic gas leakage that can lead to fatality or hazardous atmosphere. It includes also detection philosophy (alarm, set point, voting) and actions that will be performed upon gas detection.

According to (NORSOK, 2008), the main functions of GDS is to continuously monitor for presence of flammable or toxic gases, alert personnel and allow for control actions to be initiated to reduce the possibility of exposure, fire and explosions.

NORSOK S-001 specifies that GDS has interfaces to the following systems:

- ESD;
- BD system;
- ISC;
- Ventilation;
- PA and alarms system;
- Fire-fighting systems (FW)

#### 3.1.1. *Designing GDS system*

Many factors needs to be considered and evaluated when designing GDS system, the regulations and standards are only meant as a guidelines to follow but the design should be specific and adapted to the process facility or the environment that GDS will be installed.

Some of the factors and practices used in designing GDS by most industries include:

##### 3.1.1.1. *Detector Selection*

The type of detector and the technology used in designing the detector plays an important role in gas detection, the type and technology should be selected bearing in mind the target gas to be detected, for example it is not wise to select Infrared detectors when you plan to detect Hydrogen gas.

According to (NORSOK, 2008), open path detectors should be preferred where possible, and open path should be used in combination with point detectors where environmental factors may make open path detection unavailable. The standard suggest that Catalytic detectors shall not be used unless proper detection by other types is not achieved, perhaps this is also in consistence with the research on evaluation of flammable gas detector performance done by **A. KELSEY, M. A. HEMINGWAY, P. T. WALSH and S. CONNOLLY** which proves that Catalytic detectors performed slightly worse than Infrared detectors(Kelsey et al., 2002).

In general, when selecting combustible detector, it is important to select the product for the purpose who want it to serve, a view suggested by most regulations and standards about

To summarize, an analysis of the risk and equipment selection process will likely include:

- Potential leak sources
- Factors affecting rate and direction of gas diffusion when a leak occurs
- Density and other physical properties of the gas
- Detector environment, e.g., temperature, vibration, cleanliness, ventilation, etc.

### **3.1.1.2. Number of Detectors**

How many detectors should be installed? Perhaps this is one of the most important questions being asked even by experts when installing GDS system and unfortunately one that is very difficult to answer because there is no concrete answer to it. With high cost of running industries like oil and gas, and maintenance cost of detectors which runs in millions kroner yearly, it is very important to consider the cost both of maintenance and installing vs the risk involved when determining the number of detectors.

Too much than needed detectors incurs unnecessary cost while a less than needed puts the plant's integrity in jeopardy and considerably risk of hazard. Industries tackle the question of number of detectors in mainly two ways:

- Regulations vs. operator-specific practices
- Proportional to module volume

In the first point, NORSOK S-001 fourth edition page 27, suggest that dispersion simulations may be performed for optimization of the number of detectors. On the other hand, different operator may have specific practice on how to choose the number of detector.

In point two, number of detectors is choosing proportional to the module/plants volume. Then the more the volume increases the more detectors needed for adequate coverage.

### **3.1.1.3. Detectors Layout**

The positioning of detectors plays an important role in timely detection of flammable and toxic gas, the time of detection is important since the role of GDS is to detect the gas before it reaches dimensioning cloud.

According to NORSOK S-001 2008, following principles shall be applied with respect to location of detectors:

- natural flow "corridors" (e.g. walkways along flow direction) should be covered;
- detectors should be positioned in different levels in an area or module.

Also, the standard states that "Toxic gas detectors shall be provided in all areas where potentially toxic gas concentrations may be present or be formed."

Section 3.3 will emphasize more on gas detector layout optimization, we will look at practices and techniques used by companies in detector layout.

### 3.1.1.4. Set points and Voting

Every GDS system is set up to initiate alarm immediately it detects the presence of flammable or toxic gas. As required by most regulations and standards two alarms are usually used by companies:

- Low alarm and
- High alarm

Gas detectors can be set to initiate alarm at a given gas concentration. Norsok S-001 specifies set points for both point and line detectors at low and high alarm level.

#### For Low alarm limit:

**Table 6: Maximum Low alarm limit for gas detection**

Detector type	Max Alarm Limit	Note
Point	20%LEL	10%LEL for turbine enclosures
IR Open path	1 LELm	Detection distance*20%LEL(not > 1LELm) for air inlets

According to Norsok, the alarm limits for Acoustic detectors should be determined according to the background noise and should have adjustable sensitivity settings.

#### For High Alarm Limit:

**Table 7: Maximum High Alarm Limit**

Detector type	Max Alarm Limit	Note
Point	30%LEL	15%LEL for turbine enclosures
IR Open path	2 LELm	Detection distance*30%LEL(not > 2 LELm) for air inlets

### Voting Principle

Experience has shown that it is possible for a detector to initiate a false alarm, that is initiating its alarm even when it is not exposed to dangerous gas. As a result a philosophy known as voting is used by companies to avoid situations like ESD because of false alarm or detector malfunction.

Norsok S-001 specifies the voting philosophy to be used, according to Norsok the following principles shall be followed when a “2-out-of-N, where N>2 detectors” logic is used:

- Confirmed gas is when there is initiation of alarm from two gas detector
- When one alarm is activated then is Low alarm
- Automatic alarm to be initiated by an alarm from one detector
- One alarm level should be used

On the other hand, in the case of a single detector philosophy, the following rules apply according to NORSOK:

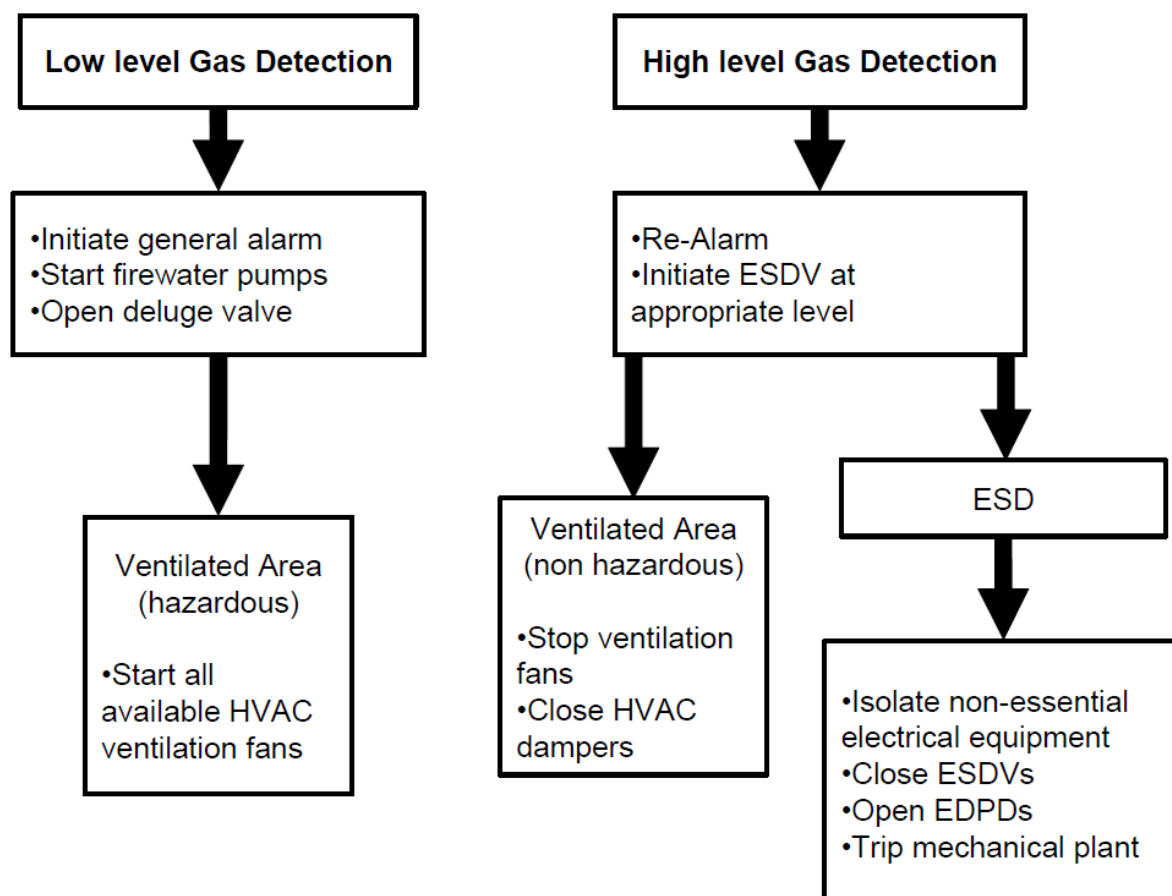
- “Confirmed” gas detection is activation of high alarm from one detection
- Low alarm is activation of low alarm from one detector
- Automatic alarm to be activated by low alarm from single/one detector
- Two alarm levels (Low and High) to be used.

#### **3.1.1.5.        *Actions to be taken upon gas detection***

The role of GDS system is mainly to detect the presence of HC gas or toxic gas, and signal by means of alarm and initiate other safety measures installed in the plant. There are other safety systems which together with GDS protects the integrity of the process plant. NORSOK S-001 specifies actions that can be initiated by the GDS when gas is detected; the following are specified by NORSOK:

- ESD system is automatically activated upon gas detection;
- ISC is automatically initiated upon gas detection through actions of the ESD system or can be executed directly by the F&G system;
- activation of FW pump start-up and deluge, if required;
- ventilation is automatically shut down upon gas detection in HVAC inlet;
- activation of PA/alarms system to alert personnel.

The regulation specifies the guidelines and minimum requirement that should be in place, in addition to this, NORSOK standard makes room for companies to install additional actions that GDS can initiate depending on many factors and the plant. The figure below from HSE 2003, summarizes graphically these actions:



**Figure 16: Actions that may be taken when gas is detected(UKOOA/HSE, 2003)**

The actions taking depend on whether low or high level gas was detected, the main difference is that when confirmed gas detected at high level, then ESD must be initiated to protect personnel.

NORSOK also specifies other regulations that should govern GDS system, example the responds time of gas detector system, according to NORSOK, the responds time that should be complied with are as follows:

- IR detector response time (T90) should be less than 5 s for general area applications, and less than 2 s if used in HVAC ducting;
- acoustic detector response time including delays employed to improve false alarm immunity should not exceed 30 s;
- the time from detector alarm limit is reached until alarm is presented/tagged on operator station should be less than 2 s.

the main advantage of specifying or adhering to these responds time is to ensure that the total time taking to react to each safety function in place can be fulfilled.

### **3.2. ENVIRONMENTAL AND OPERATIONAL FACTORS INFLUENCING GAS DETECTION**

There are many factors which should be evaluated when optimizing or evaluating performance of a fixed gas detector system:

- Ambient temperature
  - Elevation and location of the sensor
  - Direction and velocity of air that is moving past the detector, air movement around the leak source
  - Humidity of the area
  - Changes in responds as a result of detector age
  - Materials that poison or interfere with detector performance
  - Exposure to adverse temperature, liquid, water, vapour or high concentration of gas
  - Effect of changes in power supply
  - Detector installation orientation (pointing downward or upward or horizontal)
  - Interference from electromagnetic fields or radio waves
- e.t.c.

This section is mainly an introduction to these factors, bearing in mind their effect when optimizing performance of gas detector systems.

#### **3.2.1. Vapour density**

Vapour density has a measure effect on the dispersion of gas in a module or plant. As we said earlier, gases with density higher than that of air (air density is 1) tend to fall towards the ground, while those with density lower than air rise upwards. This phenomenon is very important when installing detectors, that is, one has to first determine the target gas and then check the density of the gas before determining if the detector should be located near the ground or near the ceiling or roof.

In addition, there are some other factors which can affect the behaviour of leaked gases as regards to their vapour density. During calm weather, gases behave in accordance with its vapour density but there are sometimes when factors like air current and wind can cause the gas to behave abnormally and these factors should be taking into account especially in offshore installations where these factors are daily experienced.

#### **3.2.2. Temperature**

Temperature ranges of operation of different detectors depends from manufacturer to manufacturer and on the technology used in manufacturing. In addition, a detector may be designed to withstand a certain temperature but the instrument and materials used in designing it may not.

Operating detector system at the upper and lower ends of the manufacturer approved operating temperatures may result in for example zero drift with readings in the ranges of 5-10 percent lower or higher than the actual LFL concentration.

In general, it is important that detectors are operated within the manufacturer's operating temperature and also calibration of the detector at its mean operating temperature is advised.

### **3.2.3. Wind and air current**

Many offshore installations experience severe and harsh weather conditions example in the North Sea. According to (Bonn et al., 1998) local air movements have more greater effect on the released gas than was believed before. A leaked gas quickly mixed with the local air and subsequently behaves like the local air around the area. On the other hand, some plant are heavily congested and have little or no air inside it thus released gas will fill the volume, displacing and mixing with air. In time the leaked gas is entrained or synchronized with the local movement of the air.

### **3.2.4. Air velocity and momentum**

Another factor that plays an important role in the effectiveness of a detector is the air velocity and momentum. A low release pressures gives the gas low momentum and thus the gas can easily be carried by high velocity wind or air current, thus not giving the detector time to detect the gas. On the other hand, high pressure release will at first resist the air current velocity but the momentum of the release decreases in time and is finally carried away by the wind.

Thus is very important that these factors are taking into considerations when positioning the detector including the leak point and the direction of wind and the places where the escaped gas is likely to transport the gas.

### **3.2.5. Vibrations**

Vibration is common experience in process industries; there are many sources of vibration. According to (API, 1991) vibration of the sensor is normally a problem when it has a low frequency and a high amplitude. Excessive vibrations, especially the ones with high amplitude can damage the sensor, example breaking the electrical circuit controller. Many detectors are equipped with self-check that continuously checks for detector fault.

According to (API, 1991), sensors should be installed on non-vibrating structures.

### **3.2.6. Obstructions**

In a process plant, there are many sources of obstructions of detector especially open path detectors which suffer the most from obstructions. Personnel, mobile equipment, particles like dust, rain, snow all and many more can be a source of obstruction to the detector which can result in increased detection and responds time to complete lack of responds from the detection.

Sensors should constantly be checked for obstruction both during operations and before installations.

**3.2.7. Ventilation**

Process facilities are usually equipped with ventilation systems that normalize the inflow and outflow of air in and out of the facility. The reason why this is an important factor is that when gas leaks, it is normally above the UFL concentration and therefore cannot ignite, if the leak source is close to the ventilation air inlet, then it can quickly dilute the leaked gas to the ESC or combustible cloud (flammability range) which can cause significant hazard if ignited.

In offshore installations, there are basically two sources of ventilation, natural ventilation and mechanically constructed ventilation. Usually when there is a leak, the air current caused by the inlet and outlet of ventilation systems are meant to carry the leaked gas to the outlet thereby reducing the concentration to acceptable level.

According to (NORSOK, 2000) shall be installed near or in the ventilation outlet and if gas is detected in ventilation inlet, then the fan there should be stopped.

Also, the design of facilities is such that there are areas known as “confined areas” where there is little or no ventilation. NORSOK specifies that detectors shall be installed in those areas because leaked gas may accumulate in those areas and since no or little ventilation available, can quickly develop into dangerous cloud.

**3.2.8. Other factors**

In general, there are many factors which can affect the effectiveness of sensor and thus should be evaluated before sensor placement. Other factors includes:

- Ignition source
- Direction of leak
- Power supply
- Electromagnetic interference
- Sensor calibration, maintenance
- e.t.c.

All these factors play important role in detecting the target gas before it reaches dangerous cloud.

**3.3. METHODOLOGY OF GAS DETECTOR LAYOUT USUALLY USED BY PROCESS INDUSTRIES**

Many principles apply when laying out detectors, many manufacturers suggest placing detector where leaks are likely to occur, and secondly, to place sensors near areas where a concentration of hazardous gas may accumulate.

Example of practices used in the industries includes:

- Clustering around likely leak sources (usually not recommended)
- Equal-spaced grid vs. staggered grid (given cloud size)
- Distribution according to ventilation patterns in the module or area.
- Number of point versus line detectors



It is widely believed that there is no perfect way of positioning detector, but there are good practices and rules that if followed, according to experiences have shown that they give good coverage of the plant example is following standards and regulations like ISO, NORSOK and manufacturers manual for detector layout. We shall come back to this topic as this thesis is basically about detector layout.

## **CHAPTER 4.**

There are mainly three different types of fixed detectors installed in process industries today: flame, gas (both toxic and combustible) and smoke detectors. While the scope of this thesis work is limited to flame and gas detectors, this chapter shall focus on flame detectors.

### **4.1. PRINCIPLES OF FLAME DETECTORS**

Process engineers for example in the oil and gas industries are continuously looking for a way to reduce the threat posed by dangerous and hazardous gases in their daily operations. One of the measure threat the industry face is that of fire accident. To prevent catastrophic fire, proper flame detection should be installed and to select such equipment, it is good to understand the principles flame detector and review the types of detectors available in the market.

Most flame detectors use optical methods like ultraviolet (UV), infrared (IR) spectroscopy and visual flame imaging. Flames in a refinery, for example, are generally fueled by hydrocarbons, which when supplied with oxygen and an ignition source, produce heat, carbon dioxide, and other products of combustion. Infrared and UV is emitted in the process of combustion and flame detectors are based on this principle of detecting UV and IR light at specific wavelength.

### **4.2. FLAME DETECTOR'S TECHNOLOGIES**

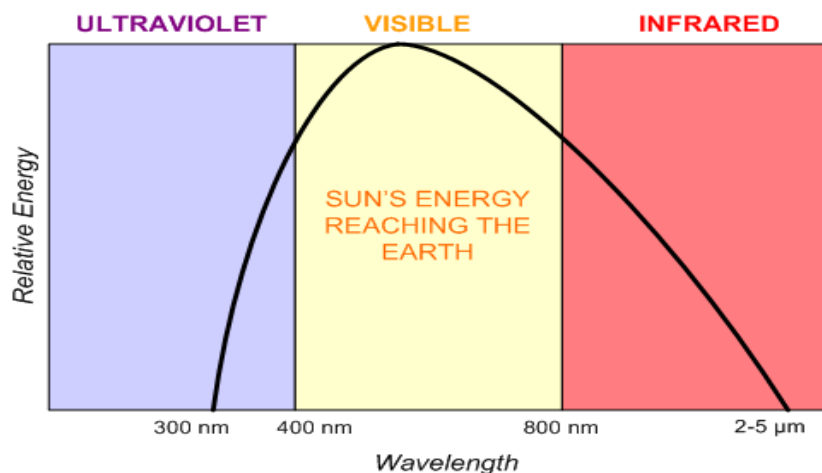
There are basically four optical flame technologies in use today;

- Ultraviolet(U.V)
- Ultraviolet/infrared (UV/IR) or Dual UV/IR
- Multi-spectrum infrared(MSIR) and
- Visual imaging.

There are other types of technologies for example:

- I.R flame detector
- Dual I.R
- Triple I.R

During combustion, U.V and I.R are emitted, and these technologies are based on LOS detection of U.V, Visible and I.R in the spectral bands.



**Figure 17: Emission energy spectrum(General Monitors, 2014c)**

#### **4.2.1. Ultraviolet (U.V) flame detector**

U.V flame detector responds to radiation in the spectral range of about 180-260nm. They detect flames at high speed (3-4 milliseconds) and offer good sensitivity at short ranges (0-50ft). The U.V because of its short-wave characteristics are absorbed in the surrounding atmosphere by air, smoke, dust and various organic materials(JACOBSON and SPECTOR, 1997). They are also affected by arc welding, halogen lamps and electrical discharge like lightning(General Monitors, 2014c), as a result they are mostly used indoors.

Another problem with U.V detector is that of attenuation, pollutants such as smoke, hydrocarbon vapours and organic materials can cause attenuation of the incident U.V radiation.

#### **4.2.2. IR flame detector**

Most flames emit infrared radiation which can be recognized by using IR technology. But flames are not the only source of IR radiation, hot surface, oven, halogen lamp, solar radiation are examples of other source of IR radiation which can coincide with flame IR radiation and can also cause false alarm. To detect exactly flame IR (not IR from other sources) radiation many techniques have been used and mostly been used is the analysis and narrow band IR threshold signals processed in the IR 4.1 μ-4.6 μ wavelength(JACOBSON and SPECTOR, 1997). However this technique is not all that effective.

#### **4.2.3. UV/IR or Dual U.V/IR flame detector**

In other to minimize or eliminate false alarm caused by other sources of I.R radiation that effects I.R flame detector, dual wavelength technology was adopted for optical flame detector.

There are two major branches of dual wavelength technology: dual UV/IR and dual I.R/I.R flame detector.

The dual UV/IR flame detector employs U.V with a high signal to noise ratio and a narrow band I.R sensor. The combined UV/IR flame detector offers increased immunity over U.V detector, responds at moderate speed and can be used indoor or outdoor.

However, the dual UV/IR flame detectors has its own short comings, the detection range may be reduced for example by heavy smoke as with U.V detector, and also it does suffer from false alarm since it affects both U.V and I.R (each by its own false alarm) channels (JACOBSON and SPECTOR, 1997).

Another type of this dual wavelength technology is the dual IR/IR flame detector. HC flames emit energy of a continuous nature of about I.R  $0.9\mu$ - $3.0\mu$  and a unique peak occurring around  $4.3\mu$  - $4.5\mu$  (due to CO<sub>2</sub> produced during combustion) this is the principle that dual IR/IR flame detector is based on. However, they have some limitations like attenuation especially in long range application.

#### **4.2.4. Multi-spectrum infrared (MSIR)**

Multi-Spectrum IR flame detectors use multiple infrared spectral regions to further improve differentiation of flame sources from non-flame background radiation, the additional IR channel helps to bridge the shortcomings of the dual IR sensor making it more immune to false alarm. Triple IR flame detector is an example of MSIR. They can be used outdoors and indoors and offer good speed at a range of about 200 feet from the flame source.

They offer high immunity to IR from other industrial sources like arc welding, sunlight, lightning and other hot sources that emit IR radiation and are commonly encountered process industry.

#### **4.2.5. Visual flame imaging flame detector**

Visual flame detectors employ standard charged couple device (CCD) image sensors, commonly used in closed circuit television cameras (CCTV), and flame detection algorithms to establish the presence of fires(General Monitors, 2014c).

The difference between UV and IR flame detectors and the visual imaging, is that, visual imaging does not depend on the emission of the products of combustion like carbon monoxide, water or the radiant heat from combustion of HC, rather it works by processing the live image from the CCD array, analysing the shape and progression of would be fires to differentiate between actual flame and non-flame sources. As a result, they are good for areas where it is required to differentiate between actual fire from accidental release of HC or combustible materials and process fire from normal operations.

Visual imaging flame detector has its own limitations, they cannot detect flames that are non-visible to naked eye like hydrogen flames, and also heavy smoke can prevent it from detecting flame as they depend on visible radiation from the fire for detection.

#### **4.2.6. Other method of fire detection**

Other methods of fire detection include:

- Heat detectors
- Smoke detectors

Another method of fire/flame detection is “heat” detection. Heat is the by-product of any combustion, thus by sensing the heat from combustion; heat detectors are able to detect the presence of fire hazard. This is an area of fire detection that has been evolving since the recent years. Heat detectors and smoke detectors are one of the oldest methods of fire detection but were out-used in the process industries because they are very slow in fire detection.

They are usually installed in residential homes and or places where it is not possible or not cost-efficient to use other optical method of fire detectors or CCTV.

### **4.3. PROCESS INDUSTRIES REQUIREMENTS FOR FLAME DETECTOR**

When evaluating different flame detectors available, process industries usually focus on important performance characteristics. Some of these parameters are evaluated below:

#### **4.3.1. False alarm immunity**

False alarm immunity is one of the measure requirement for flame detector selection because false alarm a both costly and productivity issue. It is therefore essential that flame detectors are able to differentiate between actual flames and radiation from sunlight, lightning, arc welding, hot objects, and other non-flame sources.

#### **4.3.2. Detection range and response time**

Every flame detection technology has a certain range within which it effectively recognise flame and at a certain response time. The greater is the coverage distance and shorter response time, the better is the detector in giving early warning of fires and initiating safety actions.

#### **4.3.3. Field of view (FOV)**

Field of view is an important requirement when selecting flame detectors, FOV together with detection range they define area coverage per device.

FOV of a flame detector is an important parameter when determining detector layout and number of detectors to be installed as we will see in the next section.

Most of today’s flame detector models offer fields of view (FOV) of about 90° to 120°.

#### **4.3.4. Self-Diagnostics**

Most optical flame detectors come with a built in self-diagnostics for continuous optical path monitoring (COPM). This self-check is designed to ensure that the optical path is clear, the

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detectors are functioning and that the electronic circuitry operates normally for effective fire detection. The detector carries out self-check periodically for example once every minute and if fault is detected it is communicated or outputted.

## **CHAPTER 5.**

The result of many accidents in the oil and gas industries like that of Piper Alpha, is that the industries has seen many constant improvements. Concepts like Individual Risk Analysis, Quantitative Risk Assessment, ALARP and others keep on flooding the industries and the safety engineers keep on changing and improving their philosophies and procedures. GDS system is an essential part of safety procedure, an ideal GDS should detect all gas leaks but that is impossible or near impossible since many leaks in the industries today are not detected because various reasons.

In effect, for a GDS system to stand a chance of detecting “all leaks” then it must start by optimisation of the gas detector location. There are basically two ways of detector location; location based on qualitative method and the one based on quantitative method.

This chapter will focus on the latter method and will evaluate methodology of detector optimisation.

### **5.1. METHODOLOGIES FOR GAS DETECTOR LAYOUT VERIFICATION/OPTIMIZATION**

There is no doubt that laying detectors based on quantitative method is better than qualitative method since the latter is prone to human errors and mistakes, moreover, there may not be consensus among engineers on the location points. One of the best quantitative method mostly used is based on the application of finite element as a CFD (Computational Fluid Dynamics) tool to generate dispersion data.

Both leak rate and cloud size are key factors used in gas detection, it is generally the cloud size that is detected by IR detectors while to detect actual leak, acoustic detectors are used. The detection criteria should start by determining the dangerous cloud size since this is the smallest cloud that if ignited will result in unacceptable consequences. To determine the dangerous cloud, the DAL of the facility has to be established.

The principle idea behind using CFD to evaluate performance of GDS is the direct assessment of the GDS’s ability to detect gas cloud generated by many simulated gas leaks. Practically, there will be leaks that will never be detected for example small leaks pointing away from detectors especially if they form no gas cloud, and leaks that will always be detected like large leaks that point towards detector location. So there are essentially infinitely many leak scenarios that can occur, thus the key to successful CFD based evaluation is the selection of good leak scenarios to be used for testing and evaluation of the GDS.

NORSOK S-001 specifies the criteria to follow:

- all dangerous clouds must be detected
- the GDS will be optimized based on clouds resulting from small, more frequently occurring leaks (typically 0.1kg/s leaks)

Thus, it follows that to detect all leaks; the study will be divided into two:

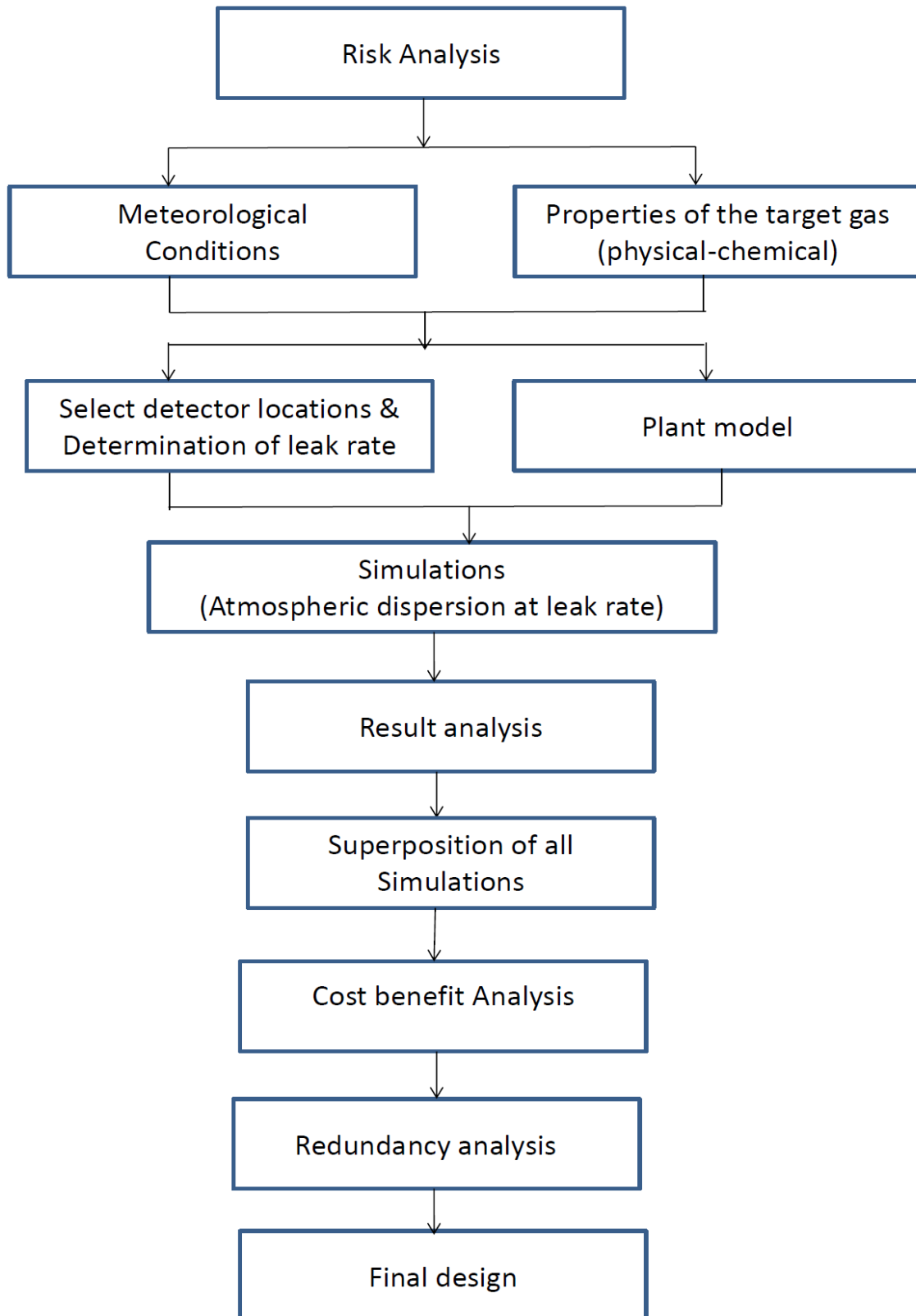
- dangerous cloud detection (involving analysis of larger leaks) and
- cloud detection (involving detecting the resultant gas cloud from small but frequent leaks).

The first step in gas detector optimization will be to obtain the geometry of the plant, here special attention is paid to inlets and outlets. Based on the geometry identify potential leak sources and install detectors there. With this first installation, run significant number of simulations with small leak and large leaks. This original methodology considers the distances between detectors.

A cost benefit analysis is necessary to identify optimal number of detectors. Finally, check redundancy and optimise number of detectors.



The figure below graphically shows the steps that can be followed in optimising gas detectors.



**Figure 18: Flow chart for gas detector optimization**

The **first level** is Risk Analysis, identifying all potential leakage sources and possible location of gas detectors. Various tools can be used in initial location of detectors including regulations and standards like NORSOK, DNV, ISO,ISA.

**Second level** is getting the meteorological/weather conditions at the place of installation, wind speed, directions, frequencies, rain, heat and other things which might affect the gas dispersion in that plant.

At this step, determination of the target gas is carried out, the chemical and physical properties example flammability limit, molecular weight. It is important to determine if the gas is heavier than air or vice-versa.

In the **third level** selection of leakage points for CFD simulations and analysis is done. It is important to start by initial detector location for old plant and consider the initial detector location done in the first step during risk analysis of the plant. Also in this step, leak rate and the amount of gas to be released is determined.

In this level also a computer model of the plant or installation area is constructed, it contains the installation itself and all the obstacles that can affect the gas flow or airflow, example structures, pipes, equipment etc.

The **fourth level** is the dispersion simulations from each release point at selected leak rates and varying weather conditions. Several weather conditions should be considered based on the statistical data for the weather at the plant. The number of iterations is important to assure convergence to solution. Since there is no unique solution, it is important to run enough number of simulations until the best solution is achieved. The best solution should in any case be able to detect all dangerous leaks before it reaches dimensioning gas cloud that can threaten the safety of the plant.

The **fifth level** is then the Result Analysis, here proper care is taking to ensure the result meets all requirements to ensure the detection of the target gas since there is no unique solution and engineering judgment and criteria affects the quality of the result.

On the **sixth level** all the results are considered together in the superposition of all the simulated results. Superposition gives the area of greater intersections of detectable zones where it will be better to install the detectors.

On the next **two levels** a Cost-benefit Analysis is carried out and a Redundancy analysis to check for redundancy. The cost benefit analysis is necessary to identify the optimal number of detectors and an economic approach is used and can apply the following parameters:

- Platform value and lifetime;
- Oil production;
- Cost of detectors (installation and maintenance);
- Cost of spurious failure

There are many other philosophies or principles and tools to be used when evaluating cost benefit analysis for example ALARP principle. It is obvious that the more the number of detectors installed the better the coverage, but this comes at an extra cost and ranges in millions of kroner per year thus it is important to find that boundary at which adequate safety is achieved at the lowest cost.

ALARP – (As Low As Reasonably Practicable) can be used as an acceptance criteria for the number of detectors vs the cost of installing and maintaining them.

Other methods includes NPV (Net Present Value, where  $ENPV > 0$  implement measure) and ICAF (Implied Cost of Averting Fatality).

The **last level** is then the final design where the number and locations of detectors are defined according to the results and analysis done earlier.

There are other methods which can be adopted for gas detector optimization using CFD for example in the flow chart in the next page, after the dispersion simulations, result is analysed and if two or more detectors detects the target gas then result is accepted otherwise continue simulations.

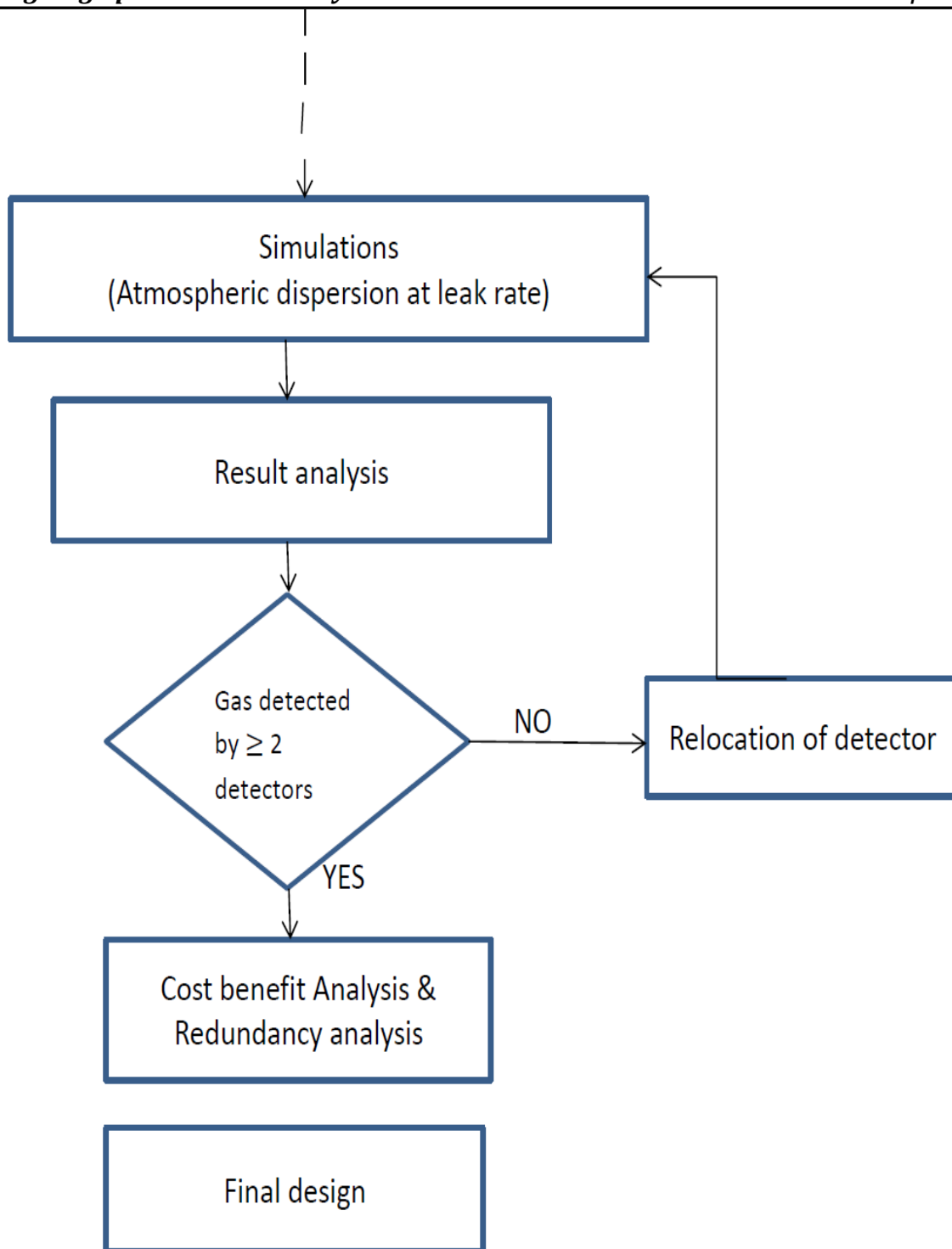


Figure 19: Another method of detector optimisation

## 5.2. METHODOLOGIES FOR FLAME DETECTOR VERIFICATION/OPTIMIZATION

As earlier stated in section 4.3.3, FOV with detection range determines the coverage area of a flame detector; fires outside FOV range are not detected. Also, FOV can be obstructed by large vessels, pipes, tanks or structural members (Heynes, 2013), thereby reducing the coverage area of the detector. Hence, the need for good mapping technique when positioning and optimizing detector.

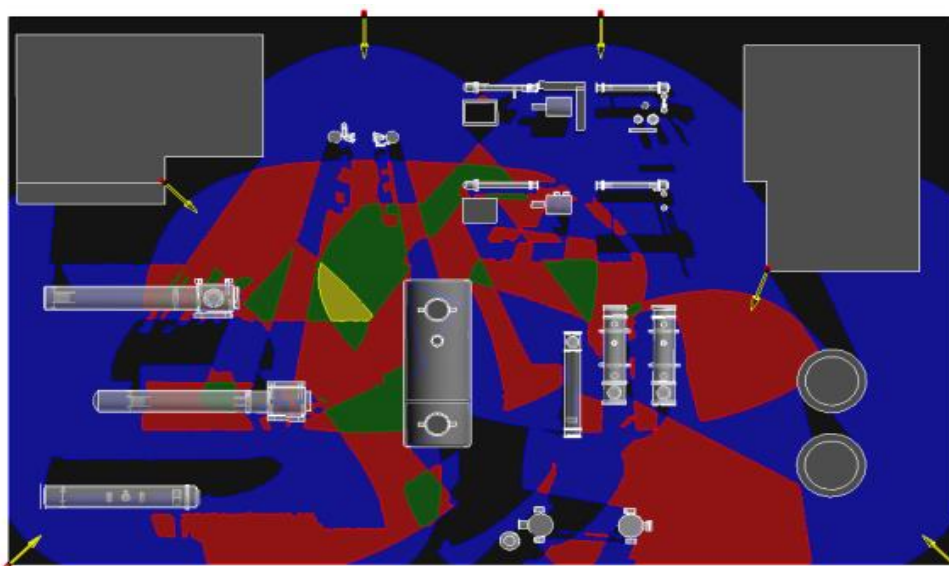
### 5.2.1. Flame detector mapping techniques

The main reason for mapping is to verify the visibility of fire areas or zones to visual flame detectors. By the help of this process, it is possible for visibility statistics to be determined based on the percentage of fire zone's that is visible to single, or multiple or no flame detector/s.

There are basically two types of flame detector mapping techniques which are explained below:

#### 5.2.1.1. Two-dimensional (2D) mapping

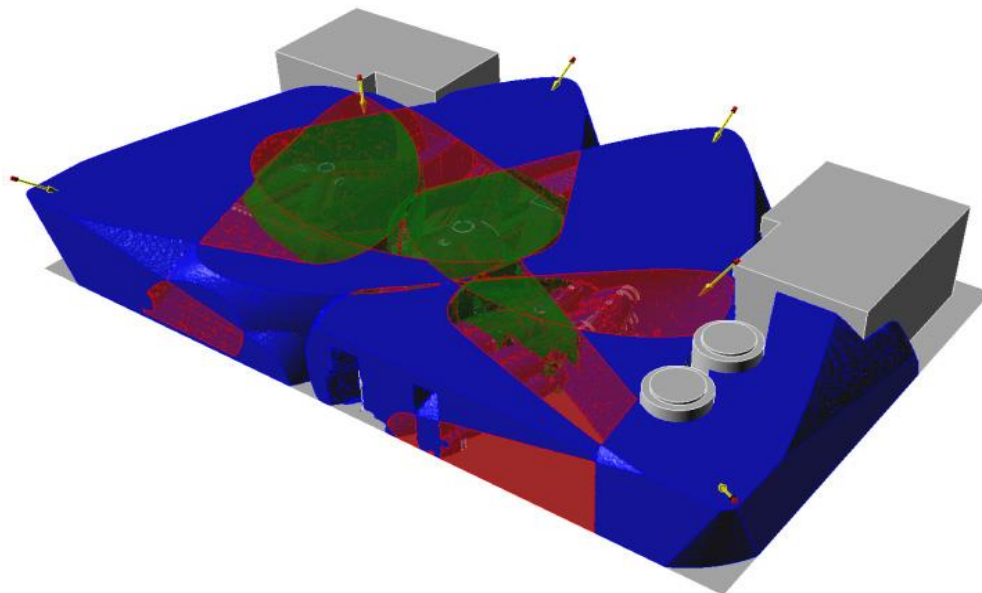
Till date 2D detector mapping has largely dominated the flame detector mapping. The main problem of 2D modelling is that it is misleading, an area may be shown to be covered by a detector in 2D modelling whilst in fact, it is not and if a fire may develop in that area it will not be detected by the detector until is too late. Another problem with 2D technique is that, it is very difficult to see the effect of obstruction by for example equipment, in that case, obstruction are either not noticed or ignored.



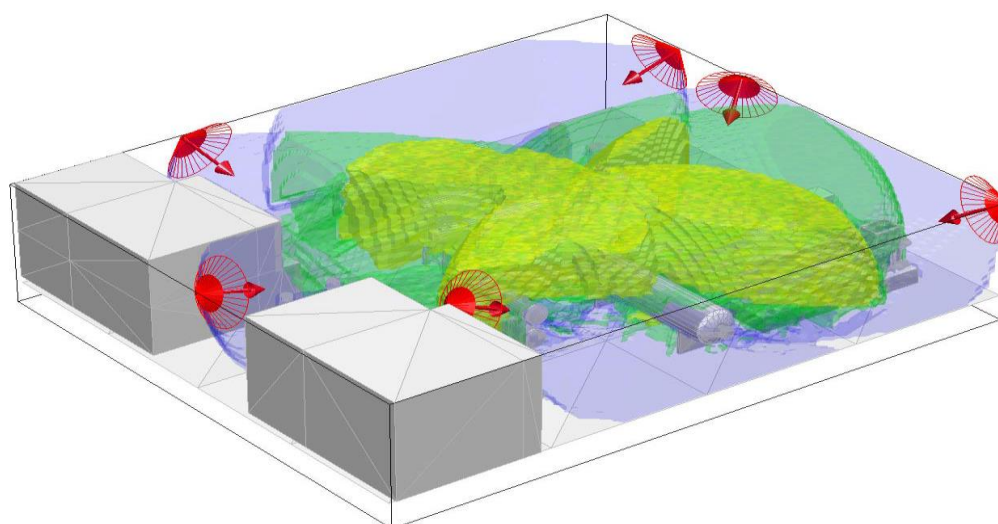
**Figure 20: Typical output from 2D mapping. Showing visibility colors: black = visible to 0 detectors, blue = visible to 1 detector, red = visible to 2 detectors, green = visible to 3 detectors, yellow = visible to 4 or more detectors.(Heynes, 2013)**

### 5.2.1.2. Three-dimensional (3D) mapping

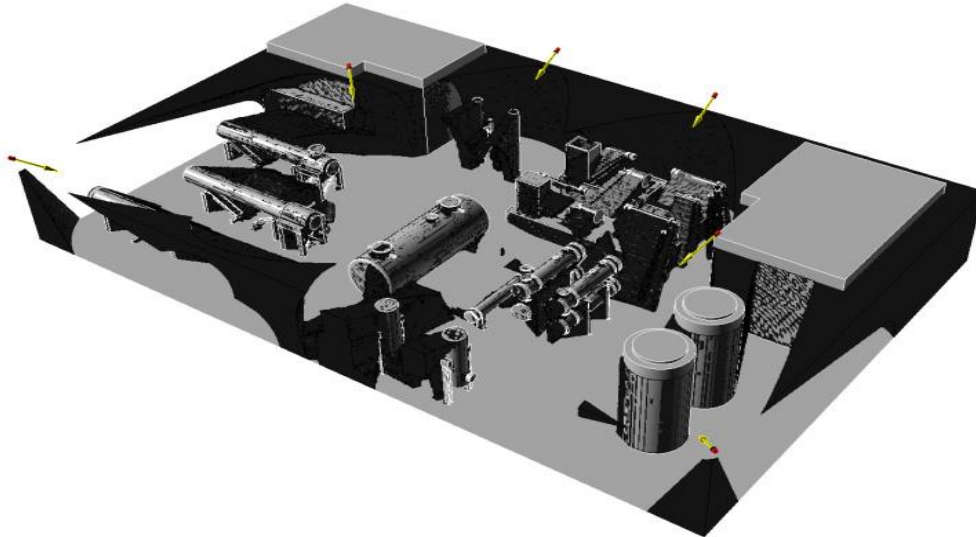
This technique is relatively new but constantly gaining acknowledgment in the oil and gas industries today. In 2D modelling, we are not able to see the effect of height dimension since it's not modelled, but in 3D we are able to model the height dimension as accurately as other dimensions rather than approximating it or neglecting it like in 2D. As a result, obstructions can be seen and accounted for when position the detectors.



**Figure 21: Output from a 3D mapping study. The geometry and flame detector placement is the same as in Figure 20. Isovolumes of visibility are shown (same color scheme) in a 3D rendering(Heynes, 2013).**



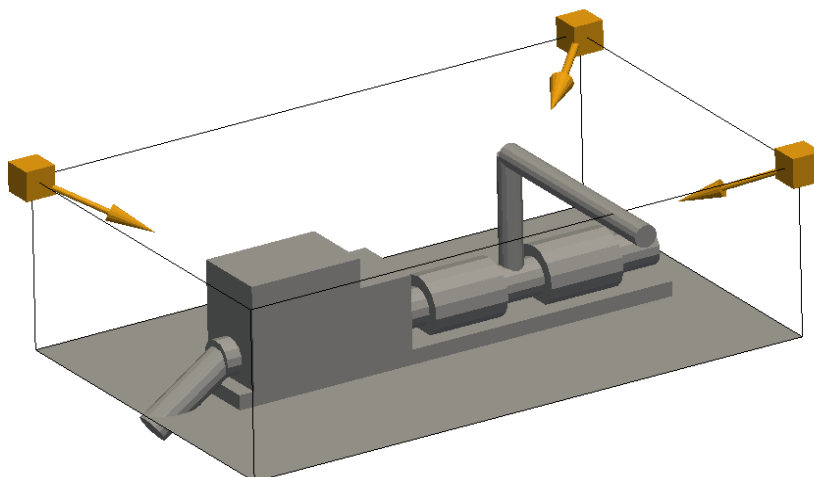
**Figure 22: Results from 3D modeling showing; blue = 1 detector, green = 2 detectors, yellow = 3 or more(Heynes, 2013).**



**Figure 23: Zero visibility isovolumes (blind spots) from a 3D mapping study, darkened areas indicating no coverage(Heynes, 2013).**

By contrast, 3D mapping does not share same flaws as in 2D. The ability to view 3D isovolumes of visibility, especially that of blind spot (the darkened area in figure 23) gives unambiguous picture of fire visibility. Also, 3D mapping helps to generate visibility statistics by volumes and percent coverage.

The figure below shows a simple model that will be investigated in the next section.



**Figure 24: Simple 3D model with three detectors layout**

The model shows a very simple module which will be investigated for detector verification/optimization using criterion by two company which will be identified here as **Company A** and **Company B**. The model was developed in FIDO software – a program developed by Knut Erik Giljarhus of Lloyds Register Consulting for evaluating the visibility field of a flame detector in 3D, taking into account the process module geometry. We will come back to this in Chapter 6.

### **5.2.2. Company A: Detector Visibility Requirement**

According to Company A, the detectors FOV shall cover the potential fire locations that needs to be covered and the distance between detector and potential fire area be set after considering the type of fire and other circumstances around the area.

For Company A, the detection coverage is the amount of modelled portion of a zone that will be detected and is expressed in percentage. So is the percentage area that is covered by the detector.

Also, Company A requires:

- 90% coverage or visibility for single detector and
- 85% coverage for two or more detectors.



**5.2.3. Company B: Detector Visibility Requirement**

Company B requires that when designing for the area to install fire detection system, the fire detector coverage or visibility shall among other things take into account flame size.

Their requirement is that for detecting both pool and jet fires a flame size of:

- 0.5m in diameter and 1m length to be covered or visible to one or more detector
- 1m diameter and 3m length should be visible to two or more detectors

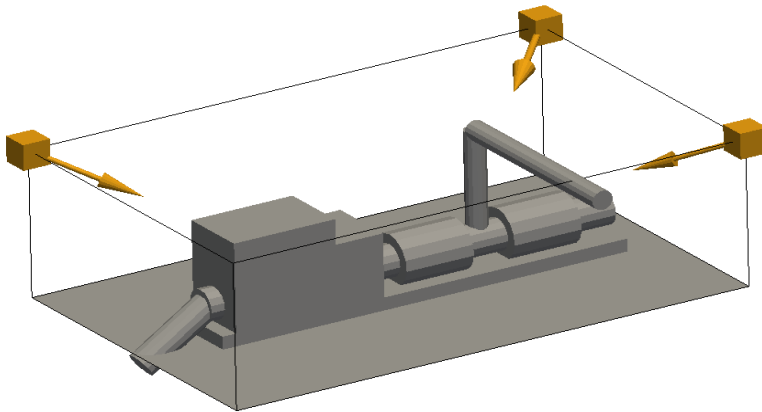
This flame sizes can be for example as seen by ignited jet gas with leakage rate of 0.1kg/s.

## CHAPTER 6.

### 6.1. Simulations

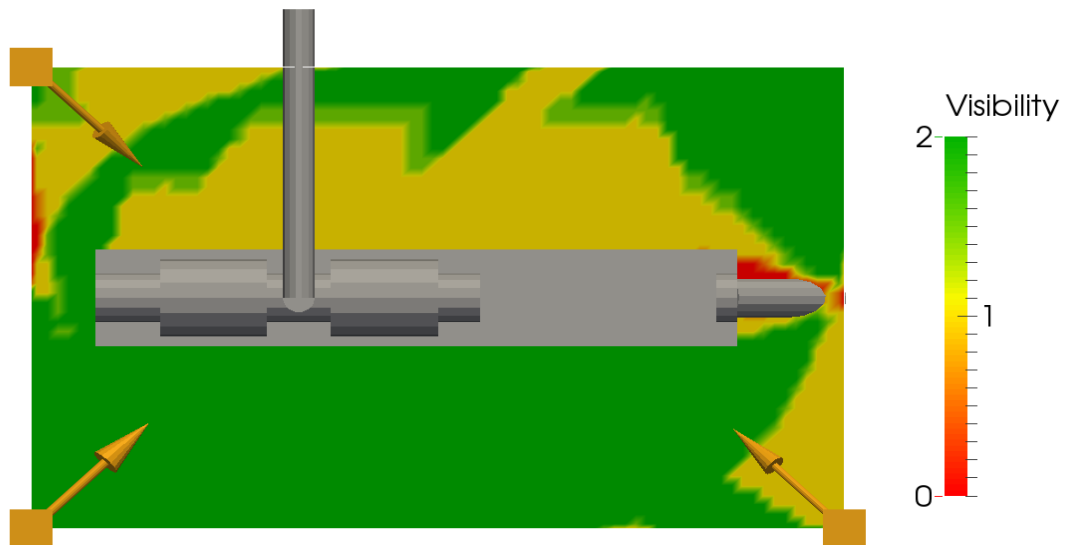
For simplicity the two modules that will be examined will be identified as Module A and Module B.

#### 6.1.1. Module A



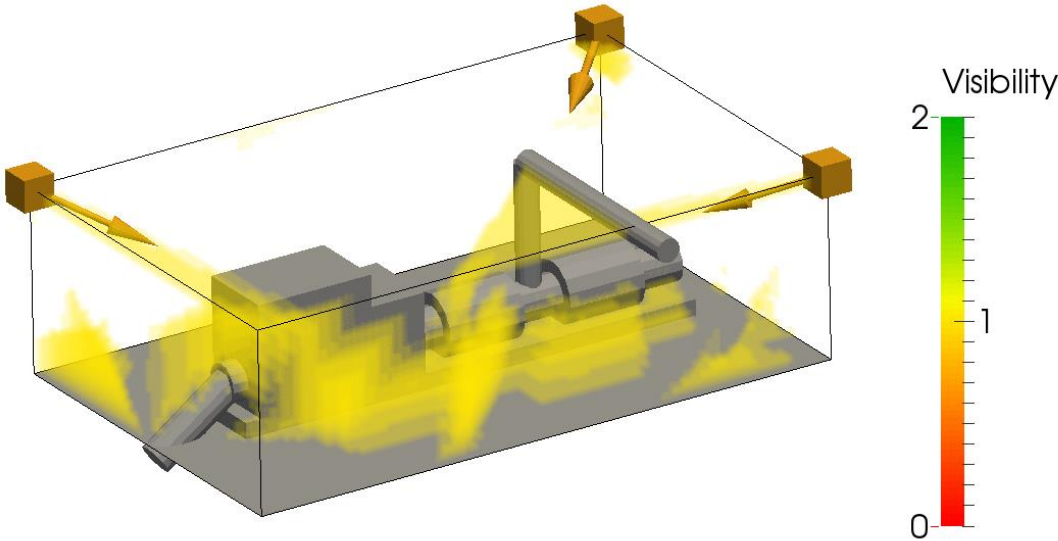
**Figure 25: Simple model showing three detector layouts**

The figure above shows a very simple module with three detectors positioned in three different corners. One very good advantage of FIDO is the ability to see the equipment through the module because of its transparency.



**Figure 26: Visibility of the detectors in unfiltered 2D showing: one detector (yellow), two or more detectors (green) and no detector (red)**

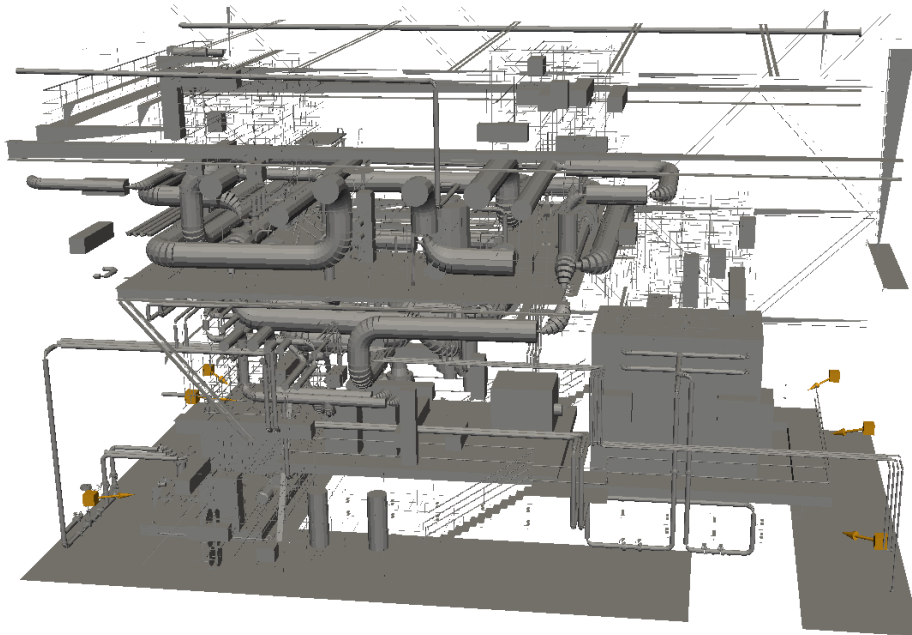
The figure above shows module A but in plane standard 2D mapping, the visibilities is shown beside with green denoting coverage by two or more detectors and red standing for not covered by any detector.



**Figure 27: Visibility of the detectors in 3D showing: one detector (yellow)**

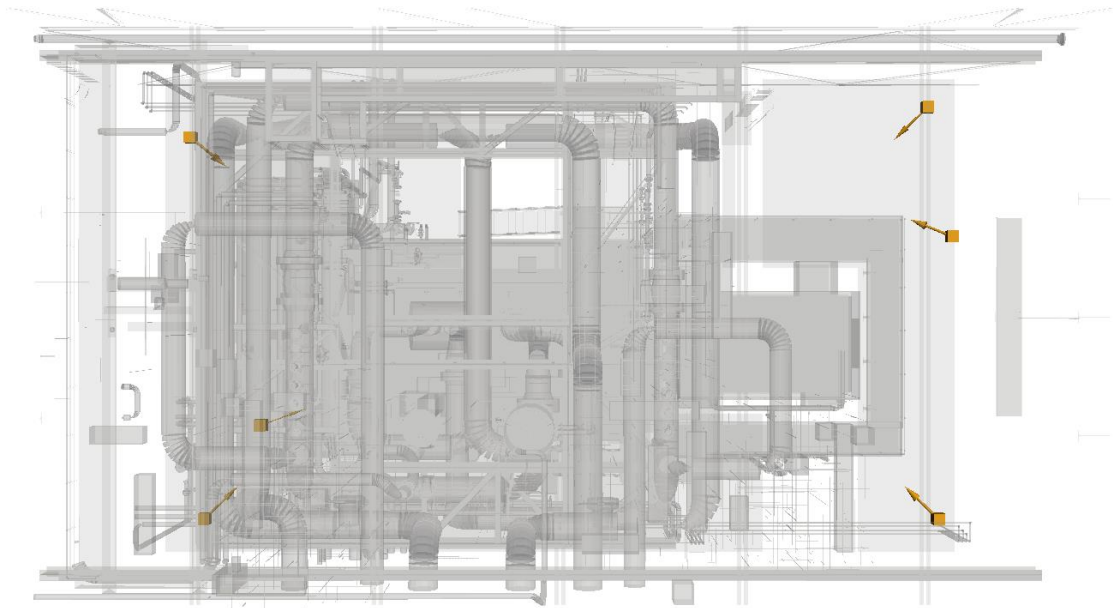
In the figure above, the areas that are covered by only one detector/s is shown. Majority of the zones are covered by one or more detectors.

### 6.1.2. Module B



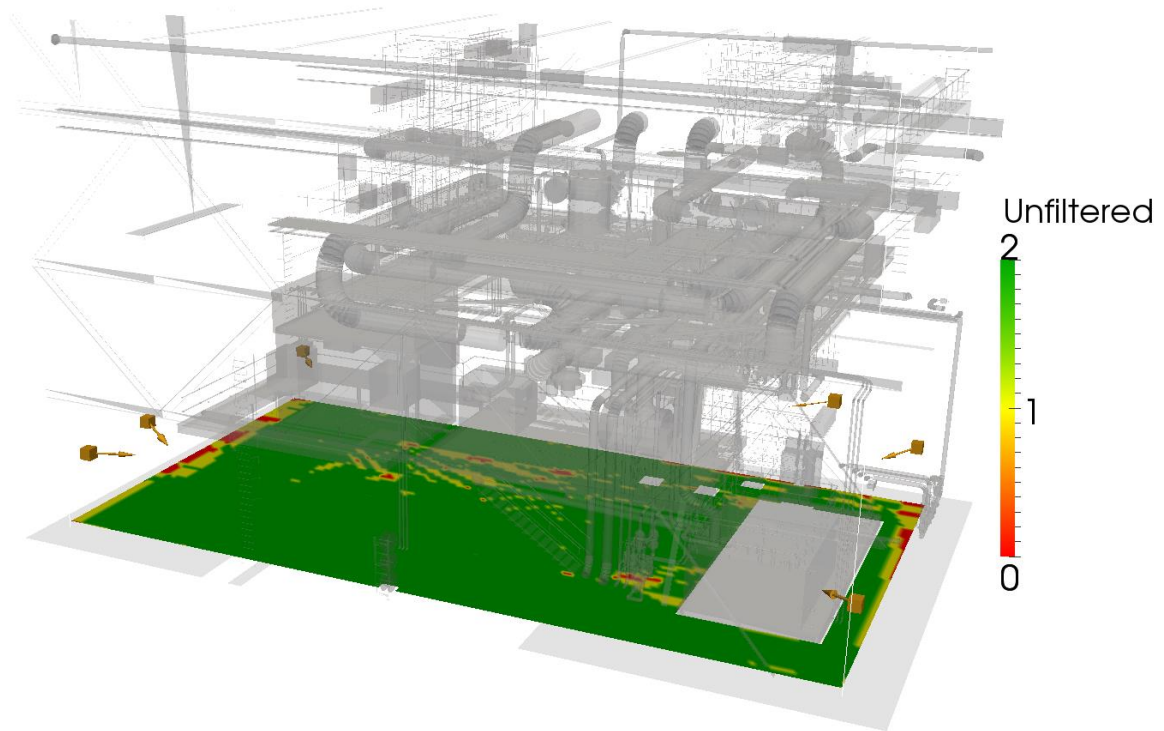
**Figure 28: A real-world onshore module with six detectors installed**

Module B in figure 28 above is a real-world onshore enclosed module with six detectors installed. The module is 3m above the ground and contains many equipment including oil tank, compressor, pipes e.t.c. We see from the figure that there are no detectors covering the upper part of the module. This module was designed in 2D mapping technique and as seen above, how it looks in 3D.



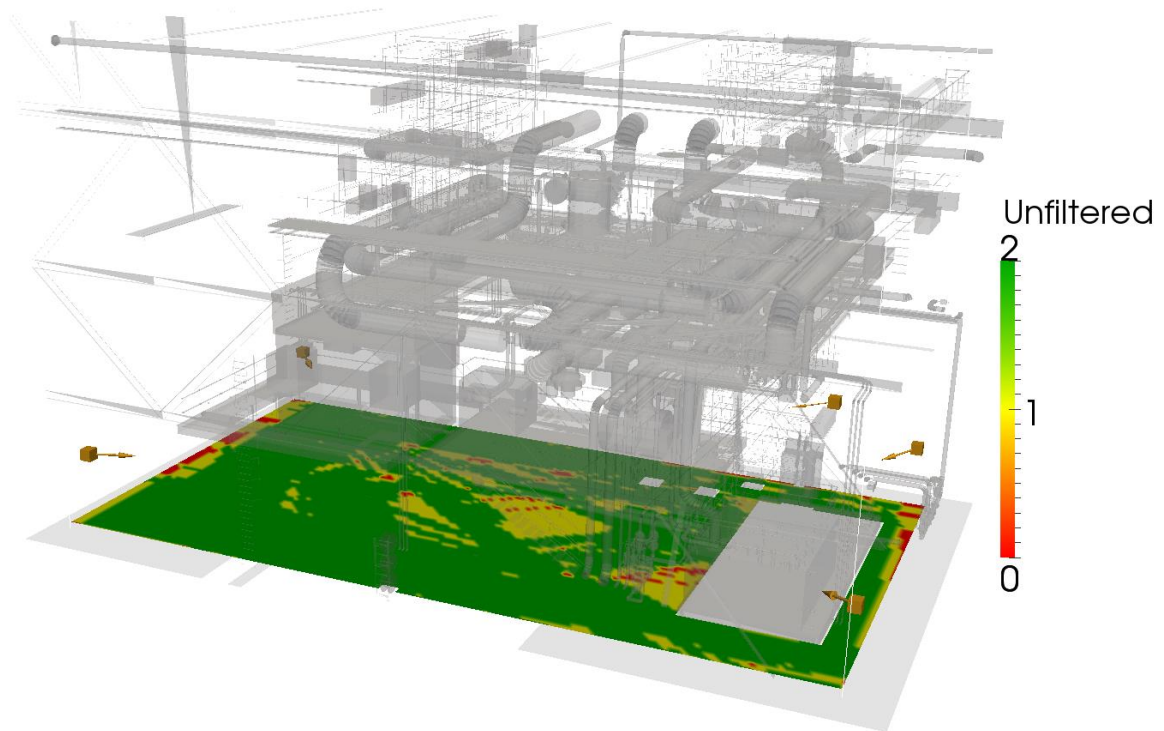
**Figure 29: Original design of Module B in 2D**

Figure 29 shows the original design of Module B, as seen above, that is why the upper part is not covered as seen in figure 28.

**Module B ground floor visibility for unfiltered and filtered case:**

**Figure 30: Module B Unfiltered, Six detector visibility unfiltered- Visibility: two or more detectors (Green), one detector (yellow), zero or no detector (Red)**

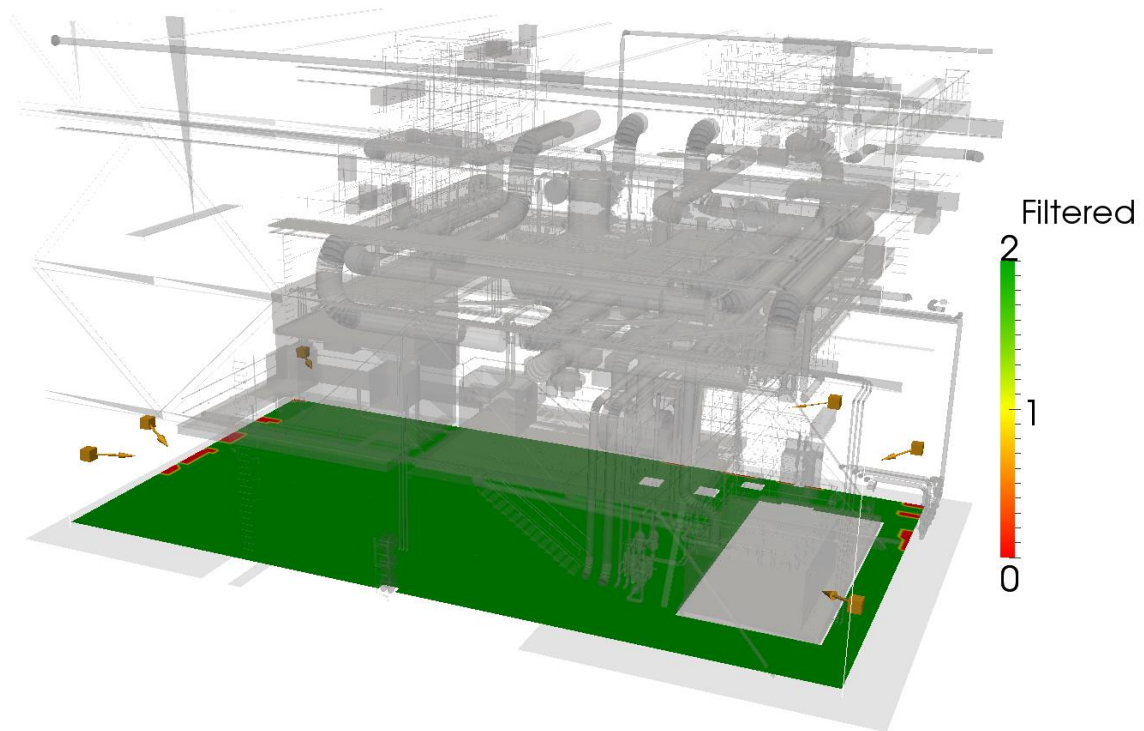
Figure 30 shows the visibility of the six detectors at ground level. We know that the entire upper part is not covered by any detectors, so we are evaluating based on the lower level that is assumed to be covered. From figure 30, if we are placing the detectors based on the requirement of Company A, then this is what we will get. Although there are few places not covered by any detector, the coverage seems to be quite good with many areas covered by two or more detectors.



**Figure 31: Module B Unfiltered - Visibility ground floor of five detectors showing coverage by one detector (yellow), two or more (green) and no detector (red)**

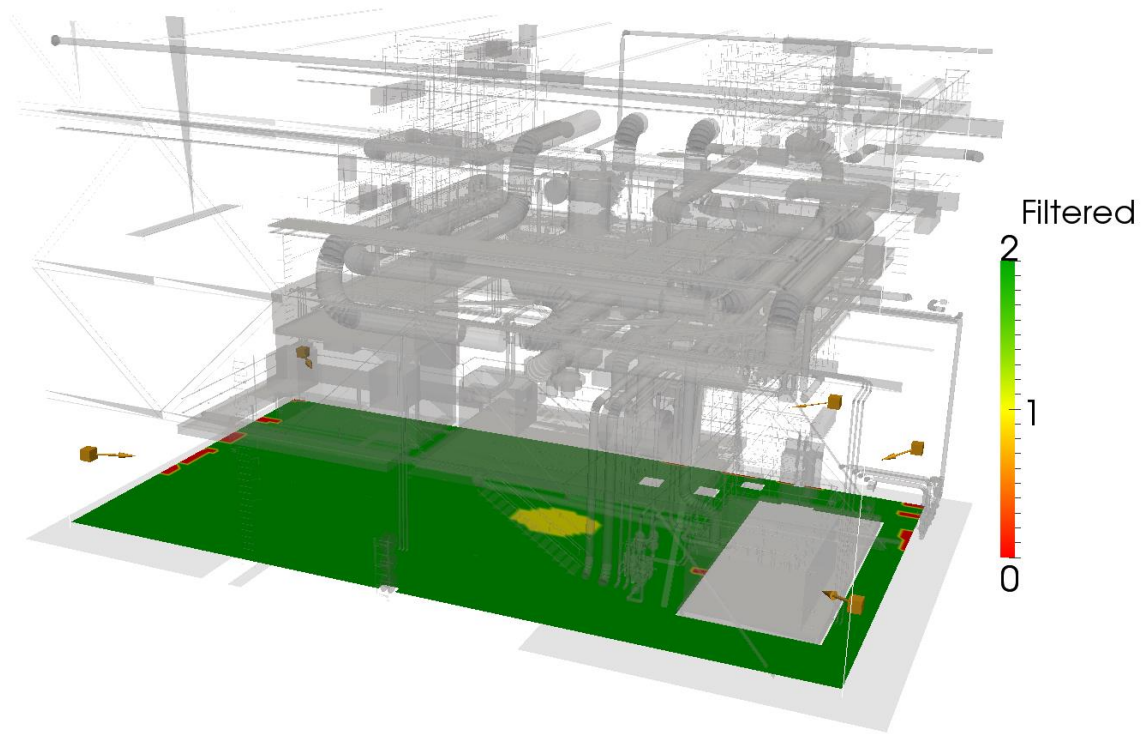
The visibility coverage with one detector removed is shown in figure 31 above. As seen from the figure, more areas are seen by only one detector than in figure 30, and few more areas covered by no detectors. Note that this is based on 2D mapping like in figure 30 as used by Company A. In this case as in figure 31, the visibility is now below the criteria required by Company A.





**Figure 32: Module B Filtered - Detector visibility of six detector - Visibility: Green – 2 or more detectors, Red – zero or no detector**

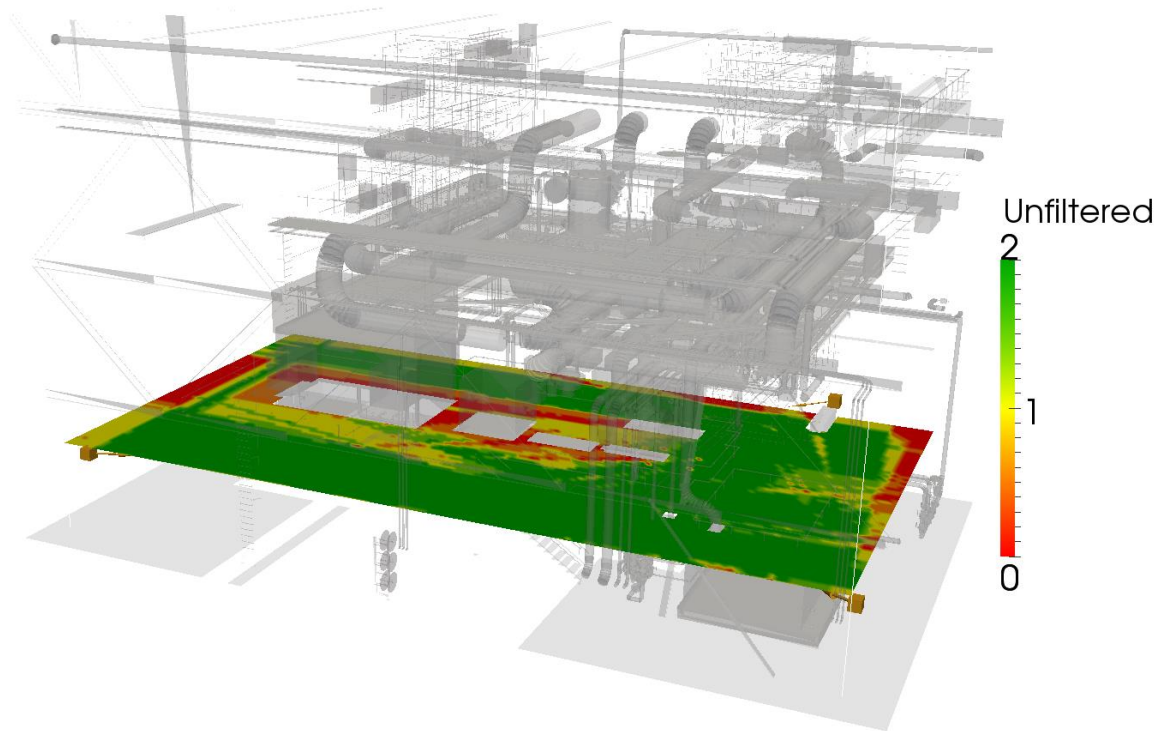
Here is a filtered analysis of six detector coverage at ground level. By doing a 3D analysis and then removing regions that are smaller than the criteria given by Company B on detector coverage, we then achieve the filtered detector visibility in the figure 32 above.



**Figure 33: Module B Filtered - Visibility ground floor of five detectors in Filtered 3D Analysis showing coverage by one detector (yellow), two or more (green) and no detector (red)**

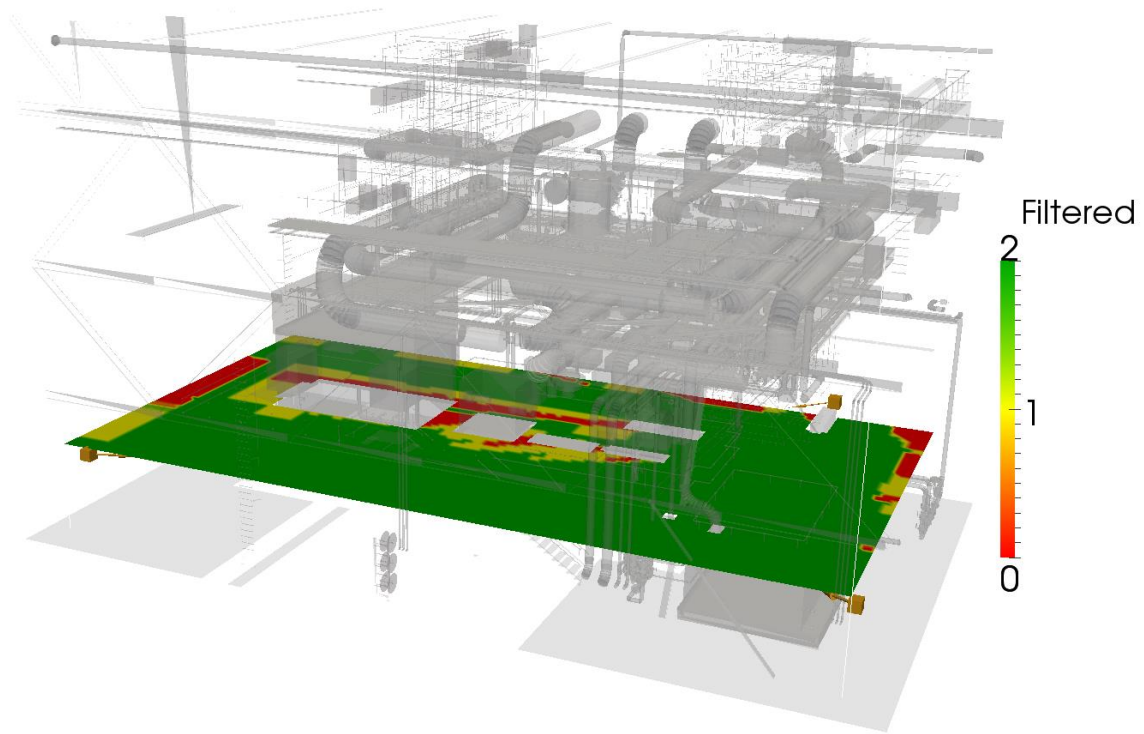
The visibility of five detectors is shown in figure 33 above. The detectors maintain quite good coverage despite removing one detector. We can see the different in this filtered case compared to the earlier unfiltered (2D analysis) which shows more uncovered areas.

**Module B visibility for little above the ground floor for unfiltered and filtered case:**



**Figure 34: Module B Unfiltered - Visibility of the module (six detectors) - 2D analysis showing coverage by coverage by one detector (yellow), two or more (green) and no detector (red)**

The visibility in figure 34 is that of five detectors, note that this is from little above the ground floor. We can see that there are many areas not seen by any detector.



**Figure 35: Module B Filtered - Visibility of the module (six detectors)-filtered 2D analysis showing coverage by coverage by one detector (yellow), two or more (green) and no detector (red)**

By doing a filtration (3D) analysis we obtain the picture in figure 35 above. Some regions have been filtered out to comply with the Company B criteria.

## CHAPTER 7.

### 7.1. DISCUSSIONS

While it is very hard to detect all leaks and fires in most process industries, with good detector coverage, dangerous ones can be detected and dealt with before it threatens the safety of the platform.

Two entirely different modules has been simulated in FIDO software which for simplicity is identified as module A and B. Discussions on these modules will focus on the coverage of the detectors installed in both modules based on the visibility requirements of two companies for safety reasons identified in this thesis as Company’s A and B.

The main difference between the requirements of these two companies is that, Company A uses 2D mapping technique while B supports 3D mapping technique. So in practice, this is comparing 2D tactics verses 3D technique in obtaining optimal detector layout.

#### Module A

This is a very simple module with three detectors installed. The visibility of the three detectors in unfiltered standard 2D analysis is shown in figure 26, in this 2D analysis it looks like there is a large area covered by one detector (yellow). For Company A, their requirement is that at least 90% coverage by single detector. The table below shows the coverage of the detectors in percentage:

**Table 8: Detector visibilities in percentage**

<b>Unfiltered 2D</b>	<b>Visibility (%)</b>
One or more detector/s	98.85
Two or more detectors	62.77
<b>Filtered 3D</b>	
One or more	100
Two or more	100

*(Filtered – filtration is done by doing a 3D analysis and removing the regions that are smaller than Company B criteria.)*

From the table above, there is almost 99% coverage by one or more detectors while about 63% for two or more in unfiltered 2D analysis (unfiltered is the standard 2D analysis). Using the criteria by Company A (refer to section 5.2.2) we should have about 86% coverage for two or more detectors. This means that using Company A criterion, a fourth detector should be installed in the last corner. In other words, this solution did not meet the criteria used by Company A in flame detector layout.

On the other, in the filtered 3D analysis, we are able to calculate the actual volume of this covered region and it shows that it is smaller than the Company B criterion (cylinder of 1m

diameter and 3m length) for two or more detector coverage as seen in table 8. It means that the criterion in this case for Company B is very well met. The module is very well covered there is no blind spots where fires can start without being detected.

While both Companies have followed different approach for detector layout, they all basically want the same thing, to save cost whilst maintaining good safety and protection of the platform. It follows that in the case of Company A, they will need to install a fourth detector in the last corner whilst Company B will most likely don't do that because their criterion is met.

Whilst it seems realistic to install a fourth detector on the last corner especially following Company A criterion, it adds additional cost to the company. The cost of installing and maintaining detectors can range in their millions of kronas per year especially in the remote offshore areas. By following the Company B criterion we able to see that any detector install in the last corner will be redundant and adds no additional protection to already protected module.

In order words, we can say here that the 3D mapping technique is much better than the 2D technique, and is less conservative and saves cost without sacrificing safety because otherwise a fourth detector would have been installed in the last corner of figure26 based on 2D analysis and Company A criterion alone.

**Module B**

This module is much more complex than module A, it is a real-world onshore module with many equipment. This module was originally designed in 2D mapping technique, as pointed out earlier 2D mapping considers only ground level as seen in figure 29, the height level is not represented and difficult to account for as seen in the figure.

If we look at figure 28, it then easy to see these flaws, we see that there are no detectors covering the upper part of the module.

Table 9 below shows the coverage of the detectors in percentage.

**Table 9: Six detector visibilities (ground floor) in percentage**

<b>Unfiltered 2D</b>	<b>Floor/Level</b>	<b>Visibility (%)</b>
One or more detector/s	Ground	96.61
Two or more detectors	Ground	86.43
<b>Filtered 3D</b>		
One or more	Ground	97.82
Two or more	Ground	97.44

From table 9 above, in the unfiltered 2D analysis, 96.61% of the area is seen by one or more detectors and 86.43% seen by two or more, fulfilling the 2D criteria of Company A which are 90% seen by one or more and 85% by two or more (refer to section 5.2.2).

In the case of 3D analysis (figure 32), what we see is that the visibility for both cases is more than 97% fulfilling the criterion for both companies.

In both cases (figure 30 and 32) a good coverage of the area is achieved and meets the criterion for both companies, so regardless of which mapping technique that is followed, the zones are well protected as such one may argue the use or investing in another mapping (3D) technique that will carry additional cost and bring with itself the need for additional training for engineers that will work with it and perhaps overhaul of some company’s safety practices to accommodate the new method.

However, to achieve optimal detector layout one needs to do also redundancy analysis and cost-benefit analysis. These two analyses will help to achieve optimal number of detectors to be installed and still maintaining good coverage.

In table 10 below, percentage coverage for both cases is shown for five detectors. In redundancy and cost analysis we want to see the detector/s which can be removed and still not sacrifice safety. In figures 31 and 33 one detector has been removed for both cases and the result is shown below.

**Table 10: Five detector visibilities (ground floor) in percentage**

<b>Unfiltered 2D</b>	<b>Floor/Level</b>	<b>Visibility (%)</b>
One or more detector/s	Ground	96.02
Two or more detectors	Ground	79.43
<b>Filtered 3D</b>		
One or more	Ground	97.75
Two or more	Ground	95.85

For the Unfiltered 2D analysis, we get that with one detector less (figure 31), about 96% of the area is seen by one or more detectors while 79.43% is now seen by two or more detectors. In this case, the criterion of Company A is now not fulfilled.

On the other hand, if we filter in the same manner as Company B (that is we evaluate using 3D analysis the same positions and the same number of detectors but following Company B criterion and method), we achieved 97.75% coverage for one or more and 95.85% for two or more detectors.

It means that by doing a 3D analysis, we are below the Company A criteria (that’s assuming we can filter in the same method as Company B criteria), while by doing only 2D (unfiltered) we are not able to fulfil Company A criterion in the case of five detectors.

## **7.2. APPROACHES**

While there exist many studies and researches in gas detector optimisation especially in oil and gas industries, there is little done in the area of flame detector optimisation.

The approach followed in this thesis for flame detector optimisation is quite unique not just because of the 3D mapping technique that is relatively new to the oil and gas industry, but also because the software used in tracing and evaluating the visibility field of flame detector.

In this section we will compare approaches to examine differences or advantages and disadvantages between different approaches to detector layout.

### **7.2.1. TRADITIONAL 2D VS 3D MAPPING TECHNIQUE**

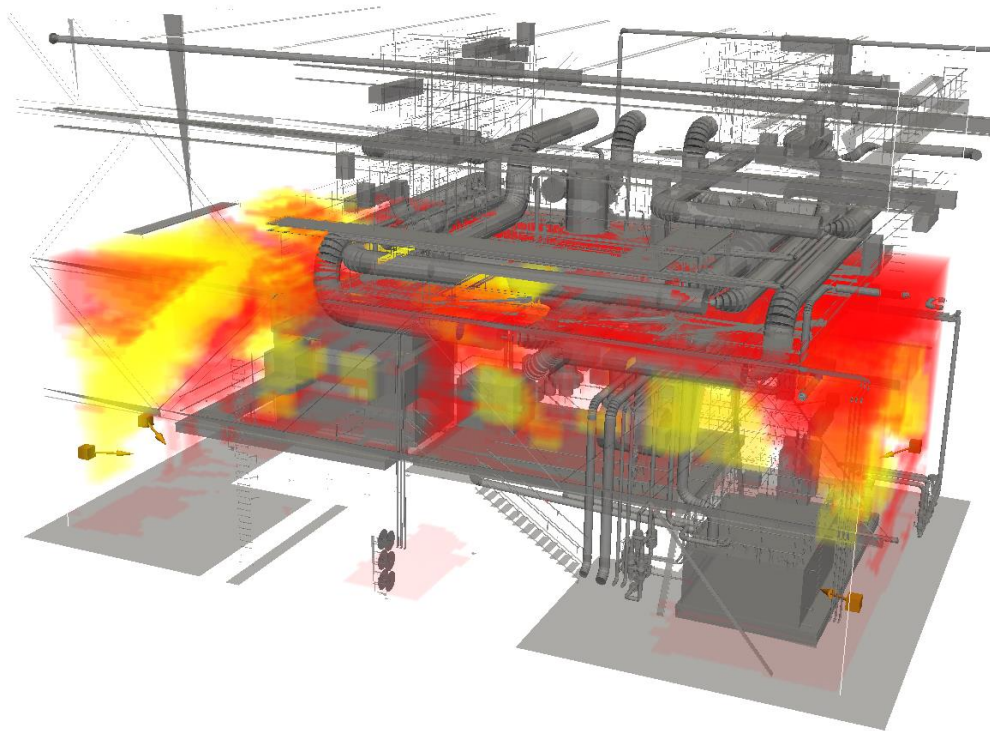
Traditional or convectional mapping method is 2D mapping, while there exist many flaws in 2D mapping; 3D mapping solves these flaws while introducing additional advantages. Figure 28 (Module B) was originally designed using 2D mapping technique and which results in no detector covering the upper part of the module.

Traditional 2D mapping can be drawn on a paper on the plant layout drawing or using computer software that considers only two-dimensional view. Therefore it considers the ground level only as seen on figure 29.

The problem with designing in 2D is that the effect from the height dimension is ignored or not accurately represented. In the plot of simple module A figure 26, there is an obstruction to the FOV of two of the three detectors by the equipment inside the module, the result is that we get a 62.77% coverage by two or more detectors resulting in criterion for Company A not being met, this is inaccurate representation as seen from the result in filtered 3D analysis.

Another advantage of 3D mapping is the ability to show the coverage in volume covered by the detectors. In the figure in the next page, the volume plot in 3D of module B is shown.





**Figure 36: Module B - Volume plot of the module in 3D showing coverage by one detector (yellow) and no detector (red)**

Figure 36 shows volume plot in 3D of the regions that are visible to one detector (yellow) and no detector (red). The plot shows only the regions with the detectors installed, that is, the entire upper part is cut-off from this analysis since we already know that the entire upper part is covered by no detector as explained earlier.

From the figure, it is obvious that only the ground level is covered by detectors, this problem is difficult to avoid by using 2D technique. On the other hand, by representing the height dimension, we can easily see where there is zero coverage.

### **7.2.2. CONVENTIONAL VS 3D MAPPING**

A largely held belief but is untrue is that, by installing multiple flame detectors, all fires will be detected. It seems realistic but in fact, it is not always the case, apart from the huge cost of installation and maintenance coupled with the redundancy of some of the detectors, flame detectors may not detect all fire because its field-of-view (FOV) does not cover the area with the fire.

While there is no perfect way of detector positioning that can guarantee 100% safety of a plant, but is always the undisputed start to protecting the plant and there is always a better way of detector layout that will maintain a good coverage of the plant or module at minimal cost. Traditional or conventional way of detector positioning (without mapping technique)

starts by identifying all the risk areas or dangerous areas that fire may occur and then installing detectors there.

The problem with this method is that is based on human judgement and it is very difficult to identify all risk areas and also flame detectors FOV may not cover the area that is thought to cover. That is to say, it is very difficult to carry out an assessment of flame detector placement by eye as there is no way to know the limits of flame detector FOV.

Traditional detector placement is not always a poor design in all cases, for example, in figure 36, if traditional had been used we would have at least installed some detectors in the upper part of the module. Even at that, a good design should start with traditional by identifying all fire zones and installing temporarily detectors there, then using a computer software 3D analysis to evaluate the coverage or visibility of that first detector placements and then re-positioning to achieve optimal layout.

### **7.3. DESIGNING OPTIMAL NUMBER OF DETECTORS (REDUNDANCY AND COST-BENEFIT ANALYSIS)**

Experience have shown that there is always a chance that one or more detectors may be redundant in detector layouts, that is that those detectors do not add any extra safety or protection and can be removed without decreasing the coverage area or the safety. For example, in the designs here, one or more detectors cover some zones while other zones are covered by two or more. In practice, a single detector should be able to detect fire that starts in the area that it is covering, sometimes is not always the case because the detector may develop fault without anyone knowing (although most flame detectors are equipped with self-diagnostic abilities), but the fire can be detected if the area is covered by more than one detectors.

On the other hand, one can argue, why not start installing detectors randomly in all the places that needs to be covered, for example installing at specific distance to each other. It is obvious that the more detectors are installed, the better the coverage or more areas that is covered, but this cannot be done without additional substantial cost to the design. Even at that, there is no guarantee that the platform or module will be 100% covered by following this method especially when is not done with the aid of computer software.

This means that a balance has to be struck between safety and cost, ALARP principal is one which can help in a case like this. ALARP (As Low As Reasonably Practicable) can be used as an acceptance criteria for the number of detectors vs the cost. According to (Vinnem, 2007), the principle implies that all risk reducing measures that are well founded should be implemented unless it may be proved that the cost and/or other negative effects are in gross disproportion to the benefits.

## **7.4. SIMULATION SOFTWARE USED**

The analysis of the flame detector coverage was done using a tool developed by *Knut Erik Giljarhus* in Lloyd's Register Consulting called **FIDO** (Fire Detector Optimization). The tool calculates the 3D visibility field, accounting for geometric obstacles and flame detector properties. The method is based on ray tracing. Several thousand rays are sent from each detector into the module volume and tracked until they hit an object. This gives an accurate visibility field for each detector. When the visibility field for each detector is added together, it becomes possible to identify regions covered by zero detectors, one detector and two or more detectors.

Some tolerance criteria are based on cylinder volumes. Hence, regions with low visibility but with volume below these cylinder volumes should not be considered in the analysis. From the 3D visibility field, these regions are extracted by FIDO using a filtering algorithm.

In FIDO software we are able to model even a compress module, showing the equipment installed and their respective heights, as a result we can see when there are obstructions to the detector visibility because the rays from the detectors hit these structures.

### **7.4.1. Verification of results from FIDO software**

The FIDO software is currently being used by Lloyd's Register Consulting AS for detector layout optimization and verification in different projects. The software has been thoroughly tested and used in many projects with proven results.

## CHAPTER 8.

### 8.1. CONCLUSIONS

The ultimate aim of every safety system installed in the process plant for example flame and gas system is to protect the lives of workers, the plant and the environment, to this end safety systems (flame and gas system, smoke detector system, heat detector system e.t.c) needs to work together to achieve this.

The combination of different gas detector principles and technologies (technology diversification) proves to have more influence in detection and reliability of the GDS since they share few common failures.

This thesis work presents the study done in optimization of flame and gas detector layout or positioning, an optimal placement of the detectors should minimize the number of detectors while still maintaining a very good coverage.

A gas detector optimization carried out by doing several CFD dispersion simulations provides optimal location of detectors. CFD is a tool to quantify and verify the performance of a gas detection system.

Flame detectors have what is called field-of-view (FOV), the FOV determines the coverage area of the flame detector, and fires outside FOV range of a flame detector are not detected. FOV can be obstructed by equipment (large vessels, pipes, tanks e.t.c) thereby reducing the coverage area of the detector, hence the need for good mapping technique to accurately evaluate the FOV of the detector and account for it when optimizing detector layouts.

Currently, the method of evaluating the coverage area of flame detector is by using two-dimensional (2D) mapping technique.

Lloyd's Register Consulting has recently developed a technique for evaluating the visibility field of a flame detector in 3D, taking into account the process module geometry. This software was used to evaluate the visibility field of detectors using two different module A and B, while module A was a simple one, B was more complex real-world onshore module which can represent an offshore module as well.

The results from 2D mapping and 3D mapping were assessed based on two different company criteria for detector layouts. The results shows some fundamental flaws with 2D mapping technique, in particular, 2D mapping results can be inaccurate or misleading, as areas shown to be not visible to flame detector was in fact visible, or even worse areas shown to be visible was not even covered and no detector was even installed there as seen in module B and undetected fires may develop in this regions and of course will be undetected until is too late.

The cost benefit and redundancy analysis provides the optimal number of gas detectors by removing redundant detectors, while this is difficult to achieve in 2D mapping, this process can easily be achieved using 3D analysis.

The conclusion from the study of these two mapping techniques suggest that 2D analysis can lead to hazardous design, on the contrast, 3D analysis not only leads to better design but also saves cost without sacrificing safety.

## **8.2. SUGGESTIONS FOR FUTURE WORK**

Future works should be concentrated on doing more simulations both for gas detectors and for flame detectors. Although the influence of the weather conditions and physical properties of the gas was introduced in this thesis, more studies needs to be done on that and simulations taking into account of these factors during simulation of gas detector optimisation.

The simulation done in this thesis was for flame detectors installed in onshore enclosed module, future work can also include simulations in offshore real-world module where there are lot more equipment installed.

Other areas that might be evaluated in the future include cost-benefit analysis and redundancy analysis as they also play a significant role in the final optimal design.

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APPENDIX A

Table 11: Flammable Gases Data (Honeywell, 2013)

Common Name	CAS Number	Formula	Mol. Wt.	B.P. °C	Rel. Vap. Dens.	F.P. °C	Flammable Limits				L.T. °C
							LFL % v/v	UFL % v/v	LFL mg/L	UFL mg/L	
Acetaldehyde	75-07-0	CH <sub>3</sub> CHO	44.05	20	1.52	-38	4.00	60.00	74	1108	204
Acetic acid	64-19-7	CH <sub>3</sub> COOH	60.05	118	2.07	40	4.00	17.00	100	428	464
Acetic anhydride	108-24-7	(CH <sub>3</sub> CO) <sub>2</sub> O	102.09	140	3.52	49	2.00	10.00	85	428	334
Acetone	67-64-1	(CH <sub>3</sub> ) <sub>2</sub> CO	58.08	56	2.00	<-20	2.50	13.00	80	316	535
Acetonitrile	75-05-8	CH <sub>3</sub> CN	41.05	82	1.42	2	3.00	16.00	51	275	523
Acetyl chloride	75-36-5	CH <sub>3</sub> COCl	78.5	51	2.70	-4	5.00	19.00	157	620	390
Acetylene	74-86-2	CH≡CH	26	-84	0.90		2.30	100.00	24	1092	305
Acetyl fluoride	557-99-3	CH <sub>3</sub> COF	62.04	20	2.14	<-17	5.60	19.90	142	505	434
Acrylaldehyde	107-02-8	CH <sub>2</sub> =CHCHO	56.06	53	1.93	-18	2.85	31.80	65	728	217
Acrylic acid	79-10-7	CH <sub>2</sub> =CHCOOH	72.06	139	2.48	56	2.90		85		406
Acrylonitrile	107-13-1	CH <sub>2</sub> =CHCN	53.1	77	1.83	-5	2.80	28.00	64	620	480
Acryloyl chloride	814-68-6	CH <sub>2</sub> CHCOCl	90.51	72	3.12	-8	2.68	18.00	220	662	463
Allyl acetate	591-87-7	CH <sub>2</sub> =CHCH <sub>2</sub> OOCH <sub>3</sub>	100.12	103	3.45	13	1.70	9.30	69	3 800	348
Allyl alcohol	107-18-6	CH <sub>2</sub> =CHCH <sub>2</sub> OH	58.08	96	2.00	21	2.50	18.00	61	438	378
Allyl chloride	107-05-1	CH <sub>2</sub> =CHCH <sub>2</sub> Cl	76.52	45	2.64	-32	2.90	11.20	92	357	390
Ammonia	7664-41-7	NH <sub>3</sub>	17	-33	0.59		15.00	33.60	107	240	630
Aniline	62-53-3	C <sub>6</sub> H <sub>5</sub> NH <sub>2</sub>	93.1	184	3.22	75	1.20	11.00	47	425	630
Benzaldehyde	100-52-7	C <sub>6</sub> H <sub>5</sub> CHO	106.12	179	3.66	64	1.40		62		192
Benzene	71-43-2	C <sub>6</sub> H <sub>6</sub>	78.1	80	2.70	-11	1.20	8.60	39	280	560
1-Bromobutane	109-65-9	CH <sub>3</sub> (CH <sub>2</sub> ) <sub>3</sub> CH <sub>2</sub> Br	137.02	102	4.72	13	2.50	6.60	143	380	265
Bromoethane	74-96-4	CH <sub>3</sub> CH <sub>2</sub> Br	108.97	38	3.75	<-20	6.70	11.30	306	517	511
Buta-1,3-diene	106-99-0	CH <sub>2</sub> =CHCH=CH <sub>2</sub>	54.09	-4.5	1.87	-76	1.40	16.30	31	365	430
Butane	106-97-8	C <sub>4</sub> H <sub>10</sub>	58.1	-1	2.05		1.40	9.30	33	225	372
Isobutane	75-28-5	(CH <sub>3</sub> ) <sub>2</sub> CHCH <sub>3</sub>	58.12	-12	2.00	gas	1.30	9.80	31	236	460
Butan-1-ol	71-36-3	CH <sub>3</sub> (CH <sub>2</sub> ) <sub>3</sub> CH <sub>2</sub> OH	74.12	116	2.55	29	1.70	12.00	52	372	359
Butanone	78-93-3	CH <sub>3</sub> CH <sub>2</sub> COCH <sub>3</sub>	72.1	80	2.48	-9	1.80	10.00	50	302	404
But-1-ene	106-98-9	CH <sub>2</sub> =CHCH <sub>2</sub> CH <sub>3</sub>	56.11	-6.3	1.95		1.60	10.00	38	235	440
But-2-ene (isomer not stated)	107-01-7	CH <sub>3</sub> CH=CHCH <sub>3</sub>	56.11	1	1.94	gas	1.60	10.00	40	228	325
Butyl acetate	123-86-4	CH <sub>3</sub> COOCH <sub>2</sub> (CH <sub>2</sub> ) <sub>3</sub> CH <sub>3</sub>	116.2	127	4.01	22	1.30	7.50	64	390	370
n-Butyl acrylate	141-32-2	CH <sub>2</sub> =CHCOOCH <sub>2</sub> (CH <sub>2</sub> ) <sub>3</sub> CH <sub>3</sub>	128.17	145	4.41	38	1.20	8.00	63	425	268
Butylamine	109-73-9	CH <sub>3</sub> (CH <sub>2</sub> ) <sub>3</sub> NH <sub>2</sub>	73.14	78	2.52	-12	1.70	9.80	49	286	312
Isobutylamine	78-81-9	(CH <sub>3</sub> ) <sub>2</sub> CHCH <sub>2</sub> NH <sub>2</sub>	73.14	64	2.52	-20	1.47	10.80	44	330	374
Isobutylisobutyrate	97-85-8	(CH <sub>3</sub> ) <sub>2</sub> CHCOOCH <sub>2</sub> CH(CH <sub>3</sub> ) <sub>2</sub>	144.21	145	4.93	34	0.80		47		424
Butylmethacrylate	97-88-1	CH <sub>2</sub> =C(CH <sub>3</sub> )COO(CH <sub>2</sub> ) <sub>3</sub> CH <sub>3</sub>	142.2	160	4.90	53	1.00	6.80	58	395	289
Tert-butyl methyl ether	1634-04-4	CH <sub>3</sub> OC(CH <sub>3</sub> ) <sub>3</sub>	88.15	55	3.03	-27	1.50	8.40	54	310	385
n-Butylpropionate	590-01-2	C <sub>6</sub> H <sub>5</sub> COOCH <sub>2</sub> (CH <sub>2</sub> ) <sub>3</sub> CH <sub>3</sub>	130.18	145	4.48	40	1.10	7.70	58	409	389
Butyraldehyde	123-72-8	CH <sub>3</sub> CH <sub>2</sub> CH <sub>2</sub> CHO	72.1	75	2.48	-16	1.80	12.50	54	378	191
Isobutyraldehyde	78-84-2	(CH <sub>3</sub> ) <sub>2</sub> CHCHO	72.11	63	2.48	-22	1.60	11.00	47	320	176
Carbon disulphide	75-15-0	CS <sub>2</sub>	76.1	46	2.64	-30	0.60	60.00	19	1 900	95
Carbon monoxide	630-08-0	CO	28	-191	0.97		10.90	74.00	126	870	805
Carbonyl sulphide	463-58-1	COS	60.08	-50	2.07		6.50	28.50	180	700	209
Chlorobenzene	108-90-7	C <sub>6</sub> H <sub>5</sub> Cl	112.6	132	3.88	28	1.40	11.00	66	520	637
1-Chlorobutane	109-69-3	CH <sub>3</sub> (CH <sub>2</sub> ) <sub>3</sub> CH <sub>2</sub> Cl	92.57	78	3.20	-12	1.80	10.00	69	386	250
2-Chlorobutane	78-86-4	CH <sub>3</sub> CHClCH <sub>2</sub> CH <sub>3</sub>	92.57	68	3.19	<-18	2.20	8.80	82	339	368
1-Chloro-2,3-epoxypropane	106-89-8	OC <sub>2</sub> H <sub>3</sub> CHClCH <sub>2</sub> Cl	92.52	115	3.30	28	2.30	34.40	86	1 325	385
Chloroethane	75-00-3	CH <sub>3</sub> CH <sub>2</sub> Cl	64.5	12	2.22		3.60	15.40	95	413	510
2-Chloroethanol	107-07-3	CH <sub>2</sub> ClCH <sub>2</sub> OH	80.51	129	2.78	55	5.00	16.00	160	540	425
Chloroethylene	75-01-4	CH <sub>2</sub> =CHCl	62.3	-15	2.15	-78 gas	3.60	33.00	94	610	415
Chloromethane	74-87-3	CH <sub>3</sub> Cl	50.5	-24	1.78	-24 gas	7.60	19.00	160	410	625
1-Chloro-2-methylpropane	513-36-0	(CH <sub>3</sub> ) <sub>2</sub> CHCH <sub>2</sub> Cl	92.57	68	3.19	<-14	2.00	8.60	75	340	416
3-Chloro-2-methylprop-1-ene	563-47-3	CH <sub>2</sub> =C(CH <sub>3</sub> )CH <sub>2</sub> Cl	90.55	71	3.12	-16	2.10		77		478
5-Chloropentan-2-one	5891-21-4	CH <sub>3</sub> CO(CH <sub>2</sub> ) <sub>3</sub> Cl	120.58	71	4.16	61	2.00		98		440
1-Chloropropane	540-54-5	CH <sub>3</sub> CH <sub>2</sub> CH <sub>2</sub> Cl	78.54	37	2.70	-32	2.40	11.10	78	365	520
2-Chloropropane	75-29-6	(CH <sub>3</sub> ) <sub>2</sub> CHCl	78.54	47	2.70	<-20	2.80	10.70	92	350	590
Chlorotrifluoroethyl-ene	79-38-9	CF <sub>2</sub> =CFCl	116.47	-28.4	4.01	gas	4.60	84.30	220	3 117	607
α-Chlorotoluene	100-44-7	C <sub>6</sub> H <sub>4</sub> CH <sub>2</sub> Cl	126.58		4.36	60	1.20		63		585



## Flammable gas data continues

Common Name	CAS Number	Formula	Mol. Wt.	B.P. °C	Rel. Vap. Dens.	F.P. °C	Flammable Limits				I.T. °C
							LFL % v/v	UFL % v/v	LFL mg/L	UFL mg/L	
Cresols (mixed isomers)	1319-77-3	C <sub>8</sub> H <sub>10</sub> O	108.14	191	3.73	81	1.10		50		555
Crotonaldehyde	123-73-9	CH <sub>3</sub> CH=CHCHO	70.09	102	2.41	13	2.10	16.00	82	470	280
Cumene	98-82-8	C <sub>9</sub> H <sub>10</sub>	120.19	152	4.13	31	0.80	6.50	40	328	424
Cyclobutane	287-23-0	C <sub>4</sub> H <sub>6</sub>	56.1	13	1.93		1.80		42		
Cycloheptane	291-64-5	C <sub>7</sub> H <sub>14</sub>	98.19	118.5	3.39	<10	1.10	6.70	44	275	
Cyclohexane	110-82-7	C <sub>6</sub> H <sub>12</sub>	84.2	81	2.90	-18	1.20	8.30	40	290	259
Cyclohexanol	108-93-0	C <sub>6</sub> H <sub>12</sub> O	100.16	161	3.45	61	1.20	11.10	50	460	300
Cyclohexanone	108-94-1	C <sub>6</sub> H <sub>10</sub> O	98.1	156	3.38	43	1.00	9.40	42	386	419
Cyclohexene	110-83-8	C <sub>6</sub> H <sub>10</sub>	82.14	83	2.83	-17	1.20		41		244
Cyclohexylamine	108-91-8	C <sub>6</sub> H <sub>13</sub> N	99.17	134	3.42	32	1.60	9.40	63	372	293
Cyclopentane	287-92-3	C <sub>5</sub> H <sub>10</sub>	70.13	50	2.40	-37	1.40		41		320
Cyclopentene	142-29-0	C <sub>5</sub> H <sub>8</sub>	68.12	44	2.30	<-22	1.48		41		309
Cyclopropane	75-19-4	C <sub>3</sub> H <sub>6</sub>	42.1	-33	1.45		2.40	10.40	42	183	498
Cyclopropyl methyl ketone	765-43-5	C <sub>6</sub> H <sub>10</sub> O	84.12	114	2.90	15	1.70		58		452
p-Dymene	99-87-6	C <sub>8</sub> H <sub>14</sub>	134.22	176	4.62	47	0.70	6.50	39	366	436
Decahydro-naphthalene trans	493-02-7	C <sub>10</sub> H <sub>18</sub>	138.25	185	4.76	54	0.70	4.90	40	284	288
Decane (mixed isomers)	124-18-5	C <sub>10</sub> H <sub>22</sub>	142.28	173	4.90	46	0.70	5.60	41	433	201
Dibutyl ether	142-96-1	(C <sub>4</sub> H <sub>9</sub> ) <sub>2</sub> O	130.2	141	4.48	25	0.90	8.50	48	460	198
Dichlorobenzenes (isomer not stated)	106-46-7	C <sub>6</sub> H <sub>4</sub> Cl <sub>2</sub>	147	179	5.07	86	2.20	9.20	134	564	648
Dichlorodiethyl-silane	1719-53-5	(C <sub>2</sub> H <sub>5</sub> ) <sub>2</sub> SiCl <sub>2</sub>	157.11	128		24	3.40		223		
1,1-Dichloroethane	75-34-3	CH <sub>3</sub> CHCl <sub>2</sub>	99	57	3.42	-10	5.60	16.00	230	660	440
1,2-Dichloroethane	107-06-2	CH <sub>2</sub> ClCH <sub>2</sub> Cl	99	84	3.42	13	6.20	16.00	255	654	438
Dichloroethylene	540-59-0	C <sub>2</sub> H <sub>2</sub> Cl <sub>2</sub>	96.94	37	3.55	-10	9.70	12.80	391	516	440
1,2-Dichloro-propane	78-87-5	CH <sub>2</sub> ClCHClCH <sub>3</sub>	113	96	3.90	15	3.40	14.50	180	682	557
Dicyclopentadiene	77-73-6	C <sub>10</sub> H <sub>12</sub>	132.2	170	4.55	36	0.80		43		455
Diethylamine	109-89-7	(C <sub>2</sub> H <sub>5</sub> ) <sub>2</sub> NH	73.14	55	2.53	-23	1.70	10.00	50	306	312
Diethylcarbonate	105-59-8	(C <sub>2</sub> H <sub>5</sub> ) <sub>2</sub> CO	118.13	126	4.07	24	1.40	11.70	69	570	450
Diethyl ether	60-29-7	(C <sub>2</sub> H <sub>5</sub> ) <sub>2</sub> O	74.1	34	2.55	-45	1.70	36.00	60	1 118	160
1,1-Difluoro-ethylene	75-38-7	CH <sub>2</sub> =CF <sub>2</sub>	64.03	-83	2.21		3.90	25.10	102	665	380
Diisobutylamine	110-98-3	(CH <sub>3</sub> ) <sub>2</sub> CHCH <sub>2</sub> NH <sub>2</sub>	129.24	137	4.45	26	0.80	3.60	42	190	256
Diisobutyl carbinol	108-82-7	(CH <sub>3</sub> ) <sub>2</sub> CHCH <sub>2</sub> CH <sub>2</sub> OH	144.25	178	4.97	75	0.70	6.10	42	370	280
Diisopentyl ether	544-01-4	(CH <sub>3</sub> ) <sub>2</sub> CHCH <sub>2</sub> O(CH <sub>2</sub> ) <sub>2</sub> CH(CH <sub>3</sub> ) <sub>2</sub>	158.28	170	5.45	44	1.27		104		185
Diisopropylamine	108-18-9	(CH <sub>3</sub> ) <sub>2</sub> CHNH <sub>2</sub>	101.19	84	3.48	-20	1.20	8.30	49	260	285
Diisopropyl ether	108-20-3	(CH <sub>3</sub> ) <sub>2</sub> CHO	102.17	69	3.52	-28	1.00	21.00	45	900	405
Dimethylamine	124-40-3	(CH <sub>3</sub> ) <sub>2</sub> NH	45.08	7	1.55	-18 gas	2.80	14.40	53	272	400
Dimethoxymethane	109-87-5	CH <sub>3</sub> OCH <sub>2</sub> OCH <sub>3</sub>	76.09	41	2.60	-21	3.00	16.90	93	535	247
3-(Dimethylamino)propionitrile	1738-25-8	(CH <sub>3</sub> ) <sub>2</sub> NHCH <sub>2</sub> CH <sub>2</sub> CN	98.15	171	3.38	50	1.57		62		317
Dimethyl ether	115-10-6	(CH <sub>3</sub> ) <sub>2</sub> O	46.1	-25	1.59	-42 gas	2.70	32.00	51	610	240
N,N-Dimethylformamide	68-12-2	HCON(CH <sub>3</sub> ) <sub>2</sub>	73.1	152	2.51	58	1.80	16.00	55	500	440
3,4-Dimethyl hexane	583-48-2	CH <sub>3</sub> CH <sub>2</sub> CH(CH <sub>3</sub> )CH(CH <sub>3</sub> )CH <sub>2</sub> CH <sub>3</sub>	114.23	119	3.87	2	0.80	8.50	38	310	305
N,N-Dimethyl hydrazine	57-14-7	(CH <sub>3</sub> ) <sub>2</sub> NNH <sub>2</sub>	60.1	62	2.07	-18	2.40	20	60	490	240
1,4-Dioxane	123-91-1	OCH <sub>2</sub> CH <sub>2</sub> OCH <sub>2</sub> CH <sub>2</sub>	88.1	101	3.03	11	1.90	22.50	74	813	379
1,3-Dioxolane	646-08-0	OCH <sub>2</sub> CH <sub>2</sub> OCH <sub>2</sub>	74.08	74	2.55	-5	2.30	30.50	70	935	245
Dipropylamine	142-84-7	(CH <sub>3</sub> CH <sub>2</sub> ) <sub>2</sub> NH	101.19	105	3.48	4	1.60	9.10	66	376	280
Ethane	74-84-0	C <sub>2</sub> H <sub>6</sub>	30.1	-87	1.04		2.50	15.50	31	194	515
Ethanethiol	75-08-1	CH <sub>3</sub> CH <sub>2</sub> SH	62.1	35	2.11	<-20	2.80	18.00	73	466	295
Ethanol	64-17-5	CH <sub>3</sub> CH <sub>2</sub> OH	46.1	78	1.59	12	3.10	19.00	59	359	363
2-Ethoxyethanol	110-80-5	CH <sub>3</sub> CH <sub>2</sub> OCH <sub>2</sub> CH <sub>2</sub> OH	90.12	135	3.10	40	1.80	15.70	68	593	235
2-Ethoxyethyl acetate	111-15-9	CH <sub>3</sub> COOCH <sub>2</sub> CH <sub>2</sub> OCH <sub>2</sub> CH <sub>3</sub>	132.16	156	4.72	47	1.20	12.70	65	642	380
Ethyl acetate	141-78-6	CH <sub>3</sub> COOCH <sub>2</sub> CH <sub>3</sub>	88.1	77	3.04	-4	2.20	11.00	81	406	460
Ethyl acetoacetate	141-87-9	CH <sub>3</sub> COCH <sub>2</sub> COOCH <sub>2</sub> CH <sub>3</sub>	130.14	181	4.50	65	1.00	9.50	54	519	350
Ethyl acrylate	140-88-5	CH <sub>2</sub> =CHCOOCH <sub>2</sub> CH <sub>3</sub>	100.1	100	3.45	9	1.40	14.00	59	588	350
Ethylamine	75-04-7	C <sub>2</sub> H <sub>5</sub> NH <sub>2</sub>	45.08	16.6	1.50	<-20	2.68	14.00	49	260	425
Ethylbenzene	100-41-4	CH <sub>3</sub> CH <sub>2</sub> C <sub>6</sub> H <sub>5</sub>	106.2	135	3.66	23	1.00	7.80	44	340	431
Ethyl butyrate	105-54-4	CH <sub>3</sub> CH <sub>2</sub> CH <sub>2</sub> COOCH <sub>2</sub> CH <sub>3</sub>	116.16	120	4.00	21	1.40		66		435
Ethylcyclobutane	4806-61-5	CH <sub>3</sub> CH <sub>2</sub> CHCH <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub>	84.16		2.90	<-16	1.20	7.70	42	272	212
Ethylcyclohexane	1678-91-7	CH <sub>3</sub> CH <sub>2</sub> CH(CH <sub>2</sub> ) <sub>4</sub> CH <sub>2</sub>	112.2	131	3.87	<-24	0.90	6.60	42	310	238
Ethylcyclopentane	1640-89-7	CH <sub>3</sub> CH <sub>2</sub> CH(CH <sub>2</sub> ) <sub>3</sub> CH <sub>2</sub>	98.2	103	3.40	<-5	1.05	6.80	42	280	262
Ethylene	74-85-1	CH <sub>2</sub> =CH <sub>2</sub>	28.1	-104	0.97		2.30	36.00	26	423	425

Flammable gas data continues

Common Name	CAS Number	Formula	Mol. Wt.	B.P. °C	Rel. Vap. Dens.	F.P. °C	Flammable Limits			I.T. °C	
							LFL % v/v	UFL % v/v	LFL mg/L		UFL mg/L
Ethylenediamine	107-15-3	<chem>NH2CH2CH2NH2</chem>	60.1	118	2.07	34	2.70	16.50	64	396	403
Ethylene oxide	75-21-8	<chem>C2H4O</chem>	44	11	1.52	<-18	2.60	100.00	47	1 848	435
Ethyl formate	109-94-4	<chem>HCOOCH2CH3</chem>	74.08	52	2.65	-20	2.70	16.50	87	497	440
Ethyl isobutyrate	97-62-1	<chem>(CH3)2CHCOOCH2CH3</chem>	116.16	112	4.00	10	1.60		75		438
Ethyl methacrylate	97-63-2	<chem>CH2=C(CH3)COOCH2CH3</chem>	114.14	118	3.90	(20)	1.50		70		
Ethyl methyl ether	540-67-0	<chem>CH3OCH2CH3</chem>	60.1	8	2.10		2.00	10.10	50	255	190
Ethyl nitrite	109-95-5	<chem>CH3CH2ONO</chem>	75.07		2.60	-35	3.00	50.00	94	1 555	95
Formaldehyde	50-00-0	<chem>HCHO</chem>	30	-19	1.03		7.00	73.00	88	920	424
Formic acid	64-18-6	<chem>HCOOH</chem>	46.03	101	1.60	42	10.00	57.00	190	1 049	520
2-Furaldehyde	98-01-1	<chem>OCH=CHCH=CHCHO</chem>	96.08	162	3.30	60	2.10	19.30	85	768	316
Furan	110-00-9	<chem>C4H4O</chem>	68.07	32	2.30	<-20	2.30	14.30	66	408	390
Furfuryl alcohol	98-00-0	<chem>OC(CH2OH)CHCH2OH</chem>	98.1	170	3.38	61	1.80	16.30	70	670	370
1,2,3-Trimethylbenzene	526-73-8	<chem>Cc1c(C)c(C)c(C)c1</chem>	120.19	175	4.15	51	0.80	7.00			470
Heptane (mixed isomers)	142-82-5	<chem>C7H16</chem>	100.2	98	3.46	-4	1.10	6.70	46	281	215
Hexane (mixed isomers)	110-54-3	<chem>C6H14</chem>	86.2	69	2.97	-21	1.00	8.40	35	290	233
1-Hexanol	111-27-3	<chem>C6H13OH</chem>	102.17	156	3.50	63	1.20		51		293
Hexan-2-one	591-78-6	<chem>CH3CO(CH2)4CH3</chem>	100.16	127	3.46	23	1.20	8.00	50	336	533
Hydrogen	1333-74-0	<chem>H2</chem>	2	-253	0.07		4.00	77.00	3.4	63	560
Hydrogen cyanide	74-90-8	<chem>HCN</chem>	27	26	0.90	<-20	5.40	46.00	60	520	538
Hydrogen sulfide	7783-06-4	<chem>H2S</chem>	34.1	-60	1.19		4.00	45.50	57	650	270
4-Hydroxy-4-methyl-penta-2-one	123-42-2	<chem>CH3COCH2C(CH3)2OH</chem>	116.16	166	4.00	58	1.80	6.90	88	336	680
Kerosene	8008-20-6			150			38	5.00			210
1,3,5-Trimethylbenzene	108-67-8	<chem>Cc1c(C)cc(C)c1C</chem>	120.19	163	4.15	44	0.80	7.30	40	365	499
Methacryloyl chloride	920-46-7	<chem>CH2=C(CH3)COCl</chem>	104.53	95	3.60	17	2.50		108		510
Methane (firedamp)	74-82-8	<chem>CH4</chem>	16	-161	0.55		4.40	17.00	29	113	537
Methanol	67-56-1	<chem>CH3OH</chem>	32	65	1.11	11	5.50	38.00	73	484	386
Methanethiol	74-93-1	<chem>CH3SH</chem>	48.11	6	1.60		4.10	21.00	60	420	340
2-Methoxyethanol	109-86-4	<chem>CH3OCH2CH2OH</chem>	76.1	124	2.63	39	2.40	20.60	76	650	285
Methyl acetate	79-20-9	<chem>CH3COOCH3</chem>	74.1	57	2.56	-10	3.20	16.00	99	475	502
Methyl acetoacetate	105-45-3	<chem>CH3COOCH2COCH3</chem>	116.12	169	4.00	62	1.30	14.20	62	685	280
Methyl acrylate	96-33-3	<chem>CH2=CHCOOCH3</chem>	86.1	80	3.00	-3	2.40	25.00	85	903	415
Methylamine	74-89-5	<chem>CH3NH2</chem>	31.1	-6	1.00	-18 gas	4.20	20.70	55	270	430
2-Methylbutane	78-78-4	<chem>(CH3)2CHCH2CH3</chem>	72.15	30	2.50	<-51	1.30	8.00	38	242	420
2-Methylbutan-2-ol	75-85-4	<chem>CH3C(CH3)2CH2OH</chem>	88.15	102	3.03	16	1.40	10.20	50	374	392
3-Methylbutan-1-ol	123-51-3	<chem>(CH3)2CHCH2CH2OH</chem>	88.15	130	3.03	42	1.30	10.50	47	385	339
2-Methylbut-2-ene	513-35-9	<chem>(CH3)2C=CHCH3</chem>	70.13	35	2.40	-53	1.30	6.60	37	189	290
Methyl chloro-formate	79-22-1	<chem>CH3OCCl</chem>	94.5	70	3.30	10	7.50	26	293	1 020	475
Methylcyclohexane	108-87-2	<chem>C6H12</chem>	98.2	101	3.38	-4	1.16	6.70	47	275	258
Methylcyclopentadienes (isomer not stated)	26519-91-5	<chem>C6H8</chem>	80.13		2.76	<-18	1.30	7.60	43	249	432
Methylcyclopentane	96-37-7	<chem>C6H12</chem>	84.16	72	2.90	<-10	1.00	8.40	35	296	258
Methylenecyclo-butane	1120-56-5	<chem>C=C(CH2)2CH2</chem>	68.12		2.35	<0	1.25	8.60	35	239	352
2-Methyl-1-buten-3-yne	78-80-8	<chem>HC#CC(CH3)CH2</chem>	66.1	32	2.28	-54	1.40		38		272
Methyl formate	107-31-3	<chem>HCOOCH3</chem>	60.05	32	2.07	-20	5.00	23.00	125	580	450
2-Methylfuran	534-22-5	<chem>OC(CH3)CHCH2</chem>	82.1	63	2.83	<-16	1.40	9.70	47	325	318
Methylisocyanate	624-83-9	<chem>CH3NCO</chem>	57.05	37	1.98	-7	5.30	26.00	123	605	517
Methyl methacrylate	80-62-6	<chem>CH2=C(CH3)COOCH3</chem>	100.12	100	3.45	10	1.70	12.50	71	520	430
4-Methylpentan-2-ol	108-11-2	<chem>(CH3)2CHCH2CH(OH)CH3</chem>	102.17	132	3.50	37	1.14	5.50	47	235	334
4-Methylpentan-2-one	108-10-1	<chem>(CH3)2CHCH2COCH3</chem>	100.16	117	3.45	16	1.20	8.00	50	336	475
2-Methylpent-2-enal	623-36-9	<chem>CH3CH=C(CH3)CHO</chem>	98.14	137	3.78	30	1.46		58		206
4-Methylpent-3-en-2-one	141-79-7	<chem>(CH3)2C=CHCOCH3</chem>	98.14	129	3.78	24	1.60	7.20	64	289	306
2-Methylpropan-1-ol	78-83-1	<chem>(CH3)2CHCH2OH</chem>	74.12	108	2.55	28	1.70	9.80	52	305	408
2-Methylprop-1-ene	115-11-7	<chem>(CH3)2C=CH2</chem>	56.11	-6.9	1.93	gas	1.60	10	37	235	483
2-Methylpyridine	109-06-8	<chem>Nc1cc(C)ccn1</chem>	93.13	128	3.21	27	1.20		45		533
3-Methylpyridine	108-99-6	<chem>Nc1cc(C)ccn1</chem>	93.13	144	3.21	43	1.40	8.10	53	308	537
4-Methylpyridine	108-89-4	<chem>Nc1cc(C)ccn1</chem>	93.13	145	3.21	43	1.10	7.80	42	296	534
α-Methyl styrene	98-83-9	<chem>C6H5C(CH3)=CH2</chem>	118.18	165	4.08	40	0.90	6.60	44	330	445
Methyl tert-pentyl ether	994-05-8	<chem>(CH3)3C(CH2)2OCH3</chem>	102.17	85	3.50	<-14	1.50		62		345
2-Methylthiophene	554-14-3	<chem>SC(CH3)CHCH2</chem>	98.17	113	3.40	-1	1.30	6.50	52	261	433
Morpholine	110-91-8	<chem>OC1CCNCC1</chem>	87.12	129	3.00	31	1.80	15.20	65	550	230

## Flammable gas data continues

Common Name	CAS Number	Formula	Mol. Wt.	B.P. °C	Rel. Vap. Dens.	F.P. °C	Flammable Limits			I.T. °C
							LFL % v/v	UFL % v/v	LFL mg/L	
Naphtha				35	2.50	<-18	0.90	6.00		290
Naphthalene	91-20-3	C <sub>10</sub> H <sub>8</sub>	128.17	218	4.42	77	0.90	5.90	48	528
Nitrobenzene	98-95-3	C <sub>6</sub> H <sub>5</sub> NO <sub>2</sub>	123.1	211	4.25	88	1.70	40.00	87	2 067
Nitroethane	79-24-3	C <sub>2</sub> H <sub>5</sub> NO <sub>2</sub>	75.07	114	2.58	27	3.40		107	410
Nitromethane	75-52-5	CH <sub>3</sub> NO <sub>2</sub>	61.04	102.2	2.11	36	7.30	63.00	187	1 613
1-Nitropropane	108-03-2	CH <sub>3</sub> CH <sub>2</sub> CH <sub>2</sub> NO <sub>2</sub>	89.09	131	3.10	36	2.20		82	420
Nonane	111-84-2	CH <sub>3</sub> (CH <sub>2</sub> ) <sub>7</sub> CH <sub>3</sub>	128.3	151	4.43	30	0.70	5.60	37	301
Octane	111-85-9	CH <sub>3</sub> (CH <sub>2</sub> ) <sub>6</sub> CH <sub>3</sub>	114.2	126	3.93	13	0.80	6.50	38	311
1-Octanol	111-87-5	CH <sub>3</sub> (CH <sub>2</sub> ) <sub>6</sub> CH <sub>2</sub> OH	130.23	196	4.50	81	0.90	7.40	49	385
Penta-1,3-diene	504-60-9	CH <sub>2</sub> =CH-CH=CH-CH <sub>3</sub>	68.12	42	2.34	<-31	1.20	9.40	35	261
Pentanes (mixed isomers)	109-66-0	C <sub>5</sub> H <sub>12</sub>	72.2	36	2.48	-40	1.40	7.80	42	236
Pentane-2,4-dione	123-54-6	CH <sub>3</sub> COCH <sub>2</sub> COCH <sub>3</sub>	100.1	140	3.50	34	1.70		71	340
Pentan-1-ol	71-41-0	CH <sub>3</sub> (CH <sub>2</sub> ) <sub>4</sub> CH <sub>2</sub> OH	88.15	136	3.03	38	1.06	10.50	38	385
Pentan-3-one	96-22-0	(CH <sub>3</sub> ) <sub>2</sub> CHCO	86.13	101.5	3.00	12	1.60		58	445
Pentyl acetate	628-63-7	CH <sub>3</sub> COO-(CH <sub>2</sub> ) <sub>4</sub> -CH <sub>3</sub>	130.18	147	4.48	25	1.00	7.10	55	387
Petroleum					2.80	<-20	1.20	8.00		580
Phenol	108-95-2	C <sub>6</sub> H <sub>5</sub> OH	94.11	182	3.24	75	1.30	9.50	50	370
Propane	74-98-6	CH <sub>3</sub> CH <sub>2</sub> CH <sub>3</sub>	44.1	-42	1.56	-104 gas	1.70	10.90	31	200
Propan-1-ol	71-23-8	CH <sub>3</sub> CH <sub>2</sub> CH <sub>2</sub> OH	60.1	97	2.07	22	2.20	17.50	55	353
Propan-2-ol	67-63-0	(CH <sub>3</sub> ) <sub>2</sub> CHOH	60.1	83	2.07	12	2.00	12.70	50	320
Propene	115-07-1	CH <sub>2</sub> =CHCH <sub>3</sub>	42.1	-48	1.50		2.00	11.00	35	194
Propionic acid	79-09-4	CH <sub>3</sub> CH <sub>2</sub> COOH	74.08	141	2.55	52	2.10	12.00	64	370
Propionic aldehyde	123-38-6	C <sub>3</sub> H <sub>6</sub> O	58.08	46	2.00	<-26	2.00		47	188
Propyl acetate	109-60-4	CH <sub>3</sub> COOCH <sub>2</sub> CH <sub>2</sub> CH <sub>3</sub>	102.13	102	3.60	10	1.70	8.00	70	343
Isopropyl acetate	108-21-4	CH <sub>3</sub> COOCH(CH <sub>3</sub> ) <sub>2</sub>	102.13	85	3.51	4	1.80	8.10	75	340
Propylamine	107-10-8	CH <sub>3</sub> (CH <sub>2</sub> ) <sub>2</sub> NH <sub>2</sub>	59.11	48	2.04	-37	2.00	10.40	49	258
Isopropylamine	75-31-0	(CH <sub>3</sub> ) <sub>2</sub> CHNH <sub>2</sub>	59.11	33	2.03	<-24	2.30	8.60	55	208
Isopropylchloro-acetate	105-48-6	ClCH <sub>2</sub> COOCH(CH <sub>3</sub> ) <sub>2</sub>	136.58	149	4.71	42	1.60		89	426
2-Isopropyl-5-methylhex-2-enal	35158-25-9	(CH <sub>3</sub> ) <sub>2</sub> CH-C(CH <sub>3</sub> )(CHO)CH <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> CH <sub>3</sub>	154.25	189	5.31	41	3.05		192	188
Isopropyl nitrate	1712-64-7	(CH <sub>3</sub> ) <sub>2</sub> CHONO <sub>2</sub>	105.09	101		11	2.00	100.00	75	3 738
Propyne	74-99-7	CH <sub>3</sub> C≡CH	40.06	-23.2	1.38		1.70	16.80	28	280
Prop-2-yn-1-ol	107-19-7	HC≡CCH <sub>2</sub> OH	56.08	114	1.89	33	2.40		55	346
Pyridine	110-86-1	C <sub>5</sub> H <sub>5</sub> N	79.1	115	2.73	17	1.70	12.00	58	398
Styrene	100-42-5	C <sub>6</sub> H <sub>5</sub> CH=CH <sub>2</sub>	104.2	145	3.60	30	1.10	8.00	48	350
Tetrafluoroethylene	116-14-3	CF <sub>2</sub> =CF <sub>2</sub>	100.02		3.40		10.00	58.00	420	2 245
2,2,3,3-Tetrafluoro-propylacrylate	7383-71-3	CH <sub>2</sub> =CHCOOCH <sub>2</sub> CF <sub>2</sub> CF <sub>2</sub> H	186.1	132	6.41	45	2.40		182	357
2,2,3,3-tetrafluoro-propyl methacrylate	45102-52-1	CH <sub>2</sub> =C(CH <sub>3</sub> )COOCH <sub>2</sub> CF <sub>2</sub> CF <sub>2</sub> H	200.13	124	6.90	46	1.90		155	389
Tetrahydrofuran	109-99-9	CH <sub>2</sub> (CH <sub>2</sub> ) <sub>2</sub> CH <sub>2</sub> O	72.1	64	2.49	-20	1.50	12.40	46	370
Tetrahydrofurfuryl alcohol	97-99-4	OCH <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> CHOH	102.13	178	3.52	70	1.50	9.70	64	416
Tetrahydro-thiophene	110-01-0	CH <sub>2</sub> (CH <sub>2</sub> ) <sub>2</sub> CH <sub>2</sub> S	88.17	119	3.04	13	1.10	12.30	42	450
N,N,N',N'-Tetra-methylmethane-diamine	51-80-9	(CH <sub>3</sub> ) <sub>2</sub> NCH <sub>2</sub> N(CH <sub>3</sub> ) <sub>2</sub>	102.18	85	3.50	<-13	1.61		67	180
Thiophene	110-02-1	CH=CHCH=CHS	84.14	84	2.90	-9	1.50	12.50	50	420
Toluene	108-88-3	C <sub>6</sub> H <sub>5</sub> CH <sub>3</sub>	92.1	111	3.20	4	1.10	7.60	42	300
Triethylamine	121-44-8	(CH <sub>3</sub> ) <sub>3</sub> CN	101.2	89	3.50	-7	1.20	8.00	51	339
1,1,1-Trifluoro-ethane	420-46-2	CF <sub>3</sub> CH <sub>3</sub>	84.04		2.90		6.80	17.60	234	605
2,2,2-Trifluoro-ethanol	75-89-8	CF <sub>3</sub> CH <sub>2</sub> OH	100.04	77	3.45	30	8.40	28.80	350	1 195
Trifluoroethylene	359-11-5	CF <sub>2</sub> =CFH	82.02		2.83		15.30	27.00	502	904
3,3,3-Trifluoro-prop-1-ene	677-21-4	CF <sub>3</sub> CH=CH <sub>2</sub>	96.05	-16	3.31		4.70		184	490
Trimethylamine	75-50-3	(CH <sub>3</sub> ) <sub>3</sub> N	59.1	3	2.04		2.00	12.00	50	297
2,2,4-Trimethyl-pentane	540-84-1	(CH <sub>3</sub> ) <sub>2</sub> CCH <sub>2</sub> C(CH <sub>3</sub> ) <sub>3</sub>	114.23	98	3.90	-12	1.00	6.00	47	284
2,4,6-Trimethyl-1,3,5-trioxane	123-63-7	OCH(CH <sub>3</sub> )OCH(CH <sub>3</sub> )OCH(CH <sub>3</sub> )	132.16	123	4.56	27	1.30		72	235
1,3,5-Trioxane	110-88-3	OCH <sub>2</sub> COH <sub>2</sub> COH <sub>2</sub>	90.1	115	3.11	45	3.20	29.00	121	1 096
Turpentine		-C <sub>10</sub> H <sub>16</sub>		149		35	0.80			254
isovaleraldehyde	580-88-3	(CH <sub>3</sub> ) <sub>2</sub> CHCH <sub>2</sub> CHO	86.13	90	2.97	-12	1.70		60	207
Vinyl acetate	108-05-4	CH <sub>3</sub> COOCH=CH <sub>2</sub>	86.09	72	3.00	-8	2.60	13.40	93	478
Vinyl cyclohexenes (isomer not stated)	100-40-3	CH <sub>2</sub> CHC <sub>6</sub> H <sub>9</sub>	108.18	126	3.72	15	0.80		35	257
Vinylidene chloride	75-35-4	CH <sub>2</sub> =CCl <sub>2</sub>	96.94	30	3.40	-18	7.30	16.00	294	645
2-Vinylpyridine	100-69-6	NC(CH <sub>2</sub> =CH)CHCHCH <sub>3</sub>	105.14	79	3.62	35	1.20		51	482
4-Vinylpyridine	100-43-6	NC(CH <sub>2</sub> =CH)CH=CH <sub>2</sub>	105.14	62	3.62	43	1.10		47	501
Xylenes	1330-20-7	C <sub>6</sub> H <sub>4</sub> (CH <sub>3</sub> ) <sub>2</sub>	106.2	144	3.66	30	1.00	7.60	44	335