Aging of mechanical components on a modeled offshore oil & gas platform and the influence on the risk level

– Incorporating renewals and surveillance

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Abstract: Life extension of offshore oil and gas platforms has become common as new technology has made available more oil and gas. It is often profitable to continue using an aging platform instead of deploying a new one. A common practice in quantitative risk analyses performed on aging platforms is to use constant failure rates for components and ignore a potential aging effect. This thesis intends to examine how failure rates of components change on aging platforms, how component maintenance can be incorporated in risk analyses and how the location specific fatal accident rate (LSFAR) is affected by aging. A simplified platform is defined and an analytical model on aging is developed. The model includes renewal and surveillance intervals and the failure rate increase due to aging. Together with a consequence analysis, the model yields LSFAR due to hydrocarbon releases. Calculations of LSFAR carried out with and without consideration of aging are compared. The results show that LSFAR increases at most 1 %. Thus, the practice of using constant failure rates on aging platforms cannot be rejected. Because the results are based on interpolated failure data, it is associated with uncertainties. To reduce these uncertainties, case specific data should be gathered.

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Sammanfattning

Det har blivit allt vanligare att olje- och gasplattformar (OOG-plattformar) i Nordsjön används längre än deras designade livslängd. Ny teknologi har gjort tillgänglig olja och gas som tidigare varit svår att utvinna. Det är ofta mer lönsamt att förlänga en plattforms livslängd än att installera en helt ny.

Ett vanligt tillvägagångssätt i kvantitativa riskanalyser (QRA) som utförs på åldrande plattformar är att använda konstanta felfrekvenser för komponenter. Eventuell inverkan av åldrande på felfrekvensen tas inte hänsyn till. Denna uppsats ämnar därför undersöka:

- hur felfrekvensen för mekaniska komponenter på en sådan plattform påverkas av åldrande,
- hur utbyte och tillsyn av komponenterna kan integreras i framtida QRA, och
- hur den platsspecifika dödsfallsfrekvensen (LSFAR) påverkas av åldrande.

För att besvara frågeställningarna så utformas en förenklad, teoretisk plattform så representativt som möjligt. Plattformen är en bemannad ”fixed topside”-produktionsplattform belägen i Nordsjön. Efter att plattformen har utformats utvecklas en analytisk modell för hur otillförlitligheten ökar för åldrande OOG-komponenter. I modellen integreras också utbyten och tillsyn av komponenterna. Tillsammans med en konsekvensanalys beräknas sedan LSFAR-bidraget från kolväteutsläpp. De slutliga LSFAR-värdena, beräknade med och utan hänsyn till komponenters åldrande, jämförs sedan.

I denna uppsats var det inte möjligt att besvara hur felfrekvensen för mekaniska komponenter på en OOG plattform påverkas kvantitativt av åldrande på grund av att relevant data saknades. Emellertid går det kvalitativt att säga att felfrekvensen i teorin ska vara Weibull-fördelad med en β-parameter mellan 2 och 4. För att kunna uppskatta hur felfrekvensen för OOG-komponenter påverkas av åldrande behövdes en interpolering göras med data taget från kärnkraftskomponenter (NPP-komponenter). Denna interpolering bedöms vara den största källan till resultatens osäkerhet men kan undvikas om relevant data finns tillgänglig. Resultaten visar att LSFAR-värdena ökar som mest 1 % på grund av åldrande. En känslighetsanalys genomfördes som istället visade en ökning på som mest 3 %. De små ökningarna av LSFAR-värdena indikerar att åldrande komponenters påverkan på LSFAR är försumbar. Därmed är det inte möjligt att säga huruvida det är korrekt eller inte att använda konstanta felfrekvenser för komponenter i framtida QRA.

I den här uppsatsen föreslås hur utbytes- och tillsynsintervall (underhåll) med hjälp av den analytiska modellen kan integreras tillsammans med åldersberoende felfrekvenser i framtida QRA.

Summary

Life extension of offshore oil and gas (OOG) platforms in the North Sea has become increasingly common. New technology has made available oil and gas that was previously unrecoverable. It is often more profitable to extend the service life of an aging platform instead of deploying a new one.

A common practice in quantitative risk analyses (QRA) performed on aging platforms is to not consider the effect of aging on component failure rate. Instead, constant failure rates for new components are generally used. The intention of this thesis is to examine:

- how the failure rates of mechanical components on such a platform are affected by aging,
- how component renewal and surveillance can be incorporated into future QRA, and
- how the location specific fatal accident rate (LSFAR) is affected by aging.

In order to answer these questions a simplified yet representative platform is defined. The platform is a manned, fixed, topside production platform situated in the North Sea. Further, an analytical model on aging of mechanical components is developed. The model incorporates the failure rate increase due to aging of such components. Renewal and surveillance intervals are also included in the model. The model, together with a consequence analysis, yields the location specific fatal accident rates (LSFAR) due to hydrocarbon releases. The LSFAR values are then compared to the LSFAR values calculated without taking aging into account.

It was not in this thesis possible to answer how the failure rates of mechanical components on an OOG platform was affected quantitatively by aging because the relevant data could not be found. However, qualitatively it can be said that the failure rates of the components in theory should be Weibull-shaped with a β-parameter value between 2 and 4. Because quantitative data for OOG components was scarce, an interpolation method was necessary to develop in order to estimate the failure rate increase due to aging. Data for the interpolation was taken for nuclear power plants (NPP) components. This interpolation method is believed to be the largest uncertainty with the results but can be avoided if the relevant data is available. The results show that the LSFAR values increase at most 1 % as a result of aging. A sensitivity analysis was conducted which yielded a higher but still small increase at 3 %. This small increase indicates that the influence of aging of components on the LSFAR values is negligible. It is therefore not possible to say that the practice of using constant failure rates in QRA performed on aging platforms is incorrect.

In this thesis it is suggested how component renewal and surveillance intervals (maintenance) can be incorporated along with failure rate increase due to aging in future QRA by using the developed model.

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Contents

Abbreviations

Abbreviation	**Description**
OOG	Offshore Oil and Gas
QRA	Quantitative Risk Analyses
FAR	Fatal Accident Rate
LSFAR	Location Specific Fatal Accident Rate
NUI	Normally Unmanned Installations
ESD system	Emergency Shut-Down System
HAZOP study	Hazard and Operability Study
Dow F&EI	Dow Fire and Explosion Index
PLL	Potential Loss of Life
LL	Loss of Life
$\mathbf{POB_{average}}$	Average number of Persons On Board
NPP	Nuclear Power Plants

Denotations

Denotation	Description	Units
$\boldsymbol{R(t)}$	Reliability	$[-]$
$\boldsymbol{Q(t)}$	Unreliability	$[-]$
$\boldsymbol{\lambda(t)}$	Failure rate	$[h^{-1}]$
$\boldsymbol{\beta}$	Shape factor in the Weibull distribution	$[-]$
$\boldsymbol{\alpha}$	Characteristic life in the Weibull distribution	$[-]$
$\boldsymbol{\gamma}$	Location parameter in Weibull distributions	$[h]$
$\Delta \boldsymbol{q(t)}$	Increase in unreliability	$[-]$
$\boldsymbol{L}$	Renewal interval	$[h]$
$\boldsymbol{T}$	Surveillance interval	$[h]$
$\dot{\boldsymbol{\lambda}}_{\boldsymbol{NPP}}$	The failure rate increase per year due to aging for a NPP component	$[h^{-1}y^{-1}]$
$\boldsymbol{\lambda}_{\boldsymbol{NPP}}$	The constant failure rate for a NPP component	$[h^{-1}]$
$\dot{\boldsymbol{\lambda}}_{\boldsymbol{OOG}}$	The failure rate increase per year due to aging for an OOG component	$[h^{-1}y^{-1}]$
$\boldsymbol{\lambda}_{\boldsymbol{OOG}}$	The constant failure rate for an OOG component	$[h^{-1}]$
$\dot{\boldsymbol{\lambda}}_{\boldsymbol{OOG\ Leaks}}$	The failure rate increase per year due to aging for an OOG component (leaks only)	$[h^{-1}y^{-1}]$
$\boldsymbol{\lambda}_{\boldsymbol{OOG\ Leaks}}$	The constant failure rate for an OOG component (leaks only)	$[h^{-1}]$

1. Introduction

In this chapter the topic that is to be examined is presented. Initially a background description is given. The aim and objective of the thesis is then presented and definitions and limitations are stated.

1.1 Background

Offshore oil and gas (OOG) platforms in the North Sea usually have a designed service life of nearly 20 years. In recent years, life extension of such platforms has become increasingly common. New technology has made available oil and gas that was previously unrecoverable. It is often more profitable to extend the service life of a platform instead of deploying a new one (Ersdal, 2005). The aging platform must however still fulfill the safety requirements regarding, for example, the condition of components and structure (Hokstad, Håbrekke, Johnsen & Sangesland, 2010).

Probability and consequence analysis – risk analysis – that is performed on aging platforms usually use output from maintenance and inspection undertakings as data support. Issues that have emerged and trends that can be seen are evaluated in order to decide whether or not components are still fit for duty (Oil & Gas UK, 2011). However, a common practice in quantitative risk analyses (QRA) on aging platforms is to not consider the effect of aging on component failure rate. Instead, constant failure rates for new components are generally used in the industry (D. Lundberg, personal communication, 2013-03-15). The practice might lead to incorrect estimations of the risk level. The intention of this thesis is therefore to examine to what extent aging affects the failure rates of components and how this translates into a changed risk level.

1.2 Aim and objective

The overall aim with this master's thesis is to investigate how the risk level, on a simplified model of an OOG platform, is affected by changes in failure rates due to aging of mechanical components. The risk measure of interest is the fatal accident rate (FAR) for different areas, defined as the location specific FAR (LSFAR). Only the contribution to LSFAR from hydrocarbon releases is of interest. The investigation is carried out by comparing LSFAR from a risk analysis performed using constant failure rates with LSFAR from an analysis performed taking aging and maintenance into account.

The objective is to determine if the change in LSFAR is substantial or if it is possible to use constant failure rates in a risk analysis carried out near the end or after the designed service life. The objective is also to make recommendations on how to incorporate aging and maintenance in such a risk analysis.

The specific research questions are formulated as:

1. How are the failure rates of mechanical components on the modeled platform affected by aging?

2. How can component renewal and surveillance be incorporated into future quantitative risk analyses (QRA)?
3. How is LSFAR affected by aging?

1.3 Delimitations

The platform on which the analysis is performed is a modeled, simplified, manned one. Its process components and parameters are chosen based on the experience of Rambøll Oil & Gas. They are chosen to be as representative as possible in order to get results that might be useful in practical applications. However, in order to perform a QRA on the platform, it must be known specifically which components that are present, the number of components, the operating pressure and temperature and the geometry of the platform. The hazardous events that are investigated are solely ignitions due to hydrocarbon releases. Because of this, and because some components and process steps will be omitted in the analysis, the results must be read with caution. What the modeled platform comprises and excludes is more thoroughly explained in Section *3.1.2 The modeled OOG platform*.

The modeled platform only covers topside process operations, see Figure 1, and not subsea, structural or well parts. It is assumed to be located in the North Sea. This might have implications on what type of degrading effects (wind speed, temperature, humidity) the platform is subject to.

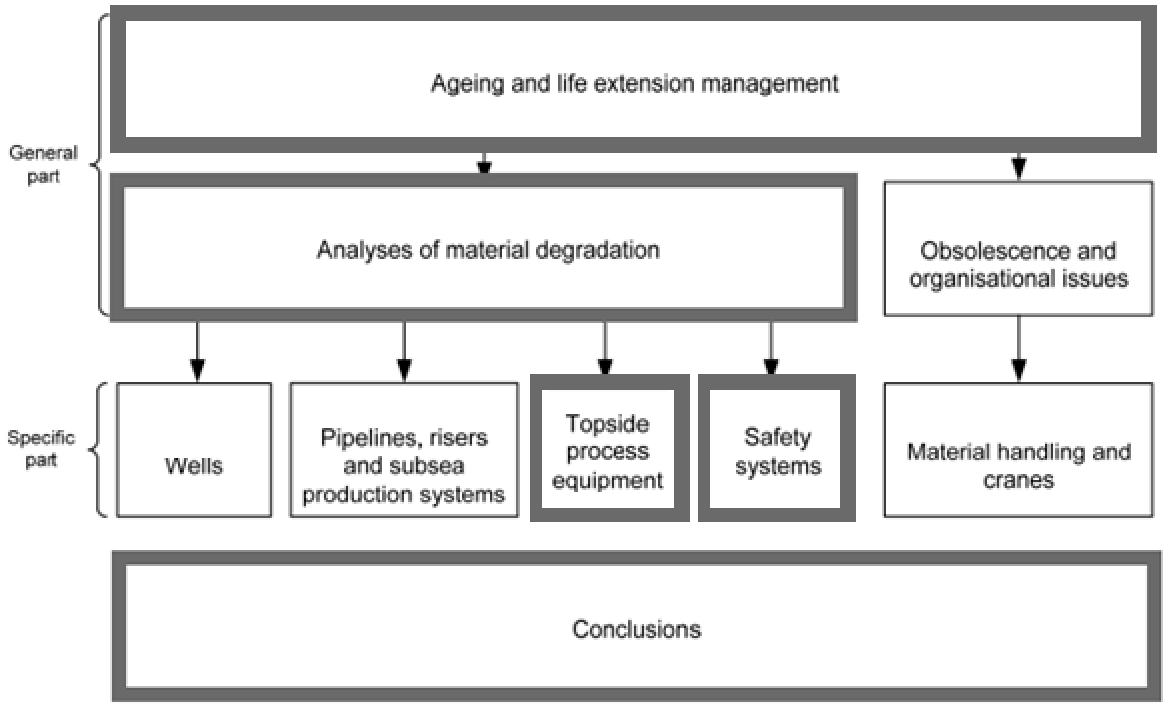

Figure 1. The emphasized areas show which parts that are included in the investigation. The other areas are not included. (Hokstad et al., 2010, p. 13)

Although aging related issues might also include changes in for example work environment, organization, laws, guidelines, economics and knowledge (Oil & Gas UK, 2011), these areas are not investigated. Neither is the potential change in environmental risk.

2. Method

The method used in this thesis is described in two different parts. The first part describes the scientific method and the second part the intended workflow of the project.

2.1 Scientific methods

Rather than using one specific method, it is common to combine and adapt different scientific methods to fit a project (Ejvegård, 2009). This thesis combines a case study with the building of a theoretical model. Figure 2 shows the steps of the method and each step is then elaborated on.

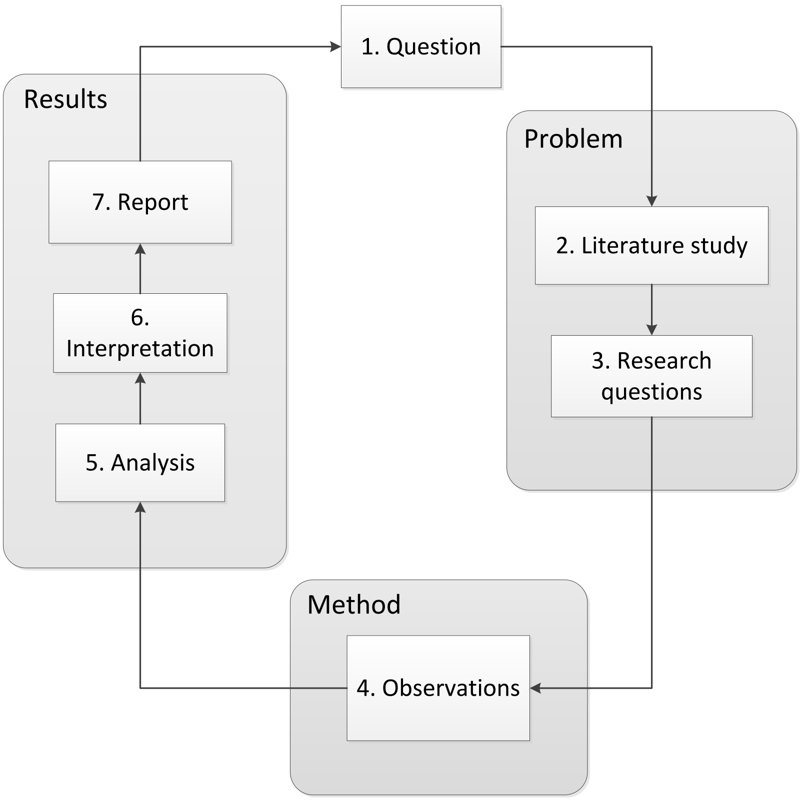

Figure 2. An illustration of the scientific method used in this thesis.

Research always starts with a *question* (1) initiated by researchers or external persons. The question itself leads to a number of sub questions and a search for more knowledge. The ability to ask the right questions is a difficult but important part of the research (Backman, 2008).

The next step of the process initiates the problem phase. A *literature study* (2) must be performed before the actual research work takes place. The literature study examines earlier research in the same field and helps to formulate appropriate research questions. The quality of the research can be dependent on the quality of the literature study (Backman, 2008). Using primary sources and a critical approach when reviewing these sources, high credibility can be gained (Backman, 2008; Ejvegård, 2009).

The question that starts the entire process is often vague and not easy to use in the further study. More accurate *research questions* (3) are desirable. The research questions should be as precise as possible and diffuse concepts need to be defined (Backman, 2008). The specific research questions of this thesis are presented in Section *1.2 Aim and objective*.

During the method phase *observations* (4) are made. This step includes collection of relevant data and can be done by for example performing tests, questionnaires, interviews, experiments, quasi experiments or direct observations. One or several methods that fit the specific research are selected (Backman, 2008). The data for this thesis is mainly compiled from literature studies of relevant databases. Statistical theory and expert judgments are then used to process the data. A model on aging is then developed and used in scenarios with different renewal and surveillance intervals.

When data has been collected, *analysis* (5) of the data is performed. This can be done with statistical tools for both quantitative and qualitative data. The main purpose of this step is to make the collected information interpretable and relate it to the research questions (Backman, 2008).

In the next step, the *interpretation* (6) of the results is performed and conclusions are drawn. Similar data from the *analysis* (5) step does not necessarily lead to the same interpretation by different researchers (Backman, 2008).

The process is finished when the entire research process is documented and made available to others through a written *report* (7).

2.2 Workflow

The workflow of this thesis is presented in Figure 3 and is then described in detail.

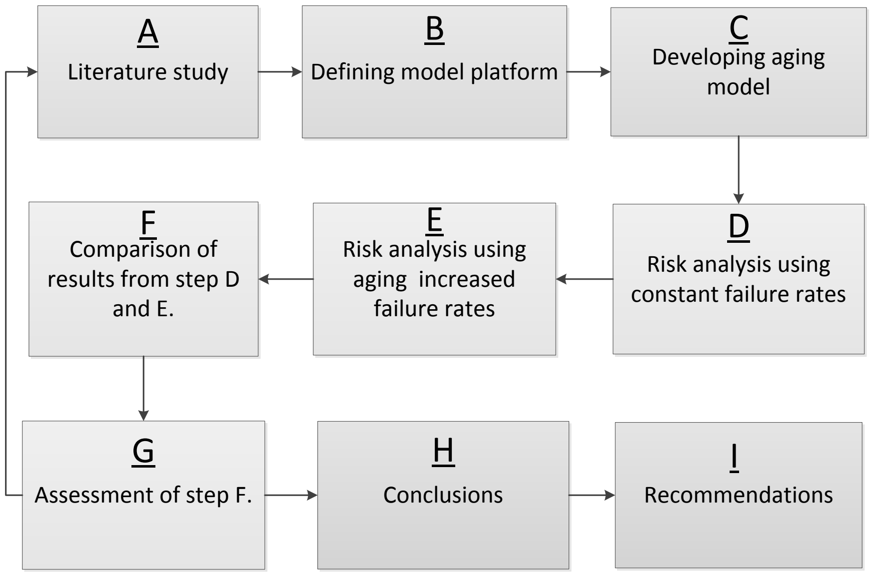

Figure 3. An illustration of the workflow in this thesis.

Literature (A) on failure rates of mechanical components is studied. Theory on component aging and its application on OOG platforms are also studied. Literature is searched for in scientific databases such as *LUBSearch* and *Google Scholar*. In the next step, a simplified but realistic topside OOG *platform (B)* is modeled. The selection of process components and process parameters is done in cooperation with Rambøll Oil & Gas. An analytical model on how the failure rates of OOG components are affected by *aging (C)* is then developed. The model incorporates renewal and surveillance intervals of the components.

In the next step, a risk analysis using *constant failure rates (D)* is performed on the modeled platform and LSFAR is calculated. This risk analysis is followed by a similar risk analysis using *aging increased failure rates (E)* instead. The results from the risk analyses are then *compared (F)* qualitatively: what methodological differences have emerged, and quantitatively: how much has LSFAR changed?

After the comparison, an *assessment (G)* is made. What are the implications? Are the results reasonable? Possible errors are identified and step A-F are performed again if necessary. Further, what *conclusions (H)* can be drawn? Finally, what *recommendations (I)* can be given regarding the effects of aging in future risk analyses? Suggestions on further research are also given.

3. Theory

In this chapter the theoretical foundation of the thesis will be presented by defining and discussing relevant concepts. The chapter is based on theories and information obtained from the literature study and from Rambøll Oil & Gas. Initially, theory on OOG platforms and the modeled platform is presented. The application of risk analysis on OOG platforms along with theory on reliability, sensitivity analysis, aging and more advanced mathematics are then presented.

3.1 OOG platforms

This section describes OOG platforms in general and some common platform types in detail. At the end of the section, the modeled, simplified platform used in the thesis is described.

3.1.1 General description of OOG platforms

There are several different types of platforms in the OOG industry. The platforms can differ in many ways depending on where the platform is situated, if it is a producing platform or a platform designed for accommodation, if the platform produces oil and gas or just one of them and so on. All these factors define the structure of the platform and its process components (Oil & Gas UK). Differences between platform types are for example:

- *Fixed or floating platform:* The structure of the platform is dependent on the location. In shallow water, the platform can be physically fixed to the bottom of the ocean by concrete columns or steel jacket structures, see Figure 4. Floating or semi-submersible platforms are used in deep water and they can be held in place by anchored chains or propellers (Oil & Gas UK).

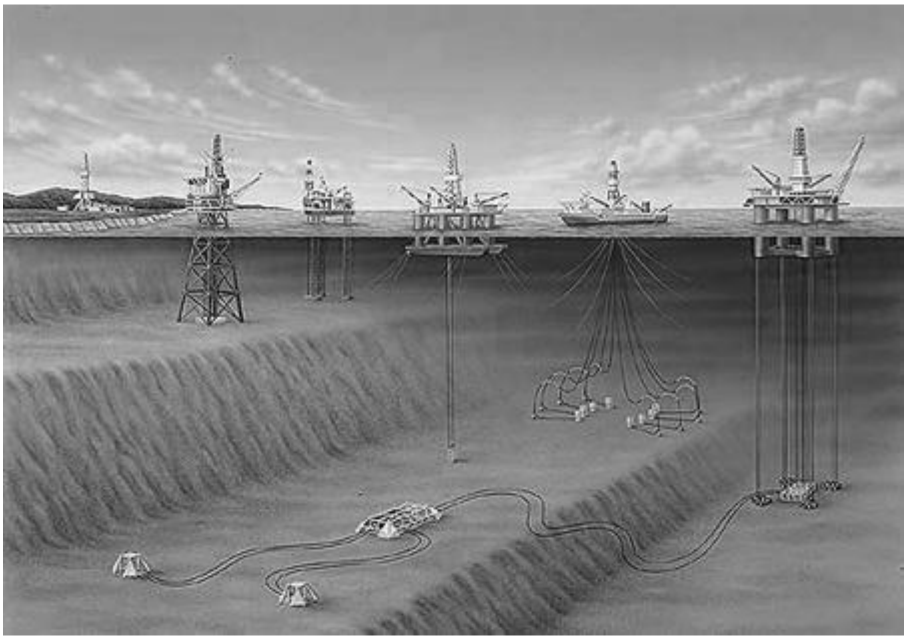

Figure 4. Illustration of fixed and floating OOG platforms. Subsea installations are also presented (Oil Spill Solutions).

- *Topside or subsea:* The well can be placed either on the seabed, see Figure 4, or above sea level on the platform itself. If the well is located on the seabed, the installation is called subsea, and if not, it is called topside. Subsea installations can consist of a network of connected wells serving one production platform (Oil & Gas UK).
- *Manned or unmanned:* On large platforms the most common solution is to place an accommodation area on the production platform itself. The staff is then flown to the platform and back home again days later. This type of platform is referred to as a manned one. There are also platforms that mainly consist of automatic installations where the staff is only needed occasionally for maintenance purpose. These types of platforms are denoted normally unmanned installations (NUI). The staff on these installations is accommodated on other platforms (Oil & Gas UK).
- *Storage or pipeline:* Another difference between different types of OOG platforms is whether the platform can store oil on site or if the oil is directly transported onshore through pipelines.

3.1.2 The modeled OOG platform

The OOG platform used in this thesis is a modeled, simplified, manned one. It is based on experience from Rambøll Oil & Gas. Although the aim is to investigate a representative platform, the modeled one has to have specific point values on for example the number of components and component types in order to be able to perform a QRA in later chapters. In this section, an overview of the platform layout is initially given. Then, the process steps are explained. Lastly, a brief explanation of the safety concepts is given. The source of information for this entire section is Rambøll Oil & Gas (D. Lundberg & L. Wahl Andersen, personal communication, 2013-06-27) if nothing else is stated.

Layout

The platform is a manned, fixed platform situated in the North Sea. An image of this type of platform is presented in Figure 5.

Figure 5. An example of a manned, fixed OOG platform situated in the North Sea (D. Lundberg & L. Wahl Andersen, personal communication, 2013-06-27).

The platform is attached to the seabed by large concrete and/or steel columns. Due to the immobility, such platforms are often designed for long term use and can thus be subject to life extension. The hull of the platform, which is placed on the large concrete/steel columns, is divided into different areas, see Figure 6. The areas of the hull are accommodation and escape, separation and processing of oil and gas, helideck (landing pad for helicopters) and wellhead area where drilling and production of oil and gas takes place. The helideck area is omitted from the further analysis.

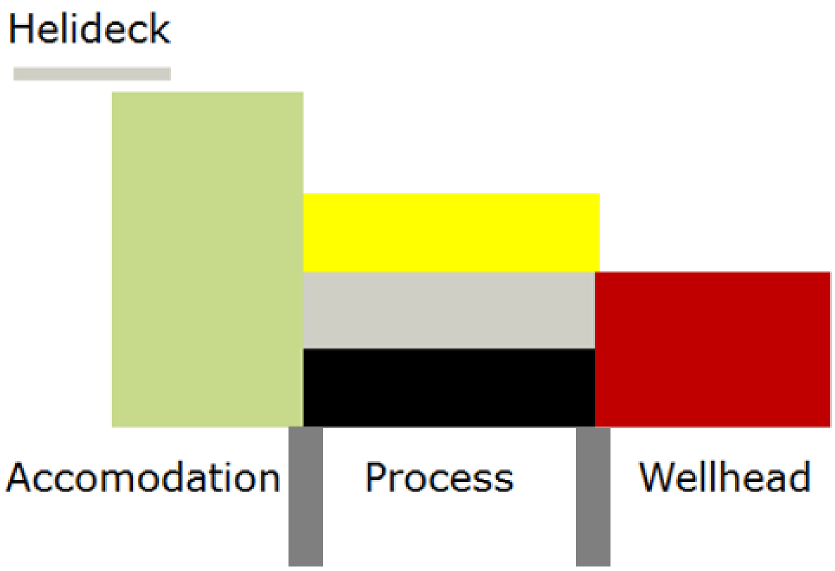

Figure 6. Illustration of the simplified layout of the modeled OOG platform (D. Lundberg & L. Wahl Andersen, personal communication, 2013-06-27).

The total area of the platform is modeled as 60 meters long, 40 meters wide and 7 meters high. All areas are assumed to have the same width. Further, the wellhead and process area are 22.5 meters long each and the accommodation area is 15 meters long.

The manning distribution of the modeled platform, divided between the three described areas, is presented in Table 1. The table also presents the number of people that reside in the different areas during day and night time.

Table 1. Manning distribution of the modeled platform divided between the different areas.

Area	Number of people (day)	Number of people (night)
Accommodation area	40	47
Process area	10	5
Wellhead area	5	3

Accommodation area: When the people on board are not working they are in the accommodation area. The area consists of cabins, showers and toilets, dining room, gym, lounge and recreational areas. Depending on the size of the platform and the number of people working there, other facilities can also be present in the accommodation area. Working stations, for example surveillance rooms and laboratories, can also be present.

An escape area, also called muster area, is located inside the accommodation area. It is the area where the people on board are gathered before evacuation in case of emergency. If evacuation through helicopter is not possible due to for example time constraints, evacuation can be conducted by falling life boats, life rafts and escape chutes.

In order to protect the people residing in the accommodation area, firewalls and blast walls separate the accommodation area from the process area.

Process area: The oil and gas enters the process area from the wellhead area at high temperature and high pressure, mixed up with water, sand and other impurities. The mix can be highly corrosive. Before it is exported from the platform through pipelines it is transported through a number of separation processes inside the process area. The process components can be spread over several floors of the platform. Gas processing is performed on the higher floors, the yellow area in Figure 6, and oil processing is performed on the lower floors, the black area in Figure 6. A more detailed description of the process area is given further on in this section.

Wellhead area: Drilling processes on the seabed are linked with the process activities on the platform through the wellhead area. The two main functions of this area are structural support and pressure containment/control. Casings running from the platform down to the wells on the seabed are attached to the wellhead area and can act as structural support. A mixture of oil and gas is transported inside these casings. The second main function, pressure containment/control, can be attained with a so called "X-mas tree". This and other safety concepts are explained in more detail towards the end of this section. The components that are present in the wellhead area are presented along with their constant failure rates for different leak sizes in Table 2.

Table 2. Components in the wellhead area and corresponding constant failure rates for three different leak sizes.

Component	Number of items	Failure rate for different leak sizes $[h^{-1}]$		
		<10 mm	10-25 mm	>25 mm
Pipes	425 meters	1.94E-08 $[h^{-1}m^{-1}]$	3.42E-09 $[h^{-1}m^{-1}]$	1.14E-09 $[h^{-1}m^{-1}]$
Instruments	160	5.48E-08	6.85E-09	0.00E+00
Flanges	470	2.05E-08	2.28E-09	1.14E-09
Manual valves	330	1.94E-08	4.57E-09	1.14E-09
Actuated valves	50	1.16E-07	1.83E-08	3.42E-09

Process description

An overview of the steps in the process area is presented in Figure 7. A more detailed flow chart (yet simplified) is presented in Appendix A.

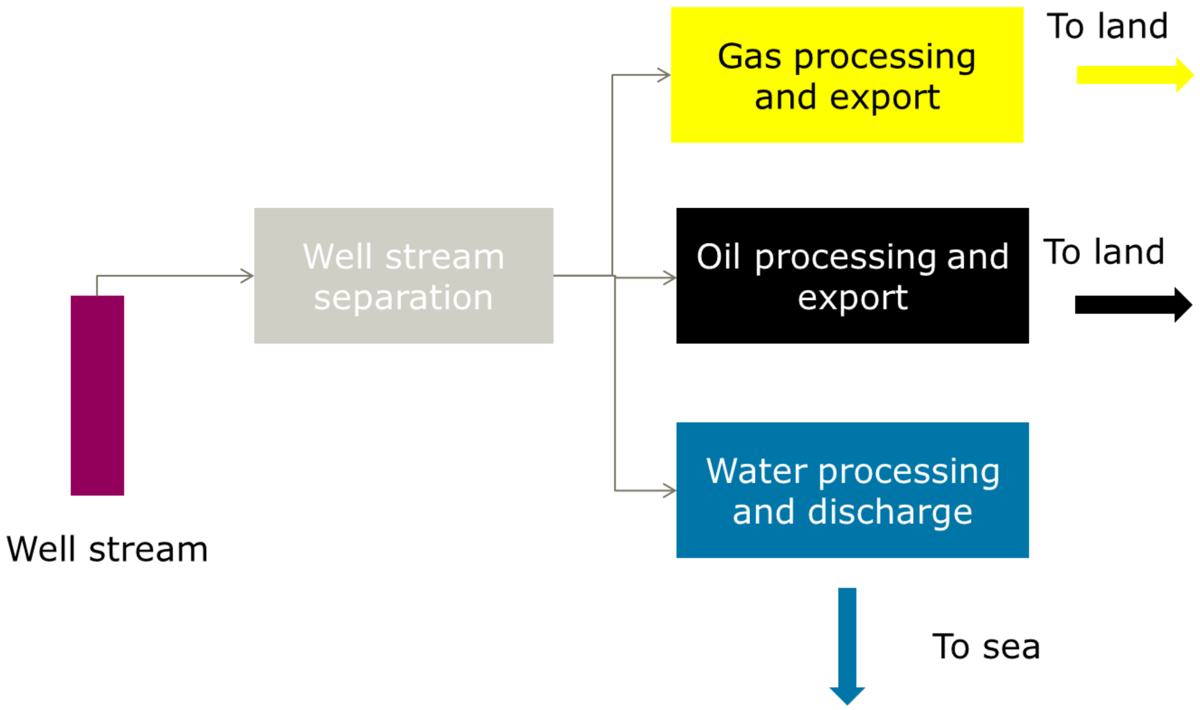

Figure 7. An overview of the steps in the process area (D. Lundberg & L. Wahl Andersen, personal communication, 2013-06-27).

The processing steps can be grouped into:

- Well stream separation
- Gas processing and export
- Oil processing and export
- Water processing and discharge

Well stream separation: The well stream entering the platform consists of oil, gas, water and impurities, for example sand and chemicals. Before exporting the oil and gas ashore, the flow has to be separated and purified. The incoming well stream can be of high temperature/pressure and highly corrosive and if it is not separated and purified the process components and offshore pipelines can be damaged.

The separation process consists of three different stages. Sand is removed in the first stage, gas with oil and water as vapor is partly removed in the second stage and the remaining gas is finally removed, through temperature and pressure regulation, in the third stage. A detailed step by step description of the separation process is presented in Figure 8.

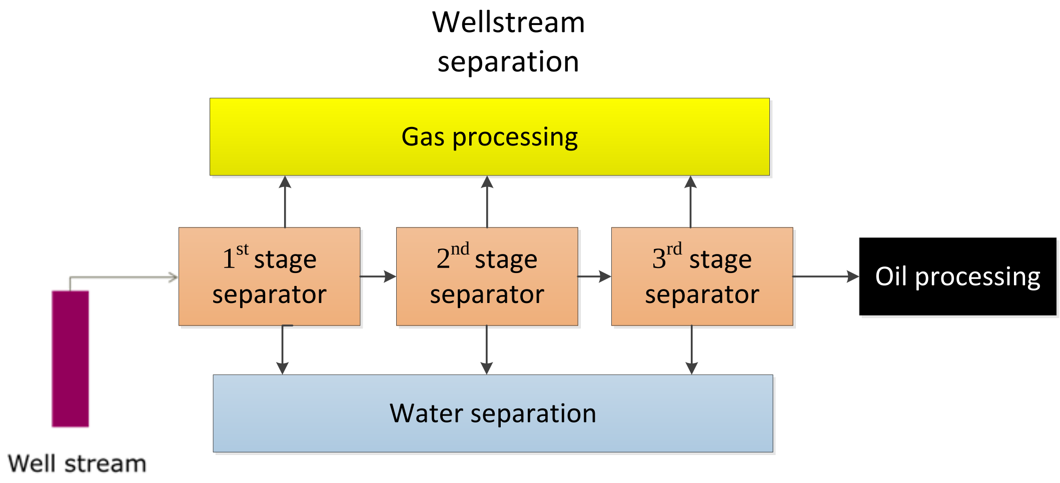

Figure 8. The separation process.

- The incoming well stream flow cools and passes through the 1st stage separator.
- Gas, with a content of oil and water vapor, is separated from the well stream flow in the 1st stage separator and directed to the gas processing. Excessive water is separated from the stream.
- The remains are directed to the 2nd stage separator.
- Gas, with a content of oil and water vapor, is separated from the remains in the 2nd stage separator and directed to the gas processing. Excessive water is separated from the stream.
- The remains from the 2nd stage separator are directed to the final 3rd stage separator.
- Gas, with a small content of oil and water vapor, is separated from the remains in the 3rd stage separator and directed to the gas processing. Excessive water is separated from the stream.
- The remaining, almost pure oil is directed to the oil processing.

The components used in the well stream separation along with the corresponding constant failure rates for three different leak sizes are presented in Table 3.

Table 3. Components in the well stream separation and corresponding constant failure rates for three different leak sizes.

Component	Number of items	Failure rate for different leak sizes $[h^{-1}]$		
		<10 mm	10-25 mm	>25 mm
Centrifugal pumps	2	7.19E-07	6.05E-08	1.60E-08
Filters	2	3.08E-07	4.79E-08	3.08E-08
Pressure vessels	6	1.26E-07	2.51E-08	1.48E-08
Heat exchanger (type: hydrocarbon tube)	3	2.74E-07	4.91E-08	3.08E-08
Pipes	280 meters	1.94E-08 $[h^{-1}m^{-1}]$	3.42E-09 $[h^{-1}m^{-1}]$	1.14E-09 $[h^{-1}m^{-1}]$
Instruments	50	5.48E-08	6.85E-09	0.00E+00
Flanges	370	2.05E-08	2.28E-09	1.14E-09
Manual valves	180	1.94E-08	4.57E-09	1.14E-09
Actuated valves	20	1.16E-07	1.83E-08	3.42E-09

The operating pressure and temperature of the three separators are presented in Table 4.

Table 4. A list of operating pressures and temperatures for the three separators.

Separator	Pressure $[bar]$	Temperature $[°C]$
1st stage	30	70
2nd stage	7	60
3rd stage	1,5	40

Gas processing and export: The gas flow, still containing oil and water as vapor, leaves the separation process with a decrease in pressure. The pressure, however, has to be increased again in order to be able to export the gas ashore through offshore pipelines. It also has to be purified even more through a number of processes. A step by step description of the gas processing and export phase is presented in Figure 9.

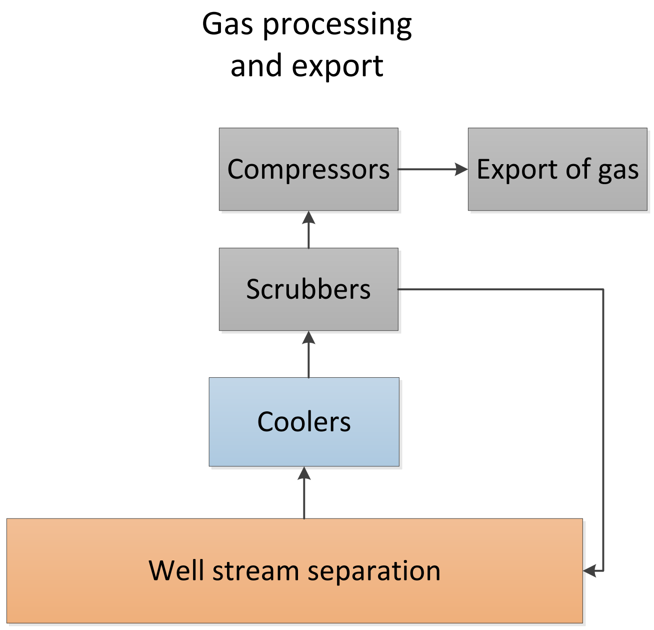

Figure 9. Gas processing and export.

- Gas, with a content of oil and water vapor, from the 1st, 2nd and 3rd stage separators is cooled through several coolers.
- Oil and water are condensed to liquid and then removed by several scrubbers.
- The gas is compressed and directed to pipelines for transportation ashore.
- The removed and condensed oil and water reenters the separation process.

The components and corresponding constant failure rates for different leak sizes used in the gas processing and export are presented in Table 5.

Table 5. Components in the gas processing and export with corresponding constant failure rates for three different leak sizes.

Component	**Number of items**	**Failure rate for different leak sizes $[h^{-1}]$**		
		<10 mm	**10-25 mm**	**>25 mm**
Filters	1	3.08E-07	4.79E-08	3.08E-08
Centrifugal compressors	5	9.59E-07	9.93E-08	4.11E-08
Pressure vessels	9	1.26E-07	2.51E-08	1.48E-08
Heat exchanger (type: hydrocarbon tube)	5	2.74E-07	4.91E-08	3.08E-08
Pipes	1315 meters	1.94E-08 $[h^{-1}m^{-1}]$	3.42E-09 $[h^{-1}m^{-1}]$	1.14E-09 $[h^{-1}m^{-1}]$

Instruments	160	5.48E-08	6.85E-09	0.00E+00
Flanges	1100	2.05E-08	2.28E-09	1.14E-09
Manual valves	705	1.94E-08	4.57E-09	1.14E-09
Actuated valves	60	1.16E-07	1.83E-08	3.42E-09

An amount of 76 million standard cubic feet gas per day is exported at a pressure of 110 bar.

Oil processing and export: In the same way as the gas flow, the oil flow also leaves the separation process with a reduced pressure. Long offshore pipelines are used for transportation ashore and the pressure therefore has to be increased again. This is performed by pumping the oil through several booster pumps and export pumps. The oil also needs to go through a purifying process.

The components and corresponding constant failure rates for different leak sizes used in the oil processing and export are presented in Table 6.

Table 6. Components in the oil processing and export with corresponding constant failure rates for three different leak sizes.

Component	Number of items	Failure rate for different leak sizes $[h^{-1}]$		
		<10 mm	10-25 mm	>25 mm
Centrifugal pumps	4	7.19E-07	6.05E-08	1.60E-08
Filters	4	3.08E-07	4.79E-08	3.08E-08
Pipes	200 meters	1.94E-08 $[h^{-1}m^{-1}]$	3.42E-09 $[h^{-1}m^{-1}]$	1.14E-09 $[h^{-1}m^{-1}]$
Instruments	30	5.48E-08	6.85E-09	0.00E+00
Flanges	180	2.05E-08	2.28E-09	1.14E-09
Manual valves	105	1.94E-08	4.57E-09	1.14E-09
Actuated valves	5	1.16E-07	1.83E-08	3.42E-09

An amount of 35000 barrels of oil per day is exported at a pressure of 49 bar.

Water processing and discharge: 2000 m^3 to 7000 m^3 water can be separated from the well stream every day. Due to the mixture of impurities, the water needs to go through a purifying process before it is pumped back to the sea.

Safety concepts

Several safety systems designed to prevent major accidents are installed on the platform. The different types of systems are:

- Passive fire protection
- Active fire protection
- Release detection
- Emergency shut-down
- Overpressure protection

Passive fire protection: The different areas on the platform are protected with firewalls and blast walls of type H-0. These passive protection walls are used to prevent escalation of fires from area to area, and are designed to function for 60 minutes (Dura Systems). Blast walls and firewalls are installed between the process area and the wellhead area as well as between the process area and the accommodation area. Other area borders are solely protected with firewalls. Important components and load bearing structures inside the areas are also protected with passive fire protection, for example fire protection coating.

Active fire protection: Active fire protection systems (detection and activation) are also installed on the platform. The detectors include heat detectors, smoke detectors and flame detectors which activate systems such as water deluge, water cooling or foam deluge. Besides the direct firefighting function, active systems also alert the staff by audible and visible alarms. Portable fire extinguishers are deployed on the platform.

Release detection: Critical levels of gas from leakages can ignite and cause large explosions on the platform. To prevent these consequences, several gas detectors are deployed in places where gas can accumulate, where leakages often occur and in the ventilation inlets. The process will be shut-down if a gas detector detects critical levels of gas and both audible and visible alarms will alert the staff. Besides the fixed installations, most of the staff also carry portable gas detectors.

Emergency shut-down: There is an emergency shut-down system (ESD system) installed on the platform consisting of several actuated valves. The system can isolate different sections or stop the whole platform process in case of a leakage of oil or gas. Activation of the ESD system can be done manually or automatically. The functions of the system include, besides the shut-down function of hydrocarbons itself, also shut-down of electricity and initiation of evacuation and firefighting.

Overpressure protection: One of the two main functions of the wellhead area is, as described earlier, containment/control of the pressure. To prevent a blow-out, i.e., an uncontrolled release of hydrocarbons due to fail of pressure control, a so called "X-mas tree" is installed on top of the wellhead or well/wells. It is a piece of equipment with actuated isolation valves and actuated choke valves designed to control the flow and pressure of the oil and gas.

3.2 Risk analysis

The definition of risk is traditionally, and in this thesis, the combination of probability and consequence of a certain hazardous event. Risk analysis is the systematic identification and estimation of such events. The purpose of the estimation is to measure the risk level, quantitatively or qualitatively (Harms-Ringdahl, 2004).

3.3 Risk analysis applied on OOG platforms

OOG platforms are similar to their onshore counterpart except for their higher vulnerability. The process area is smaller and the ventilation and escape routes are limited, enabling small errors to lead to disasters. The most dangerous steps are transportation and drilling followed by, what is partly analyzed in this thesis, process operation. Risks that are present can be divided into five categories: process related, dropped objects, structural failures, helicopter accidents and ship collisions (Khan, Sadiq & Husain, 2002).

The identification of hazards can be performed using methods such as HAZOP (Hazard and Operability) studies, what-if analysis, DOW F&EI (Fire and Explosion Index) and quantitative hazard identification. Since it is unfeasible to identify and quantify all hazards, it is important to locate where the major risks are. When the possible consequences and their probabilities are known, it is possible to estimate the individual risk that the workers on the OOG platform are exposed to (Khan et al., 2002). A common way, especially in the North Sea, to estimate the individual risk is to calculate the FAR value. FAR states how many fatalities that are expected per 10^8 exposed hours and can be calculated with Equation 1 (Holand, 1997; Vinnem, 2007):

$$FAR = \frac{PLL \cdot 10^8}{Exposed\ hours} = \frac{PLL \cdot 10^8}{POB_{average} \cdot 8760}$$

Equation 1

The FAR value can be calculated for the entire platform as well as for specific locations (LSFAR). Potential Loss of Life (PLL) is the number of expected fatal accidents during a period of time, usually one year. For OOG platforms the exposed hours can be based on the working hours (12 hours per day) or the total hours spent on the platform (24 hours per day). The average number of persons on board ($POB_{average}$) can be specified for the entire platform or different areas (Vinnem, 2007). The contribution to FAR from hydrocarbon leaks is often between two to four (Rambøll Oil & Gas, D. Lundberg & L. Wahl Andersen, personal communication, 2013-06-27).

3.4 Sensitivity analysis

A sensitivity analysis is an often required element of a risk analysis. The sensitivity analysis is a structured method to describe and calculate how the final results of the risk analysis are affected by changes in the input data (Davidsson, Haeffler, Ljundman & Frantzich, 2003). The most important variables can be identified and uncertainties with these variables can be investigated further. The input variables can be uncertain for many reasons; natural variation of the variables, lack of knowledge of the variable or uncertainties with the model itself. It can be difficult to do anything about the uncertainties but it is important to know that they exist, present them and discuss their potential effects.

If a specific variable has a great impact on the final result, the values of this variable can be altered between justifiable boundaries. The boundaries can for example be the upper or lower percentiles of the variable values. After these alterations have been carried out, something can be said about the robustness of the results (Davidsson et al., 2003).

3.5 Reliability theory and failure distributions

Reliability theory is of interest when investigating how reliable a system is. The importance of its application is growing with new complex technology. To achieve a high level of safety in a process industry it is necessary to know how long a system or component can operate without failure (Nakagawa, 2005). Reliability, denoted R, is a characteristic of components and can be defined as "The ability of an item to perform a required function under stated conditions for a stated period of time." (Naresky, 1970 p. 199). The required function must be specified before calculating the reliability. Failure can have different meanings but it is often described, also in this thesis, as a mechanical breakdown of a component. The reliability of components and systems is calculated specified durations, denoted t, and the reliability function is defined as $R(t)$ (Birolini, 2010).

The reliability can also be described by its complement, the unreliability, of the system or component. Mathematically it is defined in Equation 2 as (Lees & Mannan, 2005):

$$Q(t) = 1 - R(t)$$

Equation 2

If several items each have their own unreliability q and failures can occur independently from one another, the total unreliability of the system q_{tot} can be obtained from Equation 3 (Lees & Mannan, 2005):

$$q_{tot} = q_1 + q_2 - (q_1 * q_2)$$

Equation 3

The rate at which failures occur is also of interest when dealing with reliability. Failure rate is often denoted $\lambda(t)$ and for many practical applications $\lambda(t) = \lambda$, meaning a constant time-independent failure rate (Birolini, 2010). The reliability function, stated in Equation 4, is for constant failure rates defined as:

$$R(t) = e^{-\lambda t}$$

Equation 4

However, for mechanical components exposed to a harsh environment, the failure rate is dependent on the time in service. The reliability function, stated in Equation 5, is then defined as:

$$R(t) = e^{-\int_0^t \lambda(x)dx}$$

Equation 5

Figure 10 presents a common illustration of the failure rates of a large population of components. It is often called the bath-tub curve (Birolini, 2010). The failure rate is plotted as a function of time and changes in three different phases.

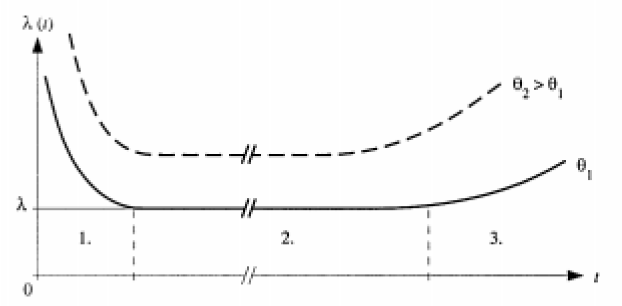

Figure 10. A common illustration of failure rates for a large population of components, called the bath-tub curve. The model is divided in three phases with different characteristics of the failure rate (Birolini, 2010, chapter 1, p. 7).

The first phase is often characterized by a larger failure rate, which can be explained by construction and installation errors as well as burn-in time. Phase two consists of a somewhat constant, lower failure rate. During phase three (wear-out phase), the failure rate increases again and this can be explained by aging, see Section *3.6 Aging.*

The phases in Figure 10 can be determined if empirical data is available. Some frequently used failure distributions are (Lees & Mannan, 2005):

The Weibull failure distribution: The Weibull distribution is presented in Figure 11. The Weibull failure rate function $z(t)$, density function $f(t)$ and reliability function $R(t)$ are defined in the following equations (Equation 6 - Equation 8):

$$z(t) = \frac{\beta}{\alpha}\left(\frac{t-\gamma}{\alpha}\right)^{\beta-1}$$

Equation 6

$$f(t) = \frac{\beta}{\alpha}\left(\frac{t-\gamma}{\alpha}\right)^{\beta-1} e^{\left[-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}\right]}$$

Equation 7

$$R(t) = e^{\left[-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}\right]}$$

Equation 8

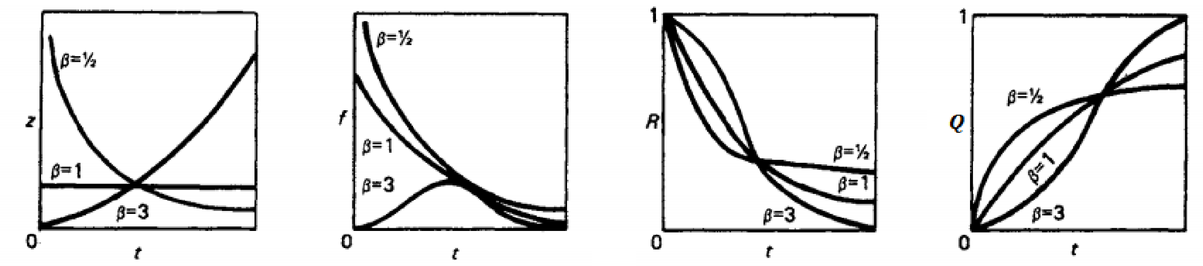

Figure 11. Weibull failure distribution. The different curves present the failure rate, failure density, reliability and unreliability as a function of time. The β-parameter is altered between 0,5, 1 and 3. (Lees & Mannan, 2005, volume 1, chapter 7, p. 15).

The Weibull distribution presented here is a three-parameter one. However, in reliability engineering the two-parameter form is often used. It is obtained by setting γ to zero. The parameter α is the characteristic life and β is the shape factor. The failure rate decreases when $\beta < 1$, becomes constant when $\beta = 1$ and increases when $\beta > 1$. The Weibull distribution is widely used in reliability engineering because of its flexibility to fit to real failure rate data (Lees & Mannan, 2005).

The Exponential failure distribution: The exponential distribution is presented in Figure 12. The Exponential failure rate function $z(t)$, density function $f(t)$, reliability function $R(t)$ and unreliability function $Q(t)$ are defined in the following equations (Equation 9 - Equation 12):

$$z(t) = \lambda t$$

Equation 9

$$f(t) = \lambda e^{-\lambda t}$$

Equation 10

$$R(t) = e^{-\lambda t}$$

Equation 11

$$Q(t) = 1 - e^{-\lambda t}$$

Equation 12

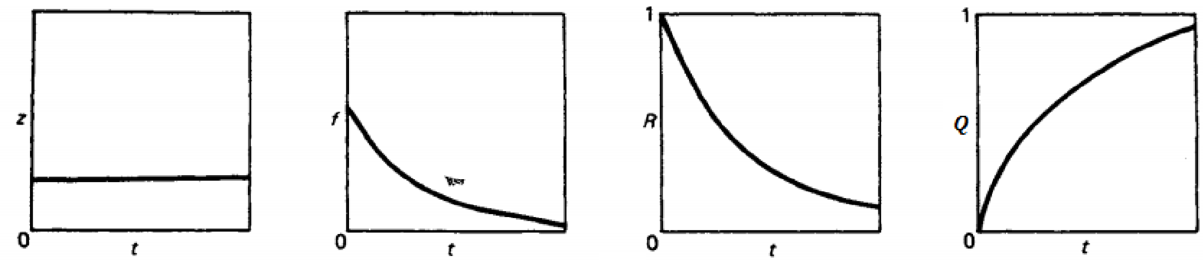

Figure 12. Exponential failure distribution. The different curves present the failure rate, failure density, reliability and unreliability as a function of time (Lees & Mannan, 2005, volume 1, chapter 7, p. 15).

The exponential distribution is a one parameter distribution characterized by a constant failure rate λ.

3.5.1 Bow-tie model

A risk analysis is, as mentioned earlier, a structured way of identifying hazardous events and quantifying the risk of the events, i.e., probability and consequence. If a quantitative approach (QRA) is used the common elements are: *identification of initiating events, cause analysis* and *consequence analysis* (Vinnem, 2007). A common way of describing and illustrating the different elements is by making a so called bow-tie diagram, presented in Figure 13.

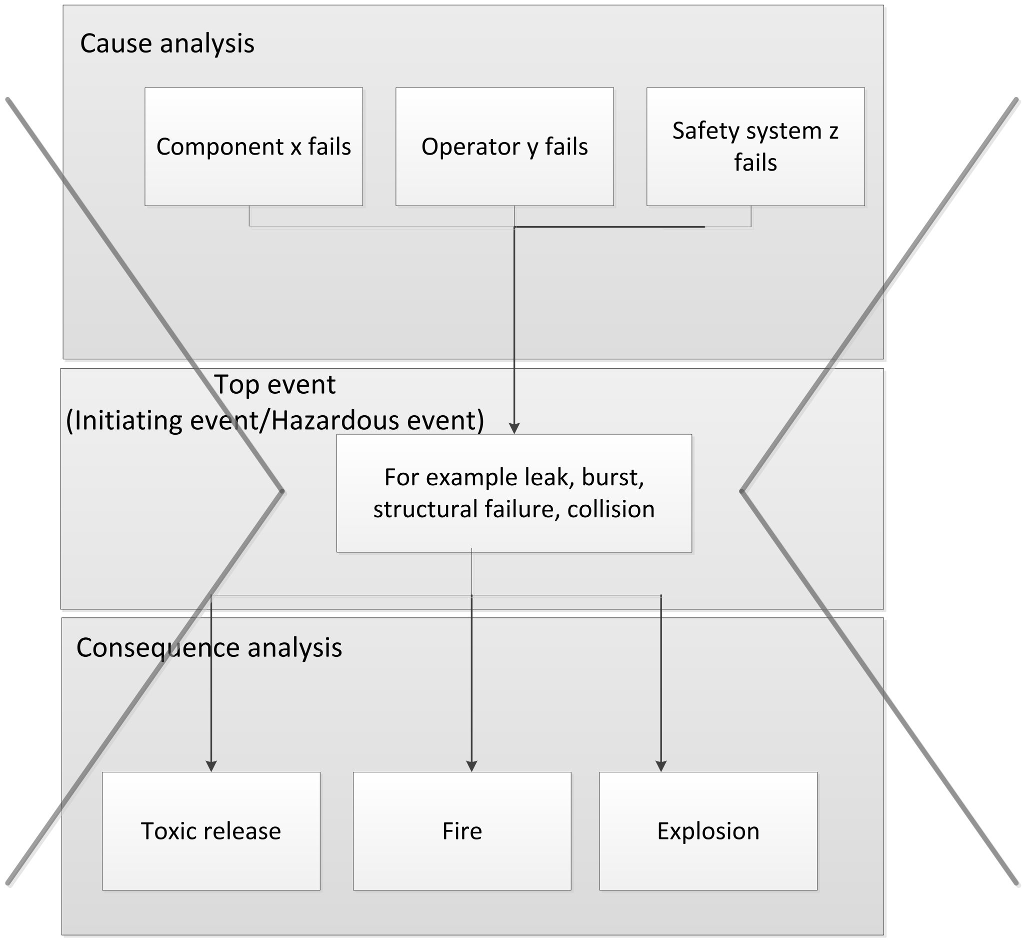

Figure 13. An illustration of a bow-tie diagram. Notice how the elements take a bow-tie shape.

The first step is the identification of hazards or initiating events. Many hazards can be found but only those hazards which have a high potential to cause damage are chosen for further analysis. A Hazard and Operability study (HAZOP) is one way of doing the identification of hazards and the selection of events. When the hazard identification is done, the cause analysis is performed. In this step, the causes that might lead to the initiating events are identified. The causes are the starting point for the whole accident sequence. In order to investigate the causes and the probabilities, a fault tree analysis can be used. The focus of the analysis is to determine how a system can reach the unwanted initiating events (also called the ”top events”). By utilizing logic trees with logic symbols it can be determined which base events (causes) that lead to the top event and what the probability for the top event is. To better illustrate the theory, a practical example is given in Figure 14.

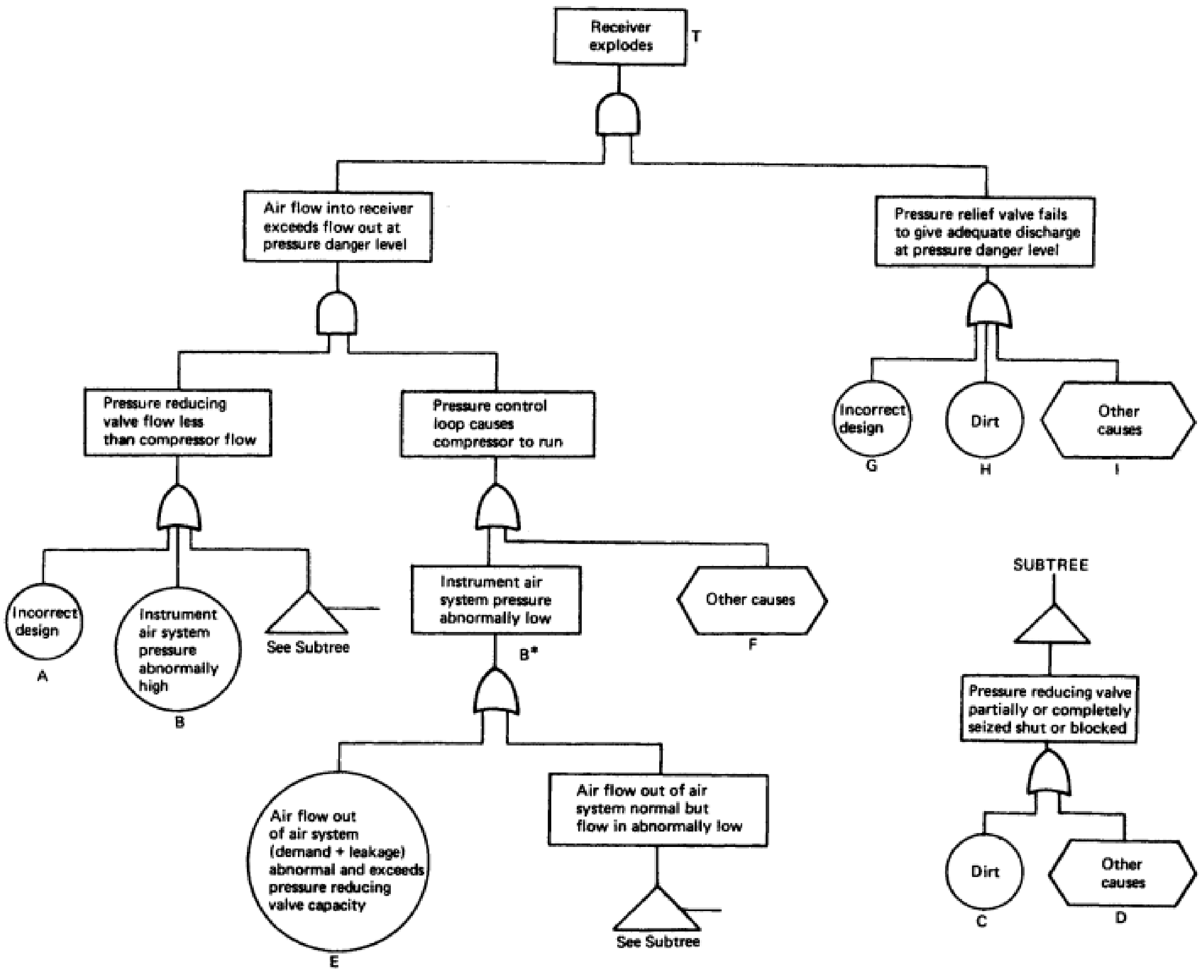

Figure 14. Example of a fault tree where the top event is an exploding air receiver. (Lees & Mannan, 2005, volume 1, chapter 9, page 19)

When the probabilities of the initiating events are calculated, the next step is to perform the consequence analysis which is illustrated by the lower part in Figure 13. The consequence analysis starts with the initiating events and investigates the possible consequences. Consequences of interest on OOG platforms can be fires from ignited hydrocarbon releases and explosions from ignition of a hydrocarbon gas cloud (Vinnem, 2007). A quantification of the consequences can be carried out by simulating the propagation and effect from fires and explosions in computer programs such as *ALOHA.*

OOG platforms often provide a number of protective barriers. The barriers are installed to prevent the initiating event from happening or to mitigate the consequence of the event. Barriers can for example be inspection, maintenance and technical safety systems (Vinnem, 2007).

3.6 Aging

Aging can be viewed as factors that over time negatively affect components or their ability to perform the desired function (Oil & Gas UK, 2011). These factors can be categorized into three different parts. The first one is *material degradation*. It is incident to operational and environmental conditions such as corrosion and wind. It also depends on material properties and how maintenance is done. The second category is *obsolescence*. New needs, changes in design or lack of spare parts make the components obsoleted. Lastly there are *organizational issues*, such as changed organization, lack of competence preserving, new requirements on competence and a heavier workload (Hokstad et al., 2010).

3.7 Mathematical theory

In this section the theory on relevant problem solving mathematics that will be used is described.

3.7.1 Least squares fitting

It is often useful to adapt a large number of observed data to a certain mathematical expression. The expression can then be used to predict new, likely forthcoming, data. The easiest way is when the data can be fitted to a linear expression (Equation 13):

$$f(x) = a + bx$$

Equation 13

However, data in reliability engineering seldom show a linear correlation. More often a nonlinear correlation can be found to which the data can be fitted, for example (Equation 14):

$$f(x) = a_1 + a_2x + a_3x^2 + \cdots + a_nx^{n-1}$$

Equation 14

The least squares method can be used to determine a_1 to a_n in Equation 14 (Riley, Hobson, & Bence, 2006). A computer program, for example *MATLAB*, can be used to determine the coefficients.

3.7.2 Simpson's rule for estimating integrals

Integrals that lack analytical solutions can be estimated using Simpson's rule, which is a numerical method that fits parabolas to the integrand function (Riley et al., 2006). The estimation can be calculated with Equation 15:

$$Integral(estimate) = \frac{1}{3}h(f_0 + f_N + 4\sum_{m\ odd} f_m + 2\sum_{m\ even} f_m)$$

Equation 15

where f represents values of the integrand function at different steps and h is the difference between the end point b and starting point a of the interval divided by the number of segmented intervals N.

The integral can be estimated with a computer program, for example *Python* with the *scipy* extension.

4. Development of an aging model

Reliability issues that can arise when components are aging as a result of life extension have been studied in the nuclear industry for many years (Kančev, Žerovnik & Čepin, 2012). An analytical model for integrating the effects of aging on component unreliability has been developed by Vesely, Kurth & Scalzo (1990). The model also incorporates renewal and surveillance intervals. Because the model is purely analytical and based on the fundamental reliability theory explained in Section *3.5 Reliability theory and failure distributions*, it is not specific to nuclear power plants (NPP). Throughout this chapter the model and its application on OOG component unreliability will be described.

4.1 Theory: Unreliability change due to aging

From Section *3.5 Reliability theory and failure distributions*, it is known that reliability is a function of the failure rate $\lambda(t)$ and that the failure rate is a function of time in service. An increased failure rate, as a result of for example aging, can thus be viewed as an increase in unreliability $\Delta q(t)$. The increase since a component is installed or renewed at time t is given by Equation 16 (Vesely et al., 1990):

$$\Delta q(t) = 1 - e^{-\int_0^t \dot{\lambda}(t) d\dot{t}}$$

Equation 16

where $\dot{\lambda}(t)$ is the failure rate increase due to aging. The increased unreliability $\Delta q(t)$ can be added to the unreliability due to the constant failure rate $q(t)$. The new unreliability consisting of both $\Delta q(t)$ and $q(t)$ can then be used in QRA where the effects of aging need to be considered. $q(t)$ may already include maintenance to some extent as its failure rate data has been collected from practical applications where maintenance has likely been carried out during the lifetime of components.

In order to also integrate the effects of maintenance, Equation 16 needs to be modified. If a component is switched to a new one every L hour, the mean value of the unreliability increase Δq during this time can be written as (Equation 17):

$$\Delta q = \frac{\int_0^L \Delta q(t) dt}{L}$$

Equation 17

Assuming that the failure rate increases linearly with a quantity a $[{}^{\frac{1}{hour}}/_{year}]$ every year

because of aging, Δq is further (Equation 18-Equation 20):

$$\Delta q = \frac{\int_0^L \int_0^t \dot{\lambda}(t) d\dot{t} dt}{L}$$

Equation 18

and:

$$\Delta q = \frac{\int_0^L \int_0^t a\dot{t} d\dot{t} dt}{L}$$

Equation 19

which is solved:

$$\Delta q = \frac{1}{6} a L^2$$

Equation 20

Switching to a new component every L hour makes the component "as good as new". This is however not the only type of maintenance that can be performed. If a component is regularly checked for aging signs, for example every T hour, it can be determined if it is in a proper working condition. The component is not renewed if only minor repairs are done. Rather, it is restored to "as good as old" and if any greater overhauls are performed, they are regarded as renewals L. Incorporating surveillance that is done every T hours into the unreliability equation gives Equation 21:

$$\Delta q(t_o, u) = 1 - e^{-\int_{t_o}^{t_o+u} \dot{\lambda}(t) d\dot{t}}$$

Equation 21

where t_o is the time that has passed since a renewal of the component and u is between 0 and T. Assuming again a linear aging model, $\Delta q(t_o, u)$ can be written as Equation 22:

$$\Delta q(t_o, u) = \int_{t_o}^{t_o+u} a\dot{t} d\dot{t} = \frac{1}{2} a(2t_o u + u^2)$$

Equation 22

The mean change in unreliability is given by averaging u between 0 and T and by averaging $\Delta q(t_o)$ over the continuous variable $t_o = 0$ to $t_o = L - T$ (Equation 23-Equation 26):

$$\Delta q(t_o) = \frac{1}{T} \int_0^T \frac{1}{2} a(2t_o u + u^2) du \rightarrow$$

Equation 23

$$\Delta q(t_o) = \frac{1}{2}a\left(t_oT + \frac{T^2}{3}\right) \rightarrow$$

Equation 24

$$\Delta q = \frac{1}{L-T}\int_0^{L-T}\frac{1}{2}a\left(t_oT + \frac{T^2}{3}\right)dt_o \rightarrow$$

Equation 25

$$\Delta q = \frac{1}{4}a(L-T)T + \frac{1}{6}aT^2$$

Equation 26

Δq thus represents the mean change in unreliability due to aging, taking into consideration renewal at intervals (L) and surveillance at intervals (T) (after the last renewal).

4.1.1 Limitations

Renewal and surveillance is assumed to restore a component to “as good as new” and “as good as old”. In reality, maintenance that is performed on a component can restore it to a condition that is somewhere in between. It has been proposed that this can be managed by dividing L and T with the efficiency of the maintenance, a number between zero and one (Vesely et al., 1990). This adjustment of efficiency is not made in this thesis. Instead, an assumption is made that the components are indeed restored to ”as good as new” when renewed and ”as good as old” when surveillance has been done. This assumption is a ”best case” scenario. It is possible to add threshold effects so that aging begins after a certain time or use nonlinear aging failure rate functions. However, the equations must then be modified. In the following section the equations will be modified to incorporate exact (and not average) change in unreliability. Nonlinear Weibull distributions instead of the linear increase (a) will be used for the failure rate, which makes the equations slightly more complicated. Threshold effects will not be considered, a component is assumed to begin aging immediately after it is installed or renewed. This assumption is a ”worst case” scenario.

4.2 Development of an adjusted model

Component data on how the failure rates of some mechanical components increase due to aging has been collected from NPP (Levy, Wreathall, DeMoss, Wolford, Collins & Jarrell, 1988). This data, which can be denoted $\dot{\lambda}_{NPP}$, is presented in Table 8. Data is only presented for those components that also exist in the modeled OOG platform; other components are not of interest in this thesis. The specific failure modes for the data are such fails that result in an inability to function, for example small or large leaks, fail to start or fail to stop. In the same table, data derived from Eide, Wierman, Gentillon, Rasmuson & Atwood (2007), on constant failure rates for the same NPP components is also presented. This data can be denoted λ_{NPP}. The failure rates are selectively chosen to only comprise such fails that lead to an inability to function. Thus, the failure modes are the same for all the data presented in Table 8, i.e. failures that lead to an inability to function.

Data on the constant failure rates from Eide et al. (2007), denoted λ_{NPP}, consists of both failures per hour and failures on demand. To quantify the data as a single value of failure to function per hour, an assumption is made that the failures on demand are evenly distributed over a year, similar to the failures per hour. However, the failure mode for demands is only “fail to start”. Equation 27 expresses the assumption:

$$\lambda_{failure\ per\ hour} = \frac{\frac{failures}{demands}}{years * 365 * 24}$$

Equation 27

For the OOG components, data on the failure rate increase due to aging, denoted $\dot{\lambda}_{OOG}$, has not been found. The data probably exists but in the possession of operators and manufacturers of the components. Requests have been sent to three manufacturers but none have provided this data. It is also possible that the data they possess has not yet been analyzed with regard to aging. Several open source databases have also been carefully studied without finding $\dot{\lambda}_{OOG}$ for components in OOG environments. Because $\dot{\lambda}_{OOG}$ is vital for the further analysis, it will be necessary to develop an interpolation method later in this section. Data on the constant failure rates for OOG components, denoted λ_{OOG}, is fortunately easier to find. In Table 9, data from OREDA (2002) and International Association of Oil and Gas Producers [OGP] (2010) is presented. The data on λ_{OOG} comprise the failure mode “inability to function” and is thus similar to the data on λ_{NPP} and $\dot{\lambda}_{NPP}$ regarding the failure mode. Not all components that are present in the modeled OOG platform are found in the data on $\dot{\lambda}_{NPP}$, provided by Levy et al. (1988). The missing components are filters and flanges. Therefore, these are assumed to only have constant failure rates and to not be subject to aging. Because flanges and filters are undoubtedly present in NPP, these might have been “included” in other components, for example pipes with flanges have been viewed as only pipes. In order to clarify the important denotations used in this section ($\dot{\lambda}_{NPP}$, λ_{NPP}, $\dot{\lambda}_{OOG}$, λ_{OOG}) these are presented in Table 7.

Table 7. Important denotations from this section and a description of them.

Denotation	Description	Unit
$\dot{\lambda}_{NPP}$	The failure rate increase per year due to aging for a NPP component	$[h^{-1}y^{-1}]$
λ_{NPP}	The constant failure rate for a NPP component	$[h^{-1}]$
$\dot{\lambda}_{OOG}$	The failure rate increase per year due to aging for an OOG component	$[h^{-1}y^{-1}]$
λ_{OOG}	The constant failure rate for an OOG component	$[h^{-1}]$

From Table 8 and Table 9 it is apparent that λ_{NPP} and λ_{OOG} are different for the same component type. The harsher environment and high pressure processing of corrosive substances at OOG platforms seem to increase the constant failure rates. In general, the constant failure rates of OOG components are higher than their counterparts at NPP. This situation can be illustrated in Figure 15. In the area denoted “2”, λ_{NPP} and λ_{OOG} of one type of component are plotted. The areas under the curves equal the unreliability q for each component (q_{OOG} and q_{NPP}). Because λ_{OOG} is a factor larger than λ_{NPP}, for example r (ratio) larger, the unreliability q_{OOG} of that OOG component is also r larger than the unreliability q_{NPP} of the NPP component. This is clearly the case for the area denoted “2” in Figure 15. The ratio is given by Equation 28:

$$r = \frac{q_{OOG}}{q_{NPP}} = \frac{\lambda_{OOG}}{\lambda_{NPP}}$$

Equation 28

As was mentioned earlier, some kind of interpolation of data would be necessary to estimate $\dot{\lambda}_{OOG}$. This interpolation is now done. First, assume that the same ratio as in Equation 28 also exists between the unreliability of the NPP and OOG components in the area denoted “3” in Figure 15. This is the area where aging is present. From Section *3.6 Aging*, it is known that the failure rate increase due to aging ($\dot{\lambda}_{NPP}$ and $\dot{\lambda}_{OOG}$) is a phenomenon which, just like the constant failure rate (λ_{NPP} and λ_{OOG}), depends on factors such as operating environment and what substances are handled.

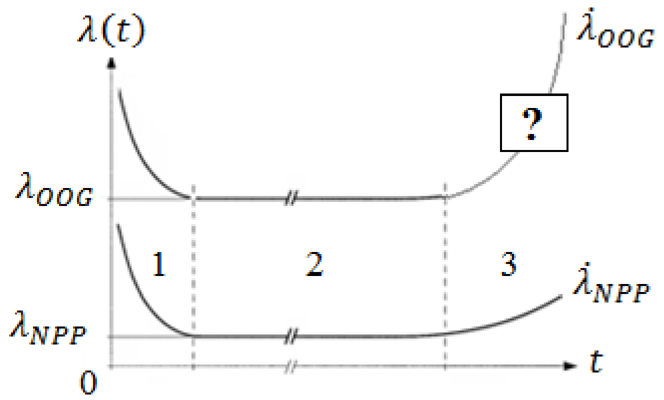

Figure 15. Constant failure rates (area denoted 2) for an OOG (λ_{OOG}) and for a NPP (λ_{NPP}) component are plotted. $\dot{\lambda}_{NPP}$ is also plotted. The yet unknown $\dot{\lambda}_{OOG}$ is also plotted. Notice that a higher constant failure rate yields a steeper failure rate increase due to aging.

The area denoted “3” in Figure 15 is plotted in a different way in Figure 16. Here, only the failure rate increase due to aging ($\dot{\lambda}_{NPP}$ and $\dot{\lambda}_{OOG}$) is present. The areas under the curves are still the unreliability, but **only** due to aging. Because the data from Levy et al. (1988) is linear, this is assumed to also be the case for OOG components. Later in this section the possible implication of this assumption will be investigated and a nonlinear $\dot{\lambda}_{OOG}$ will be applied. Let the ratio between the unreliability of the OOG and NPP component be r as suggested earlier. It is now interesting to know if there is a relation between r (the unreliability ratio) and the ratio of $\dot{\lambda}_{OOG}/\dot{\lambda}_{NPP}$. In Figure 16, the failure rates increase due to aging ($\dot{\lambda}_{OOG}$ and $\dot{\lambda}_{NPP}$) are the same as the gradients of the curves.

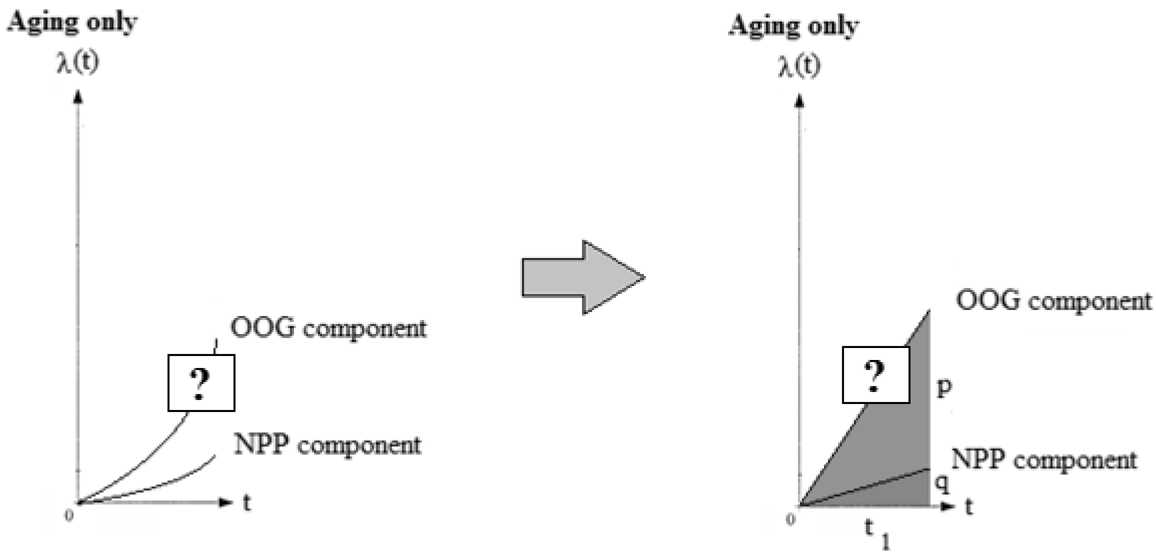

Figure 16. The theoretical failure rate increase due to aging is plotted to the left. To the right, the simplified, linear increase is plotted.

Expressions based on the geometry in Figure 16 are developed in Equation 29 and Equation 30:

$$r = \frac{q_{OOG}}{q_{NPP}} = \frac{\frac{t_1 * (p+q)}{2}}{\frac{(q * t_1)}{2}} = \frac{p}{q} + 1$$

Equation 29

$$\frac{\dot{\lambda}_{OOG}}{\dot{\lambda}_{NPP}} = \frac{\frac{(p+q)}{t_1}}{\frac{(q)}{t_1}} = \frac{p}{q} + 1$$

Equation 30

Equation 29 gives the expression for r. Equation 30 gives the expression for the ratio between the gradients of the OOG and the NPP component. It is apparent that the ratio is the same. Thus, if the ratio r is known, the gradient $\dot{\lambda}_{OOG}$ of the OOG component can be estimated. The ratio and the estimation of each OOG component's $\dot{\lambda}_{OOG}$ are given in Table 10. An example of this theory is given for a pump in Equation 31 and Equation 32:

$$r_{Pump} = \frac{\lambda_{Pump\ OOG}}{\lambda_{Pump\ NPP}}$$

Equation 31

$$\dot{\lambda}_{Pump\ OOG} = \dot{\lambda}_{Pump\ NPP} * r_{Pump} = \dot{\lambda}_{Pump\ NPP} * \frac{\lambda_{Pump\ OOG}}{\lambda_{Pump\ NPP}}$$

Equation 32

Table 8. Data on λ_{NPP} and $\dot{\lambda}_{NPP}$ from NPP is derived from Eide et al. (2007) and Levy et al. (1988)

Component	λ_{NPP} $[10^{-6}h^{-1}]$ (Eide et al., 2007)	$\dot{\lambda}_{NPP}$ $[10^{-6}h^{-1}y^{-1}]$ (Levy et al., 1988)
Centrifugal pump	6.70	2.7
Filter	-	-
Compressor	91.9	0.5
Pressure vessel	0.04205	E^-6
Heat exchanger (type: hydrocarbon tube)	0.2668	0.014
Pipes	0.000827 $[10^{-6}h^{-1}m^{-1}]$	0.03 $[10^{-6}h^{-1}y^{-1}m^{-1}]$
Instrument	0.85	0.1733
Flange	-	-
Manual valve	0.130195	2.2E-3
Actuated valve	10.1647	0.13

λ_{OOG} for some components are not explicitly stated in OREDA (2002) however. Pipes are not listed at all. Pressure vessels and instruments are listed but only as a few specific types. Because λ_{NPP} from Eide et al. (2007) on pressure vessels and instruments comprise all types, it would not be correct to use the data from OREDA (2002) for these components. For the components that lack data (pipes, pressure vessels and instruments) a different source of data is used. This source only presents the constant failure rates for the failure mode: leak. This probably leads to an underestimation of the failure rate, because there are other failures than leaks (for example fail to run).

Table 9. Data on λ_{OOG}. For the components that lack this data (failure mode: all), a different source of data is used that only presents constant failure rates for leaks (failure mode: leak).

Component	λ_{OOG} $[10^{-6}h^{-1}]$
Centrifugal pump	112.64 OREDA (2002)
Filter	-
Compressor (centrifugal compressor)	474 OREDA (2002)
Pressure vessel	0.16552 OGP (2010), leaks only
Heat exchanger (type: hydrocarbon tube)	69.62 OREDA (2002)
Pipes	0.0239726 OGP (2010), leaks only $[10^{-6}h^{-1}m^{-1}]$
Instrument	0.06164384 OGP (2010), leaks only
Flange	-
Manual valve	0.3977053 OREDA (2002), assuming same proportion between Manual and Actuated valve as in Table 8
Actuated valve	31.05 OREDA (2002)

Table 10. The ratio between the constant failure rates λ_{OOG} and λ_{NPP} and the estimate of the failure rate increase due to aging for OOG components $\dot{\lambda}_{OOG}$.
$\dot{\lambda}_{OOG}$ is calculated by multiplying the ratio with the $\dot{\lambda}_{NPP}$.

Component	Ratio of $\lambda_{OOG}/\lambda_{NPP}$ $[-]$	Estimate of $\dot{\lambda}_{OOG}$ $[10^{-6}h^{-1}y^{-1}]$
Centrifugal pump	16.811940	45.392238
Filter	-	-
Compressor	5.1577801	2.5788900
Pressure vessel	3.9362663	3.9362663E-6
Heat exchanger (type: hydrocarbon tube)	260.94452	3.6532233
Pipes	28.987424	0.8696227 $[10^{-6}h^{-1}y^{-1}m^{-1}]$
Instrument	0.0725221	0.01256809
Flange	-	-
Manual valve	3.05468950	0.00672031
Actuated valve	3.05468926	0.39710960

The implication of the assumption that $\dot{\lambda}_{OOG}$ is linear is now investigated. In theory, the failure rate often follows the bath-tub curve and thus is Weibull distributed. The linear failure rate increase in Equation 21: $\lambda(\dot{t})$, is replaced with a Weibull shaped failure rate increase in Equation 22 which yields Equation 33:

$$\Delta q(t_o,u) = 1 - e^{-\int_{t_o}^{t_o+u} \lambda(\dot{t})d\dot{t}} = 1 - e^{-\int_{t_o}^{t_o+u} \frac{\beta}{\alpha}\left(\frac{\dot{t}}{\alpha}\right)^{\beta-1} d\dot{t}}, \alpha > 0, \beta > 0, t > 0$$
$$= 1 - e^{{t_o}^{\beta} * \alpha^{-\beta} - (t_o+u)^{\beta} * \alpha^{-\beta}}$$

Equation 33

To get the mean change in unreliability the same averaging procedure that was used between Equation 22 and Equation 23 is used again. The variable u is averaged between 0 and T and $\Delta q(t_o)$ over $t_o = 0$ to $t_o = L - T$:

$$\Delta q = \frac{1}{L-T} \int_{t_o=0}^{L-T} \frac{1}{T} \int_{u=0}^{T} 1 - e^{{t_o}^{\beta} * \alpha^{-\beta} - (t_o+u)^{\beta} * \alpha^{-\beta}} \, du dt_o$$

Equation 34

Because Equation 34 lacks an analytical solution it is necessary to solve it by numeric integration. The solver that is used is found in the *Python* extension *scipy*. The source code of the program is presented in Appendix C, written in *Python 3.3.2*.

If $\beta = 2$ in Equation 34, the same linear increase of the failure rate as in Equation 21 is obtained. If $\beta > 2$ the failure rate increases non-linearly, taking the shape of the wear-out phase in the bath-tub curve. Typical values of β for mechanical components such as pumps, compressors, motors and valves range from about 2 to 4 (Bloch & Geitner, 1999). Higher and lower values exist but more infrequently. Thus, it is assumed that β for all OOG components reside between 2 and 4. The Weibull distribution is fitted to the linear $\dot{\lambda}_{OOG}$ for each component in Table 10.

Because the Weibull distribution has two parameters: α and β, α needs to be determined when fitting the Weibull distribution (for $\beta = 2, 3$ *and* 4) to the $\dot{\lambda}_{OOG}$. The fitting is done in *MATLAB R2012a* using least squares fitting. The source code is presented in Appendix B and the determined α values are presented in Table 11 for all components.

Table 11. The determined α values for different β for all components.

Component	α *for* $\beta = 2$	α *for* $\beta = 3$	α *for* $\beta = 4$
Centrifugal pump	2.10E+02	110.4529	8.00E+01
Filter	-	-	-
Compressor	8.81E+02	287.3319	1.64E+02
Pressure vessel	7.10E+05	2.49E+04	4.65E+03
Heat exchanger (type: hydrocarbon tube)	7.43E+02	2.57E+02	1.50E+02
Pipes	1.52E+03	4.13E+02	2.15E+02
Instrument	1.26E+04	1.69E+03	6.20E+02
Flange	-	-	-
Manual valve	1.73E+04	2.09E+03	7.25E+02

Actuated valve	2.24E+03	5.36E+02	2.61E+02

When β and α are known for each component, the unreliability increase $\Delta q(t)$ can be solved with Equation 34 for different L and T and later added to the unreliability calculated with constant failure rates $q(t)$. These calculations are done in Chapter *5. Risk analysis*.

The $\dot{\lambda}_{OOG}$ for components are derived from λ_{OOG} for the failure mode "inability to function". In the forthcoming chapters the failure mode of interest will only be leaks of hydrocarbons. It is therefore assumed that the same $\dot{\lambda}_{OOG}$ also applies to leaks solely, i.e. $\dot{\lambda}_{OOG\ Leaks} = \dot{\lambda}_{OOG}$. This assumption should lead to an overestimation of $\dot{\lambda}_{OOG\ Leaks}$ because all failures are not necessarily leaks. The overestimation can be regarded as a "worst case". If the correct data is available it should be used instead.

5. Risk analysis

The objective of this thesis is, as earlier mentioned, to investigate how much, if at all, LSFAR is affected by aging of mechanical components. Only the contribution to LSFAR from hydrocarbon releases was further specified as relevant. In the previous chapter, a model was developed for this purpose. The model incorporates maintenance (renewal and surveillance) and different shapes on failure rates ($\beta = 2, 3$ *and* 4). An interpolation was necessary to make between r (the unreliability ratio) and the ratio of $\dot{\lambda}_{OOG}/\dot{\lambda}_{NPP}$ in order to get $\dot{\lambda}_{OOG}$. In this chapter, a risk analysis will first be carried out using constant failure rates ($\lambda_{OOG\ Leaks}$). Then, a risk analysis will be carried out using aging affected failure rates ($\dot{\lambda}_{OOG\ Leaks}$). Before this is done, necessary simplifications and assumptions will be made in the following section.

5.1 Simplifications and assumptions

A risk analysis can be illustrated by the so called bow-tie model. Theory on the model is given in Section *3.5.1 Bow-tie model*. In Figure 17 an example is given on how a bow-tie diagram could be used if detailed data exists on the system of interest. Such data is process flow charts and reliability of safety systems (both detection and activation).

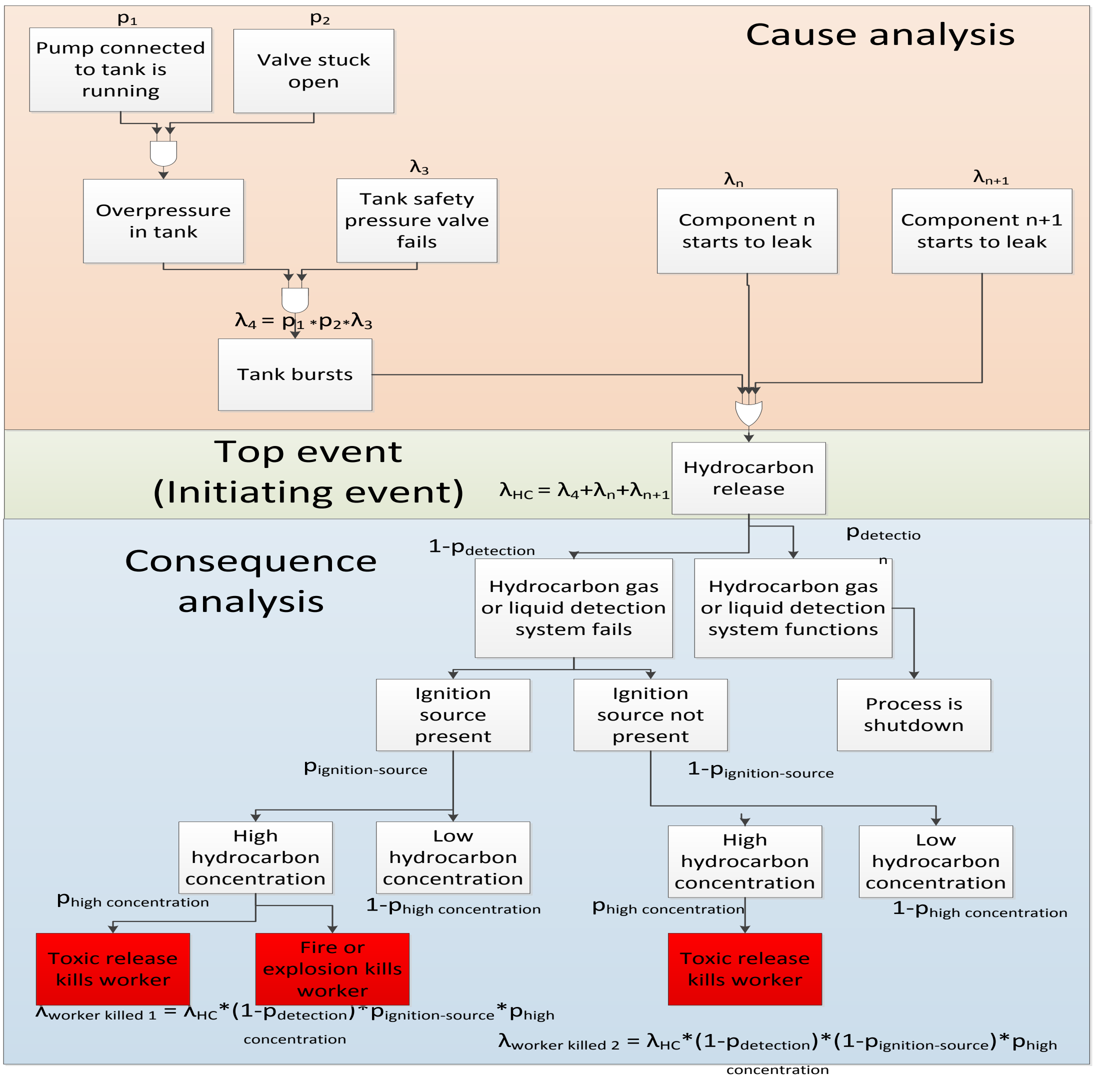

Figure 17. An example of a bow-tie diagram where the causes and consequences are extensively analyzed.

All of this data is not available however. What is known though, for the modeled platform, is how many components that are present in each platform area and their individual leak frequencies ($\lambda_{OOG\ Leaks}$). It is also known what phase and roughly what pressure and temperature the substances are handled at. Because process flow charts and data on safety systems reliability is lacking, a simplification is necessary to make of the bow-tie diagram shown in Figure 17. In Figure 18, this simplified bow-tie diagram is presented.

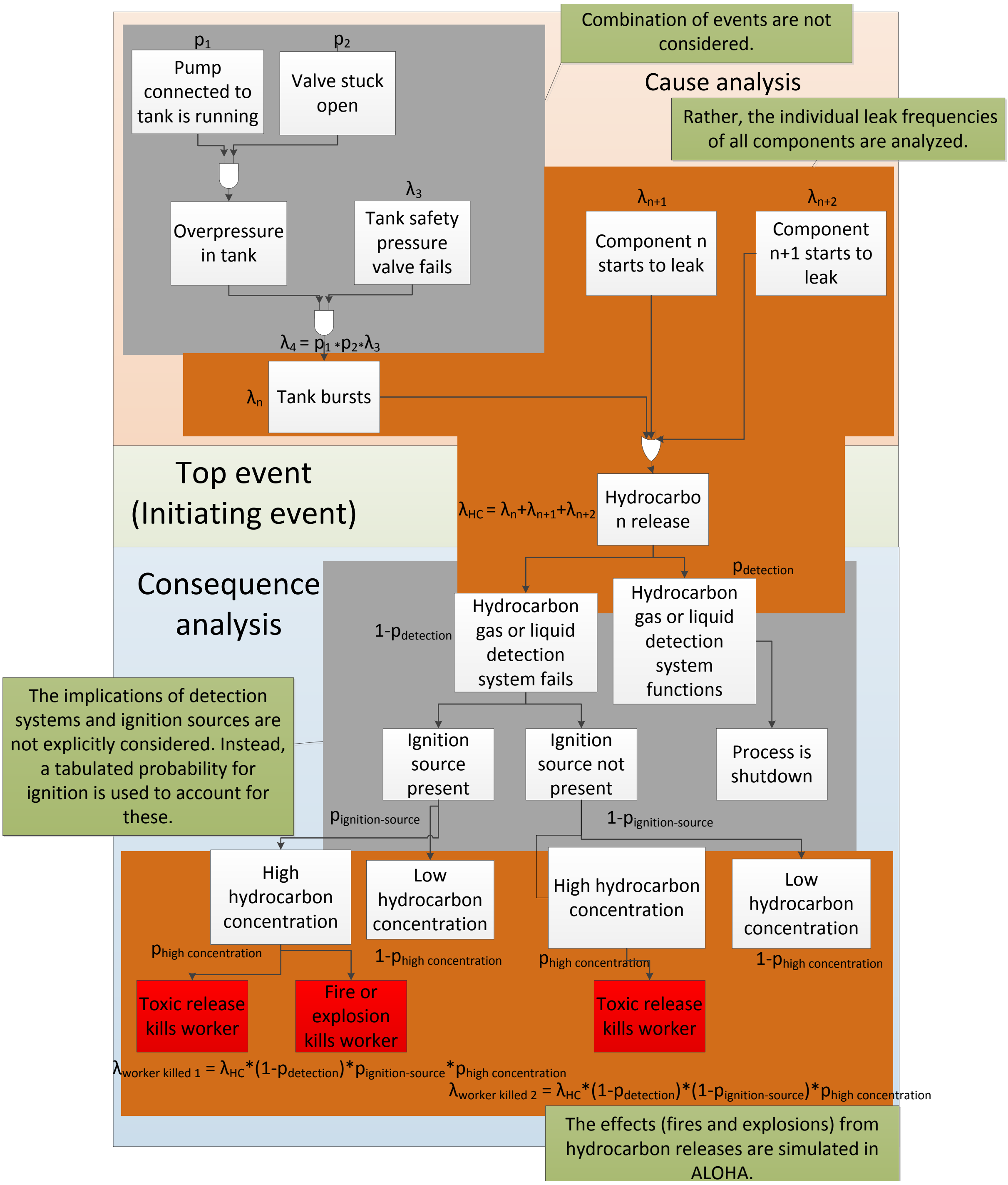

Figure 18. A simplified bow-tie diagram illustration. Because process flow charts and reliability of safety systems are lacking, it is necessary to make some assumptions and simplifications in the risk analysis. The grey areas are not considered explicitly but the brown areas are.

The grey areas in the figure are not considered explicitly in the risk analysis but the brown areas are. The green squares contain information regarding the simplifications for each step.

Because the risk measure of interest was chosen as the LSFAR (location specific FAR) contribution from hydrocarbon releases, additional simplifications can be made. Injuries, structural failures and environmental damage are not investigated. Only fatalities due to ignition following hydrocarbon releases (the initiating event) are of interest. Other initiating events are not considered. Such events are mostly work environment related but actually comprise the majority of all fatalities. This involves getting caught between or under equipment, being struck by something, falling from height and drowning. Fatalities due to pressure releases, explosions and burns amount to almost 10 % of all fatalities per year (OGP, 2012).

In Figure 18 it is apparent that the failures in the brown “Cause analysis” area only comprise such fails that lead to a leakage. It is assumed that the components on the modeled platform are subject to leaks independently from one another and that the probability for a leak is uniformly distributed over time. This might not be the case as one leak can result in, for example, a fire which leads to another leak. Such combinations of events are not analyzed further though, as is illustrated in Figure 18. It is also possible that leaks occur more often at day time because more workers are present on the wellhead and process area. However, because it is unknown if leaks occur more often during day or night time, it is assumed that leaks occur uniformly distributed over 24 hours a day. A detailed description of the probability calculations, leading to a hydrocarbon release, is presented in Section *5.1 Probability calculations*.

The consequences of the hydrocarbon releases can be fires, explosions and release of toxics, all of which can lead to fatalities. It is rare though that a release of toxics leads to fatalities (OGP, 2012). Thus, release of toxics is a consequence which is not analyzed in this thesis. The consequence analysis is presented in Section *5.2 Consequence modeling*.

Further assumptions that are made are that firewalls and blast walls remain fully functional so that the different platform areas constitute isolated cells, see Figure 19:

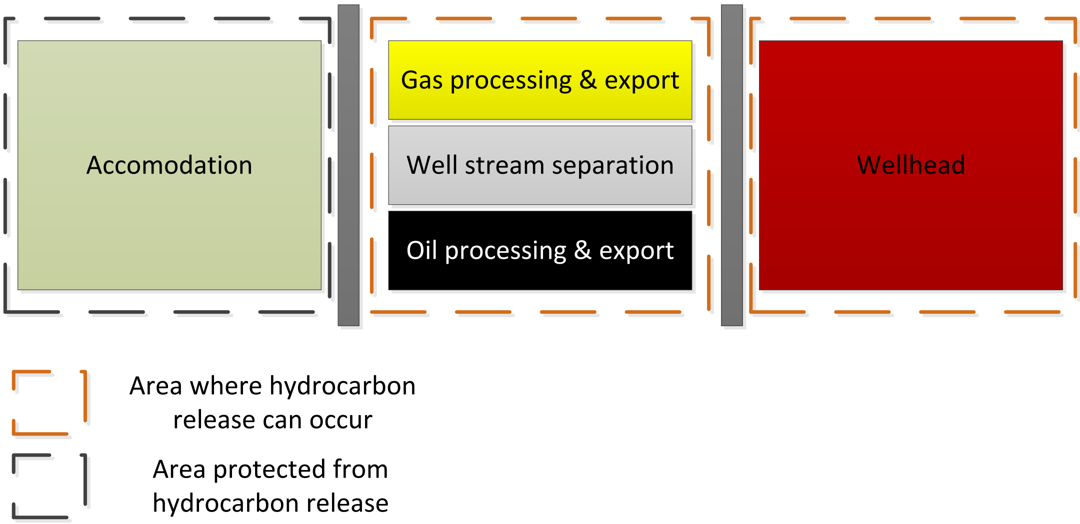

Figure 19. Overview of the different isolated areas of the platform. Areas where hydrocarbon releases can occur are marked.

Thus, the probability and consequence of such walls collapsing are not taken into account. A result of this assumption is that the staff staying in the accommodation area is not influenced by fires due to hydrocarbon releases.

The limitations that have been stated all affect the accuracy of the probability and consequence estimation. Thus, absolute values of the results from the risk analysis, the LSFAR values, must not be accepted without consideration. Because the same limitations apply to the analysis that takes aging into account as to the analysis with constant failure rates, the **difference** between the LSFAR values can however be stated with more confidence.

5.1 Probability calculations

This section presents the calculations of the probabilities of hydrocarbon releases, i.e, leaks from individual components leading to the initiating event. The calculations are carried out with constant failure rates $\lambda_{OOG\ Leaks}$, as well as with the failure rate increase due to aging $\dot{\lambda}_{OOG\ Leaks}$. As mentioned earlier the two areas of interest are the wellhead area and the process area.

The influence of gas and fire detectors, fire extinguishers and other active safety systems on the possible consequences of leaks is not explicitly considered, due to lack of detailed process flow charts and safety systems reliability data. However, statistics on how often leaks lead to ignition are used, so the effect of these systems is to some extent taken into account. It has been estimated that the probability of ignition is generally a few percent, see Figure 20. If a release is large, the probability of ignition is increased. To determine the ignition probability, the mass flows of hydrocarbon releases need to be calculated. These calculations are carried out in Section *5.2 Consequence modeling*. The estimations in Figure 20 consider both immediate and delayed ignitions.

17 – Offshore Process Liquid	
Releases of flammable liquids that do not have any significant flash fraction (10% o less) if released from within offshore process modules.	
Release Rate (kg/s)	Ignition Probability
0.1	0.0010
0.2	0.0013
0.5	0.0019
1	0.0026
2	0.0035
5	0.0051
10	0.0067
20	0.0090
50	0.0131
100	0.0175
200	0.0175
500	0.0175
1000	0.0175

20 – Offshore Process Gas Typical	
Releases of flammable gases, vapour or liquids significantly above their normal (NAP) boiling point from within offshore process modules or decks on integrated deck / conventional installations. Process modules include separation, compression, pumps, condensate handling, power generation, etc. If the module is mechanically ventilated or very congested – see curve No. 22 "Offshore Process Ga Congested or Mechanical Vented Module".	
Release Rate (kg/s)	Ignition Probability
0.1	0.0010
0.2	0.0017
0.5	0.0036
1	0.0063
2	0.0109
5	0.0183
10	0.0240
20	0.0315
50	0.0400
100	0.0400
200	0.0400
500	0.0400
1000	0.0400

Figure 20. Estimation of ignition probability following a hydrocarbon (liquid and gas) release. (OGP, 2010a, pp. 12-13).

5.1.1 Probability calculations using constant failure rates

In Figure 21 the steps that are taken in order to calculate the probability for leakage using constant failure rates is presented.

The sum of the constant failure rates for all similar components is calculated for three different leak sizes (<10 mm, 10-25 mm and >25 mm) by multiplying the number of components in that area with the corresponding $\lambda_{OOG\ Leaks}$. Ignition probabilities are also included for the different leak sizes, see step 1 in Figure 21. The constant failure rates and the number of components are presented in Table 2, Table 3, Table 5 and Table 6.

Probability calculations with constant failure rates

Step 1

The failure rates for three leak sizes are multiplied with the number of components in the process area and the ignition probability. This yields how many ignitions that occur per year for a component type for a specific leak size.

Example for pumps in a specific area:

$\lambda_{OOG\ Ignitions\ due\ to\ pump\ leak} = \lambda_{OOG\ Leaks\ pump} * number_{pumps} * p_{ignition}$

Step 2

Because the leaks are only assumed to depend on the leak size, pressure, temperature and phase, they are not specific for a component type. Thus, the frequency of ignitions for the different leak sizes is the sum of all components' leak frequencies (ignited).

Example:

$\lambda_{OOG\ Ignitions\ due\ to\ all\ leaks} = \lambda_{OOG\ Ignitions\ due\ to\ pump\ leak} + \lambda_{OOG\ Ignitions\ due\ to\ compressor\ leak} + \lambda_{OOG\ Ignitions\ due\ to\ ...\ leak}$

Figure 21. A step by step description of probability calculations using constant failure rates $\lambda_{OOG\ Leaks}$

In Step 2 the failure rates for each component type for different leak sizes are summed together. This yields the sum of all failure rates (for three leak sizes) in the specific area. In Appendix E these failure rates are presented.

5.1.2 Probability calculations using aging increased failure rates

In Figure 22 the steps that are taken in order to calculate the probability for leakage using aging increased failure rates are presented.

Probability calculations with aging increased failure rates

Step 1

Δq due to aging is solved numerically in *Python*

The unreliability due to aging Δq for each component type is calculated at different L and T intervals. For each set of L and T, three different β are used.

Step 2

$q_{constant} = 1\text{-}e^{\lambda * c * t}$

The unreliability for the constant failure rate: $q_{constant}$, for each component type is calculated for three leak sizes. The number of components in the area is denoted ”c”.

Step 3

$q_{aged} = (\Delta q + q_{constant}) - (\Delta q * q_{constant})$

Step 4

When q_{aged} is known for the component type, its failure rate λ (failures per year) is calculated. It is then multiplied with the ignition probabilities for the three leak sizes.

Step 5

The failure rates from Step 4 for the component type are added with all the other component types in order to get the total failure rate for the leak sizes: $\lambda_{OOG\ Ignitions\ due\ to\ all\ leaks}$. The failure rate states how many leaks that are expected per year in the specific area.

$\lambda_{OOG\ Ignitions\ due\ to\ all\ leaks} = \lambda_{OOG\ Ignitions\ due\ to\ pump\ leak} + \lambda_{OOG\ Ignitions\ due\ to\ compressor\ leak} + \lambda_{OOG\ Ignitions\ due\ to\ ...\ leak}$

Figure 22. A step by step description of probability calculations using aging ($\dot{\lambda}_{OOG\ Leaks}$) increased failure rates.

In Step 1, in Figure 22, the developed aging model is used to calculate the unreliability increase (Δq) using *Python*, see Appendix C. Δq is calculated for different L, T and β. In order to simplify the calculations, L and T are now measured in years instead of hours. L

usually ranges from 5 to 25 years and T from 0.5 to 2.5 years (D. Lundberg, personal communication, 2013-07-11). The unreliability ($q_{constant}$) due to the constant failure rates ($\lambda_{OOG\ Leaks}$) is then calculated with Equation 12 for all components of the same type see Step 2 in Figure 22. To add the two unreliabilities from Step 1 and 2 (Δq and $q_{constant}$), Equation 35 is used in Step 3.

$$q_{aged} = \Delta q + q_{constant} - (\Delta q * q_{constant})$$

Equation 35

In order to get how many failures that occur per year, the unreliability: q_{aged} is converted to an average failure rate by dividing the unreliability at 5 year intervals by how many years that have passed. The period of interest is 5-25 years.

In Step 5 the failure rates for each component type for different leak sizes are summed together. This yields the total failure rate (for three leak sizes and different L, T and β) in the specific area ($\lambda_{OOG\ Ignitions\ due\ to\ all\ leaks}$). In Appendix F these failure rates are presented.

When the total probability per year for ignition for each area is known, it is in the following section multiplied with potential fatalities of the specific hydrocarbon release to get the LSFAR.

5.2 Consequence modeling

In this section the consequences of hydrocarbon releases are analyzed. The areas of interest are still the process area and wellhead area. However, the process area is divided into five smaller areas presented in Figure 23.

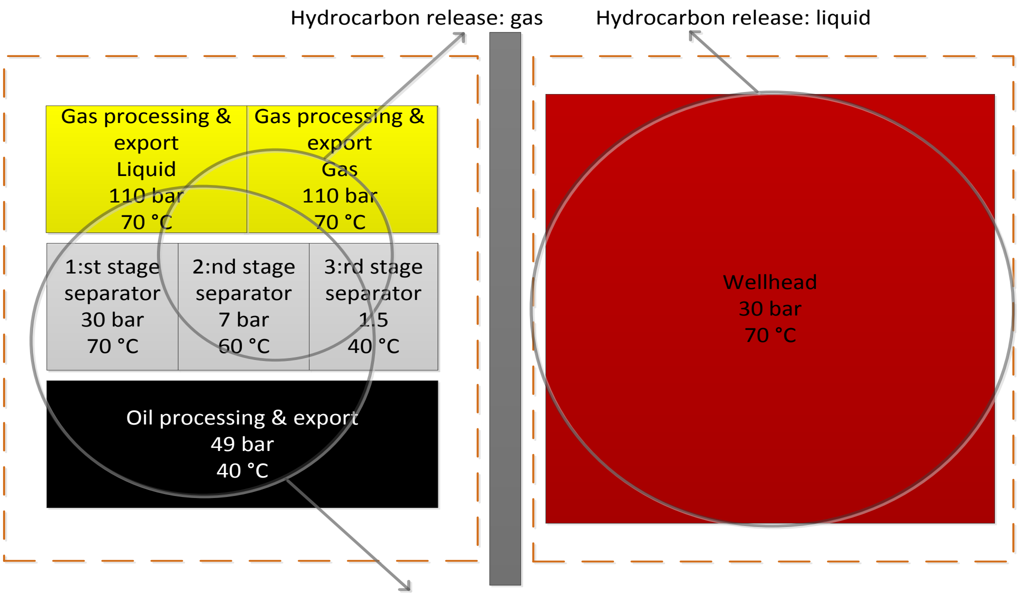

Figure 23. The different areas of the platform that is subject to the consequences of leaks at different temperatures, pressures and phases.

This is done due to the presence of different pressures and temperatures inside the process area. The consequences are dependent on these parameters and will be modeled with the differences taken into consideration. The smaller areas are not separated by firewalls or blast walls. The entire wellhead area is assumed to only handle one temperature and one pressure.

The potential consequences for different leak sizes in the different areas have to be analyzed before the LSFAR values can be determined. *ALOHA 5.4.3* is used to simulate the effects of a fire or blast due to a leak. In order to quantify how severe an explosion or fire is, it is necessary to know how much of the working area that is affected by a fatal consequence. Fatalities can be expected if a certain peak pressure is exceeded or if the workers are in direct contact with the fire. If the concentration of hydrocarbons exceeds 60 percent of the lower flammable limit (LFL), 5760 parts per million (ppm), *ALOHA* regard it as a fire. Heat radiation affecting the surroundings of the fire is not taken into consideration. This simplification is made because it is very difficult to determine the view factor due to the congested area. The fatal peak pressure is 0.34 atm (Glasstone, 1962). If a worker stands in an area where the pressure or concentration exceeds the fatal value, the worker is expected to die. The explosion or fire is simulated in *ALOHA* in order to see how large the fatal area is. An example of the fire simulated in *ALOHA* and the affected fatal area is presented in Figure 24.

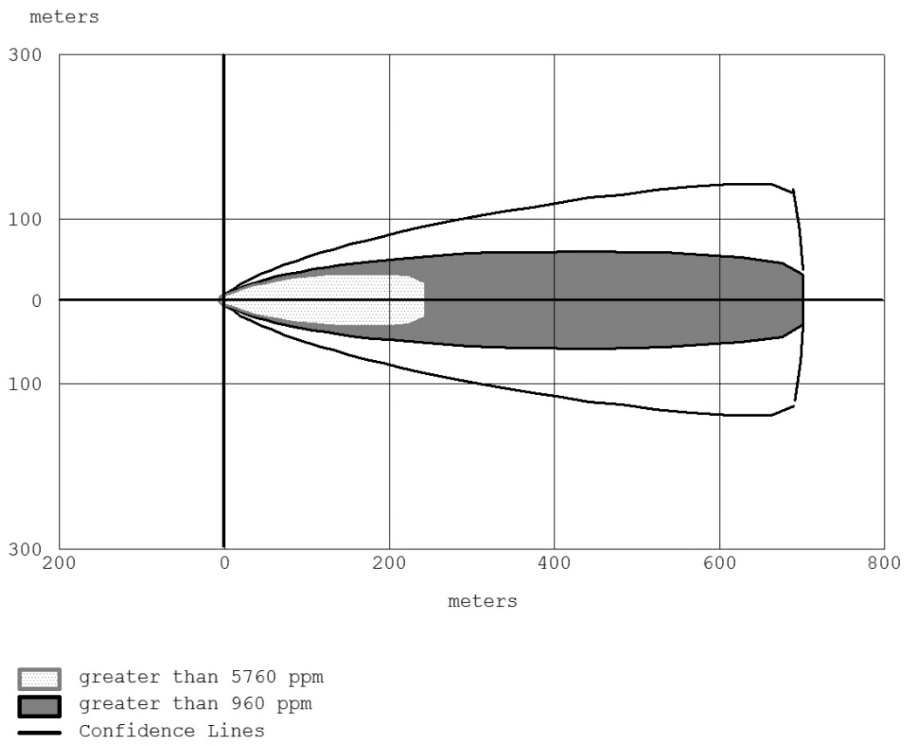

Figure 24. An illustration of the fire spread simulated in *ALOHA*. Fatalities are expected in the area where the concentration of hydrocarbons is greater than 5760 ppm.

When the fatal area is known, it is divided by the total working area. This yields a percentage on how much of the total working area that is fatal given such a leak. A summary of the source code is presented in Appendix D. Wind, temperature, humidity and cloud cover data is taken from weather statistics (Windfinder).

All the consequences due to leaks from components are simulated in *ALOHA* with a *direct release* of hydrocarbons. This simplification implies that the consequences are the same for different types of components and that only the leak sizes, the phase, the pressure and the temperature affect the release. The leak sizes that are presented in Section *3.1.2 The modeled OOG platform* are not presented as point values. Rather, an interval of values is given. In order to model the leaks in *ALOHA*, point values are needed. Thus, the leak size 0-10 mm is modeled as 10 mm, 10-25 mm as 25 mm and >25 mm as 40 mm. 40 mm is chosen because it is 15 mm wider than the smaller size, which is the case with the 10-25 mm leak sizes. It is possible that larger leaks might occur but in order to simulate the consequences a point value is necessary to determine. If more detailed results are desirable and sufficient time is available, these leak sizes can be varied within specified intervals.

In order to simulate the effects of a direct release of hydrocarbons in *ALOHA* it is first necessary to calculate the mass flow. The mass flow Q from an effective leakage area $C_D A$ in a tank containing liquid with the density ρ_l and pressure P_0 can be described by Equation 36. P_A is the atmospheric pressure at ground level. C_D is set to 0.6 because it is a release of liquids and the hole is assumed to be sharp edged (Fischer, Forsén, Herzberg, Jacobsson, Koch, Runn, Thaning & Winter, 1997).

$$Q = C_D A\sqrt{2(P_0 - P_A) * \rho_l}$$

Equation 36 (Fischer et al., 1997)

To calculate the mass flow Q from an effective leakage area $C_D A$ in a tank containing compressed gas at the pressure P_0 it is first necessary to determine whether the flow is critical or non-critical. If the requirement given by Equation 37 is met, the flow is critical and can be calculated using Equation 38. All gas flows in the consequence modeling are critical because the pressure is always at least twice the atmospheric pressure. C_D is set to 0.75 because it is a release of gas and the hole is assumed to be sharp edged (Fischer et al., 1997).

$$P_0 \geq 1.83 * P_A$$

Equation 37 (Fischer et al., 1997)

$$Q = 0.667 * C_D A * \frac{P_0}{\sqrt{R * T_0}}$$

Equation 38 (Fischer et al., 1997)

The calculated mass flows are presented in Table 12.

Table 12. Mass flows for both liquid releases and gas releases for the three leak sizes and the different areas. The Oil Processing and Export area only handles liquids. Thus, it cannot be subject to gas leaks.

Wellhead (30 bar, 70 °C)	**Mass flow (liquid)** $[kg * s^{-1}]$	**Mass flow (gas)** $[kg * s^{-1}]$
10 mm	3.01	0.28
25 mm	18.81	1.74
40 mm	48.15	4.47
Wellstream separation 1st stage (30 bar, 70 °C)	**Mass flow (liquid)**	**Mass flow (gas)**
10 mm	3.01	0.28
25 mm	18.81	1.74
40 mm	48.15	4.47
Wellstream separation 2nd stage (7 bar, 60 °C)	**Mass flow (liquid)**	**Mass flow (gas)**
10 mm	1.37	0.07
25 mm	8.55	0.41
40 mm	21.90	1.06
Wellstream separation 3rd stage (1.5 bar, 40 °C)	**Mass flow (liquid)**	**Mass flow (gas)**
10 mm	0.40	0.01
25 mm	2.47	0.09
40 mm	6.32	0.23
Gas Processing & Export (110 bar, 40 °C)	**Mass flow (liquid)**	**Mass flow (gas)**
10 mm	5.83	1.07
25 mm	36.46	6.70
40 mm	93.34	17.15
Oil Processing & Export (49 bar, 40 °C)	**Mass flow (liquid)**	**Mass flow (gas)**
10 mm	1.10	-
25 mm	6.90	-
40 mm	17.66	-

For the areas where the hydrocarbon exists as a two-phase mix of gas and liquid, the liquid phase is used in the simulations. This simplification is done due to the difficulties to simulate a mixture of different chemicals and phases in *ALOHA*. The liquid phase always yields the worst consequence in the simulations in *ALOHA* and is thus chosen instead of the gas phase where both phases exist. In other words, the consequences are chosen for the “worst case”.

Although the crude oil and gas consist of several different substances, only two pure chemicals are used in the simulations. Natural gas mainly consists of methane and is therefore assumed to behave as pure methane. The liquid phase is assumed to behave as n-octane because it constitutes the main ingredient in crude oil (U.S. Energy Information Administration [EIA]).

The liquid releases are assumed to only result in fires and not gas cloud fires or explosions. *ALOHA* detects that the ambient saturation concentration of the n-octane is below the lower explosion limit. The wind speed, temperature and atmospheric pressure at the platform make the saturation concentration of n-octane in the air too low. The gas releases are assumed to result in both fires and explosions. However, due to uncertainties with the dispersion model at short distances in *ALOHA* the flammable area is assumed to be zero in some cases.

The extent of the fatal area, simulated in *ALOHA*, is divided with the total working area. Both the wellhead area and the process area are 22.5 meters long and 40 meters wide. The ratio between the fatal area and the total working area is multiplied with the average number of persons on board ($POB_{average}$) in order to get the loss of life in case of an ignited release, see Table 13.

Table 13. Fatal areas and the number of fatalities for different leak sizes.

Wellhead ($POB_{average}$=4)	**Fatal area/total working area (ratio)**	**Loss of Life [*persons*]**
10 mm	0.56	2.22
25 mm	0.88	3.52
40 mm	1.00	4.00
Wellstream separation 1st stage ($POB_{average}$=7.5)	**Fatal area/total area**	**Loss of Life**
10 mm	0.56	4.20
25 mm	0.88	6.60
40 mm	1.00	7.50
Wellstream separation 2nd stage ($POB_{average}$=7.5)	**Fatal area/total area**	**Loss of Life**
10 mm	0.00	0.00
25 mm	0.68	5.13
40 mm	0.92	6.93
Wellstream separation 3rd stage ($POB_{average}$=7.5)	**Fatal area/total area**	**Loss of Life**
10 mm	0.00	0.00
25 mm	0.44	3.27

40 mm	0.62	4.67
Gas Processing & Export liquid ($POB_{average}$=7.5)	**Fatal area/total area**	**Loss of Life**
10 mm	0.60	4.47
25 mm	1.00	7.50
40 mm	1.00	7.50
Gas Processing & Export gas ($POB_{average}$=7.5)	**Fatal area/total area**	**Loss of Life**
10 mm	0.00	0.00
25 mm	0.17	1.27
40 mm	0.20	1.47
Oil Processing & Export ($POB_{average}$=7.5)	**Fatal area/total area**	**Loss of Life**
10 mm	0.00	0.00
25 mm	0.64	4.80
40 mm	0.86	6.47

5.3 LSFAR calculations

In Section 5.1 Probability calculations, the probability for ignition following a hydrocarbon release was calculated for each area per year ($\lambda_{OOG\ Ignitions\ due\ to\ all\ leaks}$). The calculations were performed with both constant failure rates and aging increased failure rates. The data from these calculations are presented in Appendix E and Appendix F.

In Section *5.2 Consequence modeling* the consequences of these hydrocarbon releases were simulated in *ALOHA*. The results from the simulations are presented in Table 13.

In this section, the LSFAR is calculated for the wellhead area and the process area. This is done by first multiplying the consequences (loss of life) with the probability for ignition following a hydrocarbon release (using constant failure rates). Then, the same consequences are multiplied with the probability for ignition following a hydrocarbon release (using aging increased failure rates). These calculations give the potential loss of life (PLL) for each area. Finally, to calculate LSFAR the PLL is multiplied with 10^8 and divided with the amount of exposed hours for different areas, see Equation 1. The results are presented in Chapter *6. Results* and interpreted in Chapter *7. Interpretations of results.*

6. Results

The results of the developed aging model are presented in this chapter. Also presented are the results from the final calculations of LSFAR, both the values calculated with constant failure rates for components as well as values calculated with aging taken into account. Interpretations of the results are done in Chapter *7. Interpretations of result.*

6.1 Aging model

The developed aging model used in this thesis is a refinement of a model for NPP. Details of the model are presented in Chapter *4. Development of an aging model.* The derived equation, Equation 34, is intended to be used for calculations of the increased unreliability caused by aging, renewal (L) and surveillance (T) of components. To clarify the final equation, it is presented again:

$$\Delta q = \frac{1}{L-T}\int_{t_o=0}^{L-T}\frac{1}{T}\int_{u=0}^{T} 1 - e^{{t_o}^{\beta}*\alpha^{-\beta}-(t_o+u)^{\beta}*\alpha^{-\beta}}\,dudt_o$$

The parameter α is in this thesis estimated from component failure rate data from both NPP and OOG platforms. However, if detailed data on aging from OOG platforms is available the model can be applied directly without these estimations. Due to the lack of an analytical solution to the integral in Equation 34, a numerical integration is needed. The calculations can be carried out in *Python 3.3.2.* and the source code is presented in Appendix C.

The increased unreliability can then be used together with constant failure rates to calculate the LSFAR values with aging included. In this thesis the effects of active and passive safety systems are not explicitly considered. If more detailed data exists on these systems and the process flow charts are available, they can be incorporated in QRA together with the aging model.

6.2 LSFAR values

The LSFAR values for the wellhead area and the process area are presented in this section. For the constant failure rates, presented in Table 14, the LSFAR values are, as is theoretically correct, independent of the time in service and not subject to any change.

Table 14. LSFAR values for the wellhead area and the process area calculated with constant failure rates.

LSFAR Wellhead area $[-]$	**LSFAR Process area** $[-]$
15.46323059	20.30562568

The LSFAR values for the aging affected failure rates are presented in Table 15 along with the specific β, the renewal interval (L) and the surveillance interval (T). As mentioned earlier β is the shape parameter of the Weibull distribution, seen in Equation 34, and is varied in the range from 2 to 4 as seen in Table 15.

Table 15. LSFAR values for the wellhead area and the process area calculated with aging affected failure rates.

$\boldsymbol{\beta}$	**L** $[year]$	**T** $[year]$	**LSFAR Wellhead area [−]**	**LSFAR Process area [−]**
2	5	0.5	15.4758	20.34042
2	5	1	15.4875	20.3728
2	5	1.5	15.49833	20.40279
2	5	2	15.50829	20.43037
2	5	2.5	15.51739	20.45555
2	10	0.5	15.47601	20.34101
2	10	1	15.48836	20.37519
2	10	1.5	15.50027	20.40816
2	10	2	15.51174	20.43991
2	10	2.5	15.52278	20.47047
2	15	0.5	15.47608	20.34121
2	15	1	15.48864	20.37597
2	15	1.5	15.50091	20.40992
2	15	2	15.51288	20.44306
2	15	2.5	15.52456	20.47538
2	20	0.5	15.47612	20.34131
2	20	1	15.48878	20.37636
2	20	1.5	15.50122	20.41079
2	20	2	15.51344	20.4446
2	20	2.5	15.52543	20.47779
2	25	0.5	15.47614	20.34136
2	25	1	15.48887	20.37659
2	25	1.5	15.50141	20.4113
2	25	2	15.51377	20.4455
2	25	2.5	15.52595	20.4792
$\boldsymbol{\beta}$	**L** $[year]$	**T** $[year]$	**LSFAR Wellhead area [−]**	**LSFAR Process area [−]**
3	5	0.5	15.46515	20.31095
3	5	1	15.46672	20.31528
3	5	1.5	15.46798	20.31878
3	5	2	15.46901	20.32163
3	5	2.5	15.46987	20.32401
3	10	0.5	15.46727	20.31682
3	10	1	15.47092	20.32692
3	10	1.5	15.47421	20.33603
3	10	2	15.47717	20.34422
3	10	2.5	15.47983	20.35158
3	15	0.5	15.4694	20.3227
3	15	1	15.47516	20.33864
3	15	1.5	15.48053	20.35353

3	15	2	15.48554	20.3674
3	15	2.5	15.49022	20.38033
3	20	0.5	15.47152	20.32857
3	20	1	15.47939	20.35037
3	20	1.5	15.48687	20.37106
3	20	2	15.49396	20.3907
3	20	2.5	15.50069	20.40932
3	25	0.5	15.47364	20.33445
3	25	1	15.48363	20.36209
3	25	1.5	15.4932	20.38859
3	25	2	15.50239	20.414
3	25	2.5	15.51119	20.43835
$\boldsymbol{\beta}$	**L** $[year]$	**T** $[year]$	**LSFAR Wellhead area** $[-]$	**LSFAR Process area** $[-]$
4	5	0.5	15.46353	20.30645
4	5	1	15.46373	20.30702
4	5	1.5	15.46387	20.30741
4	5	2	15.46397	20.30768
4	5	2.5	15.46405	20.30789
4	10	0.5	15.46452	20.30919
4	10	1	15.4656	20.31219
4	10	1.5	15.46651	20.31469
4	10	2	15.46725	20.31676
4	10	2.5	15.46787	20.31847
4	15	0.5	15.46621	20.31388
4	15	1	15.46887	20.32124
4	15	1.5	15.47123	20.32778
4	15	2	15.47333	20.33357
4	15	2.5	15.47518	20.33869
4	20	0.5	15.46861	20.3205
4	20	1	15.47354	20.33415
4	20	1.5	15.47806	20.34666
4	20	2	15.48219	20.35808
4	20	2.5	15.48596	20.36851
4	25	0.5	15.4717	20.32906
4	25	1	15.4796	20.35091
4	25	1.5	15.48696	20.37128
4	25	2	15.49381	20.39024
4	25	2.5	15.50019	20.40786

7. Interpretations of results

The results indicate that the LSFAR values only increase slightly as a result of aging. The smallest increase for each location is noted if $\beta = 4$, $L = 5$ years and $T = 0.5$ years. The increase is no more than a few ppm (parts per million). The highest increase, nearly 1 percent, is noted when $\beta = 2$, $L = 25$ years and $T = 2.5$ years. Thus, the influence of aging on the total failure rate of components and subsequently on the LSFAR value appears not to be of great importance.

Different values of β, the shape parameter of the failure rate curve, were chosen based on values for real components. The increase in LSFAR appears to always be larger if $\beta = 2$ (linear shape) than if $\beta > 2$ (non-linear shape). Higher values on β seem to decrease the LSFAR. This can be understood by looking at the failure rate curves for different β fitted to the linear failure rate increase, see Figure 25.

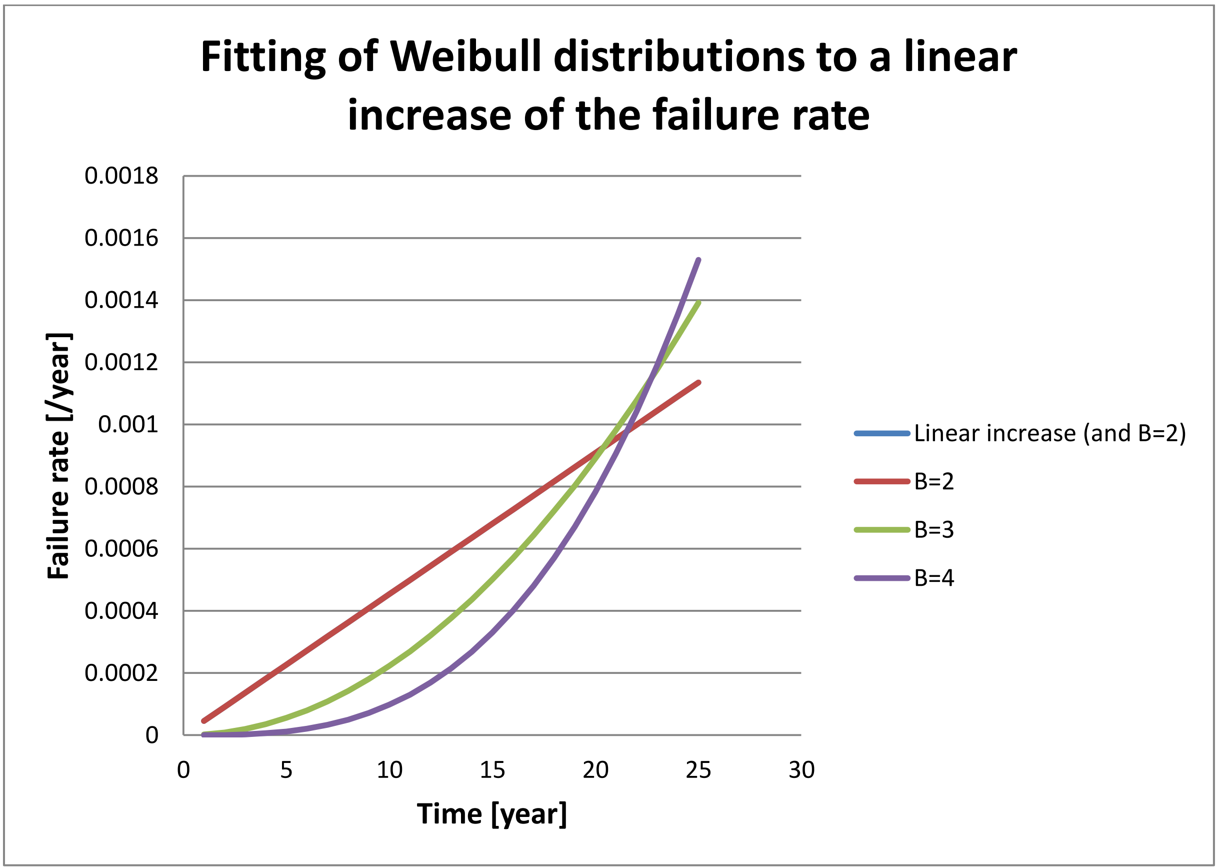

Figure 25. Fitting of Weibull distributions to a linear aging. Notice that the curve for linear increase and the Weibull distribution with β = 2 are equal.

The areas under the curves constitute the unreliability and they are smaller when β is larger. Thus, the LSFAR is also smaller. This is the case even though the failure rate is larger for $\beta > 2$ than for $\beta = 2$ (linear increase) after about 20 years in service, see Figure 25.

From Table 15 it is apparent that some sets of intervals, for example $L = 15$ years, $T = 0.5$ years and $L = 10$ years, $T = 1.5$ years, yields the same LSFAR values. This can be interpreted as: for every year that the surveillance interval is prolonged, the renewal interval needs to be decreased and vice versa in order to not get a higher LSFAR. This is illustrated in Figure 26 where similar LSFAR values are plotted in the same color.

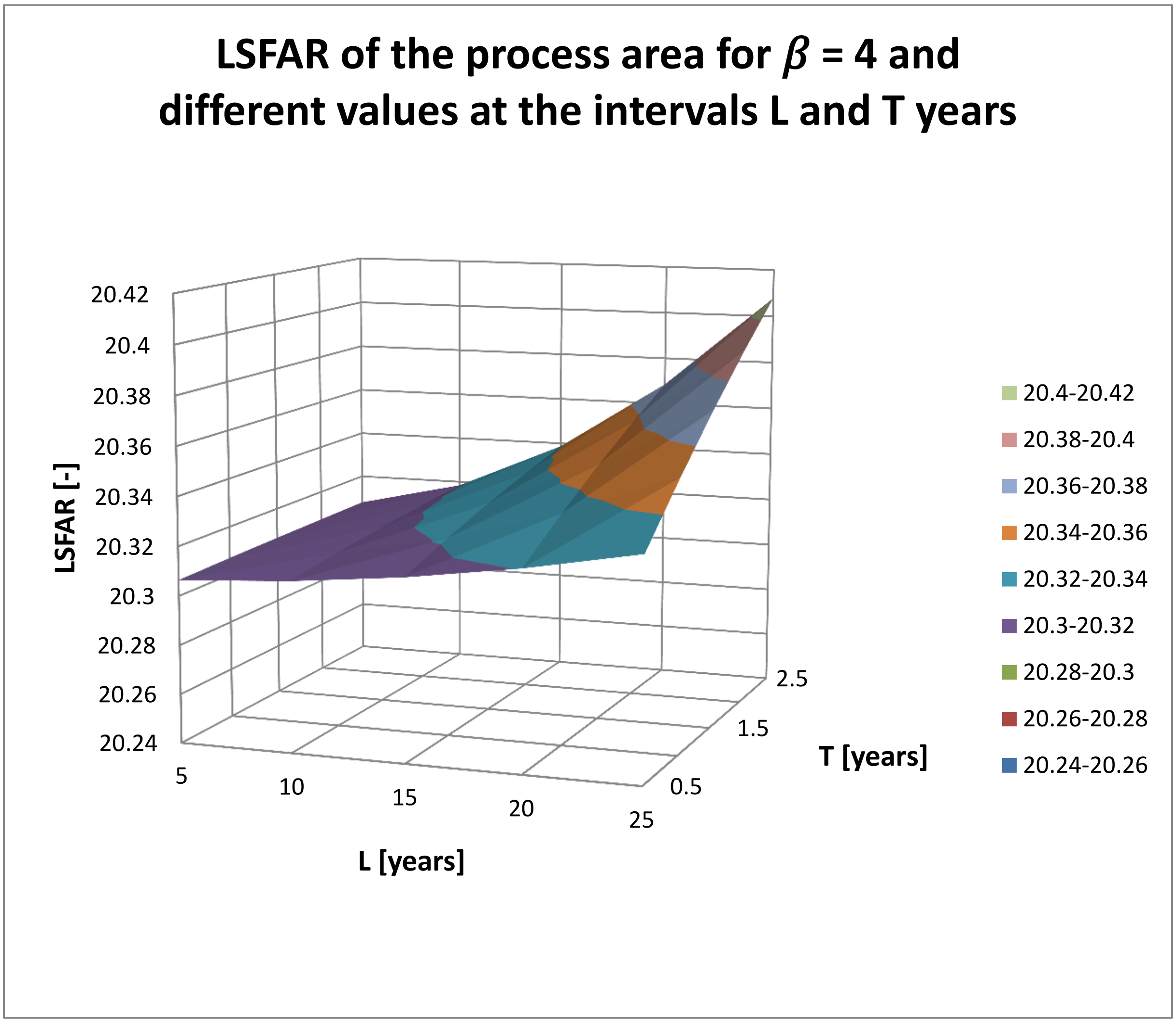

Figure 26. LSFAR of the process area for β = 4 and different values at the intervals L and T years. This type of diagram can be created with the data from Table 15 to investigate what combinations of L and T that is optimal.

7.1 Sensitivity analysis

The results contain a number of uncertainties that depend on the input data to the developed model. From Equation 34 it is apparent that the values of α and β affect the unreliability for different L and T. Different β values (2, 3 and 4) have been tested in the previous chapters and subsequently different α values have also been tested. It is possible that the linear failure rate increase due to aging ($\dot{\lambda}_{OOG}$) may be higher or lower than the estimations in Table 10. It is for that reason important to investigate how changes in $\dot{\lambda}_{OOG}$ affects the LSFAR values. Since the results from Section *6.2 LSFAR values* states that the effects of aging of components are almost negligible, a sensitivity analysis is carried out where $\dot{\lambda}_{OOG}$ is just increased and not decreased. A decrease would only result in even smaller effects.

To obtain the new $\dot{\lambda}_{OOG}$, the ratio s between $\lambda_{OOG\ 95\%}$ and λ_{OOG} is first calculated for each component, see Equation 39. $\lambda_{OOG\ 95\%}$ are in this case the 95th percentile for the OOG components (OREDA, 2002). $\dot{\lambda}_{OOG}$ is multiplied by the ratio s to get the $\dot{\lambda}_{OOG\ 95\%}$ for each component, see Equation 40:

$$s = \frac{\lambda_{OOG\ 95\%}}{\lambda_{OOG}}$$

Equation 39

$$\dot{\lambda}_{OOG} * s = \dot{\lambda}_{OOG\ 95\%}$$

Equation 40

The OOG components that are present in the database OREDA (2002) are centrifugal pump, compressor, heat exchanger, manual valve and actuated valve. The other three components: pressure vessel, pipes and instrument, are not presented in OREDA (2002). Due to this, these three components' $\dot{\lambda}_{OOG}$ are increased a factor k. The factor is calculated as the mean value from the five components on which data exists, see Equation 41:

$$k = \frac{\frac{\lambda_{1\ OOG\ 95\%}}{\lambda_{1\ OOG}} + \frac{\lambda_{2\ OOG\ 95\%}}{\lambda_{2\ OOG}} + \cdots + \frac{\lambda_{5\ OOG\ 95\%}}{\lambda_{5\ OOG}}}{5}$$

Equation 41

k is multiplied with the $\dot{\lambda}_{OOG}$ for the three components and becomes $\dot{\lambda}_{OOG\ 95\%}$ in Equation 40. New values for $\lambda_{OOG\ 95\%}$ and the estimation of $\dot{\lambda}_{OOG\ 95\%}$ are presented in Table 16.

Table 16. Data on the 95th percentile of constant failure rates taken from the database OREDA (2002). The linear failure rate increase is calculated using a difference factor (ratio s or *k*).

Component	$\lambda_{OOG\,95\,\%}$ $[10^{-6}h^{-1}]$	λ_{OOG} $[10^{-6}h^{-1}]$	Ratio (s) $\lambda_{OOG\,95\,\%}/\lambda_{OOG}$	Estimate of $\dot{\lambda}_{OOG}$ $[10^{-6}h^{-1}y^{-1}]$	Estimate of $\dot{\lambda}_{OOG\,95\%} = \frac{\lambda_{OOG\,95\%}}{\lambda_{OOG}} * \dot{\lambda}_{OOG}$ $[10^{-6}h^{-1}y^{-1}]$
Centrifugal pump	546.74 OREDA (2002)	112.64 OREDA (2002)	4.8538707	45.392238	220.34
Filter	0.3869863 OGP (2010), leaks only	0.3869863 OGP (2010), leaks only	1	-	-
Compressor	1171.64 OREDA (2002)	474 OREDA (2002)	2.4718143	2.5788900	6.37
Pressure vessel	0.475 OGP (2010), leaks only multiplied with *k*.	0.16552 OGP (2010), leaks only	2.8697438	3.9362663E-6	0.0000114
Heat exchanger (type: hydrocarbon tube)	188.25 OREDA (2002)	69.62 OREDA (2002)	2.7039643	3.6532233	9.79
Pipes	0.0688 OGP (2010), leaks only multiplied with *k*. $[10^{-6}h^{-1}m^{-1}]$	0.0239726 OGP (2010), leaks only $[10^{-6}h^{-1}m^{-1}]$	2.8699431	0.8696227 $[10^{-6}h^{-1}y^{-1}m^{-1}]$	2.50 $[10^{-6}h^{-1}y^{-1}m^{-1}]$
Instrument	0.1769 OGP (2010), leaks only multiplied with *k*.	0.06164384 OGP (2010), leaks only	2.8697109	0.01256809	0.0361
Flange	0.0239726 OGP (2010), leaks only	0.0239726 OGP (2010), leaks only	1	-	-
Manual valve	0.8599 OREDA (2002), assuming same proportion between Manual and Actuated valve as in Table 8	0.3977053 OREDA (2002), assuming same proportion between Manual and Actuated valve as in Table 8	2.1621537	0.00672031	0.0145
Actuated valve	67.14 OREDA (2002)	31.05 OREDA (2002)	2.162318	0.39710960	0.859

New α values are adapted in the same way as in Section *4.2 Development of an adjusted model*, and the aging contribution to the unreliability is calculated in *Python 3.3.2*, see Appendix C. Finally, the new LSFAR values are calculated and presented in Table 17.

Table 17. LSFAR values for the wellhead area and the process area calculated with new aging affected failure rates.

β	L $[year]$	T $[year]$	LSFAR Wellhead area $[-]$	LSFAR Process area $[-]$
2	5	0.5	15.49884415	20.41357258
2	5	1	15.53198836	20.51402879
2	5	1.5	15.56266749	20.60700916
2	5	2	15.59088448	20.69252397
2	5	2.5	15.616641	20.77057895
2	10	0.5	15.49944928	20.41540275
2	10	1	15.5344092	20.52135072
2	10	1.5	15.56811563	20.62348799
2	10	2	15.60057316	20.7218306
2	10	2.5	15.63178574	20.81639229
2	15	0.5	15.49964494	20.41599179
2	15	1	15.53519199	20.52370745
2	15	1.5	15.56987739	20.62879247
2	15	2	15.60370631	20.73126501
2	15	2.5	15.63668347	20.83114162
2	20	0.5	15.49973824	20.41627056
2	20	1	15.5355653	20.52482302
2	20	1.5	15.57071763	20.63130382
2	20	2	15.60520073	20.73573244
2	20	2.5	15.63901977	20.83812705
2	25	0.5	15.4997906	20.41642524
2	25	1	15.53577483	20.52544222
2	25	1.5	15.57118932	20.63269828
2	25	2	15.60603981	20.73821393
2	25	2.5	15.64033175	20.84200858
β	L $[year]$	T $[year]$	LSFAR Wellhead area $[-]$	LSFAR Process area $[-]$
3	5	0.5	15.46868227	20.32215042
3	5	1	15.47310939	20.33556941
3	5	1.5	15.476693	20.34643153
3	5	2	15.47961399	20.35528514
3	5	2.5	15.48205311	20.3626782
3	10	0.5	15.47468876	20.34035584
3	10	1	15.48502752	20.3716907
3	10	1.5	15.49433897	20.39991017
3	10	2	15.50271481	20.42529289

3	10	2.5	15.51024647	20.44811639
3	15	0.5	15.48070026	20.35857415
3	15	1	15.49700661	20.40798811
3	15	1.5	15.5122142	20.45406523
3	15	2	15.526387	20.49700113
3	15	2.5	15.53958844	20.53698951
3	20	0.5	15.48670661	20.37677349
3	20	1	15.508976	20.44424308
3	20	1.5	15.53009205	20.5082
3	20	2	15.55010726	20.56880682
3	20	2.5	15.56907333	20.62622327
3	25	0.5	15.49270373	20.3949403
3	25	1	15.52091332	20.48038363
3	25	1.5	15.5479088	20.56211245
3	25	2	15.57373846	20.64027939
3	25	2.5	15.59844956	20.71503312
$\boldsymbol{\beta}$	**L** $[year]$	**T** $[year]$	**LSFAR Wellhead area** $[-]$	**LSFAR Process area** $[-]$
4	5	0.5	15.46407117	20.30817359
4	5	1	15.46465643	20.30994761
4	5	1.5	15.46505631	20.31115971
4	5	2	15.46533438	20.31200255
4	5	2.5	15.46554782	20.31264954
4	10	0.5	15.46688473	20.31670173
4	10	1	15.46995372	20.32600386
4	10	1.5	15.47251261	20.33375963
4	10	2	15.47463313	20.34018659
4	10	2.5	15.47638373	20.34549233
4	15	0.5	15.47168162	20.33124042
4	15	1	15.47921183	20.35406138
4	15	1.5	15.48589956	20.37432694
4	15	2	15.49182055	20.39226745
4	15	2.5	15.49704809	20.40810553
4	20	0.5	15.47845552	20.35176758
4	20	1	15.49240757	20.39403923
4	20	1.5	15.50517094	20.43269912
4	20	2	15.51682704	20.46799679
4	20	2.5	15.52745467	20.50017324
4	25	0.5	15.48719395	20.37824003
4	25	1	15.50949337	20.44577293
4	25	1.5	15.53022488	20.50852484
4	25	2	15.54948074	20.56678308
4	25	2.5	15.50019	20.40786

The results in Table 17 show that the LSFAR values in the sensitivity analysis only increase slightly from the LSFAR values calculated without taking aging into account, see Table 14. This is the case even though the aging effect was increased. The smallest increase of LSFAR for each location is noted if $\beta = 4$, $L = 5$ years and $T = 0.5$ years. The increase is no more than a few ppm. The highest increase, nearly 3 percent, is noted when $\beta = 2$, $L = 25$ years and $T = 2.5$ years. Thus, the influence of aging on the total failure rate of components and subsequently on the LSFAR value appears not to be of great importance even when 95th percentile failure rates are used.

8. Discussion

This chapter discusses the choice of method in this thesis and how the work has progressed. Important assumptions, delimitations and approximations that have been made are highlighted, along with the potential effects they may have on the results. The chapter also reflects thoughts and opinions from the authors.

8.1 The workflow and choice of methods

The aim with this thesis has during the whole process been to investigate the influence of aging of mechanical components on the risk level on an OOG platform. The chosen risk measure has since the beginning been the fatal accident rate for specific locations on the platform (LSFAR) The aim has also been to investigate how maintenance of the components can be incorporated in future analysis. At first the plan was to define a simplified, modeled platform and perform a risk analysis using constant failure rates for components. The idea was then to compare it with a risk analysis where the aging effects on the components were taken into consideration. This has all been carried out in the thesis and the aging influence as well as the incorporation of the maintenance has been integrated in a developed aging model, see Chapter *4. Development of an aging model*. However, some adjustments of the workflow have been done during the process. It was first intended to collect data from databases derived from OOG component statistics on aging of components. The collected data though, was not as detailed as expected so the aging effects could not be evaluated. An alternative approach was necessary to use. The data on aging was instead estimated and translated from data available for NPP components. The impact of these estimations and translations on the results is discussed in the following sections. The risk analysis was from the beginning also intended to include components of the safety systems. Detailed process flow charts were not applicable on the simplified, modeled platform and more simplifications were therefore carried out regarding these systems. The impact of these simplifications is also discussed in the following sections.

Defining a simplified model platform is a difficult task. Decisions has to be taken regarding the structure of the platform, the process flow and what components to include and exclude. Every platform is unique and the simplifications can lead to an omission of potential threats along the way. However, a risk analysis always includes simplifications and judgments and the approach of using a modeled, simplified platform is by the authors not considered to be neither better nor worse than any other method. It would possible to use a real platform and perform the analysis on that one, but the results would not necessarily be more applicable on other platforms. Problems can also arise regarding classified information of the platform.

The modeled platform, which was based on the experience of consultants from real projects, could perhaps have been defined by investigating standards and regulations on platforms in the North Sea. Different platforms can however be subject to different regulations depending on their design and purpose. It is difficult to select which standard or regulation that is more appropriate than others.

Since it was difficult to find the correct data on components regarding aging, one can wonder if it would have been possible to collect the data in other ways, for example by studying a number of platforms during a long period of time. The aging phenomenon is however seen after several years and this approach would therefore not be possible in this thesis due to the time constraints. The fact that data has to be collected for a long period of time can itself be a problem. If data on aging was to be collected starting today, how can we be certain that the same technology and machinery will be used in similar components in the future? In other words, it takes time to gather data on aging of components, and when finally trustworthy data is available the technology might have changed and the data might not be applicable anymore. Other conditions might also change. The environment in which the components operate might become tougher, for example drilling in the Arctic. As was mentioned in Section *3.6 Aging*, this might affect how fast components age. This is an important topic to consider when aging is included in a risk analysis.

The scope of the work was from the beginning to only include mechanical components and excluding other parameters such as change in the organization or loss of competence when experienced personnel retire. Since the effects of the aging of mechanical components only slightly influenced the LSFAR, it might be possible to include other parameters to see if they have a larger impact. This could be done by for example doing a more qualitative analysis rather than a quantitative one.

8.2 The aging model

Although it was difficult to find data on how the failure rate of OOG components increase due to aging, the adjusted model that was developed in *4.2 Development of an adjusted model* is still valid. If better data is available, this can be used in the model to get better results. If one wants to perform a risk analysis on a life extended platform and one has access to the platform's process flow charts and component maintenance data, this information can be used in the adjusted model. More advanced fault trees can be designed and safety systems can be included in these. Because this was not possible to do in this thesis, absolute values from the results are associated with uncertainties. However, the difference between the results obtained using constant failure rates and aging increased failure rates is more accurate, because the same uncertainties apply to both cases.

In the aging model it is assumed that the unreliability due to constant failure rate can be added to the unreliability due to aging increased failure rate. The constant failure rate is however likely to include some maintenance as it is collected from practical applications where maintenance has probably been performed. How much maintenance that has been carried out and how this has affected the constant failure rate is difficult to determine. It is assumed that the unreliabilities can be added although some maintenance might be overlapping. This ought to lead to an over estimation of the final results of the increase in LSFAR (1 %).

8.3 The results

The results indicate that the LSFAR values only increase slightly as a result of aging. The largest increase is about 3 % and this is the case when the 95th percentile data on constant failure rates is used in the model. Thus, it is not possible to say that the practice of using constant failure rates in QRA performed on aging platforms is incorrect. If better data is available, the interpolation step in the model is not necessary to make and the increase in LSFAR might be more pronounced.

For one component type, namely "instrument", the failure rate appears to be higher for NPP components than for OOG components. For all other components the opposite holds true. One possible explanation for this is that not all failures in Table 8 and Table 9 have the same failure modes. In Table 9 (constant failure rates for OOG components) a few components only have "leaks" as failure mode. This leads to an underestimation of some data in this table, as more failure modes than leaks exist indeed. Comparing failure rates for different failure modes is thus not optimal. If the appropriate data is lacking however, it at least constitutes a "best case" of failure rates.

The software code for the *MATLAB* and *Python* programs can contain errors. Software errors (also known as "bugs") are errors which make the program produce incorrect or unexpected results. The bugs can be, for example, syntactic errors or incorrect choice of methods. Most syntactic errors should be discovered by the interpreter itself, for example spelling errors, but it is possible to produce errors which the interpreter regards as intentional. For example, if "=" is used to compare if two variables hold equal values, one is in fact assigned the value of the other. When comparing variables, a double "==" should be used. Incorrect choice of methods can be, for example, to use the wrong built-in function like the integral solver. When developing the program it was noticed that different results were produced when solving the integral in Equation 34 with two different built-in integral solvers. First, the double integral solver function (*Python*: dblquad) was used because the integral in Equation 34 was a double integral. However, this function produced unexpected results. When L and T were increased, the unreliability decreased. This was deemed unreasonable, as longer renewal and surveillance intervals should increase the unreliability. The program was further investigated, but errors could not be found. The integral was then solved with a single integral solver function (*Python*: quad) by first solving the inner integral and then the outer integral. This produced results that seemed reasonable. When L and T were increased, so was the unreliability.

The sensitivity analysis only investigates the increase in **failure rate** due to aging. Other variables that can be altered in a sensitivity analysis are for example the leak sizes, what chemicals that are used, what limits that are considered fatal and weather data. The efficiency of renewals and surveillance can also be adjusted within reasonable boundaries. Although this adjustment was not done (due to time constraints), it is possible to see the effect of it by looking at the LSFAR values in Table 15. As was mentioned in Section *4.1.1 Limitations,* the efficiency can be adjusted by dividing L and T with a number between zero and one. The first row in Table 15 show the LSFAR values when $L = 5, T = 0.5$ and $\beta = 2$. If the efficiency of L and T now are set to only be 20 %, the new "effective" L would equal 25 and T would equal 2.5. This set of L and T can however be seen in the last row of Table 15 (with $\beta = 2$).

Although the efficiency is set to only 20 % instead of 100 % (the default case), the increase in LSFAR still only amounts to about 0.7 %.

9. Conclusions

This chapter attempts to answer the research questions and give recommendations based on them. Suggestions on further research are also given.

The specific research questions were:

1. How are the failure rates of mechanical components on the modeled platform affected by aging?

2. How can component renewal and surveillance be incorporated into future quantitative risk analyses?

3. How is LSFAR affected by aging?

The first question (1) is not possible to answer quantitatively in this thesis because data was not found on how the failure rate increases due to aging. However, qualitatively it can be said that the failure rates of the components in theory should be Weibull-shaped with $2 \leq \beta \leq 4$.

The second question (2) was answered by developing an aging model where the unreliability could be solved for different renewal (L) and surveillance (T) intervals. If the data that was missing in the first question is available, it can be adapted to a Weibull distribution where α and β is determined and then inserted into the model along with the L and T intervals of interest.

The third question (3) was answered by calculating the LSFAR values with constant failure rates and with aging increased failure rates. The results indicate that the LSFAR values only increase slightly as a result of aging. The largest increase as a result of aging was almost 1 % when mean values of the constant failure rates were used. When the 95th percentile data on constant failure rates were used, the increase was about 3 %. Thus, it is not possible to say that the practice of using constant failure rates in QRA performed on aging platforms is incorrect. If better data is available, the assumptions and interpolation that was necessary to make in Section *4.2 Development of an adjusted model* can be avoided and the aging might become more pronounced.

9.1 Further research

The largest obstacle when using the aging model in this thesis was finding appropriate aging data. It appears as if failure data is regarded as precious property of manufacturers. If one can get data from manufacturer on all components of interest, this can be used in the aging model. Detailed maintenance records that show at what time a component has failed and with what failure mode can be used to estimate such data.

Most fatal accidents are not due to hydrocarbon releases but rather due to work environment related factors. These factors along with changes in regulations, organizations and loss of competence due to life extension of OOG platforms are suggested to be studied further.

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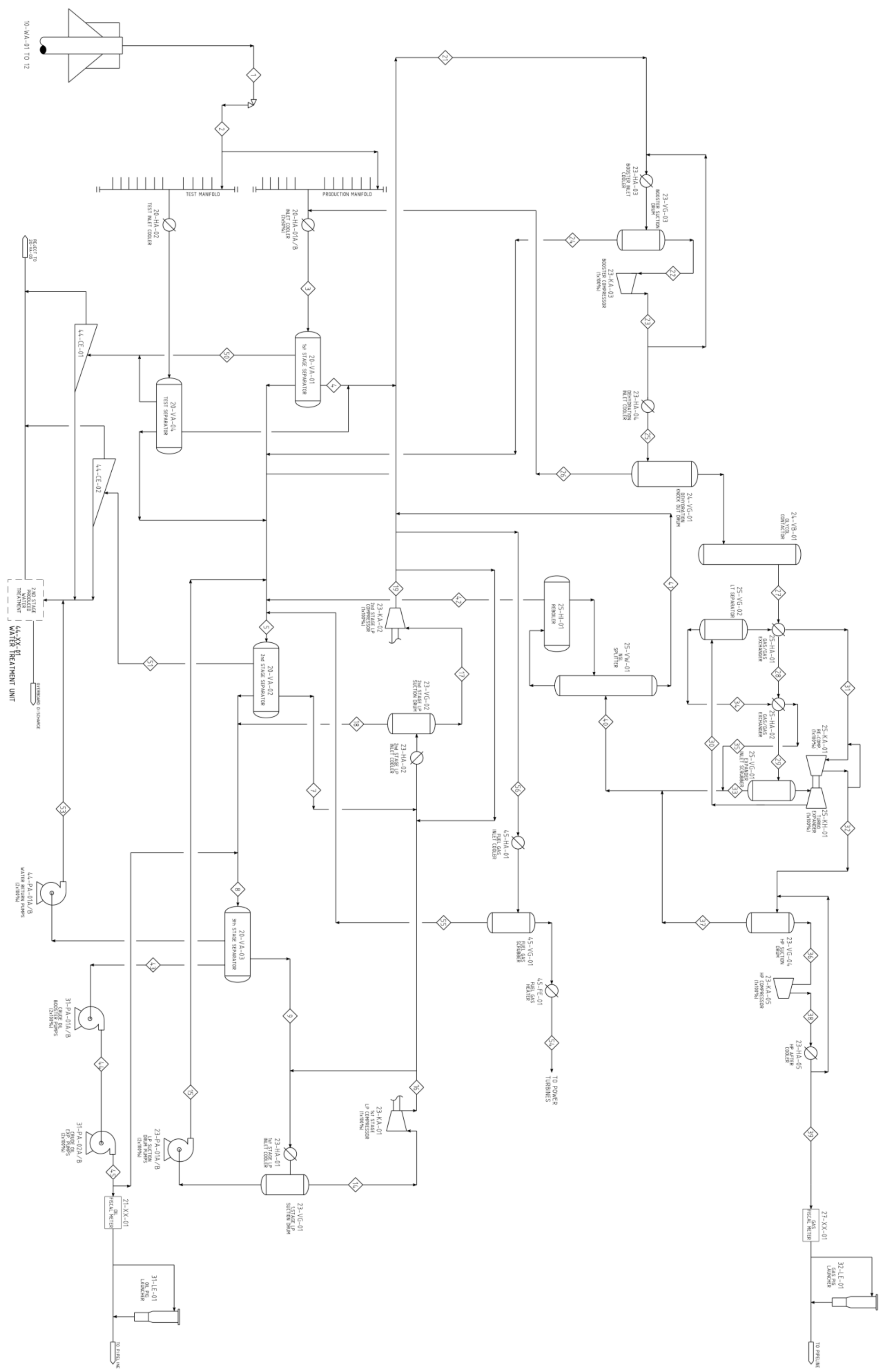
Appendix A

This simplified process flow diagram can be found at:
<https://www.dropbox.com/sh/ki5wm3dboduj763/PhAYudQcg0>



Appendix B

```
% File: least_squares_fitting.m

function results = lsf(a)

% Create a one-dimensional matrix of the years 1 to 25
x=[1:25];

% Transpose the matrix
x=x.';

% Create a new one-dimensional matrix containing the linear (a) increase in
% failure rate
y=[x*a];

% Set the first value of beta
beta=2;
while(beta <= 4)

    % Create a polynom with the same exponents as the Weibull failure
    % frequency
    A=[x.^(beta-1)];

    % Perform the least squares fitting of the polynom to the linear
    % increase (a)
    c=A\y;
    alfa=(beta/c).^(1/(beta))

    % Increase beta to next value
    beta = beta + 1;
end
end
```

In *MATLAB* shell:
Call least_squares_fitting.m with `least_squares_fitting(`$\dot{\lambda}_{aging}$`)`.

Appendix C

```
# File: delta_q.py
# Import needed libraries.
from __future__ import division
from scipy import *
import scipy.integrate as si

def dbl_integral_delta_q(L,T,alpha,beta,comp):

    # This function yields unexpected values on the unavailability.
    # When L and T is increased, the unavailability is decrased.
    # q is defined as the double integral of the Weibull failure frequency from t0 to t0+u
    q=lambda u,t: (1./(L-T))*(1./(T))*(1.-exp(comp*((t**beta)*(alpha**(-beta))-((t+u)**beta)*(alpha**(-beta)))))
    gfun = lambda u: 0
    hfun = lambda u: L-T
    result = si.dblquad(q,0,T,gfun,hfun)[0]
    return result

def integral_delta_q(L,T,alpha,beta,comp):

    # q is defined as the integral of the Weibull failure frequency from t0 to t0+u.
    q=lambda u,t: 1.-exp(comp*((t**beta)*(alpha**(-beta))-((t+u)**beta)*(alpha**(-beta))))
    return (1./(L-T))*si.quad(lambda t:(1./T)*si.quad(lambda u:q(u,t),0,T)[0],0,L-T)[0]

def delta_q(alpha,beta,comp):

    # Reset L and results.
    L=0.0
    result = ''
    results = ''
    while(L < 25):

        # Increase L by steps of 5 years.
        L = L + 5

        # Reset T for the L years.
        T = 0.0
        while (T < 2.5):

            # Increase T by steps of 0.5 years.
            T = T + 0.5

            # If the double integral solver is to be used, uncomment the next line and
            # comment out the line after that.
            # result = dbl_integral_delta_q(L,T,alpha,beta,comp).
            result = integral_delta_q(L,T,alpha,beta,comp)

            # Adapt the result to suitable Excel format
            result = "%.12f" % result
            results = results + result + '\t'
    results = results + '\t\t\t\t\t\t\t\t'

    # Write the results to a text file.
    f = open('C:\Temp\winpy\q_output.txt', 'a')
    f.write(results)

# Replace "..." with values on alpha (estimated in the MATLAB program).
# comp = "Number of components".
comp = ...
delta_q(alpha=...,beta=2,comp)
delta_q(alpha=...,beta=3,comp)
delta_q(alpha=...,beta=4,comp)
```

In command line shell:
Call “python delta_q.py” to generate “q_output.txt”.

Appendix D

SITE DATA:
Location: NORTH SEA, NORTH SEA
Building Air Exchanges Per Hour: 1.33 (sheltered single storied)
Time: August 8, 2013 0800 hours ST (user specified)

CHEMICAL DATA:
Chemical Name: N-OCTANE Molecular Weight: 114.23 g/mol
PAC-1: 300 ppm PAC-2: 385 ppm PAC-3: 5000 ppm
IDLH: 1000 ppm LEL: 9600 ppm UEL: 65000 ppm
Ambient Boiling Point: 125.6° C
Vapor Pressure at Ambient Temperature: 0.0075 atm
Ambient Saturation Concentration: 7,538 ppm or 0.75%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
Wind: 10 meters/second from W at 20 meters
Ground Roughness: open water Cloud Cover: 5 tenths
Air Temperature: 10° C Stability Class: D
No Inversion Height Relative Humidity: 75%

SOURCE STRENGTH:
Direct Source: 48.1 kilograms/sec Source Height: 0
Release Duration: 10 minutes
Release Rate: 2,890 kilograms/min
Total Amount Released: 28,860 kilograms

Appendix E

The data in this appendix can be downloaded as Excel files at:
<https://www.dropbox.com/sh/ki5wm3dboduj763/PhAYudQcg0>

(λ [ignitions/year] constant average for all component types)

	WELLHEAD		
Ignition Probabilities	0,004	0,009	0,013
	λ(konst|<10mm)	λ(konst|10-25mm)	λ(konst|>25mm)
	0,001363	0,00047655	0,00017875

PROCESS								
Wellstream separation								
1st stage separator			2nd stage separator			3rd stage separator		
0,004	0,009	0,013	0,03	0,0065	0,009	0,0017	0,0036	0,0052
λ(konst|<10mm)	λ(konst|10-25mm)	λ(konst|>25mm)	λ(konst|<10mm)	λ(konst|10-25mm)	λ(konst|>25mm)	λ(konst|<10mm)	λ(konst|10-25mm)	λ(konst|>25mm)
0,000294667	0,00010113	4,901E-05	0,00221	7,30383E-05	3,393E-05	0,000125233	0,000040452	1,9604E-05
Gas processing & export						Oil processing & export		
Gas			Liquid			Liquid		
0,0065	0,0195	0,03	0,0052	0,011	0,0174	0,0027	0,0053	0,0085
λ(konst|<10mm)	λ(konst|10-25mm)	λ(konst|>25mm)	λ(konst|<10mm)	λ(konst|10-25mm)	λ(konst|>25mm)	λ(konst|<10mm)	λ(konst|10-25mm)	λ(konst|>25mm)
0,0040131	0,00188448	0,0009285	0,00066872	0,00023221	0,000115536	0,000377325	0,00010706	5,644E-05

Appendix F

The data in this appendix can be downloaded as Excel files at:
<https://www.dropbox.com/sh/ki5wm3dboduj763/PhAYudQcg0>

WELLHEAD			PROCESS					
						Wellstream separation		
					1st stage separator (liquid is worst of the 2phase)			
	Ignition Probabilities	0,004	0,009	0,013	0,004	0,009	0,013	
L	T	λ(aged|<10mm)	λ(aged|10-25mm)	λ(aged|>25mm)	λ(aged|<10mm)	λ(aged|10-25mm)	λ(aged|>25mm)	
5	0,5	0,00136319	0,000476978	0,000179368	0,000294724	0,000101259	4,91958E-05	
5	1	0,001363367	0,000477377	0,000179944	0,000294777	0,000101378	4,93688E-05	
5	1,5	0,001363531	0,000477746	0,000180477	0,000294826	0,000101489	4,9529E-05	
5	2	0,001363682	0,000478085	0,000180968	0,000294872	0,000101591	4,96764E-05	
5	2,5	0,00136382	0,000478395	0,000181415	0,000294913	0,000101684	4,98109E-05	
10	0,5	0,001363194	0,000476986	0,000179379	0,000294725	0,000101261	4,9199E-05	
10	1	0,001363381	0,000477406	0,000179987	0,000294781	0,000101387	4,93816E-05	
10	1,5	0,001363561	0,000477812	0,000180573	0,000294835	0,000101509	4,95578E-05	
10	2	0,001363735	0,000478203	0,000181137	0,000294887	0,000101627	4,97276E-05	
10	2,5	0,001363902	0,000478579	0,000181681	0,000294938	0,00010174	4,98909E-05	
15	0,5	0,001363195	0,000476988	0,000179383	0,000294725	0,000101262	4,92001E-05	
15	1	0,001363385	0,000477416	0,000180001	0,000294782	0,00010139	4,93859E-05	**Beta = 2**
15	1,5	0,001363571	0,000477834	0,000180604	0,000294838	0,000101516	4,95674E-05	
15	2	0,001363752	0,000478242	0,000181193	0,000294893	0,000101639	4,97446E-05	
15	2,5	0,001363929	0,000478639	0,000181768	0,000294946	0,000101758	4,99176E-05	
20	0,5	0,001363195	0,000476989	0,000179384	0,000294725	0,000101262	4,92006E-05	
20	1	0,001363387	0,000477421	0,000180008	0,000294783	0,000101392	4,9388E-05	
20	1,5	0,001363575	0,000477844	0,00018062	0,00029484	0,000101519	4,95722E-05	
20	2	0,00136376	0,000478261	0,000181221	0,000294895	0,000101644	4,97531E-05	
20	2,5	0,001363942	0,000478669	0,000181811	0,00029495	0,000101768	4,99308E-05	
25	0,5	0,001363195	0,00047699	0,000179385	0,000294725	0,000101262	4,92009E-05	
25	1	0,001363388	0,000477423	0,000180012	0,000294783	0,000101393	4,93893E-05	
25	1,5	0,001363578	0,000477851	0,000180629	0,000294841	0,000101521	4,9575E-05	
25	2	0,001363765	0,000478272	0,000181237	0,000294897	0,000101648	4,97582E-05	
25	2,5	0,00136395	0,000478687	0,000181837	0,000294952	0,000101773	4,99388E-05	
L	T							
5	0,5	0,001363029	0,000476616	0,000178845	0,000294675	0,00010115	4,90384E-05	
5	1	0,001363053	0,000476669	0,000178922	0,000294683	0,000101166	4,90615E-05	
5	1,5	0,001363072	0,000476712	0,000178984	0,000294688	0,000101179	4,90803E-05	
5	2	0,001363088	0,000476747	0,000179034	0,000294693	0,000101189	4,90955E-05	
5	2,5	0,001363101	0,000476776	0,000179077	0,000294697	0,000101198	4,91082E-05	
10	0,5	0,001363061	0,000476688	0,000178949	0,000294685	0,000101171	4,90698E-05	
10	1	0,001363116	0,000476812	0,000179129	0,000294702	0,000101209	4,91238E-05	
10	1,5	0,001363166	0,000476924	0,00017929	0,000294717	0,000101242	4,91724E-05	
10	2	0,001363211	0,000477025	0,000179436	0,00029473	0,000101273	4,92162E-05	
10	2,5	0,001363251	0,000477116	0,000179567	0,000294742	0,0001013	4,92556E-05	
15	0,5	0,001363093	0,00047676	0,000179053	0,000294695	0,000101193	4,91012E-05	
15	1	0,001363181	0,000476956	0,000179337	0,000294721	0,000101252	4,91864E-05	
15	1,5	0,001363262	0,000477139	0,000179601	0,000294745	0,000101307	4,9266E-05	**Beta = 3**
15	2	0,001363338	0,00047731	0,000179848	0,000294768	0,000101359	4,93402E-05	
15	2,5	0,001363409	0,000477469	0,000180078	0,00029479	0,000101407	4,94094E-05	
20	0,5	0,001363126	0,000476832	0,000179158	0,000294704	0,000101215	4,91326E-05	
20	1	0,001363245	0,000477101	0,000179545	0,00029474	0,000101296	4,92492E-05	
20	1,5	0,001363358	0,000477355	0,000179913	0,000294774	0,000101372	4,93599E-05	
20	2	0,001363465	0,000477597	0,000180262	0,000294807	0,000101445	4,9465E-05	
20	2,5	0,001363567	0,000477826	0,000180594	0,000294837	0,000101514	4,95648E-05	
25	0,5	0,001363158	0,000476905	0,000179262	0,000294714	0,000101237	4,9164E-05	
25	1	0,001363309	0,000477245	0,000179754	0,00029476	0,000101339	4,93119E-05	
25	1,5	0,001363454	0,000477571	0,000180225	0,000294803	0,000101437	4,94539E-05	
25	2	0,001363593	0,000477884	0,000180677	0,000294845	0,000101532	4,95901E-05	
25	2,5	0,001363726	0,000478184	0,00018111	0,000294885	0,000101622	4,97208E-05	
L	T							
5	0,5	0,001363004	0,00047656	0,000178765	0,000294668	0,000101133	4,90144E-05	
5	1	0,001363008	0,000476567	0,000178775	0,000294669	0,000101135	4,90174E-05	
5	1,5	0,00136301	0,000476572	0,000178782	0,00029467	0,000101137	4,90195E-05	
5	2	0,001363011	0,000476575	0,000178787	0,00029467	0,000101138	4,9021E-05	
5	2,5	0,001363012	0,000476578	0,00017879	0,00029467	0,000101138	4,90221E-05	
10	0,5	0,00136302	0,000476594	0,000178813	0,000294673	0,000101143	4,90291E-05	
10	1	0,001363036	0,000476631	0,000178867	0,000294677	0,000101154	4,90451E-05	
10	1,5	0,00136305	0,000476662	0,000178911	0,000294682	0,000101164	4,90584E-05	
10	2	0,001363061	0,000476687	0,000178948	0,000294685	0,000101171	4,90695E-05	
10	2,5	0,00136307	0,000476708	0,000178978	0,000294688	0,000101178	4,90786E-05	
15	0,5	0,001363045	0,000476652	0,000178897	0,00029468	0,000101161	4,90541E-05	
15	1	0,001363085	0,000476742	0,000179028	0,000294692	0,000101188	4,90934E-05	**Beta = 4**
15	1,5	0,001363121	0,000476823	0,000179144	0,000294703	0,000101212	4,91283E-05	
15	2	0,001363153	0,000476894	0,000179247	0,000294713	0,000101233	4,91593E-05	
15	2,5	0,001363181	0,000476957	0,000179338	0,000294721	0,000101252	4,91866E-05	
20	0,5	0,001363081	0,000476733	0,000179015	0,000294691	0,000101185	4,90895E-05	
20	1	0,001363156	0,000476901	0,000179257	0,000294714	0,000101236	4,91624E-05	
20	1,5	0,001363224	0,000477055	0,00017948	0,000294734	0,000101282	4,92293E-05	
20	2	0,001363287	0,000477196	0,000179683	0,000294753	0,000101324	4,92905E-05	
20	2,5	0,001363344	0,000477324	0,000179868	0,00029477	0,000101363	4,93463E-05	
25	0,5	0,001363128	0,000476838	0,000179167	0,000294705	0,000101217	4,91352E-05	
25	1	0,001363248	0,000477108	0,000179555	0,000294741	0,000101298	4,92522E-05	
25	1,5	0,001363359	0,000477358	0,000179918	0,000294775	0,000101373	4,93613E-05	
25	2	0,001363463	0,000477592	0,000180255	0,000294806	0,000101444	4,9463E-05	
25	2,5	0,00136356	0,000477809	0,000180569	0,000294835	0,000101509	4,95576E-05	

PROCESS								
Wellstream separation								
		2nd stage separator			3rd stage separator			
	Ignition Probabilities	0,03	0,0065	0,009	0,0017	0,0036	0,0052	
L	T	λ(aged|<10mm)	λ(aged|10-25mm)	λ(aged|>25mm)	λ(aged|<10mm)	λ(aged|10-25mm)	λ(aged|>25mm)	
5	0,5	0,002210429	7,31312E-05	3,40586E-05	0,000125258	4,05035E-05	1,96783E-05	
5	1	0,002210828	7,32177E-05	3,41784E-05	0,00012528	4,05514E-05	1,97475E-05	
5	1,5	0,002211198	7,32978E-05	3,42893E-05	0,000125301	4,05957E-05	1,98116E-05	
5	2	0,002211538	7,33715E-05	3,43913E-05	0,00012532	4,06365E-05	1,98705E-05	
5	2,5	0,002211848	7,34388E-05	3,44845E-05	0,000125338	4,06738E-05	1,99244E-05	
10	0,5	0,002210436	7,31328E-05	3,40609E-05	0,000125258	4,05043E-05	1,96796E-05	
10	1	0,002210858	7,32241E-05	3,41873E-05	0,000125282	4,05549E-05	1,97526E-05	
10	1,5	0,002211264	7,33122E-05	3,43093E-05	0,000125305	4,06037E-05	1,98231E-05	
10	2	0,002211656	7,33971E-05	3,44268E-05	0,000125327	4,06507E-05	1,9891E-05	
10	2,5	0,002212033	7,34788E-05	3,45399E-05	0,000125349	4,0696E-05	1,99564E-05	
15	0,5	0,002210439	7,31334E-05	3,40616E-05	0,000125258	4,05046E-05	1,968E-05	
15	1	0,002210867	7,32263E-05	3,41902E-05	0,000125282	4,05561E-05	1,97544E-05	
15	1,5	0,002211286	7,3317E-05	3,43159E-05	0,000125306	4,06064E-05	1,9827E-05	**Beta = 2**
15	2	0,002211695	7,34056E-05	3,44386E-05	0,000125329	4,06554E-05	1,98978E-05	
15	2,5	0,002212094	7,34921E-05	3,45583E-05	0,000125352	4,07033E-05	1,9967E-05	
20	0,5	0,00221044	7,31336E-05	3,4062E-05	0,000125258	4,05048E-05	1,96802E-05	
20	1	0,002210872	7,32273E-05	3,41917E-05	0,000125283	4,05567E-05	1,97552E-05	
20	1,5	0,002211297	7,33194E-05	3,43192E-05	0,000125307	4,06077E-05	1,98289E-05	
20	2	0,002211715	7,34099E-05	3,44445E-05	0,000125331	4,06578E-05	1,99012E-05	
20	2,5	0,002212125	7,34988E-05	3,45675E-05	0,000125354	4,0707E-05	1,99723E-05	
25	0,5	0,002210441	7,31338E-05	3,40622E-05	0,000125258	4,05049E-05	1,96804E-05	
25	1	0,002210875	7,3228E-05	3,41926E-05	0,000125283	4,0557E-05	1,97557E-05	
25	1,5	0,002211304	7,33208E-05	3,43212E-05	0,000125307	4,06085E-05	1,983E-05	
25	2	0,002211727	7,34124E-05	3,4448E-05	0,000125331	4,06592E-05	1,99033E-05	
25	2,5	0,002212143	7,35027E-05	3,4573E-05	0,000125355	4,07092E-05	1,99755E-05	
L	T							
5	0,5	0,002210066	7,30526E-05	3,39497E-05	0,000125237	4,04599E-05	1,96154E-05	
5	1	0,002210119	7,30641E-05	3,39657E-05	0,00012524	4,04663E-05	1,96246E-05	
5	1,5	0,002210162	7,30735E-05	3,39786E-05	0,000125243	4,04715E-05	1,96321E-05	
5	2	0,002210197	7,30811E-05	3,39892E-05	0,000125245	4,04757E-05	1,96382E-05	
5	2,5	0,002210227	7,30874E-05	3,3998E-05	0,000125246	4,04792E-05	1,96433E-05	
10	0,5	0,002210138	7,30682E-05	3,39714E-05	0,000125241	4,04686E-05	1,96279E-05	
10	1	0,002210263	7,30952E-05	3,40088E-05	0,000125248	4,04835E-05	1,96495E-05	
10	1,5	0,002210375	7,31195E-05	3,40424E-05	0,000125255	4,0497E-05	1,9669E-05	
10	2	0,002210476	7,31414E-05	3,40727E-05	0,00012526	4,05091E-05	1,96865E-05	
10	2,5	0,002210567	7,31611E-05	3,41E-05	0,000125265	4,052E-05	1,97022E-05	
15	0,5	0,00221021	7,30839E-05	3,39931E-05	0,000125245	4,04773E-05	1,96405E-05	
15	1	0,002210407	7,31265E-05	3,40521E-05	0,000125256	4,05009E-05	1,96746E-05	**Beta = 3**
15	1,5	0,002210591	7,31663E-05	3,41072E-05	0,000125267	4,05229E-05	1,97064E-05	
15	2	0,002210762	7,32034E-05	3,41586E-05	0,000125277	4,05434E-05	1,97361E-05	
15	2,5	0,002210922	7,3238E-05	3,42065E-05	0,000125286	4,05626E-05	1,97638E-05	
20	0,5	0,002210283	7,30996E-05	3,40149E-05	0,000125249	4,0486E-05	1,9653E-05	
20	1	0,002210552	7,31579E-05	3,40956E-05	0,000125265	4,05182E-05	1,96997E-05	
20	1,5	0,002210807	7,32133E-05	3,41722E-05	0,000125279	4,05489E-05	1,9744E-05	
20	2	0,00221105	7,32658E-05	3,4245E-05	0,000125293	4,0578E-05	1,9786E-05	
20	2,5	0,00221128	7,33157E-05	3,43141E-05	0,000125306	4,06056E-05	1,98259E-05	
25	0,5	0,002210355	7,31154E-05	3,40366E-05	0,000125253	4,04947E-05	1,96656E-05	
25	1	0,002210697	7,31893E-05	3,4139E-05	0,000125273	4,05356E-05	1,97248E-05	
25	1,5	0,002211024	7,32603E-05	3,42373E-05	0,000125291	4,05749E-05	1,97816E-05	
25	2	0,002211339	7,33284E-05	3,43316E-05	0,000125309	4,06127E-05	1,98361E-05	
25	2,5	0,00221164	7,33937E-05	3,44221E-05	0,000125326	4,06488E-05	1,98883E-05	
L	T							
5	0,5	0,00221001	7,30405E-05	3,3933E-05	0,000125234	4,04532E-05	1,96058E-05	
5	1	0,002210017	7,30421E-05	3,39351E-05	0,000125234	4,04541E-05	1,9607E-05	
5	1,5	0,002210022	7,30431E-05	3,39366E-05	0,000125235	4,04546E-05	1,96078E-05	
5	2	0,002210025	7,30438E-05	3,39376E-05	0,000125235	4,0455E-05	1,96084E-05	
5	2,5	0,002210028	7,30444E-05	3,39384E-05	0,000125235	4,04553E-05	1,96088E-05	
10	0,5	0,002210044	7,30479E-05	3,39432E-05	0,000125236	4,04573E-05	1,96116E-05	
10	1	0,002210081	7,30559E-05	3,39543E-05	0,000125238	4,04617E-05	1,9618E-05	
10	1,5	0,002210112	7,30625E-05	3,39635E-05	0,00012524	4,04654E-05	1,96234E-05	
10	2	0,002210137	7,30681E-05	3,39712E-05	0,000125241	4,04685E-05	1,96278E-05	
10	2,5	0,002210158	7,30726E-05	3,39775E-05	0,000125242	4,0471E-05	1,96314E-05	
15	0,5	0,002210102	7,30604E-05	3,39605E-05	0,000125239	4,04642E-05	1,96216E-05	
15	1	0,002210192	7,308E-05	3,39877E-05	0,000125244	4,04751E-05	1,96374E-05	**Beta = 4**
15	1,5	0,002210273	7,30975E-05	3,40119E-05	0,000125249	4,04848E-05	1,96513E-05	
15	2	0,002210345	7,3113E-05	3,40334E-05	0,000125253	4,04933E-05	1,96637E-05	
15	2,5	0,002210408	7,31267E-05	3,40523E-05	0,000125256	4,05009E-05	1,96747E-05	
20	0,5	0,002210183	7,30781E-05	3,3985E-05	0,000125244	4,0474E-05	1,96358E-05	
20	1	0,002210352	7,31146E-05	3,40355E-05	0,000125253	4,04942E-05	1,9665E-05	
20	1,5	0,002210506	7,3148E-05	3,40818E-05	0,000125262	4,05127E-05	1,96917E-05	
20	2	0,002210647	7,31786E-05	3,41242E-05	0,00012527	4,05297E-05	1,97162E-05	
20	2,5	0,002210776	7,32065E-05	3,41628E-05	0,000125277	4,05451E-05	1,97385E-05	
25	0,5	0,002210289	7,31009E-05	3,40167E-05	0,00012525	4,04867E-05	1,96541E-05	
25	1	0,002210559	7,31594E-05	3,40977E-05	0,000125265	4,05191E-05	1,97009E-05	
25	1,5	0,002210811	7,3214E-05	3,41732E-05	0,000125279	4,05493E-05	1,97445E-05	
25	2	0,002211045	7,32648E-05	3,42436E-05	0,000125293	4,05774E-05	1,97852E-05	
25	2,5	0,002211264	7,33121E-05	3,43091E-05	0,000125305	4,06036E-05	1,9823E-05	

PROCESS							
		Gas processing & export					
		Gas			Liquid		
	Ignition Probabilities	0,0065	0,0195	0,03	0,0052	0,011	0,0174
.	T	λ(aged|<10mm)	λ(aged|10-25mm)	λ(aged|>25mm)	λ(aged|<10mm)	λ(aged|10-25mm)	λ(aged|>25mm)
5	0,5	0,004013853	0,001886739	0,000931976	0,000668875	0,000232537	0,000116054
5	1	0,004014554	0,001888842	0,000935211	0,000669019	0,000232842	0,000116536
5	1,5	0,004015203	0,001890789	0,000938206	0,000669152	0,000233124	0,000116982
5	2	0,0040158	0,001892579	0,000940961	0,000669275	0,000233384	0,000117392
5	2,5	0,004016345	0,001894214	0,000943475	0,000669387	0,00023362	0,000117767
10	0,5	0,004013866	0,001886778	0,000932035	0,000668877	0,000232543	0,000116063
10	1	0,004014605	0,001888996	0,000935448	0,000669029	0,000232864	0,000116571
10	1,5	0,004015318	0,001891135	0,000938739	0,000669176	0,000233175	0,000117062
10	2	0,004016005	0,001893195	0,000941908	0,000669317	0,000233474	0,000117535
10	2,5	0,004016666	0,001895177	0,000944956	0,000669453	0,000233761	0,00011799
15	0,5	0,00401387	0,00188679	0,000932054	0,000668878	0,000232545	0,000116066
15	1	0,004014622	0,001889046	0,000935525	0,000669033	0,000232872	0,000116583
15	1,5	0,004015356	0,001891248	0,000938912	0,000669184	0,000233191	0,000117088
15	2	0,004016072	0,001893396	0,000942216	0,000669331	0,000233503	0,000117582
15	2,5	0,00401677	0,00189549	0,000945438	0,000669475	0,000233808	0,000118063
20	0,5	0,004013872	0,001886796	0,000932064	0,000668879	0,000232546	0,000116067
20	1	0,00401463	0,00188907	0,000935562	0,000669035	0,000232876	0,000116589
20	1,5	0,004015374	0,001891302	0,000938995	0,000669188	0,0002332	0,000117102
20	2	0,004016104	0,001893492	0,000942364	0,000669338	0,000233518	0,000117605
20	2,5	0,00401682	0,00189564	0,000945669	0,000669486	0,000233831	0,0001181
25	0,5	0,004013873	0,0018868	0,000932069	0,000668879	0,000232546	0,000116068
25	1	0,004014635	0,001889084	0,000935583	0,000669036	0,000232878	0,000116592
25	1,5	0,004015384	0,001891333	0,000939043	0,00066919	0,000233205	0,000117109
25	2	0,004016122	0,001893546	0,000942448	0,000669342	0,000233527	0,000117619
25	2,5	0,004016848	0,001895725	0,000945801	0,000669493	0,000233844	0,000118121

Beta = 2

.	T						
5	0,5	0,004013215	0,001884826	0,000929032	0,000668744	0,00023226	0,000115615
5	1	0,004013309	0,001885107	0,000929464	0,000668763	0,000232301	0,00011568
5	1,5	0,004013385	0,001885334	0,000929814	0,000668778	0,000232334	0,000115732
5	2	0,004013446	0,001885519	0,000930099	0,000668791	0,000232361	0,000115774
5	2,5	0,004013498	0,001885674	0,000930337	0,000668802	0,000232383	0,00011581
10	0,5	0,004013342	0,001885207	0,000929618	0,00066877	0,000232315	0,000115703
10	1	0,004013561	0,001885863	0,000930627	0,000668815	0,00023241	0,000115853
10	1,5	0,004013758	0,001886454	0,000931536	0,000668855	0,000232496	0,000115988
10	2	0,004013935	0,001886985	0,000932354	0,000668892	0,000232573	0,00011611
10	2,5	0,004014094	0,001887463	0,000933089	0,000668924	0,000232642	0,00011622
15	0,5	0,004013469	0,001885588	0,000930205	0,000668796	0,000232371	0,00011579
15	1	0,004013814	0,001886623	0,000931797	0,000668867	0,000232521	0,000116027
15	1,5	0,004014136	0,001887588	0,000933282	0,000668933	0,000232661	0,000116249
15	2	0,004014436	0,001888488	0,000934666	0,000668995	0,000232791	0,000116455
15	2,5	0,004014715	0,001889326	0,000935955	0,000669052	0,000232913	0,000116648
20	0,5	0,004013597	0,00188597	0,000930792	0,000668822	0,000232426	0,000115877
20	1	0,004014068	0,001887383	0,000932966	0,000668919	0,000232631	0,000116202
20	1,5	0,004014515	0,001888724	0,000935029	0,000669011	0,000232826	0,00011651
20	2	0,004014938	0,001889995	0,000936984	0,000669099	0,000233011	0,000116803
20	2,5	0,00401534	0,0018912	0,000938838	0,000669181	0,000233186	0,00011708
25	0,5	0,004013723	0,00188635	0,000931377	0,000668848	0,000232481	0,000115965
25	1	0,00401432	0,001888141	0,000934133	0,000668971	0,000232741	0,000116377
25	1,5	0,004014892	0,001889856	0,000936771	0,000669089	0,000232991	0,000116771
25	2	0,004015439	0,001891498	0,000939296	0,000669202	0,00023323	0,00011715
25	2,5	0,004015963	0,001893069	0,000941714	0,000669311	0,00023346	0,000117513

Beta = 3

.	T						
5	0,5	0,004013118	0,001884533	0,000928582	0,000668724	0,000232218	0,000115548
5	1	0,00401313	0,00188457	0,000928639	0,000668726	0,000232223	0,000115557
5	1,5	0,004013139	0,001884596	0,000928678	0,000668728	0,000232227	0,000115563
5	2	0,004013144	0,001884613	0,000928705	0,000668729	0,000232229	0,000115567
5	2,5	0,004013149	0,001884627	0,000928726	0,00066873	0,000232231	0,00011557
10	0,5	0,004013177	0,001884712	0,000928857	0,000668736	0,000232244	0,000115589
10	1	0,004013242	0,001884906	0,000929156	0,000668749	0,000232272	0,000115634
10	1,5	0,004013296	0,001885069	0,000929406	0,00066876	0,000232295	0,000115671
10	2	0,004013341	0,001885203	0,000929613	0,00066877	0,000232315	0,000115702
10	2,5	0,004013378	0,001885314	0,000929784	0,000668777	0,000232331	0,000115727
15	0,5	0,004013279	0,001885016	0,000929325	0,000668757	0,000232288	0,000115659
15	1	0,004013438	0,001885494	0,00093006	0,000668789	0,000232357	0,000115768
15	1,5	0,004013579	0,001885918	0,000930713	0,000668819	0,000232418	0,000115866
15	2	0,004013705	0,001886294	0,000931291	0,000668844	0,000232473	0,000115952
15	2,5	0,004013815	0,001886626	0,000931801	0,000668867	0,000232521	0,000116028
20	0,5	0,004013422	0,001885446	0,000929986	0,000668786	0,00023235	0,000115757
20	1	0,004013717	0,001886331	0,000931348	0,000668847	0,000232478	0,000115961
20	1,5	0,004013987	0,001887142	0,000932595	0,000668903	0,000232596	0,000116147
20	2	0,004014234	0,001887882	0,000933734	0,000668953	0,000232704	0,000116317
20	2,5	0,004014459	0,001888557	0,000934772	0,000669	0,000232802	0,000116473
25	0,5	0,004013607	0,001886001	0,000930839	0,000668824	0,000232431	0,000115885
25	1	0,004014079	0,001887416	0,000933018	0,000668922	0,000232636	0,00011621
25	1,5	0,004014518	0,001888734	0,000935044	0,000669012	0,000232828	0,000116514
25	2	0,004014926	0,001889958	0,000936927	0,000669097	0,000233007	0,000116797
25	2,5	0,004015305	0,001891094	0,000938676	0,000669175	0,000233173	0,00011706

Beta = 4

PROCESS					
		Oil processing & export			
		Liquid			
	Ignition Probabilities	0,0027	0,0053	0,0085	
L	T	λ(aged|<10mm)	λ(aged|10-25mm)	λ(aged|>25mm)	
5	0,5	0,000377442	0,00010729	5,68081E-05	Beta = 2
5	1	0,000377551	0,000107503	5,71508E-05	
5	1,5	0,000377652	0,000107701	5,74681E-05	
5	2	0,000377744	0,000107883	5,776E-05	
5	2,5	0,000377829	0,000108049	5,80266E-05	
10	0,5	0,000377444	0,000107293	5,68145E-05	
10	1	0,000377559	0,000107519	5,71762E-05	
10	1,5	0,00037767	0,000107737	5,75251E-05	
10	2	0,000377776	0,000107946	5,78614E-05	
10	2,5	0,000377879	0,000108148	5,81849E-05	
15	0,5	0,000377445	0,000107295	5,68166E-05	
15	1	0,000377562	0,000107524	5,71846E-05	
15	1,5	0,000377676	0,000107748	5,7544E-05	
15	2	0,000377787	0,000107967	5,78949E-05	
15	2,5	0,000377896	0,000108181	5,82374E-05	
20	0,5	0,000377445	0,000107295	5,68176E-05	
20	1	0,000377563	0,000107527	5,71887E-05	
20	1,5	0,000377679	0,000107754	5,75534E-05	
20	2	0,000377792	0,000107978	5,79116E-05	
20	2,5	0,000377904	0,000108197	5,82634E-05	
25	0,5	0,000377445	0,000107296	5,68182E-05	
25	1	0,000377564	0,000107528	5,71912E-05	
25	1,5	0,00037768	0,000107758	5,7559E-05	
25	2	0,000377796	0,000107984	5,79215E-05	
25	2,5	0,000377909	0,000108207	5,82789E-05	
L	T				
5	0,5	0,000377343	0,000107095	5,64964E-05	Beta = 3
5	1	0,000377357	0,000107124	5,65421E-05	
5	1,5	0,000377369	0,000107147	5,65792E-05	
5	2	0,000377379	0,000107166	5,66094E-05	
5	2,5	0,000377387	0,000107181	5,66346E-05	
10	0,5	0,000377363	0,000107134	5,65585E-05	
10	1	0,000377397	0,000107201	5,66655E-05	
10	1,5	0,000377427	0,000107261	5,67618E-05	
10	2	0,000377455	0,000107315	5,68485E-05	
10	2,5	0,00037748	0,000107363	5,69265E-05	
15	0,5	0,000377382	0,000107173	5,66207E-05	
15	1	0,000377436	0,000107278	5,67896E-05	
15	1,5	0,000377486	0,000107376	5,69472E-05	
15	2	0,000377533	0,000107468	5,70942E-05	
15	2,5	0,000377576	0,000107553	5,72312E-05	
20	0,5	0,000377402	0,000107211	5,6683E-05	
20	1	0,000377476	0,000107355	5,69138E-05	
20	1,5	0,000377545	0,000107492	5,71331E-05	
20	2	0,000377611	0,000107622	5,73413E-05	
20	2,5	0,000377674	0,000107745	5,75388E-05	
25	0,5	0,000377422	0,00010725	5,67452E-05	
25	1	0,000377515	0,000107433	5,70381E-05	
25	1,5	0,000377604	0,000107608	5,73192E-05	
25	2	0,00037769	0,000107776	5,75888E-05	
25	2,5	0,000377772	0,000107937	5,78473E-05	
L	T				
5	0,5	0,000377328	0,000107065	5,64487E-05	Beta = 4
5	1	0,00037733	0,000107069	5,64547E-05	
5	1,5	0,000377331	0,000107072	5,64589E-05	
5	2	0,000377332	0,000107074	5,64617E-05	
5	2,5	0,000377333	0,000107075	5,64639E-05	
10	0,5	0,000377337	0,000107084	5,64777E-05	
10	1	0,000377347	0,000107103	5,65094E-05	
10	1,5	0,000377355	0,00010712	5,65359E-05	
10	2	0,000377362	0,000107133	5,65578E-05	
10	2,5	0,000377368	0,000107145	5,65759E-05	
15	0,5	0,000377353	0,000107114	5,65273E-05	
15	1	0,000377377	0,000107163	5,66052E-05	
15	1,5	0,000377399	0,000107206	5,66743E-05	
15	2	0,000377419	0,000107244	5,67356E-05	
15	2,5	0,000377436	0,000107278	5,67898E-05	
20	0,5	0,000377375	0,000107158	5,65974E-05	
20	1	0,000377421	0,000107248	5,67418E-05	
20	1,5	0,000377463	0,000107331	5,68742E-05	
20	2	0,000377501	0,000107406	5,69952E-05	
20	2,5	0,000377536	0,000107475	5,71057E-05	
25	0,5	0,000377404	0,000107215	5,66879E-05	
25	1	0,000377477	0,000107359	5,69194E-05	
25	1,5	0,000377546	0,000107494	5,71353E-05	
25	2	0,00037761	0,000107619	5,73364E-05	
25	2,5	0,000377669	0,000107736	5,75235E-05	