HØGSKOLEN STORD/HAUGESUND

Cause Analysis of Gas Leaks and Methods to Limit Leakage

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Leakages of hydrocarbons on process plants and terminals are undesirable due to the many risk factors associated with them. Major accidents constitute direct risk to people, environment and property. Minor gas leaks and fugitive emissions represent both direct and indirect risks within the health, environment and safety aspects.

The thesis will map out sources and causes of leaks, as well as collection of empirical data. Based on the obtained data it will be necessary to formulate a possible overall strategy for containment of hydrocarbon gas leaks. The discussion will include mechanical and organizational factors and methods of detection and measurements of leaks.

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Preface

This thesis is written as a final project upon completing a Bachelor Degree in Mechanical Engineering with major in Process and Energy Technology at Stord/Haugesund University College.

The report has a technical methodology on the issues regarding gas leaks. It will therefore be beneficial with a certain amount of technical understanding when reading. The approach towards gathering information has been to search for existing data, analyze previous reports on the matter and consult experienced people. With empirical data as the foundation I have discussed existing activities and proposed measures based on my own perception.

When I first started with this thesis I had envisioned writing a more or less straightforward technical report. As I worked through material it dawned to me that the challenges with hydrocarbon gas leaks were quite broad and complex. It might be natural for a mechanical engineer student to take out some brilliant formulas to do calculations in the thesis work. I have learned that taking part of an industry as important as the natural gas industry requires a broader understanding of how things function. My thesis work has taken some unexpected turns along the way. I have enough unused notes to fill up an equally large report. Luckily this is information I am able to bring along as an engineer.

During my work I have been privileged to speak with a lot of talented people who willingly shared their knowledge and experience, too many to mention by name. I would like to thank Willy Røed at Norwegian Oil and Gas for giving me advice along the way and encouraging me during my work. I am thankful for Gassco providing a good foundation for my research, especially my mentor Karsten Leland. Mr. Leland is a mechanical guru with an immense amount of experience in the field. Finally, I would like to thank my advisor at HSH, Sanjay Khattri for his understanding, encouragement and academic advice.

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Date and place

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Summary

Hydrocarbon gas leaks create potential dangerous situations with major accidents representing worst case scenarios. Smaller gas leaks are also unwanted as they represent risk of escalation and often lead to shut down or reduced production. Small gas leaks also represent in total a significant amount of gas which is detrimental to our atmosphere. Gassco supplies about 20 % of the natural gas consumed in Europe. Economic loss is a direct consequence initiated by shutdown or reduced production, as well as reliance regarding deliveries towards gas customers.

The natural gas industry continuously invests considerable resources into prevention of gas leaks. Regarding the subject of hydrocarbon leaks, there exists an abundance of information, reports, procedures and suggestions. There is not always coherence between the available information so the essential for any operator in the industry is to select the relevant, and most important, information to ensure a safe operation.

The discussion in this report has shown the complexity of hydrocarbon gas leaks. There are technical, human, and organizational factors contributing to the undesirable risk of gas leaks within the Gassco operatorship.

Certain technical components more prone to leak are valves, flanges, gaskets, and heat exchangers. It is therefore important to ensure joint integrity on the facilitation and the execution level. Approximately 20 % of technical leak sources are due to technical degrading. Corrosion under insulation (CUI) has been introduced as an integrity challenge in this area. In order to improve integrity of process facilities it is necessary for Gassco to invest in measures to improve or reduce technical degrading, such as continuous programs for monitoring, inspection and maintenance.

As the human factor is underlying cause of the majority of gas leaks the main focus area for Gassco is to get an overview of organizational factors creating risk. Within this area of concern there should be an increased investment in exchange of experience with more frequent workshops as a proposed measure. Reducing risk of possible misinterpretations of governing documents should also be assessed.

Within gas detection there are some methods with distinct characteristics. Infrared technology enables visualization of fugitive emissions and continuous monitoring. The handheld gas camera FLIR GD320 is an efficient method of inspection. The stationary Gas Vision System appears to have potential to become an essential part of monitoring process facilities.

Based on the discussion in this report it becomes natural to conclude that the most important safety barrier within the natural gas industry is the human factor. There has been an increased focus on the human factor in recent years with positive results of improvement. However, the industry aims at continuing the positive trend.

1. Introduction

1.1 Background

This thesis is based on a report prepared for Gassco during a summer internship in 2013. The research was made in the intent to get an overview of hydrocarbon gas leaks based on potential consequences ranging from major accidents to fugitive emissions. Barrier integrity and technical measures to reduce fugitive emissions according to governing documents were described. Certain methods of gas detection and measuring were mentioned roughly. As the report mainly described existing activities there seemed to be potential for a more thorough research in the field of hydrocarbon leaks.

1.2 Description

Hydrocarbon gas leaks create potential dangerous situations with major accidents representing worst case scenarios. Smaller gas leaks are also unwanted as they represent risk of escalation and often lead to shut down or reduced production. Small gas leaks also represent in total a significant amount of gas which is detrimental to our atmosphere. The natural gas industry continuously invests considerable resources into prevention of gas leaks.

Gassco supplies about 20 % of the natural gas consumed in Europe. Economic loss is a direct consequence initiated by shutdown or reduced production, as well as reliance regarding deliveries towards gas customers. Most situations involving gas leaks or large emissions will be covered by local, national or even international media. Thus there will also be a reputational aspect associated with gas leaks regardless of the leakage rate and the extent of the situation. It will consequently be of Gassco's interest to prevent such situations.

Regarding the subject of hydrocarbon leaks, there exists an abundance of information, reports, procedures and suggestions. There is not always coherence between the available information so the essential for any operator in the industry is to select the relevant, and most important, information to ensure a safe operation.

This thesis will discuss sources and conditions that might lead to hydrocarbon leaks. Previous incidents will be described with the intent to get an understanding of direct and underlying factors contributing to risk of gas leaks. Gas detection is foremost used for generating alarms to initiate safety measures. The report will also describe some gas detection methods which can function as possible proactive measures to prevent escalation of fugitive emissions. The final purpose will be to formulate a possible overall strategy for reducing risk of hydrocarbon gas leaks.

1.3 Limitations

This report focuses mainly on land-based activities such as processing plants and terminals. Thus there are some elements intentionally omitted that may seem natural to consider in connection with gas leaks. The purpose of this report is to describe the challenges Gassco as operator face in junction with gas leaks. To exemplify some areas of discussion, specific examples and cases have been used. Statoil is one of the Technical Service Providers (TSP) of Gassco operated facilities and performs measures to reduce gas leaks themselves. Some elements in the report are therefore generally described with examples from Statoil.

The report covers hydrocarbons except in cases where other gases are specified.

1.4 Definitions

LEL	Lower Explosive Limit: The lowest concentration of gas in the air required for the gas cloud to ignite. Concentrations of gas under LEL will not be able to ignite
% LEL	Percentage of LEL: Expresses the degree of hazard - how near the gas present in the surrounding air is to the flammable region. 100 %LEL means the gas present has a gas/air ratio which can easily ignite in the presence of an ignition source.
LELm	Denotes the gas concentration as %LEL multiplied with the length of the gas cloud. Does not describe how flammable the gas cloud is.
Barrier	Technical, operational and/or organizational elements that individually or together shall prevent a concrete chain of events from occurring, or influence the events in an intended direction by limiting damages and/or losses
Isolation	Use of physical barrier to separate a plant and equipment from energy sources

1.5 Abbreviations

BAT	Best Available Technology
BREF	BAT Reference Document
EX	Explosion proof/category
FLIR	Forward-Looking Infrared Radiometer
GVS	Gas Vision System
GWP	Global Warming Potential
HC	Hydrocarbon
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
NMVOC	Non-Methane Volatile Organic Compounds
NCS	Norwegian Continental Shelf
NDT	Non-Destructive Testing
NEA	Norwegian Environment Agency (Nor. *Miljødirektoratet*)
OLF	Oljeindustriens landsforening
POI	Points-Of-Interest
PPM	Parts-Per-Million
RNNP	Risikonivå i norsk petroleumssektor
TEMA	Tubular Exchanger Manufacturers Association
TSP	Technical Service Provider
VOC	Volatile Organic Compounds

2. Necessity to Limit Gas Leaks

Hydrocarbon gas leaks within the petroleum industry create potential dangerous situations. The possible outcomes may be major accidents or other situations that are unwanted, and many disasters have hit the gas industry over the last century. Furthermore, gas emissions to the atmosphere have been proven detrimental to the environment. Many companies also realize that loss of gas equals loss of money. This chapter will describe hydrocarbons and their properties as well as potential incidents with gas leaks.

2.1 Hydrocarbons

Hydrocarbons are organic compounds that only consist of hydrogen and carbon. The simplest group is the saturated hydrocarbons which have single bonds and are fully saturated with hydrogen. These are called alkanes. Unsaturated hydrocarbons have double or triple bonds and are called alkenes or alkynes. Cycloalkanes are constructed of one or more carbon rings. The aromatic hydrocarbons, also called arenes, have one or more aromatic rings. It is the saturated hydrocarbons that create the basis for petroleum products. Natural gas is a mixture of hydrocarbons but may contain traces of other gases such as nitrogen, carbon dioxide (CO_2) and hydrogen sulfide (sulfur). Further references to natural gas will refer to saturated hydrocarbons as HC [1].

The main components of natural gas are [2]:

- Methane
- Ethane
- Propane
- Butane
  - Iso-butane
  - N-butane
- Naphtha
- Condensate

The composition of the gas determines whether it is rich gas, dry gas or wet gas. Rich gas is raw gas consisting of methane, ethane, propane, butane, etc. Dry gas is natural gas with liquid hydrocarbons under normal pressure and temperature conditions, consisting essentially of methane and some ethane. Wet gas is natural gas with liquefied petroleum compounds, such as ethane, propane, butane and naphtha. It has high energy content and is often referred to as "bottled gas". Under atmospheric pressure the gas is partially liquid and must be transported by tankers. Natural gas is odorless and colorless, so sulfur compounds are added to provide a pungent smell [2].

2.1.1 Methane

Methane is the smallest hydrocarbon and is mainly used as an energy source. Natural gas consists of between 75-95 % methane [2]. In combination with oxygen methane is explosive. All combustible gases have a specific flammable region in which the concentration is able to ignite. The region is bounded by the Lower Explosive Limit (LEL) and the Upper Explosive Limit (UEL).

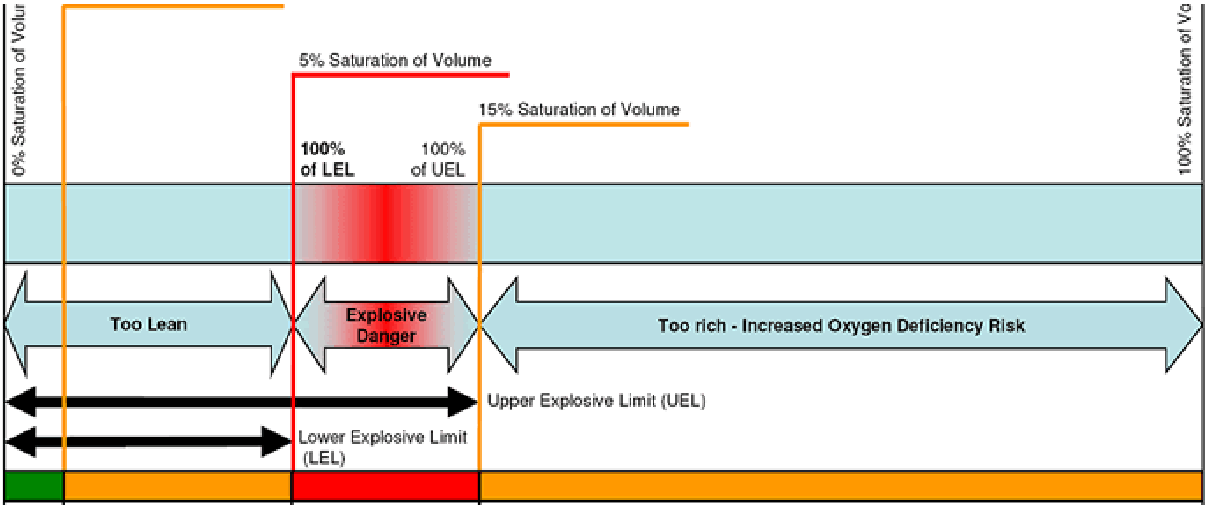

Figure 1 - Flammability limits for methane[1]

Concentrations of gas in air below LEL are too lean for combustion and concentrations above UEL are too rich to ignite. LEL and % LEL are therefore important terms when considering the flammability of gases. For methane the LEL is 5 % volumetric concentration of the gas in air and UEL is 15 %. If a “gas cloud” has a concentration of 5 % methane it has reached the flammable region and constitutes 100 % LEL. Therefore, ignition sources must be avoided in areas where there might be presence of methane and oxygen.

Below are listed some properties of methane.

Table 1 - Properties of methane [3]

Compound	Methane
Molecular formula	CH_4
Content in natural gas	75-95 %
Molar mass	16,04 g/mol
Density (25°C, 1 atm)	0,656 kg/m^3
Melting point	-182,5 °C
Boiling point (1 atm)	-161,49 °C
Specific heat capacity	35,69 J/K*mol
Higher heating value	55,5 MJ/kg
Lower heating value	50,0 MJ/kg
Lower explosion limit (LEL)	5 %
Upper explosion limit (UEL)	15 %

[1] Shell presentation on “Gasslekkasje workshop - Bygnes 10.04.2014”

Carbon dioxide (CO_2) has an atmospheric lifetime of several hundred years. For methane this atmospheric lifetime is around 12 years. However, it has become known in recent years that methane has a much higher heating value and therefore “collects” more solar heat in the atmosphere. It is multiple times more harmful than CO_2, even in the long term of 500 years. In short term of 100 years it is estimated that methane is about 25 times more harmful than CO_2. Thus methane is a greater contributor to global warming than previously assumed. From an environmental perspective it is therefore desirable to reduce methane emissions. Complete combustion of HC will produce a flue gas consisting of CO_2 [4].

Global warming potential (GWP) is an index to compare the relative contributions from different gases to the greenhouse effect. CO_2 is used as a reference point and therefore has a GWP value of 1 [4].

Table 2 - Comparison of Global Warming Potential for carbon dioxide and methane [4]

			Global Warming Potential		
Compound		**Lifetime (years)**	***20 years***	***100 years***	***500 years***
Carbondioxide	CO_2	50-200	1	1	1
Methane	CH_4	12	72	25	7,6

The GWP index is a tool used to calculate CO_2-equivalent emission. One emission permit is calculated as one ton CO_2. Consequently one ton of methane equals 25 permits [5].

2.1.2 Volatile Organic Compounds (VOC)

Volatile Organic Compounds (VOC) are organic compounds with low boiling point which easily evaporates. The term covers solvents, gasoline and polycyclic aromatic hydrocarbons, as well as the saturated hydrocarbon gases. VOC have negative health effects for humans and can damage vegetation. They can react with nitrogen oxides under the influence of sunlight to form ozone near the ground. Ozone is toxic to humans and can be harmful to animals, vegetation and materials [6].

Since methane is the primary component of natural gas we often distinguish between methane and Non-Methane Volatile Organic Compounds (NMVOC).

2.2 Political Aspects

The Norwegian Environment Agency (NEA) regulates the emission permits in Norway on behalf of The European Union Emission Trading Scheme. The permit system is based on the Kyoto agreement of 1997. The emission permits include all the greenhouse gases and are expressed as CO_2-equivalents. One permit (quota) equals one ton of CO_2. In accordance with the GWP index methane equals 25 CO_2-equivalents and therefore one ton of methane is 25 emission permits [5].

The permits are assigned to companies which have emissions of greenhouse gases and companies can also buy additional permits [5]. Within the permits NEA demands that the companies perform certain activities regarding abatement of emissions as well as reporting of actual emissions. Companies are required to conduct regular measurements of emissions. In cases where actual emission is impossible to measure, an estimated amount is calculated on the basis of activity data.

Typical activity data estimation can be based on sampling and must be calculated after the following formulas [7, p. 5]:

1. *CO2-emission = Activity data* Emission Factor * Oxidation Factor (boilers, turbines, vents)*
2. *CO2-emission = Activity data*Lower Heating Value*Emission Factor * Oxidation Factor (fugitive emissions, fire- pumps/training/generators)*

In order to comply with political regulations, Gassco has to ensure a proper reporting of emission data as well as documentation of measures to limit emissions. These abatement demands are in compliance with The European Integrated Pollution Prevention and Control Bureau's Best Available Techniques reference document for refineries (BREF) [8]. The BREF emphasizes that the term Best Available Techniques (BAT) has to be applied in all areas where emissions and pollution can occur.

2.3 Social Responsibility

Gassco has developed a procedure regarding social responsibility called Management of Corporate Social Responsibility. Purpose of the document is to establish the importance of integrating social responsibility in Gassco's governance processes. The procedure emphasizes the need to continuously prevent pollution, as well as emission of greenhouse gases, and other activities that may impact the environment. Within this action lies the need to identify sources of emissions and measurements. The document is based on international industry standards regarding social responsibility as well as internal governing documents.

2.4 Potential Incidents

Gas leaks regarding HC are normally associated with accidents or major accidents. Major accidents such as Piper Alpha in 1988, where 167 people died [9], and the Deepwater Horizon in 2010, in which 11 died and 20 were injured [10], represent the potential extent of major gas leaks. Gas leaks can roughly be divided into major accidents, accidents (Nor. *Nestenulykker*) and fugitive emissions.

The Major Accident Regulation (Nor. *Storulykkeforskriften*) defines a **major accident** as an event, such as a major spill, fire or explosion, as a result of an uncontrolled development that either immediately or later poses a serious risk to people, environment or material assets [11]. **Accidents** can be defined as gas leaks that are taken under control without major spills or ignition. These will also represent a degree of risk. A leakage rate under 0,1 kg/s is considered a **fugitive or diffuse emission**. This limit was originally recognized by The Petroleum Safety Authority because a rate of 0.1 kg/s has sufficient energy to create potential for a major accident[2]. An overview of types of gas leaks are shown in Table 3.

Table 3 - Overview of types of gas leaks

Type of event	Gas leak	Consequence
Major accident	Major leak	Major spill, fire, explosion
Accident	Small or major leak	Controlled: no major spill or ignition
Fugitive emission	Leakage rate <0,1 kg/s	Large total emissions all sources

[2] E-mail from Willy Røed at Norwegian Oil and Gas (28.04.2014)

All HC leaks above 0.1 kg/s are registered and reported to authorities, as well as the total fugitive emissions. Gassco operated facilities register all unwanted events for internal review. In order to evaluate the extent of risk Gassco has developed a risk matrix which show relationship between probability of an incident occurring and potential consequences. The matrix is used to pre-evaluate new designs, evaluate existing designs and also to evaluate occurred events and the risk of escalation. In the case of an event the outcomes could have been different under changed circumstances. A small gas leak might have had potential to develop into a major accident under slight change of conditions.

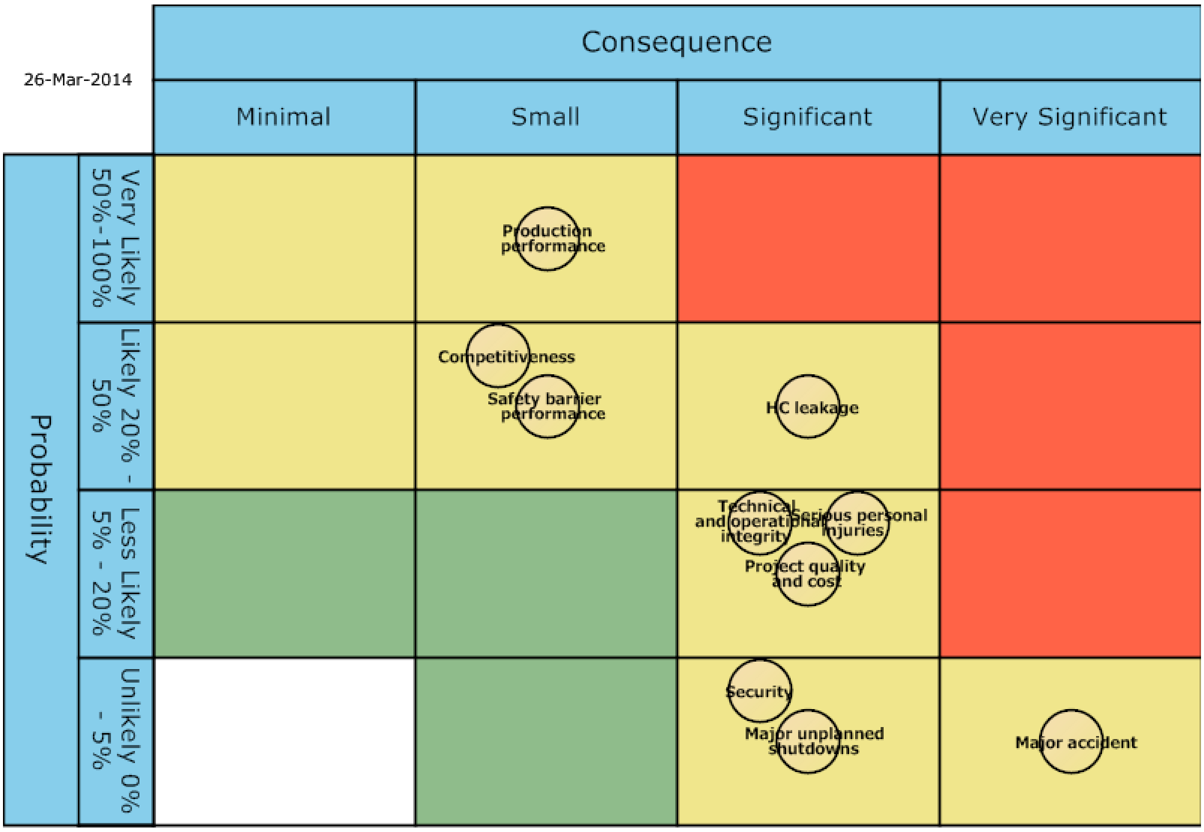

Figure 2 - Gassco Risk Matrix: Graded green (acceptable risk), yellow (acceptable risk, but actions to minimize risk must be implemented) and red (high risk)[3]

During the period 2008-2011 there were 56 registered HC leakages above 0.1 kg/s on the Norwegian Continental Shelf [12]. In order to visualize the possible extent of HC leaks Norwegian Oil and Gas use the following example:

<u>Example</u> [13, p. 23]

Why has it been decided to concentrate on hydrocarbon leaks larger than 0.1 kg/s? Reasons include the fact that such leaks have the potential to cause a major accident if the hydrocarbons ignite. The higher the release rate, the more serious the consequences could be. ***Examples of what a 1 kg/s leak could cause include:***

[3] Gassco document

- ***Unignited leak****: release of toxic gas which fills most of an offshore module in seconds. Taking two-three breaths of this gas could cause loss of consciousness because of its narcotic effect.*
- ***Immediate ignition****: a jet fire with flames up to 12-15 meters long. Possibilities of escalation if the flames reach other process equipment or structures without passive fire protection.*
- ***Delayed ignition****: explosion with deadly overpressure in the whole module. High probability of a subsequent fire, and a possibility of escalation to other equipment/areas.*

This example demonstrates the potential consequences an HC gas leak can have with or without ignition.

3. Sources and Conditions Leading to Hydrocarbon Leaks

In general, gas leaks are results of equipment that are not 100 % sealed and therefore enabling HC to be released to the environment. Gas leaks can lead to accidents or dangerous situations of varying degree. Fugitive emissions contribute to large total emissions. This chapter will look at gas leaks as a whole and discuss various sources and conditions.

The Petroleum Safety Authority annually presents trend reports on risk level in the petroleum sector on the Norwegian Continental Shelf (RNNP[4]). A matrix with overview of initiating events from the phase 7 report has been used in order to label potential sources in the following subchapters. An initiating event is defined as a technical failure that might lead to a gas leak. The thorough analysis from the phase 7 report intends to supply information about the use of barriers to prevent actual leaks. It is a reasonable assumption that these characteristics are in compliance with international industry norms and therefore are representable for Gassco operated facilities. The types of initiating events are in RNNP categorized as follows [14, p. 70]:

A. *Technical degrading of the system*
B. *Human intervention introduces hidden faults*
C. *Human intervention causes immediate leakage*
D. *Process disturbance*
E. *Built design weakness*
F. *External influences*

These initiating events are in correlation with a causal analysis performed by Norwegian Oil and Gas in the period 2008-2011 [12]. During this period there were 56 HC leaks on the Norwegian Continental Shelf with a rate larger than 0,1 kg/s. The figure below displays the main causes of these 56 HC leaks.

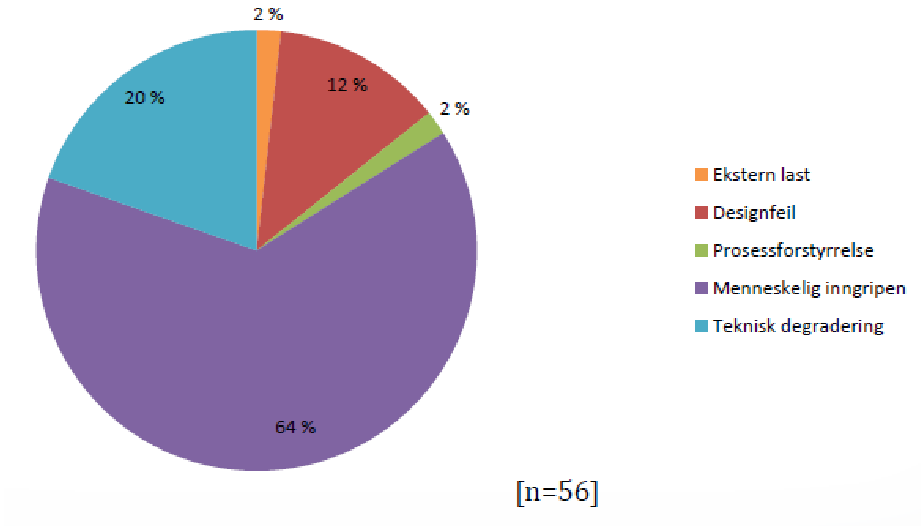

Figure 3 - Overview of causes 56 hydrocarbon leaks 2008-2011: Yellow – External load; Red – Design errors; Green – Process disturbance; Purple – Human interference; Blue – Technical degrading [12]

[4] Nor. *Risikonivå i norsk petroleumssektor (RNNP)*

Based on this classification it is prominent that most sources can be traced back to the human factor:

1. Direct influence from personnel causing leaks (B+C/Human interference, F/External load)
2. Indirect influence concealed in design weakness; deviation between designed capacity and operating capacity (D/Process disturbance, E/Design errors)

Considering this rough generalization it seems as if technical degrading and third party external influences (such as force majeure, accidents, etc.) are the only events that cannot be traced to the human factor "on-site". External influence includes events caused by activities, such as lifting, that are not related to process operations. One can also argue whether technical degrading should be accounted for during the primary design process and in standard maintenance programs. However, there are certain technical areas that are particularly vulnerable to gas leaks. In the subsequent chapters sources and conditions are divided into process, technical and human factors.

3.1 Process conditions

Standard operating parameters, such as temperature, pressure and fluid velocity, are essential to account for when designing process equipment. Deviation between design and operating parameters can result in fatigue or rupture. Operational conditions should never exceed design limits more than allowed by the design standard.

Cavitation is a phenomenon where the pressure sinks to below vapor pressure of the fluid and bubbles form in the gas. This boiling of the gas becomes problematic when the pressure rises again as the bubbles will implode. Implosion of the bubbles near metal surfaces might erode small parts of equipment. Below is an example of cavitation on the tubesheet in a heat exchanger.

Figure 4 - Cavitation on tubes in a heat exchanger[5]

Leakage in a process line will create change in fluid conditions as the fluid becomes more turbulent around this point. Depending on the size of the leak the change in turbulence gives off sound waves that might be detectable in the hearing range. The turbulence might contribute to a chain reaction of events leading to a larger leak or create other sources. It is therefore important to take indications of fugitive emission seriously.

[5] Statoil PowerPoint presentation, *«Inspeksjonsfunn - Aldringsprosjektet»*

In a process pipe with continuous flow there will be a balanced distribution of forces (see left side of Figure 5). If valves in connection with the pipe are operated quickly, there might occur pressure pulses due to change in acceleration of the fluid. This applies especially to valves with large differential pressure and in pipes with high fluid velocities. Pressure pulses create an imbalance in the distribution in forces if they reach bends or large expansion in cross sections and reflect back and forth (see right side of Figure 5).

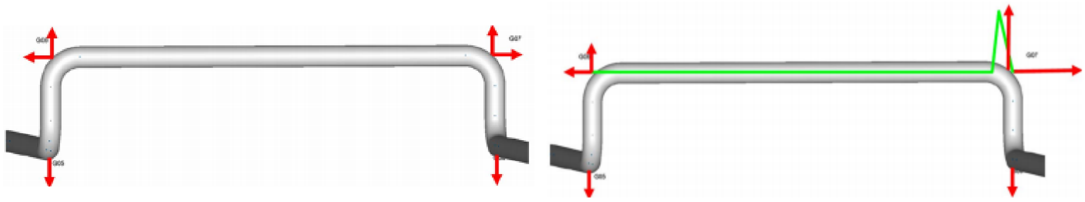

Figure 5 - Distribution of forces in a pipe: balanced forces (left) and unbalanced forces (right) [15]

Pipe systems with expected pressure pulses are normally designed with reinforced support in vulnerable areas. Without supporting constructions pressure pulses can lead to rupture of the pipe.

Some process operations can have higher fugitive emissions relative to high temperatures and pressures. The effect of this correlation is dependent on other parameters such as catalyst activities and availability of utilities. [8, p. 507]

3.2 Technical conditions

Typical sources for leaks are connections that are not welded and therefore constituting weakness in sealing ability. Flanged connections are used to enable pipe split for removal or blinding during maintenance or change of operational mode. To enable pipe split it is equally difficult to ensure a fully sealed area. This enables in particular fugitive emissions as well as the risk of escalation. Smaller scale pipes, called tubing, and the connecting fittings also constitute an important source of leaks. In addition to motion and vibrations technical degrading could lead to points that allow leaks. For emergency shutdown valves the risk is that they are normally stationary. After use they have a greater risk of leaking. Internal leakage, called internal passing, also represent a risk as the gas can be released to unexpected areas.

Examples of possible sources of leaks are as follows:

- Valves/Packing boxes
- Emergency shutdown valves – ESDV (internal passing)
- Blowdown valves (internal passing)
- Flanges/Gaskets
- Grease nipples
- Couplings
- Underneath insulation (Corrosion under insulation - CUI)
- Tube connections
- Compressor Seals
- Flare
- Heat exchangers
- Tank floating roof seals
- Ship loading
- Others

These examples have in common that they are connections. In the following subsections the most typical technical sources of leaks will be described: valves, flanges, tubing and heat exchangers. Technical degrading will also be described.

3.2.1 Valves

Valves represent the majority of the total fugitive emissions with contribution of approximately 50-60 % [8, p. 91]. According to perception in the industry about 60 % of these emissions are again result of the packing boxes. Valves that are operated frequently, such as control valves, can easily wear and further introduce a source of gas leak. Gate valves and globe valves have rising stems and can more often leak in comparison to quarter-turn type valves such as ball valves and plug valves [8, p. 91].

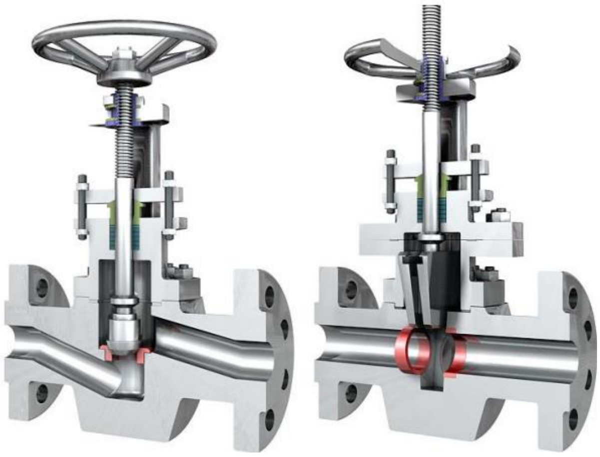

Figure 6 - Valves with rising stems: globe valve (left) and gate valve (right) [15]

Figure 7 - Quarter-turn type valves: ball valve (left) and plug valve (right) [15]

The possibility of leakage through valves is dependent on design, aging, maintenance, fluid properties, and especially sealing design.

3.2.2 Flanges

Flanges are connections designed to create flexibility in the process line. Equipment is connected to pipes with bolted flanges to enable maintenance or replacement. Example of a flange is shown below.

Figure 8 - Example of a bolted flange [16]

The bolts have to be mounted properly according to standards and specifications with sufficient torque and tension. Improper mounted flanges can easily become source of gas leaks. Depending on the design of the sealing system flanges can contribute to fugitive emissions as well as larger leaks. The possibility of leakage through flanges is also dependent on design, aging, maintenance, fluid properties, and sealing design.

3.2.3 Small Bore Tubing

Small bore tubing, often referred to as tubing, is defined as the discipline covering pipes with an outside diameter up to 2''/50mm [17]. Below is an image describing the main terms regarding the tubing discipline. Compression fittings is the general term for all the connecting components.

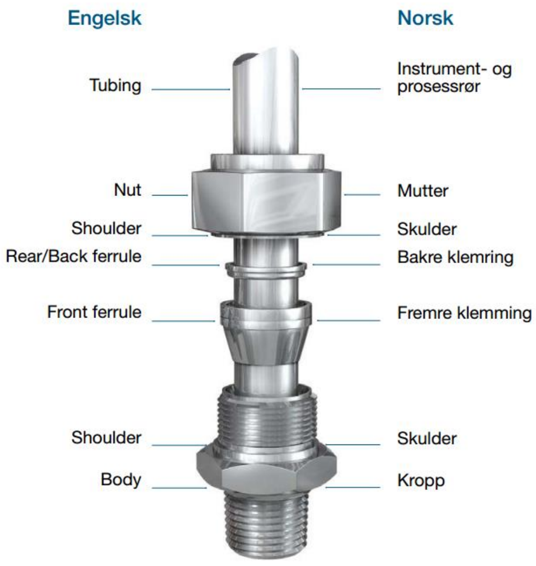

Figure 9 - Main terms within the tubing discipline [17]

There are several different brands supplying fittings. Combining components from different suppliers will not provide a fully sealed system and therefore introduce risk of leakage [17].

Tubing and fittings are managing the same fluids and fluid conditions as the larger pipes but quality control is normally less strict than for piping. Vibrations may be destructive for tubing, as well as for piping. Fatigue induced ruptures is an element important to consider when designing equipment and fluid parameters.

3.2.4 Heat Exchangers

Major factors that can cause leaks in heat exchangers are vibrations, fatigue and corrosion.

Pitting corrosion differs from global corrosion as it occurs as pits and can develop holes through the material. It is difficult to observe the extent of the pitting corrosion in the tubes without use of non-destructive-testing, such as Eddy Current or similar methods. Tubes with insufficient wall thickness are plugged.

Figure 10 - Pitting corrosion[6]

[6] Statoil presentation at «Gasslekkasje workshop – Bygnes 10.04.2014»

Heat exchangers and their components have large fluctuations in temperature and pressure. Pressure cycles and especially temperature cycles are challenging for the flange connections. Rapid changes may lead to material fatigue.

Types of flow induced vibrations for shell and tube heat exchangers include mechanical resonance and acoustic resonance in the tube bundle. The Tubular Exchanger Manufacturers Association (TEMA) has developed software to assess the possibility of vibration in relation to specific heat exchangers. Process parameters and heat exchanger parameters are plotted in the program which calculates possible occurrence of various types of flow induced vibrations. For tubular heat exchangers vibration can result in damage of surfaces, ruptures of the tubes or breach in the connection between the tubes and the tubesheet.

Figure 11 - Examples of vibrational damage in heat exchangers[7]

Normally in tubular exchangers, gas flows in the tubes and the heating/cooling medium flows on the shell side. The medium used can be water/steam or gas. Leakage in the tube bundle, so called internal passing, can lead to gas mixing with the shell side outflow. It is therefore crucial to have gas detectors close to the water outflow.

In addition to fatigue and pitting leaks, heat exchangers have natural potential leak sources such as flanges.

3.2.5 Technical Degrading

Approximately 20 % of potential HC leak sources are due to technical degrading. Technical degrading includes the following [14, p. 70]:

- *Degrading of valve seats*
- *Degrading of flange gaskets*
- *Reduced tension in bolts*
- *Fatigue*
- *Internal corrosion*
- *Exterior corrosion*
- *Erosion*
- *Other*

[7] Statoil document, *«Inspeksjonsfunn - Aldringsprosjektet»*

Erosion is a process where small pieces of a metal surface are grinded down. This effect is reinforced when the fluid contains particles, such as sand, and also if cavitation occurs simultaneously. Over time there might develop visible damages impairing the pipe or equipment.

Figure 12 - Damages due to cavitation and erosion[8]

Corrosion under insulation (CUI) is a widespread problem in the industry representing perhaps the largest integrity challenge. Corrosion causes reduction in the wall thickness and can ultimately lead to holes or cracking of the pipe or equipment.

3.3 Human Factors

According to the HC project by Norwegian Oil and Gas 36 of the 56 HC leaks during the period 2008-2011 were caused by human interference [12]. The causal analysis shows that in some of the events more than one factor resulted in the leak. Table 4 displays the distribution of causes.

Table 4 - Distribution of human related causes HC leaks 2008-2011 [12]

Cause of HC leak	Number
Improperly executed isolation (blinding)	6
Improperly executed flanges/bolts during maintenance	11
Valves in wrong position after maintenance	8
Wrong gaskets or improper mounting of gaskets	2
Improper operation of valves	5
Improper use of temporary process lines	2
Removal of barriers during maintenance	5
Work on equipment unknowing of still pressurized	2

There exist procedures on planning, execution and completion of these operations which includes use of barriers and verification.

[8] Statoil document, *«Inspeksjonsfunn - Aldringsprosjektet»*

3.4 Examples of Previous Incidents

The following chapter will briefly describe some incidents within Gassco operatorship involving HC leaks during the previous years in order to get an overview of trends of main causes. In all cases safety measures were taken and no major accidents occurred. These measures are excluded from this discussion. Economic losses directly caused by the incidents and indirectly due to reduction of production in other areas of operation have not been calculated. The first incident is not an actual accident but is used to describe necessary testing and technology qualification.

3.4.1 Titanium Seal – Technology Qualification

The report "Perspectives on Technological Change and Innovation in Norwegian Natural Gas Industry" [18] refers to testing of a flange gasket during the development of the natural gas industry in the late 1980s. The flange was new technology and the vendor had specified to use a standardized gasket of stainless steel. Under pressure tests with nitrogen the flange showed that the connection leaked. Several tests with attempts of innovation were executed but leakage was still the result. The final, successful conclusion was to produce a titanium seal with silver coating. The report emphasizes the importance of technology qualification, also considering sub-components such as gaskets. It is fundamental to have knowledge of this lesson where the main problem was the combination of familiar and new technology. With a gas industry that is constantly developing, it is important to have knowledge of materials to prevent gas leaks. Assumptions and empiricism is not necessarily good enough arguments to implement new technology into existing processing equipment. In such cases testing is required.

3.4.2 Gas Leakage Butane Splitter at Kårstø (2007)[9]

On the 22nd of March 2007, a leakage was registered in a flange between the cylinder head and the main section of the boiler 24-HA-405 during start-up of the Butane splitter 24-VE-403 at Kårstø. The investigation report pointed to several factors that resulted in a synergic effect leading to the leakage. Among the factors the following five were the main causes:

- Wrong gasket type
- Uneven surface
- Insufficient roughness
- Marginal torque
- Span in flange connection

The sealing ring used was of graphite laminated steel without serrations. This is considered less robust than the specified cam profile sealing ring. The surface of the flange should preferably be more serrated to increase the forces applied to each contact point. The uneven surface was measured to approximately 1.5 mm. During assembly the supplier's recommendation on tightening torque had been applied. The report refers to a general consensus that the torque value recommendation was too low for the circumstances of the respective flange. The span in the flange connections may have contributed to less tolerance for other weaknesses. The report states that there is no direct cause for criticism, but points to several negative elements and weaknesses. The situation was handled in a good way avoiding injury and property damage. Operating loss was calculated to 156 MSm^3 rich gas during the four days production was shut down.

[9] Statoil document, *«Gransking av Gasslekkasje, NG – Kårstø»*

3.4.3 Condensate Leakage at Kollsnes (2009)

During normal operation on 19th of May 2009 there was a condensate leak at Kollsnes as result of a gasket blown out of a flange. The incident could have had serious consequences, but the material damages were limited and there were no injuries. Kollsnes process plant was shut down for 2.5 days so the economic consequence was corresponding to the down time. The investigation report concluded that the precipitating cause of the incident was use of far too low tension on the bolts on the flange. Correct tension should be 300Nm with hydraulic tensioning tool while surveys showed that actual tension was between 80-100Nm. The bolts were only manually tightened and the bolt tensioning tag had not been removed giving misleading information. The report stated that the event was caused by lack of tension on the flange bolts, lack of verification between delivery from supplier to Statoil Hydro Operations and lack of compliance with the supervisory duty. There are procedures covering these operations but they were not complied with [19].

3.4.4 Gas Leak Butane Splitter T300 at Kårstø (2010)[10]

The Sleipner Condensate processing facility at Kårstø started up in 1993. A new butane column was installed in connection with the Kårstø Expansion Project in 2005 (KEP2005) introducing changes in the feed stream conditions. Previously the column was designed for a two-phase feed while the new changes were one-phase feed. No further modifications were performed. Some operating periods have had low inlet fluid velocities as well as low inlet temperatures. This led to quenching and collapse of gas. Since the expansion in 2005 there have been reports of vibration giving off sound in the feeding pipes in the butane splitter.

On the 17th of March 2010 a leak in the inlet flange of the butane splitter column was detected. The leakage rate was approximately 0.025 kg/s. Main factors causing the leak were the changes in feeding conditions with no further modifications of the column and operating periods with low feeding rate.

The internal investigation concluded that there had been no breach of governing documents but there were some barriers that were broken.

3.4.5 Hydrocarbon Leakage at Mongstad (2010)

During startup of the reactor R-5006 at Mongstad on the 12th of September 2010, HC odor was registered by an operator. The operator applied gas tests at the reactor several times. When he finally found a leakage in the stuffing box on a thermowell he tried to pull the nut attached to this. The entire thermowell blew out with 23 bar back pressure upon which the operator got hurt in the hand. According to the contingency plan, the reactor was shut down, isolated and depressurized to flare. During the shutdown there was another prolonged butane leak on the heat exchanger of approximately 2.5 hours. [20]

Direct causes of leakage in the reactor were as follows [20]:

1. Installed thermowell was designed for lower pressure
2. Mechanical connection between flange and thermowell instead of welded
3. Pipe fitting was mounted with pressure tool as it was perceived that it was a standard bolt

Direct causes of leakage in the heat exchanger were as follows [20]:

[10] Statoil document, «*Dybdestudie – Gasslekkasje T300 butansplitter 02.08.2010*»

1. The differential pressure in the heat exchanger increased by shutdown of the reactor
2. Wrong gasket type: ran out of specified package (double jacket), too long delivery - ordered another gasket (massive steel gasket)
3. Too low torque (600Nm instead of 800Nm)
4. Leak test had been performed with too low pressure

3.4.6 Hydrocarbon Fire Next to Butane Boiler in T200 Kårstø (2013)[11]

On the night of February 9th 2013 a fire occurred by the butane boiler in T200 at Kårstø. HSE-work had already been implemented in conjunction with a registered fugitive HC leakage and it was this leakage that ignited. The fire was put out and personal injuries were avoided. Two days before the incident there was registered leakage of steam, tripping of the cooling compressor, increased temperature in the steam system and blocked steam valves.

The risk evaluation showed that the possible severity of both personal injury and property damage could increase under slightly different circumstances. The subsequent report concluded with two broken barriers: current specifications for isolating flanges were not followed and there was inadequate risk assessment for HSE in conjunction with the fugitive leak.

3.4.7 Hydrocarbon Leak in T410 Expander Building Kårstø (2013)[12]

On 23rd of May 2013 a gas leakage occurred on the oil expander on the train T410 at Kårstø through one of the sight flow indicators. The rubber seal on the sight glass had slipped out and ruptured. This was the third incident of the same character since 2007. The internal investigation team identified weaknesses in the design of the sight glass and routines regarding them. The manufacturer of the glasses had specified a torque of 79-84Nm. According to the specifications the bolts should be tightened daily after assembly until no further change in torque. Measured torque after the incident showed that the values for both glasses were far below specification.

[11] Statoil document, *«Brann rundt butankoker i T200, Presentasjon av dybdestudie, 09.02.13»*
[12] Statoil document, *«Dybdestudierapport - Gasslekkasje fra seglass oljesystem T410, 20.06.13»*

3.4.8 Summary of Incidents

Below is a summary of the incidents and causes.

Table 5 - Summary of previous incidents

Incident	Consequence	Cause
Titanium seal - technology qualification	• Leak in pressure vessel	• Lack of TQ (wrong seal)
Gas leakage butane splitter Kårstø (2007)	• Leak in heat exchanger girth flange	• Wrong gasket according to specification • Uneven surface • Insufficient roughness • Marginal torque • Span in flanged connection
Condensate leakage Kollsnes (2009)	• Gasket blew out	• Low torque • Lack of verification • Lack of supervisory duty
Gas leak butane splitter T300 Kårstø	• Fugitive leak	• Change in feeding conditions • Low cycle operating periods
Hydrocarbon leakage Mongstad (2010)	• Thermowell blew out • LPG leak reactor	• Design for lower pressure • Improper mounted flange • Improper mounted fitting
	• Butane leakage in heat exchanger	• Increased differential pressure • Wrong gasket • Low torque • Wrong leak test
HC fire next to butane boiler Kårstø (2013)	• Pipe flange leakage	• Breach of specification • Inadequate risk assessment
HC leak in expander building Kårstø (2013)	• Gasket slipped out	• Low torque • Weakness design • Inadequate routines

Based upon this overview of occurred events it seems natural to make two conclusions:

1. Causes are directly linked to the human factor in such a way that human interference introduces hidden faults. For example will lack of torque on bolts not be visible at first but constitute a weakness until an event occurs.
2. There is a synergic effect between several factors leading to a gas leak, implying the importance of barriers.

4 Preventive Measures to Reduce Risk of Gas Leaks

In order to reduce risk of gas leaks it is necessary to have proactive measures to prevent gas leaks from occurring as well as reactive actions to limit the consequences. This chapter will mainly focus on the proactive aspect. Based on the discussion in chapter 3 it emerged that the human factor represent higher risk of gas leaks than technical conditions. Thus will some conditions from the technical subchapter be accounted for under the following subchapter regarding human factors.

4.1 Reducing Process Related Leak Factors

Since the main process related leak factors can be linked to deviation between design and operating parameters, it is essential to account for potential changes in operation during the design phase. Use of the TEMA software described in chapter 3.1.4 is one activity that enables increase of capacity in heat exchangers.

Sounds due to cavitation and vibration are events that indicate critical process factors. Reports of such must be reported to competent personnel for inspection and monitoring.

The level of fugitive emissions can be influenced by process design conditions such as temperature, pressure and vapor pressure. Fugitive emissions are relatively lower in some operations with lower operating temperatures and pressures, where the vapor pressures are lower. In operations with high fugitive emissions there should be assessment whether lowering of operating conditions might be beneficial [8, p. 507].

4.2 Reducing Technical Leak Sources

As discussed in chapter 3.1 there are certain technical components more prone to leak. To discuss reduction of technical leak sources the following actions are considered:

- Reduce number of potential leak sources
- Ensuring joint integrity
- Precautions of technical degrading
- Monitoring, inspection and maintenance

4.2.1 Reduce Number of Potential Leak Sources

When designing new process lines it is possible to reduce the actual number of sources. During the pre-assessment phase the number and types of flanges and valves should be assessed towards risk of leaks. Valves and flanges are natural sources of fugitive emissions and also constitute potential for larger leaks.

4.2.2 Ensuring Joint Integrity

Bolted flanges are joints with potential to leak and it is therefore essential to mount the bolts with proper tension and torque. These values are specified by the suppliers of the flanges according to certain conditions, which might be insufficient for the intended use. TSP's also have specifications including different, or even stricter, methods and values for mounting. Flanges have to be marked with tags with information about all performed operations: values, when it was performed and by whom. Norwegian Oil and Gas (Nor: *Norsk olje og gass*)[13] has developed detailed manuals[14] covering

[13] Previously OLF (Oljeindustriens landsforening) 1989-2012

execution of work on flanges, valves and tubing. Training courses are offered by certified providers in accordance with the manual on flange work. These training courses are mandatory for mechanics working on HC-bearing equipment within Gassco operated facilities.

The joints must be equipped with proper sealing systems for non-standard joints. Technology qualification is an important factor as different materials have different sealing qualities. Implementation of a seal in a flange or a valve must be assured according to Gassco governing document on Technology Qualification. Empirical data and assumptions are not sufficient.

The UK company Hydratight has developed a service called Joint Integrity Assurance (JIA). The principle behind JIA is to assure all phases of work on bolted flanges. According to Hydratight their philosophy is based on the *ASME stated principle that all bolted joints should be treated like it were welds*[15].A weld has to be thoroughly documented on material choice, competence of the welder, NDT verification, hydrostatic testing, etc. Implementing this strict philosophy onto flange work will raise the integrity of the joints. Hydratight has also developed an identification system giving the specific joint a unique number which is configured in software to give an overview of the project. Every joint is attached a 4-part weatherproof tag to visualize the status of the specific joint. The four parts are "Joint to be broken", "Joint to be assembled", "Joint to be tightened" and "Joint tightened". Every part has an electronic identification code (barcode) on the back and has to be signed continuously during the project. Joint activity history can be linked to the ISO drawing, enabling each joint to be identified on the Piping and Instrumentation Diagram (P&ID). This form of standardization and monitoring enables a more detailed overview of joints and their integrity. Previous history has shown that routines regarding flange work and especially tagging has introduced weakness concerning joint integrity.

4.2.3 Precautions of Technical Degrading

Technical degrading of pipelines and equipment is inevitable. Assuring good integrity is essential to reduce the risk of leaks. As previously discussed, corrosion under insulation (CUI) constitute a major integrity issue. Locating damaged areas prior to actual leaks is a key factor. Non Destructive Testing (NDT) is continuously applied to give overview of wall thickness. Pipes and equipment with large reductions will be replaced. Statoil at Kårstø process plant has since 2003 applied a new approach to the facility's oldest part with distance insulation[16]. The method uses a perforated spacer between pipe and insulation enabling natural ventilation and cooling with air and also draining water particles. Historical inspection data have shown no severe cases of CUI in areas with use of distance insulation.

Beerenberg is an innovative company within the CUI field. The company's research and development (R&D) department is currently working on three technologies in their CUI project[17]. As these technologies are patent pending and under R&D they will only be described in brief:

1. Drain plug with indicator (patent pending – ready for production): intended to detect, collect and visualize water
2. Hygroscopic cable (patent pending – under testing): intended to detect moisture through a Time-Domain Reflectometer with possibility to detect and position several spots
3. Advanced fiber technology (patent pending – R&D phase): gives possibility for real time monitoring of changes in corrosion or pipe wall thickness, and detecting moisture

[14] Previously *OLF Guidelines 118, 119, 120*
[15] Hydratight presentation by Paul Holland on «Gasslekkasje Workshop - Bygnes 10.04.2014»
[16] Statoil presentation by Svein Lohne on «Gasslekkasje Workshop - Bygnes 10.04.2014»
[17] Beerenberg presentation by Geir Harris on «Gasslekkasje Workshop - Bygnes 10.04.2014»

Testing of the hygroscopic cable has shown that the technology represent advantages such as easy and flexible installation, detection with great accuracy without need for dismantling existing insulation, and easy collection of data. The collected data has to be analyzed by specialist. These three technologies are preventive measures to reduce the risk of corrosion based leaks and it will therefore be of Gassco's interest to follow up on further development.

4.2.4 Monitoring, Inspection and Maintenance

Ensuring necessary integrity of process facilities requires good routines for monitoring, inspection and maintenance.

Monitoring routines supplies overview of the overall integrity. All operations on pipes and equipment have to be documented with necessary data and verification. Any observations of non-conformities have to be registered for further inspection. Daily visual inspections enable for example detection of small emissions and other indications prior to actual incidents. Gas detectors have a set point of 20 % LEL which is higher than fugitive emissions.

Based on registrations of non-conformities inspections can be conducted with necessary equipment. Regular inspection on areas of concern provides information for assessment whether further maintenance or repair should be initiated.

All process facilities have routinely maintenance programs according to standards and specifications on all pipes and equipment. These maintenance programs are regardless of non-conformities and are essential to ensure high integrity.

Programs with regular monitoring, inspection and maintenance are crucial for reducing risk of gas leaks.

4.3 Reducing Human Related Leak Sources

In order to reduce human related leaks it is utmost important to understand the complexity of the actual causes. To simplify further discussion human factors have been divided into three levels:

1. Technician level: This level represents the "work force" executing work on hydrocarbon bearing equipment
2. Supervisory level: This level represents the responsible unit that receives work orders, plan projects, organize technicians and verify upon completion
3. Management level: This level represent the entire management system that are responsible for safe operation; Gassco as operator is included in this category

4.3.1 Reducing Risk on Technician Level

Below is a visualization of the risk factors associated with Technician Level.

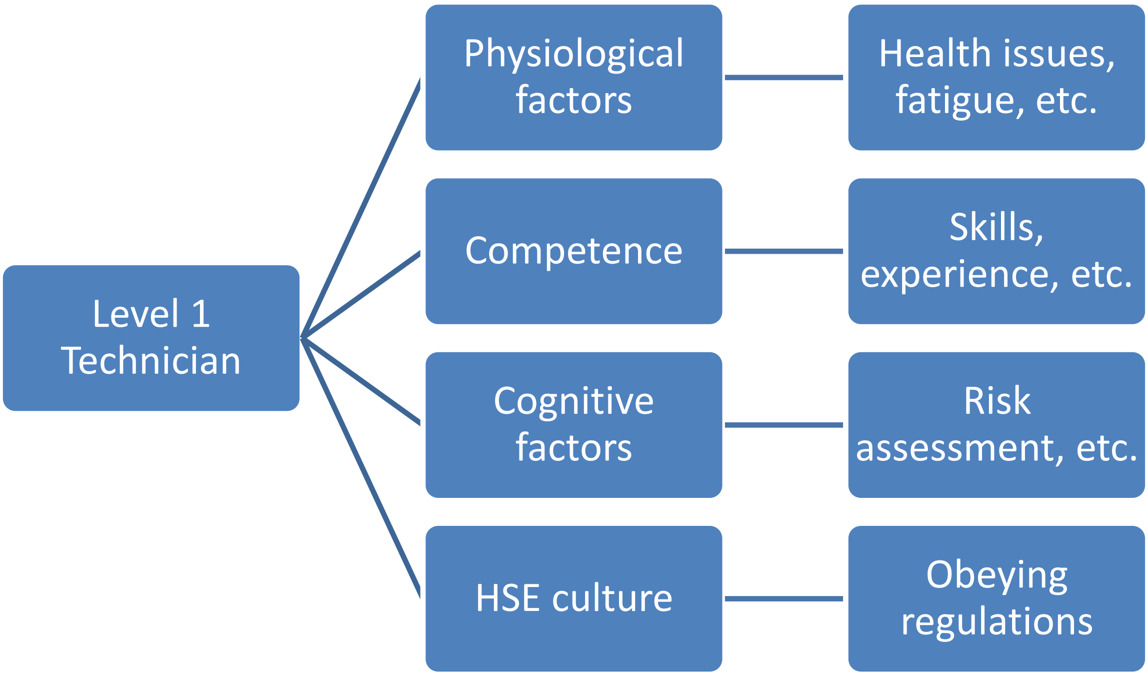

Figure 13 - Factors associated with Technician Level

Technicians' physiological factors, such as health issues, may affect the quality of the work performed. Measures to reduce errors based on physiological factors are beyond the scope of this report.

Competence is a concept influenced by skills and experience. Initial skills are achieved by education and training, and maintained by further training. Experience is also achieved through training as one will establish a certain routine and understanding of operations. Certification ensures sufficient level of competence. Statoil has developed a verification program at the Kollsnes process plant where technicians are tested in flange work at an on-site test facility [21]. Use of separate training facilities to regularly test workers is a good measure to maintain these certified skills.

A technician's psychological ability to perceive situations and assess possible outcomes is part of the cognitive aspect. Competence and cognitive factors combined is perhaps the most important part of a well-functioning process facility, as well as the area with most potential for errors. It is essential that personnel working with different operations regarding HC bearing equipment have sufficient competence and risk assessment to handle any situation, that being standard operation or unwanted events. Coursing of personnel according to the Norwegian Oil and Gas manual on flange work is an effective measure in this field. Verification courses or test rigs in relation to tubing should also be implemented.

Standardization of certain areas of operation will contribute to reduced risk of skill-based errors. Technicians alternating between projects must be able to recognize the correct components and procedures. For an example can color coding on components lead to incorrect choice if suppliers apply different colored tags.

Attitude towards HSE rules and instructions on a technician level is an area receiving limited attention. This aspect is brought up in this report to introduce discussion around the topic for future research. Some issues to consider evaluating the HSE culture on the technician level are as follows:

- Do technicians respect HSE regulations?
- Do technicians follow HSE regulations?
- Are procedures violated with intent?
- Does experience lead to more "shortcuts"?

If technicians perceive the organization as hierarchical there might develop a certain disrespect of governing documents which can spread to the overall HSE culture. A healthy HSE culture is important to ensure safe operations.

4.3.2 Reducing Risk on Supervisor Level

Below is a visualization of the risk factors associated with Supervisor Level.

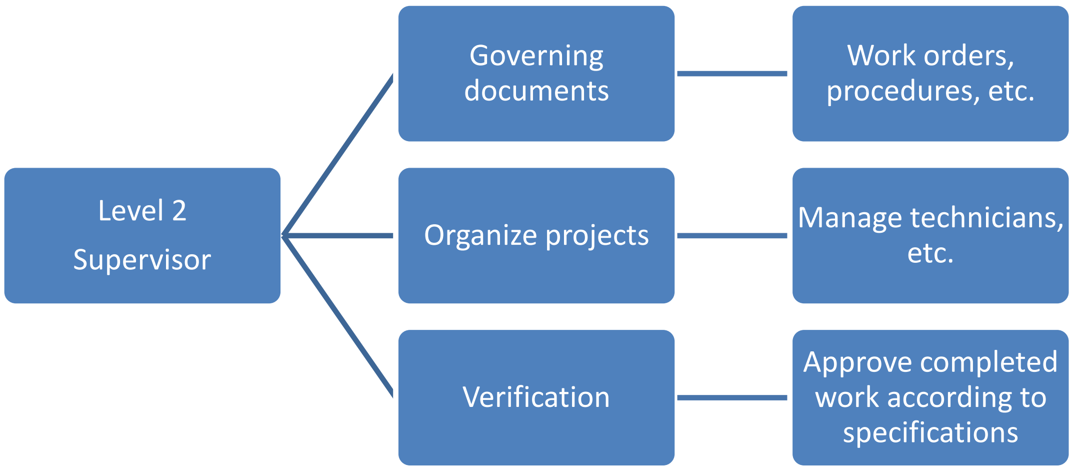

Figure 14 - Factors associated with Supervisor Level

The Supervisor unit receives governing documents such as work orders with detailed description of projects. In compliance with current procedures specific work operations must be organized. To reduce possibility of errors within these project stages it is essential that the documentation received is clear without room for misinterpretation: *what are the criteria for the operation, what procedures apply for the specific operation, which barrier (isolation) system is to be used, which components and materials are to be used, and so forth*.

Table 4 shows distribution of direct causes of previous HC leaks. However, all the mentioned operations require verification which indicates that this is an area of concern. Verification is intended to function as a safety barrier, where performed work is verified by another process operator. Human error in execution of operations on HC bearing equipment must be eliminated during the verification process. Possible measures to strengthen this barrier are workshops with focus on risk assessment, ensuring governing documents are clear and training of relevant personnel. Norwegian Oil and Gas has made a short film to illustrate the importance of verification [22].

In order to maintain a correct overview of process facilities it requires reliable documentation and tagging. It is important that registered data is accurate. Although it is within Technician Level's instruction to fill out documentation it is initially the Supervisor Level's responsibility to ensure this is achieved.

After gas leaks investigations are conducted to identify causes. These incident reports mainly focus on direct causes, often technical factors, and underlying causes such as lack of verification. However, it might be of interest for Gassco and the relevant TSP to conduct more thorough qualitative investigations. Workshops including technical specialists, HSE representatives and people related to the incident can contribute to a broader, qualitative causal analysis.

It is within the Supervisor Level's responsibility to register all non-conformities and observations. In order to follow up on these findings it is important that the quality of the data and the general routines are appropriate.

4.3.3 Reducing Risk on Management Level

Below is a visualization of factors the Management Level must comply with.

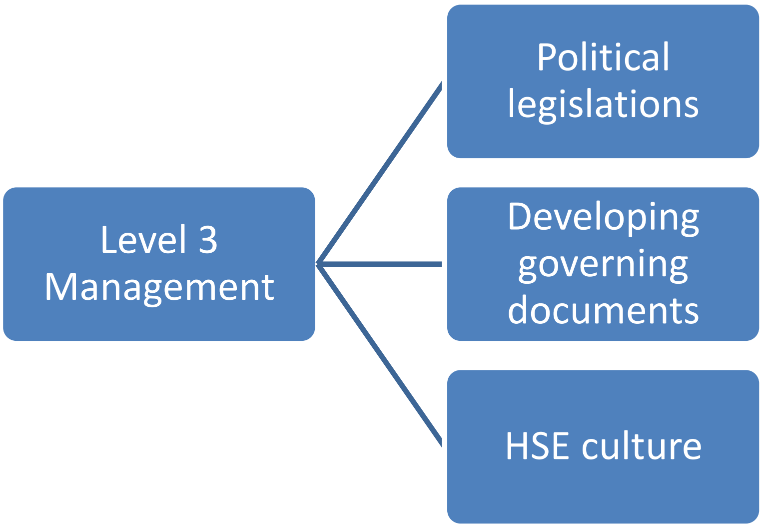

Figure 15 - Factors the Management Level must comply with

International and national legislations set guidelines for company operations. It is within the Management Level's responsibility to implement applicable legislations into governing documents and ensure that the entire organization complies. In relation to risk factors discussed under Supervisor Level it is important that governing documents leave no room for misinterpretation.

In addition to legislations there will naturally be a certain amount of empirical data to consider. This data can be internally registered based on unwanted events or retrieved from other participants in the industry. Workshops involving several different representatives build a solid foundation for exchanging experience. Representatives from TSP's, industry organizations, suppliers, and others are able to contribute with a substantial amount of experience. Stimulating to a flow of empirical knowledge across the industry will improve the Management Level of operation. Gassco as operator has the executive responsibility and is included in this Management level. It will therefore be within Gassco's responsibility to facilitate workshops of this kind on a regular basis.

Gassco has yearly arranged gas leak workshops since 2011 with the intent to[18]:

- *Increase knowledge and understanding of the risk linked to HC leaks*
- *Share experiences, positive and negative*
- *Openly discuss areas of improvement and "best practices"*
- *Present and discuss new technology*
- *Identify possible measures and actions*

Workshops of this kind involve participants with different backgrounds and with unique competence. The informal framework contributes to a strengthening of the Management Level's ability to reduce risk of gas leaks. The general recommendation to improve organizational factors to reduce risk is increased focus on workshop in terms of frequency, length and participants. It might be of relevance to include representatives from the Supervisor Level or even Technician Level. Involving Technician Level representatives in workshops might also have a positive effect if the organization is perceived as hierarchical.

As discussed in chapter 4.5.1 HSE culture is the foundation of safe operations. A healthy culture is established by the Management Level. This aspect is also beyond the scope of this thesis.

[18] Introduction by Alvin Hansen at «Gasslekkasje workshop Bygnes 10.04.14»

5 Secondary Measures to Reduce Gas Leaks

This chapter will consider secondary measures to reduce gas leaks. The preventive measures in chapter 4 are intended to either avoid gas leaks or reduce fugitive emissions. Experience confirms that fugitive emissions are inevitable, but it will be of Gassco's interest to limit these to a minimum.

Gas detection is often categorized based on toxic or combustible gases. HC gases are combustible thus gas detection in this chapter will focus on this category. In any case involving gas leaks it is utmost important that this is detected and that the surroundings are aware of its presence. Primary gas detection will generate alarm when sensing a given amount of gas in order to notify that the area might be explosive. However, most fugitive emissions will not achieve a leakage rate that immediately will trigger gas detectors. It is therefore necessary with gas detection that can locate sources of small leaks as well.

5.1 Biological Methods

Biological methods of gas detection include the use of humans or animals. Trained personnel can inspect parts of a plant using vision, sense of smell or hearing. Gas leaks can emit distinctive noises or vibrations which can be observed by humans. Specially trained dogs can also be used for detecting gas leaks. Using dogs for gas detection will be difficult on Gassco's process facilities due to limited access. However, dogs can be used to detect corrosion.

5.1.1 Use of Dogs to Detect Corrosion

Fjellanger Detection and Training Academy (FDTA) is in the final process of developing an efficient method of CUI detection by using dogs. The project is funded by Gassco and supported by Statoil. Air samples are taken at the process plant in specially designed capsules and transported to FDTA for analysis by special trained dogs. During the two years project period the method has shown reliable detection of corrosion. Implementing this method in maintenance programs enables early detection of CUI and actions can be taken to prevent gas leaks. [23]

5.2 Visual Methods

Visual methods are based on the use of visual signs of gas leaks.

5.2.1 Visual Inspection

Visual inspection by operators on process facilities are conducted on a regular basis. Any observations which can indicate possible gas leaks are reported and further inspected with use of additional equipment. Visual inspection will also reveal other integrity issues.

5.2.2 Soap Test

The soap test is an easy and well-used method to locate small leak sources and detect fugitive emissions of the scale grams per hour. Soap, or a soap mixture, is applied to an area and a leak will be visible as small bubbles on the surface. This is a simple method that is easily applied: training is not required, there is no need for comprehensive preparations and it will instantly detect the presence of a leak. It is mostly used on an already assumed leak source, or to examine a newly installed flange or valve. Covering a large area will be time consuming. In such a way the method can be categorized as a simple but limited method of leak detection.

5.3 Vacuum Method

This method uses a portable vacuum system with an extended probe which is carried over a supposed leak to detect small leakages. The devices are often referred to as “sniffers” and are widely used on Gassco facilities. Sniffers provide results of the calibrated gas, for example methane, in parts-per-million (ppm), volume percentage (vol %) or in correlation with LEL (%LEL). Below is an example of a vacuum device.

Figure 16 - E-instruments Gas Sniffer Model 7899 [24]

The method can be used to verify that a newly installed component is mounted correctly. Sniffers are easy to use without comprehensive training or preparation. However, it is time consuming to screen a large area.

5.4 Infrared Methods

Infrared (IR) radiation is electromagnetic radiation with wavelengths in the range of 700nm - 1mm which is longer than visible light. Gas detection technologies using IR radiation is based on energy difference between a medium and the environment. Gases absorb a certain amount of energy depending on the molecular composition. HC gases absorb radiation with wavelengths around 3.3 micrometer[19] [25].

IR gas detectors emit radiation and the receiver can detect presence of gas in the form of reduced received signals. This technology is used in point- and line detectors to generate alarms in the concentration range 0-100 % LEL. These detectors are calibrated for the gas most likely to be present.

IR technology is also used to visualize gas leaks by using thermographic cameras.

5.4.1 Infrared Point Detectors

IR point detectors consist of a transmitter and an optical receiver that is calibrated to detect gas in an area between them. The point detector constitutes a single unit so it must be in direct contact with the gas, and thus detecting the concentration in the surrounding air. In presence of gas, some of the energy from the emitted IR beams is absorbed by the molecules in the gas. The received signal will

[19] 3.3 micrometer = 3300 nm

have a reduction of intensity which is proportional to the concentration of gas. The detectors are connected to an electronic computer system. A reduction in the received signal relative to a given percentage of LEL will generate a gas alarm. [26]

Figure 17 – Simrad GD10 Infrared Point Detector [26]

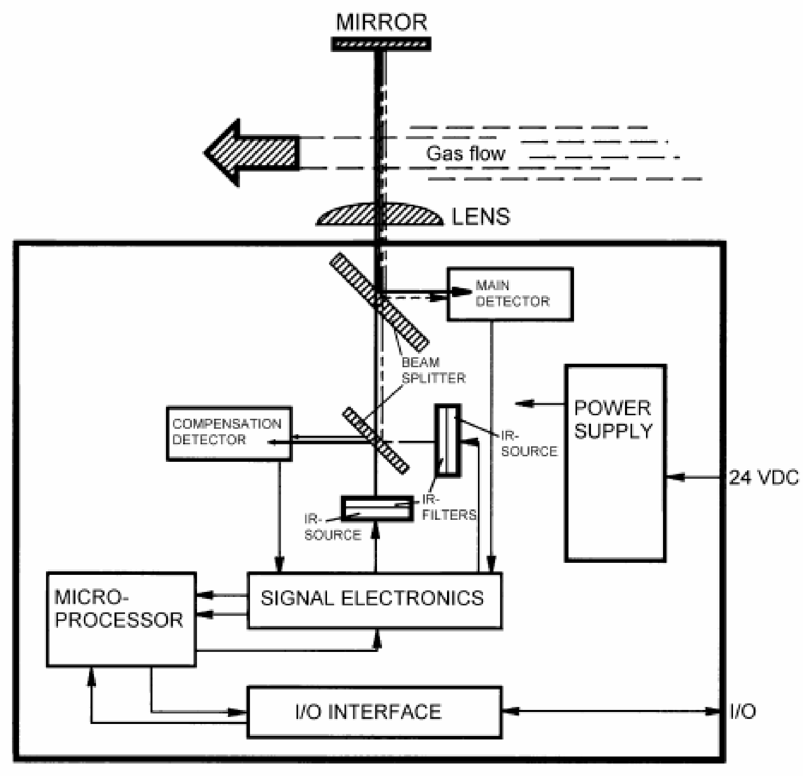

Figure 18 – Block diagram of Simrad GD10 Infrared Gas Detector [26]

The gas alarm set point for methane is usually 20 % LEL (See Figure 1) indicating low alarm and 30 % LEL for high alarm [27].

If only one detector generates alarm it is classified as "Single gas"[20]. Actions within this alarm are automatic disconnections of ignition sources, such as temporary equipment and non-EX equipment,

[20] Norske Shell presentation on «Gasslekkasje Workshop - Bygnes 10.04.2014»

until the situation is under control. “Confirmed gas” is when two detectors in the same area generate alarms. Responsive action to this will be the same as for “single gas” but shutdown procedures will also be initiated.

5.4.2 Infrared Open Path Detectors

IR open path detectors work according to the same principle as point detectors with IR signals from the transmitter and an optical receiver. The difference is that open path detectors consist of two units placed in a distance from each other. Transmitter and receiver can be placed in the same device with a reflective unit placed at a distance to reflect the IR beams back into the sensor. This is referred to as a short range detector. An open path detector can also consist of two separate units for the transmitter and the receiver. The principle is shown in Figure 19 using Searchline Excel Open Path IR Detector [27].

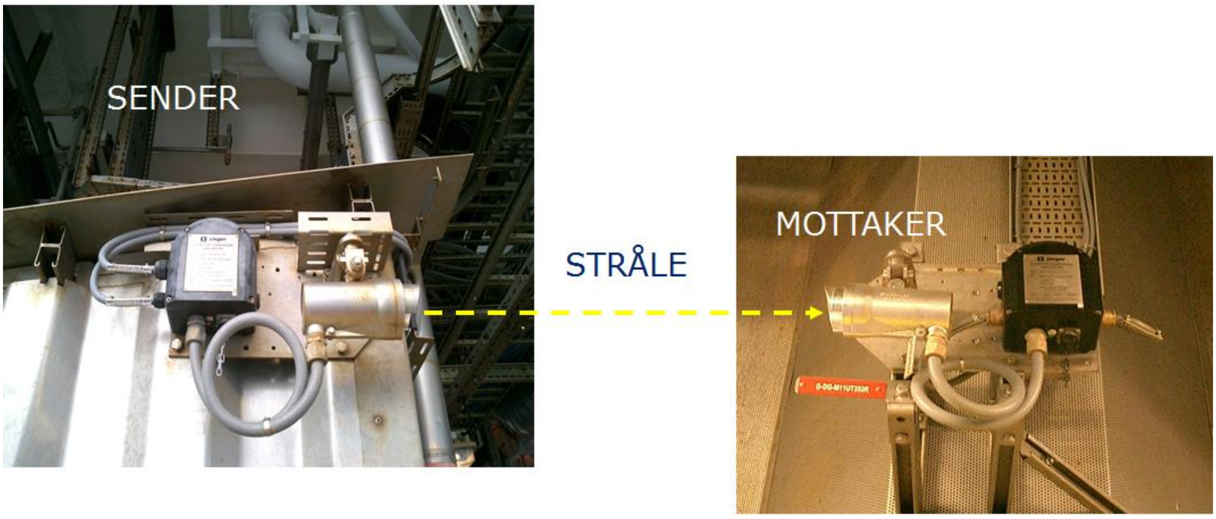

Figure 19 - Principle Searchline Excel Open Path IR Detector [27]

The range of an open path detector can be up to 200 m. A long range enables detection of small gas clouds with concentrations below 20 % LEL. Open path detectors measure gas concentrations as LEL-meter (LELm) which is the percentage of LEL multiplied by the range. Alarm set point for these detectors is from 1 LELm, dependent on the area classification [27].

According to the supplier of Searchline Excel the frequency used is so intense that it rejects other light sources such as interference from sunlight, lightning, flare and welding. Nor shall it be affected by water vapor, fog or inert environments [28].

Because of the long distance between transmitter and receiver, there is a possibility that workers unintentionally disrupt the beam and consequently generate a false gas alarm.

For best utilization a combination of point detectors and open path detectors should be mounted in a matrix system to cover a broad area, both vertically and horizontally. As a general rule open path detectors can be used to frame in areas and critical equipment while point detectors monitor a site.

5.4.3 Handheld Infrared Camera

An IR camera is in short terms heat sensitive photography. The images visualize a color spectrum that looks like a cloud in the area photographed. From the visualization trained persons can interpret various information about the leak such as which gas is leaking, approximate size and source. Advantages of these cameras are that examination can be done from a safe distance and can cover large areas where a potential leak source is not specified. [29]

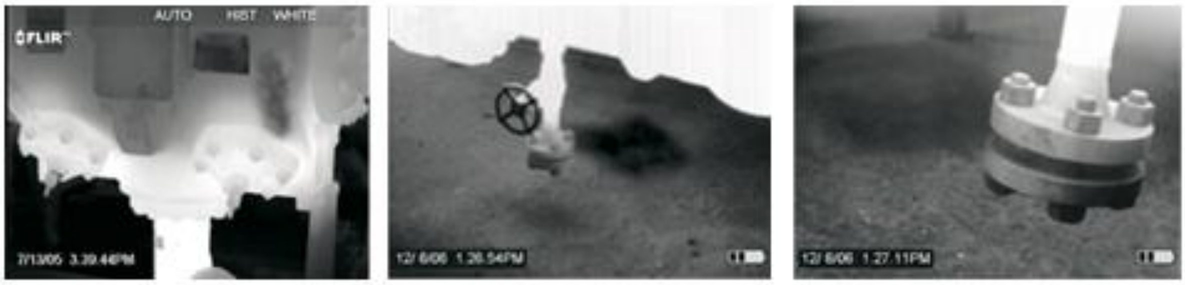

Figure 20 - Examples of infrared gas images [30]

FLIR[21] Systems Inc. is a commercial international company providing thermographic cameras. The handheld camera FLIR GF320 is specially designed to detect methane and other VOC. The camera weighs 2.4 kg and can easily be transported around for inspection. This enables detection of gas leaks without shutting down parts of the plant. The inspection is visualized in real time as a video or images which can be stored on a standard computer with the appropriate software. FLIR camera can detect both major leaks and fugitive emissions. Analysis of the images must be performed by competent personnel to separate gas from any possible interference. GF320 is not EX-proof so specified work permit is required when using this in a process plant [29].

Figure 21 - FLIR GF320 Infrared Camera [29]

FLIR GD320 is implemented into the regular inspection program by Shell at Nyhamna with good results[22].

[21] FLIR: Forward Looking Infrared Radiometer
[22] Shell presentation at «Gasslekkasje workshop - Bygnes 10.04.2014»

5.4.4 Gas Vision System[23]

The Gas Vision System (GVS) uses a technique called gas correlation imaging to continuously monitor a given area. Two IR camera sensors, one of which contains an optical cell with methane, take two simultaneous images. The methane gas cell is intended to filter out the effects of a methane leak. Together they create a differential signal which provides a superimposed visual image of a gas leak. The spectroscopy technology will color any methane in the combined image presenting a realistic visualization with a colored leak cloud.

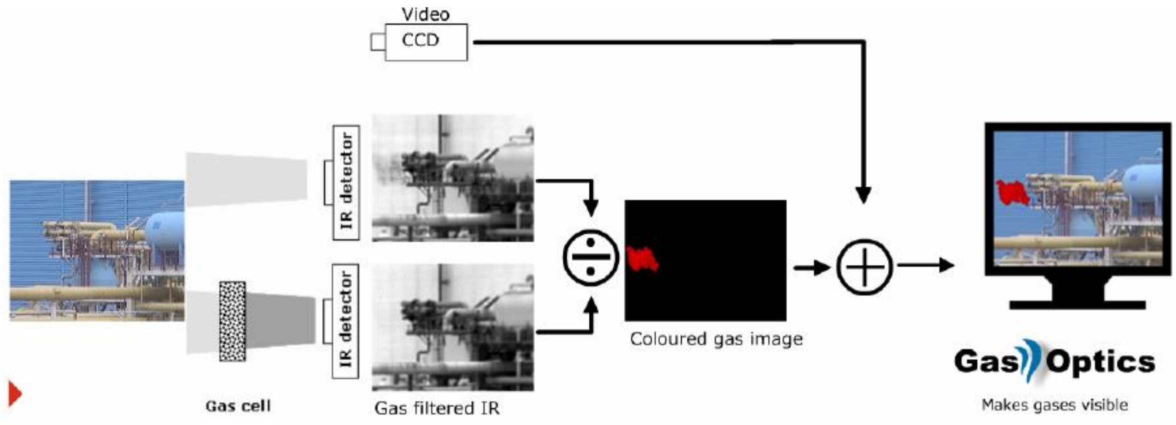

Figure 22 - Block diagram of the Gas Vision System[14]

The GVS is a stationary camera which is set according to Points-Of-Interest (POIs). The sensors can aim at several POIs and rotate automatically between them. It is possible to override the predefined monitoring points and control the device manually. Video signals are continuously sent to the control room for interpretation.

A pilot project on Kalstø Landfall Valve Station at Karmøy has confirmed that GVS provides a reliable automatic detection of methane emissions within specified criteria (greater than 0.2 LELm concentrations). The project has shown improvements towards the conventional manual detection of fugitive emissions. Compared to point and open path detectors GVS represent a significant improvement in gas detection (see Figure 23 and Figure 24). This is due to large area coverage and combination of real-time visualization and automatic gas alarm based on IR visualization. Point detectors are only able to monitor the surrounding air which results in a large number of units. Open path detectors only monitor a given "line".

[23] Statoil document, '*Technology First Use Report – Gas Vision System*', (May 2013)

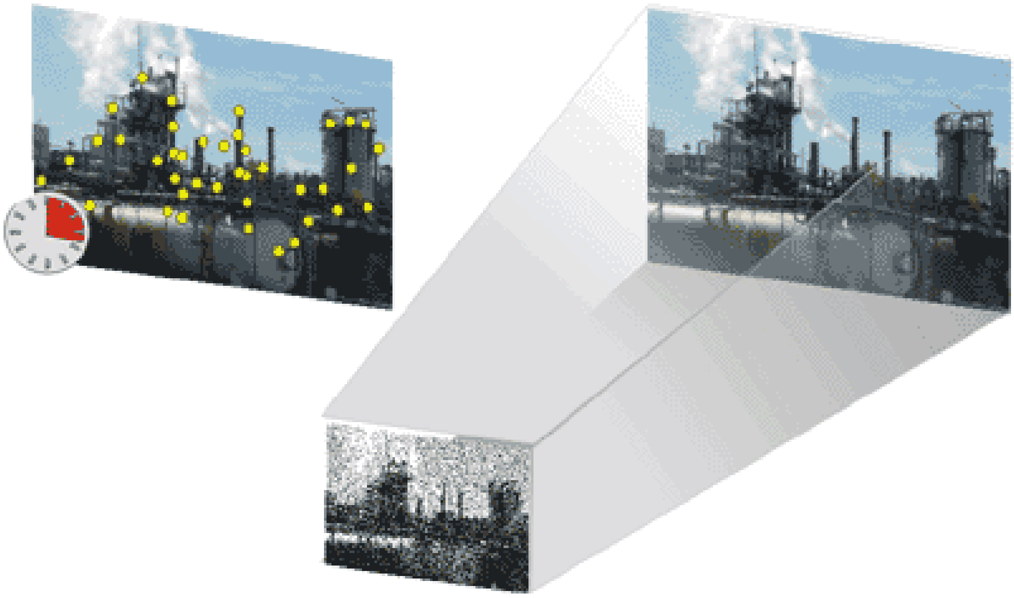

Figure 23 - Comparison point gas detector (left) and GVS (right)[14]

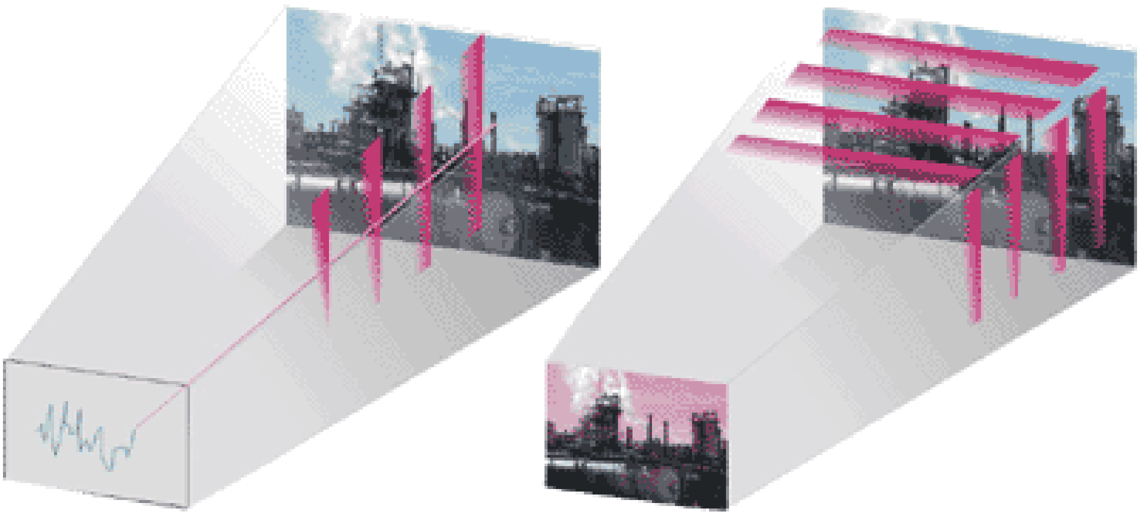

Figure 24 - Comparison open path detector (left) and GVS (right)[14]

The weakness of GVS is that the system is sensitive to fog and heavy rain. As the technology is based on temperature difference between methane and the environment, there will also be challenges associated with snowfall and extreme cold. This is a challenge with all IR based technology so the general recommendation is to use a combination of technologies. Rotation between multiple POIs results in several minutes between scans of one specific point.

5.5 Catalytic Gas Detection

Catalytic sensors are based on the principle that combustible gases oxidize on the surface of a catalyst leading to increase in temperature. Catalytic gas detectors consist of an active element functioning as a catalyst and a coated inactive element serving as a temperature compensator. The two elements are connected through a Wheatstone Bridge circuit. In the presence of combustible gases the surface of the active element will oxidize and lead to increase in temperature in the circuit and further initiate an increase in resistance. Although considered robust, catalytic detectors have the risk of contamination due to exposure of certain gases, such as lead, sulfur and silicone. The detection range is also limited as high concentrations of combustible gases might lead the sensor to display incorrect values [31].

Statoil has reported that catalytic point detectors have underestimated concentrations of process gases containing more than one compound [27].

6 Conclusion

The discussion in this report has shown the complexity of hydrocarbon gas leaks. There are technical, human, and organizational factors contributing to the undesirable risk of gas leaks within the Gassco operatorship.

Certain technical components more prone to leak are valves, flanges, and heat exchangers. It is therefore important to ensure joint integrity on the facilitation and the execution level. Approximately 20 % of potential leak sources are due to technical degrading. Corrosion under insulation (CUI) has been introduced as an integrity challenge in this area. There are technologies under development to prevent CUI. In order to maintain a sufficient integrity of process facilities it is necessary for Gassco to invest in measures to improve or reduce technical degrading.

As the human factor is underlying cause of the majority of gas leaks the main focus area for Gassco is to get an overview of organizational factors creating risk. Within this area of concern there should be an increased investment in exchange of experience with more frequent workshops as a proposed measure. Possible measures to reduce risk of misinterpretations of governing documents should also be assessed.

Within gas detection there are some methods with distinct characteristics. Infrared technology enables visualization of fugitive emissions and continuous monitoring. The handheld gas camera FLIR GD320 is an efficient method of inspection. The stationary Gas Vision System appears to have potential to become an essential part of monitoring process facilities.

Based on the discussion in this report it becomes natural to conclude that the most important safety barrier within the natural gas industry is the human factor. There has been an increased focus on the human factor in recent years with positive results of improvement. However, the industry aims at continuing the positive trend.

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