NTNU – Trondheim
Norwegian University of
Science and Technology

Performance of dynamic safety barriers-Structuring, modelling and visualization

Olga Wikdahl

Reliability, Availability, Maintainability and Safety (RAMS)
Submission date: November 2014
Supervisor: Jørn Vatn, IPK

Norwegian University of Science and Technology
Department of Production and Quality Engineering

RAMS
Reliability, Availability,
Maintainability, and Safety

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November 2014

PROJECT THESIS

Department of Production and Quality Engineering

Norwegian University of Science and Technology

Supervisor: Jørn Vatn

NTNU
Faculty of Engineering Science and Technology
Department of Production and Quality Engineering

Date 2014.05.21 Our reference JVA/KEDA

MASTER THESIS
2014
for stud. techn. Olga Wikdahl

Performance of dynamic safety barriers – Structuring, modelling and visualization

(Ytelse av dynamiske sikkerhetsbarrierer – Strukturering, modellering og visualisering)

Many incidents and accidents can be traced back to weaknesses in barrier management. This has been emphasized by the Norwegian Petroleum Safety Authority (PSA) among others, and proactive barrier management has been put on the agenda in the oil- and gas industry in recent years. During normal operation most safety barriers are dormant in the meaning that they will only be activated upon a process upset, and will change status from passive to active. Some operations like drilling and well intervention are more difficult to structure since it is not always evident which barriers are really in place for a given operation sequence. The situation is often referred to as dynamic safety barrier analysis.

The objective of this master thesis is to structure, model and visualize the performance of dynamic safety barriers.

Questions to be addresses and discussed as part of this master's project are:

1. What is really understood by the concept of a dynamic safety barrier?
2. What are reasonable performance measures related to dynamic safety barriers?
3. What are the weaknesses in reliability models for static safety barriers when they are to be applied on dynamic safety barriers?
4. How is it possible to distinguish the dynamic behaviour of a safety barrier in the analysis phase versus the operational phase?
5. What are the important factors to emphasize when dynamic safety barrier performance is to be visualized in the operational phase?

Following agreement with the supervisor(s), the questions may be given different weights.

The assignment solution must be based on any standards and practical guidelines that already exist and are recommended. This should be done in close cooperation with supervisors and any other responsibilities involved in the assignment. In addition it has to be an active interaction between all parties.

Within three weeks after the date of the task handout, a pre-study report shall be prepared. The report shall cover the following:

- An analysis of the work task's content with specific emphasis of the areas where new knowledge has to be gained.
- A description of the work packages that shall be performed. This description shall lead to a clear definition of the scope and extent of the total task to be performed.
- A time schedule for the project. The plan shall comprise a Gantt diagram with specification of the individual work packages, their scheduled start and end dates and a specification of project milestones.

The pre-study report is a part of the total task reporting. It shall be included in the final report. Progress reports made during the project period shall also be included in the final report.

The report should be edited as a research report with a summary, table of contents, conclusion, list of reference, list of literature etc. The text should be clear and concise, and include the necessary references to figures, tables, and diagrams. It is also important that exact references are given to any external source used in the text.

Equipment and software developed during the project is a part of the fulfilment of the task. Unless outside parties have exclusive property rights or the equipment is physically non-moveable, it should be handed in along with the final report. Suitable documentation for the correct use of such material is also required as part of the final report.

The student must cover travel expenses, telecommunication, and copying unless otherwise agreed.

If the candidate encounters unforeseen difficulties in the work, and if these difficulties warrant a reformation of the task, these problems should immediately be addressed to the Department.

The assignment text shall be enclosed and be placed immediately after the title page.

Deadline: 8 October 2014.

Two bound copies of the final report and one electronic (pdf-format) version are required according to the routines given in DAIM. Please see http://www.ntnu.edu/ivt/master-s-thesis-regulations regarding master thesis regulations and practical information, inclusive how to use DAIM.

Responsible supervisor: Professor Jørn Vatn
E-mail: jorn.vatn@ntnu.no
Telephone: 73597109

DEPARTMENT OF PRODUCTION AND QUALITY ENGINEERING

Per Schjølberg
Associate Professor/Head of Department

Jørn Vatn
Responsible Supervisor

Preface

The following report is the master's thesis written as partial fulfilment of MSc program in Reliability, Availability, Maintainability and Safety, at the Department of Production and Quality Engineering (IPK) at the Norwegian University of Science and Technology (NTNU). The report was written during May – November 2014 under the supervision of Jørn Vatn, Professor at the IPK Department. It is assumed that reader of the report has some knowledge about safety barriers and dynamic risk analysis.

In relation to submitting the thesis, I would like to thank my supervisor, Professor Jørn Vatn, for valuable conversations, advises and for helping to structure the thesis. I would also like to thank PhD Candidate Geir Ove Strand for sharing his knowledge and ideas on dynamic safety barriers. I am also grateful to Xue Yang for being a great discussion partner and supportive friend during my studies.

Trondheim,

26th of November 2014

Olga Wikdahl

Summary

The main objective of this master thesis is to discuss performance of dynamic safety barriers. A comprehensive literature review is performed in order to get understanding what dynamic safety barrier is. Three different concepts of dynamic safety barriers based on various meanings of dynamic were derived from the literature review:

- dynamic safety barriers related to motion or physical force

- dynamic safety barriers as updated barriers from dynamic risk analysis

- dynamic safety barriers in the operations with dynamic complexity.

Focus in the report is given to barriers in operations with dynamic complexity, where barriers vary over the time, the activation of the barrier depends on the current situation, there is no pre-made sequence of barrier activation and effect over time of interventions is not obvious. In this thesis dynamic safety barriers during drilling operational phase are discussed. Literature study on well operations was conducted and concepts such as well integrity, well control are discussed. Performance of dynamic safety barriers is discussed based dynamic safety on the examples of dynamic safety barriers in drilling- drilling mud and blowout preventer.

Physical and actuarial approaches to reliability modelling of dynamic safety barriers are discussed. Strength- stress interference model of dynamic safety barrier, drilling mud is made.

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Acronyms

ASP- Accident Sequence Precursors

BOP- Blowout Preventer

BHP- Bottom Hole Pressure

DRA –Dynamic Risk Assessment

ECD- Equivalent Circulating density

ET- Event Tree

FT- Fault tree

IPL- Independent Protection Layer

LWC- Loss of Well Control

PSA- Petroleum Safety Authority

Chapter 1

Introduction

1.1 Background

Many incidents and accidents can be traced back to weaknesses in barrier management. This has been emphasized by the Norwegian Petroleum Safety Authority (PSA) among others, and proactive barrier management has been put on the agenda in the oil- and gas industry in recent years. During normal operation most safety barriers are dormant in the meaning that they will only be activated upon a process upset, and will change status from passive to active. Some operations like drilling and well intervention are more difficult to structure since it is not always evident which barriers are really in place for a given operation sequence. The situation is often referred to as dynamic safety barrier analysis.

1.2 Objectives

The main objective of this master's thesis is to discuss performance of dynamic safety barriers. This done by answering following questions:

1. What is understood by dynamic safety barriers?

2. What are the reasonable performance measures related to dynamic safety barriers?

3. What are the weaknesses in reliability models for static safety barriers when they are to be applied on dynamic safety barriers?

4. How is it possible to distinguish the dynamic behaviour of a safety barrier in the analysis phase versus operational phase?

5. What are the important factors to emphasize when dynamic safety barrier performance is to be visualized in operational phase?

1.3 Limitations

The main limitation is the author practical experience of well operations. Theoretical understanding was established based through the literature review, discussions with supervisor and industry representatives, but it took much more time than expected and thus limited amount of research and practical verification of results.

Research treats only dynamic safety barriers in the well operations/ Oil and gas industry, examples from another industries are not discussed.

1.4 Approach

In order to fulfil the objectives of the master's thesis the following have been performed:

- a theoretical study based on the literature review on the topics such as dynamic risk analysis/assessment, safety barriers, dynamic, drilling operations, reliability models;

- meetings and discussions with supervisor, Jørn Vatn, through the period of writing the thesis;

- meeting and discussion with PhD candidate Geir Ove Strand (working on "Well drilling safety") on the 8th of October at IPK department;

- discussion of findings and conclusions, as well as recommendations for further work in the last part of the thesis.

1.5 Structure of the Report

Report consists of 5 Chapters. Chapter 1 is introduction, where background is reviewed and objectives are set.

Chapter 2 explains by the literature review what is understood by the concepts of dynamic safety barrier. Also fundamental principles of well control are described.

Chapter 3 treats well barriers and mainly focused on the examples of dynamic safety barriers in drilling operational phase.

Chapter 4 is devoted to reliability modelling of dynamic safety barriers.

Chapter 5 are conclusions and recommendations for further work

Chapter 2

Literature review

2.1”Dynamic safety barrier” concept in the literature

2.1.1 Introduction

In spite of the fact that dynamic safety barrier analysis are applied on the practice, discussed in the literature, no common definition of the concept “dynamic safety barrier” has been found in the literature. Dynamic risk analyses are mainly focused on the developing of accident scenarios and there is no explicit focus on barriers. “Safety barrier” or terms with similar meaning such as barrier, independent protection layer are defined and categorised by many authors. But what exactly do we mean when we say “dynamic safety barrier”?

In the online dictionary (Merriam-Webster, Incorporated, 2014) “dynamic” as adjective is defined as:

- always active or changing
- having or showing a lot of energy
- or relating to energy, motion, or physical force

Oxford Dictionaries online (Oxford Dictionaries Language matters, 2014) give the following definition of dynamic:

> “a process or system characterized by constant change, activity, or progress”

Same as dynamic has different meanings, so term “dynamic safety barrier” or terms with a similar meaning are also found to be used differently.

Also there are many publications on dynamic risk assessment (DRA) methods and safety barriers are also part of it. Thus, the dynamic safety barrier concept could also be derived from the DRA as shown later in this report.

This chapter aims to explain by the literature review and discussion what is understood by the concept of dynamic safety barrier. It is also found necessary to present DRA procedure for explain dynamic safety barrier concept.

2.1.2 "Dynamic safety barriers" related to motion or physical force

By applying characteristics of "dynamic" to "safety barrier" categories, terms with similar meanings such as functional barrier, active barrier, and activated barrier have been found in use by different authors.

In Hollnagel's (1999) barriers classification functional (active or dynamic) barriers work by impeding the action to be carried out, for instance by establishing a logical or temporal interlock. Functional barrier predetermines pre-conditions that must be met by the system or human operator before something can happen. These barriers are not always visible by operator, but their availability is always pointed out to the system user. Physical or logical locks are examples of a functional barrier, first one demands key to be opened and second one demands password or identification.

In accordance to Kjellen (2000) active barriers "are dependent on actions by the operators or on a technical control system to function as intended". Active barriers are influenced by daily operations and operators' actions are crucial in the quick control of accident risks. In case of major accident risks if operators are unable to keep the process in the boundaries the technical control system will be activated to control the process. Safety instrumented systems are example of active barrier.

In CCPS (2001) safety barriers are called protection layers and passive and active independent protection layers are defined. Active Independent protection layer is required to move from one state to another in response to a change in a measurable process property (level, pressure, temperature), or signal from another source. An active independent protection layer (see Figure 1) consists of: sensor of some type (instrument, mechanical, or human), a decision making process (logic solver, relay, spring, human etc), an action (automatic, mechanical, human). Process control systems, safety instrumented systems are examples of IPL.

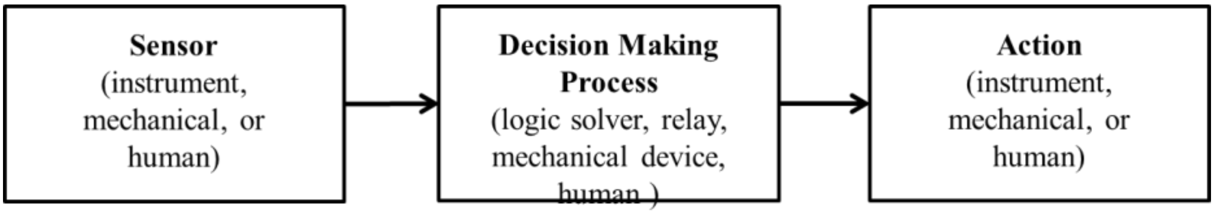

Figure 1: Basic components of active IPL (CCPS, 2001)

In ARAMIS project (Dianous & Fievez, 2006) activated barriers are defined as a safety barrier category. Similar to Hollnagels' (1999) functional barriers these barriers set up pre-conditions to be met before the action start. These barriers have to be automated or need human action to function.

Based on the synthesis of discussed in the literature and industry common characteristics of the barriers, Sklet (2006) proposed classification of safety barriers, where he distinguish between passive and active barriers. Part of Sklet's classification related to active barriers is illustrated on Figure 2.

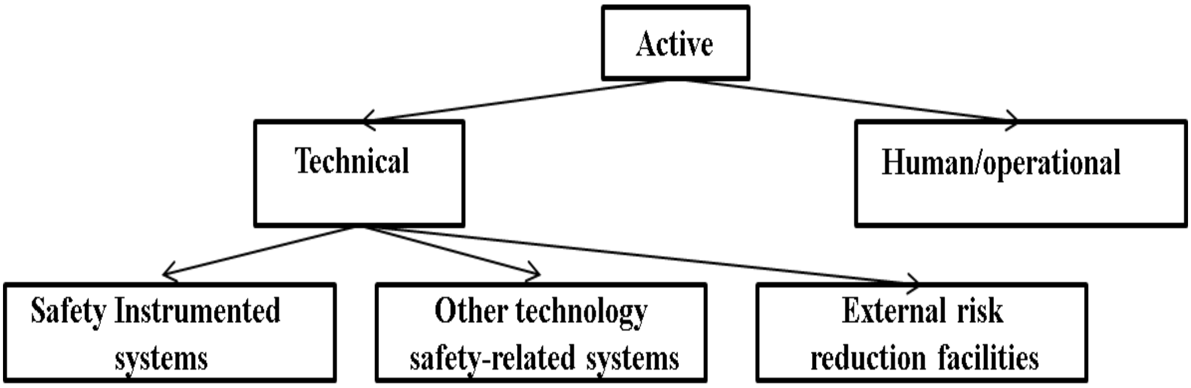

Figure 2: Active barriers classification (Sklet (2006)).

In accordance to Sklet (2006) active barrier systems often are combination of technical and human/ operational elements. They are divided into 3 groups (as explained in Rausand (2011)):

- Safety instrumented system- safety system, which consists of logic controller, sensors and activating units, such as valves, engines
- Other technology safety related system- it is active system that does not have logic unit, could be emergency stop button or pressure relief valve

- External risk reduction facilities- safety systems that are not part of the protected unit, could be ambulances, rescue teams.

2.1.3 “Dynamic safety barrier” as “updated barrier” derived from dynamic risk analysis methods

Literature review shows an interest among engineers to dynamic risk assessment (DRA) caused by industry demand to increase safety and prevent major accidents. Reason for new risk analysis methods is due to inability of classic risk analysis methods to update risk during the life of a process. Event tree (ET) and fault tree (FT) are the most popular methodology to probabilistic risk assessment, but they are restricted to model dynamic systems as they could not catch up changes and deviations which almost always occur in the operational phase. There are many efforts in the literature attempting to update conventional fault trees and event trees with new observations. Cepin and Mavko (2002) have proposed a dynamic fault tree method, which represents extension of classic FT with the time requirements. Bucci et. al. (2008) have proposed a methodology that uses Markov modelling to construct dynamic FTs/ETs models and addresses the concerns with the traditional ET/FT methodology.

In 2006 Meel and Seider have developed plant-specific dynamic failure assessment method to predict the frequencies of abnormal events using near misses and incident data, helping to achieve inherently safer operations. Failure probabilities of safety systems in the method are estimated using Bayesian analysis. Accident precursor data are used to modify dynamically the primary estimates of failure probabilities to receive posterior failure probabilities.

Based on Meel and Seider (2006) method, Kalantarnia, Khan and Hawboldt (2009) have proposed dynamic risk assessment method with objective of formation a real time failure frequency function of a process. Bayesian theory is used for updating the likelihood of the event occurrence and also failure probability of the safety system. Near misses and incident data (so called Accident Sequence Precursors- ASP) are required as precondition for this method.

Step-by-step procedure of dynamic risk assessment is shown on Figure 3. DRA may be implemented to a selected unit in 5 steps (Kalantarnia, Khan and Hawboldt ,2010):

Step 1: Scenario identification

This step identifies most likely scenarios, consequences, type of failures and related safety barriers. A bow-tie model is used to visualize all the possible accident sequences, causes and related safety barriers in place to prevent or control hazards.

Step 2: Prior function calculation

With all safety barriers and failure frequencies known the next step is to build ET for this scenario. Using design stage data or data prior to the start of operation prior failure probabilities are calculated.

Step 3: Formation of likelihood function

Process real-time data inferred from ASPs are used in this stage to form the likelihood function, which is later used to update the prior failure function.

Step 4: Posterior function calculation

A posterior failure function of the safety barrier ($f(p_i|Data)$) is obtained from the prior ($f(p_i)$) and likelihood functions ($g(Data|p_i)$) using Bayesian inference. Bayesian inference is a tool which uses data to improve an estimate of parameter. The posterior function is the same type distribution as the prior with the parameters updated by the likelihood function. Using Bayesian inference the posterior function can be formulated as shown below:

$$f(pi|Data) \propto g(Data|pi)\, f(pi)$$

Step 5: Consequence analysis

Consequences analyses are conducted on the scenario in order to estimate the potential consequences of all possible scenarios.

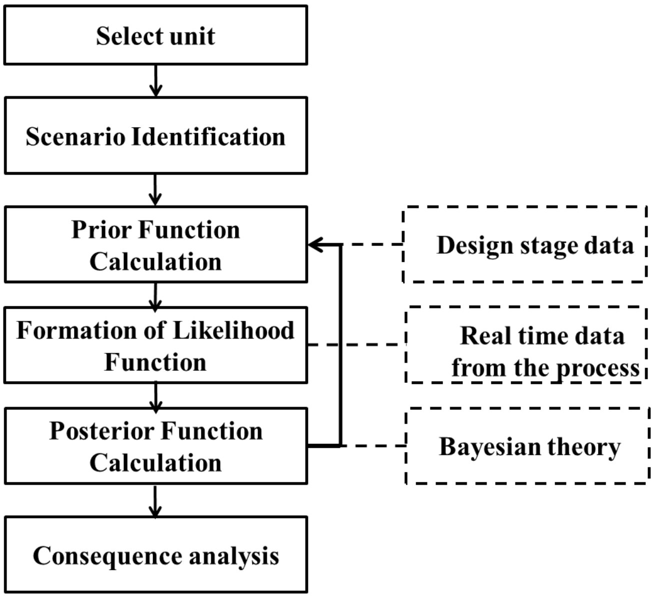

Figure 3: Dynamic risk assessment methodology (Kalantarnia, Khan, & Hawboldt, 2010)

From the dynamic risk assessment methodology dynamic safety barrier concept could be derived. *Dynamic safety barrier* in this case *is an updated barrier*, meaning that failure function of the safety barrier (f(pi|Data)) obtained from the initial generic data in the design phase is dynamically updated using Bayesian inference when new data is supplied.

2.1.4 "Dynamic safety barrier" in the operations with dynamic complexity

Barrier systems usually consist of number of barriers to protect from actions and events that can lead to major accident. Because of dynamic system behaviour, status and performance of barrier systems and their deviations are changing and it is not known what barriers are actually in a place. To identify steps in the operation when two barriers are not in the place or to identify unreliable barriers combinations dynamic barrier analyses are performed (Holand, 1997). Some typical well barriers are shown in a table 1.

Holand (1997) distinguish between static and dynamic barrier situations related to the well operational phases. A static barrier situation is when same barriers are available for over a "long" period of time and production is the most static barrier situation.

In accordance to Holand (1997) there are three operational phases with dynamic barrier situation:

Drilling- is the process of drilling a hole in the ground for the extraction of hydrocarbons.

It is divided for *exploration drilling* – drilling to find hydrocarbons or to determine the extent of a field and *development drilling*- is drilling of production or injection wells. In principal they are identical, but due to increased reservoir knowledge in the development drilling, the blowout frequency is lower for the last one. In this thesis distinction between types of drilling is not made.

Well completion - procedure to prepare a development well for production after drilling is finished.

Well workover – is well maintenance operation.

During drilling, workover and completion barriers vary over the time, the activation of the barrier depends on the current situation, there is no pre-made sequence of barrier activation and effect over time of interventions is not obvious. It is common to name barriers during dynamic operational phases as "dynamic safety barriers". But not all well barriers in dynamic barrier situation are dynamic. Some barriers are embedded in the well design and they are always static, such as casing, tubing they are usually called passive barriers (see table 1).

Barrier type	Description	Example
Operational barrier	A barrier that functions while the operation is carried out. Barrier failure will be observed when it occurs	Drilling mud, Stuffing box
Active barrier (Standby barriers)	An external action is required to activate the barrier. Barrier failures are normally observed during regular testing	BOP, Christmas tree, SCSSV
Passive barriers	A barrier in place that functions continuously without any external action	Casing, tubing, kill fluid, well packer
Conditional barriers	A barrier that is either not always in place or not always capable of functioning as a barrier	Stabbing valve

Table 1: Typical well barriers (Holand, 1997)

The most hazardous event in the well operations is blowout. SINTEF blowout database shows that in the period between 1980 and 1994 most blowouts (82 blowouts out of 125) occurred during drilling operational phase (Table 2). Since most blowouts occurred in drilling, further in the report focus is given to dynamic safety barriers in drilling operational phase. Dynamic safety barriers in the drilling operational phase are drilling mud and blowout preventer (BOP) and they are discussed in the Chapter 3.

Phase Area	Exploration drilling		Development drilling		Completion	Work-over	Production	Wire-line	Unknown	Total
	Shallow	Deep	Shallow	Deep						
Norway	7	5	1	-	-	1	-	-	-	14
UK	2	2	2	1	-	-	2	1	-	10
US GoM OCS	20	11	20	11	7	18	10	3	1	101
Total	**29**	**18**	**23**	**12**	**7**	**19**	**12**	**4**	**1**	**125**

Table 2: Overview of the number of blowouts related to operational phases (Holand, 1997)

2.2Well control

In order to discuss dynamic safety barriers in drilling it is found necessary to describe basic principles of well control. This section aims to explain main principles of well integrity and kick.

2.2.1 Fundamental principles and definitions related to the well control

Blowouts are among the most undesired accidents during drilling operations which often leaving deaths, injuries, great material losses and significant amount of oil spill. In accordance to Holand (1997) blowout is "*an uncontrolled flow of fluids from a wellhead or wellbore*", what means that pre-existing barriers have failed to stop the flow.

Blowout is an ultimate consequence of a kick. Kick is unwanted influx of formation fluids into the wellbore due to the loss of well control (LWC). A kick can result in blowout if it is not detected and prevented in a good time (Khakzad, Khan, & Amyotte, 2013).

The safety objective of drilling operations is to reduce the risk of LWC and maintain well integrity. Well integrity is defined in the standard NORSOK D-10 (2013) as *"the application of technical, operational and organizational solutions to reduce risk of uncontrolled release of formation fluids"*. Process of maintaining the well integrity and reducing risk of LWC trough kick prevention, kick detection, blowout prevention and kill operations is called well control (Figure 4).

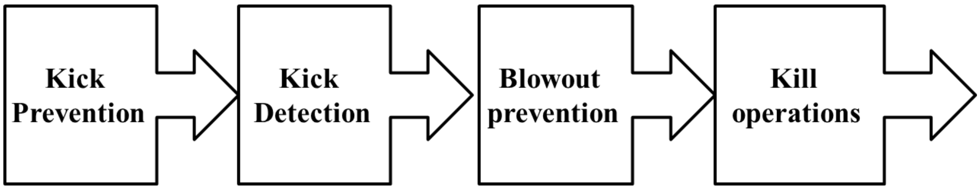

Figure 4: Steps of well control process (Khakzad, Khan, & Amyotte, 2013)

The first three steps in figure 4 related to loss of well control and the last one is related to the regain of well control and performed only if a blowout can be prevented. Only steps related to the well control are discussed in this master thesis.

The means to prevent kick, well leakage and blowout in a well are called safety barriers. Petroleum Safety Authority Norway (2013) gives the following definition of safety barriers: "*technical, operational and organisational elements which are intended individually or collectively to reduce possibility for a specific error, hazard and accident to occur, or which limit its harm/ disadvantages".*

Norwegian regulations (NORSOK, 2013) require that during drilling at least two independent and tested barriers should be available to prevent undesired events: kick, well leakage and blowout. The same principle is followed in UK and USA. Two independent barriers are usually called primary and secondary in relation to location to reservoir, primary is the closest one (Holand, 1997).

During drilling operations operational primary barrier is column of drilling mud. Kick occurs if primary well barrier, column of drilling mud, fails in a drilling phase. Drilling mud, as safety barrier is aimed to maintain, the wellbore bottom hole pressure *(BHP)* greater than the pore pressure (P_p) but less than the fracturing pressure (F_p). Drilling mud as dynamic safety barrier id discussed in the following chapter 3.

2.2.2 Overview of causes of kick

A kick of gas or oil occurs if following two events happen at the same time:

1. Penetration of a porous and permeable reservoir with hydrocarbons present

2. The pore pressure (P_p) is greater than the BHP

It is important to emphasize that kick will never happen if a porous, permeable and hydrocarbon-bearing reservoir has not been penetrated (Tuset, 2014). The following kick causes are different situation, when P_p > BHP: too low mud density, gas cut mud, swabbing and surging, lost mud circulation. Kick causes mechanism is explained in chapter 3 as an integral part of performance of primary well barrier, drilling mud.

2.2.3 Blowout fundamental principles

Blowout occurs as a result of failure of the well secondary barriers. Secondary barriers during drilling operational phase are the blowout preventer (BOP) combined with structural barrier elements such as the wellhead and casing. Kick can escalate to blowout either to mechanical failure of the secondary barrier or due to human failure of non-detection of the kick and not activating barriers. Whether kick escalate to blowout or not depends on how quickly kick is detected and preventive measures are implemented (Khakzad, Khan, & Amyotte, 2013).

Chapter 3

Examples of dynamic safety barriers

This subchapter aims to explain the main principles of dynamic safety barriers during drilling operations, drilling mud and BOP preventer, and is mainly based on a theory from Chief Counsel's Report (2011).

3.1. Drilling overview

Drilling mud and drill bit are typical components of onshore and offshore drilling consists of together with circulating pressures to clear cuttings through the annulus to the surface (Figure5). Drilling crew, using drilling mud and rotary drill bits, bore a hole into the ground. Drillers pump the mud down through a drill pipe that turns a bit. The mud flows out of holes of the drilling bit and then circulates back to the rig through the space between the drill pipe and the sides of the well. Mud cools the bit and carries cuttings away from the well. On the surface cuttings are sieved out of the mud and mud is pumped back down the drill string.

Figure 5: Drilling the well (Chief Counsel's Report, 2011)

3.2. Barriers in a well during drilling

Figure 3 shows barriers in a well during drilling. Table 2 provides description and function of primary and secondary barriers in the drilling well. Dynamic safety barriers such as drilling mud and BOP are also discussed more in detail in the following subchapters.

Well barrier	**Description**	**Function/purpose**
Drilling mud	Column of drilling mud inside wellbore	To maintain the wellbore bottom hole pressure (BHP) greater than the pore pressure but less than fracturing pressure in order to prevent well influx
BOP	Specialized valve or similar mechanical device which consists of series of rams and annual preventers	To seal, control and monitor oil well.
In-situ formation	The formation that has been drilled through and is located beside the casing annulus, isolation material or plugs set in the wellbore.	To provide a permanent and impermeable hydraulic seal preventing flow from the wellbore to surface/seabed or other formation zones.
Production Casing	Large diameter pipe that is assembled and inserted into a recently drilled section of a borehole and typically held into place with cement.	The purpose of casing/liner is to provide an isolation that stops uncontrolled flow of formation fluid or injected fluid between the casing bore and the casing annulus.
Annular cement	Consists of cement in solid state located in the annulus between concentric casing strings, or the casing/liner and the formation.	To provide a continuous, permanent and impermeable hydraulic seal along hole in the casing annulus or between casing strings, to prevent flow of formation fluids, resist pressures from above or below, and support casing or liner strings structurally
Shoe- track cement	Full-sized length of casing placed at the bottom of the casing string	Cement left inside the casing to guarantee that the fluid left outside the casing is good-quality cement.

Table 3: Description and function of safety barriers in a drilling well

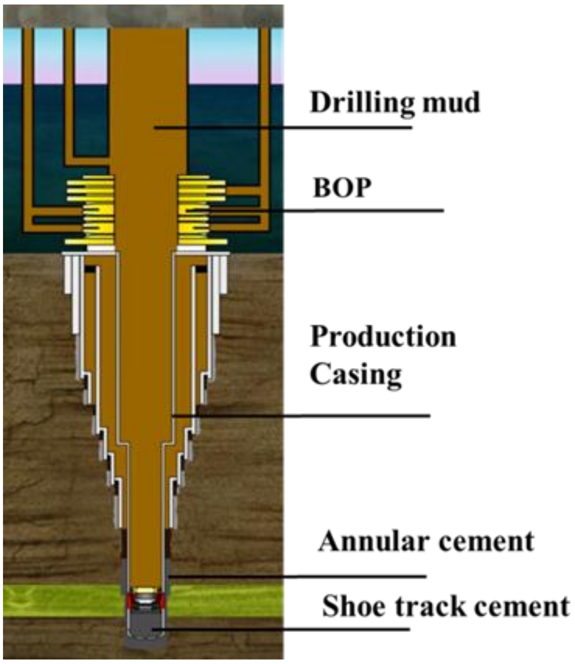

Figure 6: Barriers in a well (Chief Counsel's Report, 2011)

3.2.1 Drilling mud as dynamic safety barrier

Drilling mud, a viscous substance that comes in varying densities, is pumped down through the drill pipe and then returns back to the rig through the space between drilling pipe and the sides of the well. As it flows, mud viscosity curries pulverized rock (cuttings) out of the well. When mud returns to the rig, cuttings are separated and mud pumped back to the drill string. When pulling pipe from a well it is very important to keep the hole full of drilling fluids. The volume taken out must be replaced by adding drilling mud. Failure to do this may cause underbalance. The effectiveness of drilling mud as barrier is reduced when level of fluid in the well is dropping.

In addition to take cuttings out of the well, drilling mud also controls pressure in the well as it being drilled by offsetting the pressure of hydrocarbons and the rock formation. Drilling mud, as safety barrier is aimed to maintain, the wellbore bottom hole pressure *(BHP)* greater than the pore pressure (P_p) but less than the fracture pressure (F_p). Mud engineer strive to keep the mud weight between these two curves: pore pressure (P_p) and fracture pressure (F_p) as shown on Figure 7. Weighting agents are added to the mud to increase it density and, therefore, its pressure on the walls. Both pressure gradients are expressed in terms of an equivalent mud weight. Density of drilling mud is typically represented in terms of pounds per gallon (ppg).

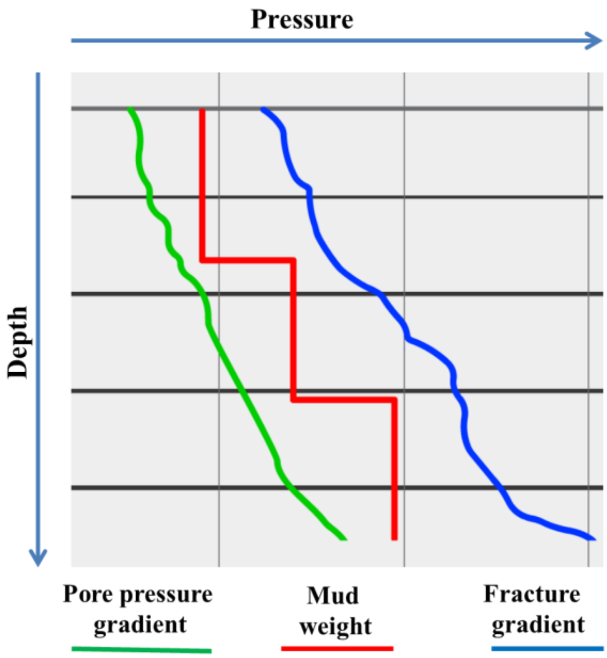

Figure 7: Pore pressure and fracture gradient (Chief Counsel's Report, 2011)

Pore pressure or formation pressure (P_p) is a pressure exerted by fluids within the pores of reservoir. If pore pressure exceeds the hydrostatic pressure *(P_h)* exerted by the mud inside the well, the well is underbalanced. This means that the mud pressure is no longer sufficient on its own to prevent hydrocarbon flow and unexpected influx or kick of formation fluids in the wellbore can happen. If formation pressure increases, mud density should also be increased to balance the pressure. *Fracture pressure (F_p)* is a pressure above which injection of fluids will break down the formation. In this situation drilling mud can flow out of the well into the formation and circulation is lost. Both formation pressure and fracture pressure vary by depth and define boundaries of the drilling process.

While primary provided by hydrostatic pressure of the mud column, BHP consists of severel other pressure components:

$$BHP = P_h + P_j - P_{sw} + P_{sg} ,$$

where P_h is hydrostatic pressure due to height of the drilling mud column above the wellbore bottom, P_j is frictional pressure due to pumping of the drilling mud through the drillstring, P_{sw} and P_{sg} are swabbing and surging pressures due to drillstring tripping out and tripping in the wellbore. The hydrostatic pressure, P_h, can be calculated from the following formula:

$$P_h = \rho gh,$$

where = drilling mud density, g = gravity, h = drilling mud height. Therefore, factors that either cause h to decrease (annular loses) or ρ to decrease (gas cut mud) result in decline of hydrostatic pressure and consequently in *BHP*. When pulling a drillstring out of the wellbore the negative pressure gradient P_{sw} is created which reducing *BHP* and kick can occur. This situation is called s*wabbing*. When drillstring put into the wellbore, positive pressure gradient is created P_{sg} and this effect is called *surging.* (Khakzad, Khan, & Amyotte, 2013)

The drilling mud barrier properties could also be reduced by lost mud circulation. During the drilling, mud circulation applies pressure to the wellbore from dynamic friction necessary to push the mud from the well. The resulting equivalent circulating density (ECD) is higher than static mud weight and when static mud weight approaches to the fracture gradient margin, the applied ECD minimizes that margin. ECD could be increased by different reasons: mud pump pressure in applied to the wellbore, mud properties changed and viscosity increased, rate of penetration increasing the cuttings load in the annulus. Combination of static mud weight, ECD and small margin between mud weight and fracture gradient can result in lost circulation of drilling mud (Shaughnessy, 2013).

The drilling mud barrier may become less effective also due to mishandling mud at the surface such as opening wrong valve on the pump and allowing a light weight fluid to be pumped, washing off shale shakers, clean-up operations (Wikipedia, 2014).

To summarise the written above, drilling mud barrier effectiveness problems range from the complexity of dynamic pressures changes associated with running pipe to mud mishandling errors on the surface. Dynamic pressure changes in the mud column are not always related to time they are also situation dependent: how much cuttings are added to drilling fluid and taken to surface and how this effects density of the drilling mud, how much fluid has to be pumped into the well and what is fluid density . Also some result of analysis (Tuset, 2014) shows that human error causing dynamic pressure changes in the mud column are the most critical for primary well control during the operation.

3.2.2 BOP as dynamic safety barrier

Blowout preventer (BOP) is specialized valve or similar mechanical device which consists of series of rams and annual preventers used to seal, control and monitor oil well. BOP is considered as single barrier. Figure 6 shows BOP position in a well. BOP is barrier to flow only when it closed. BOP is dynamic barrier, to close off the well and prevent hydrocarbons flow – individual rams in BOP has to be closed to handle different situation. It takes from 40 seconds to a minute to close a ram when activated.

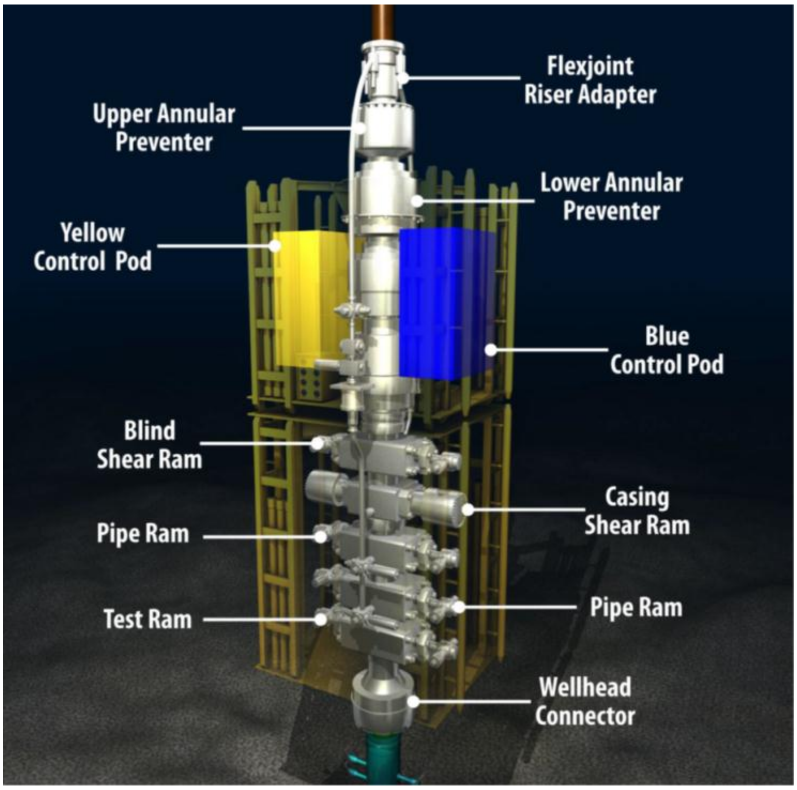

Figure 8: Blowout preventer (Chief Counsel's Report, 2011)

Different parts of BOP are shown in Figure 8:

An annular preventer is a large rubber seal designed to close around the drill pipe and seal off the annulus. If there is pipe in the annular preventer, the annular preventer seals around it, even if pipe is rotating. Regulations require that an annular preventer be able has to completely seal the entire opening, but they are not as effective as ram preventers to close an open hole;

A pipe ram is designed to close around the drill pipe and seal off the annulus in the well below. Variable bore rams are a type of pipe ram with several concentric semi-circular pieces which allow sealing around several different sizes of pipe;

A blind shear ram consists of two metal blocks with blades. It is designed to cut the drill string and seal off the annulus and the drill string in the well below. It can withstand and seal a substantial amount of pressure from below. Blind shear rams are designed to cut even through drill pipe, but will not cut through a tool joint (the place where two pieces of pipe are threaded together), casing hangers, or multiple pieces of pipe;

The casing shear ram is designed to cut through casing as it is being lowered into the wellbore and when there is no drill string in place. It does not seal the wellbore completely;

A test ram, if installed, sits at the bottom of the BOP stack and resist downward pressure. If BOP and test ram are closed than BOP can be pressure-tested above the ram.

Each ram of BOP is activated separately. BOP rams can be activated manually from the rig, robotically by remotely operated vehicles, and automatically (when certain conditions are met).

BOP is seen as dynamic safety barrier, because its ability to seal the well is changing in different situations: where is a pipe, what size of pipe. BOP also could not seal due to improper position of drill pipe tool joint as drill pipe position is not known in every moment. Also BOP barrier properties are reduced due confusion regarding responsibilities to close BOP.

Chapter 4

From examples to theory

4.1. Performance measures of dynamic safety barriers

Petroleum Safety Authority in Norway (2013) recommends that performance requirements have to be established for technical, operational and organisational barrier elements.

Based on experience from several projects and a synthesis of the reviewed literature Sklet (2006) recommends the following measures to characterize the performance of safety barriers:

- Functionality/effectiveness: The ability to perform a specified function under given technical, environmental, and operational conditions

- Reliability/availability: The ability to perform a function with an actual functionality and response time while needed, or on demand

- Response time: The time from a deviation occurs that should have activated a safety barrier, to the fulfilment of the specified barrier function

- Robustness: The ability to resist given accident loads and function as specified during accident sequences

- Triggering event or condition: The event or condition that triggers the activation of a barrier

4.2 Reliability modelling of dynamic safety barriers

In hardware reliability 2 different approaches are used: physical approach and actuarial approach.

4.2.1 Introduction to physical approach

In the physical approach the strength of a technical item is modelled as a random variable *S*. The item is exposed to a load *L* that is also modelled as random variable. The distributions of the strength and the load in specific time *t* are illustrated in Figure 9.

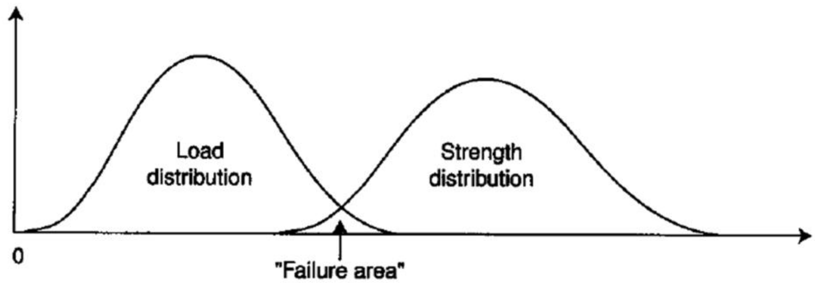

Figure 9: Load and strength distribution (Rausand & Høyland, 2004)

A failure occurs as soon as load is higher than strength. The reliability *R* of the item is defined as the probability that the strength is greater than the load,

$$R= Pr(S>L)$$

The load vary in time and may be modelled as a time – dependent variable *L(t).* The strength of item is also function of time, *S(t).* The time to failure T of the item is the time until *S(t) < L(t),*

$$T=min \{t;\ S(t)<L(t)\}$$

The reliability R(t) of the item maybe defined as *R(t)=Pr(T>t)* (Rausand & Høyland, 2004)

This physical approach is often called "stress-strength interference model".

4.2.2 Stress-strength interference model for dynamic safety barriers

As discussed in chapter 3, drilling mud, as safety barrier is aimed to maintain, the BHP greater than the pore or formation pressure (P_p). If formation pressure exceeds the hydrostatic pressure (P_h) exerted by the mud inside the well, this means that the mud pressure is no longer sufficient on its own to prevent hydrocarbon flow and unexpected influx or kick of formation fluids in the wellbore can happen. Weighting agents are added to the mud to increase it density and, therefore, its pressure on the walls.

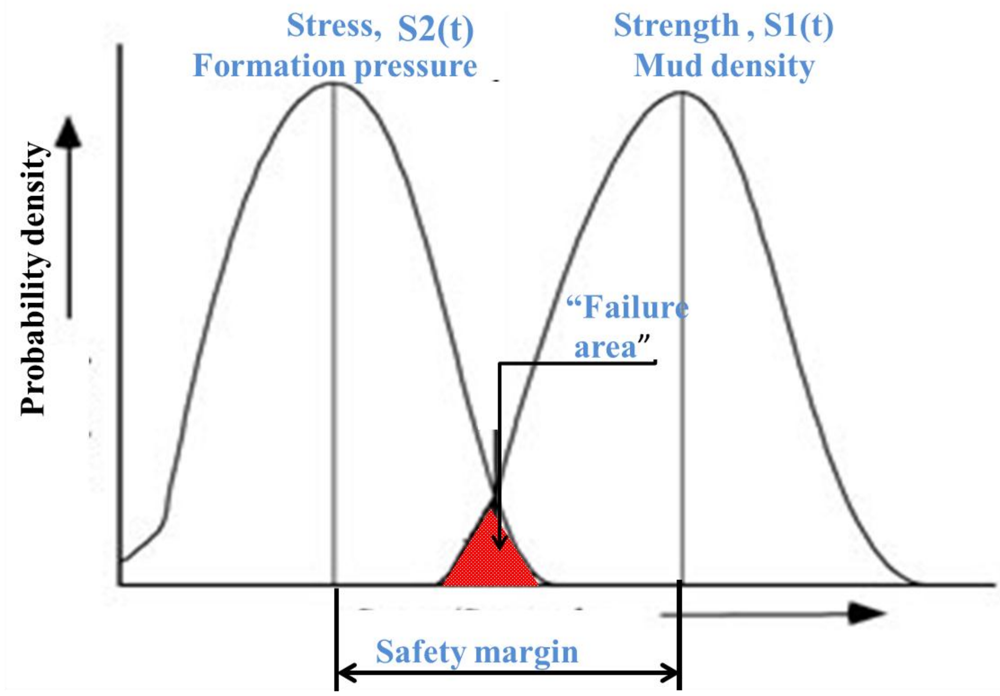

Figure 10: Probability density functions of formation pressure and Mud density at specific time t

Drilling mud as a safety barrier is exposed to stress, which is formation pressure S2(t). Mud density in this situation is strength, S1(t). Strength – stress interference model of dynamic safety barrier “drilling mud” at a specific time t is shown on the figure 10. Figure 10 shows probability density functions of stress (which is formation pressure as given in the example above) and strength (which is mud density or movement of BOP ram). Probably normal distributions are not totally realistic, but still can be used for graphical representation. If we select enough strength to handle the worst case stress situation, this will shift strength curve to the right reducing potential failure region or even avoiding failure.

Safety barrier fails as soon as stress is higher than strength. Reliability of the safety barrier could be defined as $R(t)=Pr(T>t)$, where $T=\min\{t;\ S1(t)<S2(t)\}$.

Theoretically, if we have probability density function of pore pressure and mud density, we can calculate the reliability of safety barrier analytically or numerically. But practically, it is often difficult to know the exact distribution of stress and strength. Also dynamic barrier can be exposed to stresses from different directions and have to be modelled as vectors what makes analysis complex.

4.2.3 Actuarial approach

In the actuarial approach all the information about component loads and strengths is described in the probability distribution function F(t) of the time to failure T. No explicit modelling is needed. Reliability characteristics like failure rate and are deduced directly from the probability distribution function F(t). When few components are combined into a system, the analysis is called system reliability analysis (Rausand & Høyland, 2004)

In order to build a reliability model logical structure of components should be created. Event tree (ET) and fault tree (FT) are the most popular methodology to probabilistic risk assessment, but they are restricted to model dynamic systems as they could not catch up changes and deviations which almost always occur in the operational phase. Reliability models are designed to illustrate static relationships between logical variables and do not treat time, process variables, human behaviour which affects the system response. In drilling apart from static parameter such as formation porosity, there are also dynamic parameters such as the formation temperature and pressure which are different on different levels of the well. Also drilling parameters such as the weight and volume of drilling mud are always sensitive to unexpected changes such as losses in formation, gas in the well.

Chapter 5

Summary and recommendations for further work

5.1 Summary and conclusions

The main objective of this master thesis is to discuss performance of dynamic safety barriers. A comprehensive literature review is performed in order to get understanding what dynamic safety barrier is. Three different concepts of dynamic safety barriers based on various meanings of dynamic were derived from the literature review:

- dynamic safety barriers related to motion or physical force

- dynamic safety barriers as updated barriers from dynamic risk analysis

- dynamic safety barriers in the operations with dynamic complexity.

Focus in the report is given to barriers in operations with dynamic complexity, where barriers vary over the time, the activation of the barrier depends on the current situation, there is no pre-made sequence of barrier activation and effect over time of interventions is not obvious. In this thesis dynamic safety barriers during drilling operational phase are discussed. Literature study on well operations was conducted and concepts such as well integrity, well control are discussed. Performance of dynamic safety barriers is discussed based dynamic safety on the examples of dynamic safety barriers in drilling- drilling mud and blowout preventer.

Physical and actuarial approaches to reliability modelling of dynamic safety barriers are discussed. Strength- stress interference model of dynamic safety barrier, drilling mud is made.

5.2 Recommendations for further work

Unfortunately due to luck of time and family situation not all set objectives are met.

“Dynamic safety barriers performance” is very interesting and important research topic and in further work would be practically useful to analyse:

- How is it possible to distinguish the dynamic behaviour of a safety barrier in the analysis phase versus operational phase?

- Important factors of dynamic safety barrier performance visualization in operational phase.

Dynamic safety barriers in industries other than oil and gas are also recommended for further work.

Appendix 1

Pre-study report

1. Background

Many incidents and accidents can be traced back to weaknesses in barrier management. This has been emphasized by the Norwegian Petroleum Safety Authority (PSA) among others, and proactive barrier management has been put on the agenda in the oil- and gas industry in recent years. During normal operation most safety barriers are dormant in the meaning that they will only be activated upon a process upset, and will change status from passive to active. Some operations like drilling and well intervention are more difficult to structure since it is not always evident which barriers are really in place for a given operation sequence. The situation is often referred to as dynamic safety barrier analysis

2. Objectives

The objective of this master thesis is to structure, model and visualize the performance of dynamic safety barriers.

3. Approach

The objective should be fulfilled mainly through literature: papers, books or thesis

4. Problems to be addressed

The Master thesis is divided in five tasks listed below with a short comment of how the work is planned to be executed and/or challenges

Activity 1: To discuss what is really understood by the concept of a dynamic safety barrier

This task is important foundation for the thesis and will give a better understanding of dynamic safety barrier. Different understandings of dynamic in the literature should be discussed, but focus should be given to operational dynamic.

Activity 2: To discuss and propose reasonable performance measures related to dynamic safety barriers

Activity 3: To discuss weaknesses in reliability models for static safety barriers when they are to be applied on dynamic safety barriers

Activity 4: How is it possible to distinguish the dynamic behaviour of a safety barrier in the analysis phase versus operational phase

Activity 5: To emphasize important factors of dynamic safety barrier performance visualization in operational phase

Activity 6: To summarize, conclude and give recommendations for further work

5. Work scope

The Master thesis is done over 20 weeks and how these weeks will be distributed between the tasks, completion and proofreading is shown in the table below. Activity "planning" includes start up, planning the project and writing the pre-study report. Completion consists of writing preface, abstract, conclusions.

	Project plan- Master Thesis, Performance of dynamic safety barriers																				
Activity/week	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
Planning																					
Activity 1																					
Activity 2																					
Activity 3																					
Activity 4																					
Activity 5																					
Completion																					
Proof-reading																					

Milestones:

20.06.14 – Pre-study report

08.10.14- Master thesis submission

References

Bucci, P., Kirschenbaum, J., Mangan, L. A., Aldemir, T., Curtis, S., & Wood, T. (2008). Construction of event-tree/fault-tree models from a Markov approach to dynamic system reliability. *Reliability Engineering and System Safety*, 1616-1627.

CCPS. (2001). *Layer of protection analysis:Simplified process risk assessment.* New York: American Institute of Chemical Engineers.

Cepin, M., & Mavko, B. (2002). A dynamic fault tree. *Reliability Engineering and System Safety*, 83-91.

Chief Counsel's Report. (2011). *Macondo:The Gulf Oil Disaster.* National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling.

Dianous, V., & Fievez, C. (2006). ARAMIS project: A more explicit demonstration of risk control through the use of bow-tie diagrams and the evaluation of safety barrier performance. *Journal of Hazardous Materials*, 220-233.

Holand, P. (1997). *Offshore blowouts: causes and control.* Huston, Texas: Gulf publishing company.

Hollnagel, E. (1999). Accidents and barriers. Linkoping: Graduate School of Human-Machine Interaction.

Kalantarnia, M., Khan, F., & Hawboldt, K. (2009). Dynamic risk assessment using filure assessment and Bayesian theory. *Journal of Loss Prevention in the Process Industries*, 600-606.

Kalantarnia, M., Khan, F., & Hawboldt, K. (2010). Modelling of BP Texas City refinery accident using dynamic risk assessment approach. *Process Safety and Environmental PRotection*, 191-199.

Khakzad, N., Khan, F., & Amyotte, P. (2012). Dynamic risk analysis using bow-tie approach. *REliability Engineering and System Safety*, 36-44.

Khakzad, N., Khan, F., & Amyotte, P. (2013). Quantitative risk analysis of offshore drilling operations: A Bayesian approach. *Safety Science*, 108-117.

Kjellen, U. (2000). *Prevention of accidents through experience feedback.* London: Taylor & Francis.

Meel, A., & Seider, W. D. (2006). Plant- specific dynamic failure assessment using Bayesian theory. *Chemical Engineering Science*, 7063-7056.

Merriam-Webster, Incorporated. (2014). Retrieved september 10, 2014, from An Encyclopedia Britannica Company: http://www.merriam-webster.com/dictionary/dynamic

NORSOK, D.-1. (2013). *Well integrity in drilling and well operations.* Lysaker: Standards Norway.

Oxford Dictionaries Language matters. (2014). Retrieved july 15, 2014, from Oxford University Press: http://www.oxforddictionaries.com/definition/english/dynamic

Paltrinieri, N., Scarponi, G. E., Khan, F., & Hauge, S. (2014). Addressing Dynamic Risk in the Petroleum Industry by Means of Innovative Analysis Solutions. *Chemical Engineering Transactions*, 36,451-456.

PSA. (2013). *Principles for barrier management in the petroleum industry.* Petroleum Safety Authority Norway.

Rausand, M. (2011). *Risk assessment:Theory, methods, and applications.* Hoboken,New Jersey: John Wiley & Sons, Inc.

Rausand, M., & Høyland, A. (2004). *System Reliability Theory:Models, Statistical Methods, and Applications. 2nd Edition.* New Jersey: John Wiley & Sons, Inc.

Rowley, C. W., & Batten, B. A. (2009). Dynamic and Closed-Loop Control. In D. Joslin R, & N. Miller D, *Fundamentals and Applications of Modern Flow Control* (pp. 115-148). AIAA Progress in Astronautics and Aeronautics .

Shaughnessy, J. (2013). *Drilling it safely.* Retrieved September 2014, from Drilling Contractor: http://www.drillingcontractor.org/improving-well-control-calls-for-continuous-evaluation-of-barriers-21463

Siu, N. (1994). Risk assessment for dynamic systems: An overview. *Reliability Engineering and System Safety*, 43-73.

Sklet, S. (2006). Safety barriers: Definition, classification, and performanc. *Journal of Loss Prevention in the Process Industries 19*, 494-506.

Strand, G. O. (2014, October 08). Conversation with Geir Ove Strand on Dynamic safety barriers in drilling,Trondheim, IPK.

Tuset, G. D. (2014). *Operational Barrier Elements in Critical Drilling Operations.* Trondheim: NTNU,Master thesis .

Wikipedia. (2014). *Pore pressure gradient*. Retrieved September 12, 2014, from Wikipedia: http://en.wikipedia.org/wiki/Pore_pressure_gradient

Wikipedia. (2014). *Well Control*. Retrieved September 2014, from Wikipedia: http://en.wikipedia.org/wiki/Well_control

CURRICULUM VITAE

Personal information

Name	Olga Wikdahl
Date of birth	23.03.1980
Nationality	Ukrainian
Address	26 F Martin Saeterhaugs vei, Trondheim, 7056, Norway
E-mail	olga_flyunt@yahoo.com
Telephone	(+47)463-55-640
Languages	Ukrainian-native, Russian, English-fluent, Norwegian-beginner

Education

Dates	August 2011-November 2014
Title or qualification awarder	Master in RAMS (expected)
Principal subjects/occupational skills covered	Risk Analysis, RAMS Engineering and Management, Safety and Reliability Analysis, Methods and Tools in HSE practice, Risk Assessment(specialisation project)
Name of educational organisation	Norwegian University of Science and Technology, Trondheim, Norway
Dates	September 1997-December 2002
Title or qualification awarder	Master with honours in Automation and Computer Integrated Technologies
Principal subjects/occupational skills covered	Automation and Optimisation of Chemical Technological Processes, Technological Measurements and Instruments, Automatic Control Theory
Name of educational organisation	Lviv National Polytechnic University, Lviv, Ukraine

Work experience

Dates	June 2010-July 2011
Occupation and position held	Real Estate and Technical Purchasing Manager
Main job activities and responsibilities	• Ensuring that city and state regulations related to maintenance of all store engineering systems, fire protection and safety are met all the times; • Initiating and carry out projects that improve efficiency and reduce operating costs and energy consumption; • Track, analyse and improve key maintenance parameters of OBI stores such as maintenance costs, schedule compliance, energy consumption; • Communicate and negotiate with local and foreign business partners, local authorities, subtenants, vendors, service providers, Landlords on all issues regarding Rent/Service/Supply Agreements, controlling signed agreements terms;

	• Responsible at some level for buying of goods and services needed by the OBI Hypermarkets in Ukraine: seeking vendors or suppliers to provide quality equipment for store needs(forklifts, woodcutting machines, storage systems etc.), services for stores (maintenance subcontractors, cleaning etc.) at reasonable prices;
Name of employer	OBI Ukraine Franchise Centre, Kyiv, Ukraine
Type of business	OBI is German building and DIY retailer operating in 13 European countries http://www.obi.com

Dates	September 2007-June 2010
Occupation and position held	Information and Process Specialist (Real Estate Department)
Main job activities and responsibilities	• Corresponding with local and foreign partners, local authorities; • Organising Head of Expansion meetings and business trips; • Real Estate Audit preparation and follow up; • Taking part in Investment proposals preparation, market potential analysis for new and existing projects, catchment area analysis, competitors overview; • Subtenants management, rent payments control, search and negotiations with subtenants, sublease agreements signing; • Developing Real Estate Department Policies and up-dating them; • Making sure that inbound and outbound information flows are managed effectively and in time; • Improving database and
Name of employer	OBI Ukraine Franchise Centre, Kyiv, Ukraine
Type of business	OBI is German building and DIY retailer operating in 13 European countries http://www.obi.com