University of Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/Specialization: Offshore technology – Industrial Assets Management	Spring semester, 2011 open
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Title of thesis: Positioning of gas detectors at offshore installations	
Credits (ECTS): 30	
Key words: Gas detection, principles and technologies Gas dispersion FLACS Detection time	Pages: 64 + enclosure: 10 Stavanger, 14.06.2011

Abstract

The safety level at offshore installations is considerably influenced by in which degree undesired gas releases are detected. The primary functions of a gas detection system are to detect the presence of gas and inform other safety functions and systems if gas is presented.

Gas detectors are essential components in the gas detection system and their position are important in order for the gas detection system to ensure quick and reliable detection of released gas. The gas detector positions affect the functionality of the gas detection system, meaning the ability to detect released gas and initiate control actions in form of other safety functions and systems. In addition the gas detector positions affect the reliability of the gas detection system, which is the ability of the system to perform its intended functions under different conditions over time.

This thesis studies different factors which must be considered when selecting the best suited positions for gas detectors at offshore installations where production of oil and gas takes place and evaluate their degree of impact on the functionality and reliability of the gas detection system. The different factors' influence on the risk level related to undesired gas releases are discussed as well.

In addition to a literature review gas dispersion simulations have been carried out using FLACS in order to study how different physical factors such as wind speed, wind direction, leak source, leak direction, leak rate, gas composition and the geometry of a given module influence the behaviour of released gas, which again determine the best suited positions of the gas detectors.

Since fast detection of escaped gas is one of the main requirements with respect to the gas detection system the detection time must be regarded as a critical factor with respect to functionality and reliability of the system. Low detection time allows the initiation of control actions at an early stage and increases the probability of preventing the formation of flammable fuel-air clouds. The ignition probability, the effect of preventive and consequence reducing barriers and the risk related to a leak are highly affected by the detection time.

The combination of different gas detector principles and technologies seems to have a considerable influence with respect to functionality and reliability of a gas detection system since detection methods share few common failures.

Results from the gas dispersion simulations carried out using FLACS indicate a slightly reduction in detection time with an increasing number of monitor points. Plots from simulations carried out in FLACS indicated how the behaviour of escaped gas is influenced by variation in different physical parameters. An inadequate number of simulations were carried out with respect to point out governing parameters in general, but the influence of some parameters was more evident than others. The wind vector seems to have the most evident influence on the escaped gas in the simulations. Especially areas with intermediate and low gas concentrations were influenced by the wind vector.

In connection with future studies a considerably higher number of simulations should be carried out with more variation in parameters in order to study the degree of influence different physical factors have with respect to escaped gas in more detail.

Acknowledgements

This thesis concludes my Master of Science degree in Offshore technology at the University of Stavanger.

I would like to thank Professor Jayantha Prasanna Liyanage and Ørjan Stien for good guidance and comments during the work with this thesis.

I would also like to thank Jerome Renoult for providing basic training in FLACS.

Finally a special thank to my dear Samantha for being very patient and supporting during the work with this thesis.

Julian André Båfjord

June 2011

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1 Introduction

1.1 Background

Along with the production of oil and gas comes the risk of undesired releases of combustible and toxic gases. Undesired gas releases can lead to disastrous consequences involving great damage on personnel, structures and environment. The released gas can be ignited immediately and cause a fire or form a combustible fuel-air cloud that can be exposed to delayed ignition and cause a gas explosion.

The safety level at offshore installations is considerably influenced by in which degree undesired gas releases are detected. The primary functions of a gas detection system are to detect the presence of gas and inform other functions and systems if gas is presented. Confirmed gas detection will activate several safety functions and safety systems, control actions. An undesired gas release represents a risk for an offshore installation and with respect to risk reduction during a gas leak, the most important safety systems are the ISC (Ignition Source Control) and the ESD (Emergency Shutdown System).

Gas detection in the early phases of a gas leak will reduce the risk made by a gas leak because initiated safety functions and systems will reduce the ignition probability and limit the consequences in case of an explosion. If the gas detection system is unable to detect an undesired gas release, no safety system actions will be initiated, and the gas release will continue without being exposed to any mitigating functions.

The gas detection system along with fire detection and alarm systems are the focus of particular attention during the conceptual design, and rank among the design aspects that contribute the most to the safety of an installation (Benmebarek and Hanlon, 2006).

1.2 Study Objective

Gas detectors are essential components in the gas detection system and their position are important in order for the gas detection system to ensure quick and reliable detection of escaped gas. Incorrectly positioned gas detectors need more time to detect a gas and in worst case the gas will not be detected at all.

The gas detector positions affect the functionality of the gas detection system, meaning the ability to detect released gas and initiate control actions in form of other safety functions and systems. In addition the gas detector positions affect the reliability of the gas detection system, which is the ability of the system to perform its intended functions under different conditions over time.

The fire and gas detection systems in many of the existing facilities have according to (Ashraf Shabaka, 2006) traditionally been designed in a conventional method without software modelled design and therefore their performance is questionable. Gas detector positions which are based on conventional methods where detectors are distributed randomly will have disregarded several factors which must be considered in order to achieve the intended functionality and reliability of the gas detection system. By using programs involving CFD (Computational Fluid Dynamics) one can better assess factors such as wind speed, wind direction, leak sources, leak direction, leak rate, ignition sources and the interaction between gas flow and the geometrical layout of a module. Hence, finding the best suited positions for gas detectors to ensure a high level of functionality and reliability with respect to the gas detection system.

Many factors must be considered when selecting the best suited positions for gas detectors at offshore installations where production of oil and gas takes place:

- Characteristics of released gas
- Gas detection principles and technology
- Regulations set by the authorities and the standards which they refer to
- Role and functional requirements of the gas detection system
- Physical factors such as wind speed, wind direction, leak sources, leak direction, leak rate, gas composition, ignition sources and the geometry of a module

These factors will be described and their degree of impact on the reliability and functionality of a gas detection system will be evaluated. A factor that has a significant impact on the reliability and functionality of a gas detection system will also affect the risk related to undesired gas releases. In which degree the risk level related to undesired gas releases are influenced by different factors will be discussed.

1.3 Methods

A literature review regarding the different factors to be considered with respect to gas detector position will be performed and relevant information will be gathered.

In addition CFD simulations of gas dispersions will be performed using FLACS in order to illustrate how physical factors such as wind speed, wind direction, leak source, leak direction, leak rate, gas composition and the geometry of a given module influence the behaviour of released gas, which again determine the best suited positions of the gas detectors. CFD simulations can be used to optimize gas detector positions and hence increase both reliability and functionality of the gas detection system.

1.4 Limitation

This thesis will concentrate on offshore installations located in the Norwegian sector where the Norwegian Petroleum Safety Authority (PSA) makes the prevailing regulations. Combustible gas detection will be prioritized, but toxic and asphyxiating gases will get briefly introduced.

1.5 Structure of the thesis

This master thesis is divided into 8 chapters. Chapter 1 is the introduction of this thesis which covers the background, the study objective, methods, limitations and the structure of the thesis. Chapter 2 covers the theoretical background for this thesis beginning with relevant abbreviations, definitions and terms relevant with respect to gas detection. Then follow characteristics of combustible, toxic and asphyxia gases. After that different gas detection principles and technologies will be introduced ending with an introduction to role and requirements regarding the gas detection system. Chapter 3 introduces several physical factors to be considered with respect to gas detector positioning. In chapter 4 one will be given an introduction to a CFD tool called FLACS, which will be applied for dispersion simulations. Chapter 5 presents a description of characteristic regarding the dispersion simulations to be performed. In chapter 6 the results from the dispersion simulations will be presented. Chapter 7 provides a discussion of the results found in this thesis and a conclusion is finally presented in chapter 8.

2 Theory

This chapter will cover the theoretical background for this thesis beginning with relevant abbreviations, definitions and terms relevant with respect to gas detection followed by an introduction to groups of gases which can represent a hazard along with their characteristics. It will be emphasized on flammable gases. After that the reader will gain an insight into different gas detection principles and technologies. Finally roles and requirements with respect to a gas detection system will be presented.

2.1 Abbreviations

ESD: Emergency shutdown (NORSOK S-001, 2008).

FES: Fire and explosion strategy. Results of the process that uses information from the fire and explosion evaluation to determine the measures required to manage these hazardous events and the role of these measures (ISO 13702, 1999).

ISC: Ignition source control (NORSOK S-001, 2008).

PA: Public address (NORSOK S-001, 2008).

BD: Blow down (NORSOK S-001, 2008).

FW: Fire water (NORSOK S-001, 2008).

2.2 Basic definitions and terms

Alarm Set Point: The selected gas concentration level at which an alarm is activated (MSA, 2007).

Asphyxiant: A substance that impairs normal breathing by displacing oxygen (MSA, 2007).

Oxygen deficient atmosphere: An atmosphere containing less than 19,5% oxygen by volume (MSA, 2007).

Stoichiometric concentration (Cst): Defines the optimum molar concentration of combustible for complete reaction with the particular oxidant (Joseph M. Kuchta, 1985).

Flammability limits: A premixed fuel-air mixture will only burn as long as the fuel concentration is between the upper and lower flammability limits, i.e. UFL and LFL. The flammable range varies between different gases. For methane in air UFL=15% and LFL=5%. For propane in air UFL=9,5% and LFL=2,1%. These values are for fuel-air mixtures at 1 atm. and 25°C (Joseph M. Kuchta, 1985).

Combustion: The burning of gas, liquid, or solid in which fuel is oxidised involves heat release and often light emission. Combustion of gaseous fuel in air can occur in two different modes. One is the fire, where fuel and oxygen is mixed during the combustion process. In the other case the fuel and air is premixed and the fuel must be within the flammability limits (Dag Bjerketvedt et. al, 1993).

Combustion of methane (CH4) in air can be described by the simplified chemical equation:

$CH_4 + 2(O_2 + 3{,}76N_2) \rightarrow CO_2 + 2H_2O + 2(3{,}76N_2) + \text{Energy}$

Combustible material: A combustible material is a solid, liquid, or gas that may undergo the chemical reaction combustion (Det-tronics, 2011).

Explosion: An event leading to a rapid increase of pressure. This pressure increase can be caused of combustion of gas in air (Bjerketvedt et. al, 1993).

Explosion limits: Has the same meaning as the flammable limits. LEL=LFL and UEL=UFL (Bjerketvedt et. al, 1993).

Explosive range: The region between the LFL and UFL. As for LFL and UFL it varies with the particular gas or vapour (Det-tronics, 2011).

Vapour density: This is the relative density of the vapour/gas as compared with air (MSA, 2007).

Hazardous area: A three-dimensional space in which a flammable atmosphere may be expected to be present at such frequencies as to require special precautions for the control of potential ignition sources (NORSOK S-001, 2008).

Dimensioning accidental load: The most severe accidental load that the function or system shall be able to withstand during a required period of time, in order to meet the defined risk acceptance criteria (NORSOK S-001, 2008).

Area classification: Division of an installation into hazardous areas and non-hazardous areas and the sub-division of hazardous zones (NORSOK S-001, 2008).

Fire area: Area separated from other areas either by physical barriers (fire/blast partition) or distance which will prevent dimensioning fire to spread (NORSOK S-001, 2008).

Non-hazardous area: An area in which an explosive gas atmosphere is not expected to be present in quantities such as to require special precautions for the construction, installation and use of electrical apparatus and equipment in normal operation (NORSOK S-001, 2008).

Toxic substance: A chemical compound that can cause a wide range of damage to humans, ranging from minor irritations to the most extreme situation leading to death. Toxic chemicals may be ingested, inhaled or absorbed through the skin (Det-tronics, 2011).

2.3 Gas hazards and characteristics

Gases which can represent a hazard are divided into three groups; flammable gases, toxic gases and asphyxiating gases (Honeywell, 2007). The reader must be aware of that the terms flammable and combustible will be interchangeable for the purpose of this thesis. Chapters 2.3.1, 2.3.2 and 2.3.3 will give an introduction to the different gases which can represent a hazard.

2.3.1 Flammable gases

A flammable gas has the ability to undergo the chemical reaction combustion as explained in chapter 2.2. In order to cause a combustion three factors must be present; a source of ignition, oxygen and fuel in the form of a gas (Honeywell, 2007). In the fire triangle in figure 1 one can see how the three factors depend on each other. The absence of one factor will prevent combustion.

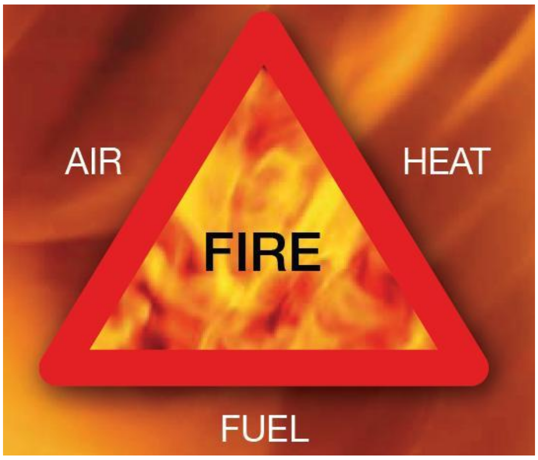

Figure 1,The fire triangle (Honeywell, 2007)

In addition to the three factors mentioned above the concentration of a gas must be within its flammable range. As one can see from figure 2 below the flammable range lays between UFL (UEL) and LFL (LEL) of a given gas. From now on only UFL and LFL will be used as designations to avoid confusion.

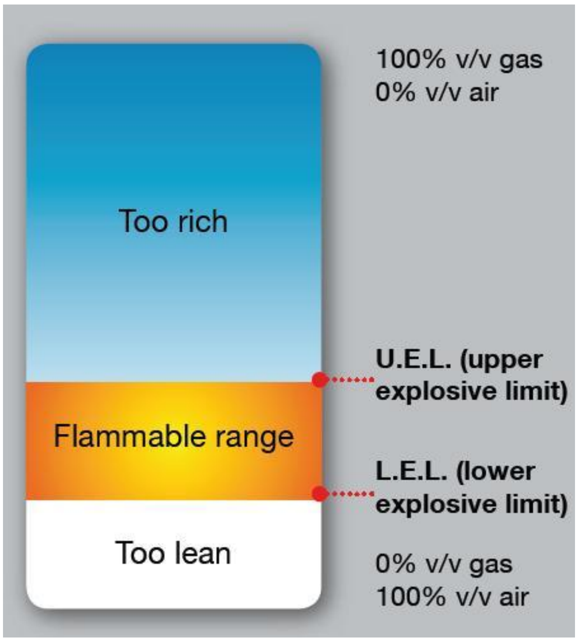

Figure 2, Flammable range (Honeywell, 2007)

In the area above UFL there is too much gas compared to air and under LFL the amount of gas is to less. At offshore installations where production of oil and gas takes place there are many potential sources with respect to leaks of flammable gases. Potential leak sources are discussed in chapter 2.5.7. In case of an undesired gas release the escaped gas can be ignited immediately and cause a fire or form a combustible fuel-air cloud that can be exposed to delayed ignition and cause an explosion. Since a flammable gas must be within its flammable range in order to cause a fire or an explosion one wants to prevent escaped flammable gases from reaching their flammable range due to potential hazard towards personnel, structures and environment.

In order to prevent flammable gases from reaching their flammable range one should first of all get an overview of the flammability limits of gases which one expects to occur at an offshore installation.

Flammable gases	Formula	Mol wt	LFL	UFL
Methane	CH_4	16,04	5 %	15 %
Ethane	C_2H_6	30,07	3 %	12,4 %
Propane	C_3H_8	44,11	2,1 %	9,5 %
Hydrogen Sulphide	H_2S	34,08	4,4 %	44 %

Table 1, Flammable gases (Joseph M. Kuchta, 1985)

Table 1 shows some selected flammable gases with their formula, molecular weight and flammability limits. Regarding methane, ethane and propane one can see that the flammable range reduces with increased molecular weight. Hydrogen sulphide sets apart from this trend by having the greatest flammable range while being second heaviest.

The composition of hydrocarbons in a well stream from a reservoir will vary depending on different factors. Size of the volume fractions of the different components will vary between different reservoirs and depend on the production stage of a given reservoir.
Since the main fraction of a gas leak will consist of hydrocarbons, the hydrocarbons will represent most of the risk related to hazardous events such as fire and explosion.

LFL is used as unit of measurement in order to detect the presence of flammable gases because one wants to detect a gas before it reaches a flammable mixture with air. By using LFL as a unit of measure, alarm limits may be stated as a percentage or fraction of LFL. Alarm limits for combustible and toxic gases will be discussed in chapter 2.6.3. Principles and technologies with respect to detection of flammable gases will be introduced in chapter 2.4 and 2.5.

2.3.2 Toxic gases

According to (Det-tronics, 2011) a toxic gas has the ability to cause a wide range of damage to humans, ranging from minor irritations to the most extreme situation leading to death. The main concern with toxic gases is inhalation. Some gases are both toxic and flammable, for instance hydrogen sulphide, see table 1 in chapter 2.3.1. Only small concentrations of toxic gases are needed to have a negative effect on the human body. And that's why the measurements most often used for the concentration of toxic gases are parts per million (ppm) and parts per billion (ppb) (Honeywell, 2007). Beside gas concentration the time of exposure will affect the effect on the human body as well. Exposure time depends on the reaction time of the gas detection system which thereafter is influenced by the response time of the gas detectors. Fast detection will result in low exposure time. According to (Honeywell, 2007) one will expect to find toxic gases such as hydrogen sulphide and carbon monoxide at offshore installations dealing with oil and gas.

2.3.3 Asphyxiating gases

According to (Honeywell, 2007) normal ambient air contains an oxygen concentration of 20,9% v/v. (MSA, 2007) states that an atmosphere containing less than 19,5% oxygen v/v can be regarded as an oxygen deficient atmosphere. An asphyxiating gas has the ability to induce suffocation due to oxygen depletion. The oxygen depletion can be caused by several processes. The oxygen content in the atmosphere can be reduced by combustion of flammable gases, displacement, oxidation or chemical reactions (Honeywell, 2007).

Asphyxiating gases	Formula
Acetylene	C_2H_2
Ethane	C_2H_6
Ethylene	C_2H_4
Hydrogen	H_2
Methane	CH_4
Propylene	C_3H_6
Carbon dioxide	CO_2
Carbon monoxide	CO

Table 2, Asphyxiating gases (MSA, 2011)

Table 2 shows some asphyxiating gases which can reduce the oxygen content in the ambient atmosphere.

2.4 Gas detection principles

A gas detection system consists of several gas detectors which utilize different technologies and principles in order to detect the presence of various combustible and toxic gases. This chapter will provide an introduction to point detection and open path detection which are principles used within gas detection. Different gas detection technologies will be introduced in chapter 2.5. First of all the basic structure of a gas detector must be explained. The following description of the basic structure of a gas detector in general is largely retrieved from (Anderson and Hadden, 1999).

In simplicity a gas detector consists of three components; a sensor, a transmitter and a control module. The function of the sensor is to convert the presence of a combustible or toxic gas into an electrically measureable signal. Then the signal is amplified by the transmitter and sent to the control module. The transmitter together with the sensor is called the detector head. The control module can be located at the same place as the detector head or elsewhere. Some of the functions of the control module are alarm set point adjustments along with readouts, indication of status and give recorder outputs.

As will be explained the point detection principle and the open path detection principle have different areas of application.

2.4.1 Point detection

A point gas detector measures the concentration of the target gas at the point of the detector. The concentration of combustible gases is measured in %LFL and the concentration of toxic gases is measured in ppm or ppb (Honeywell, 2007). A point gas detector will cover a limited area around its location and it needs to be in "physical contact" with the target gas in order to measure the concentration. Gas detection technologies such as catalytic, infrared, electrochemical and semiconductor utilize the point detection principle. These technologies will be introduced in chapter 2.5.

Since a point gas detector is only able to measure the gas concentration in a given point the gathering of information regarding gas dispersion in a module requires several point gas detectors distributed throughout the module. Point gas detectors are useful for coverage of limited areas.

2.4.2 Open path detection

An open path gas detector measures the amount of the target gas along a beam path. This principle is only applied for combustible gas detection and the infrared detection technology is the only detection technology which utilizes the open path detection principle. The amount of combustible gas along the beam path is measured in LFLm. LFLm is the gas concentration times the length of the beam path. According to (Det-tronics, 2011) one LFLm equals 100% LFL over a path of one meter. As a consequence of this two different gas clouds can give the same output. A small dense gas cloud with 100% LFL over one meter gives the same output as a large dispersed gas cloud which has 10% LFL over 10 meters. Figure 3 taken from “A Practical Guide to Gas Detection” made by Det-tronics, showed below, illustrates these two types of clouds.

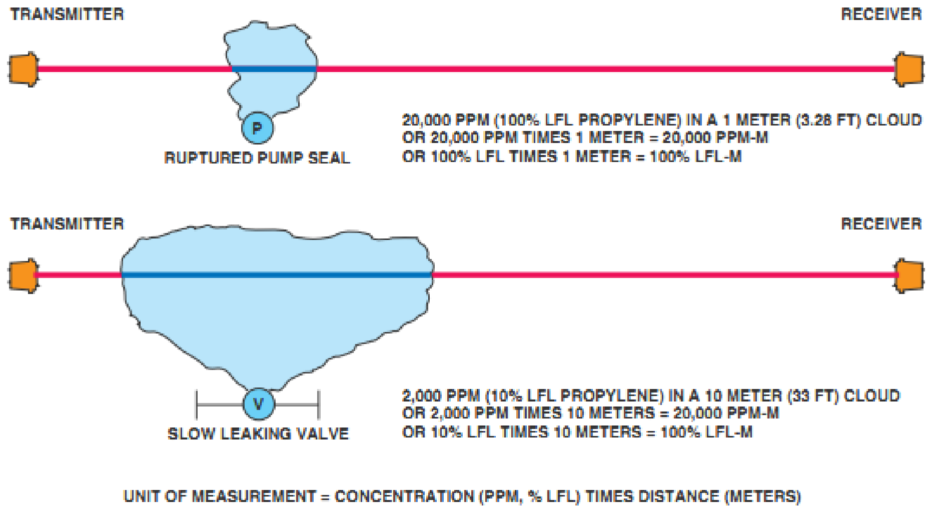

Figure 3, Two clouds which gives the same value (Det-tronics, 2011)

An open path gas detector measures the amount of gas along the beam path and do not measure the gas concentration in a given point. The detection of escaped gas in a module is prioritized before identifying the exact location of the escaped gas. In case of gas detection control actions will be initiated independent of the gas location in a given module. Since open path gas detectors have a long monitoring range they can be used for enveloping areas and critical equipment.

A high level of functionality and reliability of a gas detection system requires that the different gas detection principles are applied in accordance with their characteristics. Point detectors applied for enveloping areas may allow gas to go through loopholes and thus avoid detection. Open path detectors applied for coverage of limited areas in the middle of a module may find it difficult to find obstruction-free zones for their beam path due to high equipment concentration and moving parts and personnel.

The characteristics of a gas detector must fit the area in which it’s positioned. In case of a gas leak the probability of detecting the escaped gas will get reduced and the risk related to the leak will increase if application of detection principles is inadequately considered. As one can see from subchapter 2.4.1 and 2.4.2 the presence of combustible gases can be detected with both point detection and open path detection while detection of toxic gases is limited to application of point detection.

2.5 Gas detection technologies

There exist several gas detection technologies applied for detection of combustible gases and toxic gases. This chapter will provide an introduction to different commonly used gas detection technologies such as:

- Catalytic
- Infrared
- Electrochemical
- Semiconductor
- Ultrasonic

2.5.1 Catalytic

The catalytic gas detection technology applies the point detection principle as explained in chapter 2.4.1. A catalytic sensor works on the principle that a combustible gas can be oxidized to produce heat. The catalytic sensor consists of an active element and a passive element. The active element is made by winding a small coil of wire, sealing it in a ceramic or glass substance, and then coating it with a catalyst (Anderson and Hadden, 1999). The passive element is made identical to the active element except in place of the catalyst, a passivating substance is used (Anderson and Hadden, 1999). Both of the elements are enclosed behind a flameproof sinter (Det-tronics, 2011).

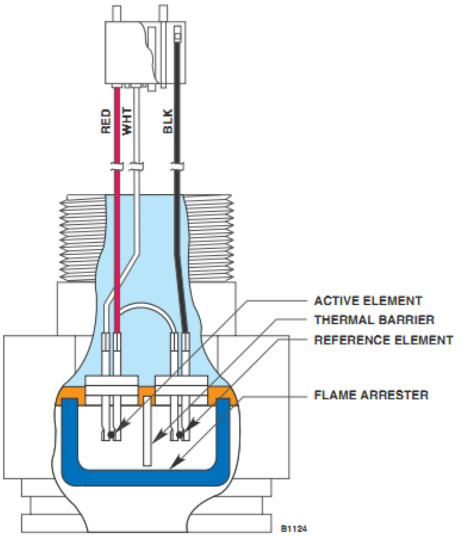

Figure 4, Catalytic sensor (Det-tronics, 2011)

Figure 4 shows a typical catalytic sensor with an active and a passive element separated by a thermal barrier. A combustible gas is oxidized when it comes in contact with the catalytic surface. During the oxidation heat is released and causing the resistance of the wire to change. The gas concentration is a function of the resistance change and can be found by placing the sensor pair into a Wheatstone bridge. A Wheatstone bridge is a circuit which in this case produce a differential voltage between the active and passive element. The passive element retains the same electrical resistance because it doesn’t oxidize the combustible gas (Det-tronics, 2011).

Regarding detector positioning the catalytic sensor is capable to detect a wide range of combustible gases and vapours in addition to fast response time (MSA, 2007). But since the catalytic sensors only exist as point detectors there is a need for several detectors in order to monitor a hazardous area. Due to limited range the position of a catalytic sensor is critical to ensure fast and reliable gas detection. Routine calibration must be performed approximately every three months (Det-tronics, 2011). According to "The Gas book" by Honeywell the catalytic sensor is low cost proven technology. (Det-tronics, 2011) states that the catalytic sensor operates without a fail-safe function, meaning that the sensor isn't able to detect and indicate conditions in which it is blind to gas (Det-tronics, 2011). Response time and calibration with be further discussed with respect to detector positioning in chapter 2.8.

2.5.2 Infrared

This chapter is largely retrieved from "A Practical Guide to Gas Detection" made by Det-tronics. The infrared gas detection technology applies both the point detection principle and the open path detection principle as explained in chapter 2.4.1 and 2.4.2.

The infrared (IR) method of gas detection relies on the IR absorption characteristics of gases to determine their presence and concentration (Det-tronics, 2011). The detector consists of a light source and a light detector. These two components are used to measure the intensity both at the absorption wavelength and a non-absorbed wavelength. When a gas is present between the light source and the light detector it will affect the intensity of the transmitted light.
Based on values from the affected light intensity one can determine the type of gas which is present between the two components. This method works only for gases that can absorb infrared radiation (Det-tronics, 2011).

Point detection
The IR point detector has a distance of 30 to 150 mm between the light source and the light detector. These values are taken from (Det-tronics, 2011) and may vary with different manufacturers. One assumes uniform concentration of gas along the path between the source and the detector, beam path. The light detector has an active sensor and a passive sensor. The active sensor is set in the absorption band of the gas being monitored, while the reference sensor is not (Det-tronics, 2011). One can determine the presence of a gas by comparing the ratio between the wavelengths from the active and the passive sensor. The point detector measures the gas concentration in %LFL.

As for the catalytic sensor the position of an IR point detector is critical to ensure fast and reliable gas detection due to limited detection coverage. Det-tronics provides IR point detectors which are fail-safe. The fail-safe function makes this detector more reliable than the catalytic sensor which operates without the fail-safe function. Only hydrocarbon based gases can be detected using the IR point detector.

Open path detection

As for the point detector the open path detector has a light source and a light detector. The most evident difference between these detection principles is the distance between the light source and the light detector which for the open path detector can be between 10 and 100 m. These values are taken from (Det-tronics, 2011) and may vary with different manufacturers. As explained in chapter 2.4.2 the output from the open path detector is the gas concentration in %LFL times the length of the surveillance path, LFLm.

Figure 5, IR open path detection (Honeywell, 2007)

Figure 5 above shows an IR open path detector. Between the infrared light source and the light detector one can see the beam path made visible with help of the infrared light.

With its long surveillance path the IR open path detector has the ability to monitor large areas and thus reduce the number of required detectors. But the long surveillance path makes the detector more vulnerable for obstructions in form of equipment and personnel. Obstructions will be discussed further in chapter 3. In addition the long surveillance path (Det-tronics, 2011) states that it's more difficult to identify the specific location of a gas leak or cloud concentration when using the IR open path detector. But as explained in chapter 2.4.2 the exact position of a cloud concentration within a module isn't important since the control actions initiated in case of a gas leak are applied to the whole module. According to "The Gas book" by (Honeywell, 2007) the IR open path detector is available in both flammable and toxic versions.

2.5.3 Electrochemical

The electrochemical gas detection technology is used for detection of toxic gas. According to "The Gas Detection Handbook" by (MSA, 2007) this technology applies an electrochemical reaction to generate a current proportional to the gas concentration. An electrochemical sensor consists of a diffusion barrier, an anode, a cathode and an electrolyte, which together are essentially the same as a fuel cell (Anderson and Hadden, 1999). A third electrode (reference) is used to build up a constant voltage between the anode and the cathode (MSA, 2011). When a chemically reactive gas passes through the diffusion barrier oxidation occurs at the anode and reduction takes place at the cathode. When the positive ions flow to the cathode and the negative ions flow to the anode, a current proportional to the gas concentration is generated.

As for other point detectors the positioning of an electrochemical gas detector is critical to ensure fast and reliable gas detection due to limited detection coverage. Several detectors are required in order to monitor a hazardous area. (Honeywell, 2007) states that failure modes remain unrevealed unless advanced monitoring techniques are used. According to (Det-tronics, 2011) there are some restrictions with respect to the application of electrochemical gas detectors in some cold temperature environments.

2.5.4 Semiconductor

This section is largely retrieved from "The Gas Detection Handbook" by (MSA, 2007). The semiconductor gas detection technology, also called metal oxide semiconductor (MOS), can be applied in both combustible and toxic gas detection. The MOS is 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). In the MOS metal oxide is applied to a non-conducting substance between two electrodes. Metal oxide is a semiconducting material. The non-conducting substance is heated to a temperature at which the presence of a gas can cause a reversible change in the conductivity of the metal oxide. When no gas is present, oxygen is ionized onto the surface and the sensor becomes semi-conductive; when molecules of the gas of interest are present, they replace the oxygen ions, decreasing the resistance between the electrodes (MSA, 2007). The change in resistance between the electrodes is measured electrically and is proportional to the concentration of the gas being measured.

MOS detectors apply point detection and the detector position has the same level of criticality as other point detectors. According to (Det-tronics, 2011) the MOS detector has none fail-safe function and this reduce the reliability of the gas detector. (Det-tronics, 2011) further states that the MOS detector is very sensitive to atmospheric disturbances such as rain and humidity changes.

2.5.5 Ultrasonic

Conventional gas detection methods such as point and open path technologies rely on the gas to come into physical contact with the detectors or the transmitted infrared light. The ultrasonic gas leak detection (UGLD) technology on the other hand detects gas leaks by sensing the airborne ultrasonic noise produced by escaping pressurised gas (Gregory et. al, 2007).

According to (Gregory et. al, 2007) a specially designed microphone unit is used as the main transducer in an ultrasonic gas leak detector. When the ultrasonic noise is detected by a sensor one can determine the leak rate since there is a proven proportionality between the ultrasonic noise produced by escaping pressurised gas and the leak rate.

As for all gas detectors the establishment of alarm levels and detector positions is of crucial importance. Alarm limits for conventional combustible gas detection methods are based on %LFL and LFLm, but UGLD use the leak rate as basis. Dependent on ventilation conditions and whether the gas leak is located in a confined area a certain leak rate must exist in order to form a potentially dangerous cloud. The leak rate unit of measurement is kg/s and it tells how many kilograms of gas are released through the leak orifice per second (Gregory et. al, 2007). According to (Gregory et. al, 2007) health and safety organisations within the oil and gas industry have classified gas leaks into three categories based on the potential explosion risk that a leak would cause. The three leak categories are presented in table 3 below.

Leak rates	
Small leak	< 0,1 kg/s
Medium leak	0,1 kg/s to 2,0 kg/s
Large leak	> 2,0 kg/s

Table 3, Leak categories (Gregory et. al, 2007)

From table 3 one can see that a small leak has a leak rate less than 0,1 kg/s and a large leak has a leak rate higher than 2,0 kg/s. Leak rates from 0,1 kg/s to 2,0 kg/s represent medium leaks. The potential explosion risk related to a specific leak rate may vary depending on module design, but that will be further evaluated in the chapter dealing with formulation of detection criteria.

UGLD requires the establishment of an ambient ultrasonic background noise level to decide the alarm level and assist with selection of the optimal location (Naranjo and Neethling, 2010). A survey of the level of background interference makes it easier to detect abnormal conditions in form of gas leaks. (Naranjo and Neethling, 2008) states that the position of UGLDs is based on identifying potential sources of gas leaks. Gaskets, weld joints, and valves in high pressure installations are potential sources of gas leaks.

According to (Naranjo and Neethling, 2010) the UGLD works especially well in open, ventilated areas where other methods of gas detection may not be independent of ventilation. As opposed to conventional gas detectors which are dependent on physical contact with the gas, the UGLD is able to detect gas leaks by listening to ultrasonic noise. Due to the need for physical contact with the leaked gas the conventional gas detection will be affected by ventilation conditions in a module. Ventilation will be discussed further in chapter 3. Trials performed by (Gregory et. al, 2007) showed that the UGLD sometimes didn't differentiate between a process gas leak and other ultrasonic noise sources. Given this result it was recommended not to initiate a process shutdown based on UGLDs alone.

Several detection technologies with respect to combustible and toxic gases have been introduced in this chapter. In order to find the best suited positions for gas detectors it is crucial to take into consideration advantages and limitations of each detection technology. From the chapters above one can see that advantages and limitations will vary between different gas detector technologies, and even between different gas detector manufacturers. A gas detection system which consists of a single gas detection technology will be very vulnerable under certain operating conditions in which the limitations of the gas detectors get revealed.

Gas detection diversity is the principle of applying two or more gas detection technologies. (Naranjo et. al, 2009) applied Markov models to illustrate the potential risk reduction as a function of gas detection diversity. One of the conclusions was that detection diversity improves the odds that a gas leak is detected early on, independent of the number of detectors installed, their reliability, and geographic coverage. By applying several different detection technologies one can make use of the advantages of each detector and avoid a situation where all installed detectors share the same limitations. For example certain operating conditions which may be bad for an UGLD might not affect an IR open path detector. It may happen that an UGLD isn't able to differentiate between a process gas leak and other ultrasonic noise sources, but an IR open path detector can detect the presence of the escaped gas by disruption in the beam path.

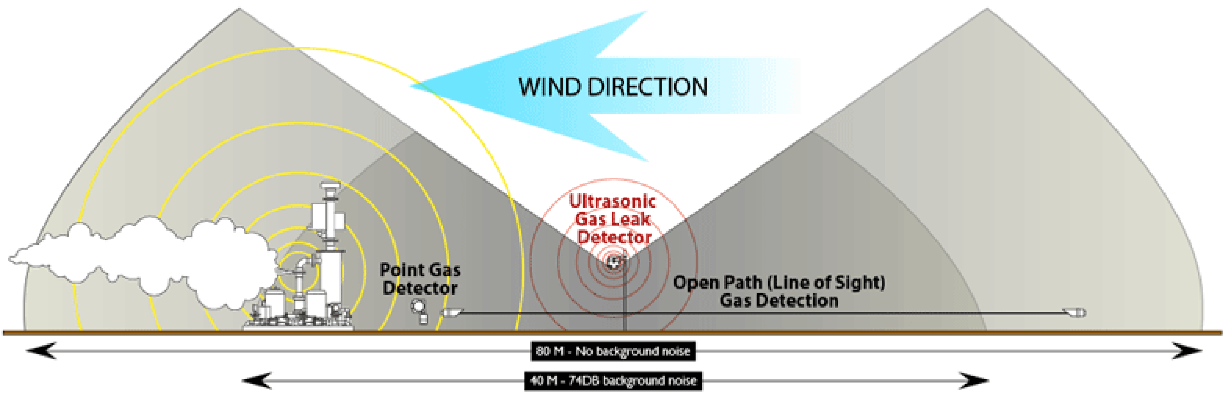

Figure 6, UGLD versus point and open path detector (Net Safety Monitoring, 2011)

Figure 6 shows an example of a situation where the wind direction prevents escaped gas from a leak to be detected by point and open path gas detectors. But the UGLD which doesn't need to be in physical contact with the escaped gas can discover the leak by listening to the ultrasonic noise.

The application of different detection technologies in a given module will result in a more robust gas detection system with respect to different operating conditions, thus increase the reliability of the gas detection system. The combination of different detection technologies within a given area can contribute to faster detection of escaped gas because one can make use of the individual advantages from each technology. By achieving faster detection control actions can be initiated earlier leading to lower ignition probability and limitations of possible consequences related to ignition, hence reduced risk in case of a gas leak. Faster gas detection and earlier initiation of control actions leads to increased functionality of the gas detection system, given that the measurements done by the gas detectors are correct, ref. UGLD.

Table 4 and 5 show a summary of advantages and limitations of the different gas detection technologies as presented in the previous chapters.

	Advantages
Catalytic	Fast response time, wide range of combustible gases, low cost proven technology
Point infrared	Fail-safe function
Open path infrared	Both flammable and toxic gas detection, can monitor large areas, positioning not so critical
Electrochemical	Can measure toxic gases in low concentrations
Semiconductor	Both flammable and toxic gas detection
Ultrasonic	No need for physical contact, not affected by ventilation conditions

Table 4, Summary of detection technologies and advantages

	Limitiations
Catalytic	No fail-safe function, positioning is critical
Point infrared	Positioning is critical
Open path infrared	Vulnerable regarding obstructions
Electrochemical	Restrictions in cold temperature environments, positioning is critical
Semiconductor	Positioning is critical, no fail-safe function
Ultrasonic	Must be combined with other technologies due to low reliability under certain conditions

Table 5, Summary of detection technologies and limitations

By carrying out gas dispersion simulations in FLACS (see chapter 4) one can see how escaped gas will behave in a given module under defined operating conditions. Results from such simulations can contribute to the assessment of advantages and limitations of the different detection technologies and make a good basis for decision making regarding which detection technologies to apply and hence optimize functionality and reliability of the gas detection system.

2.6 The Gas detection system

This chapter will provide an introduction to role and requirements regarding the gas detection system and the basis for these. In order to evaluate the degree of impact different factors have on the reliability and functionality of a gas detection system one should study the role and requirements of a gas detection system and take a look at the approach taken to ensure these demands.

The Norwegian authorities in form of the Petroleum Safety Authority (PSA) make the prevailing regulations regarding the gas detection system. These regulations provide a basis for design of the gas detection system and state general requirements and roles of the gas detection system. For more formal specifications one refers to standards such as (NORSOK S-001, 2008) and (ISO 13702, 1999). Both regulations and standards are composed in collaboration with representatives from the oil and gas industry. The standards provide different specific recommendations but act only as guides due to considerably variations between different offshore installations regarding design and operation conditions. The operator has the main responsibility to optimize the gas detection system to an offshore installation. Fundamental requirements from the PSA regulations and relevant standards will be presented in chapter 2.6.1.

The gas detection system alone isn’t enough to reduce the risk related to undesired gas releases. In case of gas detection other safety systems and functions must be informed and initiated in order to prevent accident situations and mitigate damage caused by accidents. These safety functions and systems will be introduced in this chapter 2.6.1 as well.

In order for the gas detection system to initiate other safety functions and systems a set of alarm limits must be established. The alarm limits depend on type of gas detector, the gas to be detected and decisions made by the operator for the given installation. Alarm limits will be discussed in chapter 2.6.2.

The time from a gas leaks starts to initiation of safety functions and systems will be referred to as response time and will be studied in chapter 2.6.3.

With respect to gas detector positioning the PSA and the relevant standards have several recommendations and opinions which will be briefly presented in chapter 2.6.4.

Different subjects to be considered when formulating the detection criteria for a gas detection system will be discussed in chapter 2.6.5.

This chapter will end with brief introduction to requirements to the gas detection system regarding accessibility with respect to testing, inspection and maintenance in chapter 2.6.6.

2.6.1 Introduction to role and requirements

Activities related to the production of oil and gas at offshore facilities bring along many challenges. One of these challenges is to reduce the risk of hazards and accident events. A hazard can be a gas leak or the combustible fuel-air cloud which can be formed if a gas leak occurs. An accident event can occur if the gas leak is ignited immediately, forming a fire, or by delayed ignition to initialize a gas explosion.

According to section 11 in the Framework Regulations (PSA, 2011) the risk of harming people, the environment or material assets shall be reduced to the extent possible, provided that the costs are not significantly disproportionate to the risk reduction achieved. This is better known as the ALARP principle and is meant to trigger risk reduction beyond what is required in the regulations.

In order to reduce the risk one shall according to section 5 in the Management Regulations (PSA, 2011) establish barriers. Safety functions are one example of barriers and according to section 8 in the Facilities Regulations (PSA, 2011) facilities shall be equipped with necessary safety functions. It is required that the safety functions can at all times:

1.	**Detect abnormal conditions**
2.	**Prevent abnormal conditions from developing into hazard and accident situations**
3.	**Limit the damage caused by accidents**

Table 6, Tasks of safety functions and systems (NORSOK S-001, 2008)

According to section 32 in the Facility Regulations (PSA, 2011) facilities shall have a fire and gas detection system that ensures quick and reliable detection of near-fires, fires and gas leaks. In addition it is required that other relevant safety functions and systems are activated in the event of fire or gas detection. With other words the safety function of the fire and gas detection system is to detect abnormal conditions, point 1 in table 6 above. The tasks of preventing abnormal conditions from developing into hazard and accident situations and limit the damage caused by accidents belong to other safety functions and systems as shown below:

- Emergency shutdown system (ESD)
  According to (NORSOK S-001, 2008) the purpose of the ESD system is to prevent escalation of abnormal conditions into a major hazardous event and to limit the

extent and duration of any such events that do occur. ESD system actions are as stated in (NORSOK S-001, 2008):

- Shut down of wells
- Shut down and sectioning of the hydrocarbon process facilities
- Initiation of BD
- Ignition source isolation
- Shut down of main power generation
- Start/stop of emergency power generator
- Shut down of drilling, intervention and work-over equipment not required for well control

The ESD system applies to point 2 and 3 in table 6.

- Blow down (BD) and flare/vent system
  According to (NORSOK S-001, 2008) the purpose of this system is during an accidental event or emergency situation to:
  - In the event of a fire to reduce the pressure in process segments to reduce the risk of rupture and escalation
  - Reduce the leak rate and leak duration and thereby ignition probability
  - In some cases avoid leakage at process upsets, e.g. in case of loss of compressor seal oil/seal gas
  - Route gases from atmospheric vent lines to safe location

The BD and flare/vent system applies to point 2 and 3 in table 6.

- Ignition source control (ISC)
  According to (NORSOK S-001, 2008) the ISC function shall minimize the likelihood of ignition of flammable liquids and gases following a loss of containment. This means that the ISC function applies to point 2 in table 6.

- Heating, ventilation and air conditioning system (HVAC)
  According to (NORSOK S-001, 2008) the HVAC system shall, with respect to accidental events:
  - Prevent ingress of smoke or gas
  - Dilute gas leakages (mechanically ventilated areas with leak sources)
  - Provide smoke ventilation for internal fire conditions
  - Ensure acceptable environment for personnel and equipment

The HVAC system applies to both point 2 and 3 in table 6.

- Public address (PA), alarm and emergency communication
  According to (NORSOK S-001, 2008) this system shall warn and guide personnel quickly as possible in the event of a hazardous or emergency situation. This system applies to point 3.

- Fire fighting systems
  According to (NORSOK S-001, 2008) the purpose of this system is to provide quick and reliable means for fighting fires and mitigate explosions effects. The fire fighting

system involves firewater (FW) supply system, deluge system, sprinkler system and foam system. This system applies to point 3 in table 6.

The safety systems and functions mentioned above will not be initiated unless fire or gas have been detected by the fire and gas detection system. Which safety systems and functions to be initiated are defined by Fire Protection Data Sheets and Cause and Effect documents for the given module. A Fire Protection Data Sheet provides information about combustible hazards, ventilation conditions, area classification, potential leak sources, potential ignition sources, area enclosure, extinguishing equipment and type of detection utilized in a given module. The Cause and Effect document describes what kind of control actions to be initiated given in case of gas detection. Fire Protection Data Sheets and Cause an Effect documents are established by the operator of an offshore installation. Response to detected gas will vary between operators, installations and modules.

The NORSOK S-001 standard supplements the definitions regarding role and functional requirements of a gas detection system as stipulated in section 32 in the Facility Regulations (PSA, 2011). The role of the gas detection system is defined as follow:

“The gas detection system shall monitor continuously for the presence of flammable or toxic gases, to alert personnel and allow control actions to be initiated manually or automatically to minimise the probability of personnel exposure, explosion and fire.”

This definition regards the importance of alerting personnel and allows manual or automatic initiation of control actions in form of other safety functions and systems.

Further (NORSOK S-001, 2008) requires that:
“The gas detection function shall provide reliable and fast detection of flammable and toxic leaks before a gas cloud reaches a concentration and size which could cause risk to personnel and installation.”

Reliable and fast detection is also mentioned in section 32 in the Facility Regulations (PSA, 2011) and the degree of fulfilling these requirements is highly influenced by the position of the gas detectors. Fast detection is achieved if the gas detector is located nearby the leakage point and in the gas flow. The gas flow is influenced by leak rate, leak direction, wind and ventilation directions. Some of these physical factors will be studied in chapter 3. The gas detection system should preferably detect the presence of combustible gas long before it manages to form a cloud capable of being more destructive than the dimensioning gas cloud.

The main purpose with implementing safety functions and systems such as the fire and gas detection system and the other systems mentioned above is to reduce the overall risk level at offshore installations where production of oil and gas takes place. The gas detection system, which is emphasized in this thesis, is the first system in the process of reducing the risk related to undesired gas releases. Figure 7 below will be used to describe the risk picture when a gas leak occurs. At the centre of figure 7 is a hazard in form of a gas explosion/fire. On the left side are preventive barriers which try to prevent the hazard from occurring. And on the right side are consequence reducing barriers which try to reduce the severities following the occurrence of the hazard. A gas leak has occurred outside the figure on the left side. In order for the preventive barriers to be initiated the gas detection system must detect the gas leak, the abnormal condition. When the gas leak is detected different control actions will be initiated, type and sequence will depend on the Fire Protection Data Sheet and the Cause and Effect document for the given module. If these barriers do not manage to prevent a gas explosion/fire one must rely on the consequence reducing barriers. Safety functions and systems which applies to point 2 in table 6 are located on the left side of figure 7 and those which applies to point 3 are located on the right side. Some safety functions and systems are located on both sides.

In order to initiate the preventive barriers and reduce the probability of the potential hazard the gas leak must be detected of the gas detection system. In addition the gas leak should be detected as early as possible to reduce the hazard probability further. If one is unable to prevent the hazard an early initiation of preventive barriers will at least reduce the combustible gas cloud and further limit consequences after an explosion or fire. It is important to ensure a high level of functionality and reliability with respect to the gas detection system in order to keep the overall risk level as low as possible, because the other safety systems and functions rely on it.

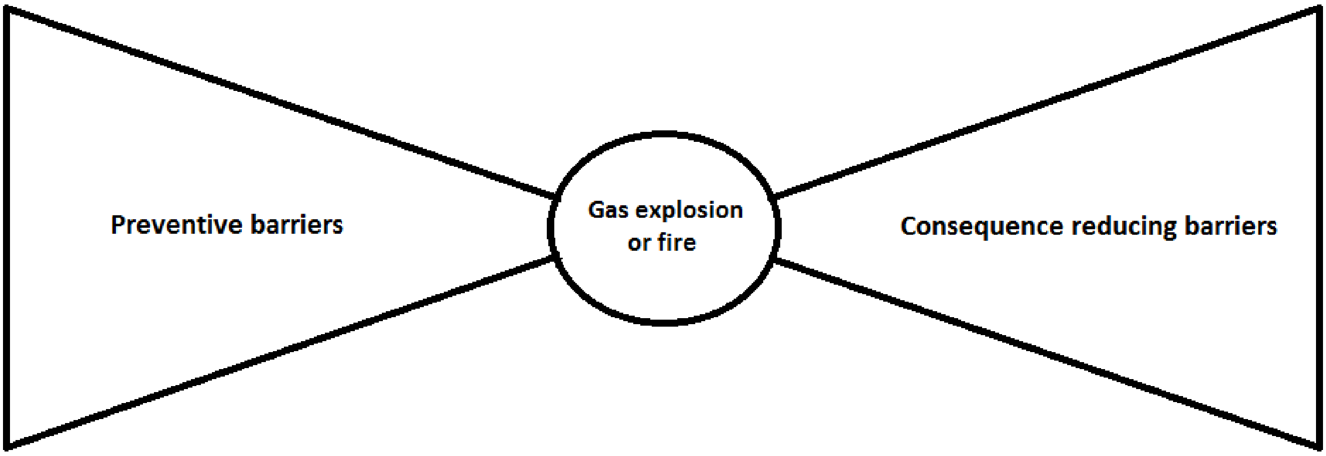

Figure 7, Bow-tie diagram

2.6.2 Alarm limits

The NORSOK S-001 standard has stated alarm limits for several types of gases. The alarm limits for hydrocarbon gas detection and H_2S gas detection will be presented. In chapter 2.3 the use of LFL as measuring unit was explained by the need for detecting a combustible gas before it reaches a flammable mixture with air. The measuring unit for the concentration of H2S is ppm. There are two types of alarms; low alarm and high alarm. There exist several alarm levels due to possible false alarms and voting is used to manage the uncertainty within the gas detection system. The voting methodology requires that the presence of gas in a given area must be detected by two or more gas detectors in order to state confirmed gas detection. Confirmed gas detection will normally result in a complete production shutdown, depending on the Fire Protection Data Sheet and the Cause and Effect document for the given module. The number of alarms which qualify for confirmed gas detection will vary depending on the system and the risk level in the given module. Table 7, 8 and 9 show some alarm limits stated by (NORSOK S-001, 2008). These values may be regarded as guiding limits. One can see that the alarm limits depend on the detection principle (point or open path) and detector location.

Point detectors	Max low alarm	Max high alarm
In general	20 % LFL	30% LFL
Turbine enclosure	10% LFL	15% LFL

Table 7, Alarm limits for point detectors (NORSOK S-001, 2008)

Open path detectors	Max low alarm	Max high alarm
In general	1 LFLm	2 LFLm
Air inlets	not > 1 LFLm	not > 2 LFLm

Table 8, Alarm limits for open path detectors (NORSOK S-001, 2008)

H_2S detection	Max low alarm	Max high alarm
In general	$10*10^{-6}$	$20*10^{-6}$

Table 9, Alarm limits for H2S detection (NORSOK S-001, 2008)

Table 7 and table 8 shows the guiding alarm limits for point and open path combustible gas detectors as stated in (NORSOK S-001, 2008). As one can see from table 7 there are different alarm limits for a general position and turbine enclosure regarding point detectors. Table 8 shows that open path detectors have different alarm limits for general positions and air inlets. According to (NORSOK S-001, 2008) the low alarm limit and the high alarm limit in air inlets shall be detection distance multiplied with 20% LFL (low) and 30% LFL (high). But there are maximum values as shown in table 8. Turbine enclosure and air inlets are given other alarm limits due to the considerably high level of risk caused by the presence of hydrocarbon gas in these areas. Table 9 shows guiding alarm limits for H_2S detection (toxic).

Low alarm limits between 10 and 20%LFL and high alarm limits between 30 and 60%LFL for point detectors are representative throughout the industry. Alarm levels should be adjusted to the risk level at an offshore installation and in the different modules.

There aren't given any alarm limits for acoustic detectors in (NORSOK S-001, 2008), but one is advised to base the alarm limits on background noise measurements.

The alarm limits together with the voting methodology determine the number of gas detectors which must detect gas and at which gas concentrations in order for the gas detection system to initiate alarms and inform other safety systems and functions. The voting methodology increases the reliability of the gas detection system since several detectors must detect gas in order to confirm gas detection. In this way one can manage to reduce the number of unnecessary production shutdowns and at the same time reduce the risk related to gas leaks.

2.6.3 Response time

Response time in this thesis is defined as the time from a gas leak starts to initiation of control actions. The response time includes the time which is needed for the gas detection system to detect the gas leak (detection time) and the time which is needed to initiate necessary control actions. The response time is influenced by:

- Voting methodology,
- Gas detector positions
- Physical factors in form of leak location and air currents caused by ventilation and wind.

The voting methodology affects the time between detected gas and initiation of necessary control actions. If the voting methodology requires a large number of detectors with confirmed gas detection the response time will be high and control actions will be initiated at a later point in time compared to a less strict voting methodology.

The gas detector positions affect the time from a gas leak starts until the escaped gas is detected. Potential leak locations and directions of air currents should be taken into consideration before detector positions are determined. Physical factors will be studied more thoroughly in chapter 3.

The functionality of a gas detection system is considerably dependent of the response time since fast detection of combustible and toxic leaks is one of the main functional requirements as stated by NORSOK S-001. Fast response time lead to initiation of control barriers at an early stage and increase the probability for preventing escaped gas from forming a gas cloud which can cause an explosion by delayed ignition. With other words fast response time has a considerable risk reducing effect with respect to personnel and the integrity of an offshore installation. Fast response time under different conditions with respect to leak locations and air currents will have a positive effect on the reliability of a gas detection system.

2.6.4 Gas detector position

According to section 32 in the Facility Regulations (PSA, 2011) the placement of detectors shall be based on relevant scenarios and simulations or tests. The use of CFD simulations is one way to find the best suited gas detector positions. FLACS is a CFD tool which will be introduced in chapter 4 and used for simulations in chapter 5. For a more detailed description of the design of the gas detection system one refers to following standards; (NORSOK S-001, 2008) and (ISO 13702, 1999). While deciding the detector positions it’s very important to have in mind the requirements of a gas detection system as explained in chapter 2.6.1. Requirements such as fast and reliable detection are strongly influenced by the position of the gas detectors. Several physical factors must be considered in order to find the best suited detector position and they will be explained in chapter 3. (NORSOK S-001, 2008) has several recommendations with respect to detector positions.

According to (NORSOK S-001, 2008) the following principles shall be applied:

- natural flow “corridors” should be covered
- detectors should be positioned in different levels in an area or module

Natural flow “corridors” can be for instance walkways along the flow direction. Then one can determine the presence of gas in areas where personnel might be located. Different levels in an area or module should be covered because the density of escaped gas, flow direction of gas leakage, ventilation conditions, wind direction and wind speed can affect the location of the escaped gas. These physical factors will be explained further in chapter 3. (NORSOK S-001, 2008) states that hydrocarbon detectors should as a minimum be installed in following areas:

- zone 1 and zone 2 areas
- ventilation outlet from hazardous areas (except paint containers)
- enclosed areas if gas can enter/be trapped
- air inlets

Zone 1 and zone 2 are designations used in area classification. Zone 1 is an area in which an explosive gas atmosphere is likely to occur in normal operation (HSE, 2004). Zone 2 is an area in which an explosive gas atmosphere is not likely to occur in normal operation and, if it occurs, will only exist for a short time (HSE, 2004). In both these areas there might be an explosive atmosphere, but one wants to avoid the gas concentration from reaching the LFL. Gas detectors can be installed and control actions can be initiated based on their measurements in order to prevent the flammable gas from reaching the LFL.

Combustible gases from hazardous areas can be transported via the plant ventilation. It’s therefore important to cover the ventilation outlet from hazardous areas in order to detect the presence of combustible gas. Escaped gas can accumulate and form a combustible fuel-air mixture in both enclosed and open areas, but enclosed areas are more exposed to bad ventilation conditions which give escaped gas a low mobility. Hence one should have gas detectors in these areas.

The ISO 13702 standard proposes that in order to prevent ignition of escaped gas in non hazardous areas the air intakes to these areas or the areas themselves should be covered with gas detectors. This is only necessarily if the gas can reach these areas in an emergency. In the Snorre A incident in November 2004 an uncontrolled gas blow-out took place on the seabed under the platform (G. Pettersen et. al, 2006). The sea started to “boil” and gas was detected all over the platform. This incident demonstrates that one shall expect gas to appear anywhere in case of an emergency.

The position of a gas detector in a hazardous area is very critical since the activation of safety systems and functions requires fast detection of the gas. In addition to the recommended detector locations presented above the NORSOK S-001 standard provides a table with gas detection main principles covering several areas such as the wellhead area and the HC process area. This table will not be presented in detail because this thesis emphasizes on the factors which must be considered in order to find the best suited detector positions.

The operator at an offshore installation has the main responsibility for finding the best suited gas detector positions and to ensure a satisfying level of reliability and functionality with respect to the gas detection system. Information in (NORSOK S-001, 2008) and (ISO 13702, 1999) regarding gas detector positions act as recommendations based on industrial experience. The operator of an offshore installation may use this information in combination with results from relevant scenarios and CFD simulations or tests in order to determine the best suited detector positions. As will be shown in chapter 3 there are several physical factors to be considered when deciding detector positions and these will vary between different modules and installations. Suitable detector positions in one module might not me adequate in another module due to other operating conditions.

2.6.5 Formulation of detection criteria

The detection criteria define the required performance of a gas detection system and are established by the operator of an offshore installation. The detection criteria are based on the detection philosophy of the given operator and the risk level at an offshore installation. In connection with this thesis there haven't been found any evidence that indicates common detection criteria among the operators on the Norwegian continental shelf. Variation in detection criteria may be explained by different factors taken into account when formulating the detection criteria or a deviation in the assessment of the different factors. One should also take into account that none offshore installations are identical.
The operator has the superior responsibility for formulating detection criteria that ensure safe operation for personnel and installation. A set of factors to be taken into account when formulating detection criteria will be presented.

Escaped gas that represents a potential explosion risk should be detected as early as possible in order to initiate safety functions and systems such as ESD. The ESD system will limit the emission of gas and potentially limit the size of the gas cloud formed by escaped gas. Gas detection at the early stage in a gas leak will increase the mitigating properties of the ESD system and hence reduce the explosion risk.

A gas cloud should be detected independent of its location. This statement requires that the gas detection system should be able to detect a combustible gas cloud in a module where an explosive gas atmosphere is likely to occur irrespective of the location of the cloud. A heavy gas near the ground and a light gas near the roof shall both be detected. A gas detection system providing poor detection coverage can miss areas where a combustible gas cloud might settle down.

The detection criteria should reflect the overall risk at an installation and the risk related to each module. The explosion risk in a module depends on, beside other factors, its degree of confinement. Given the same cloud size, location, geometry and ignition point, a confined module can produce a higher explosion pressure compared to a deck (unconfined). In other words, the confined module can produce the same explosion pressure as the deck with less amount of gas. By taking this into consideration one should establish more strictly detection criteria with respect to the confined module. The explosion risk can deviate between two confined modules. A module contains a lot of process equipment and hence the potential for gas leaks are considerable. The second module on the other hand has no process equipment from which a gas leak can occur. Hence, the first module should have more strict detection criteria compared to the second module. There exist several ways of formulating detection criteria. Size of leakage, size of gas cloud and time aspect can be used.

The detection criteria establish several requirements regarding functionality and reliability regarding the gas detection system and describe how the system shall handle the risk level at an installation with respect to gas leaks. The detection criteria are important basis for the gas detector positions because they state requirements with respect to size of leakages to be detected, size of gas clouds and response time. The content in detection criteria will vary between different operators and installations. If some factors are overlooked during the formulation of the detection criteria the detection criteria will not be able to fulfil its intentions and it will be difficult to reduce the risk.

Insufficient formulation of detection criteria can lead to incorrectly positioned gas detectors which will have a negative effect on the gas detection system performance in terms of functionality and reliability. Incorrectly positioned detectors can lead to increased response time due to greater distance between potential flow path of escaped gas and gas detector location. Increased response time leads to later initiation of control actions and more escaped gas into the given module, hence a higher risk level.

2.6.6 Accessibility regarding testing, inspection and maintenance

According to guideline to section 8 in the Facility Regulations the safety functions should be designed so they can be tested and maintained without impairing the performance. Regarding access (NORSOK S-001, 2008) stipulates that gas detectors shall be located such that they can be accessed without scaffolding. (ISO 13702, 1999) states further that plans for a periodically inspection and testing should be established to ensure that there are no hidden failures which would prevent a system from performing the essential functions and achieving reliability targets given in the functional requirements. (MSA, 2007) states that one should consider ease of access to sensors for maintenance requirements, such as periodic calibration. After some time gas detectors need to be calibrated and checked for wear and tear in general. According to (Anderson and Hadden, 1999) sensors should be installed in a location permitting reasonable access and with sufficient room to allow the calibration adaptor and calibration apparatus to be connected easily.

These requirements make it necessary to considerate factors such as the need for maintenance and access when selecting gas detector position. A table in (ISO 13702, 1999) shows that a typical inspection and testing frequency for gas detectors may vary from 3 months to 1 year. It's further mentioned in (ISO 13702, 1999) that the frequency of testing detectors will be dependent upon the detector type and SIL[1]-requirements regarding the system. The SIL describes the relative risk-reduction level of a safety function.

[1] Safety Integrity Level
[2] Process and instrumentation diagram
[3] Computer Aided Scenario Definition

Inspection, testing and maintenance are important in order to maintain the functionality and reliability of a gas detection system. Response time, coverage of enclosed areas and different height levels must be considered regarding gas detector positions in addition to access. There will be situations where some factors ends up second in line due to prioritizing. The prioritizing is based on in which degree the different factors affect the risk level. A gas detector positioned in the ceiling will make it more difficult to perform inspection, testing and maintenance. If the detector is re-positioned at a lower level one will have better access, but accumulations of gas in the ceiling due to air currents will not be detected. In terms of risk it's better to use more time on inspection, testing and maintenance than not to detect a hazardous gas cloud in the ceiling. It's more favourable regarding the functionality and reliability of the gas detection system to prioritize the detection of gas before the access to the detector. The activities of testing and maintenance can be performed in time intervals of months, depending on reliability calculations of the system at the given installation and type of detector while the gas detector must monitor continuously for the presence of escaped gas. The disability of a gas detector to detect the presence of gas will have far more serious consequences than intricate access regarding maintenance and thus contribute to a higher risk level at an offshore installation. But one shouldn't disregard risk caused by activities related to the necessary scaffolding.

3 Physical factors regarding positioning of gas detectors

When gas is released inside a module there will be an interaction between the geometrical layout and the gas flow. According to (Høiset et. al, 2008) both the gas dispersion characteristics and the turbulent combustion in case of an explosion are rather sensitive to the geometrical layout. This chapter will concentrate on how different physical factors influence the dispersion of leaked gas in a module. An introduction to these factors will be given in this chapter while some of them will be studied in more detail in chapter 5 using FLACS simulations. In addition to the geometrical layout, the gas flow will get affected by environmental conditions such as air currents caused by wind and ventilation. Physical properties of the escaped gas are relevant with respect to dispersion and the risk it represents.

3.1 Vapour density

The vapour density of a gas influences the distribution of the gas cloud throughout the affected module. A vapour density higher than 1 indicates a vapour/gas heavier than air, and a value lower than 1 indicates a vapour/gas lighter than air (Det-tronics, 2011). Gases, which are heavier than air, tend to fall towards the ground, whereas those that are lighter than air will tend to rise upwards (Zellweger analytics, 2002). Gases with a vapour density close to that of air will behave unpredictably. (Andersen and Hadden, 1999) recommend that sensors should be located near the ground for gases which are heavier than air and near the ceiling to detect gases lighter than air. (Zellweger analytics, 2002) states that vapour density has obvious implications as regards the positioning of a sensor in order to detect any gas leaks. In addition one mention that other factors often do intrude. A calm atmosphere will indeed permit a gas to behave in accordance with its' vapour density. However, at an offshore installation one will find a restless atmosphere because of wind and air currents. Variable wind direction and strength makes the atmosphere more unstable. Convection caused by hot surfaces may influence the gas behaviour as well. A table with four gases and their vapour density is shown below.

Gas/Vapour	Formula	Vapour density
Methane	CH_4	0,55
Ethane	C_2H_6	1,04
Propane	C_3H_8	1,52
Hydrogen sulphide	H_2S	1,19

Table 10, Vapour densities (Joseph M. Kuchta, 1985)

As one can see from table 10 the vapour density of methane indicates the gas to be lighter than air. Ethane has a vapour density close to that of air while propane and hydrogen sulphide have vapour densities higher than 1. The well stream which enters the process facilities at an offshore installation will most probably liberate different gases with different vapour density. In case of a gas leak these gases will enter the module and the vapour density of each gas will affect the following dispersion. Due to varying vapour density and the interaction between gas flow and air currents gas detectors should be positioned in different levels with respect to height in a module.

3.2 Wind and air currents

The North Sea is known for its harsh environment and offshore installations located in this area are being exposed to severe wind conditions. Air currents caused by wind have a significant impact on the behaviour of gas released in a module. According to (Bonn and Moros, 1998) local air movements have far greater influence than was once believed. In addition one mention that once released and mixed with air, the density of the gas is very similar to that of air so the buoyancy effect is easily overcome by local air flows.

Air currents are able to change the direction of escaped gas from a leak, depending on wind velocity and momentum in the leakage point. Low release pressures gives the escaped gas a low momentum, thus an air current with high velocity can easily change the direction of the gas flow. A high pressure release on the other hand can resist the air currents, but the momentum of the escaped gas will gradually decrease. When the escaped gas reaches a certain distance from the leakage point air currents will be able to change the direction of the gas flow due to low momentum in the gas flow. One should consider the ability of air currents to change the direction of escaped gas when selecting positions for gas detectors and places where escaped gas is likely to be transported by air currents. The gas flow can end up in an enclosed area which will be dealt with in chapter 3.5.

(Andersen and Hadden, 1999) recommend to locate sensors where prevailing air currents are likely to contain the maximum concentration of the gas being monitored. It's further recommended to consider the possibility of changes in wind direction at different times of the day or during different seasons. The climate at the Norwegian continental shelf provides a great variation in wind conditions throughout a year. One should have in mind that depending on weather conditions air currents can lead the escaped gas in several different directions in a module.

According to (Edwin Choo, 2008) one should apply detection technology that is more impervious to wind direction/speed and other environmental conditions where it's possible. For example a UGLD which is not affected by wind conditions.

3.3 Obstructions

At offshore installations, especially in process areas there are a lot of process equipment and pipes which escaped gas can run into. Equipment in the gas flow path may cause turbulence and speed up the mixing process between escaped gas and air. In other words the turbulence can reduce the time which is needed for the gas-air mixture to reach LFL. With many obstructions comes the demand of faster gas detection. Regarding obstructions (Andersen and Hadden, 1999) say that even small structures, such as piping and equipment, between the possible leak source and the proposed sensor location can change the normal flow of air. It's therefore necessary to evaluate all obstructions carefully.

According to (Det-tronics, 2011) the open path IR detector is susceptible to obstructions since the detector must have a free beam path in order to perform its' intended functions. The planned beam path should be checked for obstructions before installation of the detector. Mobile equipment such as scaffolding and personnel should be avoided as well as fixed obstructions.

3.4 Ventilation

According to (Høiset et. al, 2008) platform modules are traditionally built with open ends, providing natural ventilation that has favourable effect on accumulation of a flammable gas cloud from a potential gas leakage as well as on explosion pressure reduction. (Tam and Dawson, 1991) explain further that adequate ventilation is important to ensure that small leakages of flammable or toxic gases do not accumulate, and are diluted and removed quickly from the platform. Ventilation is provided from natural ventilation and mechanical ventilation. Natural ventilation is made by open surfaces in walls while the mechanical ventilation comes under the ventilation system.

A ventilation system needs inlets and outlets in order to perform its' functional requirements. The exchange of air done by the ventilation system leads to formation of air currents. In case of a gas leak the ventilation system shall reduce the following gas concentration down to an acceptable level. Air currents caused by the ventilation shall lead the gas flow to the air outlet. The ventilation system will affect the direction of the gas flow, but it will provide a good gas detector position in the air outlet as well.

Regarding ventilation in hazardous areas (NORSOK S-001, 2008) states that potential stagnant zones shall be evaluated and precautions taken where considered necessary. Stagnant zones are areas in which the ventilation effects are considerably reduced, and if present, escaped gas can accumulate. An example of a stagnant zone is a confined area, which will be dealt with in chapter 3.5.

3.5 Confined area

In some modules the design with respect to walls may result in areas which are less influenced by factors such as ventilation and air currents caused by wind. In this thesis such areas are called confined areas. Large equipment such may also arrange small confined areas. In a confined area the gas cloud formed following a release will according to (Ashraf E. Shabaka, 2006) accumulate due to limited air flow and pose an explosion hazard. If not removed during the design stage of an offshore installation confined areas should be regarded as potential locations for gas detectors. An undetected gas cloud in a confined area may reach the LFL without being exposed to any mitigation functions and develop into a major hazard.

3.6 Leak sources

Potential leak sources must be considered when a gas detector position is to be determined. According to (Anderson and Hadden, 1999) components like mechanical seals, valve steam seals and expansion points are most likely to leak. (Naranjo and Neethling, 2010) further mention weld joints, gaskets and valves in high pressure installations as potential leak sources. (Det-tronics, 2011) add pump and compressor seals as potential leak sources. As one can see there are many leak sources to be aware of.

In addition to positions of potential leak sources one should consider different leak directions as well. The dispersion path of released gas is influenced by the direction of the gas leak. But one should also include possible effects caused by geometry, wind and ventilation. (Det-tronics, 2011) recommend to review P&ID[2], facility maps and hazardous area classification drawings for help in finding potential leak sources.

The leak rate quantifies the amount of released gas each second from a leak source. A categorical presentation of different leak rates was provided in chapter 2.3.3, but categorisation of gas leaks will vary throughout the industry. A gas release with a high momentum is called a jet release. Figure 8 below shows an illustration of a jet release.

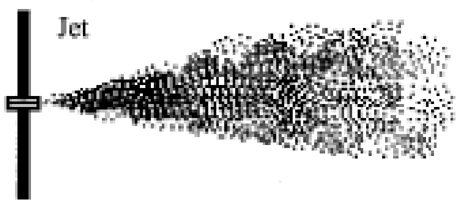

Figure 8, Jet release (Bjerketvedt. et al, 1993)

As one can see from figure 8 the cross-sectional area of a jet release increases proportionally with the distance from the release point. The dispersion of escaped gas increase with the distance as well. At the release point the gas concentration will be above UFL which means too much gas compared to air. After a certain distance from the release point the gas concentration will reach the flammability range. The flammability range is between LFL and UFL. According to (Honeywell, 2007) gas detectors should be positioned a little way back from high pressure parts to allow gas clouds to form, because otherwise any leak of gas is

[2] Process and instrumentation diagram

likely to pass by in a high speed jet and not be detected. Gas detectors applying LFL measurements have to follow this principle while UGLDs which apply sound measurements are excepted.

3.7 Ignition sources

According to (ISO 13702, 1999) ignition occurs when sufficient energy is present to cause combustion. (Bjerketvedt et. al, 1993) state that in order to ignite a gas cloud an ignition source with sufficient strength is required. The minimum ignition energy (mJ) is a measure of the energy which is needed to ignite a gas cloud, and it depends on fuel concentration and type of fuel.

(ISO 13702, 1999) presents a set of ignition sources that may be present on offshore installations; chemical reactions, electric sparks and arcs, mechanical sparks, static electrical sparks, flame, hot surfaces and heat of compression. It should be taken into consideration the fact that some ignition sources arise more frequently than others and hence represents a higher ignition probability. The literature highly recommends positioning of gas detectors between potential leak sources and ignition sources (MSA, 2007) (Andersen and Hadden, 1999) (Det-tronics, 2011). These recommendations are due to the need of detecting a combustible gas before ignition. As for leak sources a gas detector should be positioned a certain distance from an ignition source. A certain distance from the ignition source is needed because the gas detection system needs time to initiate other safety systems and functions such as ISC.

3.8 Vibration

In the process area at an offshore installation there are many sources for vibration. Sensitivity regarding vibration may vary among gas detectors depending on type and manufacturer. According to (Det-tronics, 2011) excessive vibration can damage the detector and lead to unreliable results. In order to avoid damage caused by vibration (Andersen and Hadden, 1999) recommend anchoring the gas detector to a wall or a firm base rather than to a vibration source such as a motor housing. Locations with potentially high vibration levels should be identified in order to avoid such areas when gas detectors are installed.

3.9 Future modifications

Before installation of gas detectors one should take future modifications into consideration. The present detector layout should be adjusted according to planned modifications in the future. New equipment may interrupt the beam path of an open path IR detector and lead to erroneous measurements. Introduction of new wells in the well area will result in more leakage sources and increased probability for leakages. Gas detectors should be positioned in accordance with the present module design and be adjusted regarding future modifications.

4 FLACS

4.1 Introduction to FLACS

With the help of Computational Fluid Dynamics (CFD) one can model and simulate real life processes using fundamental conservation equations (mass, momentum and energy balances) and digital computers (Kees van Wingerden, 2010). (Edwin Choo, 2008) recommends usage of CFD modeling techniques to approximate gas cloud dispersion scenarios under different environmental conditions. He further states that knowing where the probable gas dispersion path would be will greatly increase the ability of the engineer to place gas detectors more precisely.

FLACS is one of several specialized CFD tools available. FLACS is an acronym for FLame ACceleration Simulator and is a three-dimensional gas explosion and gas dispersion simulation model (Bjerketvedt et. al, 1993). During simulations this model takes account of the interaction between the gas flow and complex 3D geometries. According to (Høiset et. al, 2008) CFD simulations are important to investigate the geometrical effects, i.e. the interaction between the geometrical layout and the fluid flow. At an offshore installation these complex geometries can consist of structures, process equipment and pipe work. In case of a gas leak FLACS can simulate how the escaped gas will disperse in a module with given geometrical characteristics. The quality of the results from such a simulation depends on input provided and requirements related to the output.

Regarding this thesis FLACS will be used to carry out dispersion simulations. According to (Lars Rogstadkjernet, 2010) the objective of a dispersion simulation is to generate a representative range of gas cloud sizes. By varying leak rate, leak direction, leak locations, gas composition, wind directions and wind speeds one can simulate how these different parameters will affect the dispersion of a gas cloud at a given offshore installation. Simulations can be carried out for the whole installation or each module.

Gas dispersion simulations in FLACS is relevant regarding this thesis because by carrying out different simulations with variation in the parameters as presented in the previous section, one can see how different physical parameters affect the behavior of a gas flow which again affects the best suited positions of combustible gas detectors.

Geometries which are to be used in the dispersion simulations can either be transferred to FLACS from an external program or created directly in a preprocessor to FLACS called CASD[3]. Regarding gas dispersion simulations details can be crucial because one would want the simulations to be as realistic as possible. In order to achieve a realistic simulation the geometry of a module must be recreated in detail. According to (Kees van Wingerden, 2010) the FLACS interfaces can handle 100.000 objects and more. The geometry handling in FLACS is based on the porosity concept and sub-grid modeling. Porosity is the measure of void spaces in a material.

[3] Computer Aided Scenario Definition

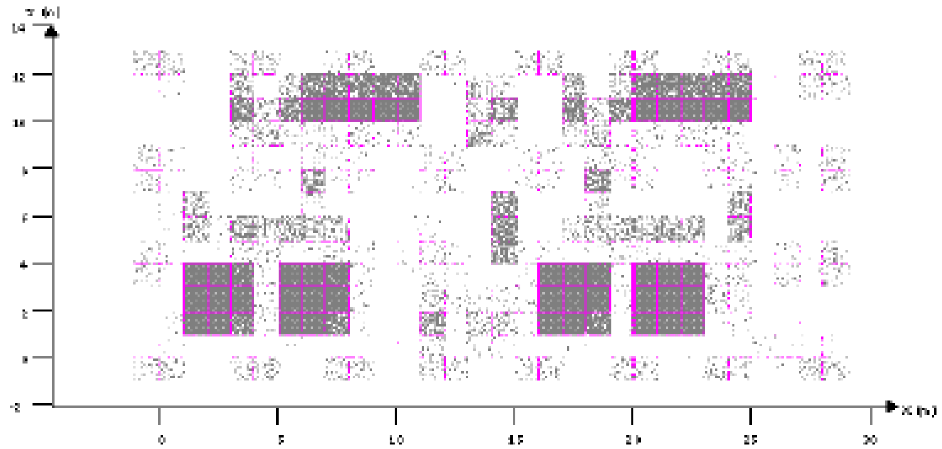

Figure 9, Porosity in a module (Kees van Wingerden, 2010)

Figure 9 shows how the porosity concept acts in a given module. Thousands of grey dots are present in the figure and their concentrations indicate the porosity in a given area. Areas colored in dark grey have very low porosity and may represent solid and compact equipment such as a separator. Areas with immediate concentrations of grey dots may represent small pipes and empty areas may represent walkways.

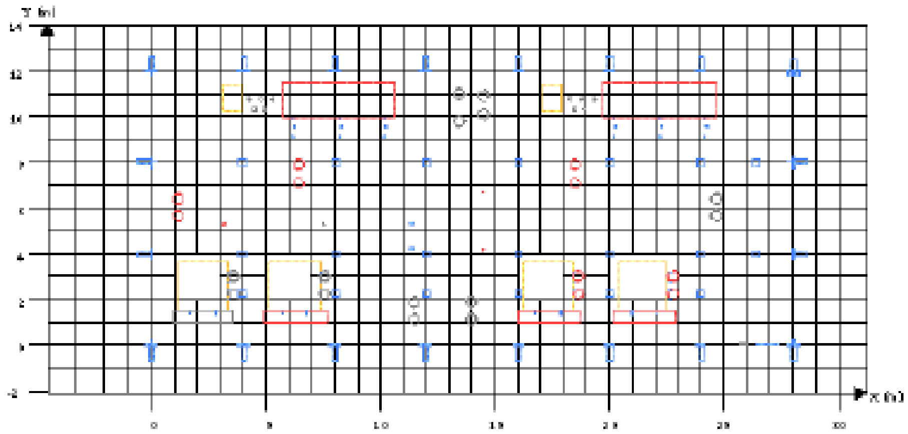

Figure 10, A module divided into grids (Kees van Wingerden, 2010)

Figure 10 shows how sub-grid modelling is applied in FLACS. The module in figure 10 is divided into grids of 1*1m. At leak locations the grid must be adjusted to the leak orifice in order to obtain a realistic flow velocity. The grid must be adjusted to different leak rates as well.

4.2 Program interface and parameters

The FLACS program consists of the FLACS Run Manager, the FLACS pre-processor and the FLACS post-processor.

4.2.1 FLACS pre-processor

In the FLACS pre-processor called CASD[4] one can develop a 3D model by starting from scratch or transfer geometry from PDMS[5].

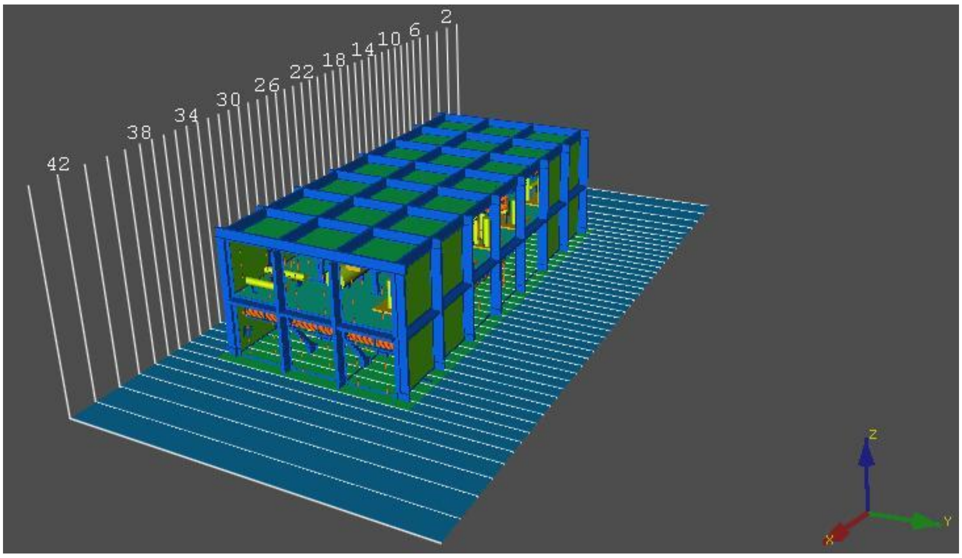

Figure 11, A module in CASD

Figure 11 shows a module in CASD which will be used in FLACS simulations for this thesis and will be described in more detail in chapter 5.

When the geometry is completed one can start to establish settings for the intended dispersion simulations. The settings which are relevant for this thesis are as follows:

- Monitor points
- Single field scalar output
- Single field 3D output
- Simulation and output control
- Boundary conditions
- Initial conditions
- Gas composition
- Leaks

There are many variables and parameters in the different settings, but only those who are relevant regarding this thesis will be mentioned.

[4] Computer Aided Scenario Definition

[5] Plan Design Management System, a 3D Computer-aided design program

4.2.1.1 Monitor points

Monitor points are user defined locations in the simulation domain where one or more variables are to be monitored during the simulation (GexCon, 2009). The number and position of monitor points must be determined. When monitor points are defined the variables to be monitored must be specified, see subchapter 4.2.2 and 4.2.3. At the beginning one can distribute the monitor points randomly. After some simulations some monitor points will turn out to be useless and these can be removed. The number and position of monitor points can gradually be adjusted to the gas dispersions which appear during the simulations.

4.2.1.2 Single field scalar output

This setting allows the user to specify output variables. For each output variable, the user may enter one or more numbers indicating the monitor point number(s) (GexCon, 2009). For dispersion calculations volume gas concentration (FMOLE), lower flammability limit (ERLFL) and flow velocity (UVW) may be used as variables.

4.2.1.3 Single field 3D output

This is an output facility in FLACS which enables the user to generate plots of the spatial distribution of the variables at different moments in time (GexCon, 2009). For dispersion FMOLE and WEC will be the most common variables to report, (GexCon, 2009). The directional velocities U, V and W are included in the velocity vector WEC.

4.2.1.4 Simulation and output control

This setting allows the user to specify parameters for general simulation and output control. TMAX is the maximum time interval (seconds) that the simulation will last (GexCon, 2009). DTPLOT is the time interval (in seconds) for field output (GexCon, 2009).

4.2.1.5 Boundary conditions

In the boundary conditions settings one can specify boundary conditions for the outer boundaries of the simulation domain. One can determine wind speed and wind direction using these settings. The lower boundaries in X-Y- and Z-direction are denoted by XLO, YLO and ZLO respectively, and the upper boundaries likewise by XHI, YHI and ZHI (GexCon, 2009). Wind and Nozzle are boundary conditions which will be used in dispersion simulations regarding this thesis. If one wants a wind direction from the negative x-axis direction to the positive x-axis direction XLO must be denoted as “Wind” and XHI must be denoted as “Nozzle”.

4.2.1.6 Initial conditions

In the initial conditions setting one can determine values for temperature, pressure and turbulence fields at the beginning of the simulation. Information about the gravity conditions, parameters for the atmospheric boundary layer and the composition of the air can also be determined (GexCon, 2009).

4.2.1.7 Gas composition and volume

Using this setting one can define a box shaped cloud region, the gas concentration and composition (GexCon, 2009). Specification of gas components and volume fractions will be most useful in this application.

4.2.1.8 Leaks

This setting allows the user to define leak location, leak direction, start time of leak and duration.

4.2.2 FLACS Run Manager

In the FLACS Run Manager runs an inventory of the different dispersion simulations. Here one can initiate and stop dispersion simulations. The progress of a running simulation can be monitored using the FLACS Run Manager. Plots of pressure [barg], velocity [m/s] and fuel [kg] against time are shown. Lists of information from each dispersion simulation are provided as well, such as input files, output files and output variables.

4.2.3 FLACS post-processor

Flowvis is the postprocessor for the CFD-code FLACS and is a program for visualizing results from computer aided simulations of gas explosions, gas dispersion and multi phase flow (GexCon, 2009). For instance, a plot of the movement of escaped gas in a module along with its flammability limits.

5 FLACS Simulations

This chapter will provide an introduction to a set of FLACS simulations which will be carried out. Objective of the simulations will be presented in chapter 5.1. Scenario definitions regarding 3D geometry, alarm limits, measuring points and parameters will be introduced in chapter 5.2.

5.1 Objective

The objective of the FLACS simulations to be performed is to illustrate, describe and discuss how physical factors such as wind speed, wind direction, leak location, leak direction, leak rate and gas composition interacts with the geometrical layout of a module and influence the behaviour of released gas, which again determine the best suited positions of the gas detectors. The effect an increasing number of monitor points has on the detection time will be examined as well. Results from the simulations will be used in the evaluation of in which degree different physical factors affect the functionality and reliability of a gas detection system.

5.2 Scenario definitions

5.2.1 Scenario geometry

An offshore module 28m long, 12m wide and 8m high with two floors will be used in the FLACS simulations. Figure 11 shows the geometrical layout of the module. The module is open at the shorts sides and in the middle of one of the long sides. Figure 12 below shows the roof of the module in the xy-plane in CASD. The long side with an opening is at the top in the figure. This module is used for testing purposes and wasn't developed in connection with this thesis.

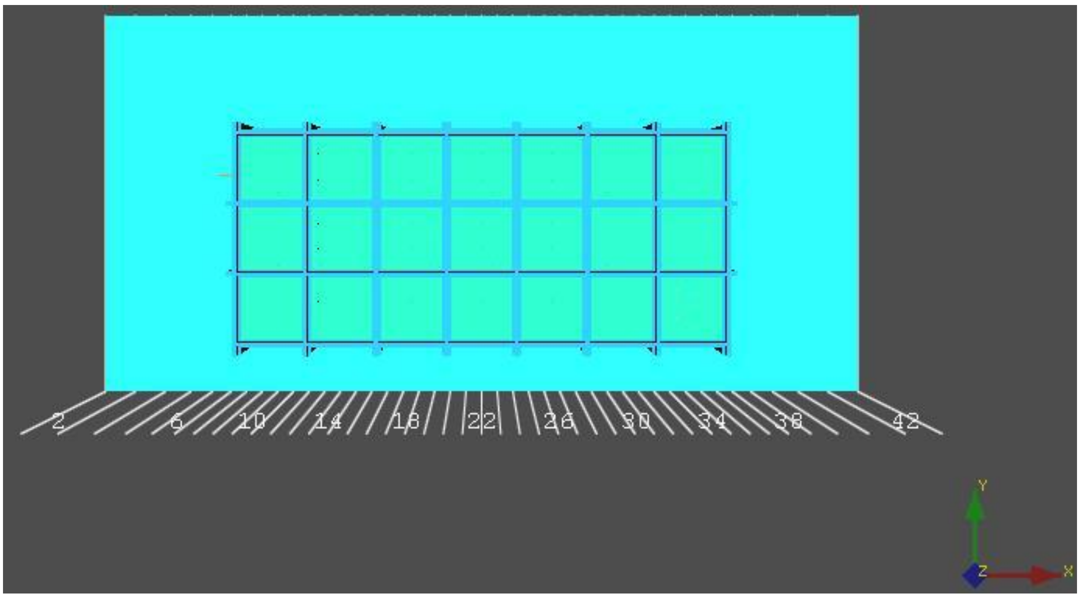

Figure 12, Module in xy-plane in CASD

5.2.2 Simulation parameters

In order to limit the number of simulations and amount of data one leak location will be applied. The coordinates of the leak are x=23, y=6, z=2, ergo the leak is located in the ground floor. Table 11 below provides an overview of the simulations to be performed. As one can see 7 simulations will be performed with variation in parameters such as leak rate, leak direction, gas composition, wind speed and wind direction for each simulation are shown.

Simulations

Simulation	Leak rate [kg/s]	Leak direction	Gas composition	Wind speed [m/s]	Wind direction
1	2	-X	Methane	5	+X
2	4	-X	Methane	5	+X
3	2	+Y	Methane	5	-X
4	2	+Y	Methane	5	+X
5	2	+Y	Methane	5	-Y
6	2	-X	Methane	3	+X
7	2	-X	Ethane/Propane	5	+X

Table 11, Simulation data

The start time of the gas leak is set to 5 seconds after simulation initialization because the wind needs some time to establish its effects on the module. TMAX is set to 80 seconds but simulations may be ended before one reaches this limit due to possible steady states where the supply of gas equals ventilated gas. The leak rate in a given simulation will be kept constant because pressure drop in the process system is disregarded.

5.2.3 Alarm limits

Low alarms and high alarms in the simulations are defined as shown in table 12 below. The low alarm limit is determined as 20% LFL and the high alarm limit is determined as 40% LFL.

Alarm type	% LFL
Low alarm	20
High alarm	40

Table 12, Alarm limits in simulations

5.2.4 Monitor points

336 monitor points are distributed throughout the module in 4 different height levels. Figures 13, 14, 15 and 16 show the monitor points at their respective height levels in the xy-plane.

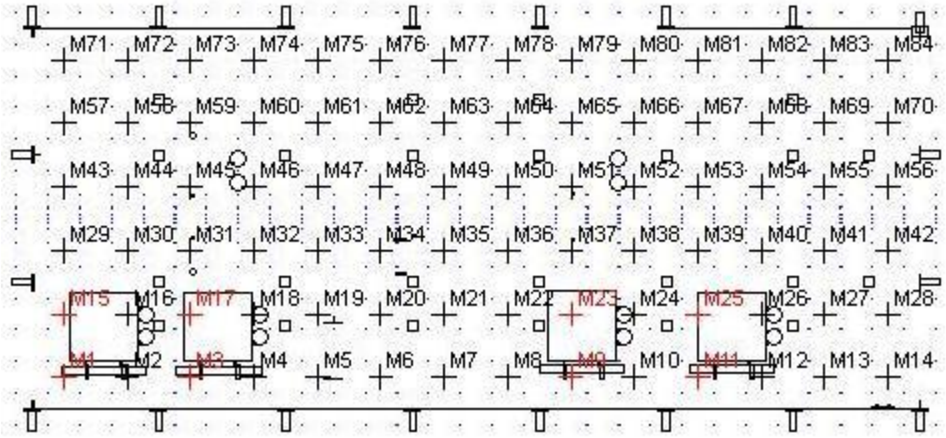

Figure 13, Monitor points 1-84, Z=1,3m (Flowvis)

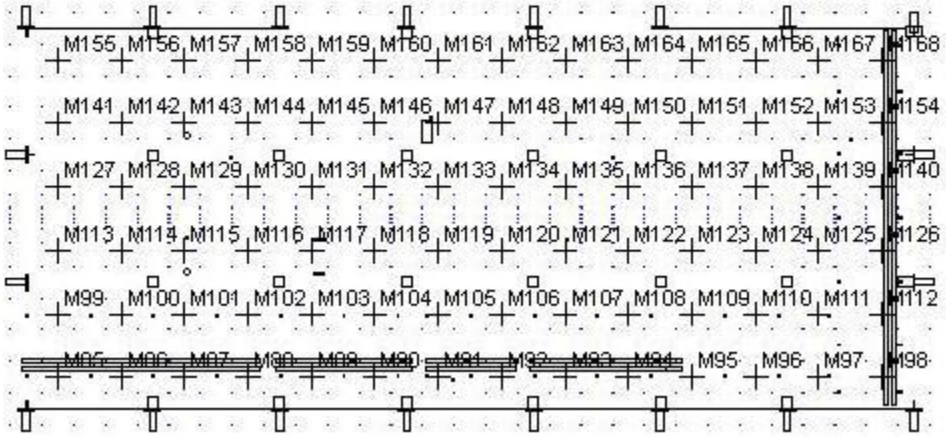

Figure 14, Monitor points 85-168, Z=3,5m (Flowvis)

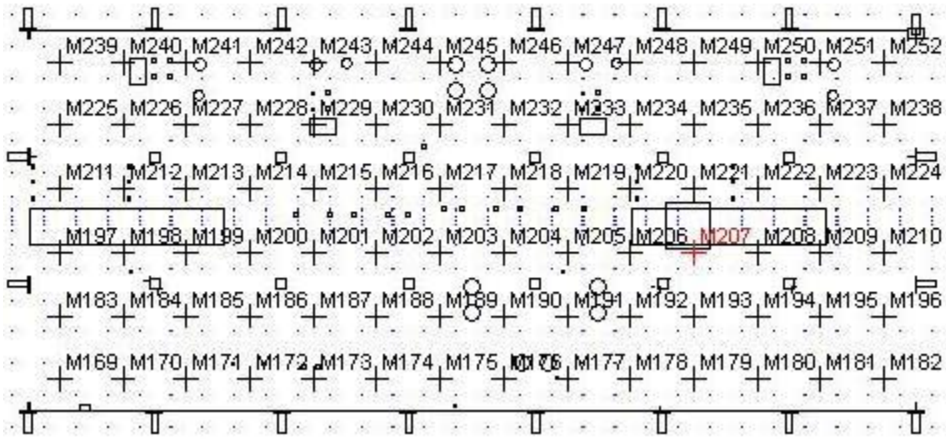

Figure 15, Monitor points 169-252, Z=6m (Flowvis)

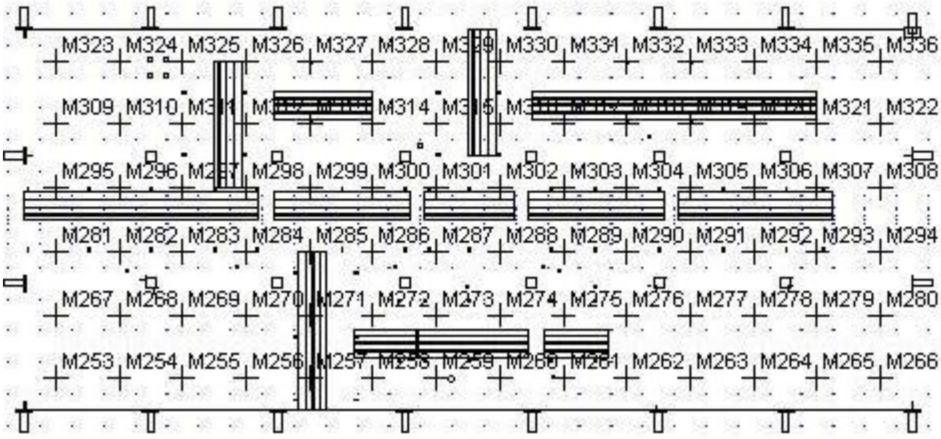

Figure 16, Monitor points 253-336, Z=8m (Flowvis)

To start with, 5 monitor points will be chosen and information about the time which is needed for each monitor point to reach low alarm and high alarm will be gathered. The number of monitor points will increase by 5 until one reach 35 monitor points. Will an increasing number of monitor points have an effect on the detection time with respect to low alarm and high alarm?

6 Results from FLACS simulations

This chapter will present results from the 7 FLACS simulations which have been carried out. Plots of % LFL, wind speed and wind direction against time in the module will be presented for each simulation in chapter 6.1. Chapter 6.2 will introduce graphical representations of the detection time with respect to low alarm and high alarm against the increasing number of monitor points for each simulation. A graph with the average detection time against monitor points will be presented as well.

6.1 Plots from simulations

All simulations reached their steady state within 40 seconds and were ended shortly after.

6.1.1 Simulation 1

Figure 17 shows simulation 1 in the xy-plane 10 seconds after initiation and 5 seconds after leak start-up. The leak is directed in negative x-direction, but some gas flows in positive x-direction due to wind. The ERLFL measurements indicate that escaped gas get concentrated in the centre of the module. Red areas have high gas concentrations while yellow and green have intermediate concentrations. Blue areas have low gas concentrations. One can see that areas with gas concentrations corresponding to 20% and 40% LFL are colored in light blue and light green.

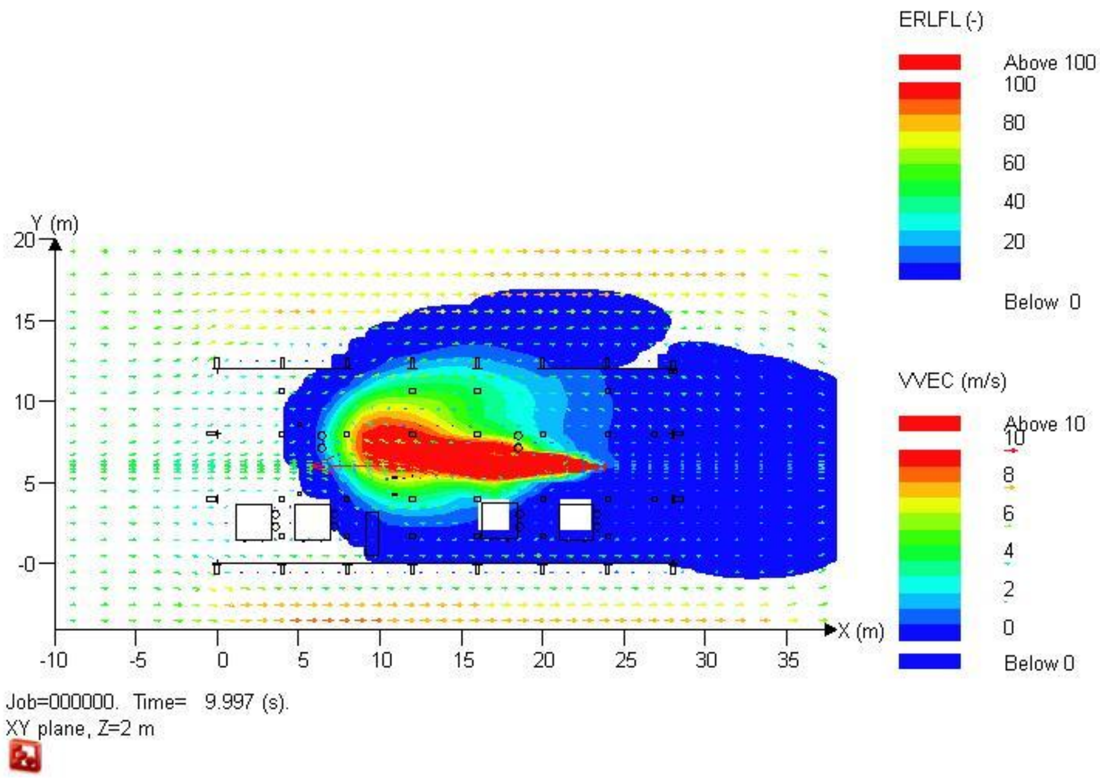

Figure 17, Simulation 1 in the xy-plane 10 seconds after initiation (Flowvis)

Figure 18 shows simulation 1 in the xy-plane 40 seconds after initiation. At this time steady state had been reached and simulation was ended. The gas amount inside the module has increased compared to figure 17. Areas with high and intermediate gas concentrations have increased while areas with low gas concentrations have creased. It seems that the area with intermediate gas concentrations is being pushed by the wind in the positive x-direction while the area with high gas concentrations is stagnant and less influenced by the wind.

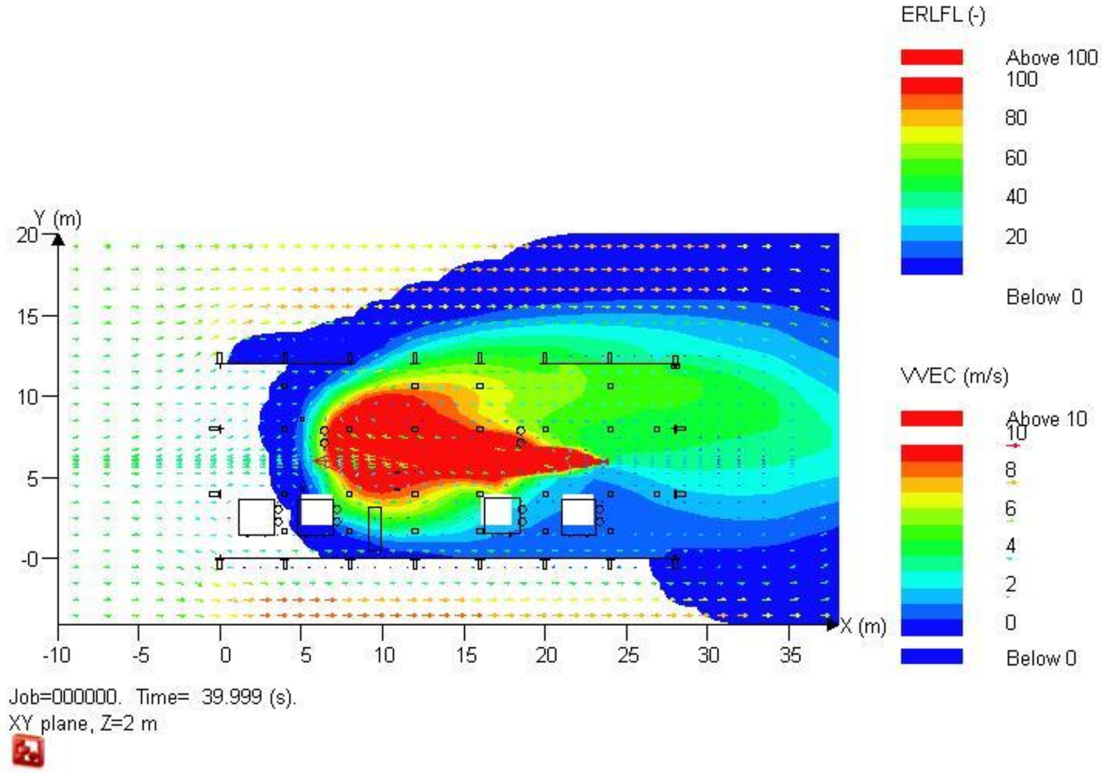

Figure 18. Simulation 1 in the xy-plane 40 seconds after initiation (Flowvis)

Figure 19 on next page shows simulation 1 in the xz-plane 40 seconds after initiation. When the escaped gas reaches a certain distance from the leakage point air currents change the direction of the flow due to low momentum in the flow and the gas is dispersed in positive x-direction. As one can see from table 9 only methane is released in this simulation while ethane and propane are released in simulation 7. A plot of simulation 7 in the xz-plane will be presented in chapter 6.1.7.

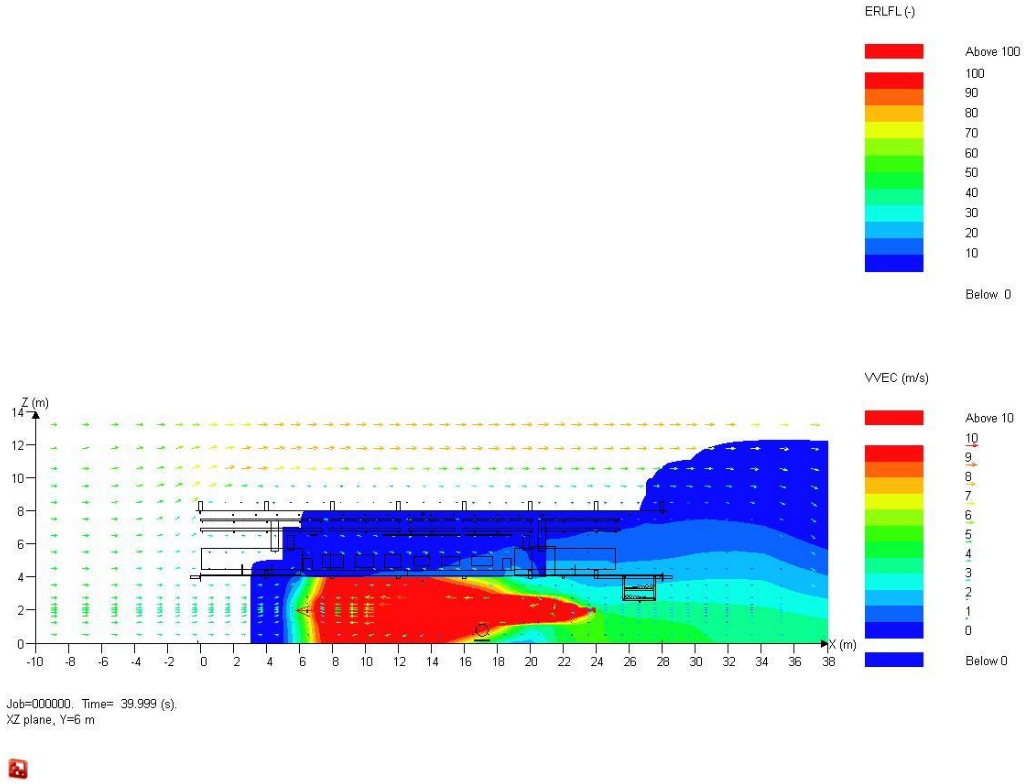

Figure 19, Simulation 1 in the xz-plane 40 seconds after initiation (Flowvis)

6.1.2 Simulation 2

Figure 20 on next page shows simulation 2 in the xy-plane 10 seconds after initiation. According to table 9 the leak rate is doubled to 4 kg/s compared to simulation 1. The high concentration zone has the same size which simulation 1 needed 40 seconds to achieve.

Figure 21 on next page shows simulation 2 in the xy-plane 40 seconds after initiation. Zones with high and intermediate concentrations fill the whole module. In this plot one can see the same tendency as in figure 18, areas with intermediate gas concentrations are pushed in the positive x-direction by the wind.

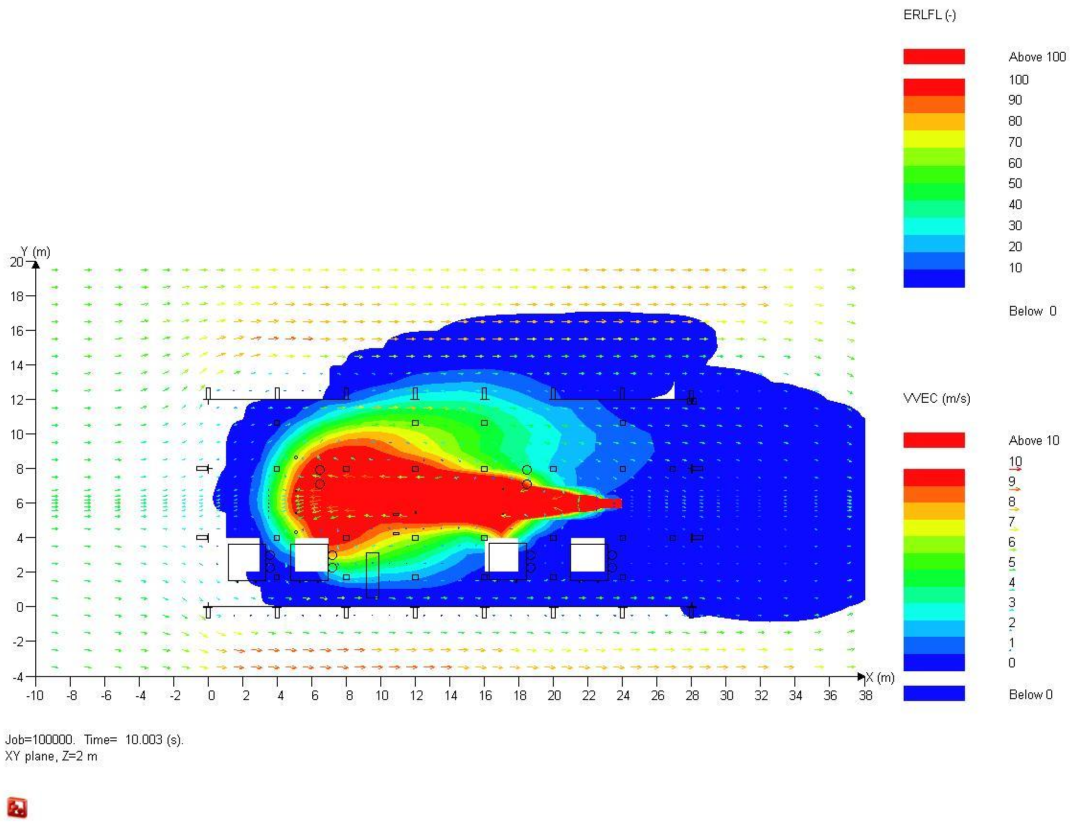

Figure 20, Simulation 2 in the xy-plane 10 seconds after initiation (Flowvis)

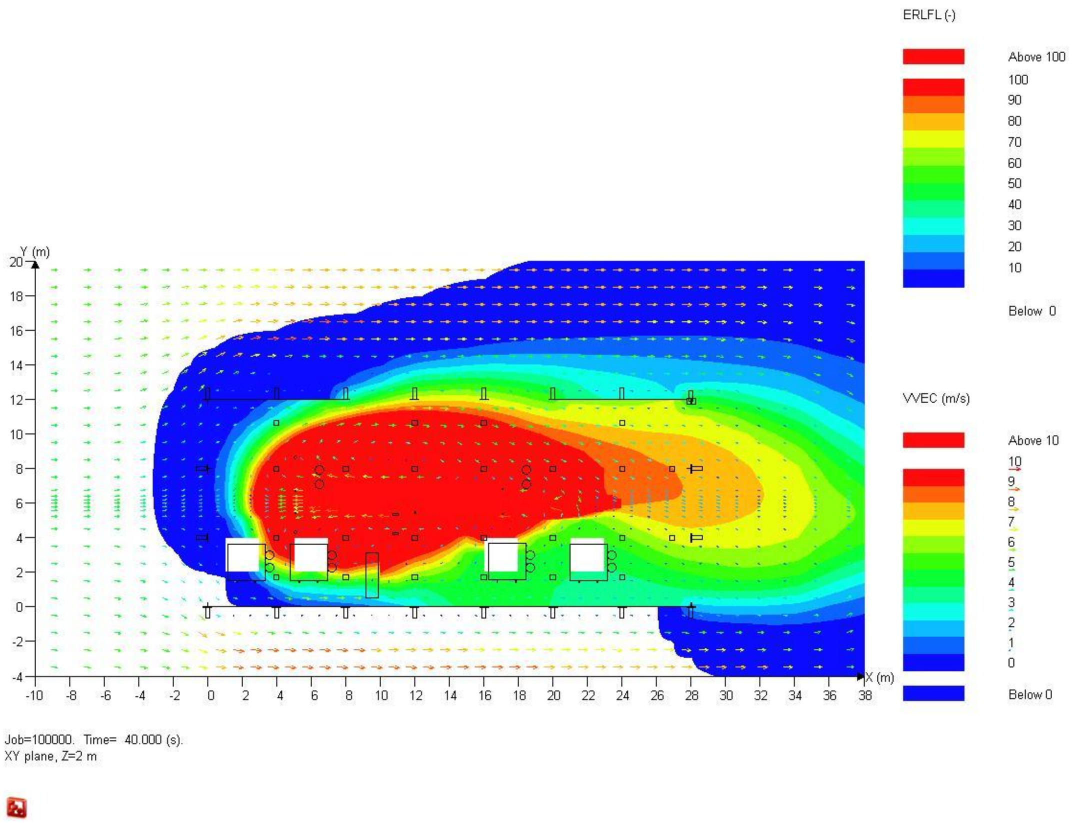

Figure 21, Simulation 2 in the xy-plane 40 seconds after initiation (Flowvis)

6.1.3 Simulation 3

Figure 22 shows simulation 3 in the xy-plane 10 seconds after initiation. The leak direction is in positive y-direction. Some gas is forced in the negative x-direction by wind, but most of the gas remains concentrated in a limited area.

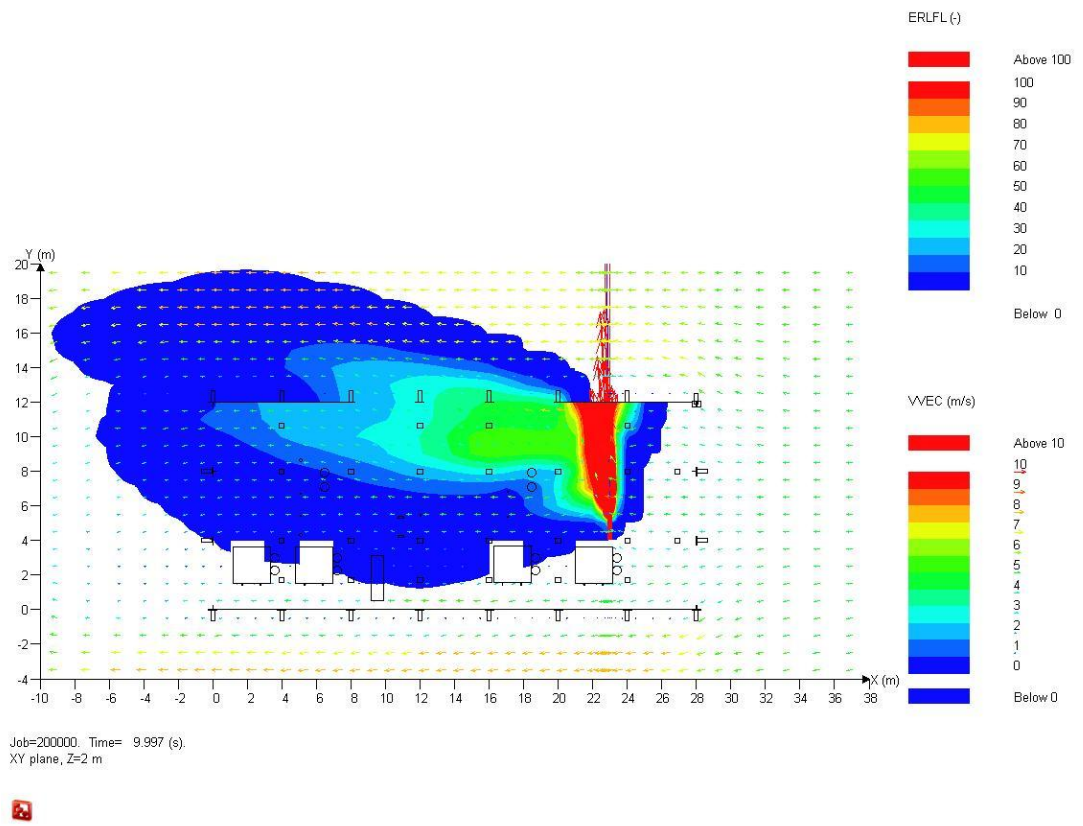

Figure 22, Simulation 3 in the xy-plane 10 seconds after initiation (Flowvis)

Figure 23 on next page shows simulation 3 in the xy-plane 40 seconds after initiation. One can see that the zone with intermediate concentrations has increased in the negative x-direction while the zone with high concentrations remains unchanged.

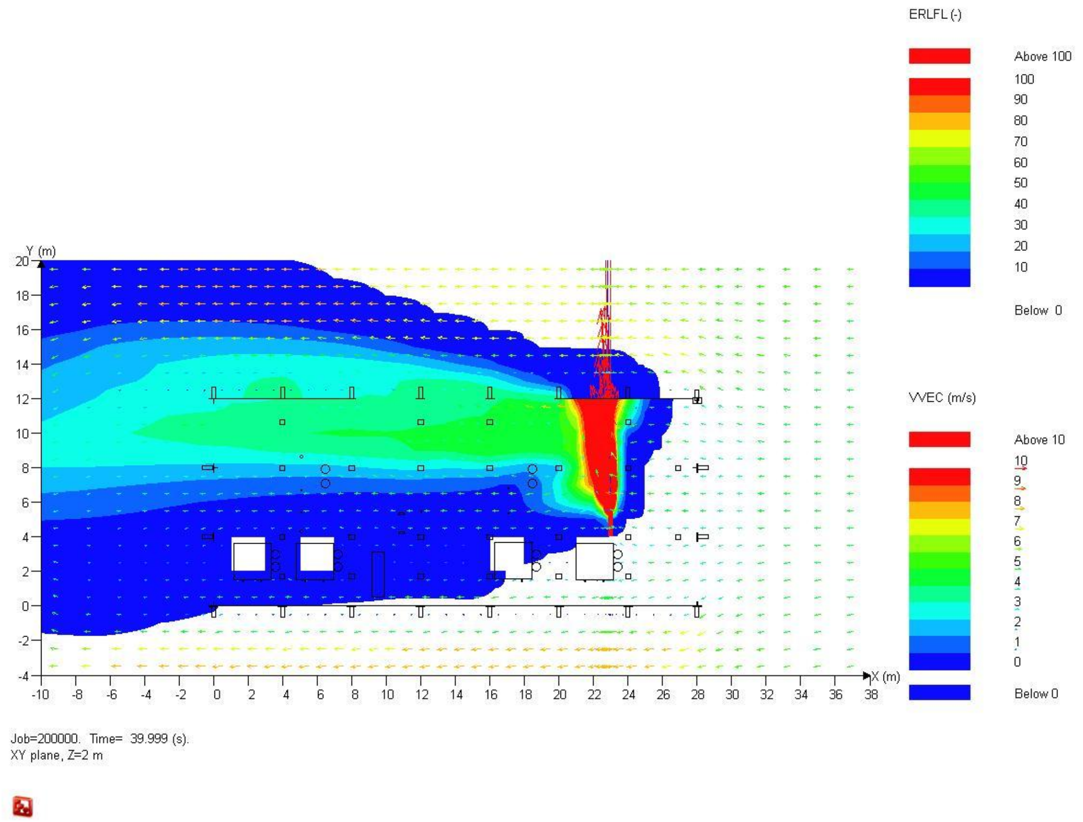

Figure 23, Simulation 3 in the xy-plane 40 seconds after initiation (Flowvis)

6.1.4 Simulation 4

Figure 24 shows simulation 3 in the xy-plane 10 seconds after initiation. The wind goes in opposite direction compared with simulation 3. A small area in the module has gas concentrations within the alarm limits. Wind in positive x-direction prevents gas dispersion in negative x-direction.

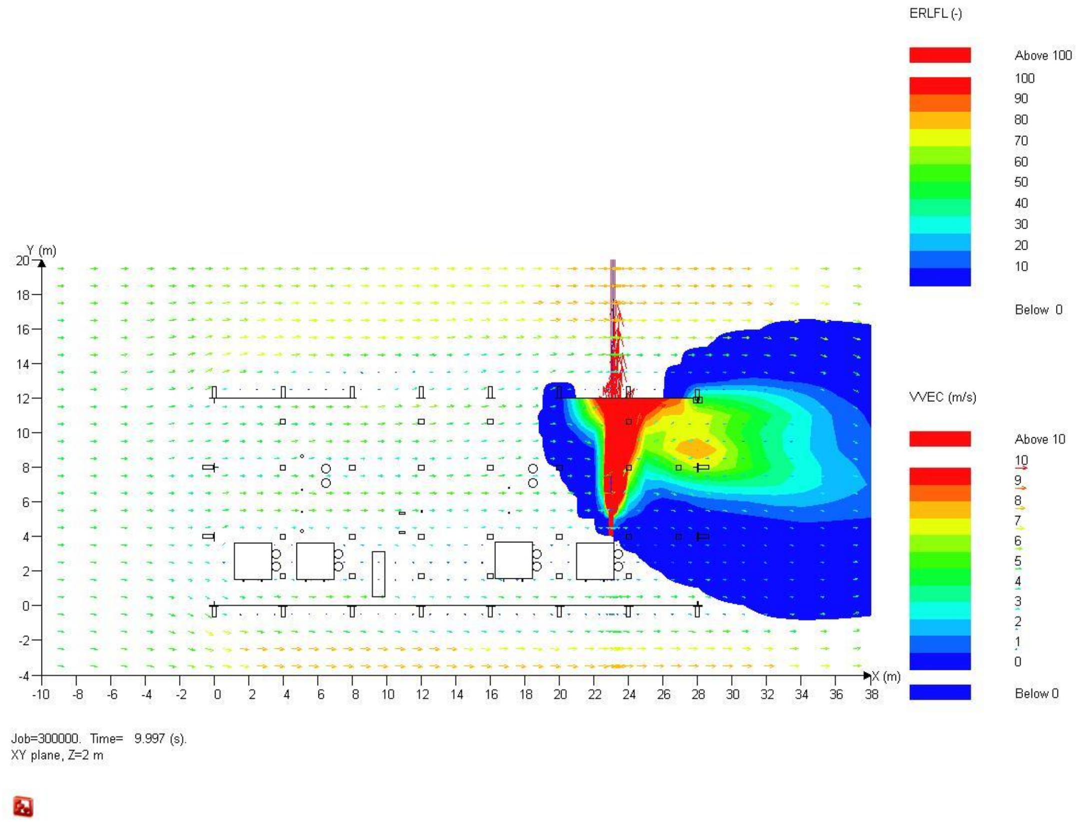

Figure 24, Simulation 4 in the xy-plane 10 seconds after initiation (Flowvis)

Figure 25 shows simulation 4 in the xy-plane 35 seconds after initiation. There are only minor changes in the gas dispersion compared to 25 seconds earlier. This leak has reached steady state at an early stage.

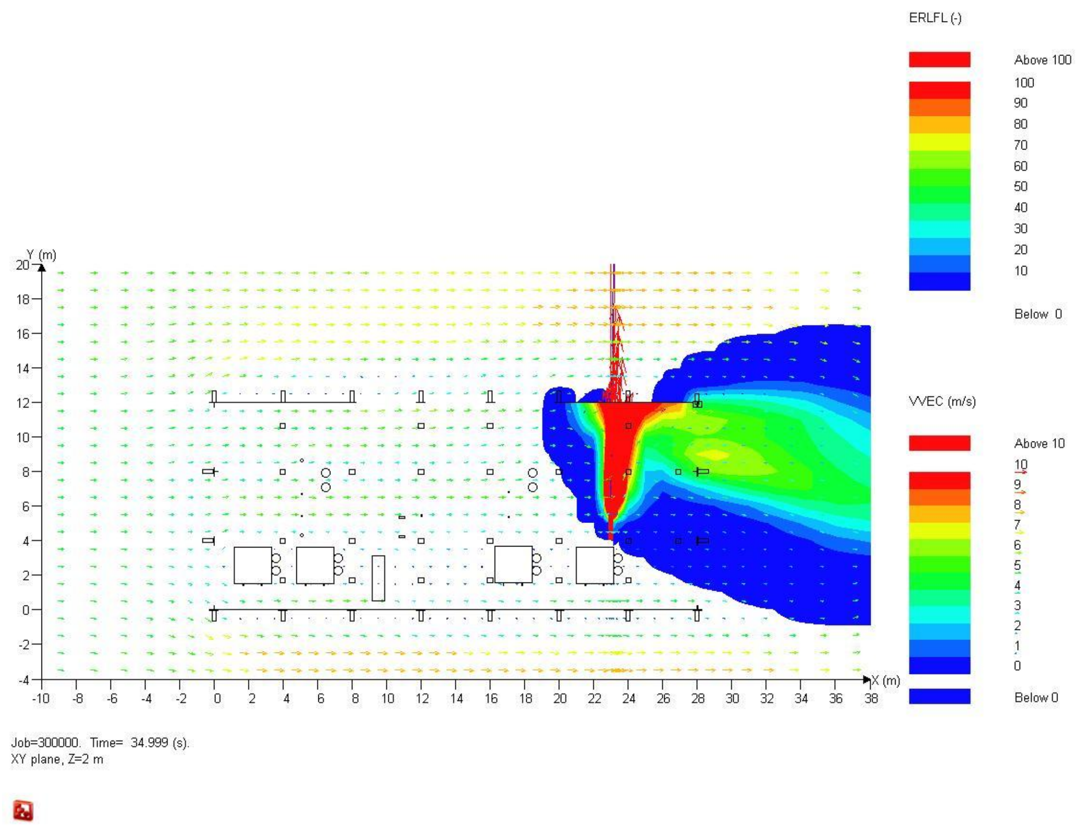

Figure 25, Simulation 4 in the xy-plane 35 seconds after initiation (Flowvis)

6.1.5 Simulation 5

Figure 26 shows simulation 5 in the xy-plane 10 seconds after initiation. The gas leak has the same direction as simulation 3 and 4, but the wind direction is different. Wind in negative y-direction prevents gas dispersion in negative x-direction. Most of the escaped gas is concentrated in a limited area. When entering the opening at the long side the wind gets a curve in positive x-direction. This simulation shows how the wind direction can be changed due to interaction with the module geometry.

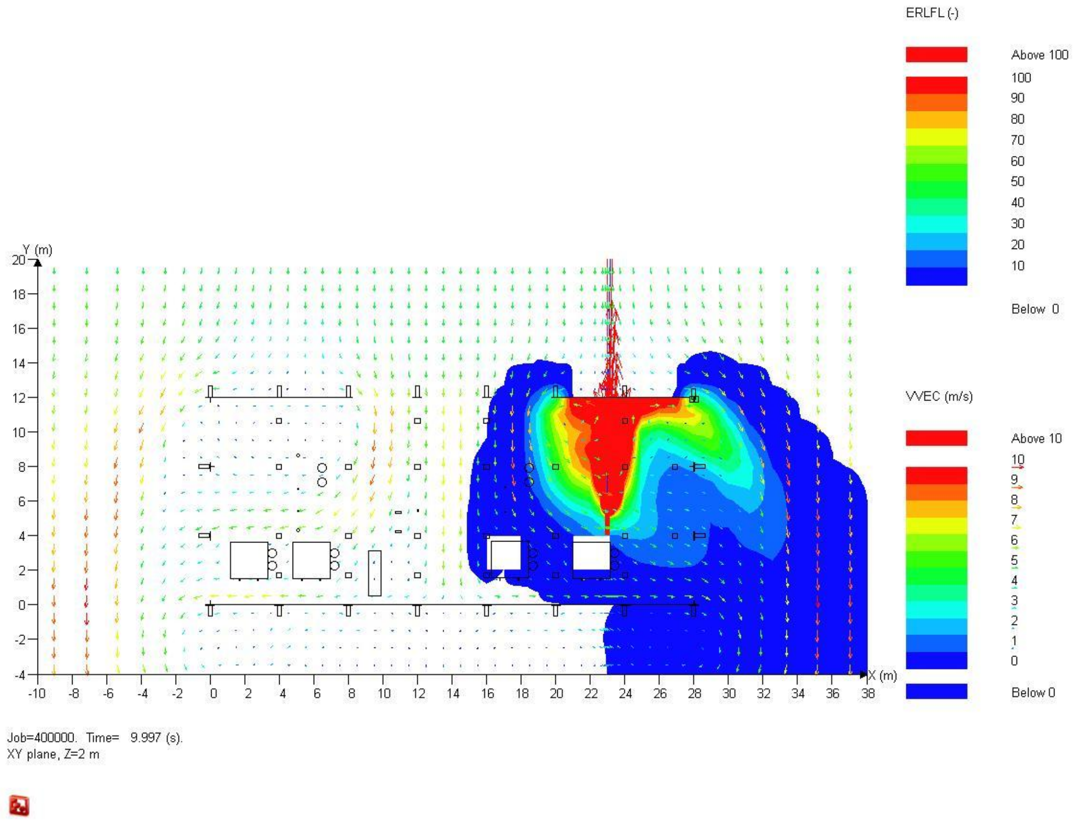

Figure 26, Simulation 5 in the xy-plane 10 seconds after initiation (Flowvis)

Figure 27 on next page shows simulation 5 in the xy-plane 40 seconds after initiation. There are only minor changes in the high concentration area while the intermediate concentration area has a more evident increase compared to figure 26.

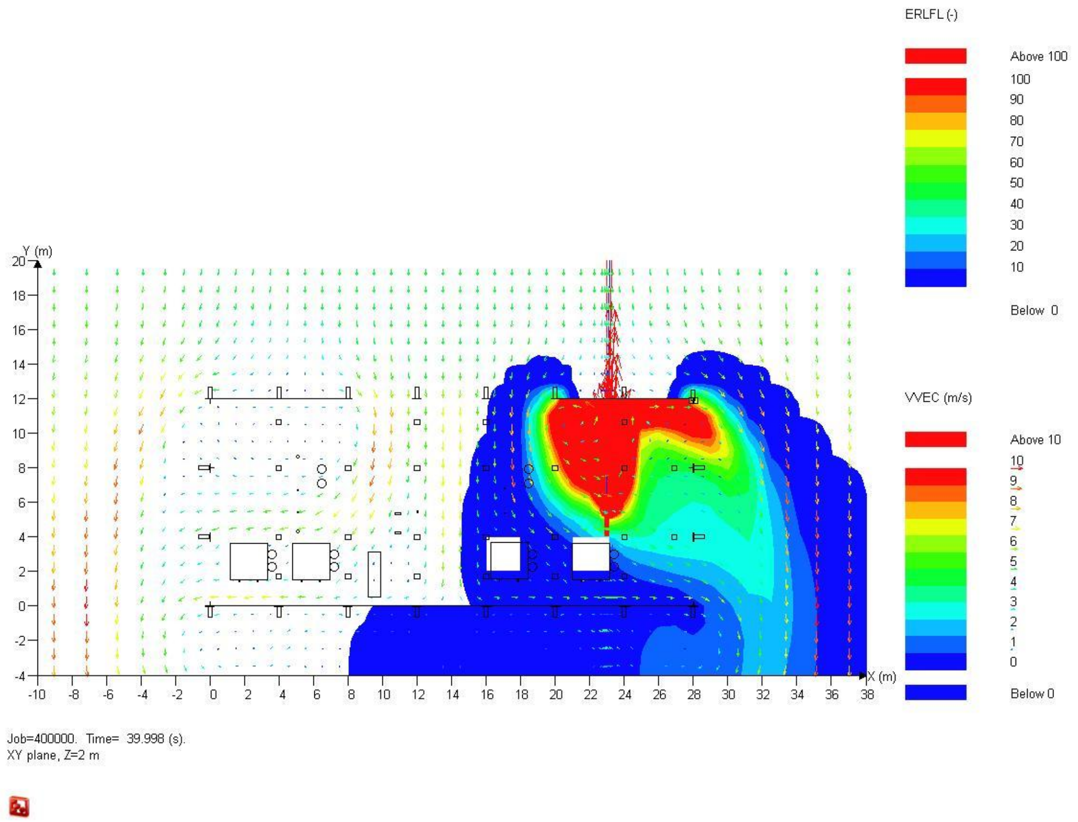

Figure 27, Simulation 5 in the xy-plane 40 seconds after initiation (Flowvis)

6.1.6 Simulation 6

Figure 28 and 29 on next page show simulation 6 in the xy-plane 10 and 40 seconds after initiation. The scenario is almost identical to simulation 1 with same leak direction, leak size, wind direction and gas composition, but the wind speed is reduced to 3 m/s.

Compared to figure 17 (Simulation 1 after 10 seconds) the gas leak in figure 28 seems to be less affected by the wind. The high concentration area reaches a longer distance than in simulation 1. The leak is more resistant against low winds speeds and escaped gas keep concentrated in a small flow. After 40 seconds there are clearly more gas in the module in simulation 6 (figure 29) compared to simulation 1 (figure 18). Lower wind speed has reduced the ventilation effects made by the wind and thus less gas is lead out from the module. This results in increased area with high gas concentrations.

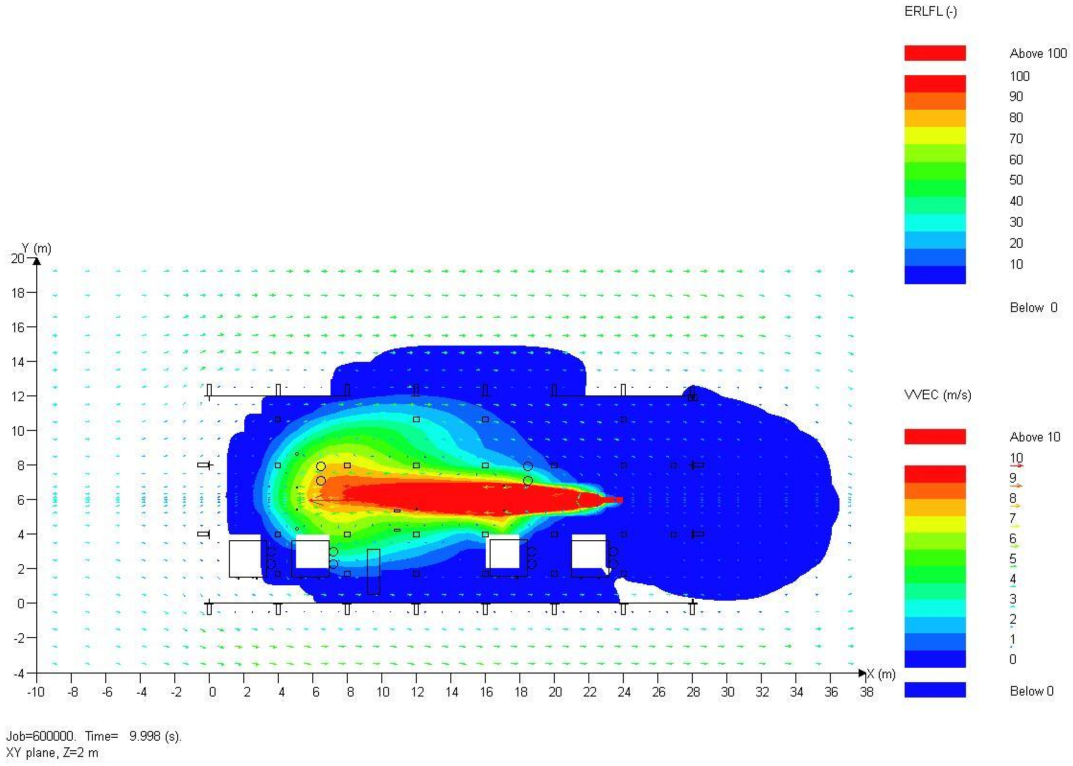

Figure 28, Simulation 6 in the xy-plane 10 seconds after initiation (Flowvis)

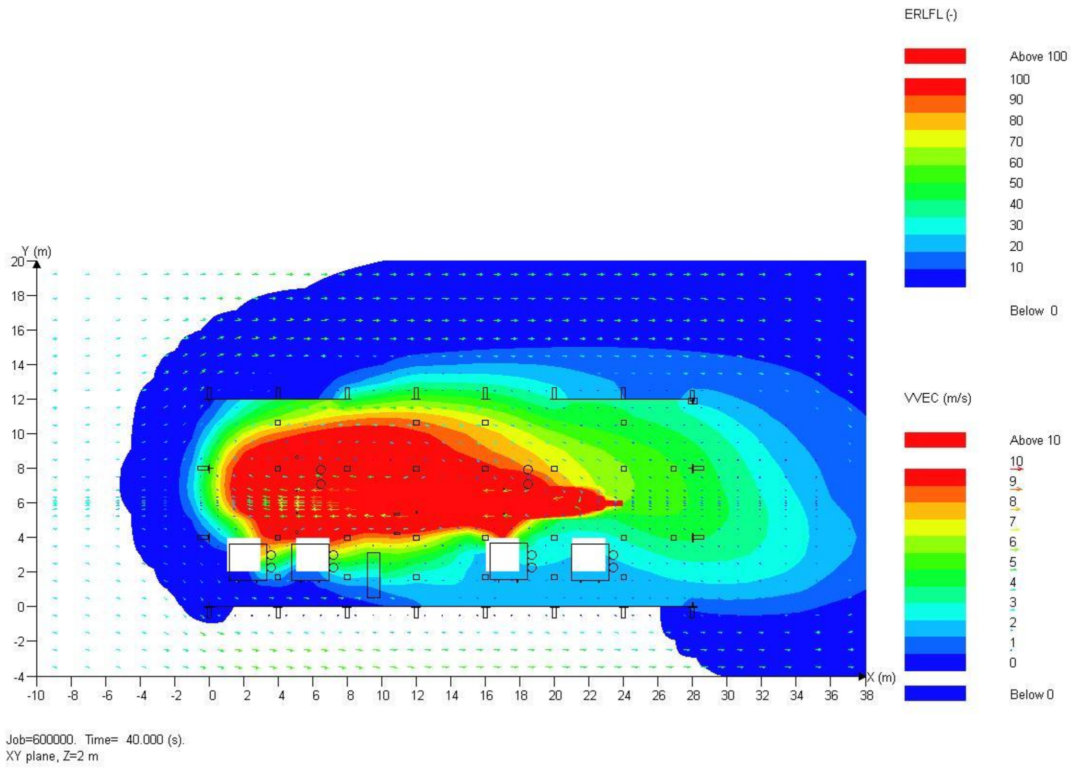

Figure 29, Simulation 6 in the xy-plane 40 seconds after initiation (Flowvis)

6.1.7 Simulation 7

Figure 30 and 31 show simulation 7 in the xy-plane 10 and 40 seconds after initiation. The gas composition is changed to 50% ethane and 50 % propane compared to simulation 1 with 100 % methane.

Compared to figure 17 (Simulation 1 after 10 seconds) the escaped gas in figure 30 is more concentrated. The new gas composition leads to increased vapour density (table 8) and thus the dispersion ability of the escaped gas gets affected. Figure 31 on next page shows minor changes in the area with high concentrations even 35 seconds after leak start-up while the area with intermediate concentrations has increased considerably. The escaped gas gets dispersed in positive x-direction due to wind in the same direction.

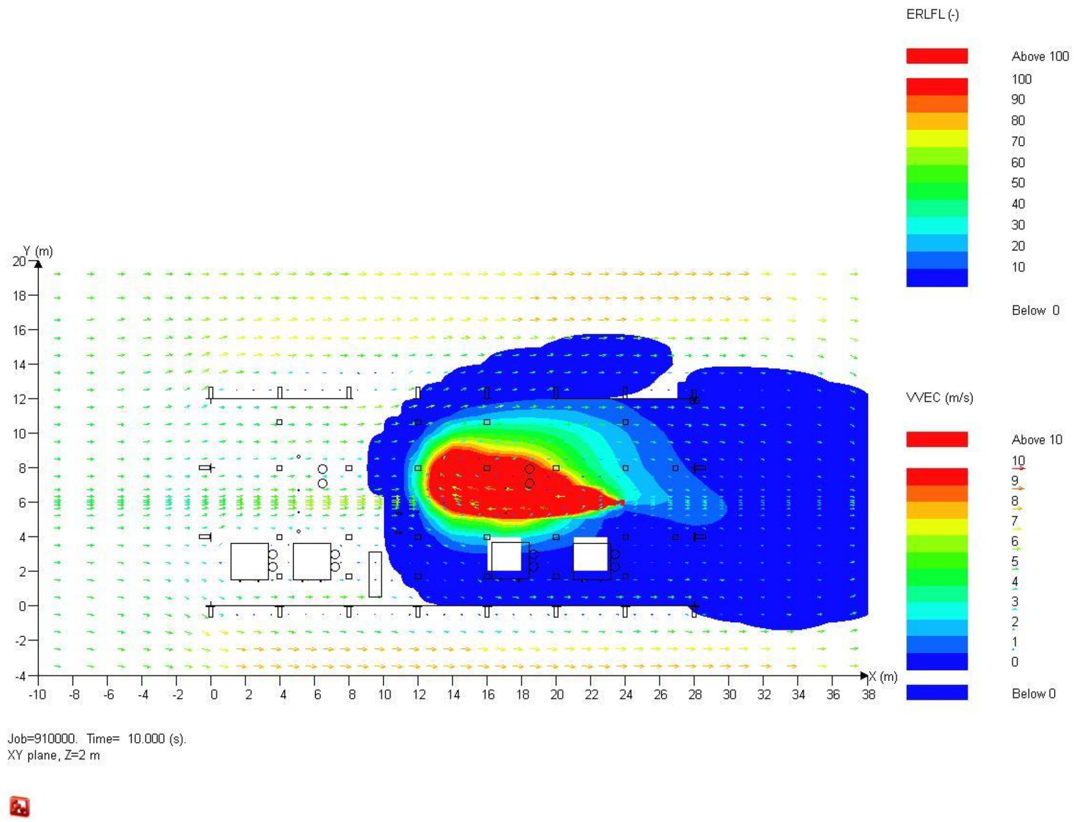

Figure 30, Simulation 7 in the xy-plane 10 seconds after initiation (Flowvis)

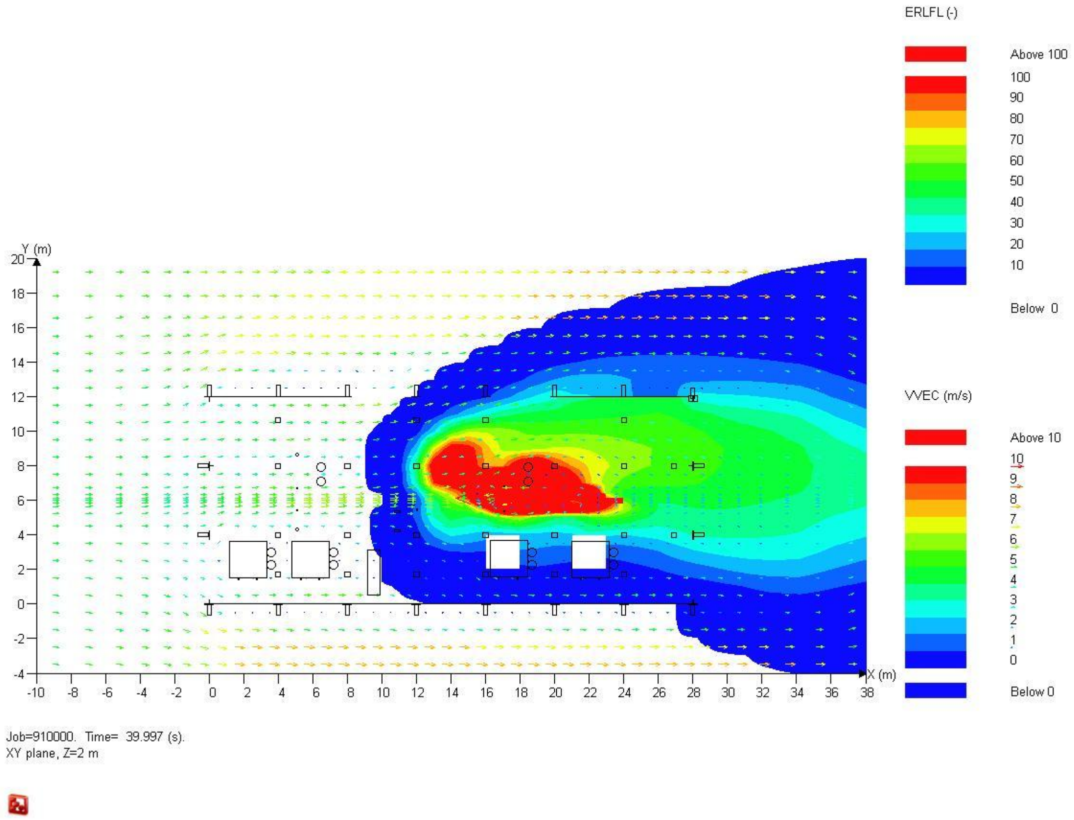

Figure 31, Simulation 7 in the xy-plane 40 seconds after initiation (Flowvis)

Figure 32 shows simulation 7 in the xz-plane 40 seconds after initiation. Compared to figure 19 (Simulation 1 in the xz-plane after 40 seconds) the escaped gas gets less dispersed in the module and remains more stagnant due to heavier components. One can see that the escaped gas tends to rise to the ceiling even though both ethane and propane have vapour density higher than 1, see table 8. This indicates that the dispersion of escaped gas in this scenario is more influenced by air currents than its vapour density.

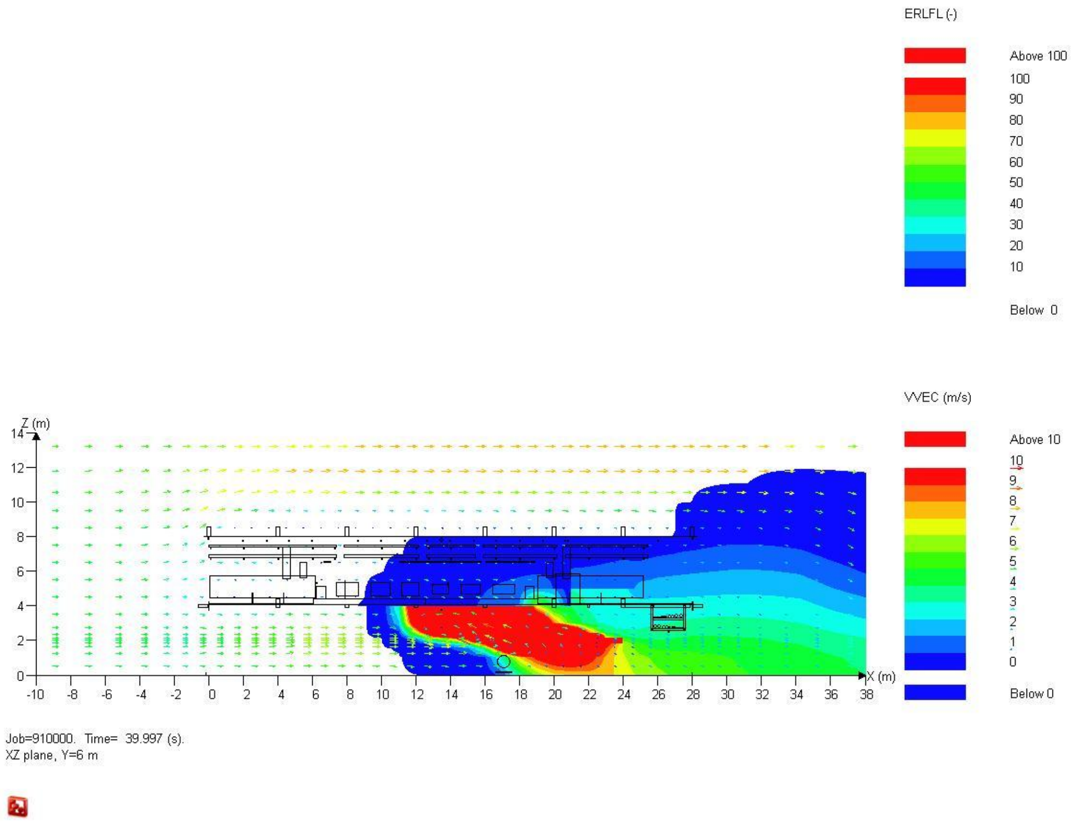

Figure 32, Simulation 7 in the xz-plane 40 seconds after initiation (Flowvis)

7 simulations have been carried out with variation in following 5 parameters: Leak rate, leak direction, gas composition, wind speed and wind direction. Several plots haven been presented in order to illustrate how variation in different parameters affects the gas dispersion. The number of simulations performed in connection with this thesis is very limited compared to industrial practice. Given this limited number of simulations an evaluation of the different parameters with respect to their degree of impact on the gas dispersion will be done.

The gas composition seems to affect the compactness of the escaped gas. By comparing plots from simulation 1 (methane) and simulation 7 (ethane and propane) one can see that the escaped gas in simulation 1 is more dispersed than in simulation 7. The only difference between these simulations is the gas composition. The compactness of the escaped gas in simulation 7 can be explained by increased resistance against wind due to increased density. Even if ethane and propane have vapour densities higher than 1 the escaped gas in simulation 7 tends to rise to the ceiling. Given these observations based on a limited number of simulations it seems that geometry and wind are dominating physical factors compared to the vapour density. The effects of density may increase with the distance from the leak location.

By comparing plots from simulation 1 with simulation 2 one can see how the amount of gas inside the module is influenced by the leak rate. A doubling of leak rate in simulation 2 resulted in an area with high gas concentration equivalent to simulation 1 within a fourth part of the time. After 40 seconds over 50% of the module is filled with a high concentration zone with respect to the LFL.

As can be seen from the plots variation in the leak direction had a significant impact on the amount of gas inside the module. In the simulations where the leak was in negative x-direction much more gas was observed inside the module compared to simulations with the leak in positive y-direction. Especially areas with high and intermediate gas concentrations had a clearly reduction in size when the leak was directed in positive y-direction.

The wind direction seems to have minor influence on areas with high gas concentration. In simulation 3, 4 and 5 where the leak was in positive y-direction the area with high gas concentration remained almost unchanged with variation in wind direction. Areas with low and intermediate gas concentrations on the other hand were considerably influenced by the wind direction.

By studying the plots from simulation 1 and 7 reduced wind speed seems to reduce the ventilation effects and as a result of this more gas gets accumulated inside the module.

6.2 Detection time versus monitor points

6.2.1 Simulation 1

Figure 33 shows the detection time with respect to low (20% LFL) and high (40% LFL) alarm against increasing number of monitoring points for simulation 1. A small reduction in detection time for low alarm is observed and the curve flattens out at 30 and 35 monitor points. Compared to the detection time for low alarm the detection time for high alarm has a big reduction, and the curve is still sloping at 35 monitor points.

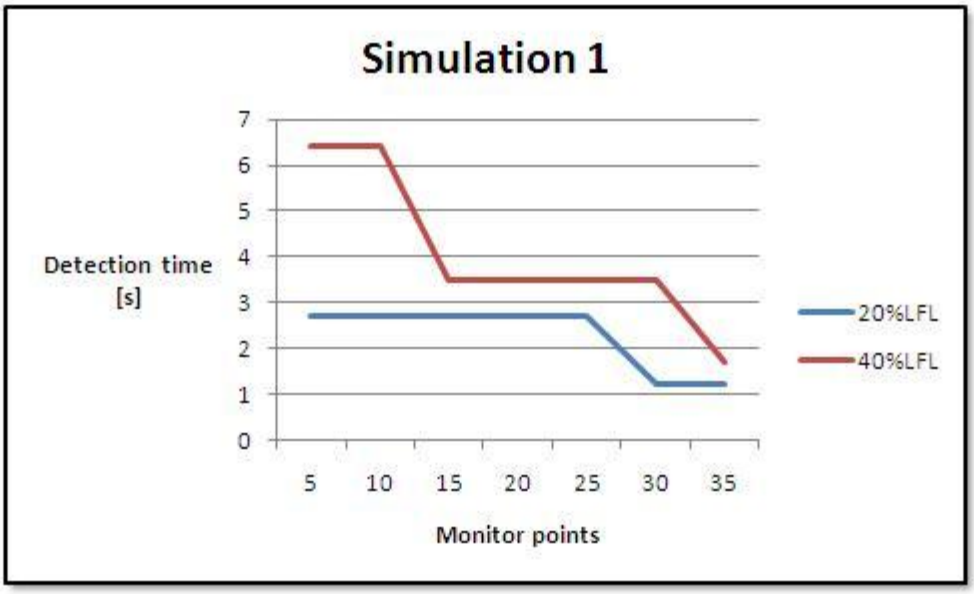

Figure 33, Detection time with respect to low and high alarm against increasing number of monitor points, simulation 1

6.2.2 Simulation 2

Figure 34 shows the detection time with respect to low and high alarm against increasing number of monitoring points for simulation 2. The reduction in the detection time for high alarm is more abrupt than the curve for low alarm up to 15 monitor points. After that the curves goes parallel all the way to 35 monitor points where they have flatten out.

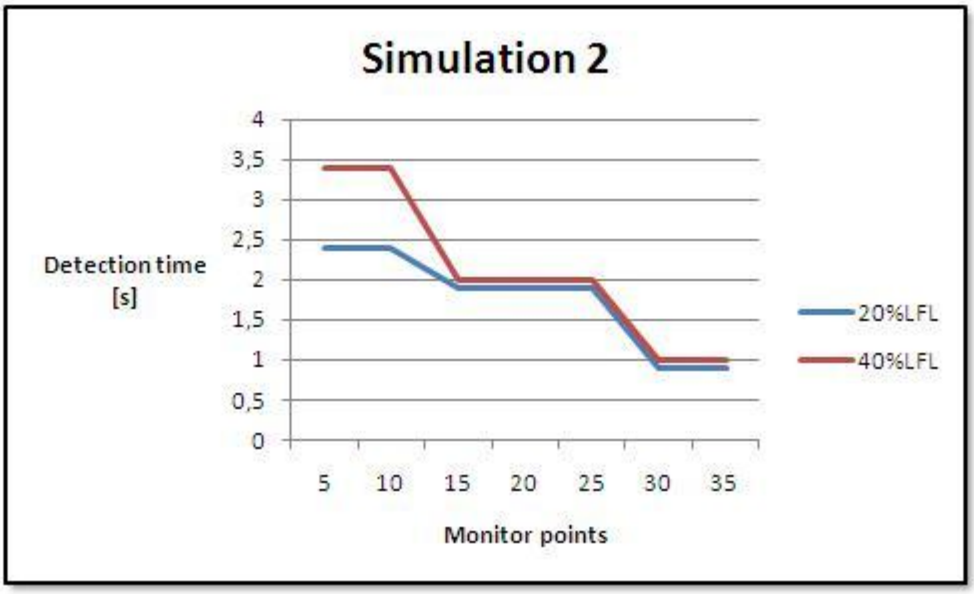

Figure 34, Detection time with respect to low and high alarm against increasing number of monitor points, simulation 2

6.2.3 Simulation 3

Figure 35 shows the detection time with respect to low and high alarm against increasing number of monitoring points for simulation 3. The curve of the low alarm sinks more than the curve of the high alarm. Both of the curves flatten out after 30 monitor points.

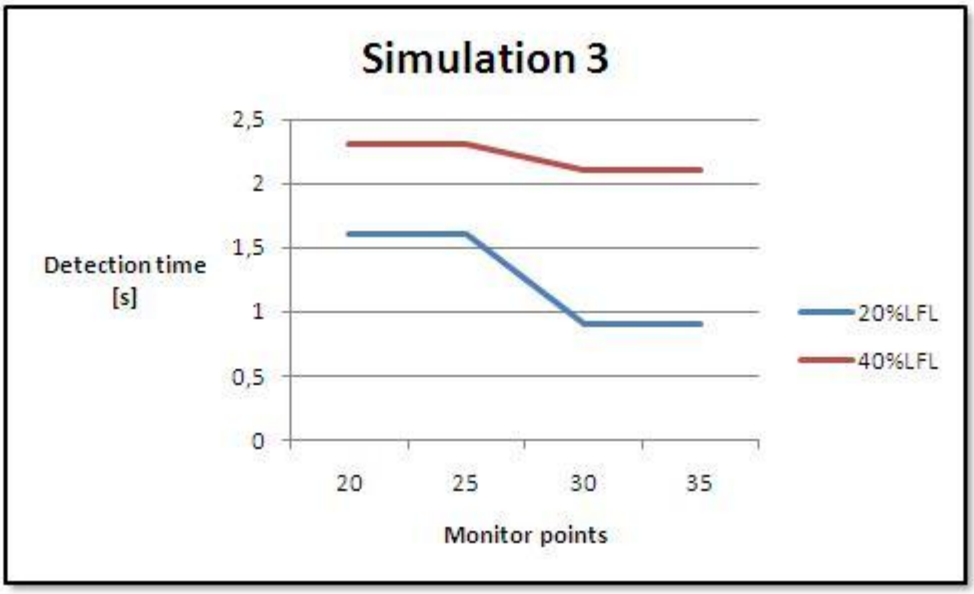

Figure 35, Detection time with respect to low and high alarm against increasing number of monitor points, simulation 3

6.2.4 Simulation 4

None of the measurements from the 35 monitor points managed to reach the alarm limits. This is strange since simulation 4 is almost identical to simulation 3.

6.2.5 Simulation 5

Figure 36 on next page shows the detection time with respect to low and high alarm against increasing number of monitoring points for simulation 5. The detection time for high alarm has a more evident reduction than for the low alarm. The curve for low alarm has a small slope at 35 monitor points while the curve for high alarm flattened out already at 20 monitor points.

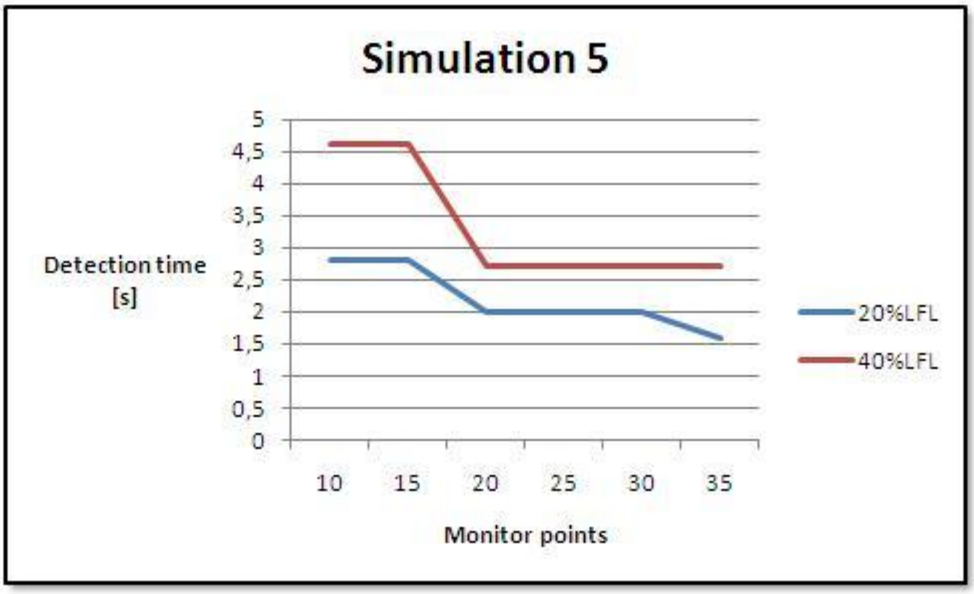

Figure 36, Detection time with respect to low and high alarm against increasing number of monitor points, simulation 5

6.2.6 Simulation 6

Figure 37 shows the detection time with respect to low and high alarm against increasing number of monitoring points for simulation 6. The curve for high alarm flattens out at 15 monitor points while the curve for low alarm flattens out at 30 monitor points.

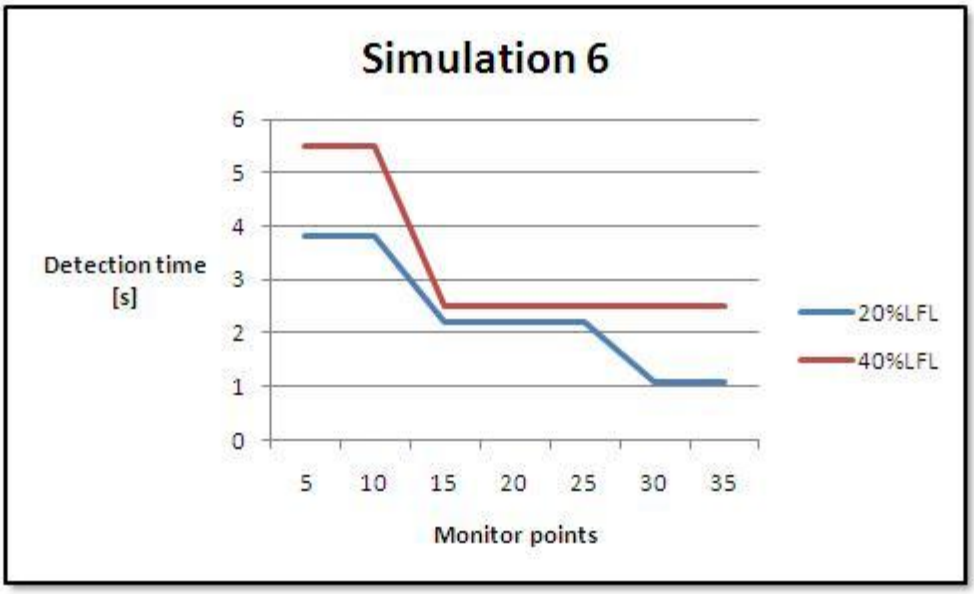

Figure 37, Detection time with respect to low and high alarm against increasing number of monitor points, simulation 6

6.2.7 Simulation 7

Figure 38 shows the detection time with respect to low and high alarm against increasing number of monitoring points for simulation 7. The curve for high alarm has a little more abrupt slope than the curve for low alarm from 25 to 30 monitor points. Except from this deviation both curves go parallel all the way to 35 monitor points where they have flattened out.

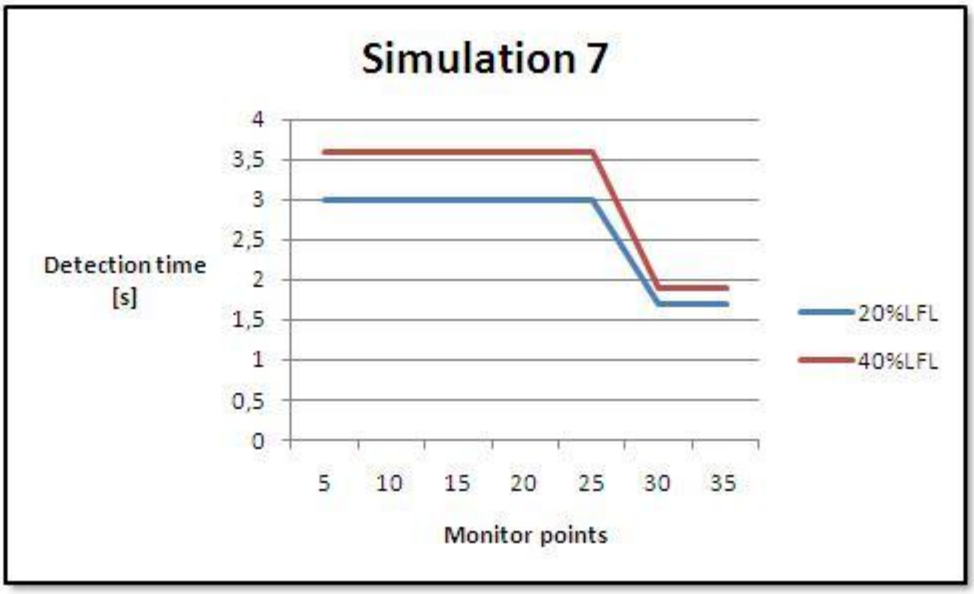

Figure 38, Detection time with respect to low and high alarm against increasing number of monitor points, simulation 7

6.2.8 Average detection time

Figure 39 shows the average detection time from simulations against monitor points. The reduction in detection time doesn't flatten out at 30 and 35 monitor points, but the abruptness in the slope gets reduced. These data are based on a very limited number of simulations and one may get other results if more simulations are carried out.

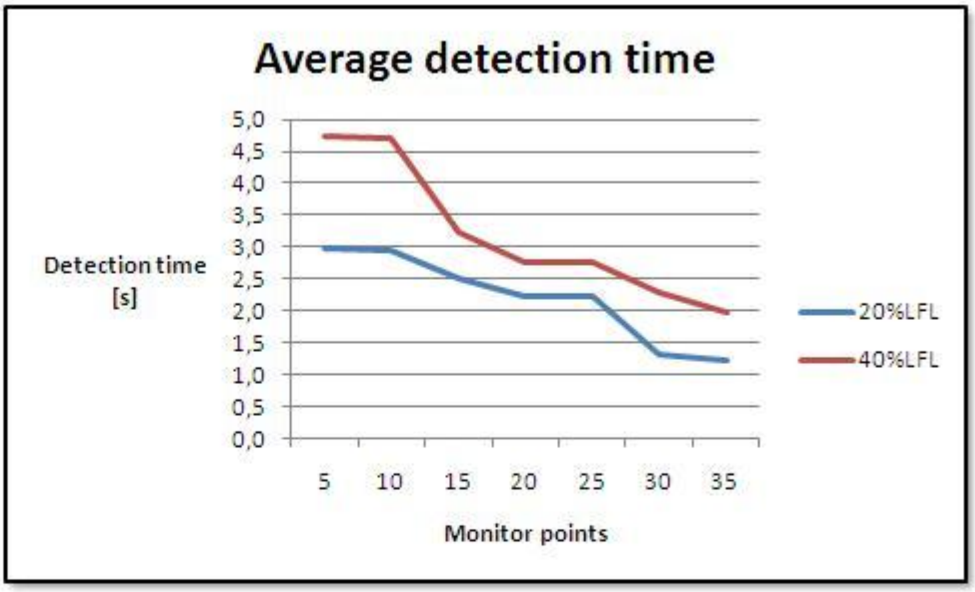

Figure 39, Average detection time from simulations against monitor points

7 Discussion

In order to find the best suited gas detector positions a great spectre of factors must be considered. This is a very complex process due to the high number of variables and the fact that each offshore installation is unique. Because of this complexity it will be inappropriate to make up a detailed recipe for how to determine the best suited positions for the gas detectors based on the relative limited amount of data acquired during the work with this thesis. However, one can make an effort to point out which factors to emphasize on during the decision making regarding positioning of the gas detectors.

The selection of these factors will be based on in which degree they influence the reliability and functionality of the gas detection system. In addition the chosen factors should have a considerable impact on the risk related to undesired gas releases.

Requirements regarding the gas detection system as stated by the authorities are very general in nature and there are several reasons for this. First of all, the owner of an installation has the overall responsibility to make sure that the gas detection system is adjusted to the given installation. Each installation is unique and the owner has plenty of firsthand knowledge and resources which give him the best basis for establishing more specified requirements. The level of functionality and reliability of a gas detection system is directly influenced by in which degree these requirements are fulfilled. In order to reduce the risk related to undesired gas releases the definition of the requirements should be based on an understanding of the actual risk level at the installation.

Fast response time is necessary in order to initiate control actions at an early stage and increase the probability of preventing the formation of flammable fuel-air clouds. The ignition probability, the effect of preventive and consequence reducing barriers and the risk related to a leak are highly affected by the response time. The detection time is a part of the response time and is influenced by the positions of the gas detectors. Since fast detection of escaped gases is one of the main requirements with respect to the gas detection system the detection time must be regarded as a critical factor with respect to functionality and reliability of the system. The detection time shall be low under different operating conditions as well. Low detection time requires optimization of gas detector positions. In order to optimize the gas detector positions one can find out how escaped gas is likely to behave under different scenarios. Plots from simulations carried out in FLACS indicated how the behaviour of escaped gas is influenced by variation in different physical parameters. An inadequate number of simulations were carried out with respect to point out governing parameters in general, but the influence of some parameters was more evident than others. The wind vector seems to have the most evident influence on the escaped gas in the simulations. Especially areas with intermediate and low gas concentrations are influenced by the wind vector.

A connection between an increasing number of monitor points and detection time was indicated in the results from the FLACS simulations. A reduction in the detection time was observed, but also a tendency of decline in the reduction when a high number of monitor points was reached. Some of the simulations reached a point where the detection time remained unchanged by adding more monitor points. A stagnation in the reduction of detection time after adding more monitor points indicates that the first monitor points are well positioned with respect to the leak. By carrying out a considerably higher number of simulations with more variation in parameters one will form a better basis for finding the most effective monitor points (detector positions). With a high number of simulations it will be easier to identify dispensable monitor points. Hence make the applied gas detectors more effective. Results from the limited number of simulations show a reduction in detection with a couple of seconds in average by increasing the number of monitor points from 5 to 35. How critical are these couple of seconds with respect to risk? Is it appropriate to increase the number of monitor points with 30 in order to reduce detection time with a couple of seconds? The owners of an installation with knowledge about the actual risk level will have to decide that.

In simulation 4 the measurements from the monitor points didn't manage to reach the alarm limits. Escaped gas with a rate of 2kg/s didn't initiate any alarms. Only the wind direction separates simulation 3, 4 and 5. The wind direction may be the decisive factor or an error in the data output may have occurred.

FLACS is considerably verified through different tests and projects in order to ensure realistic behaviour of released fluids and interaction with the geometry, but one must not forget that there is a certain level of uncertainty in the simulations. In order to increase the quality of the assessment of relevant factor FLACS simulations should be combined with experience and knowledge when the best suited gas detector positions are to be found.

The characteristics of released flammable gases such as LFL and vapour density have been studied briefly. Simulations carried out using FLACS showed variations in the compactness of the cloud formed by escaped gas when gas composition was changed. Plots from the simulations indicated that the dispersion of escaped gas was more influenced by wind and geometry than vapour density. The restless atmosphere at an offshore installation will contribute to reducing the effects of different vapour densities. Thus one should distribute gas detectors along the elevation independent of vapour densities of escaped gas instead of having detector positions based on the given vapour densities which is indicated in some parts of the literature. On should learn from the Snorre A incident and expect gas to appear anywhere in case of an emergency.

The LFL of a given gas affects the calibration of the gas detectors with respect to the different alarm limits, but the LFL itself seems to have limited influence on the gas detector positions. One can say that the LFL affects the reliability and the functionality of a gas detection system via the degree of successful calibration. It's rather locations where escaped gas can reach the LFL which is relevant regarding detector positioning. By identifying and monitor such areas one can detect gas in the early phases of a leak, hence attain low detection time.

Gas detectors should be able to monitor for the presence of gas under different operating conditions. Advantages and limitations regarding operating conditions will vary between different gas detection principles and technologies. The application of several types of gas detectors makes the gas detection system more robust with respect to different operating conditions because one can make use of the different advantages of each type of detector. In this way the gas detection system will have other detectors available if a certain detector type has considerable limitations under current operating conditions at a point in time. The detection time may get reduced as well if several gas detector types are applied. Hence the combination of different gas detectors within a given area will have a high degree of influence on functionality and reliability of the gas detection system and the risk related to escaped gas.

Before simulations were carried out in FLACS an introduction in the program was provided by a highly experienced user. Even if training were provided the complexity of the program required a lot of effort in order to perform the simulations. The procedure of gathering information about at which time the alarm limits were exceeded in the different monitor points was very time consuming since this had to be done manually. A function which gathers this information automatically could have been added in the program. This would have saved time and increased the user-friendliness. Due to limited storage capacity and no previous experience with FLACS a limited number of simulations were carried out. Given the limited number of simulations only assumptions and descriptions of tendencies can be made regarding governing physical factors. In connection with future studies a considerably higher number of simulations should be carried out with more variation in parameters. Especially the leak location should be varied compared to simulations performed in connection with this thesis.

Interviews with some representatives from different parties in the oil and gas industry were carried out in connection with this thesis. These interviews aren't included in this report because the results weren't relevant with respect to the objective of this thesis.

8 Conclusion

The purpose of this assignment was to study factors that must be considered when selecting the best suited positions for gas detectors at offshore installations where production of oil and gas takes place and evaluate their degree of impact on the reliability and functionality with respect to the gas detection system.

The process of finding the best suited gas detector positions has showed to be a comprehensive task involving many factors in complex interconnections. The functionality and reliability of a gas detection system depend on in which degree one manages to assess these factors and design a system which fulfils established requirements and is able to reflect the actual risk level at an offshore installation.

Since fast detection of escaped gases is one of the main requirements with respect to the gas detection system the detection time must be regarded as a critical factor with respect to functionality and reliability of the system. Low detection time allows the initiation of control actions at an early stage and increases the probability of preventing the formation of flammable fuel-air clouds. The ignition probability, the effect of preventive and consequence reducing barriers and the risk related to a leak are highly affected by the detection time. Results from a limited number of gas dispersion simulations carried out using FLACS indicate a slightly reduction in detection time with an increasing number of monitor points.

The combination of different gas detector principles and technologies seems to have a considerable influence with respect to functionality and reliability of a gas detection system since detection methods share few common failures.

Plots from simulations carried out in FLACS indicated how the behaviour of escaped gas is influenced by variation in different physical parameters. An inadequate number of simulations were carried out with respect to point out governing parameters in general, but the influence of some parameters was more evident than others. The wind vector seems to have the most evident influence on the escaped gas in the simulations. Especially areas with intermediate and low gas concentrations were influenced by the wind vector.

In connection with future studies a considerably higher number of simulations should be carried out with more variation in parameters in order to study the degree of influence different physical factors have with respect to escaped gas in more detail.

References

Anderson, G. and Hadden, D. *The Gas Monitoring Handbook*. Ickus Guides, Avocet Press Inc, New York, 1999.

Benmebarek, S. and Hanlon, S., Petro-Canada. 2006. *FPSO Gas-Detection System Performance Enhancement and Monitoring*. Society of Petroleum Engineers. SPE 98846.

Bjerketvedt, D., Bakke, J., Wingerden, K. *Gas Explosion Handbook Version 1.2*. CMR Gexcon, Bergen, 1993.

Bonn, R. and Moros, A., BP Exploration. 1998. *Designing for a step change in benefit from combustible gas detection systems*. Society of Petroleum Engineers. SPE 46637.

Choo, Edwin., General Monitors Systems Asia, Singapore. 2008. SIL 104: *Impact of gas detection coverage on SIF SIL rating*. Available from: < www.gmigasandflame.com/sil_104_article.pdf>. [Downloaded 02.03.11].

Det-tronics. *A Practical Guide to Gas Detection*. Available from: < www.det-tronics.com/utcfs/ws-462/Assets/92-1015%20v2.pdf>. [Downloaded 07.02.11].

GexCon AS. 2009. FLACS manual v9.1. Available in the FLACS program.

Gregory, N. and Mads, K, Gassonic, and Teerapong, R. Mike, and B. Peter, SPE, PTTEP. 2007. *The Viability of Ultrasonic Detector for Hydrocarbon Gas Leak Detection*. Society of Petroleum Engineers. SPE 108662.

Honeywell. 2007. *Gas book*. Available from: < http://www.honeywellanalytics.com/en-GB/Pages/default.aspx>. [Downloaded 09.02.11].

HSE, Health and Safety Executive. 2004. Available from: <http://www.hse.gov.uk/index.htm>

Høiset, S., StatoilHydro ASA. Fossan, I., Scandpower AS. Kaasa, Ø., StatoilHydro ASA. 2008. *Managing Explosion Risk in Arctic Areas*. Society of Petroleum Engineers. SPE 111583.

International Organization for Standardization. 1999. *ISO 13702*. Available from: < http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=22675 >. [Downloaded 14.02.11].

Kuchta, J. *Investigation of Fire and Explosion Accidents in the Chemical, Mining, and Fuel-Related Industries – A Manual*. 1985. Dept. of the Interior, Bureau of Mines, U.S.

MSA, The Safety Company. 2007. *Gas Detection Handbook*. Available from: < http://www.msanorthamerica.com/catalog/product503774.html>. [Downloaded 25.02.11].

Naranjo, E., General Monitors. Neethling, G., Gassonic A/S. 2010. *Best Practices in the Allocation, Commissioning, and Maintenance of Ultrasonic Gas Leak Detectors*. Society of Petroleum Engineers. SPE 133543.

Naranjo, E., Choo, E., Kombech, M., General Monitors. 2009. *Improvement of Safety Instrumented System (SIS) Performance Through Detection Diversity*. Society of Petroleum Engineers. SPE 123400.

Net Safety Monitoring Inc. 2011. Available from: < http://www.net-safety.com/>.

Norsk sokkels konkurranseposisjon. 2008. *NORSOK S-001 Technical Safety edition 4*. Available from: < http://www.standard.no/en/Sectors/Petroleum/NORSOK-Standard-Categories/S-Safety-SHE/S-0011/>. [Downloaded 10.02.11].

Petroleum Safety Authority, Norway. 2011. *Framework HSE, Management and Facilities Regulations* . Available from: < http://www.ptil.no/regulations/category216.html>.

Pettersen, G., SPE. Moldskred, I. and Ytredal, E., Statoil ASA. 2006. *The Snorre A Incident 28 November 2004: Lessons Learned*. Society of Petroleum Engineers. SPE 98739.

Rogstadkjernet, L. *CFD explosion analyses & structural design*. From "Gas Explosion Hazards on Offshore Facilities, 3rd – 4th May 2010. CMR Gexcon.

Shabaka, A., ZADCO. 2006. *Can the Existing F&G Detection System Provide Safe Guard Against All Possible Gas Releases? (Case Study)*. Society of Petroleum Engineers. SPE 101422.

Tam, V. and Dawson, R., BP Research. 1991. *Natural Ventilation in Offshore Modules Using Wind Wall and Double Louvres: A Wind Tunnel Study*. Offshore Technology Conference. OTC 6501.

Wingerden, K. *Introduction to use of CFD and FLACS in particular*. From "The use of CFD to solve today's safety challenges, 22-24 June 2010". Gexcon AS, Bergen, 2010.

Zellweger analytics. *Gas Detection – A basic guide*. 2002. Available from: < http://www.honeywellanalytics.com/en-US/Pages/default.aspx>. [Downloaded 07.02.11].

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Appendix A

Measurements from each monitor point

Simulation 1					
5 Monitor points	**96**	**103**	**125**	**128**	**148**
20% LFL [s]	-	8,3	-	-	2,7
40%LFL [s]	-	11,6	-	-	6,4
10 Monitor points	**185**	**190**	**231**	**235**	**277**
20% LFL [s]	-	-	11,7	-	-
40%LFL [s]	-	-	-	-	-
15 Monitor points	**20**	**47**	**54**	**269**	**288**
20% LFL [s]	5,8	2,9	6,8	-	-
40%LFL [s]	7,2	3,5	11,5	-	-
20 Monitor points	**66**	**110**	**175**	**234**	**315**
20% LFL [s]	3,8	-	-	-	-
40%LFL [s]	6,3	-	-	-	-
25 Monitor points	**138**	**193**	**213**	**254**	**310**
20% LFL [s]	10,6	-	-	-	-
40%LFL [s]	-	-	-	-	-
30 Monitor points	**6**	**59**	**116**	**120**	**204**
20% LFL [s]	-	-	8,4	1,2	-
40%LFL [s]	-	-	11	9,8	-
35 Monitor points	**151**	**68**	**33**	**119**	**77**
20% LFL [s]	7,6	5,6	4,5	1,4	3,7
40%LFL [s]	30	9,3	5,7	1,7	5

Simulation 2					
5 Monitor points	**96**	**103**	**125**	**128**	**148**
20% LFL [s]	13,4	2,9	13,3	4,7	2,4
40%LFL [s]	46,3	3,4	18,5	5,2	5,5
10 Monitor points	**185**	**190**	**231**	**235**	**277**
20% LFL [s]	5	6,7	5,2	10,6	11,9
40%LFL [s]	5,9	10,5	8,3	14,2	19,9
15 Monitor points	**20**	**47**	**54**	**269**	**288**
20% LFL [s]	2,5	1,9	5,5	9,3	9,3
40%LFL [s]	3,2	2	8,1	-	14,8
20 Monitor points	**66**	**110**	**175**	**234**	**315**
20% LFL [s]	3,2	13,2	8,9	9,6	7,7
40%LFL [s]	5	22,8	-	13,1	10,6
25 Monitor points	**138**	**193**	**213**	**254**	**310**
20% LFL [s]	9,2	11,1	3,9	-	8,5
40%LFL [s]	13,4	18,8	4,3	-	18,3
30 Monitor points	**6**	**59**	**116**	**120**	**204**
20% LFL [s]	22,5	4,3	2,7	0,9	7,1
40%LFL [s]	-	5,6	2,9	1	10,1
35 Monitor points	**151**	**68**	**33**	**119**	**77**
20% LFL [s]	6,7	4,6	2,1	1,1	2,7
40%LFL [s]	10,7	7,7	2,4	1,2	3,4

Simulation 3

5 Monitor points	**96**	**103**	**125**	**128**	**148**
20% LFL [s]	-	-	-	-	-
40%LFL [s]	-	-	-	-	-
10 Monitor points	**185**	**190**	**231**	**235**	**277**
20% LFL [s]	-	-	-	-	-
40%LFL [s]	-	-	-	-	-
15 Monitor points	**20**	**47**	**54**	**269**	**288**
20% LFL [s]	-	-	-	-	-
40%LFL [s]	-	-	-	-	-
20 Monitor points	**66**	**110**	**175**	**234**	**315**
20% LFL [s]	1,6	-	-	-	-
40%LFL [s]	2,3	-	-	-	-
25 Monitor points	**138**	**193**	**213**	**254**	**310**
20% LFL [s]	-	-	-	-	-
40%LFL [s]	-	-	-	-	-
30 Monitor points	**6**	**59**	**116**	**120**	**204**
20% LFL [s]	-	0,9	-	-	-
40%LFL [s]	-	2,1	-	-	-
35 Monitor points	**151**	**68**	**33**	**119**	**77**
20% LFL [s]	-	-	-	-	1,9
40%LFL [s]	-	-	-	-	2,9

Simulation 4					
5 Monitor points	**96**	**103**	**125**	**128**	**148**
20% LFL [s]	-	-	-	-	-
40%LFL [s]	-	-	-	-	-
10 Monitor points	**185**	**190**	**231**	**235**	**277**
20% LFL [s]	-	-	-	-	-
40%LFL [s]	-	-	-	-	-
15 Monitor points	**20**	**47**	**54**	**269**	**288**
20% LFL [s]	-	-	-	-	-
40%LFL [s]	-	-	-	-	-
20 Monitor points	**66**	**110**	**175**	**234**	**315**
20% LFL [s]	-	-	-	-	-
40%LFL [s]	-	-	-	-	-
25 Monitor points	**138**	**193**	**213**	**254**	**310**
20% LFL [s]	-	-	-	-	-
40%LFL [s]	-	-	-	-	-
30 Monitor points	**6**	**59**	**116**	**120**	**204**
20% LFL [s]	-	-	-	-	-
40%LFL [s]	-	-	-	-	-
35 Monitor points	**151**	**68**	**33**	**119**	**77**
20% LFL [s]	-	-	-	-	-
40%LFL [s]	-	-	-	-	-

Simulation 5					
5 Monitor points	**96**	**103**	**125**	**128**	**148**
20% LFL [s]	-	-	-	-	-
40%LFL [s]	-	-	-	-	-
10 Monitor points	**185**	**190**	**231**	**235**	**277**
20% LFL [s]	-	-	-	2,8	-
40%LFL [s]	-	-	-	4,6	-
15 Monitor points	**20**	**47**	**54**	**269**	**288**
20% LFL [s]	-	-	3,2	-	-
40%LFL [s]	-	-	5,4	-	-
20 Monitor points	**66**	**110**	**175**	**234**	**315**
20% LFL [s]	2	-	-	-	-
40%LFL [s]	2,7	-	-	-	-
25 Monitor points	**138**	**193**	**213**	**254**	**310**
20% LFL [s]	3,9	-	-	-	-
40%LFL [s]	10,3	-	-	-	-
30 Monitor points	**6**	**59**	**116**	**120**	**204**
20% LFL [s]	-	-	-	-	-
40%LFL [s]	-	-	-	-	-
35 Monitor points	**151**	**68**	**33**	**119**	**77**
20% LFL [s]	2,1	1,6	-	-	-
40%LFL [s]	3,4	2,7	-	-	-

Simulation 6

5 Monitor points	**96**	**103**	**125**	**128**	**148**
20% LFL [s]	28,2	3,8	24,4	5	7,2
40%LFL [s]	-	5,7	36,5	5,5	14,9
10 Monitor points	**185**	**190**	**231**	**235**	**277**
20% LFL [s]	5,9	12,5	10,8	20	30,8
40%LFL [s]	7,8	29,6	17,4	27,1	39,9
15 Monitor points	**20**	**47**	**54**	**269**	**288**
20% LFL [s]	3,8	2,2	11,7	10,1	15
40%LFL [s]	40,9	2,5	20,7	25,9	24,9
20 Monitor points	**66**	**110**	**175**	**234**	**315**
20% LFL [s]	6,9	24,6	20	18,2	13,9
40%LFL [s]	15,5	-	-	24,9	19,7
25 Monitor points	**138**	**193**	**213**	**254**	**310**
20% LFL [s]	18,4	19,3	4,6	-	9,3
40%LFL [s]	26,1	45,1	5,1	-	12,7
30 Monitor points	**6**	**59**	**116**	**120**	**204**
20% LFL [s]	-	5,3	3,1	1,1	12,3
40%LFL [s]	-	8,3	3,5	9,8	20,1
35 Monitor points	**151**	**68**	**33**	**119**	**77**
20% LFL [s]	15,4	14,2	2,5	1,3	5
40%LFL [s]	22,8	22,2	3,1	1,5	12,4

Simulation 7

5 Monitor points:	**96**	**103**	**125**	**128**	**148**
20% LFL [s]	-	-	11,2	-	3
40%LFL [s]	-	-	-	-	3,6
10 Monitor points:	**185**	**190**	**231**	**235**	**277**
20% LFL [s]	-	-	18,6	17,5	-
40%LFL [s]	-	-	-	-	-
15 Monitor points:	**20**	**47**	**54**	**269**	**288**
20% LFL [s]	-	-	3,9	-	-
40%LFL [s]	-	-	5,6	-	-
20 Monitor points:	**66**	**110**	**175**	**234**	**315**
20% LFL [s]	3,4	-	-	9,5	-
40%LFL [s]	4,4	-	-	-	-
25 Monitor points:	**138**	**193**	**213**	**254**	**310**
20% LFL [s]	3,8	-	-	-	-
40%LFL [s]	6,9	-	-	-	-
30 Monitor points:	**6**	**59**	**116**	**120**	**204**
20% LFL [s]	-	-	-	1,7	8,5
40%LFL [s]	-	-	-	1,9	-
35 Monitor points:	**151**	**68**	**33**	**119**	**77**
20% LFL [s]	3,8	4,8	-	2,7	-
40%LFL [s]	5,4	6,2	-	6,1	-

Appendix B

Measurements from monitor points with lowest detection time in a group

Simulation 1

20%LFL		40%LFL	
Monitor points	Detection time [s]	Monitor points	Detection time [s]
5	2,7	5	6,4
10	2,7	10	6,4
15	2,7	15	3,5
20	2,7	20	3,5
25	2,7	25	3,5
30	1,2	30	3,5
35	1,2	35	1,7

Simulation 2

20%LFL		40%LFL	
Monitor points	Detection time [s]	Monitor points	Detection time [s]
5	2,4	5	3,4
10	2,4	10	3,4
15	1,9	15	2
20	1,9	20	2
25	1,9	25	2
30	0,9	30	1
35	0,9	35	1

Simulation 3

20%LFL		40%LFL	
Monitor points	Detection time [s]	Monitor points	Detection time [s]
5	-	5	-
10	-	10	-
15	-	15	-
20	1,6	20	2,3
25	1,6	25	2,3
30	0,9	30	2,1
35	0,9	35	2,1

Simulation 4

20%LFL		40%LFL	
Monitor points	Detection time [s]	Monitor points	Detection time [s]
5	-	5	-
10	-	10	-
15	-	15	-
20	-	20	-
25	-	25	-
30	-	30	-
35	-	35	-

Simulation 5

20%LFL		40%LFL	
Monitor points	Detection time [s]	Monitor points	Detection time [s]
5	-	5	-
10	2,8	10	4,6
15	2,8	15	4,6
20	2	20	2,7
25	2	25	2,7
30	2	30	2,7
35	1,6	35	2,7

Simulation 6

20%LFL		40%LFL	
Monitor points	Detection time [s]	Monitor points	Detection time [s]
5	3,8	5	5,5
10	3,8	10	5,5
15	2,2	15	2,5
20	2,2	20	2,5
25	2,2	25	2,5
30	1,1	30	2,5
35	1,1	35	2,5

Simulation 7

20%LFL		40%LFL	
Monitor points	Detection time [s]	Monitor points	Detection time [s]
5	3	5	3,6
10	3	10	3,6
15	3	15	3,6
20	3	20	3,6
25	3	25	3,6
30	1,7	30	1,9
35	1,7	35	1,9

Average detection time

20%LFL		40%LFL	
Monitor points	Detection time [s]	Monitor points	Detection time [s]
5	3,0	5	4,7
10	2,9	10	4,7
15	2,5	15	3,2
20	2,2	20	2,8
25	2,2	25	2,8
30	1,3	30	2,3
35	1,2	35	2