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MASTER'S THESIS

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Abstract

The primary purpose of this study was to examine what kind of threats are associated with functioning of the shale gas well testing installation, and also how failures of the installation influence the safety of the residents living nearby. With the development of the shale gas industry in Poland, the discussion about the influence of hydraulic fracturing on the social and environmental safety has been raised. This discussion neglected the risks associated with the surface operations, which the author wanted to study.

The risk assessment was performed in two parts. It began from qualitative analysis in a form of the Structure What-If Template on the overall facility level. Next, on the basis of the SWIFT results, the major hazardous elements of the installation were chosen to simulate their failure consequences in the PHAST software. These simulations were part of the Quantitative Risk Assessment, which revealed information about required setbacks and risk contours.

In conclusion, the thesis argued about severity of the Polish setback rules, negligence of the risks associated with the surface well site functioning and lack of transparency from the operators. Even though the assessment had many shortcomings and was weakened by different types of uncertainty, it may be a good starting point for the discussion how the operators are guaranteeing the surface operations safety for the local residents.

Acknowledgments

This master thesis is the final step on my way to finishing my two years studies in Stavanger which were an important period of my life. A lot of people helped me to survive these years and kept me moving forward. I cannot decide who helped me the most as each person’s support is incommensurable, as some of you just simply gave me time and let me do my things. To all those that I am writing to. Thank you.

Andrzej

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Nomenclature and technical abbreviations

API	American Petroleum Institute
ALARP	As Low As Reasonable Practicable
DNV	Det Norske Veritas
FTA	Fault Tree Analysis
HAZOP	Hazard and Operability Study
HAZID	Hazard Identification
LEL	Lower Explosive Limit
MMbtu	One million British Thermal Unit
Nm^3	Normal cubic meter
P&ID	Process & Instrumentation Diagram
PHAST	Process Hazard Analysis Software Tool
ppm	Parts per million
QRA	Quantitative Risk Assessment
SWIFT	Structured What-If Te
UEL	Upper Explosive Limit
NORSOK	Norsk Sokkels Konkuranseposisjon

1. Introduction

1.1 Background of the thesis

It was known from 19th century that in the shale there may be trapped a lot of natural gas. But until 1998, when the first slick-water fracturing was performed in the shale formation, the shale gas was seen as an uneconomic source of hydrocarbons and its role was marginal. There were only several production wells, all located in United States, all characterised by low performance (Wang & Krupnick, 2013). Everything changed when the slick-water fracturing technique was firstly performed in the formation of this kind. It was a breakthrough that made shale gas exploitation cheaper, becoming an interesting alternative to the conventional methods. It boosted the whole industry in such a way, that the total production share of shale gas rose from below 1% level in 1998 to almost 40% in 2012, which is an equivalent of 9,7 trillion cubic feet. What is more, the prediction says that shale gas will grow even more to 53% in 2040, reaching a production level of almost 20 trillion cubic feet (EIA, 2015).

Many countries, especially those which were not rich in conventional natural resources, had seen a great opportunity in developing the shale gas industry in their countries. It was a chance for them to increase their energetic independency and take advantage of other economical benefits. One of those countries was Poland which 32% of energy resources was imported in 2008, but the domestic gas production was covering below 30% of the demand (Kaliski et al., 2010). That is why, the government saw a great opportunity in shale gas production to improve the Polish energy security and improve the overall economy. It was caused by the common appearance of shale formations in Poland and initial estimations of United States Energy Information Administration, which stated that Poland had 5,3 trillion Nm^3 of recoverable gas in shale (Marocchi & Fedirko, 2013). The Figure 1 shows the map of the shale basins of Poland and their perceptiveness.

These estimations and no objections against hydraulic fracturing encouraged many petroleum companies to acquire concessions and explore three Polish shale basins. After initial exploring the first well was drilled in 2010 and in 2012 the gas finally started to flow and the first tests were carried out. Unfortunately the first estimations of potential resources were far too optimistic. The most recent report of Polish Geological Institute states that the shale gas resources are between the 346,1-767,9 billion Nm^3(PGI, 2012), however these predictions are based on the analysis of 39 wells drilled from 1950 to 1990, which means that their reliability is questionable. To accurately assess the potential of these basins basing on the more practical knowledge, dozens of wells have to be drilled. By the end of 2014, the number of drilled wells was only 68(MoE, 2015), comparing to 25 145 in United States by the end of 2007 (Vidas & Hugman, 2008). This information and results of first well testing resulted in slightly less concessions acquired. From 2009 to 2011 there were 97 concessions granted and in the beginning of 2015 there are only 47 valid concessions(MoE,2015).

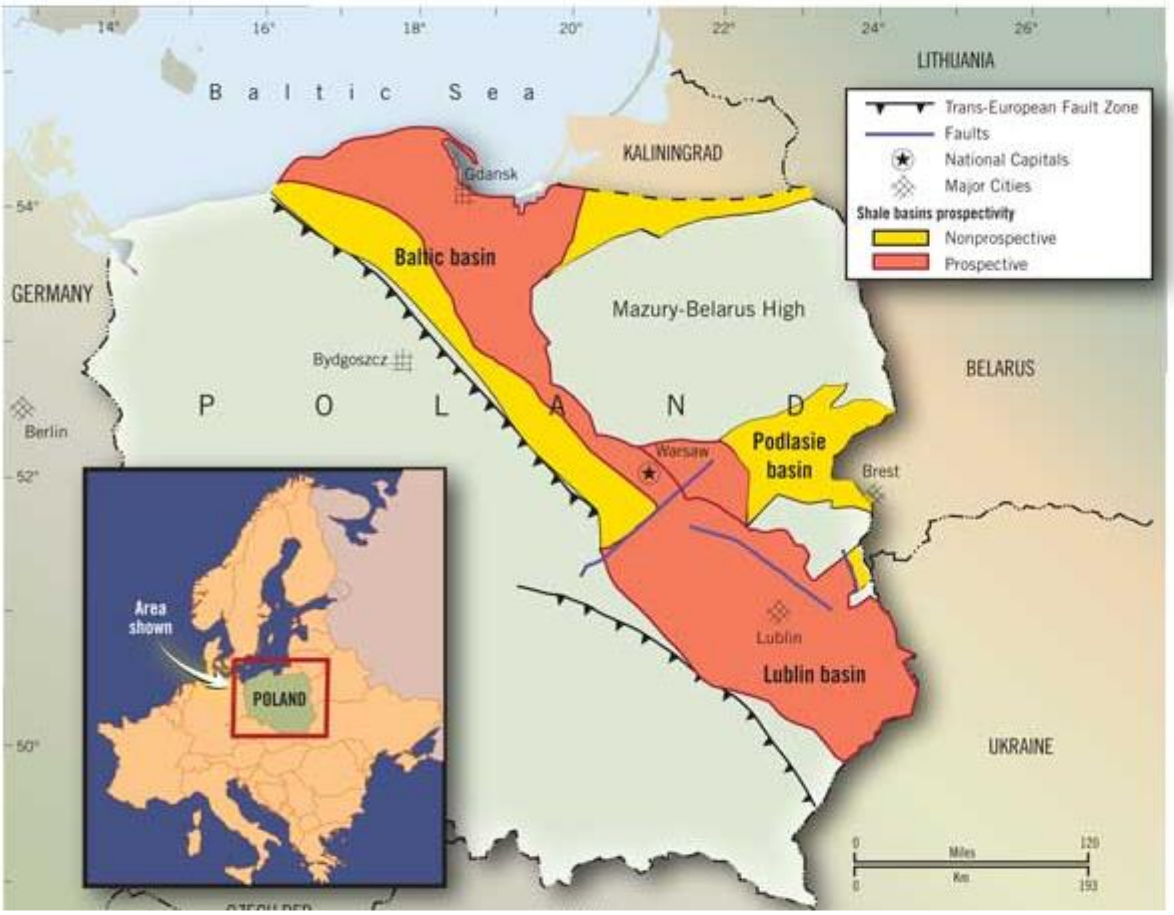

Figure 1 Shale basins of Poland (ARI, 2011)

Not only the estimations are slowing down the development, but also the high costs of drilling and other expenses connected to gas production. In the United States costs are way smaller as industry is more developed and the technology is well-established, in opposition to Poland, where oil and gas industry is slightly underdeveloped. What is more, the breakeven point for the polish shale gas is said to be somewhere between 5-12$ per MMbtu(IEA, 2012)(JRC, 2012), depending on the reservoir and infrastructure conditions, whereas the price of imported gas to the European Union in the last five years was in the range 7,5-13$ per MMbtu(YCharts, 2015). This means that the potential shale gas production in Poland would balance on the verge of profitability. Nevertheless, the government is committed to facilitate administrative procedures and offer tax reductions in order to encourage the petroleum companies to invest in Poland. These steps are reasoned by a strong will to improve the energy security and become more independent from foreign suppliers.

Polish society is one of the most enthusiastic supporters of the shale gas development, especially comparing to other European nations, community surveys showed that only 9% of poles are afraid of possible threats to the environment(Łupki Polskie, 2013). These surveys were performed on a random population, which are not giving a good picture of how enthusiastic are the people living close to the wellsite. These wellsites are mostly located in countryside in weakly urbanized areas, where the percentage of high-educated people is little. Their knowledge about petroleum industry is commonly limited to discoveries of Ignacy Łukasiewicz, which means that they are not able to properly assess the reliability of information spread by for and against lobbyists. On the one hand they are afraid about their lives and water sources, on the other, they see a great benefits for the commune from the royalty tax. As a result, in several countries in Europe like Germany or France the social anxiety was so great that shale gas exploitation was banned without detailed investigation of its influences on the society and environment(Petro Global News, 2013).

1.2 Aim of the thesis

The desire of every petroleum company searching for hydrocarbons is establishing beneficial production. This is done in several stages, whereas the first one in seismic exploration and geological surveys, the second one is drilling, the well testing is the third and setting up the production is the final phase. Each step can be only performed when the previous one is successful. In this thesis the well testing will be thoroughly analysed in the context of hazards and risk. It is an important phase as it is revealing the biggest amount of information about the reservoir and on the basis of this tests the production predictions are created. In case of weak reservoir parameters the fourth step can be forfeit, and the well can be closed. This scenario is very probable in Poland where the geology of shale is still not sufficiently recognized and to improve the geological knowledge many wells have to be drilled, from which only a small percentage will probably appear to be beneficial.

The aim of this thesis is to investigate if the shale gas well testing installation is dangerous for the residents living nearby the facility. The thesis will be performed in form of extensive risk analysis from the perspective of these people. It will be concentrating on their safety, not the safety of workers or profits of the company. The thesis will also raise issues of Polish safety standards, if they are rigorous enough comparing to the international ones. Moreover the most dangerous parts of the installation will be identified, which may result in valuable feedback to the operator safety solutions. The description of the theory will be an introduction to risk analysis of the existing installation on well LE-1 near Strzeszewo. The analysis will include both qualitative and quantitative risk assessments which are complimentary to each other.

Nevertheless, the main aim of this thesis is to determine the real hazard which shale gas well testing installation is causing, so that people could have a reliable source of information and no longer have to rely on rumours and unconfirmed information. There are several examples in Polish press, where local residents are describing their fears concerning the installation(Lebork Nasze Miasto, 2013)(Kurier-W, 2014). If the installation is really life-threatening then it may be necessary to create proper safety procedures, improve the Polish safety standards or even consider banning the development of the shale gas production.

1.3 Limitations

This thesis has no intention to analyze the threats and dangers associated with hydraulic fracturing which is said to be polluting water sources. This analysis will concentrate on assessing the risk and consequences related to the installations and activities which are taking place on the surface.

Also it must be underlined that the thesis will not try to find solutions for decreasing the risk, but it would rather concentrate on identifying the most hazardous elements, events and consequences of its failure. Moreover the thesis will not include any detailed recommendations for the company owning the facility or the workers. As the data about their existing safety procedures and systems is unknown.

Finally, the analysis will try to stay politically neutral, as the shale gas development is strongly influenced by politicians and various lobbyists. Obviously the risk picture will not be influenced by the politics, but the further recommendations and conclusions could be.

2. Location and installation description

2.1 Location

The facility is located 300 meters west from village Strzeszewo in the administrative district of Gmina Wicko, within Lębork County, Pomeranian Voivodeship, in northern Poland, only about 10 kilometres from coast in straight line and next to the provincial road number 213. The Figure 2 shows the Strzeszewo area map, whereas the wellsite is marked with the orange square.

Figure 2 Strzeszewo area map (Google, 2015)

According to national census the population of Strzeszewo is 241. Most of residents are living from farming and rural tourism. The facility has been established in fourth quarter of 2012 and the first drilling started in December 2012, in second quarter of 2013 there was performed the first hydraulic fracturing. From the end of 2013 the well testing has started.

Unfortunately the test results revealed an insufficient reservoir parameters which resulted in closing the well and not proceeding to the production phase. The peak production during tests has reached 8 000 Nm^3 per day, which was below the break-even point.

2.2 Role of well testing

Well testing is one of the most important phases of establishing the production facility. During the well testing the final decision about continuing the exploration is taken. That is why in the future the number of well testing installations might be a way larger than the number of production facilities. The ratio of reservoirs which exploration is finished during well testing to the ones that are producing gas for years is especially large when the knowledge about the geology and reservoirs parameters is little, like in Poland.

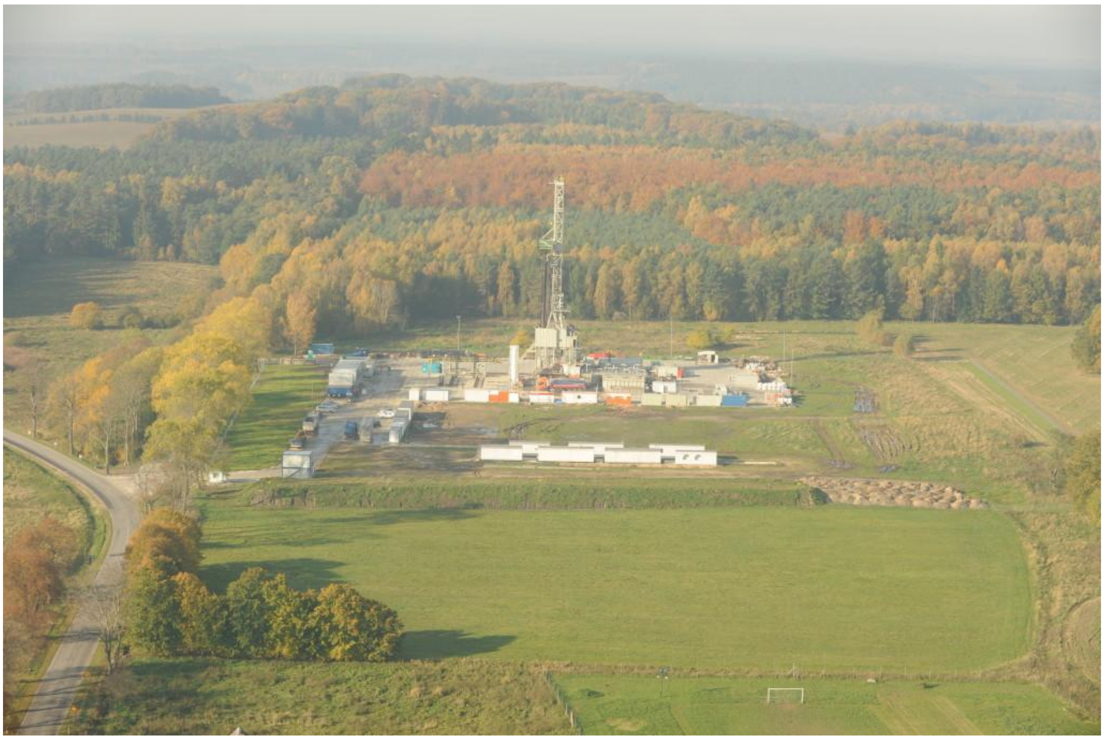

Figure 3 Wellsite in Strzeszewo (3legs Resources, 2015a)

After the well is drilled, the shale is fractured and the gas is present in the well, the testing installation can be installed. The aim of such an installation is to determine the characteristics of the reservoir like pressure, boundaries, permeability or zone contribution. These parameters are necessary to finally describe the potential of a given well and its economical feasibility, as a presence of a gas in well is not an only requirement to become a production well.

The installation itself is a simplified and minimized production installation. The treatment of the gas is quite similar to the production process, but in case of well testing it is flared, not stored. Figure 3 presents the existing wellsite in Strzeszewo, before it was closed. The well is located in the centre of the parcel, whereas the installation is adjacent to it. The surrounding area is occupied by many other structures like spare parts magazines, offices and living quarters. The core operational personnel consists of about 40 people, which are working daily on two twelve hours shifts continuously for two weeks, and then they have two week vacation. However, this is not a rule, as the amount of people present at the facility may change along with phase of development.

The well site is covered with concrete slabs and surrounded with heaped 2 meters high bund. This is a safety feature that in case of liquid leaking will prevent liquid from dwindle away into ground or spill to next properties. On the east side of the facility there were located storage pits were the water from the well was stored, but they were not build yet when the photo in Figure 3 was taken. Before the installation will be described in detail, one more thing should be pointed out, which may have a significant importance later. Looking closer at the photo reveals that in the foreground there is a goal and probably a whole football pitch, which is not that far from the wellsite.

2.3 Main elements of the installation

As the risk analysis is focusing on the hazards connected to the surface well testing installation, it's main elements have to be presented. The Figure 4 shows the simplified well testing installation based on the actual P&ID on well LE-1 in Strzeszewo (EXPRO, 2013). In the next subchapters each of these elements will be described from the functioning and hazardous perspective.

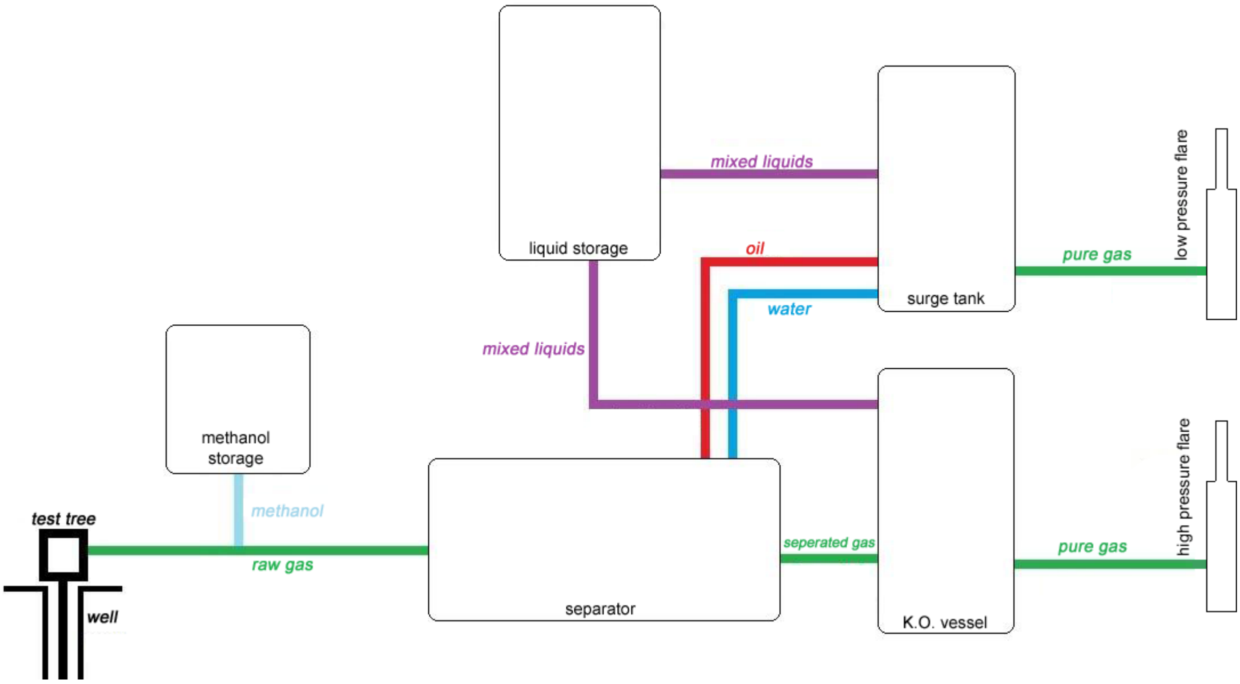

Figure 4 Simplified well testing installation.

2.3.1 Test tree(flowhead)

It is the only connection and safety barrier between production well and the surface processing installation. Its name is commonly mistaken with wellhead which is placed on the top of the well during drilling, afterwards the wellhead is switched by the test tree which is a collection of different types of valves and spools. The most important function of these valves and spools is to prevent hydrocarbons from the well to spread out. The second major function of the flowhead is controlling the well upstream flow rate. Therefore choosing the proper test tree is a very important process as it not only has to fit to piping specification, but also handle the pressure conditions inside the well. Furthermore such a tree should be equipped with a collection of safety cutouts which in case of hazardous situation can immediately close the inflow of the hydrocarbons to the installation. These emergency shutdown systems are typically hydraulically operated, which means that in case of loss of hydraulic pressure in the system the valves are automatically closed(fail safe close). In the Figure 5 the flowhead is photographed during the stimulation activities.

Figure 5 Test tree (3Legs Resources, 2015b)

The reliability of the test trees is said to be on extremely high level, it means low frequency of failure(King, 2010)(HSE, 2002), as its failure in case of blowout is one of the biggest threats to the whole facility, not to mention the failure during common operations. The blowout may appear any time during operation of the facility even when the production is stopped. According to EIA(2004) the historical blowout frequency in gas wells during testing/production equals $9{,}8x10^{-5}$ per well year. Despite the flowhead and downhole safety valves work properly, the overpressure may lead to rupture of every single element of the installation, causing a life threatening situation. In the worst case the tree is blown off and the hydrocarbons are leaking straight from the well, causing a great fire which cannot be extinguished without closing the well. According to EIA(2004) the blowout frequency per well

2.3.2 Flares

In these high vertical stacks, which are commonly associated to hydrocarbons exploitation, the gas from installation is burnt. Due to lack of gas storages or gas pipelines the gas has to be flared even if it a waste of money and source of carbon dioxide emission. There are two types of flares at the facility – high and low pressure. The first one is connected to the knock out drum and is constantly operating. The second one is only operating when the overpressure or evaporation in the surge tank occurs, however the small flame is always burning powered by external source of propane so that in case of overpressure the gas is immediately burnt. The flares are not dangerous in themselves but they are a source of ignition. So in case of any uncontrolled leak or formation of flammable cloud, it is just a matter of time when it ignites, because of continuous work of the flare.

2.3.3 Test separator

It is the first element of the installation where raw gas is treated and water droplets and gasoline is separated. There are many separators with different construction and solutions, but most of them are separating liquid phase from gas by flowing gas through a foam catcher, where the small droplets of liquid are caught and flown down to the bottom of the separator, whereas the initially separated gas is flowing to the next separator. Meanwhile liquid phase is separated, due to difference in relative density between water and gasoline, and transported to the surge tank. Separators are the next potential threat at the facility as the hydrocarbons flowing through them are under high pressure reaching almost 100bar, which means that in case of failure the decompressed gas will have tens of times larger volume than inside the separator.

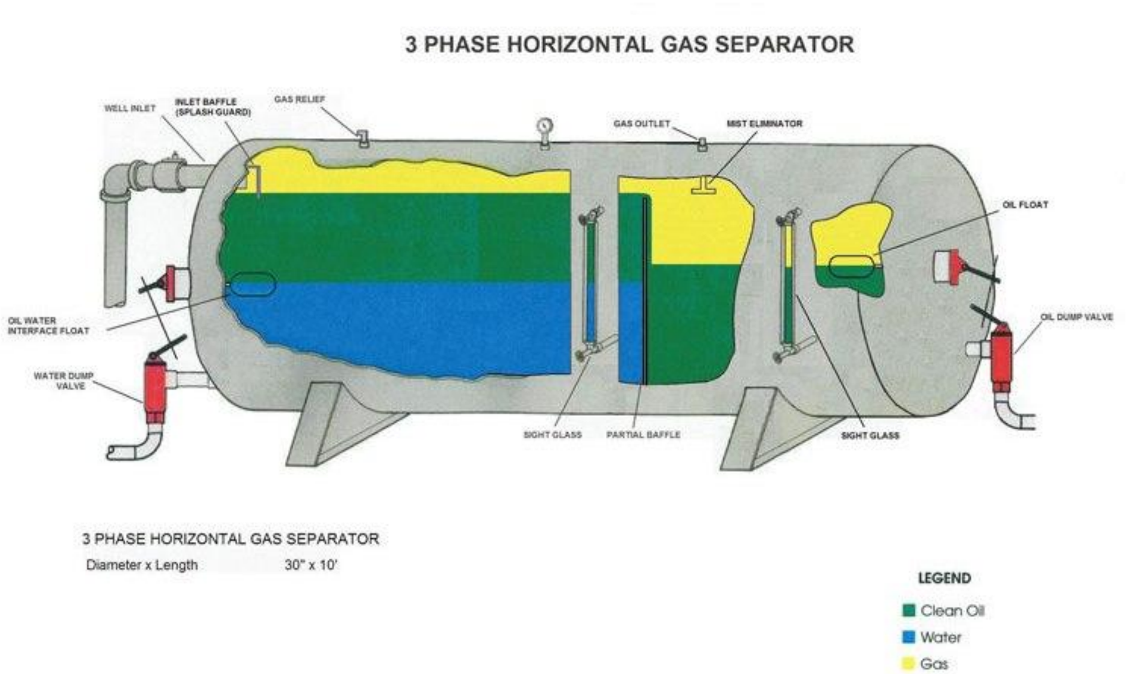

Figure 6 Three phase horizontal test separator (Fox Tank Company, 2013)

2.3.4 Methanol tank

In order to prevent formation of hydrates inside the installation, methanol has to be injected in the installation between the flowhead and the test separator. The dosing is performed by a methanol pump which is the connector between the tank and the raw gas pipe. The tank is a small spherical vessel where methanol is stored under atmospheric pressure and ambient temperature. Although this vessel is not a main element of the installation, the methanol which is stored inside is a toxic substance, and any leaks may appear to be dangerous.

2.3.5 Knock out(K.O.) vessel

The second stage separator which is known under several names like flash drum or knock out drum. Gas from the first separator is flown to this device for a more thorough separation. The functioning of this separator is quite similar to the previous one, as the gas is separated by flowing through different types of filters. Hazards connected to this device are similar to the first sage separator, although the working pressure is lower, reaching only 5 bars in opposite to the volume which is $3m^3$ bigger. Because of the simplicity of this device the probability of any kind of failure is about 3 times lower than the first stage separator(OREDA, 2002).

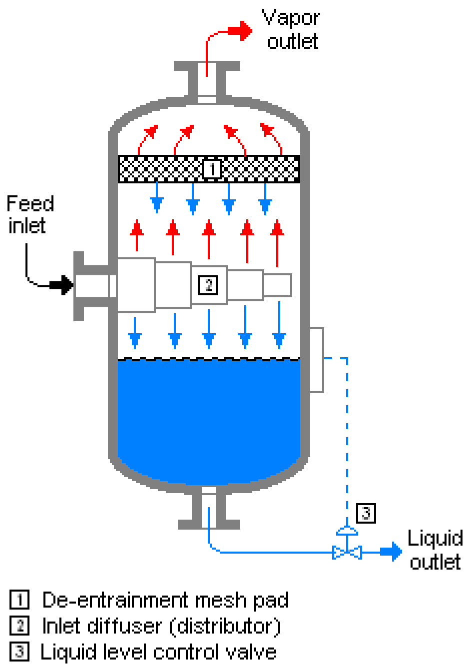

Figure 7 K.O. vessel (Wikipedia, 2007)

2.3.6 Surge tank

The vessel which have two main functions, firstly it is a protection in case of a sudden rise of a pressure inside the installation, as well as the penultimate storage for the liquid phase. Originally it was developed as a second stage separator, but with more advanced devices developed its functions changed to the mentioned ones(McAleese, 2000). The most important parameter of the surge tank during functioning is the level of fluid which is monitored by side glasses or high and low level alarms. Also in surge tank the separation is present as the gas trapped in the liquid phase is vaporizing and transported to the low pressure flare.

2.3.7 Liquid storage

The final deposit of the liquid phase from the installation, it is a big pit which is surrounded by a bund and lined with impermeable material so that the liquid is not getting into the ground. The production of the water from the well could reach almost 80m^3 per day, so the size of the pit is considerable. As the liquid is mainly consisting of water with small addition of heavy hydrocarbons it can be stored this way, as it is not a possible source of fire.

Figure 8 Storage pits (3Legs Resources, 2015c)

3. Gases and fluids

The gas treatment is a multistep process, where many substances are added or separated from the gas. These gases and fluids are often toxic, flammable or explosive, so their processing or storing has to be carefully planned. The important issue of risk analysis is to investigate what type of potentially hazardous substances are present at the facility and what is their possible negative impact on people and overall safety. In this chapter the most dangerous substances will be described. It has to be highlighted that there are more potentially hazardous substances used at the facility but their amount is insignificant and they cannot be treated as a threat in the scale of the whole installation.

3.1 Methane

This simplest alkene is the main component of shale gas, the raw gas can consist over 90% of this hydrocarbon. The main goal of the whole facility is to produce this gas on the industrial scale. The more gas is produced, the bigger success is achieved. Two main factors that are influencing the success of the well is size and pressure of the reservoir, which can exceed 300 bar. The high pressure and explosive nature of methane are putting enormous importance on the safety systems. As for example in case of leakage under such pressure, the LEL of 5% is achieved rapidly. Furthermore methane is present in almost every part of installation from the separator to the surge tank, when the daily flow rate of 10 000 Nm^3 is added, we have an image of the installation where even a small failure can lead to fatal consequences. Especially that it is located in the open air, so the high amount of oxygen is available and the flare is constantly burning. Therefore the level of methane at the facility has to be carefully controlled by special detectors as it odourless and humans are not able to smell it. A pure methane is not toxic to the humans and is not causing skin or eye damage, however it displaces the oxygen and makes breathing difficult, which is a very serious threat(CCOHS, 2015). Fortunately in this case the only threat is fire or explosion, as the methane is lighter than air and due to outdoor installation it will not cumulate, rather just spread to the atmosphere. To extinguish methane fire an dry chemical powder or high expansion foam should be used.

3.2 Methanol

Methanol is the simplest aliphatic alcohol and like most of alcohols it is highly flammable and potentially explosive. It is not a product of the separation, it is an additive which is injected right after the flowhead to prevent formation of hydrates in the installation. Without adding methanol in the pipes the hydrates may appear, causing choking and leading to failure of the whole system. The methanol is stored in the spherical storage which volume is about 1,5m^3 in a liquid phase under atmospheric pressure. Typically failure is the leakage from the tank, where the methanol is spilling and creating pool which is slowly evaporating(Smith et. al, 2002). Methanol is highly poisonous for humans, even a small portion swollen may lead to death. Although it should not be expected that anybody at the facility will drink the methanol, it should be expected that they may appear methanol vaporous which are strong toxics. Even a small amount of around 500ppm can cause discomfort and disabling if the exposure time is over one hour. The danger is growing along with higher concentration and exposure time, so for example exposure for 5 minutes in atmosphere consisting 40 000ppm of methanol vapours is lethal. Once again relying on the smell is not sufficient, as methanol has a typical alcohol odour, but it is impossible to evaluate how big is the concentration(Kavet & Nauss, 1990). Moreover methanol vapours are explosive, their LEL equals 6%, UEL 36% and auto ignition temperature. 455C. So in case of fire at the facility it may be necessary to sprinkle the methanol tank with water to lower the temperature and prevent the possible explosion. Next important safety issue is that the methanol is heavier than air and it vapours after leakage will cumulate close to the ground creating a serious threat to the crew and residents.

3.3 Oil/condensate

The raw gas from the well is always consisting alkenes of higher numbers than methane. The composition varies in different reservoirs as well in different wells. These hydrocarbons are normally in form of liquid condensate or light oil which is separated from the gas in the first separator and then in the flush drum. Afterwards it is moved to surge tank where it is mixing with water from the reservoir creating emulsion. Finally this emulsion is stored in the pit, where it is waiting for the transport to a refinery or other type of water treatment facility. It is hard to describe the exact composition of this fluid however in it pure form before mixing with water it is dangerous for the safety of people and the installation, as the rest of hydrocarbons. It is flammable, often its vapours are explosive and possible spills can strongly pollute the environment and water sources. Therefore it is important that the pit, facility surface and surrounding bunds are impermeable to assure that any spill will not get into the ground.

3.4 Hydrogen sulphide

The most dangerous component of raw gas which is known for its rotten eggs odour and toxicity. It is so dangerous because the dose of just around 2000ppm is killing immediately, the effects of lower doses exposure are presented in Table 1. Due to its highly negative effects on humans it was used as a chemical weapon during World War I(Foulkes, 2001). Moreover, the concentration above 150ppm is paralysing the olfactory sense, which can lead to wrong interpretation of effects and improper decisions(PHE, 2009).

Concentration [ppm]	Effect
20 – 30	Conjunctivitis
50	Objection to light after 4 hours exposure, lacrimation
150 – 200	Objection to light, irritation of mucous membranes, headache
200 – 400	Slight symptoms of poisoning after several hours
250 – 600	Pulmonary edema and bronchial pneumonia after prolonged exposure
500 – 1000	Painful eye irritation, vomiting
1000	Immediate acute poisoning
1000 – 2000	Lethal after 30 to 60 minutes
> 2000	Rapidly lethal

Table 1 Effects of exposure to hydrogen sulphide (HSE, 2014)

Although in this well during tests the hydrogen sulphide did not appear, its appearance, even highly unlikely, cannot be neglected. The hydrogen sulphide blowouts are extremely dangerous events with dozens of fatalities, like in China in 2003, where there was a blowout in a gas well which contained hydrogen sulphide. As a consequence 243 people were killed, 9 thousand were injured and 64 thousand people had to be evacuated. It was during the drilling activities, yet blowouts also occurs during well testing(UNEP, 2011). In Poland there are dozens of gas wells where hydrogen sulphide is present, but it is not exceeding 1% share of the raw gas. These may seems like a small contamination, but this 1% is ten times bigger than the instant lethal dose. Moreover there are also several high-sulphur oil wells for example in Kamien Pomorski where concentration is reaching almost 12%(Mamczur et al., 1997). Presence of hydrogen sulphide in raw gas is connected to type of rocks surrounding the reservoir. Often it is present in carbonate rocks like limestone or dolomites, whereas it is not observed in sandstones. Thus the Polish shale gas which is mostly surrounded by sandstones is stated to be free of hydrogen sulphide(San Leon Energy, 2013). However there is never a complete certainty that it will not appear somehow as in the United States there are shale gas reservoirs where hydrogen sulphide is present(Weiland & Hatcher, 2012). So it is a common practice to place special detectors inside the installation to monitor the level of hydrogen sulphide. It is forming an explosive mixture with air at concentration from 4% to 46%. Next possible hazardous scenario assumes that hydrogen sulphide suddenly appears in the well, but the installation is still working normally which means that the gas would be burnt on the flare creating a lot of sulphur dioxide. This substance is not only heavier than air but also highly toxic and will accumulate close to the ground causing potential threat. Summing up the sudden presence of hydrogen sulphide should be always considered during design phase as neglecting this issue may have the most severe consequences from all possible negative scenarios.

4. Regulations

4.1 Regulations in Poland

Shale gas extraction as any other hydrocarbons extraction is regulated in detail by the Polish mining law, the violation of which may lead to the withdrawal of concessions or not granting it in the first place. Although the first shale gas wells appeared a few years ago, the mining law has not changed significantly since then. The only changes were connected to additional acts concerning hydraulic fracturing, not the surface issues and it was only created after pressure from the society(ODLA, 2015). Therefore in this chapter the facility functioning will be analysed on the basis of a common law which is obligatory for all hydrocarbon wells.

As we know, all phases from drilling, through testing, to the production of hydrocarbons are connected to certain degree of risk. This risk is unavoidable, however with proper safety measures the risk can be controlled. As the functioning of the facility may have a serious impact on the surrounding area including plants, animals and people, the standardized safety requirements have to be created. These requirements may vary in different countries, but their objective is the same, to assure safety of workers, local residents and environment. This is an important issue as without a proper law companies may forget about the safety in the pursuit for the profits. A good example of such regulations is the location of the well. Often well is not located in the best place from the geological or economical point of view but where the setback rules are letting it to be placed. The most important articles specifies the setback rules for the gas wells(SMA, 2014):

§ 44. 1. Well must be located at least:

1) 50 meters from objects with open fire, exploration drilling activities in search for open, with drilling works the purpose of finding, identification of oil and gas or extracting oil and gas from reservoirs, as well as in areas with an expected occurrence in subsurface accumulations of combustible gases;

2) The 1,5 height of the rig or mast away from railways, canals, reservoirs, rivers, public roads and other buildings, in addition the distance from overhead high-voltage lines is 1.5 height of the tower or mast, but not less than 30 m.

§ 45. In the case of locating the well in a forest area or at a distance less than 100 meters from the edge of the forest, where the presence of oil or natural gas is expected, the method of fire protection forest area must be agreed with the owner, operator or user.

This means that the distance between the actual objects is important here, not the boundaries of the parcel. Furthermore, there is §161 which specified the distance between the installation located at the facility connected to hydrocarbon processing.

§ 161. *1. The distance between any object or installation connected to oil and gas exploitation, as well as, (...), gas treatment installation (...) must not be less than 50 meters – from public roads, railways, administrative and residential buildings, and other objects with open fire not connected to the facility functioning.*

Clearly there is some contradictions as well can be located 30 meters from other objects, but the installation have to be located at least 50 meters. Besides, there is additional paragraph § 161. 3. which states that in exceptional case the distance can be reduced after permission from the State Mining Authority. It may seem that the mining law in this regard is very lenient, that only 50 meters can separate someone's house from the well, but in practice, none locates facilities in such close proximity, apart from roads and railroads. It is not surprising as developing the facility, especially drilling the well is a very noisy process, and the local residents would perhaps strongly protest against it. This would probably result in a poor reputation of a company and problems with its further development. In Strzeszewo case the distance between the well and the closest building is about 350 meters.

When there is probability that in the raw gas may contain hydrogen sulphide or that drilling will go through the layers with hydrogen sulphide, the setback regulations are getting more severe.

§ 79. 1. For each well:

1) in which the hydrocarbon reservoir containing hydrogen sulphide will be extracted, the category of the hydrogen sulphide hazard is defined as well as the radius of the expected hydrogen sulphide contamination in case of the surface eruption;

§ 80. In areas of a known capacity and the concentration of hydrogen sulphide the radius of the contamination zone and the obligatory distance separating the well and other objects is determined based on the following criteria:

Category of risk	The radius of the anticipated contamination zone H_2S [m]	The minimal distance [m] from the well:		
		a single residential house	buildings occupied by:	
			less than 30 people (jointly) :	more than 30 people:
I	*> 3500*	*100*	*500*	*1500*
II	*from 3500 to 1000*	*100*	*500*	*500*
III	*less than 1000 to 500*	*100*	*100*	*100*
IV	*less than 500 to 150*	*100*	*100*	*100*

Table 2 Setback rules in Poland for wells with hydrogen sulphide (SMA, 2014)

As we can see the setback rules are more restrictive in case of hydrogen sulphide, but it is questionable if the distance is long enough, as according to what was mentioned in the previous chapter the accidents with hydrogen sulphide are often connected to fatalities and other serious consequences. Also it is interesting that a single residential house is treated with the same respect no matter what is the level of risk. Moreover the regulations allows that occupied building are in range of probable contaminated zone, which with knowledge about severity of inhaling hydrogen sulphide even in minimal doses is a risky practice. In next paragraph the Polish setback rules will be compared with other international standards.

3.2 Setback rules in United States

Abroad, notably in the United States, set back rules are described in greater detail, we know this is due to the long period of exploration and experience arising from that fact. It may be reasonable to take them as an example and base for creating the more detailed regulations in Poland. This would significantly contribute to the further development of this subject instead of coming to the same effect through a few years of trial and error, which can be highly dangerous method in this case.

The mining law in America is regulated at state level, which means that each state has different setback rules. Although the states regulations vary, they are all based on the API standards(Richardson et. al, 2013), which contain the practical recommendations for placing oil and gas facilities and their influence on overall safety. In the figure there are presented minimum setback distances between well and non-facility buildings in feet.

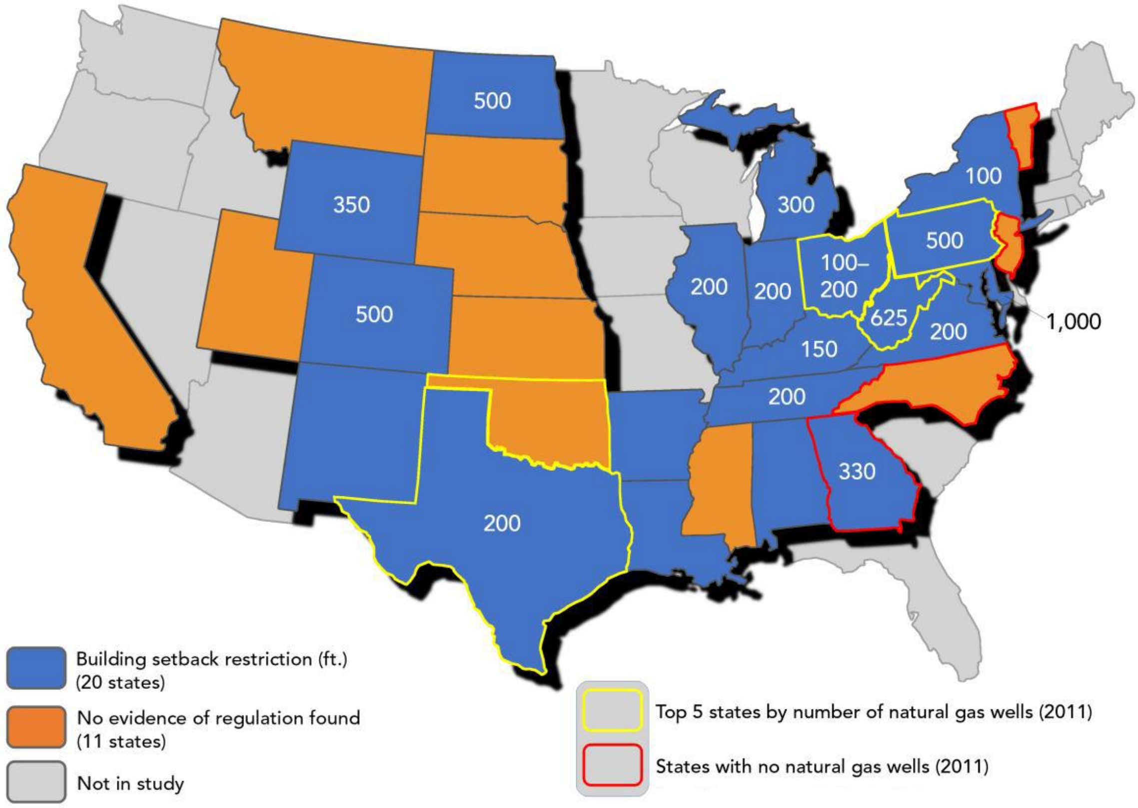

Figure 9 Setback distances in United States (Richardson et. al, 2013)

As the figure shows, the variety is mostly dependent on the states' population density and the level of urbanization, as for example Pennsylvania and Colorado are relatively urbanized states comparing to others and their setback is set to as much as 500 feet. Although it is hard to explain why the setback in North Dakota is also set to 500 feet, whereas its population density is one of the smallest in United States. It may be connected to the phrase in API standard which states:

"when feasible, the well site and access road should be located as far as practical from occupied structures and places of assembly." (API, 2011)

This phrase "as far as practical" and its interpretation is probably the cause of the differences in setback. This is potentially dangerous situation where such respected standards as API are not giving a clear answer what is the minimal setback. It can be also highlighted that these regulations are not always obeyed, as the neighbouring landowners to the facility may let the well to be drilled closer than the setback distance is. Also the interpretation of the rules varies, some of the minimum setback is concerning only important buildings like schools hospitals or churches and others concerns all objects build by human. Not only wells location is described, many states like Ohio have rules concerning gas treatment locations(300 feet) or storage pits in New Mexico(1000 feet).

3.3. Setback rules worldwide

In other European countries the setback rules are set rather on the case-by-case basis like in United Kingdom(DE&CC, 2014), which in my opinion is a good practice only when the people which are responsible for the case are experts and are conscious of the threats that such a facility is creating. Nevertheless the Scottish Government, which has announced plans to set a minimum distance between sites and populated areas (DE&CC, 2014).

5. PHAST description

5.1 PHAST

To perform reliable quantitative risk assessment the comprehensive software to calculate probabilities and consequences is needed. PHAST (Process Hazard Analysis Software Tool) is one of these programs. It was developed in 1990s by DNV to model risk and consequences of various events connected to gas and fluids dispersions as well as explosions. The greatest advantage over other tools is its simplicity, in a relatively short time the accurate analysis could be performed with respect to international safety standards. On the other hand its advantage is also disadvantage as its simplicity makes it hard to calculate very accurate dispersions which may be needed when placing gas detectors. Therefore it is mostly used to model consequences at big facilities like: refineries, chemical plants or oil rigs.

PHAST to model the dispersions of the fluids and gases is using the Unified Dispersion Model which was created by British Association(DNV, 2006). It can describe the behaviour of simple gases to complicated mixtures in terms of various scenarios from jet dispersion to pool fires. The whole method is relying on Gaussian Puff model, which was tested and verified to become reliable risk analysis tool.

However PHAST has been tested and verified it is still a simple programme which is not able to simulate the real world behaviour. It is relying on mathematical formulas which are using many constant values which in fact may vary. For example there have been performed study proving that only one parameter, which is the angle of dispersion of a leaking gas from the hole has a significant influence on the results of the analysis(Pandya, Gabas & Marsden, 2011). Therefore it must be always remembered that relying too much on the quantitative risk assessment tools is connected with certain dose of uncertainty and could lead to severe consequences.

5.2 Influential Factors

As modelling the fluid mechanics is very complex issue, it must consider many factors in the calculations. These factors can be divided in many groups like internal and external or constant and variable. For example the volume of the separator is always the same, but the pressure inside may vary, depending on the flowhead pressure, production phase or any other reason. Further, the parameters of installation can be assessed with a great dose of certainty, but the assessing the external influencing factors is much harder. Thus, the statistics have to be used. They are not a perfect and infallible tool, but using statistics is much more reliable than relying only on experience or superstition. There is possibility that properly used statistics may reveal some information which are not visible at first sight and support the risk assessment with an invaluable aid.

5.2.1 Stability classes

One of the most important influential factors is the weather. It is not only determining the design of the installation, but it has significant influence on the effects of the failure. It may reduce the negative consequences or speed them dramatically. A simple example, there is hydrogen sulphide blowout at the facility which is located close to the village, the direction and speed of the wind may err on whether the residents will survive or not. Not only wind is influencing the dispersion of gases, but also the stability classes, which are quantising tendency of a parcel of air to move upward or downward after it has been displaced vertically by a small amount (Woodward, 1998)

In 1961 Frank Pasquill was the first to standardize the weather stability classes, he created the six level scale from A to F categorizing the amount of atmospheric turbulence(Pasquill, 1961). This scale is well-known worldwide and probably the most popular one, as it has a perfect balance between simplicity and level of details. The Table 3 presents the name of each level, and in the Table 4 there are requirements for choosing the proper stability class for given conditions.

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Stability class	Definition
A	Very unstable
B	Unstable
C	Slightly unstable
D	Neutral
E	Slightly stable
F	Stable

Table 3 Definition of stability classes

Surface wind speed	Daytime incoming solar radiation			Night time cloud cover	
m/s	Strong	Moderate	Slight	50% <	50% >
2 >	A	A - B	B	E	F
2 – 3	A - B	B	C	E	F
3 – 5	B	B – C	C	D	E
5 – 6	C	C – D	D	D	D
6 <	C	D	D	D	D

Table 4 Stability classes requirements

The process of choosing the right class is greatly influencing the results of the QRA, as the more unstable the surrounding is, the greater hazardous zone becomes. The stability class of the region where the facility is located is between C and D, so because of safety consideration and conservative approach it was set in simulations to level C.

5.2.2 Wind

Further the average wind direction and its force have to be found. It is not only useful for placing the gas detector(Bafjord, 2011), but also it is important for the layout of the facility as well as it placing in configuration with living area. As Strzeszewo is a very small village there are no weather historical data, fortunately there is only 20km to Łeba where the weather station has been working for many years and the data is available. The error in approximation the weather data from Łeba to Strzeszewo is negligible as both of this places are lying on the same ground level and the distance from the seaside of Strzeszewo is less than 10km in straight line and the weather station in Łeba is not placed directly on the beach.

The Table 5 presents the historical average wind speed in Łeba and the data availability. As a result the average wind speed is 16,6 km/h and average availability equals nearly 96%. For the purpose of this work the availability is high enough, especially if we consider that it was gathered for 18 years, from January 1996 to December 2014. In Table 6 there are values of average wind speed from a different source, their similarity to the first source are proving that the accuracy of the measurement is sufficient.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Speed [km/h]	19,2	19,3	17,7	15,8	15,4	16,6	15,1	14,7	14,9	16,3	16,1	17,8
Data availability [%]	95	94	94	94	94	94	94	95	99	99	99	99

Table 5 Historical average wind speed (WeatherOnline, 2015)

Month of year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
	01	02	03	04	05	06	07	08	09	10	11	12	1-12
Dominant wind direction	SW	WSW	W	NE	NE	W	W	W	W	SW	SW	SSW	W
Wind probability >= 5 m/s [%]	39	37	46	39	39	42	40	37	36	35	33	39	38
Average wind speed [m/s]	6	6	6	6	6	6	6	5	5	5	5	6	5

Table 6 Historical wind statistics (WindFinder, 2015)

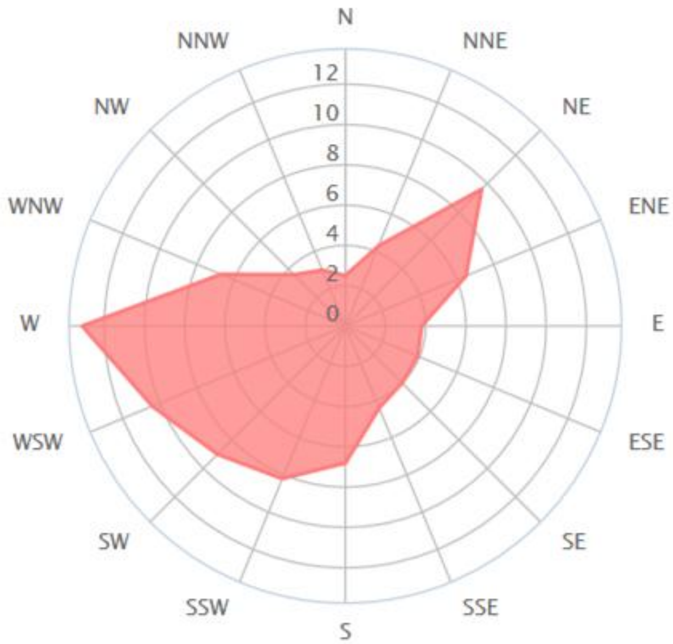

Figure 10 Wind direction distribution in percentages (WindFinder, 2015)

Not only the wind speed is important, but also its direction. The weather in northern Poland is greatly influenced by the Gulf Stream, in consequence the wind is blowing mostly from the western directions. Figure 10 presents the distribution of wind directions in percentages based on the statistical data from WindFinder(2015). The wind direction distribution is an important factor during the location analysis of the high-risk facilities, which are using toxic gases and fluids. The probability says that it is safer to locate the facilities downwind from the residential areas, however it is only probability and nothing guarantees that during the real leakage the wind will not be blowing directly towards the residential area. The facility in Strzeszewo is placed on the worst possible location, on the east side of the village, which means that most of the time the leaked substances will disperse directly to Strzeszewo. It cannot be said that someone made a mistake locating the wellsite there, especially if we consider that it is not a wooden shed, but a high risk facility which is worth millions of dollars. Probably the wind direction was neglected during the location choosing as there are many other more important factors that are influencing the final location. It can be assumed that the company is fully conscious about the threat, but it is confident about its safety solutions and wind direction is not a factor.

6. Risk analysis methods

There are many risk analysis or assessment methods, but none of them is perfect. Each method has some advantages and disadvantages, which have to be taken into consideration, when choosing the right method. It is an important aspect of the work organisation, as the chosen methodology will guide the whole process of risk assessment. The choosing should start from defining the objective, scope and limitations of the assessment and then the most suitable method can be assigned. The correct method is the one that takes into account all possible risks and results, which are in the scope of assessment and is suitable for the amount of the data possessed. Sometimes one method is not enough, as it is not covering all necessary issue, thus other complementary methods have to be used to fulfil the initial requirements.

In the collection of different methods, the two main approaches can be indentified the qualitative and the quantitative ones. The first approach is describing the risk using statements(e.g. low, moderate, high), whereas the quantitative is using defined values. In this thesis both of this methods will be used, to ensure that the risk assessment identified and assessed most of the possible negative consequences of facility functioning thoroughly.

6.1 SWIFT analysis

As the Structured What-If Technique will be used in the next chapter, it is important to discuss the pros and cons of this approach. SWIFT is the qualitative risk assessment which analysis the risk by asking the question "what if?" something happen and what are the consequences of this event. The analysis is made by a team, preferably multidisciplinary, in a form of a brainstorming discussion, where everyone is trying to identify different sources of risk and associated consequences (Kritzinger, 2006). The optimal number of team members is 6-10, as too small number may not possess enough necessary knowledge, and too big may have problems with too broad discussions (OMV, 2013). This technique was developed as an alternative to a technique called HAZOP, as it is less detailed which means it can be done faster and cheaper. It was developed for the chemical and petrochemical plants, but now it is widely used in other disciplines due to its structured form and ease of use. Also it is a useful tool for analysing the domino effect events, which are a great threat at all high-risk facilities. However there is a new approach to analyse the domino effect events using

The main pros of the SWIFT are (ISO/IEC, 2009):

- Variable forms of application, from physical plants and systems to organisations and activities;
- Relatively small preparation effort by the team, which gives a possibility to involve in the assessment a lot of multidisciplinary specialists, as well as, people who are responsible for the existing systems;
- Simplicity and rapidness of the process, the major hazards and risks quickly identified;

- System oriented approach, which gives participants possibility to model the systems' behaviour on the basis of different scenarios;
- Creating risk register and its treatment is relatively effortless comparing to other techniques;
- It can be used to identify risks and hazards that can be taken forward into a quantitative study;
- Improvement of systems and processes can be based on the recommendation included in SWIFT.

The cons of the SWIFT (ISO/IEC, 2009):

- The efficiency of the SWIFT is very dependable on the experience and abilities of the facilitator;
- Without proper preparation, it can be a very time-consuming process;
- If the experiences and knowledge of the team is not covering all the aspects of the analysis, some risks or hazards may not be identified;
- If the technique is used on too high level it may fail to identify complex, detailed or correlated causes.

6.2 QRA

QRA is a formalised and standardized form of analysing the potentially hazardous events estimating the likelihood and consequences of those events, and expressing the results as risk to people, the environment or the business(DNV, 2013). To perform such an analysis a specialized software is often necessary, which can calculate and model all the events and their consequences. A good software is characterized by ability to input all the data acquired so that everything what is known about given event is taken into consideration. The result of such an assessment is a detailed risk picture with all possible consequences presented in a real numbers or countable values. QRA is often an essential element of application form for acquiring concession from the government for some high-risk systems like power plants, bridges or petrochemical facilities. Without estimating the risk in countable values and modelling the possible consequences to surrounding area the concession are not granted. QRA can be used on different levels of details, it means that the software can be used to model the functioning of a single valve or the whole facility, it only depends on choosing the right software and adjusting it to the needs. Moreover, if the right software is used, there is possibility to repeatedly update the assessment with new safety barriers or solutions and observe how the risk picture changes. It is very effective tool especially during designing ALARP safety systems. According to Kardell & Lööf(2014) QRA can also be used to analyse the domino effect scenarios, although it is connected to a great degree of uncertainty.

One of the biggest disadvantages of QRA is it time and money consumption, to make a reliable QRA a lot of information have to be gathered and sometimes a special software has to be designed to fit to the requirements of the QRA. That is why this type of assessment is used only when it is really necessary and before it is performed the detailed boundaries of analysis are set, to assure that the analysis will not grow infinitely. There are studies(Abrahamsson, 2002) that proved that lack of QRA standardization is leading to insufficient reliability of the QRA results, which resulted in the situation where several teams had been asked to perform the QRA of the same facility and the variations between their results were unacceptable.

In this thesis there will be used a QRA software called PHAST which will be used to model the consequences of failures at the installation and potential threats to people living nearby. It will concentrate mainly on their safety, so that the economic and environmental hazards will be disregarded.

6.3 Uncertainty

One of the most important part of any risk assessment is describing its uncertainties, which according to NORSOK Z-013 standard (NORSOK, 2010) is an essential requirement to validate the analysis. The importance of assessing the uncertainty is connected to lack of full confidence that the assessment has taken into consideration all the events. Also the consequences that were assigned to each event may not happen, or the failure will happened in unplanned and surprising way. These QRAs are just a simulations, and unfortunately the real life scenarios are sometimes completely different from what was planned or predicted.

As there uncertainty is a very broad concept, according to Parry(1998) we can identify three classes of uncertainty causes – parameter, model and completeness uncertainty. This definition is not taking into account all the uncertainty causes, which are necessary to identify, to make the analysis more reliable. Hence, according to Armacosta & Pet-Edwards(1999) and Zimmermann(2000) we can indentify not three , but six major causes of uncertainty:

- Lack of information(or knowledge) – the most common cause of uncertainty is lack of necessary knowledge, data or information, which lack is displaced by approximations. It can be both qualitative(when the analyst possess the accurate data to describe some event but does not know whether it is safe or hazardous/good or bad) or quantitative(when the analyst knows that there is probability of an event but does not the exact value of it). In this thesis, this type uncertainty has a strong influence on the final results. Due to small amount of information about the installation, significant part of data was taken from other sources or approximated, however it must be highlighted that all approximation in this thesis are very conservative, so that the final risk picture is higher than it would be with standard approximations.
- Abundance of information – second cause is connected to excess of information, when there is so much data that human is incapable of identifying the most important one and neglects it which makes the final risk picture incomplete. This type of uncertainty is not connected to this thesis as the amount of information was rather insufficient.
- Conflict of different pieces of data – situation when there is data that is contradicting with the other one. This may happen when the data is taken from different sources which may be not relevant to the given scenario. There are two ways to decrease this cause, to gather more data or to eliminate the irrelevant option. However both of this

option have significant disadvantages, firstly additional data may still be contradictive, secondly the right option may be eliminated. This cause of uncertainty was not present on any stage of this analysis.

- Measurements errors – risk assessments greatly relies on measured data, which can never be said to be completely accurate. There is always some dose of probability that the measuring instrument was not accurate or the measuring human made a mistake. It is hard to judge how big is this uncertainty in this thesis as I was not personally involved in any measurement that was used in this thesis. However the data that the thesis is relying on was taken from reliable sources such as for example OREDA.
- Linguistic ambiguity – many people which are not familiar with other languages may have problems to identify the context or the true meaning of many words or statements, especially in qualitative assessments which may influence the risk picture. This cause is not relevant to my analysis
- Subjectivity of analyst opinions – when the analysis are performed by single person or small teams which have similar opinions/knowledge, there is a chance that the risk picture will be inaccurate. This cause is the most relevant to my thesis as I was doing it on my own, but I tried to reduce this uncertainty by validating my work by other people who are working daily as risk analysts.

These were the major causes of uncertainty in risk analysis, which are existing on a certain level in every risk assessment. It is important to be conscious about their existence and what is their level as it is a base for the risk informed decisions making.

The uncertainties have different causes, as well as, different types (Zio & Pedroni, 2012):

- Aleatory uncertainties – these types of uncertainty is mostly connected to reliability analysis when the failure rate is defined by some probabilistic model(e.g. Poisson, binomial distributions). Although these models try to present the probabilistic picture of when the failure will occur it is not telling when exactly it will happen. For example in this thesis the important factor is failure rate of Christmas tree which is said to happen once in 300 years, but because of aleatory uncertainty it may also happen twice in one year. This type of uncertainty is irreducible.
- Epistemic uncertainty - this one is connected to lack of information about analysed phenomena which are divided for model and parameters uncertainties. It means that all the influential factors were not taken into account or information about their influence was not detailed enough. This type of uncertainty can be reduced by gathering more and more data, but this process can be endless especially in the open world when the number of possible events is infinite. In this thesis the data has been acquired as long as I was subjectively assured that the analysis would be reliable enough.

In many cases the robustness of the QRA will as important as its results. It gives the decision maker an information about how dependent decisions are on assumptions made in the QRA. It must be highlighted that describing the level of uncertainty even if it is high is not weakening the results of the analysis. Moreover, identifying key sources of uncertainty can help prioritise resources where they matter most in terms of influence on risk. By addressing the uncertainty from an early stage in the QRA process, there is an opportunity to perform further studies or implement measures in order to take the uncertainty into account (DNV, 2015).

7.1 SWIFT results

As it was mentioned before the risk analysis will begin with Structured What-If Template. Normally such an analysis is performed in multi-disciplinary teams, workshops or other types of working group, unfortunately in this case it did not happen. Not only there was no possibility to contact people responsible for the design and running the facility in Strzeszewo, but also the requirements of the master thesis were limiting the enhanced group work. Nevertheless I tried to perform this assessment is the most objective way possible with regarding to OMV recommendations for the proper application of SWIFT (OMV, 2013).

Firstly, the events which may be hazardous were established, obviously the selection of events focused on the overall facility level, so the minor failures were neglected. Some of the chosen events may seem rather impossible or even hard to imagine, but the risk assessment analysis, especially qualitative should include them. A simple identification of possible black swans does not necessarily lead to finding the solution for avoiding the risk, but may just help to realize that there is such a possibility. For example the terrorist attack on the installation in Poland is highly improbable, but it is unknown if there is somebody who will get an idea on performing this action. In this case should the crew be trained in personal defence or full time armed? Definitely not, but a short training on how to act, what to do, what surely not to do or who should be phoned immediately, in such a situation may be a life saving activity.

Further, the possible negative consequences were assigned to each event. As single event may result in several different consequences only the most important were allocated. Next, the severity and probability scales were created, they are presented in the table 3.

Level of probability	Frequency once per [years]
Unlikely	100<
Remote	10 – 100
Quite possible	1 – 10
Possible	<1

Table 7 Level of probability description

Level of severity	Consequences
Critical	Fatalities
Degraded	Severe injuries
Incipient	Minor injuries

Table 8 Level of severity description

Since, the classification of each event on the probability and severity scale is the process where the opinions in working teams are varying the most, I could not rely only on my own, probably objective, point of view. Hence, I asked four people, who has been working within petroleum industry or have a daily contact to similar installations to categorize each event. To increase the level of objectivism, each person get a blank template and assess the probability and severity on their own. The final levels are simple averages of their answers.

What if?	Consequence	Likelihood	Consequences
Failure of sensors/abnormal readings	Bad interpretation of current situation and possible bad decisions	possible	degraded
Corrosion - different types	Walls cracking	possible	incipient
Formation of hydrates	Choking/plugging of pipes/inflows/outflows	possible	incipient
Formation of paraffin	Choking/plugging of pipes/inflows/outflows	possible	incipient
Leaking from seals	Leaking of process medium	possible	incipient
Sand abrasion	Walls cracking	possible	incipient
Vibration of welds	Softening of welds	quite possible	degraded
Leak at cleaning valve	Leaking of process medium	quite possible	incipient
Not properly tighten pipes	Leaking of process medium	quite possible	incipient
Fire at the facility	Overpressure in tanks	remote	critical
Too high wellhead pressure	Too high load for installation	remote	critical
Accumulation of fluid or gas between pipe and isolation	Leaking of the process medium	remote	degraded
Leaving some objects inside installation	Choking/plugging of pipes/inflows/outflows	remote	degraded
Failure of orifice	Overpressure in the installation	remote	degraded
Failure of downhole orifice	Sudden rise of the pressure	remote	degraded
Manual valves not tighten properly	Leaking of the process medium/unwanted flow of fluids	remote	incipient
Extreme weather condition/extremely cold	Choking/plugging of pipes/inflows/outflows	remote	incipient
Leaking from paker	Leaking of the process medium	remote	incipient

Appearance of hydrogen sulphide	Highly dangerous poisoning of people	unlikely	critical
Terrorist attack	Possible detonation of the installation	unlikely	critical
Too soft wellhead	Threat of disintegration	unlikely	critical
Badly installed wellhead	Threat of disintegration	unlikely	critical
Failure of wedge gate valve	Overpressure in installation	unlikely	critical
Shut down valve failure	Overpressure in tanks	unlikely	critical
Mechanical fracture	Sudden rupture or leaking from the installation	unlikely	degraded
Badly designed installation	Lower efficiency, lower safety	unlikely	degraded
Badly constructed/assembled installation	Leaking of process medium/possible	unlikely	degraded

Table 9 Structured What-If Template

The presented template is missing two elements, which are included in the standard SWIFT, these are environmental and economic consequences, as well as, recommendations. Firstly the aim of the thesis is not to evaluate the level of economic losses and effects on downtime and functioning of the facility, as it is not influencing the safety of residents. The environmental consequences were also not in the scope of the analysis, but most of them are connected to underground activities and failures. Finally the recommendations were not included as the detailed information about existing safety systems and solutions at the facility were unavailable. Thus, there was no point in creating any safety recommendations which may have been already realized.

This crude analysis has showed that there are many threats and risks associated with well testing installation, however most of them are not relatively danger. The one that are the most common have incipient consequences, whereas those that have critical consequences are very unlikely to happen. As we can see most of the events will result in leaking of process medium, which can lead to appearance of flammable cloud and sudden rupture. In the next chapter the consequences of such leaking and ruptures will be modelled. Further, in the discussion chapter, the detailed SWIFT interpretation and analysis will be performed with regarding to the overall picture.

8. QRA results

In the qualitative analysis the major threats have been identified. Even a crude analysis of the template shows that all sorts of tanks and vessels are the sources of potential fires or explosions, including the well safety systems. Therefore, five elements of the installation were chosen for the quantitative analysis. These are: flowhead, test separator, flush drum, surge tank and methanol tank. In the Table 10 there are presented the main parameters of these elements which were used for the simulation. To simplify the simulation, values are constant throughout the whole simulation, whereas in the real world they are changing continuously. The volume values are taken from the existing installation, and the volume of the flowhead was assumed to be infinite for the purpose of the simulation. This is caused by the pressure and volume of the reservoir, which in case of uncontrolled blowout and complete rupture of the flowhead will produce the raw gas in such an amount that even after hour the pressure does not drop significantly. The pressure values are set to the maximal working pressures that were assumed in the P&ID. The temperature is set in the middle of the assumed working ranges in the P&ID. The content of the surge tank is assumed to be nonane, normally it would be a water with additions of some light liquid hydrocarbons, but to follow the conservative approach of the thesis, the nonane was chosen. The methanol tank is filled with pure methanol and the rest of the elements is assumed to be filled with pure methane as the influence of additional substances of the raw gas is negligible for the results. The probability of the flowhead was taken from RADD(2010a), the rest of the probabilities were taken from OREDA(2002). However according to RADD(2010b), the probability of failure frequency cannot be taken ad hoc, as this data is based on the historical knowledge and is not considering the trends over time and improvement of technology. So the experienced analysts with proper background knowledge may be able to modify the probability values to better imitate the real ones. In this thesis the failure frequencies are taken without modifications.

	Volume [m3]	Pressure [psi]	Temperature [F]	Contains	Probability
Separator	2	1440	130	Methane	0,2525
Flush drum	5	72,5	120	Methane	0,0974
Surge tank	16	150	110	Nonane	0,0832
Methanol tank	2,4	Atmospheric	Ambient	Methanol	0,2534
Flowhead	infinite	4 351	158	Methane	7,8e-5

Table 10 Parameters of installation

The first simulations revealed that the leaking of these elements of the installation or minor failures would have negligible influence on the safety of residents living nearby. Only people located near the installation, like operating personnel would be exposed to the consequences of failure. Therefore the most severe conditions and improbable as well were simulated, whereas complete rupture of each element is simulated both individually and collectively. The PHAST offers so many different graphs and functions that it would be impossible to present them all in this thesis, hence only the most important were selected. Moreover, the explosion effects were not simulated as the possibility of such an event is relatively small, as the simplicity and outdoor location of the installation facilitates the ventilation and prevents gas to concentrate. Finally, the results of this QRA should not be solely used to draw conclusions, as QRA always has to be based on a certain background knowledge (many assumptions and suppositions). Hence, QRA will not be able to reflect all uncertainties(Mirzaee, 2012).

8.1 K.O. vessel

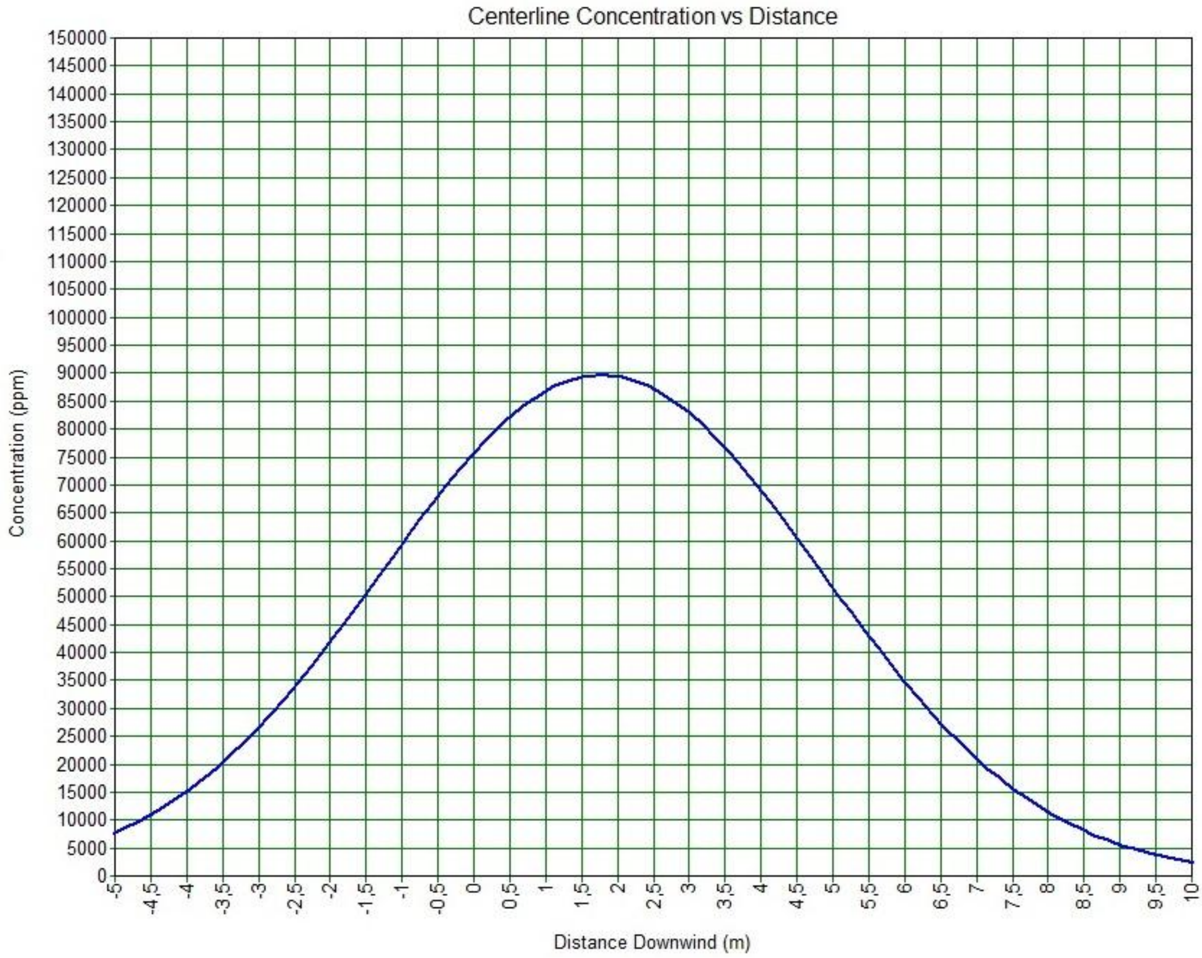

Figure 11 Function of centreline concentration and downwind distance for the K.O. vessel rupture

Figure 11 shows the function of centreline concentration and downwind distance from the K.O. vessel after 18,75s, this value is the flammable averaging time and will be used for all the underneath concentration graphs. This value was proposed by Wilson (1995), who stated that if the concentration is not exceeding LEL after than 18,75s, then it will not ignite at all. The maximal concentration of 90 000ppm is achieved at about 2 meters downwind. The explosive atmosphere is achieved when the concentration is in the range of 50 000ppm to 150 000ppm, which means that from 1,5m upwind to 5m downwind such an atmosphere exists. However the explosion is rather connected to leaking scenarios and the ruptures are resulting in the fires, thus the fireball scenarios was simulated. The toxicity of methane which causes problems with breathing is at about 10 000ppm, which sets the toxic zone between 5-10m depending on the wind direction.

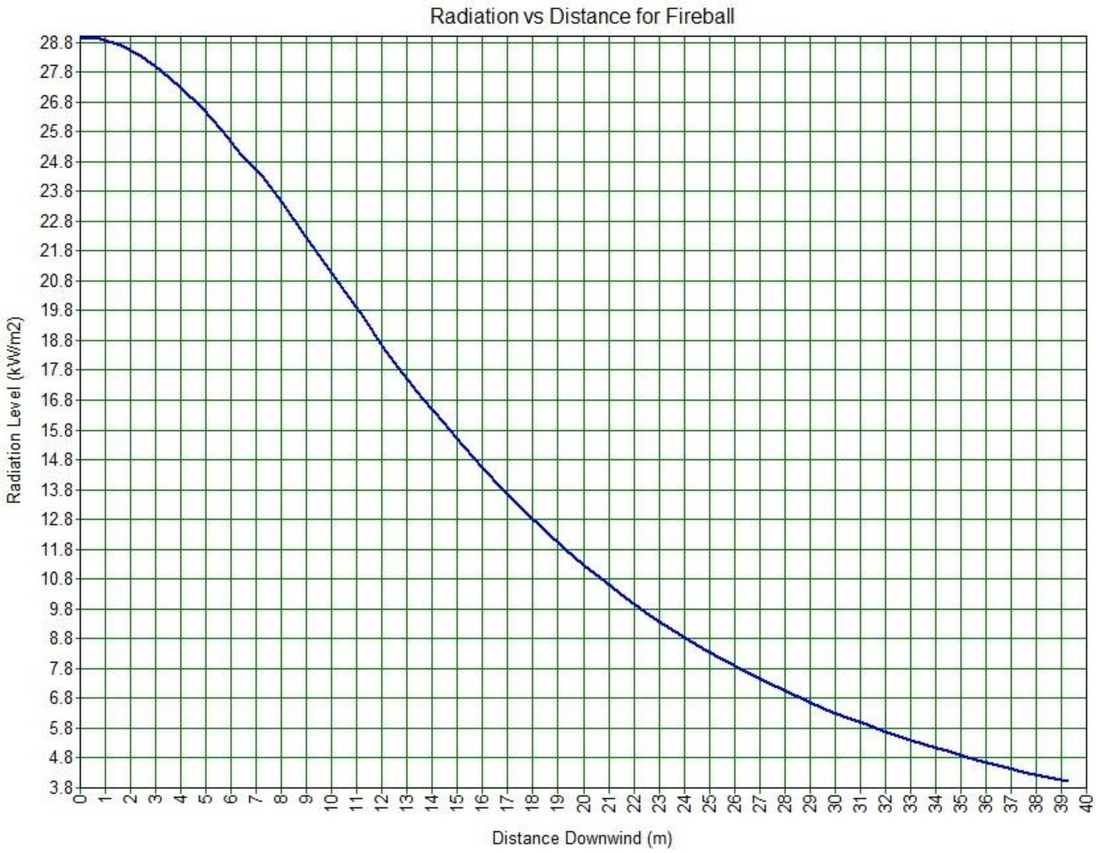

Figure 12 Function of radiation and downwind distance for a fireball after the K.O. vessel rupture

Figure 12 shows the function of radiation versus distance downwind in case of fireball. The appearance of fireball is connected not only to flames but also to heat, which is calculated in watts per square meter(W/m^2). In Table 11 there are presented values of radiation and its effects on humans. As a consequence, the zone where the first injuries may appear is less than 40m.

Thermal radiation kW/m^2	**Effect**
1.2	Received from the sun at noon in summer
2	Minimum to cause pain after 1 minute
Less than 5	Will cause pain in 15-20 seconds and injury after 30 seconds exposure
Greater than 6	Pain within approximately 10 seconds rapid escape only is possible
12.5	Significant chance of fatality for medium duration exposure. * Thin steel with insulation on the side away from the fire may reach thermal stress level high enough to cause structural failure
25	* Likely fatality for extended exposure and significant chance of fatality for instantaneous exposure. * Spontaneous ignition of wood after long exposure. * Unprotected steel will reach thermal stress temperatures that can cause failure.
35	* Cellulosic material will pilot ignite within one minute's exposure. * Significant chance of fatality for people exposed instantaneously.

Table 11 Effects of thermal radiation on humans (HSE, 2014)

8.2 Methanol tank

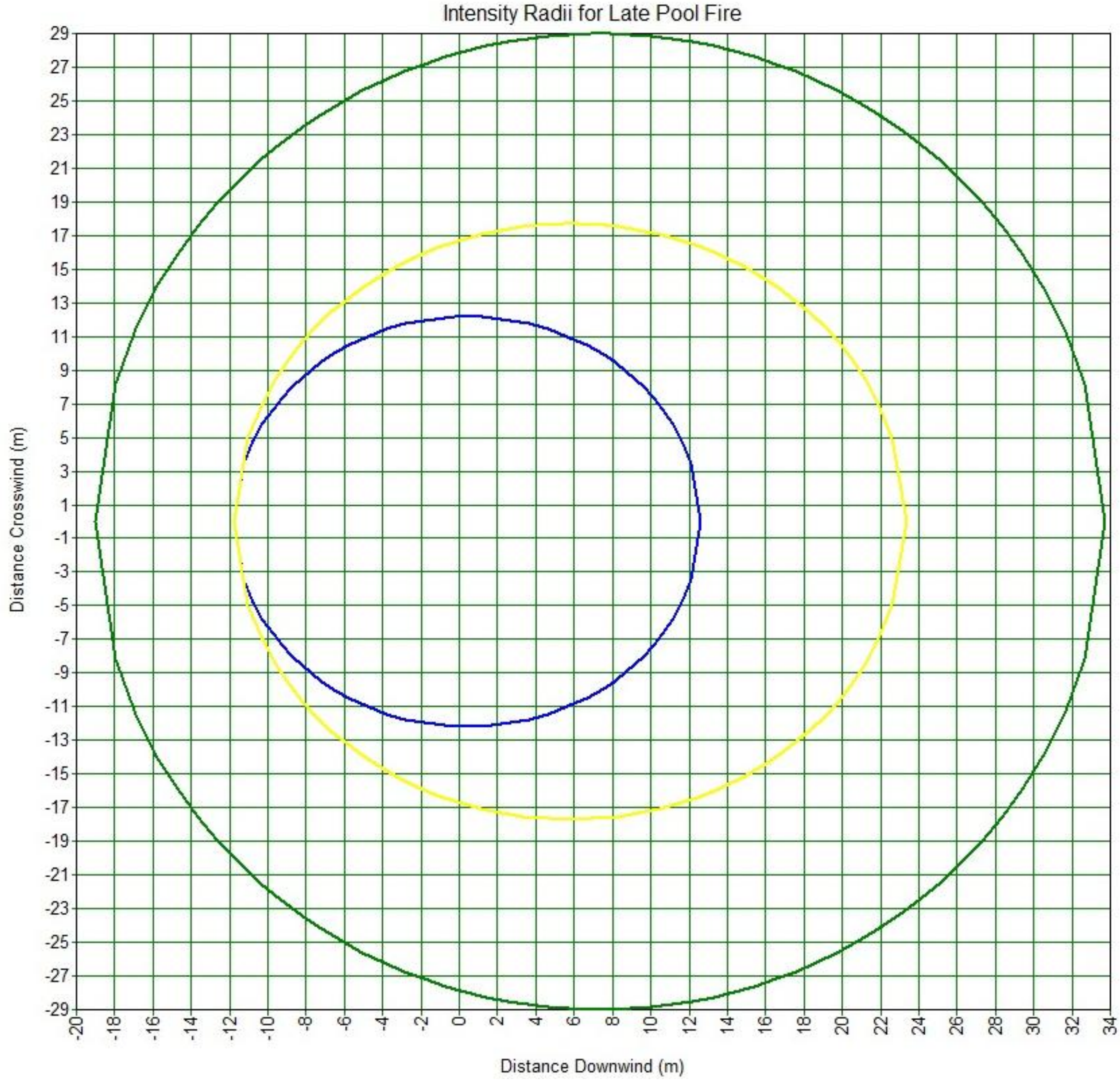

Figure 13 Function of thermal radiation and distance for the pool fire after methanol tank rupture

Figure 13 shows the function of thermal intensity radiation for the late pool fire in case of the full methanol tank rupture, the three circles show the intensity respectively – $4kW/m^2$(green), $12,5kW/m^2$(yellow), $35kW/m^2$(blue). We can see that the wind is playing an important role in case of fire as the difference between upwind and downwind border of the $4kW/m^2$ zone is almost 15m. Moreover the green circle is marking the zone where the exposure for longer than 30s in normal uniform is dangerous. The simulation did not take into account any bunds which are made for the safety purpose or other elements of the installation. If the bunds were included the shape of the pool would change along with thermal radius zones, probably decreasing the negative effects as the surface of the pool would be smaller, so as the evaporation. In this simulation the maximal radius of the pool after the rupture reached 11m after 23s, afterwards it started to decrease, the mass evaporation averaged 800kg per hour.

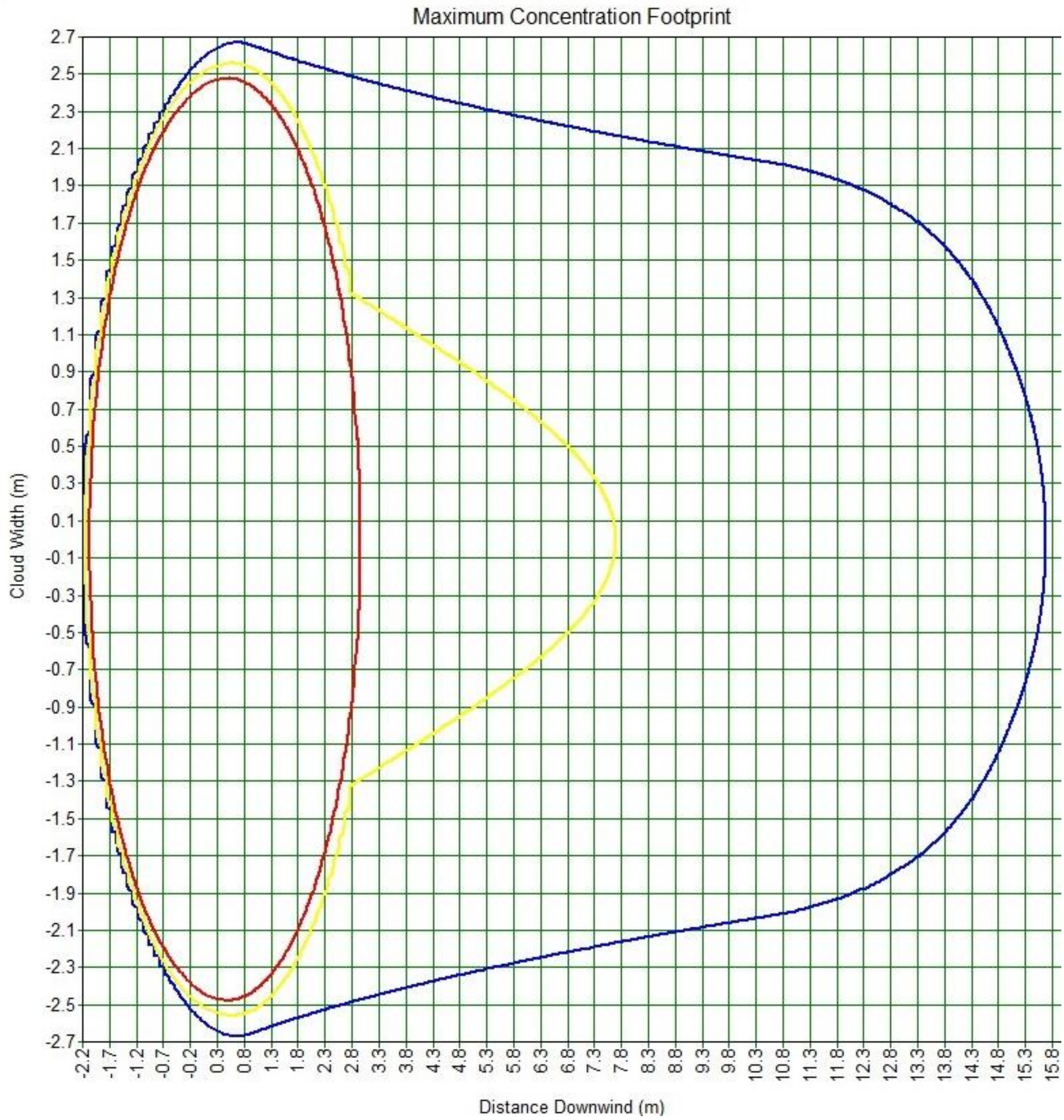

Figure 14 Function of concentration footprint and distance for the methanol tank rupture

Figure 14 shows the concentration footprints after the methanol tank rupture. The three circles shows the concentration respectively – 36 500ppm(blue), 73 000ppm(yellow) and 360 000ppm(red). The shape of the red circle is a consequence of evaporation right above the pool, whereas the yellow and blue ones are showing how the methanol vapours spread with the wind. The difference between upwind and downwind zone borders is bigger than in case of thermal radiation as the wind has a bigger influence on the dispersion of gases then fluids. According to Kavet & Nauss(1990) 40 000ppm concentration for 5 minutes is a lethal dose, so it can be assumed that the blue circle is showing the lethal zone for the humans without oxygen mask in case of the rupture.

8.3 Separator

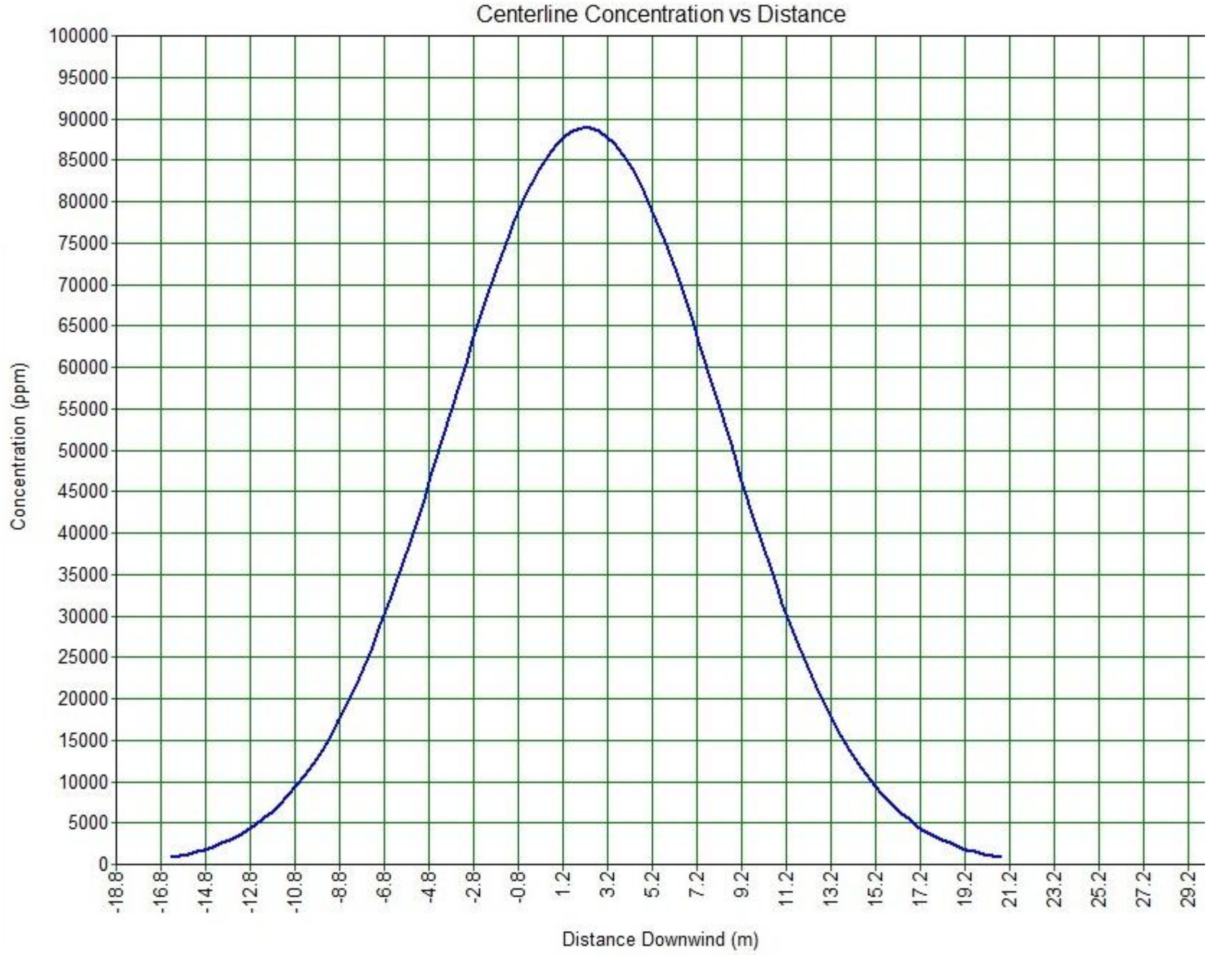

Figure 15 Function of methane's centreline concentration and distance for a rupture of the separator

Figure 15 shows the function of centreline concentration of methane and distance after the rupture of the separator after 18,75s. The maximal concentration of 90 000ppm is achieved at about 3 meters downwind. The explosive atmosphere is expected to be in the range 5m upwind and 9m downwind. The toxic zone(first symptoms of breathing problems) is between 10-15m depending on the wind direction. Furthermore, there is similarity between Figure 15 and 11, on both of these graphs the maximal concentration reaches about 90 000ppm, although the separator and K.O. vessel have different size and inside pressure. This can be caused by the volatility of methane, which accelerates the mixing of methane with air, preventing the accumulation of methane in high concentration clouds.

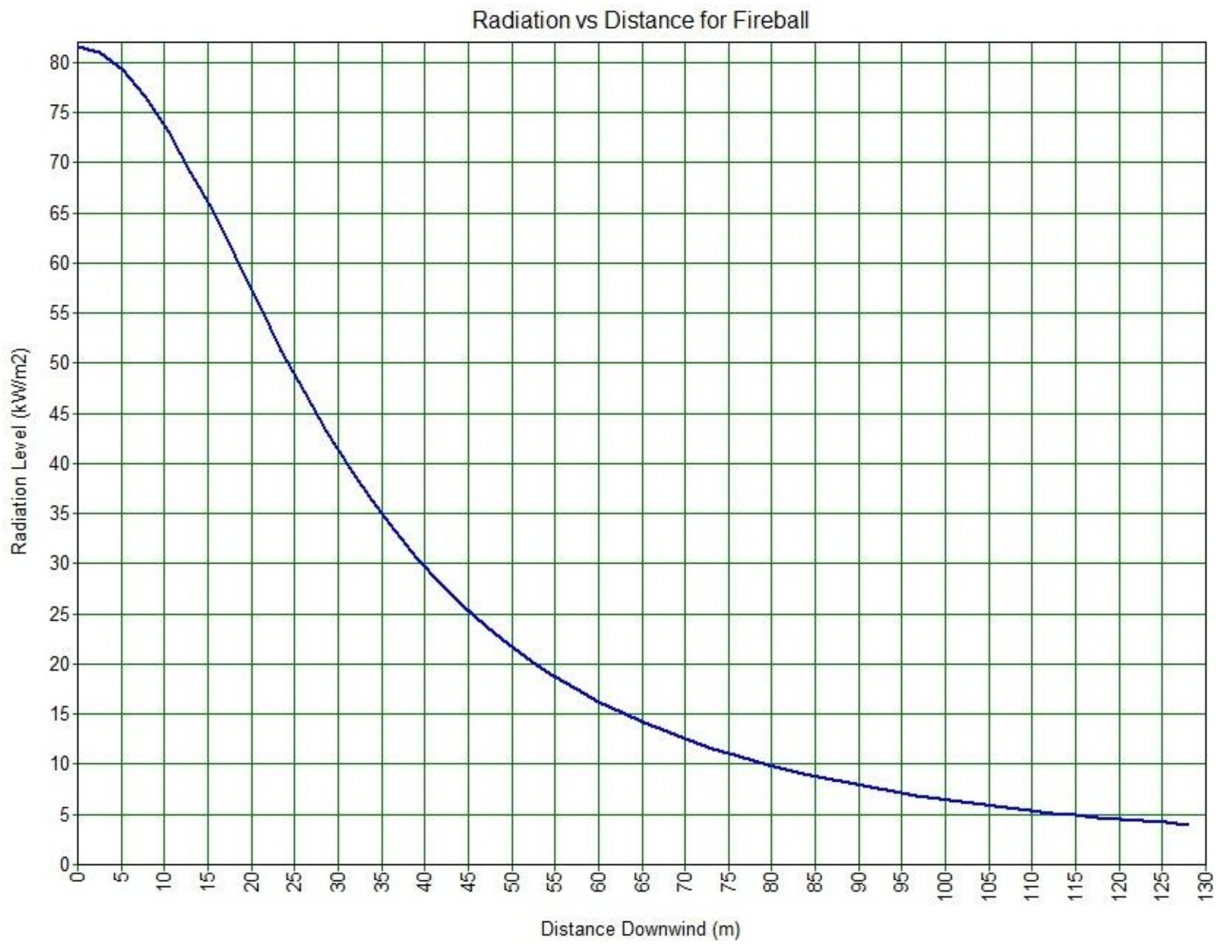

Figure 16 Function of radiation and downwind distance for a fireball after rupture of the separator

Figure 16 shows the function of radiation and distance downwind for the fireball in case of ignition of methane after the rupture. According to Table 11 the probable instant lethal zone is in the range of 40m downwind from the separator and the "pain" zone is starting at about 115m from the separator. It should be underlined that this radiation will take only for a few seconds as it is a fireball case, not a constant fire. This is caused by lack of continuous inflow of fuel(methane). The amount of fuel is limited by the volume of the separator and the inside pressure.

8.4 Surge tank

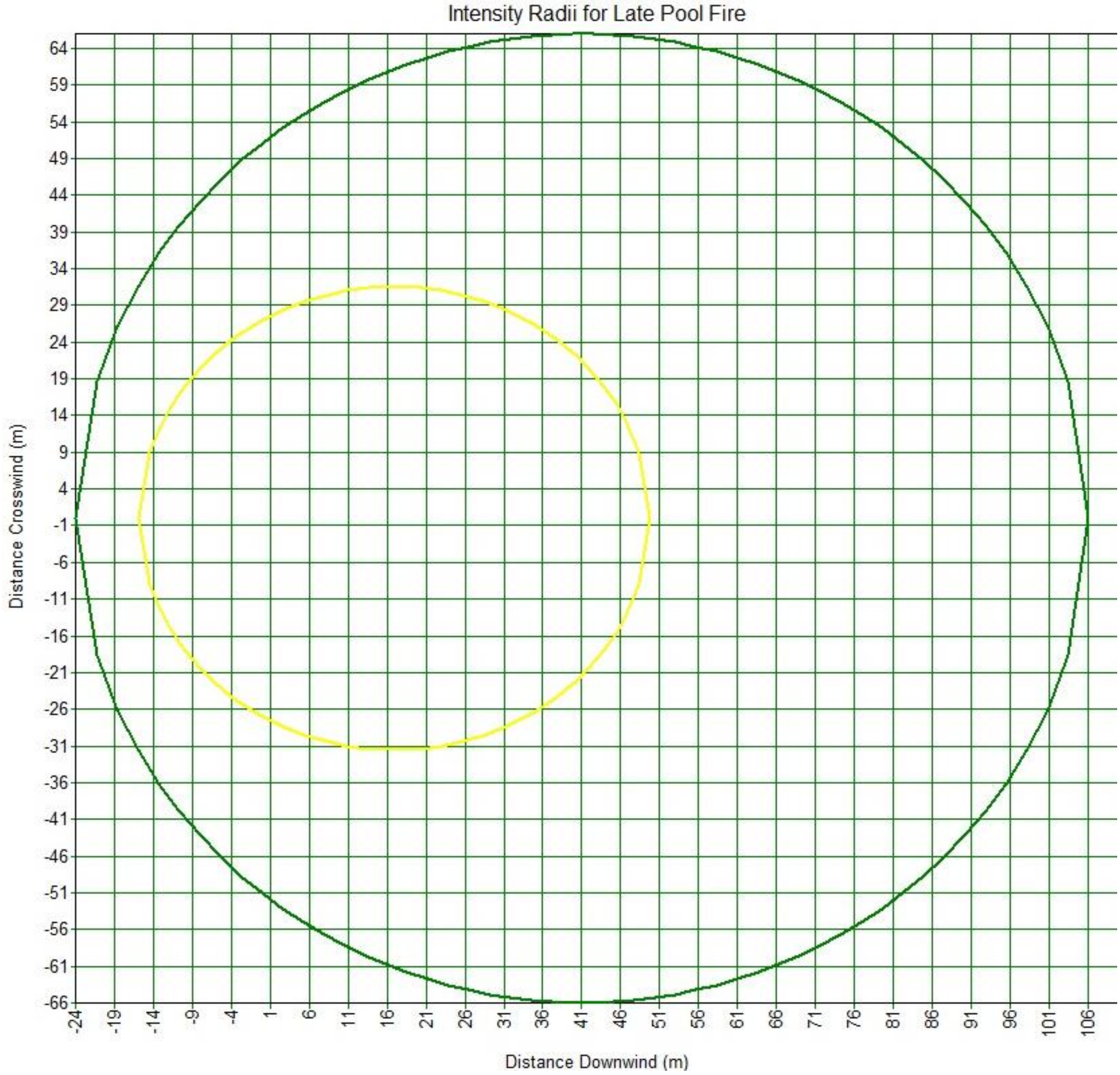

Figure 17 Function of thermal radiation and distance for the pool fire after the surge tank rupture

Figure 17 shows the function of thermal radiation intensity and distance for the pool fire of nonane spilled after rupture of the surge tank. The two circles show the intensity respectively – 4kW/m^2(green), 12,5kW/m^2(yellow). Once more it can be noticed that the zones are greatly depending on the wind direction, the green zone is reaching 100m downwind and only 25m upwind. The late pool fire is a different scenario than fireball for the ruptures of separators, the fuel in this case is delivered for longer time, which means that humans located in the range of green zone when the pool ignites should immediately escape in the opposite direction to the pool fire. However if we are surprised by the fire on the downwind side of the surge tank it may be safer to escape perpendicularly to the wind direction as this way the radiation intensity is decreasing faster. Hence, at many facilities the windsocks are located to facilitate choosing of the escape route.

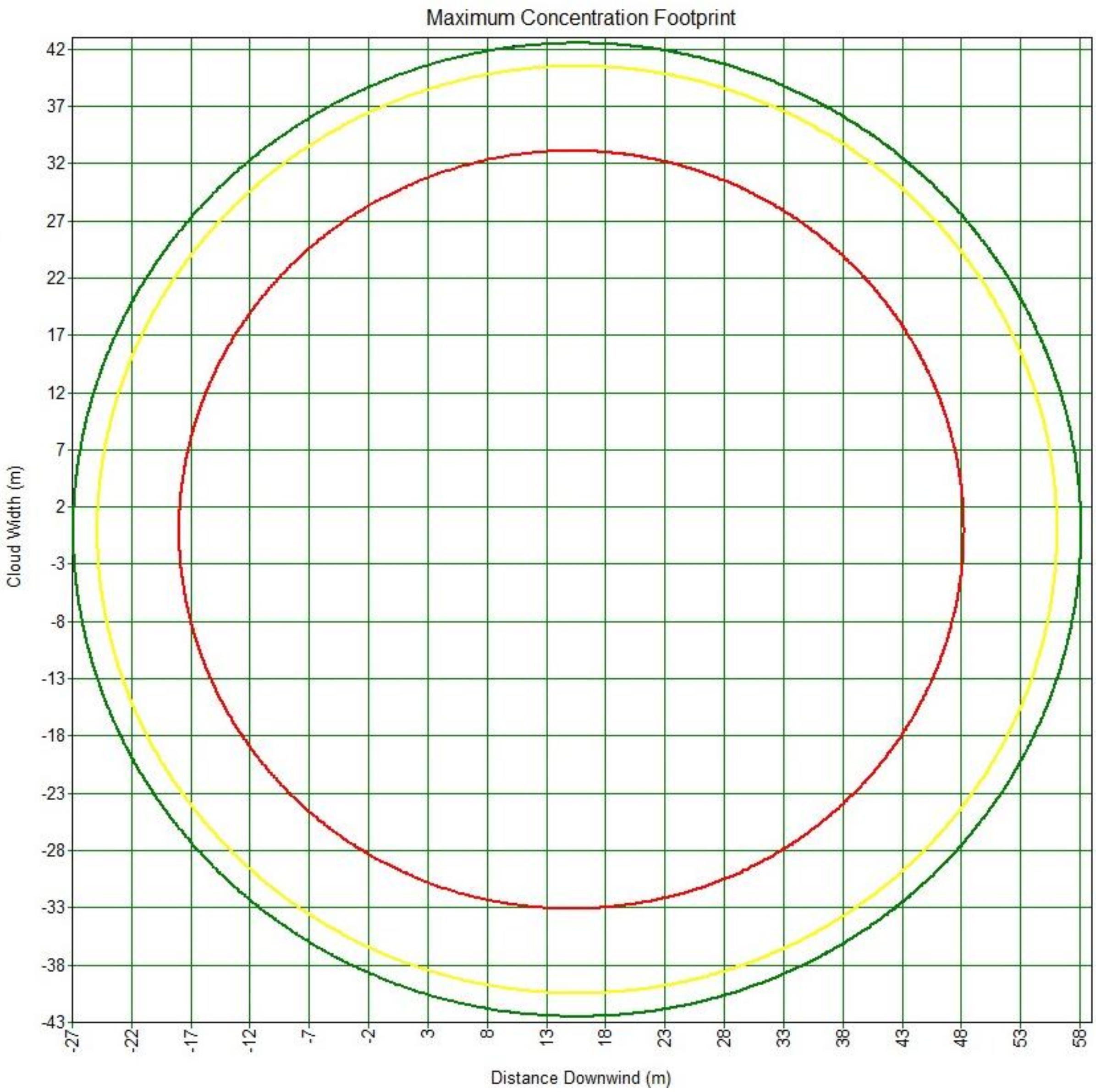

Figure 18 Function of concentration footprint and distance for the surge tank rupture

Figure 18 the concentration footprints after the surge tank rupture. The three circles shows the concentration of the nonane vapours respectively – 3 500ppm(green), 7 000ppm(yellow) and 56 000ppm(red). The shape of the circles is not overlapping with the thermal radiation as these two graphs are describing two states of thee pool, ignited and not ignited. Also here the shape of the concentrations zones is round because of assumption of idealized creation of the nonane pool. If any bunds were included the shape would also change. The LEL for nonane is 8 000ppm and UEL equals 29 000ppm, thus the explosive atmosphere should be expected in the zone between red and yellow circles. The threshold limit value, at which worker can work daily, for nonane vapours equals 200ppm(CDC, 2011). However it should be again highlighted that in real conditions the surge tank would not be filled with pure nonane, but a mixture of water and other lighter and heavier hydrocarbons.

8.5 Well

Figure 19 Function of methane cloud height and downwind distance for the flowhead rupture

Figure 19 shows the side view of the methane cloud after flowhead rupture. The three domed shapes show the concentration of methane in the atmosphere after 18,75s respectively – 22 000ppm(blue), 44 000ppm(yellow) and 165 000ppm(red). It can be argued whether in this case the value of 18,75s is correct as raw gas is going to flow from the well unstopped until the reservoir presser equals atmospheric one, which can be calculated in days. Fortunately for safety issues the methane is lighter than air, and the outlet of the well is directed upright, so theoretically released methane will float to higher levels of atmosphere. However, in the real conditions the outlet could be directed in other directions or due to Joule-Thomson effect the cooled methane will be heavier than air. Finally raw gas may not disperse at all due to immediate ignition.

8.6 Risk contours

Figure 20 Risk contours

Figure 20 shows the risk contours, which are created basing on the probability and severity of all the ruptures. A cursory analysis indicates that the pink circle(1e-5 a year) is outside the wellsite and the risk zones with lower probability are almost overlapping with the pink one. Further, the next distinctive zone is the red one(1e-3 a year), which is ending at the parcel's boundaries, the smallest yellow zone(1e-2 a year) with the highest probability of risk is just around the installation not even reaching the magazines and offices. According to UK HSE standards the tiers for individual risk are(DNV Software, 2001):

- Maximum tolerable risk for workers: 10^{-3} per year;
- Maximum tolerable risk for members of the public: 10^{-4} per year;
- Negligible risk: 10^{-6} per year.

This means that the tolerable risk contours for the members of the public are not exceeding the wellsite boundaries, however, the area closest to the installation is overreaching the tolerable risk for the workers. This can be caused by the conservative approach of the thesis and too high probabilities of the failures. Also including safety measurements used at the wellsite could decreased the risk levels to the required values. Nevertheless the risk contours proved that neither workers' living quarters, nor Strzeszewo are exposed to the hazards concerning failure of the installation. But it must be underlined that the results of such an analysis should never be the only basis for decision making, but rather contribute to making risk-informed decision (Apostolakis, 2004)

9. Discussion

The aim of the thesis was to investigate if there are any threats connected with the shale gas well testing installation functioning. The analysis showed that the installation is not flawless and many hazardous situations can occur. In the most severe cases they may even end up with fatalities. This statement is supported by the results of both SWIFT and QRA. Even though both of these assessments have shortcomings and different type of uncertainties were influencing the results, it cannot be denied that well testing installation are potentially dangerous not only to the operating personnel, but also to the people living nearby.

The analysis has begun with SWIFT which due to its simplicity and limitation to the overall facility level did not include all possible hazardous events. This minor events, like pipes leaking or valves choking, were not included because of their negligible effect on the whole facility if they happen alone. However, these single events may arise to serious threat if they are connected with other failures occurring parallel or sequentially. It is impossible to identify all such events as the only limitation here is imagination and number of combinations of such cause and effect chains is infinite. It may be discussed if this approach is reasonable, as the probability of those negative scenarios does not equal zero, so they may appear and they may have greater negative consequences than the ones included in SWIFT. For instance, the probability of winning the main prize in a lottery is less than 1 out of 10 millions, but every week someone is winning. The same situation can happen in here, that the most improbable set of events may become a real threat, which is called black swan.

According to Aven & Krohn(2014) there are three types of black swans – unimaginable events, events that are judged to have a negligible probability and events not addressed in relevant risk assessment. All those three types can occur during the functioning of the installation and probably only after they occur they will be considered as explainable and predictable. Thus to reduce the risk connected to black swans the multidisciplinary teams should be formed, which broad knowledge may help to predict the unpredictable. Their brainstorming sessions and out of the box thinking can have a beneficial influence on analysing the risk picture from new perspectives or improving the existing safety solutions. In contradiction to following the same old standard procedures for years.

The discussion about those events and possible combinations could be shorter if the safety systems functioning at the facility were known. This would also give opportunity to include recommendations in SWIFT how to decrease the risk. According to the Polish law the company has to reveal in detail what kind of fluids were used during the hydraulic fracturing. But why the companies do not have an obligation to reveal, what kind of safety systems, procedures or measurements are implemented at the facility, as the consequences of the failures in many cases will be not limited by the parcel's boundaries. It should be citizens right to know if their safety is provided and how it is provided. Even if the facility was meeting all the safety and setback requirements, it would give a possibility for everyone to decide on his own if he wants to live nearby or move out. A further implication of this solution is that companies may build up their public relations on showing how good are their safety systems. Also such a transparency of operators would cut all the rumours and conjectures about the possible negative effects of failure at the facility. Presumably the companies would not be eager to reveal how are they providing safety at their wellsites without administrative restriction, however there is a simple denouement. The companies which do not want to share these information are obliged to buy or lease a certain amount of land around the wellsite, bigger than normally. It would be hard to fit this rule into the mining law, but the companies could decide how much worth is their confidentiality.

Soon, the Polish government is planning to facilitate the mining law and administrative procedures, as the existing one are full of complexities and ambiguity, which discourage western companies to invest in Polish shale. This might be a great opportunity to discuss the severity of this law, especially the setback rules, which in my opinion, on the basis of the thesis results, are not strict enough. For instance setback for wells with appearance of hydrogen sulphide from a single house is always 100m no matter if the radius of the anticipated contamination zone is 150m or 3 500m. Following this rule may lead to situation when someone will live in such a close distance to the well that, without even knowing on what kind of threat he is daily exposed, as according to the law all requirements are met. The disaster in China showed that neglecting the appearance of hydrogen sulphide can be a huge mistake. Although it was a blowout not a leakage, it cannot be assumed that during the well testing even in shale the hydrogen sulphide would not appear. Or what is worse it would not leak somehow from the installation. After the leakage occurs the released gas is unstoppable, this means that unless there is impermeable shield surrounding the facility, the gas can threaten residents life. The only simple way to prevent this to happen is to rise the setback. Even though this thesis is not answering the question to what level the setback should be raised it showed that the existing ones are too indulgent.

The issue of hydrogen sulphide is discussed so thoroughly, because failures with its appearance are amongst the most severe, and even one event may have more fatalities than several other with a sulphur-free gas. If the setback was not changed it may be feasible to make some training for the residents living nearby, how to act when the hydrogen sulphide is released to the atmosphere. Such a training may be a life-saving experience, as the history shows many people instead of escaping when the contamination is bearable are closing at home at thinking that it will save their life which is a fatal mistake. Unfortunately such trainings can be misunderstood, as many people will not understand its preventive role, rather think that it is a sign that wellsite is more dangerous than they thought before.

If we look only on the QRA and SWIFT results, without drawing deeper conclusions, then clearly, Strzeszewo village and any other residential areas located not closer than 100m from the installation are completely safe. Only the operating personnel is exposed to the hazards, but it is their job and they are conscious where they are working. On the other hand every company which is performing well testing is hoping for positive results and stepping into production phase. In other words, if the results are promising the well testing installation will be replaced by the production one. This kind of installation is much more complicated and the gas is not longer flared, but have to be thoroughly treated and transported by the pipeline or liquefied. Both of these options are associated with additional risks, that are said to be more serious than gas flaring(EDM Services, 2008). This implies that even before the well is drilled, the risk analysis for a given location should be performed, concerning that in this location the well testing and production installations will be functioning. So that, it will not appear that the reservoir parameters are satisfying for setting up the production, but the residents settlements are too close.

Another issue is lack of clear standards regarding tolerable risk in Poland. The common question for risk analysts is "how safe is safe?". As can be expected the operators in Poland are decreasing the predicted risk to the level which they regard as sufficient, which sustaining is not charging the budget too much. The lack of prospective reservoir discoveries is leading to emigration of companies form Poland or decreasing their budget for the further exploration activities. Consequently it may appear that the operators will cut the costs on the safety which is inexcusable.

In my opinion, if Poland wants to continue the dream about the shale gas Eldorado the government have to act quickly and make necessary changes to create a win-win situation, as soon as possible. Firstly, the strict safety standards have to be implemented, which are clear for everybody and leaves no room for any dangerous deviations. Secondly, due to complicated geological structure of Polish basins, the companies have to be encouraged somehow to invest their money. This can be done by offering them tax reliefs, simplified to maximum administrative procedures, postponed taxes or any other solution which is lowering their costs. Still it must not be economized on safety. If Poland do not want to miss its chance it cannot wait for the gas prices to rise to the profitable level with the existing law and administrative conditions. Poland should strike while the iron is hot.

Finally, the strengths, weaknesses and reliabilities of those two methods, SWIFT and QRA, and their results should be discussed. It cannot be said that these types of assessment are the most suitable for the risk analysis of well testing installation, as they were chosen primarily because of the master thesis requirements and secondly because of their advantages. It is possible that if the multidisciplinary team was obliged to perform such an assessment it would choose totally different methods. However it must be highlighted that those teams also have to search for a compromise between the most suitable methods and amount of available time, money and information. The main weakness of the assessments and their results is small degree of objectivism for SWIFT and a great amount of assumptions for the QRA. That is why the conservative approach was chosen to assure that even if the results are wrong, they are wrong in the safe direction for the locals. The main strength of these assessments is their simplicity and the level of details at where they are performed. As it was mentioned before the risk assessment should never be the sole indicator for the decision making process, but it should be used as a support for the risk informed decision making. Thus, even such simple methods are fulfilling this requirement. Moreover, if the client is not satisfied with the robustness of the risk analysis, he still knows what issues should be analysed more thoroughly and the further assessments may concentrate only on these issues.

10. Conclusions

The study was set out to explore the risks associated with functioning of the shale gas well testing installation and has identified the possible negative consequences of its failure. Lack of studies or literature about the negative surface consequences of operation of such an installation was the main reason for this thesis. The growth of shale gas industry led to increased fears concerning the hydraulic fracturing on a national scale, neglecting other threats connected to facilities of this kind. However, the residents living nearby the existing facilities were full of anxiety about their safety. That is why the thesis has tried to answer the question whether their fears are justified.

The SWIFT results indicated that the biggest threat, if the severity and probability are combined, is the abnormal sensors reading and the improper decision making on the base of these readings. Furthermore it was revealed that the most severe failures' consequences would be created by the rupture of the biggest elements of the installation filled with hydrocarbons and methanol, as well as, rupture of the flowhead. The QRA focused on modelling the consequences of such ruptures of respectively K.O. vessel, test separator, surge tank, methanol tank, and flowhead. As a result the risk contours were created, which proved that the ruptures are not going to influence the safety of locals.

Apart from these two assessments the discussion was performed on whether the mining law is strict enough, especially concerning the appearance of hydrogen sulphide and the overall setback rules. In comparison to international standards and with knowledge about historical disaster, the Polish setback rules were found to be not strict enough.

Although the thesis were full of uncertainties and assumptions it has provided reliable risk picture, probably not detailed enough to place the gas detectors but that was not a goal. The results of the thesis may be used for two purposes. Firstly it may be used to question the reliability of the operator's existing safety solutions and how they are providing safety for the residents. Secondly, the government or State Mining Authority may be asked to justify the low severity of the existing law in contradiction to complexity of administrative procedures in response to results of this thesis.

If there was any possibilities to continue or improving this study, it should begin with eliminating the uncertainties and assumptions to practicable minimum. It may also be feasible to simulate the dispersion of the raw gas containing different levels of hydrogen sulphide and the required setbacks for each concentration. Any further study should focus on analysing the production installation and its implications on the overall safety. Because it is very probable that the well testing installations will be replaced by the production ones, but the surroundings will not.

There are many pros and cons of developing the shale gas industry, but undoubtedly it is a great chance for a Polish society which may be not happen again soon. If in the pursuit for the money the safety standards are not neglected, then Poland may benefit from this industry for years without negative consequences for environment or society.

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