NTNU – Trondheim
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Reliability Analysis of Blowout Preventer Systems

A comparative study of electro-hydraulic vs.
all-electric BOP technology

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PREFACE

This Master Thesis work has been carried out at the Department of Marine Technology at the Norwegian University of Science and Technology, NTNU, during the spring semester 2014. This thesis is the final step towards my M.Sc. degree, where my specialization lies within the operation of marine systems and maintenance engineering.

Before beginning my thesis work I had limited knowledge of blowout preventer systems. The gathering of reliability data, performing analyses and comparing results have been challenging aspects of this thesis. It has, however, been motivating to work with realistic problems and new technology.

I would like to express my deepest thanks to my supervisor Professor Ingrid Bouwer Utne at NTNU for her valuable help and guidance during this semester. Also, I would like to thank Odfjell Drilling and Electrical Subsea & Drilling for participating in my work from start to end – and for attending the workshop in April. I would especially like to thank the Discipline manager for B.O.P. Systems in Odfjell Drilling, Tarjei Stautland, for making suggestions about the outline of the thesis, as well as providing help and feedback on the overall work. Additionally, I would like to thank Magne Rød and Egil Eriksen for sharing their new technology concept, and for good advice and follow-up during the thesis process.

Finally, I would like to thank my co-students and friends at Tyholt for sharing their experiences during the preparation of this thesis. Special thanks go to the girls at office A.1.007 for support along the way – and all the good moments over the last 5 years.

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SUMMARY

A blowout preventer (BOP) is a large valve used to seal, control and monitor oil and gas wells. It serves as an important barrier against blowouts. Excessive downtime on the BOP is a problem for drilling companies worldwide, which causes increased costs and delays for everyone involved in a drilling project. The background for this thesis is Odfjell Drilling's experience with downtime on the BOP during drilling operations on board their mobile offshore drilling units.

The downtime and associated cost due to failure on the BOP increases with the water depth of a drilling project because the time it takes to recover and re-install the BOP stack increases. In a deepwater operation the unproductive downtime from a problem that requires the BOP stack to be recovered to the surface may be 1-2 weeks. The magnitude of the resulting daily loss, both for the owner and the client involved, illustrates how important reliability of the BOP is.

Deepwater drilling operations may also experience new challenges compared to operations in more shallow depths. Examples include increased loads on the riser system, higher pressure and temperature in the well and energy loss in subsea accumulators. Today, drilling companies worldwide have a strong focus on reducing BOP downtime. Improved technology and new solutions for subsea BOPs are therefore believed to be a necessity for future deepwater drilling.

This thesis is a case study of the electro-hydraulic BOP on board Deepsea Stavanger, a drilling unit owned and managed by Odfjell Drilling. The first focus is to analyse BOP failures that have led to downtime on this rig and to relate them to the technical mode of operation of the BOP.

The company Electrical Subsea & Drilling AS (ESD) is working on developing an all-electrically operated BOP. They claim that their new technology can provide many benefits versus the electro-hydraulic BOP systems, both with respect to environmental and operational safety, as well as cost reduction for drilling- and oil companies. Additionally, they claim that their BOP concept is more reliable and less prone to excessive downtime. The second focus is therefore to establish a thorough system description of this concept, to analyse potential failure modes and to compare them with the failures experienced on board Deepsea Stavanger.

The overall goal for this thesis is to compare the conventional electro-hydraulic BOP system with the all-electric BOP concept developed by ESD, with respect to reliability. The purpose of such a comparison is to see if any of the recurring failures Odfjell Drilling experiences on board Deepsea Stavanger are less likely to occur if the BOP is all-electrically operated.

To compare the two BOP concepts, a reliability analysis is performed on each system. The reliability analyses are performed in four steps:

1. Functional analysis
2. FMECA
3. Reliability block diagram analysis
4. Fault tree analysis

Reliability data is gathered from experience data on board Deepsea Stavanger, engineering judgment input from a workshop performed with Odfjell Drilling and ESD, previous reliability studies and comparative components in OREDA.

The results from the reliability analyses yield that the all-electric BOP concept is more reliable and less prone to failures than existing electro-hydraulic BOP systems. However, this is a result based on a single case study with numerous assumptions involved. There are also other factors, in addition to reliability, that are important to consider when assessing a BOP system.

There are many arguments in favour of the all-electric BOP concept. An electric system contains fewer and more reliable components than an electro-hydraulic one, making the all-electric concept simpler than existing BOP systems. The lack of a shuttle valve and the use of subsea batteries instead of accumulators are the most obvious advantages with the all-electric concept. In addition, the concept is weight saving, has a greater amount of redundancy in the control system, offers better and more precise monitoring and is less polluting. Still, there is considerable uncertainty associated with the new technology, both with respect to human impacts, maintenance, repair hours and profitability – and there are more issues to be examined before a certain conclusion can be drawn regarding which system contributes the least to BOP downtime.

For new technology to be developed and implemented there must exist some market drivers. The fact is that today there are no market drivers for an all-electric BOP system. A promise of high reliability is not enough to create success. An all-electric BOP concept can solve many of the challenges the drilling industry is facing in the years to come, but time will show whether or not the concept proves to be both technically and financially profitable.

SAMMENDRAG

En utblåsingsventil (engelsk: Blowout Preventer, BOP) er en stor sikkerhetsventil som omslutter en oljebrønn. Den fungerer som en viktig barriere mot olje- og gassutblåsninger. Feil og vanskeligheter med utblåsingsventilen utgjør et problem ved oljeboring, både i Norge og internasjonalt, som bidrar til forsinkelser og økte kostnader for alle som er involvert i et boreprosjekt. Bakgrunnen for denne oppgaven er Odfjell Drillings erfaring med BOP-nedetid under boreoperasjoner om bord på sine mobile offshore boreenheter.

Nedetid og tilhørende kostnader på grunn av BOP-feil øker med vanndypet i et boreprosjekt fordi tiden det tar å trekke og re-installere BOP-systemet avhenger av dybde. Ved dypvannsoperasjoner kan et problem som krever at BOPen trekkes til overflaten føre til en uproduktiv nedetid på 1-2 uker. En slik situasjon medfører store økonomiske tap, både for riggeieren og operatøren som er involvert, og illustrerer hvor viktig påliteligheten til BOP-systemet er.

Ved dypvannsboring utsettes BOPen for mer krevende operasjonsforhold enn ved boring på grunnere vanndyp. Eksempler er økt belastning fra stigerør, høyere trykk og temperatur i brønn og energitap i undervannsakkumulatorer. I dag har boreselskaper over hele verden et sterkt fokus på å redusere nedetid på BOP. Forbedret teknologi og nye BOP-løsninger blir ansett som en nødvendighet for fremtidig dypvannsboring.

Denne oppgaven er et casestudie av den elektrohydrauliske BOPen om bord på Deepsea Stavanger, en boreenhet som eies og driftes av Odfjell Drilling. Det første fokuset er å analysere BOP-feil som har ført til nedetid på denne riggen, og å relatere dem til den tekniske virkemåten til BOPen.

Electrical Subsea & Drilling AS (ESD) arbeider med å utvikle en helelektrisk drevet BOP. Selskapet hevder at deres nye teknologi har mange fordeler kontra det konvensjonelle elektrohydrauliske BOP-systemet, både med hensyn til miljø- og driftssikkerhet, samt kostnadsreduksjon for olje- og boreselskaper. I tillegg hevder de at deres BOP-konsept er mer pålitelig og mindre utsatt for overdreven nedetid. Det andre fokuset er derfor å etablere en grundig systembeskrivelse av

dette konseptet, å analysere potensielle feilmoder og sammenligne dem med de feil som en opplever på BOP-systemet om bord på Deepsea Stavanger.

Det overordnede målet for oppgaven er å sammenligne det konvensjonelle elektrohydrauliske BOP-systemet med det helelektriske BOP-konseptet utviklet av ESD, med hensyn til pålitelighet. Målet med en slik sammenligning er å se om noen av de BOP-problemene Odfjell Drilling opplevelser om bord på Deepsea Stavanger er mindre sannsynlige at skjer dersom BOP-systemet er helelektrisk drevet.

For å sammenligne de to BOP-konseptene, er det utført en pålitelighetsanalyse på hvert system. Pålitelighetsanalysene er utført i fire steg:

1. Funksjonsanalyse
2. FMECA
3. Pålitelighetsblokkdiagram-analyse
4. Feiltreanalyse

Pålitelighetsdata er hentet fra erfaringsdata fra Deepsea Stavanger, ekspertvurderinger fra workshop sammen med Odfjell Drilling og ESD, tidligere pålitelighetsstudier og sammenlignbare komponenter i OREDA .

Resultatene fra analysene tilsier at det helelektriske BOP-konseptet er mer pålitelig og mindre utsatt for feil enn eksisterende elektrohydrauliske BOP-systemer. Dette er imidlertid et resultat som er basert på ett enkelt casestudie, hvor en rekke antagelser er involvert. Det er også andre faktorer, i tillegg til pålitelighet , det er viktig å belyse ved vurdering av godheten til et BOP-system.

Det er mange argumenter i favør av et helelektrisk BOP-konsept. Et elektrisk system inneholder færre og mer pålitelige komponenter enn en et elektrohydraulisk system, noe som gjør det elektriske konseptet enklere enn eksisterende BOP-systemer. Ingen skyttelventil og bruk av batterier i stedet for akkumulatorer er de mest åpenbare fordelene ved det helelektriske konseptet. I tillegg er konseptet vektbesparende, har større grad av redundans i kontrollsystemet, gir mulighet til bedre og mer nøyaktig overvåkning og er mindre forurensende. Likevel er det betydelig usikkerhet knyttet til den nye teknologien, både med hensyn til vedlikehold, reparasjonstid og lønnsomhet. Resultatene fra denne masteroppgaven gir ingen klare svar, og det må forskes mer før en kan konkludere med hvilket konsept som bidrar til minst nedetid.

For at ny teknologi skal utvikles og tas i bruk må det finnes noen markedsdrivere. Løfte om høy pålitelighet er ikke nok til å skape suksess. Et helelektrisk BOP-konseptet kan løse mange av de utfordringene boreindustrien står overfor i årene som kommer, men tiden vil vise hvorvidt et slikt konsept er både teknisk og økonomisk lønnsomt.

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LIST OF ABBREVIATIONS

AC	Alternating Current
API	American Petroleum Institute
BOP	Blowout Preventer
BP	British Petroleum
BSR	Blind Shear Ram
CCU	Central Control Unit
CSR	Casing Shear Ram
DC	Direct Current
DNV	Det Norske Veritas
DSS	Deepsea Stavanger
ESD	Electrical Subsea & Drilling AS
FMECA	Failure Modes, Effects and Criticality Analysis
GE	General Electric
HPU	Hydraulic Power Unit
LA	Lower Annular
LMRP	Lower Marine Riser Package
LPR	Lower Pipe Ram
MUX	Multiplex
NMA	Norwegian Maritime Authority
NOV	National Oilwell Varco

NPD	Norwegian Petroleum Directorate
OCS	Outer Continental Shelf
OREDA	Offshore Reliability Data Handbook
PCT	Patent Cooperation Treaty
PSA	Petroleum Safety Authority
RBD	Reliability Block Diagram
RCM	Reliability Centred Maintenance
ROVE	Remotely Operated Vehicle
SCU	Subsea Control Unit
SEM	Subsea Electrical Module
SNA	Snorre Alpha
SPM	Sub Plate Mounted
UA	Upper Annular
UPR	Upper Pipe Ram
UsGoM	US Golf of Mexico

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Excessive downtime on the blow out preventer (BOP) is a problem for drilling companies worldwide, which causes increased costs and delays for everyone involved in a drilling project. The background for this thesis is Odfjell Drilling's experience with downtime on the BOP during drilling operations on board their mobile offshore drilling units.

The day rate for a semisubmersible drilling rig is typically 4 – 7 hundred thousand dollars (NOK 2.5 – 4 million). If downtime is caused by failure on the rig owner's equipment, the client will not pay day rate and the rig owner loses money. Nevertheless, the loss can get as high as double the original cost for the client, due to delays and increased costs later in the project. In fact, the client has an even greater interest in avoiding downtime than the rig owner.

The downtime and associated cost due to failure on the BOP increases with the water depth of a drilling project because the time it takes to recover and re-install the BOP stack will increase. In a deepwater operation, the unproductive downtime from a problem that requires the BOP stack to be recovered to the surface may be 1-2 weeks. The magnitude of the resulting daily loss, both for the owner and the client involved, illustrates how important reliability of the BOP is.

Deepwater drilling operations may also experience new challenges compared to operations in more shallow depths. For the BOP examples include increased loads from the riser system, higher pressure and temperature in the well and energy loss in subsea accumulators. Today, drilling companies worldwide have a strong focus on reducing BOP downtime. Improved technology and new solutions for subsea BOPs are therefore believed to be a necessity for future deepwater drilling.

1.2 OBJECTIVES

This thesis is a case study of the electro-hydraulic BOP on board Deepsea Stavanger, a drilling unit owned and managed by Odfjell Drilling. Currently this rig is operating in Angola on contract with British Petroleum (BP). The first focus is to analyse BOP failures that have led to downtime on this rig and to relate them to the technical mode of operation on the BOP.

The company Electrical Subsea & Drilling AS (ESD) is working on developing an all-electrically operated BOP. They claim that their new technology can provide many benefits versus the electro-hydraulic BOP systems, both with respect to environmental and operational safety as well as cost reduction for drilling- and oil companies. Additionally, they claim that their BOP technology is more reliable and less prone to excessive downtime. The second focus is therefore to establish a thorough system description of this concept, analyse potential failures and compare them with the failures experienced on board Deepsea Stavanger.

In sum, this thesis addresses the following:

- BOP reliability literature study, including relevant previous blowout accidents, standards for BOP operations, and basic BOP principles applied in drilling.
- Description of the technical mode of operation of the BOP, covering both the electro-hydraulic system and the all-electric concept.
- Assessment of potential BOP failure modes, and how these relate to the technical mode of operation.
- Qualitative analysis of potential faults.
- Comparison of the electro-hydraulic BOP system and the all-electric operated system.
- Conclusions and recommendations for further work.

1.3 Scope and Limitations

The overall goal for this thesis is to compare the conventional electro-hydraulic BOP system with the all-electric BOP concept developed by ESD, with respect to reliability. The purpose of such a comparison is to see if any of the recurring failures Odfjell Drilling experiences on board Deepsea Stavanger are less likely to occur if the BOP is all-electrically operated.

The system boundaries for the analytical part are defined as;

- The panels necessary to activate a required BOP function
- The signal transmission and hydraulics/ electrical power necessary
- The individual valves and equipment of the BOP

In order to be included in the analyses, the failure effects of potential component failures must be significant in terms of system reliability and downtime. Additionally, reliability data or operating experience from the actual part, or similar parts, must be available.

1.4 STRUCTURE OF REPORT

The thesis work is performed in three main steps; initial literature review, detailed case study of the electro-hydraulic BOP system and the all-electric BOP concept, followed by qualitative, semi-quantitative and quantitative reliability analyses. The emphasis has been on the third step, which is performed as described in Chapter 4 - Method.

Chapter 2 gives an introduction to offshore drilling concepts. Chapter 3 documents the literature survey, discussing previous BOP reliability studies and accidents, as well as regulations and guidelines relevant to BOP systems.

Chapter 5 presents the case study, including differences and similarities between the two BOP concepts. Chapter 6 addresses the BOP system boundaries, system functions and potential failure modes of the two concepts. The analyses are given in detail, with results, in Chapter 7. A thorough discussion of the results is presented in Chapter 8.

Finally, the thesis is summarized and concluded in Chapter 9, and recommendations and ideas for further research are suggested.

CHAPTER 2

OFFSHORE DRILLING CONCEPTS

2.1 EXPLORATION, DRILLING & COMPLETION

Oil production starts with exploration. Geologists use modern theory of plate tectonics, together with historical and seismic data to identify oil or gas deposits of sufficient size to be drilled, developed and produced.

Drilling an oil well is an extensive task. Major challenges related to technology, profitability and organizational factors must be overcome to drill a well 3000 metres below the sea surface, or even deeper, to reach hydrocarbon reservoirs as efficiently and safely as possible. A summary of the most important principles in drilling is given on the next pages, based on literature by Steve Devereux (Drilling Technology in a Nontechnical Language, 2012).

For deepwater drilling, either a semisubmersible drilling rig or a drillship is used, as illustrated in Figure 1. All necessary equipment to perform a drilling operation is placed on board the unit.

Specifications and layout for a drilling operation may vary, but in general, the drill bit is connected to the bottom of the drill string, where the drill collars can be attached to add more weight, as shown in Figure 2.

Lowering and raising these sets of drill pipes are done with drawworks in the derrick on board, simultaneously as the pipes are rotated as the well is drilled deeper.

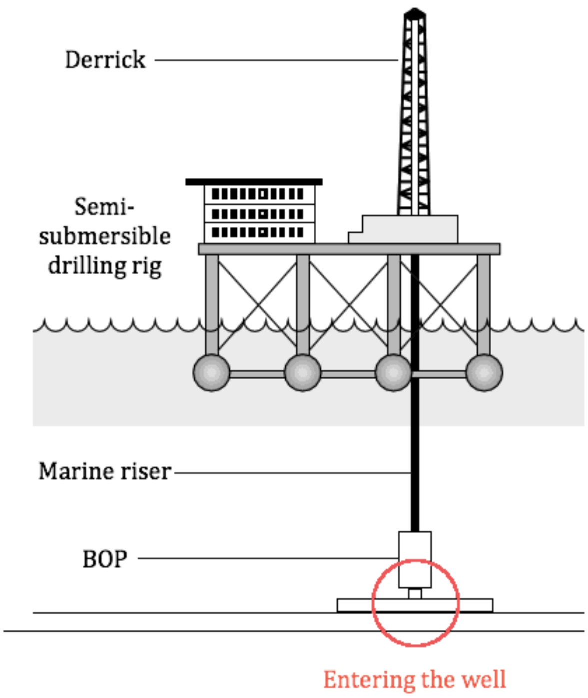


FIGURE 1: SEMISUBMERSIBLE DRILLING RIG. MODIFIED FROM (STEVE DEVEREUX, 2012)

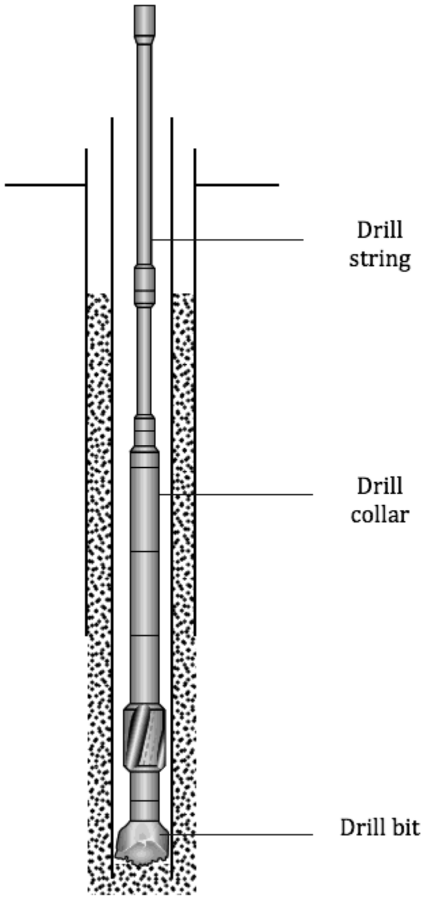


FIGURE 2: DRILL PIPES. MODIFIED FROM STEVE DEVEREUX (2012)

During drilling, mud is circulated down the drill string and up the borehole annulus (the space between the drill string and the walls of the well). The drilling mud circulation is illustrated in Figure 3. As the drill bit goes deeper, it faces increasing pressure in the formation, due to the weight of the various rock layers and the column of water above it. If downhole pressures are not kept under control, an uncontrolled release of oil or gas, called a *blowout*, can lead to loss of life, massive environmental damage, damage to underground reservoirs, and damage to the rig.

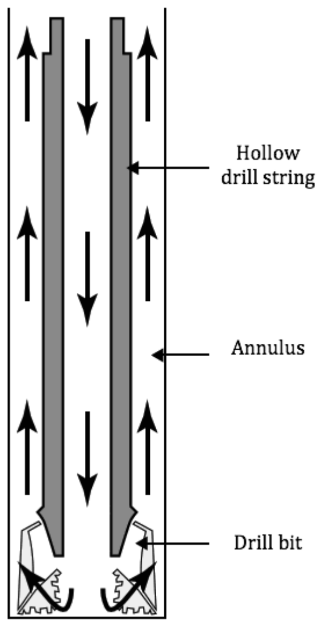


FIGURE 3: DRILLING MUD. MODIFIED FROM STEVE DEVEREUX (2012)

The pressures at the bottom of the hole determine which mud weight that is suitable. Three things can happen as the weight of the mud is varied:

1. If the mud is *too light* to contain the pressures encountered, the wellbore may cave in, or worse, the oil and gas may come uncontrollably spewing up the wellbore.

2. If the mud is *too heavy,* it may overwhelm the strength of the rock, fracture the sides of the well, and leak off into the formation.
3. If the mud is *just right* the wellbore maintains its integrity, and any hydrocarbons encountered are kept in the formation until the well can be evaluated and completed.

In addition to pressure control, the drill mud performs two other functions. As the mud flows down the drill pipe, out the jets on the drill bit, and up the borehole annulus it cools the drill bit and carries away drilling cuttings. A mud logger monitors the cuttings as they are separated from the mud at the surface.

Mud weight is precisely and continuously calculated for each well and applicable well depth. Heavy mud is a challenge in deepwater wells, because the riser is then subjected to large forces. If 'sudden loss' of mud in the riser occurs, for example due to emergency disconnect from the wellhead, vacuum will form inside the riser. This, combined with high pressure on the outside of the riser can lead to riser collapse. Pictures showing examples of this behaviour are shown in Figure 4 and Figure 5.

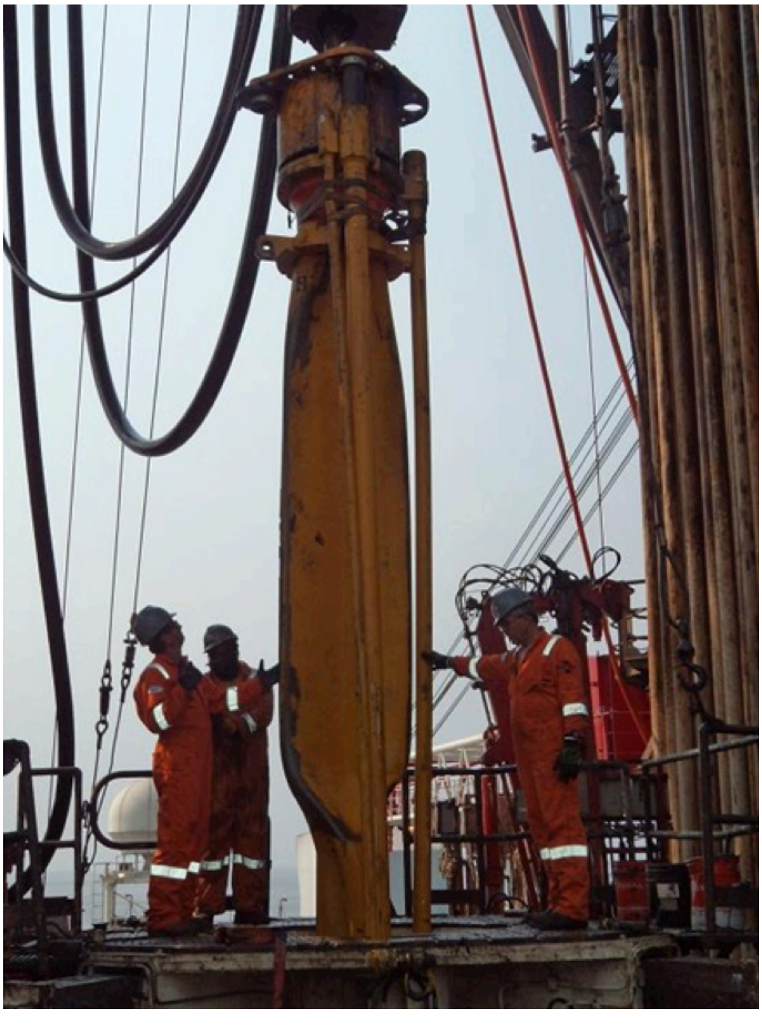


FIGURE 4: RISER COLLAPSE AT 1300 METRES (WWW.GCAPTAIN.COM, 2013)

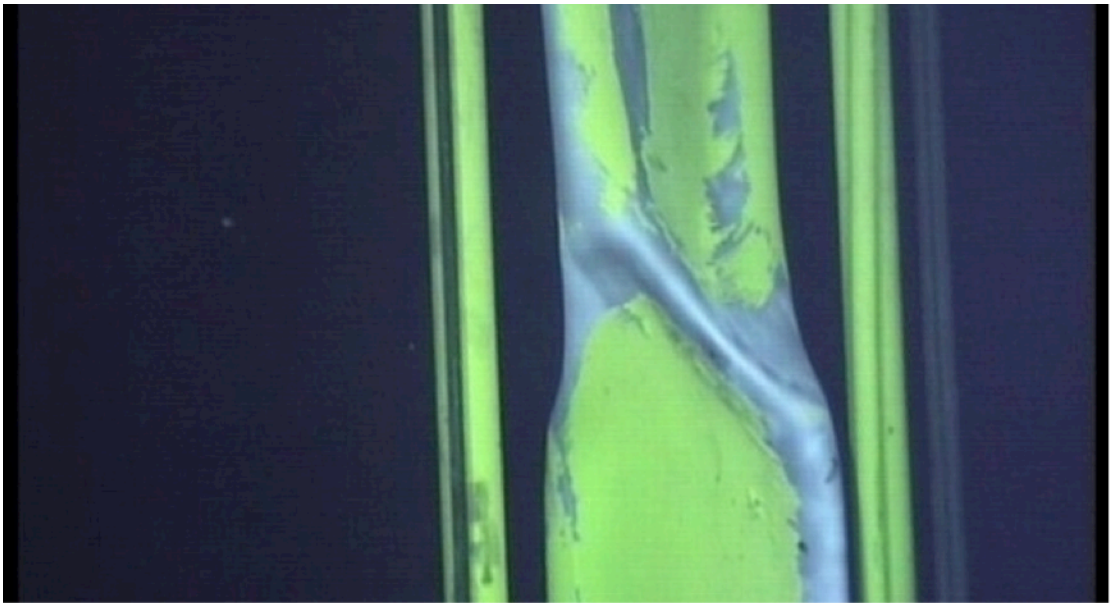


FIGURE 5: RISER COLLAPSE DUE TO MUD VACUUM (WWW.GCAPTAIN.COM, 2013)

As the well goes deeper, heavier mud is needed to offset the higher pressures encountered. The mud is homogenous, and the heavier it is, the more pressure it puts on the wellbore at intermediate depths. In worst case, the weight of the mud may increase to the point where it can fracture the rock up hole. To prevent fracture and to protect the weaker rock formations, steel casing is run in the well and cemented in place.

Casing has to be run several times to cover weak formations and allow the drill bit to reach the targeted total depth. Each new string of casing has a smaller diameter – because it has to fit inside the previous run casing to get to the bottom of the borehole.

The mud system is the main barrier against unusual surges in wellbore pressure. As another precaution, every well is fitted with a BOP system. The BOP can seal off fluid flow from the well through one or more devices activated from the rig. Well control is discussed thoroughly in Section 2.2, and the BOP is the main topic in this thesis and is described more in detail in Chapter 5.

After the drill bit reaches the target depth, the bit is pulled and the well is evaluated. The well can either be temporarily abandoned by placing cement plugs in the wellbore, and then disconnection at the BOP, or the well can be completed. To produce oil and gas effectively, a well has to be completed with additional casing (tubing) through which the production flows. Additionally, a tree has to be installed at the top of the well, safety devices need to be put in place and a kit has to be installed to keep sand from clogging up the well. A drawing of a typical well drilled from a semisubmersible drilling rig in the North Sea is given in Figure 6.

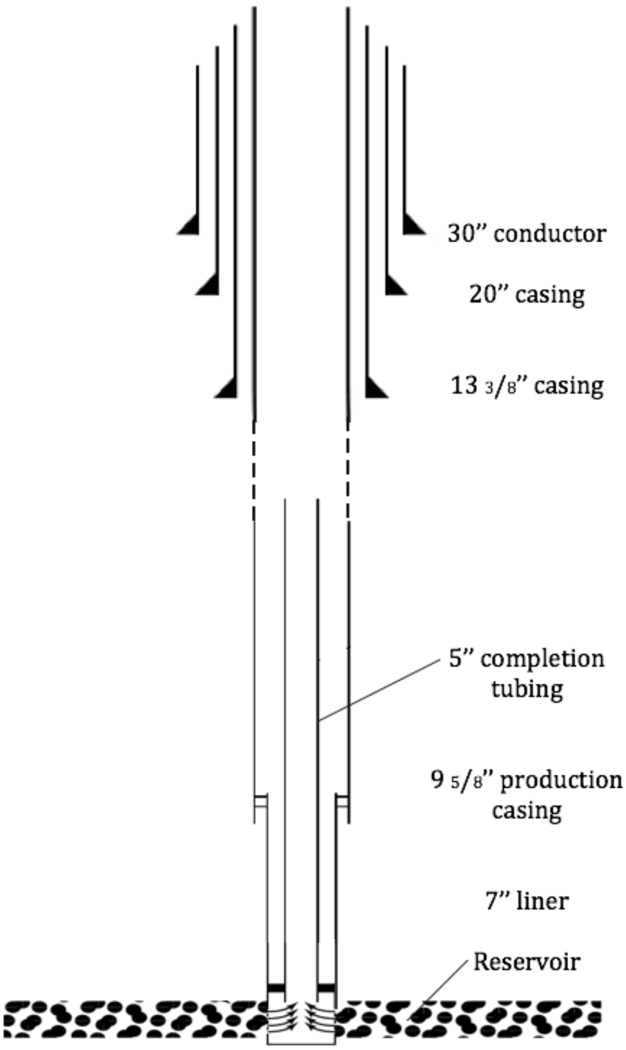


FIGURE 6: TRADITIONAL WELL DRILLING. MODIFIED FROM STEVE DEVEREUX (2012)

2.2 WELL CONTROL

The term well control refers to the control of fluid- and equipment pressures in the well. The principles of fluid pressures are fundamental to many aspects of oil well drilling and are briefly described in Section 2.1. Also mentioned is the importance of the drilling mud. If the formation pressure is higher than the hydrostatic pressure of the drilling mud during drilling, the mud is pushed up the well by the pressure in the formation. This is called a *kick*. Kicks can either occur as a result of much higher pressures in formation than normal, a weak formation surrounding the well which allows the level of mud in the annulus to drop, insufficient filled hole when pulling out of the hole or due to swabbing operations.

There are three distinct well control levels that may occur during drilling operations. In the following, theses three levels are described, in addition to the process and equipment involved in kick detection and control.

2.2.1 PRIMARY, SECONDARY AND TERTIARY WELL CONTROL

Primary well control
The first line of defence is primary well control, which results from maintaining the density of the drilling fluid such that hydrostatic pressure at all depths where formations are exposed, exceeds formation pore pressures:

$$Mud\ hydrostatic\ pressure\ > Formation\ pore\ pressure$$

The well is planned and drilling operations are controlled with the intention that primary well control is always maintained. The only exception to this is underbalanced drilling, which will not be further addressed in this report. If a kick occurs, the primary well control has been lost due to one of the reasons mentioned in the introduction to Section 2.2.

Secondary well control
If formation fluids start to flow into the well, secondary well control is initiated by closing the BOP to seal off the annulus. This stops mud from leaving the well at the seabed, where the BOP is installed. As fluid enters the well due to a kick, pressure in the well will increase until the total pressure exerted by the mud on the kicking formation equals the formation pore pressure. The pressure exerted by the mud equals mud hydrostatic pressure plus the BOP pressure:

$$Mud\ hydrostatic\ pressure + BOP\ pressure = Formation\ pore\ pressure$$

Figure 7 shows the situation after closing the blowout preventer. Fluid influx has entered the well, the BOP is closed and the pressures have stabilized. Notice that the influx is in the annulus. The density of all the fluids in the annulus is not known. However, the drill string is full of clean mud of known density. As the mud hydrostatic pressure in the drill string and seabed pressure are both know, the pressure in the bottom of the well can be calculated.

Restoring primary control is done by remove all of the influx out of the well and then replace the mud in the well with a fluid that is heavy enough to again exert sufficient hydrostatic pressure to control the downhole formation pressures with the BOP open.

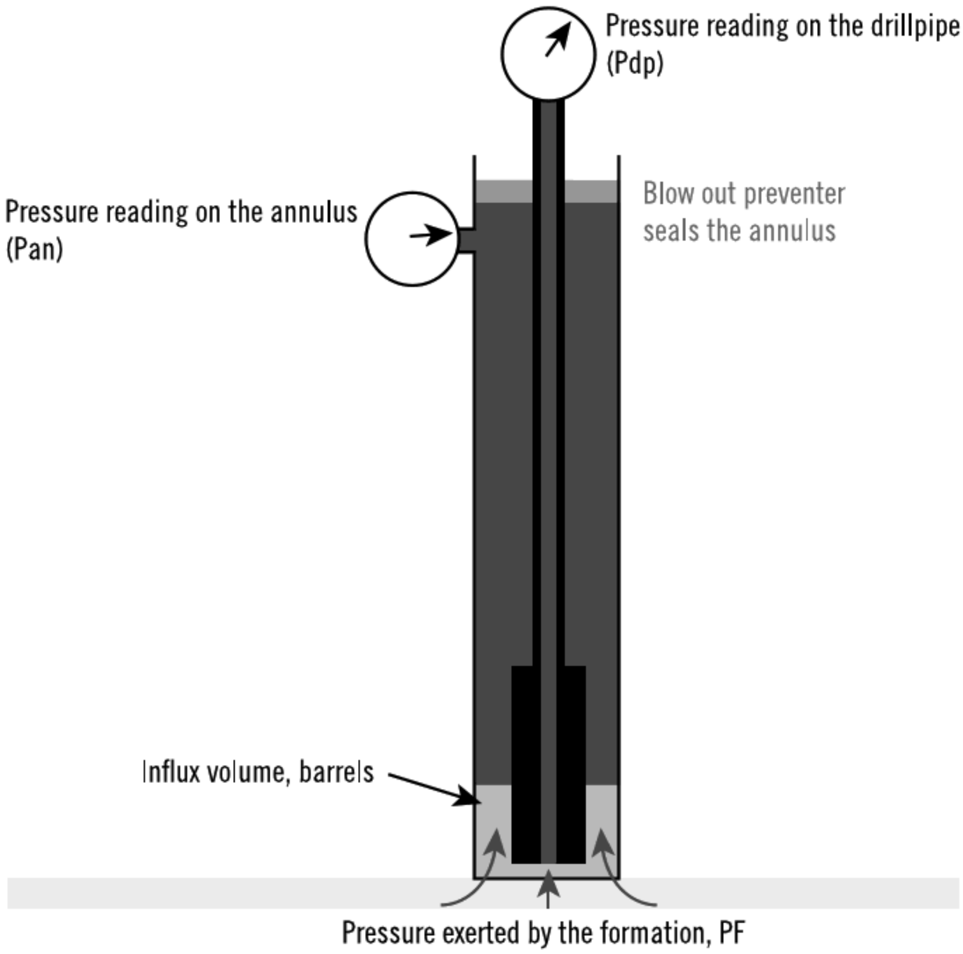


FIGURE 7: BOP CLOSED ON INFLUX (STEVE DEVEREUX, 2012)

Tertiary control

It sometimes happens that the blowout preventer fails or the hole starts to allow fluid to leak away into an underground formation. Secondary control cannot be maintained, and formation fluid again starts to enter the wellbore. This is now a dangerous situation calling for extreme measures to restore control. If control is not restored, the end result is a blowout.

Tertiary control involves pumping substances into the wellbore to try to physically stop the flow downhole. This may involve pumping cement, although the risk is then high of having to abandon the well afterwards. However, there is another method that may be employed, called a barite plug.

Mixing heavy slurry and barite in water or diesel oil sets a barite plug. It has to be kept moving while mixing and pumping. Once the slurry is in position downhole and pumping stops, the barite rapidly settles out to form an impermeable mass that will hopefully stop the flow of formation fluid. The main risk is that if pumping stops with the slurry inside the pipe, barite will settle out in the pipe and plug the drill string.

2.2.2 Kick Detection and Control

When planning and drilling wells, the assumption is made that a kick is always possible. Even if the well is the 100th drilled in the immediate area, primary control can still be lost for some reason. That is why BOPs are always attached to the top of the casing at the seabed. A detailed description of the BOP system is given in Chapter 5.

Kick detection equipment
There are two main kick detection systems in the mud system that give direct indication of a kick:

1. The pit volume totalizer
2. The flow indicator

Generally the flow indicator will give the first positive indicator of a kick, followed by an increase in the active volume. However, the flow indicator is prone to false alarms due to cuttings and other debris in the mud.

If the surface instruments indicate that a kick is in progress, the driller will stop drilling and pick up the drill string so that the bit is above the bottom of the hole, and stop the pumps. The BOP is then closed as quickly as possible, before *well killing* can begin.

Killing the well
The operations involved in restoring primary control during a kick are known as *killing the well*. Heavy mud is circulated down the kill line and into the annulus. The choke/kill system is addressed in Chapter 5. Once the kill operation is complete, the pumps are stopped. If no pressures remain on drill pipe or annulus, the BOP is re-opened and drilling can proceed.

CHAPTER 3

LITERATURE REVIEW

This chapter presents the most relevant literature and standards related to reliability of BOP systems, in addition to a review of important blowout accidents. The source literature can be good as additional reading for achieving a deeper awareness of reliability issues for subsea BOP systems.

3.1 BOP RELIABILITY STUDIES BY SINTEF

From 1981 to 1999, SINTEF has documented results from a number of detailed reliability studies of subsea BOP systems on behalf of the Norwegian Petroleum Directorate (NPD) and various oil companies, both operating in the Norwegian sector and internationally.

The following studies have been carried out:

Phase I Analysis of failure data from 61 exploration wells drilled from semisubmersible rigs and BOP system analysis (Rausand M., 1983).

Phase II Analysis of failure data from 99 exploration wells from semisubmersible rigs and mechanical evaluation of BOP components (Rausand, Holand, Husebye, Lydersen, Molnes, & Ulleberg, 1985) & (Hals & Molnes, 1984).

Phase III Evaluation of operation and maintenance of subsea BOP components, test procedures and operational control (Holand & Molnes, Reliability of Subsea BOP Systems - Phase III Testing and Maintenance, Main Report, 1986).

Phase IV Analysis of 58 exploration wells, drilled during the period 1982-1986. Fault tree analysis was used to assess the availability of the BOP (Holand P., 1987).

Phase V Analysis of 47 exploration wells, drilled during the period 1987-1989. Recommendations regarding BOP test intervals were given (Holand P., 1989).

Phase I DW Analysis of 140 wells drilled from 1992 to 1997. Fault tree analysis was used to compare three types of control systems regarding their ability to close in a well when a kick occurred (Holand P., 1997).

Phase II DW Analysis of 83 wells drilled in water depths of 400-2000 metres during the period 1997-1998. The report is written for The Mineral Management Service, and evaluation of both the safety and downtime aspect of failures are presented (Holand P., 1999).

The report 'Deepwater Kicks and BOP Performance' (Holand & Skalle, 2001) is a follow up study of Phase II DW. Fault tree analysis has been used to analyse the BOP as a safety barrier based on BOP configurations and the relevant kick experience. The fault tree is based on Shaffer (Koomey) pilot system from the early 80s, and can therefore not be directly compared to the Shaffer Electro-Hydraulic MUX control system that is addressed in this thesis.

The most recent BOP reliability studies, Phase II DW and 'Deepwater Kicks and BOP Performance', are the main sources for reliability data in this thesis, and are shortly referred to as Holand's reliability studies.

3.2 SINTEF OFFSHORE BLOWOUT DATABASE

SINTEF Offshore Blowout Database is a comprehensive event database for blowout risk assessment. The database includes information on 573 offshore blowouts/well releases that have occurred world-wide since 1955 and overall exposure data from the US Gulf of Mexico (US GoM), Outer Continental Shelf (OCS) and the North Sea. The blowouts/well releases are categorized in several parameters, emphasizing blowout causes and operational phase. ExproSoft has been contracted to operate the Offshore Blowout Database from 1st May 2001 by SINTEF. Oil production and oil service companies are participants and sponsors in the project (SINTEF, 2014).

Data from the US GoM, OCS, Norwegian and UK waters are in general better documented than blowouts from other regions. From 1st January 1980 through 1st January 2008, a total of 237 blowouts/well releases from these areas were consolidated in the database. Table 1 shows an overview of blowouts occurrence by operational phase (development drilling, exploration drilling, unknown drilling, completion, workover etc.).

TABLE 1: BLOWOUTS DURING DIFFERENT OPERATIONAL PHASES (SINTEF, 2014)

AREA	Dev. drlg	Expl. drlg	Unk. drlg	Comp-letion	Work-over	Production		Wire-line	Un-known	Total
						External cause*	No ext. cause*			
US GoM OCS	53	50		12	35	6	10	2	5	**173**
	30.6%	28.9%	0.0%	6.9%	20.2%	3.5%	5.8%	1.2%	2.9%	**100.0%**
UK, and Norwegian waters	9	31	2	6	9	1	2		4	**64**
	14.1%	48.4%	3.1%	9.4%	14.1%	1.6%	3.1%	0.0%	6,3	**100.0%**
Total	62	81	2	18	44	7	12	2	9	**237**
	26.2%	34.2%	0.8%	7.6%	18.6%	3.0%	5.1%	0.8%	3.8%	**100.0%**

*** EXTERNAL CAUSES ARE TYPICAL; STORM, MILITARY ACTIVITY, SHIP COLLISION, FIRE AND EARTHQUAKE**

Some statistics from the database are presented in the following references;

- *'Offshore Blowouts Causes and Trends'*, Doctoral Dissertation, NTNU (Holand P., Offshore Blowouts Causes and Trends, 1996)
- '*Offshore Blowouts Causes and Control*', (Holand P., 1997)

Table 1 shows that blowouts are most likely to occur during development and exploration drilling in addition to during completion. Also the statistics from the references above underline this trend.

3.3 BLOWOUT ACCIDENTS

History shows that uncontrolled releases of hydrocarbons have caused several major accidents. Experience from accidents in the past is an important source of information to prevent the occurrence of similar tragedies in the future.

Important BOP accidents from the second half of the twentieth century are listed in Table 2 below. Also accidents that had major accident potential and near misses that could have developed into disastrous accidents are included.

TABLE 2: BLOWOUT ACCIDENTS AND NEAR MISSES. MODIFIED FROM VINNEM (2014)

Hazard Area	Blowout
UK	• Ocean Odyssey, 1989
Norway	• Ekofisk B, 1977 • West Vanguard, 1985 • 2-4-14, 1989 • Snorre A, 2004 • Gullfaks C, 2010
Brazil	• Enchova, 1984 • Frade, 2011
South China Sea	• Seacrest, 1989
US	• Ixtoc, 1979 • Macondo, 2010
Other areas	• Temsah, 2004 • Montara, 2009

The main sequence of events and lessons learned, with respect to prevention of blowouts, are spelled out explicitly for each of the North Sea accidents in the rest of this section. For technical description of the BOP System, it is referred to Chapter 5. For some of the accidents, information is available in great depth, especially if an official commission took place after the accident. In other circumstances, comprehensive investigations did not take place, and the available information is more limited.

For the Ekofisk B and the West Vanguard blowout no BOP was installed, according to normal practice at the time, and these accidents are therefore only discussed briefly. The Macondo blowout is discussed in detail in Section 3.4. For the Enchova, Frade, Seacrest, Ixtoc, Temsah and Montara blowout reference is given to accident reports and discussions by Vinnem (2014).

Holand (1997) underlines that most blowout accidents have complex causes. The direct cause may often seem simple, but the indirect causes are more complex. Causes related to inadequate training, inadequate use of personnel, high personnel turnover, low manning, lack of decisions, inadequate preventive maintenance, inadequate procedures, influence from other work and working environment are examples of indirect factors. The emphasis in this thesis is on the technical BOP equipment, but it is still important to be aware of the (human controlled) environment the system is relying on.

3.3.1 Ocean Odyssey Burning Blowout

The semisubmersible drilling rig Ocean Odyssey suffered a serious fire as a result of a subsea blowout on 22nd September 1988. The rig was drilling in the Fulmar area of the North Sea, approximately 160 km from Aberdeen, Scotland. The rig was drilling a reservoir with abnormally high gas pressures and the well drilling program was designed accordingly with special equipment installed.

There is no official reporting of this accident, the available documentation is from the investigation carried out by the Sheriff Principal of Grampian, Highlands and Islands (Ireland, 1991) and Vinnem (2014).

At a drilling depth of 4,900 metres, the drilling took a kickback. According to the company, annular preventers were closed and heavy mud was being circulated down the drill pipe and back through the choke line. It is thought that the choke line developed a leak; gas flowed to the surface and exploded underneath the rig, possibly also damaging the hydraulic BOP control system.

The first explosion came from the mud-processing module, suggesting that gas had somehow been ignited as it was dissolved out of the mud. A second explosion occurred beneath the surface of the water, shown by a large bubble of gas, indicating the beginning of the blowout. A fire followed the blowout and swept up from the moonpool to affect the cellar deck and the mud pump room. The accommodation module also suffered severe damage. The fire burned for ten hours.

A support vessel was brought onto the scene to help control and extinguish the fire. Anchor lines were later cut and the rig was towed clear of the well. Of the 67 men on board, a radio operator died in the incident.

3.3.2 Ekofisk B Blowout

A blowout occurred on 23rd April 1977, on the steel jacket wellhead platform Ekofisk Bravo, during a workover on a production well. The BOP was not in place on the platform. The well was mechanically capped by well control specialists from the USA seven days after the blowout. The oil spill was approximately 20,000 m^3, although no oil ever reached shore. Production on the platform was stopped for six weeks to allow clean-up operations. There was virtually no material damage to the platform. The Ekofisk Bravo blowout is the only blowout in the Norwegian sector where a substantial amount of oil was spilled into the sea.

3.3.3 WEST VANGUARD GAS BLOWOUT

The semi-submersible West Vanguard experienced a shallow gas blowout on 6th October 1985 while conducting exploration drilling in the Haltenbanken area in the Norwegian Sea. This review is based on the investigation report by SINTEF (Bjørkhaug, Danielsen, Håverstad, Jacobsen, & Pedersen, 1985).

Drilling of a pilot hole had commenced earlier the same day, with the marine riser connected, but no BOP installed. As the bit entered a thin gas layer 236 metres below the seabed, three subsequent influxes caused a gas blowout.

When the drilling crew realised what was happening, they started pumping heavy mud and opened the diverter valve to deviate the flow of gas away from the drill floor. Just a few minutes' erosion in the bends of the diverter caused these to leak and the gas entered the cellar deck from below. Attempts to release the marine riser wellhead coupling on the seabed were not successful, due to the perceived ignition hazard in all areas on the platform.

Ignition probably occurred in the engine room, setting off a strong explosion, subsequent fire, and further explosions. One person was never found after the accident, it was suspected that the person could have been blown overboard in the initial explosion. All personnel from two lifeboats were rescued, in addition to two persons picked up from the sea.

The lessons learned from this accident are particularly related to well control and operations, and it may be noted that drilling through shallow zones is now usually done without a marine riser, if a BOP is not installed (Vinnem, 2014).

3.3.4 TREASURE SAGA UNDERGROUND BLOWOUT

Operator Saga Petroleum struggled for 14 months to deal with a sub-surface blowout in well 2/4-14 near the Albuskjell field in January 1989. Every day for almost a year, 20 000 barrels of oil flowed out into the bedrock beneath the seabed from what became known colloquially as the "phantom well". This summary is solely based on an article published by the Petroleum Safety Authority (PSA, 2013), as no official investigation report is publically available.

Drilling operations went smoothly until higher-than-expected pressure was suddenly encountered. The drillers tried to seal the well, but the cement plug disintegrated. A strong gas flow developed on the drill floor, and the BOP on the seabed had to be activated.

The personnel on the rig tried to restore control over the well by pumping heavy mud down through the kill line. The latter suddenly broke the next morning, and Treasure Saga's only option was to move off the site.

Treasure Saga started drilling a relief well eleven days after the kick. The jack-up Neddrill Trigon was approved for killing operations. This unit was intended to re-enter 2/4-14 via the BOP on the seabed, while Treasure Saga set to work on drilling a relief well.

Many methods were tried for killing the well. A series of accidents and periods of little progress meant that the operation dragged on. During the autumn, Saga discovered that the well was on the verge of collapse – increasing the danger that oil would flow right up to the seabed. Efforts to enter the well directly through the BOP were abandoned, and attention was concentrated on drilling the relief well. Saga finally managed to kill the rogue well on 13th December 1989. Clean-up work was not finished until March 1990, and Saga could finally abandon a properly plugged well after 14 months of intensive work.

This accident does not seem to have been easily preventable. There are few distinct errors as the main causes, somewhat in contrast to several recent blowouts and well incidents. However, knowledge on these aspects may be limited due to the absence of an investigation report in the public domain. There were no injuries during the well operations on either of the rigs involved, but one person was killed on Treasure Saga in connection with handling of drill pipes on the drill floor.

The failure of the initial cement plug was an unwanted incident. The failure of the flexible hose in the kill system was also an unwanted incident that contributed to the negative consequences. The well was the first high pressure/ high temperature well drilled in the Norwegian sector, which at the time may have been new and unconventional.

3.3.5 Snorre A Subsea Gas Blowout

An uncontrolled subsea gas blowout occurred on the Snorre Alpha (SNA) platform in the Norwegian North Sea on 28th November 2004. The P-31 well was drilled as an observation well in 1994. The well performed satisfactory until 2001 when several problems occurred and a plug was installed above the reservoir section in 2003. The operation plan in 2004 was to drill a new well through the same well slot.

Swabbing (an unwanted piston effect in a well when pipe sections are retrieved) was observed several times during retrieval of production string parts from the well in the period up to the blowout. Mud was circulated through the well each time in accordance with normal practice, and the well was observed for any influxes, which were not observed. However, there were several losses of mud to the formation observed throughout the afternoon, and the BOP annular preventer was closed once.

A reverse circulation was attempted, but increase in mud return was observed and the BOP was closed again, which also caused a significant pressure build up in the well. Gas was then detected below drill floor, based on gas leaking gradually through the BOP. Working pressure in the hydraulics was increased in order to stop this leak.

Several gas alarms were observed during the evening, and personnel detected that the sea around the installation was 'boiling' with gas. The well was observed throughout the night, and preparations for the final well killing operation were made. The final bullheading of mud down through the drill string started on 29th November, after one hour zero pressure reading was recorded in the drill string as well as in the annular space outside. At that time the only remaining mud on board was less than 10 m^3, implying that if this attempt had been unsuccessful, full evacuation was the only option left.

The accident was investigated by the operator Statoil and by the PSA (2005), the latter is the main source of this section. It was realised that gas had leaked through the formation, which was confirmed later by several craters that were found on the seabed under the platform. PSA characterizes this event as one of the most serious on the Norwegian continental shelf, based on the great potential of the event and the extensive failure of barriers.

3.3.6 Gullfaks C Well Incident

The severe well kick on Gullfaks C on 19th May 2010 occurred less than one month after the Macondo blowout, and received a lot of attention due to this, but also because it was seen to demonstrate that the operator had not learned the necessary lessons after the Snorre Alpha subsea blowout in 2004 (Section 3.3.5).

Nobody was hurt and no hydrocarbons escaped, but according to the PSA investigation the incident was very serious (2013). Under slightly different circumstances, it could have developed into a major accident in the shape of a sub-surface blowout and/or explosion.

The well on Gullfaks C was drilled in managed pressure drilling mode to a total depth of 4,800 m. During the final circulation and reservoir section hole cleaning on 19th May 2010, a hole occurred in the casing, with subsequent loss of drilling mud to the formation. The casing was a common well barrier element, and the hole in the casing implied loss of both well barriers. Loss of backpressure lead to influx from the exposed reservoirs into the well, until solids or cuttings packed off the well by the liner shoe. The pack-off limited further influx of hydrocarbons into the well (Vinnem, 2014).

The work of regaining control over and re-establishing barriers in the well lasted for more than two months. The incident caused a gas release on the platform and the production on the platform was shut down for almost two months.

3.4 MACONDO BLOWOUT

The Macondo blowout, also referred to as the Deepwater Horizon accident, claimed eleven lives and is considered the largest accidental marine oil spill in the history of petroleum industry. The description given in this section is based on investigation reports made by DNV (2011), SINTEF (2011) and The Bureau of Ocean Energy Management, Regulation and Enforcement (2011).

3.4.1 THE EQUIPMENT

Deepwater Horizon was a semisubmersible, dynamically positioned drilling unit that could operate in waters up to 2,500 metres deep and drill down to a maximum depth of 9,100 metres. The rig was owned by Transocean and under lease to BP.

The BOP Stack, built by Cameron, was in use on the Deepwater Horizon since the commissioning of the rig in 2001. The BOP Stack consisted of the following systems, sub-systems and components:

- A lower marine riser package (LMRP) containing two annular preventers and two control pods
- The lower section of the BOP stack contained five sets of rams; the blind shear rams (BSR), the casing shear rams (CSR), upper variable bore rams (VBR), middle VBRs and lower VBRs. The LMRP was placed on top of the lower section of the BOP.
- Two electronic control pods were located or fitted to the LMRP. These control pods received signals from the control panels that were located on the rig itself, and then activated various hydraulic circuits and mechanical components on the BOP Stack.

At the time of the accident, the rig was drilling an exploratory well at a water depth of approximately 1,500 metres in the Macondo Prospect in the Gulf of Mexico.

3.4.2 THE ACCIDENT

On the evening of 20th April 2010 control of the well was lost, allowing hydrocarbons to enter the drilling riser and reach the Deepwater Horizon, resulting in explosions and subsequent fires. The fires continued to burn for approximately 36 hours. The rig sank on 22nd April 2010. Over the next 87 days, almost 5 million barrels of oil (= 700 million litres) were discharged to the Gulf of Mexico, before the well was permanently plugged with cement and ‘killed’ on 19th September 2010.

Prior to the loss of well control, the upper annular (UA) was closed as part of a series of two negative leak-off tests. Some 30 minutes after the conclusion of the second leak-off test, fluids from the well began spilling onto the rig floor. At 21:47 the standpipe manifold pressure rapidly increased. The first explosion was noted as having occurred at 21:49. At 21:56 the emergency disconnect sequence (EDS) was activated from the bridge. This was the final recorded well control attempt from the surface before the rig was abandoned at 22:28. The upper VBRs were closed prior to the EDS activation.

A drill pipe tool joint was located between the UA and the upper VBRs. With both the UA and the upper VBRs closed on the drill pipe, forces from the flow of the well pushed the tool joint into the annular element. This created a fixed point arresting further upward movement of the drill pipe. The drill pipe was then fixed but able to pivot at the UA, and horizontally constrained but able to move vertically at the upper VBRs. Forces from the flow of the well induced a buckling condition on the portion of drill pipe between the UA and upper VBRs. The drill pipe deflected until it contacted the wellbore just above the BSRs. The portion of the drill pipe located between the shearing blade surfaces of the BSRs was off centre and held in this position by buckling forces.

As the BSRs were closed, the drill pipe was positioned such that the outside corner of the upper BSR blade contacted the drill pipe slightly off centre of the drill pipe cross section. A portion of the pipe cross section was outside of the intended BSR shearing surfaces and would not have sheared as intended. As the BSRs closed, a portion of the drill pipe cross section became trapped between the ram block faces, preventing the blocks from fully closing and sealing.

In the partially closed position, flow would have continued through the drill pipe trapped between the ram block faces and subsequently through the gaps between the ram blocks. When the drill pipe was sheared on 29th April 2010, using the CSRs, the well flow pattern changed to a new exit point. At this point, the flow expanded through the open drill pipe at the CSRs and up the entire wellbore to the BSRs and through the gaps along the entire length of the block faces and around the side packers.

The primary cause of failure was by DNV identified as the BSRs failing to fully close and seal due to a portion of drill pipe trapped between the blocks.

Contributing causes to the primary cause included:

- The BSRs were not able to move the entire pipe cross section into the shearing surfaces of the blades.
- Drill pipe in process of shearing was deformed outside the shearing blade surfaces.
- The drill pipe elastically buckled within the wellbore due to forces induced on the drill pipe during loss of well control.

- The position of the tool joint at or below the closed Upper Annular prevented upward movement of the drill pipe.
- The Upper VBRs were closed and sealed on the drill pipe.
- The flow of fluids was uncontrolled from downhole of the Upper VBRs.

FIGURE 8: DEEPWATER HORIZON ACCIDENT (US CHEMICAL SAFETY BOARD, 2013)

3.4.3 Accident Potential

Vinnem (2014) argues one lesson learned from the Macondo blowout which is somewhat special; the similarity between offshore and nuclear accidents. Accidents such as Three Mile Island, Chernobyl and Fukushima had worldwide effects. Regardless of which country they occurred in – a whole world felt the repercussions.

For offshore petroleum activities it has often been claimed that unless it takes place very close to shore, there is normally no 3rd party risk to consider, neither with respect to personnel, environmental or financial matters. The Deepwater Horizon accident proves this wrong, and is a clear evidence of how enormous the consequences from an offshore accident can get – and how much the consequences affect the surroundings across national borders, rules and regulations. This similarity between the accident potential for nuclear and offshore activities again emphasizes the importance of reliability of offshore petroleum equipment, including the BOP.

3.5 STANDARDS

API standards have been widely used in the offshore industry over the years and are still a main set of standards in the industry. In the subsea industry, where Norway is in the forefront, ISO standards have been developed and adopted in later years, replacing API standards. In addition, NORSOK standards are also used.

The main BOP standards used in the drilling industry are:

- API 53
- DNV-OS-E101 & DNV-RP-E-101
- NORSOK D001 & D010
- The oil companies also have their own specifications and barrier philosophy

API 53 is the most widely used and recognized standard worldwide. DNV and NORSOK are mostly used in the Norwegian and UK sector, but also internationally.

API 53 has been revised after the Macondo blowout - 'should' was formerly widely used in the text, but has mostly been replaced with 'shall' in the new revision, so that there are fewer possibilities for rig owners for interpreting the guidelines. In US waters one are normally required to follow the API 53, for example in the Gulf of Mexico.

The Norwegian Oil and Gas Association (Norwegian Oil and Gas, former The Norwegian Oil Industry Association – OLF) is a professional body and employer's association for oil and supplier companies engaged in the field of exploration and production of oil and gas on the Norwegian Continental Shelf. The association has developed a guideline (*OLF guideline no. 070*) to support the use of *IEC 61508/ 61511*. In the new regulations from the PSA specific references are given to the IEC standards and the OLF guideline. Drilling and well intervention, including BOP equipment, is considered in a separate chapter in the guideline.

CHAPTER 4

METHOD

This method chapter is meant to provide greater awareness of the quality of the work in this thesis, in addition to documenting how the work is performed, as well as what it contains.

4.1 RELIABILITY ANALYSIS

To compare the two BOP concepts, a reliability analysis is performed on each system. The reliability analyses are performed in the following steps:

1. Functional analysis
2. FMECA
3. Reliability block diagram analysis
4. Fault tree analysis

These steps can be recognized as parts of an RCM process. Reliability centred maintenance (RCM) is a systematic approach for identifying effective and efficient preventive maintenance tasks for items in accordance with a specific set of procedures and for establishing intervals between maintenance tasks (IEC 60300-3-11, 2009).

A major advantage of the RCM analysis process is a structured, and traceable approach to determine the optimal type of preventive maintenance. The results from the analysis may also be used in relation to corrective maintenance strategies, spare part optimization, and logistic considerations. This is achieved through a detailed analysis of failure modes and failure causes, which is also the objective in this thesis.

A brief review of reliability theory is given in this section, as well as a short discussion of strengths and weaknesses of the involved methods and the use of them. Literature by Rausand & Høyland (2004) and Kobbacy & Murthy (2008) form the basis for this review. For a more thorough debate, it is referred to the source literature.

4.1.1 Functional Analysis

The objectives of the functional analyses of the BOP systems are to:

- Identify and describe the required functions of the systems
- Describe input interfaces required for the two BOP systems to operate
- Identify the ways in which the systems might fail to function

Several types of diagrams can be used to illustrate the structural and the functional interrelationships in a system. For a complex BOP system it may be beneficial to illustrate the various system functions as a tree structure.

> A function tree is a hierarchical functional breakdown structure starting with a system function or a system mission and illustrating the corresponding necessary functions on lower levels of indenture (Rausand & Høyland, System Reliability Theory, 2004).

Rausand & Høyland address how a mixture between functions and physical elements often are seen in functional block diagrams, which are recommended by IEC 60812 and MIL-STAD 1629A as a basis for failure modes, effects, and criticality analysis and as basis for RCM.

4.1.2 Failure Modes, Effects and Criticality Analysis

Failure mode, effects and criticality analysis (FMECA) involves reviewing as many components, assemblies, and subsystems as possible to identify failure modes and causes and effects of such failures. For each component, possible failure modes and their resulting effects on the rest of the system are recorded in a specific FMECA worksheet. Criticalities are assigned to the failure mode effects. There are numerous variations of such worksheets. In this thesis, a sheet developed by Odfjell Drilling is used, and can be seen in Appendix B. The belonging risk matrix is given in Figure 9.

CONSEQUENCE	PROBABILITY				
SEVERITY RATING	A (1) 0-20%	B (2) 20-40%	C (3) 40-60%	D (4) 60-80%	E (5) 80-100%
	Has occurred in industry	Once in ten years	More than once in ten years	Once in one year	Once in one month
5 (75) SEVERE	75	150	225	300	375
4 (25) MAJOR	25	50	75	100	125
3 (10) CONSIDERABLE	10	20	30	40	50
2 (5) LIMITED	5	10	15	20	25
1 (1) LOW	1	2	3	4	5

FIGURE 9: RISK MATRIX (ODFJELL DRILLING, 2013)

There are two approaches to FMECA, bottom-up and top-down. The top-down approach is mainly used in an early design phase before the whole system structure is decided. A bottom-up approach is used for the BOP systems in this thesis. Each component on the lowest level of indenture is studied one-by-one. The result highlights failure modes with relatively high probability and severity of consequences, allowing comparison of the most critical components in the two BOP systems.

An FMECA may be very structured and reliable for evaluating a system where system failures most likely are the result of single component failures. The concept and application are easy to learn and makes evaluating even complex systems easy to do. Each failure is considered individually as an independent occurrence with no relation to other failures in the system. Thus an FMECA is not suitable for analysis of systems with a fair degree of redundancy. For such systems a fault tree analysis is a better alternative. In addition, the approach is not suitable for analyzing systems where common cause failures are considered to be a significant problem.

A second limitation of FMECA is the human influence and errors. Also, the FMECA process may be tedious and time-consuming (and expensive). A final drawback is the equal attention given to all component failures, included those that do not have any significant consequences.

The overall goal with the FMECA analysis in this thesis is to highlight the components and functions in the BOP systems that are most exposed to failure/downtime – and therefore critical with respect to reliability of the system. As far as possible, the analysis items are selected and defined in a clear and unambiguous way. For items where the OREDA database is used as source for reliability data, it is strived for defining the analysis items in compliance with the 'equipment units' in OREDA.

4.1.3 Reliability Block Diagram Analysis

Some components in a system may obviously be more important than others in determining whether the system is functioning or not. A component in series with the rest of the system will, for example, be at least as important as any other component in the system.

> A reliability block diagram (RBD) is a success-oriented network describing the function of the system. It shows the logical connections of (functioning) components needed to fulfil a specified system function (Rausand & Høyland, System Reliability Theory, 2004).

Reliability block diagrams are suitable for systems of non-repairable components and where the order in which failures occur does not matter. The

RBD is established for a specific system function, and a number of components are required to work to fulfil this function – and are therefore considered relevant components. When one considers a component to be irrelevant, this is always with respect to a specific system function. The same component may be highly relevant with respect to another system function. The components that can bring the system into a failed state, can be listed as cut sets of the system.

> A cut set is a set of components in which by failing causes the system to fail. A cut set is said to be minimal if it cannot be reduced without losing its status as a cut set (Rausand & Høyland, System Reliability Theory, 2004).

When assessing the BOP systems, RBDs give a graphical representation of the systems' logic. RDBs give an extensive understanding of the components and the system requirements – and the interactions between the functions of the system.

4.1.4 FAULT TREE ANALYSIS

A fault tree is a logic diagram that displays the interrelationships between a potential critical event in a system and the causes for this event. It is a technique based on deductive logic. An undesirable event is first defined and causal relationships of the failures leading to that event are then identified. A fault tree analysis may be qualitative, quantitative, or both, depending on the object of the analysis. In this thesis fault trees have been used to find the probability that a critical event will occur during a specified time interval, in addition to review of minimum cut sets.

Fault tree analysis is a binary analysis. All events are assumed either to occur or not to occur; there are no intermediate options. In giving the same treatment to hardware failures and human errors in fault tree analysis, the conditions affecting human behaviour cannot be modelled explicitly.

The fault tree analysis, contrary to the FMECA, is performed as a top-down study. It takes on a deductive approach defining the events and sub-event, which may cause the top event to occur. The relationship between these events is governed by their logical relationship to each other. The level that the deductive approach could be taken down to is a basic event. These basic events can be the failure modes of components or functions, as identified in the FMECA.

When the fault tree is limited to only AND-gates and OR-gates, it may be converted to a RBD – using respectively series- and parallel structures.

The graphical layout of the fault tree symbols is dependent on what standard that is chosen. The fault tree symbols used in this thesis are based on the software CARA fault tree, and are described in Appendix C.1.

4.2 Reliability Data

The basis for every quantitative reliability analysis is reliability data. The main sources used in this thesis are briefly discussed below. For a more thorough debate, it is referred to the source literature. Reliability data from the literature has been discussed and adjusted to fit the BOP Case Study in this thesis in a Workshop together with Odfjell Drilling and ESD in April, 2014, as specified in Section 4.2.3.

4.2.1 Reliability Studies by SINTEF

As described in Section 3.1 – BOP Reliability studies by SINTEF. Mostly used is 'Reliability of Subsea BOP Systems for Deepwater Application, Phase II DW' (Holand P., 1999).

4.2.2 OREDA

Offshore Reliability Data Handbook (SINTEF, 2009), OREDA, is a project organisation sponsored by eight oil and gas companies with worldwide operations. OREDA has established a comprehensive databank with reliability and maintenance data for exploration and production equipment from a wide variety of geographic areas, installations, equipment types and operating conditions. Offshore subsea and topside equipment are primarily covered, but onshore equipment is also included.

The subsea items are grouped into equipment classes according to main function of the item, as listed below.

- Control Systems
- Flowlines
- Manifolds
- Pipelines
- Risers
- Running Tools
- Templates
- Wellhead & X-mas Trees

The BOP is not covered in OREDA, but reliability data for certain parts of the control system and flowlines are used as estimates for specific parts of the BOP system. It is specified in the FMECA/ fault tree data input which source that is applicable.

4.2.3 Workshop

A workshop was performed with Odfjell Drilling and ESD during week 15, 2014 at Sandsli in Bergen. The participants in the workshop are listed in Table 3 on the next page.

TABLE 3: WORKSHOP PARTICIPANTS

Odfjell Drilling:	Tarjei Stautland Kim André Hope	Discipline manager BOP Systems Subsea, Deepsea Stavanger
Electrical Subsea & Drilling:	Magne Rød Egil Eriksen	Commercial Manager Technical Manager
Subsea Hydraulic Components:	Jens Grøtheim	Technical Sales Manager
Hellenes:	Agnar Hellenes	Part time CEO/ CTO, ESD

The theme for the workshop was initially to set system boundaries for both BOP systems and to assess which components that were to be further studied.

Secondly, in collaboration with Odfjell Drilling, reliability data from Holand and OREDA was reviewed and adjusted to experience data from Deepsea Stavanger.

In collaboration with ESD, data from OREDA was related to relevant components in the all-electric concept. For components that did not fit to reliability data neither in OREDA nor in the studies by Holand, relevant vendors were contacted. Specifically, Gylling Teknikk AS and A123 Systems were contacted regarding the subsea batteries.

NB: It is strived for making this thesis as objective and correct as possible. ESD is currently in a process to establish a Joint Industry Partnering Project for development of all-electric BOP controls and is seeking financial and other support from such companies. It is therefore stressed not to make this thesis a promotion of their product, but a truthful comparison of the all-electric BOP concept with existing BOP technology.

CHAPTER 5

CASE STUDY

5.1 DESCRIPTION OF SUBSEA BOP SYSTEM

The terms blowout preventer, blowout preventer stack and blowout preventer system are often used interchangeably in a general manner to describe an assembly of several stacked blowout preventers of varying type and function, as well as auxiliary components. This thesis deals with the BOP system as a whole, and the shorter term BOP is therefore used equivalent, unless other specifications are given.

Subsea BOP systems for floating drilling rigs consist of several components. The primary function of the system is to act as the final safety barrier if well control is lost. In addition, the BOP is used for a range of routine operations, such as testing of casing pressure and formation strength.

An electro-hydraulic BOP system comprises of three main elements; the lower marine riser package (LMRP), the BOP stack and the control system. Based on literature reviews (McCrae, 2003), (Leffler, Pattarozzi, & Sterling, 2003), previous master thesis works at NTNU (Klakegg, 2012), (Pinker, 2012) and consultations with supervisors in Odfjell Drilling and ESD are the main components in these elements described in this section.

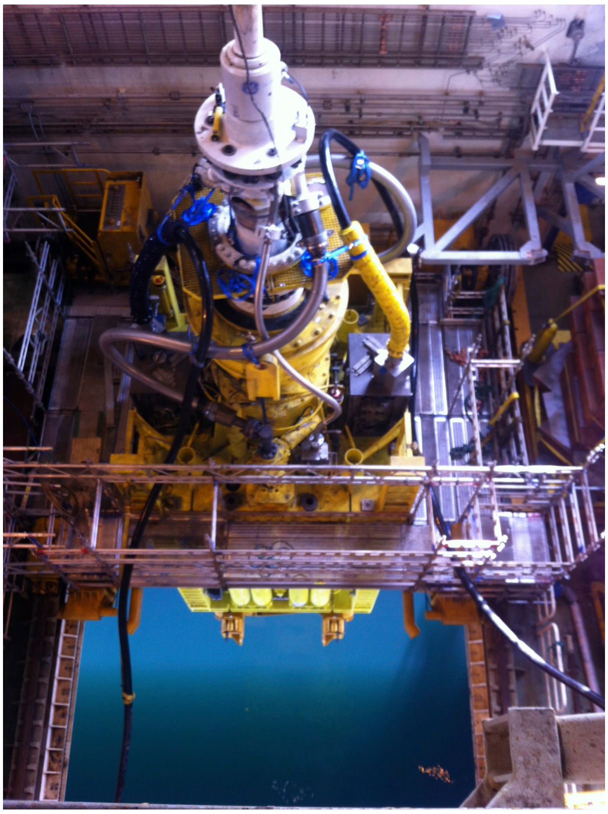


FIGURE 10: SUBSEA BOP SEEN FROM ABOVE

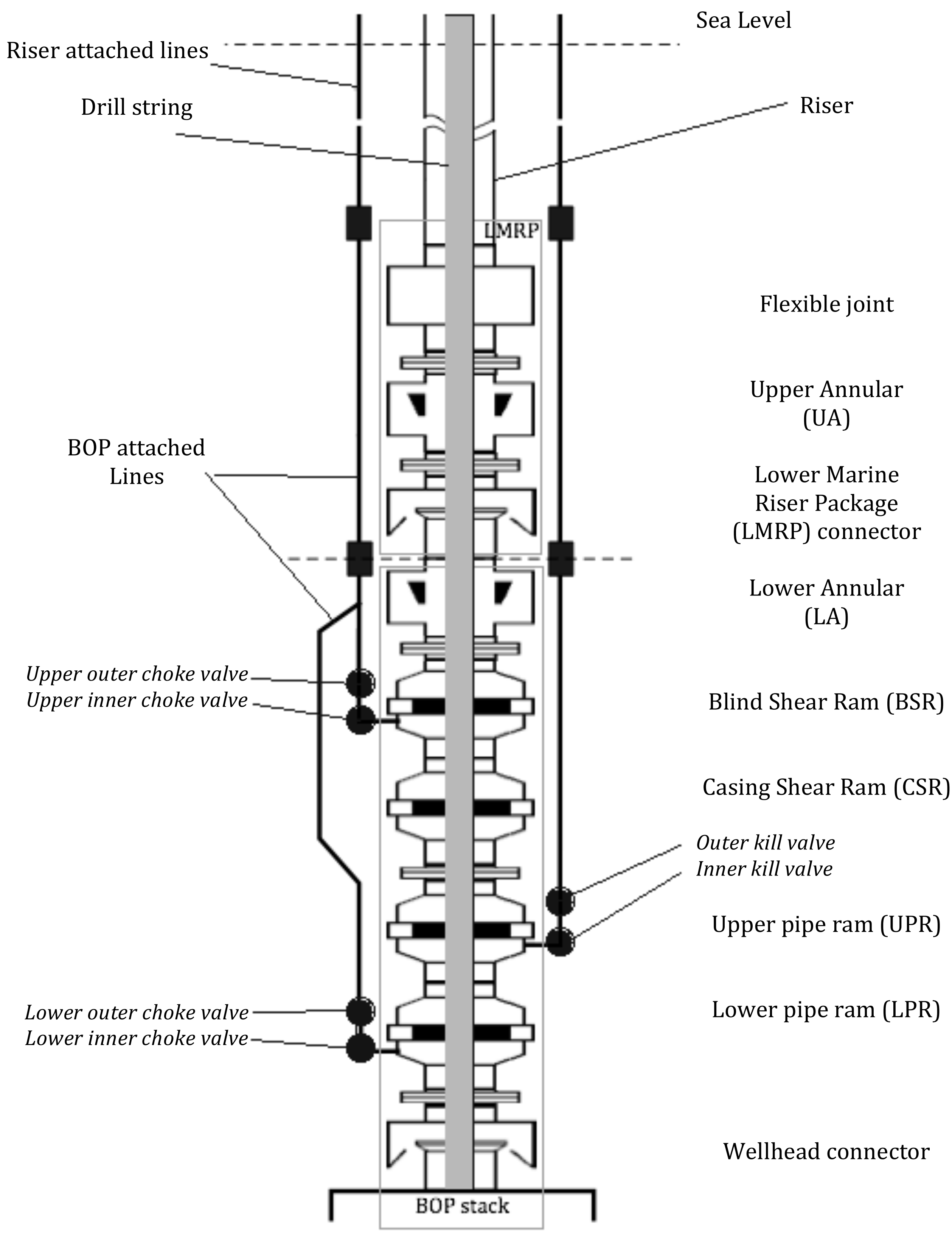


FIGURE 11: TYPICAL CONFIGURATION OF A SUBSEA BOP. MODIFIED FROM HOLAND (1999)

5.1.1 LOWER MARINE RISER PACKAGE

The LMRP is an interface between the riser system and the BOP stack. In case of bad weather during subsea drilling, the LMRP ensures that it is possible to close in the well, disconnect the marine riser and move the rig off location. In the event of a kick, the BOP stack is then the primary barrier, instead of the mud column (which have been circulated back to the rig). The LMRP consists of a flexible joint, an annular preventer and a connector.

Flexible joint
Due to possible horizontal movements of the drilling rig, a flexible joint is installed as the uppermost component of the LMRP. The flexible joint is normally designed to compensate for up to 10 degrees angular deflection of the marine riser from the vertical axis of the BOP.

Annular preventer
The main function of an annular preventer is to close and seal the wellbore and, at the same time, allow the drill string to be moved through the closed preventer. One annular BOP is normally positioned in the LMRP and one in the BOP stack. The annular preventer consists of a large internal rubber packing ring (sealing element), a piston, a closing/opening chamber and an hydraulic connection enclosed in a steel housing. The annular can seal around most objects in the wellbore, such as drill collars, casing, and drill pipe. Annular preventers are also capable of sealing an open wellbore. However, closing on open hole significantly shortens the packing element's life, so this operation is not recommended unless absolutely necessary (McCrae, 2003).

The annular preventer is also used for *stripping,* which is required if the well kicks while pulling out of the hole. Stripping means to lower pipe into the hole with the annular preventer closed against well pressure. This is done to get the drill bit back on bottom to better control the well. Annular preventers are available in several pressure rating and sizes. They normally have a lower pressure rating than the ram preventers.

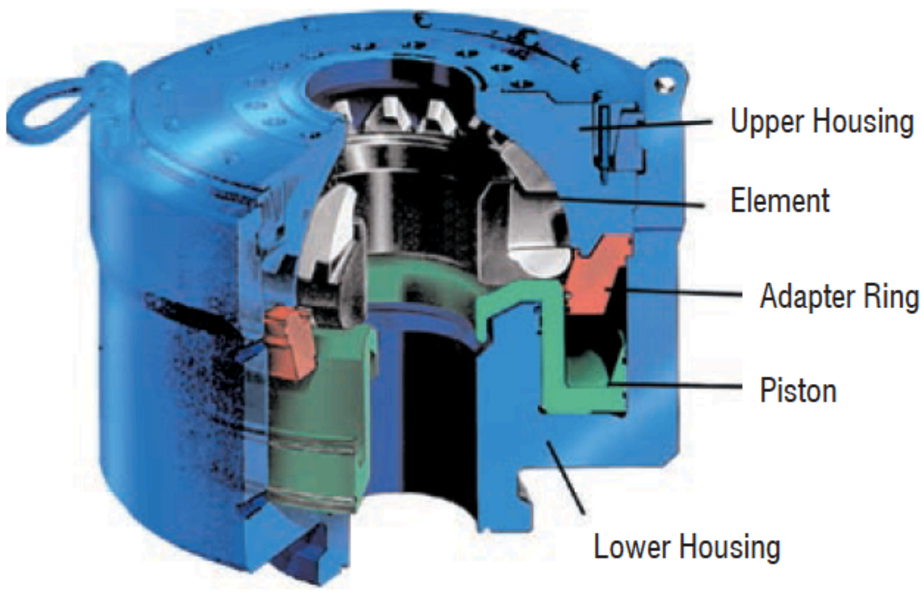


FIGURE 12: ANNULAR PREVENTER (NOV, 2013)

LMRP connector
The LMRP connector is a hydraulically operated connection between the bottom of the LMRP and the top of the BOP stack. The connector enables the LMRP to be separated and removed from the BOP stack. This can either be done for safety reasons or for repairs/maintenance.

5.1.2 BOP Stack

The BOP stack consists of several stacked ram preventers of varying type and function, as well as a wellhead connector, choke and kill lines and valves. Regardless of type, ram preventers operate in the same way and serve the same purpose; they close around the drill string or on open hole to seal the hole. There is a tendency in the industry towards wanting to increase the number of rams in the stack as a measure towards increasing the reliability of the BOP.

Blind shear ram
The blind shear ram (BSR) preventer is the only ram in the BOP stack fitted with both ram blocks that can shear the drill string, as well as rubber sealing which can seal off the well. The BSR is intended to completely seal off the well if well control cannot be maintained through other non-destructive actions. Activating the BSR will severely damage the drill string, and is therefore considered a last resort option in case of an emergency – since the cost impact will be huge both in terms of equipment damage and rig downtime.

Manufacturers supply various grades of BSR that have different sharing capabilities. The rig crew must be aware of the capabilities of the installed BSR and they must ensure that sufficient hydraulic pressure is available to carry out the shear operation. In an escalated well control situation, failure of the BSR will lead to complete loss of well control, and a blowout through the bore annulus and/ or drill string is likely to occur. Ensuring that the BSR is reliable is therefore very important from a safety perspective.

Casing shear ram

A casing shear ram (CSR) can be used in addition to the BSR in the BOP stack, and is usually installed bellow the BSR. The CSR is similar to the BSR, but is a higher capacity shear ram that is capable to cut through the heaviest drill string and casing. The BSR above is used to seal the well after shearing.

The CSR is a critical component in cases where the well control situation escalates to a scenario where the shearing requirement exceeds the capability of the BSR. Figure 13 illustrates a triple BOP equipped with blind shear rams and casing shear rams.

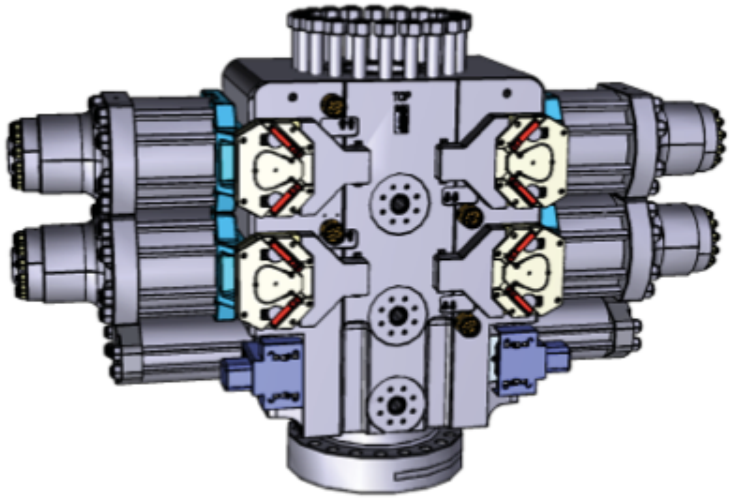


FIGURE 13: TRIPPLE BOP (NOV)

Pipe rams

Pipe ram preventers seal the annulus space between the drill sting and the wellbore. Usually, two or three preventers are installed. The upper pipe ram (UPR) and the lower pipe ram (LPR) are shown in Figure 11.

Manufacturers provide ram blocks in all sizes of drill string and casing normally run through the BOP. The main types are

- Fixed-size ram blocks. Can close and seal only on the size of string for which they are designed.
- Fixed-bore ram. Can support the load of the drill string when it is necessary to hang off the drill string. (Hanging off the drill string means to close the pipe rams just below a tool joint. When weight on the drill string is slacked off, the closed ram blocks support the drill string. Hanging off may be required during rig move).
- Variable bore rams. Can close and seal on a range of pipe sizes.

Rams closing principle

Closing and opening of blind/casing shear rams and pipe rams follow a common principle. A detailed description of closing of the blind shear preventer is outlined and illustrated below.

The operation is controlled by the BOP control system, which is described in Section 5.1.3. Hydraulic fluid enters the ram shuttle valve from one of two inlet ports and pushes a metal 'shuttle' to one side and flows down the stem of the T-shaped valve. Further, the fluid flows behind pistons, which drive the ram to shear the drill pipe. The wedge locks then slide in to prevent the pistons from moving back. Finally, rubber seals and the ram close off the well. Hydrocarbons pushing up from the well add pressure below and behind the ram, helping to keep the ram closed.

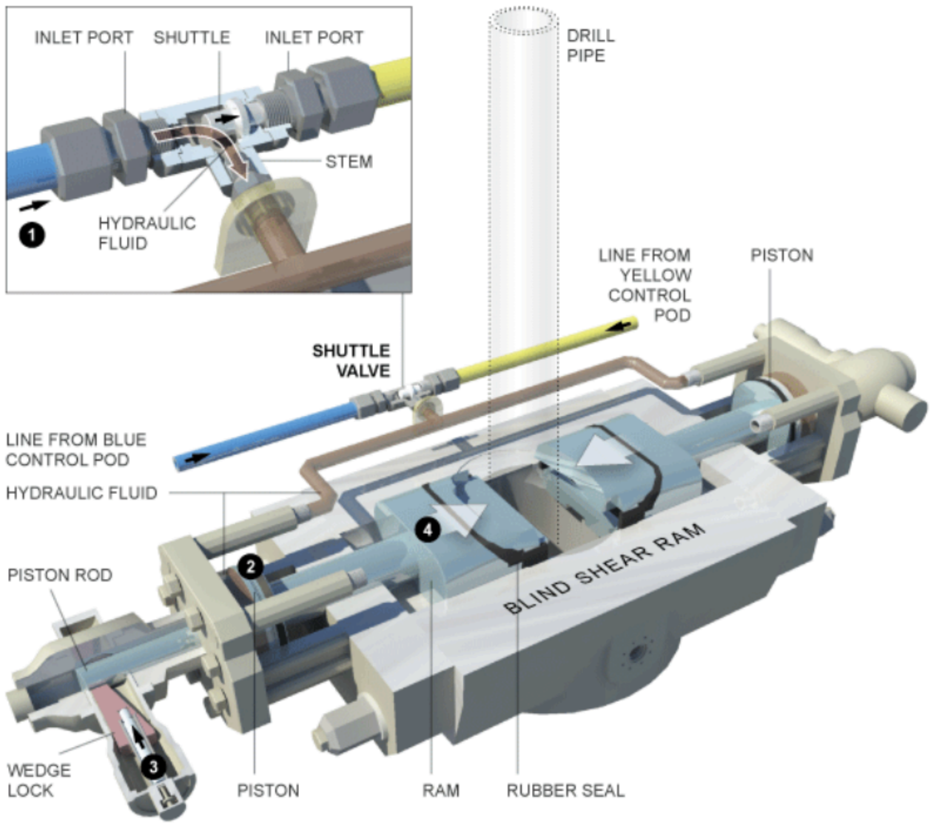


FIGURE 14: CLOSING OF BSR (GRÖNDAHL, PARK, ROBERTS, & TSE, 2010)

Choke and kill lines and valves

The choke and kill lines and valves are used to circulate out a kick or to kill a well. To do this, heavy mud is circulated down the kill line and into the annulus. The choke/kill system is also used during pressure testing of the BOP system. The position of the lines on the BOP stack depends on design specifications. Usually, the choke line has two outlets and the kill line has one outlet connected to the BOP stack. The lines are manifolded together on the surface, which permits either line to be used as choke or kill line. This arrangement provides additional redundancy to the well control system.

The valves are placed in series and designed with a fail-safe close mechanism, implying that if the hydraulic pressure is lost, loaded springs will force them to close.

Wellhead connector
The wellhead connector is a hydraulic operated connection between the bottom of the BOP stack and the top of the wellhead housing.

5.1.3 CONTROL SYSTEM

There are two main types of control systems being used on subsea BOPs; hydraulic and electro-hydraulic multiplex (MUX) system. The response time for the hydraulic system increases with water depth, and is therefore not practical to use for deepwater drilling. To overcome signal delays MUX control systems are used in water depths greater than 1500 metres (McCrae, 2003).

A simplified MUX system is shown in Figure 15. The control system consists of several components located both topside and subsea. Coded commands from the topside facility are transmitted by electrical signals to the subsea control pods. There, the signals are decoded, confirmed and performed through hydraulic fluid.

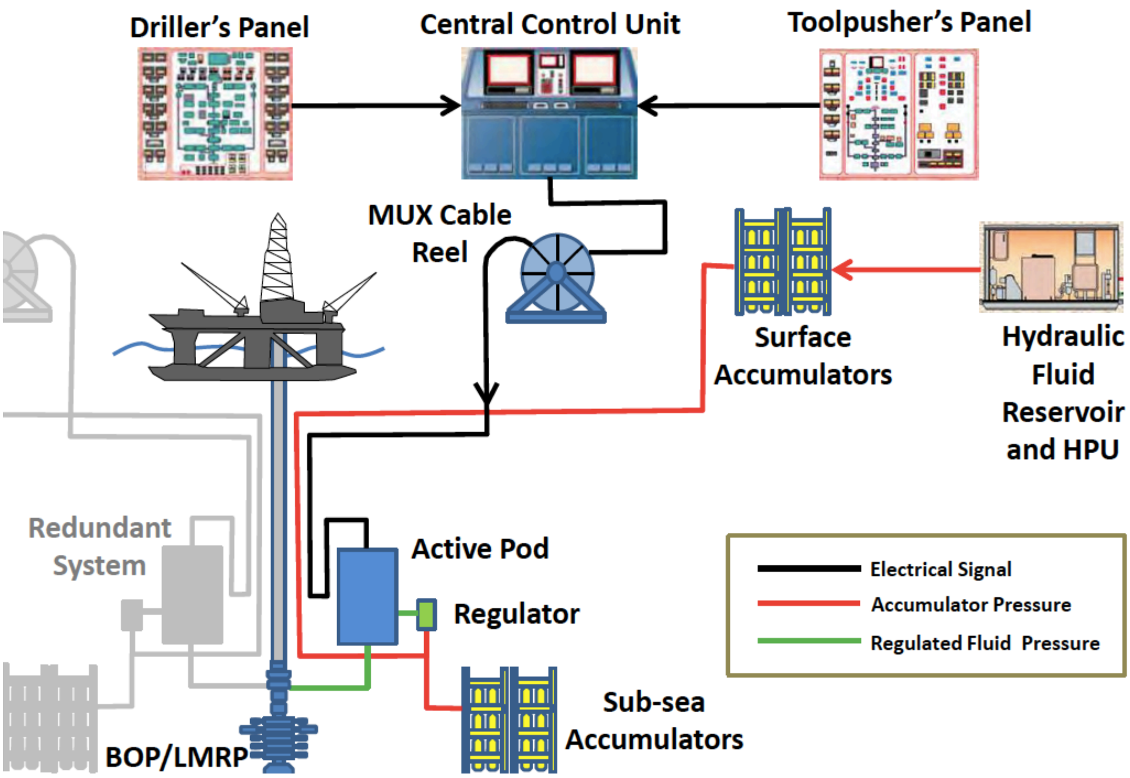


FIGURE 15: MUX CONTROL SYSTEM (REES & DANIEL, 2011)

Topside

The main topside components of a MUX control system are control panels, electric and hydraulic supply utilities. Each BOP function must be activated manually by pressing push buttons on the control panels. According to NORSOK (D-010 Well integrity in drilling and well operations, 2013) it shall be possible to activate the BOP from at least three locations on the facility; one activation panel at the driller's position, one independent activation panel in a safe accessible area (usually the tool pusher's position) and one 3rd remote back-up control (see Section 5.1.4). The control panels shall be equipped with a securing device against unintentional operation of essential functions (e.g. shear ram, riser connection).

The central control unit (CCU) serves as a tie-in between the driller's or the toolpusher's panel and the MUX cables. The cables are stored in reels on the rig floor, and run down along the riser in two sets of lines, one to each of the subsea control pods.

The hydraulic fluid used to activate the BOP is delivered from a hydraulic power unit (HPU), located topside. The fluid is supplied from a reservoir connected to the HPU. There are also accumulators on the rig as backup. Accumulator volumetric capacity, pressure requirements and BOP response time shall be in accordance with applicable standards.

Subsea control pods and accumulators

One electro-hydraulic subsea control module, also called 'pod' is installed on each side of the LMRP. The two control pods, often denoted the blue and yellow pod, are identical, redundant and dedicated to control and lead the communication between the topside control system and subsea BOP system. Since the pod is such an important part of the BOP control system, every BOP subsea system is required to be equipped with two independent pods (API, 2012). Both pods should be capable of performing all the functions of the BOP.

Figure 16 shows the logical arrangement of the BOP hydraulic fluid system. Hydraulic fluid is directed towards either of the two pods through a pod selector valve, depending on which is selected by the operator. The fluid is transported down along the riser via rigid and flexible conduit lines in the umbilical. The pod contains a solenoid valve dedicated to each preventer, a hydraulic regulator and a control valve (SPM valve). The fluid is further directed to the subsea accumulators, through a shuttle valve and finally to the preventer(s) via hard lines.

Hydraulic outputs from the control modules to the preventers rely on the reliable functioning of the shuttle valve that directs the fluid from the control valve outputs to the preventer. The line from the shuttle valve to the preventer is not redundant. The shuttle valve is therefore a very important element in the hydraulic distribution and changeover of control of the hydraulic preventers on the BOP/LMRP stack from one subsea BOP control module to another. Criticality of the various components in the BOP system is further addressed in Chapter 6 and Chapter 7.

If there is a major problem with one of the pods, drilling will be suspended and the LMRP and marine riser will be retrieved to the surface so that the pod can be repaired and tested. In a safety point of view, the reliability of the pods is extremely important.

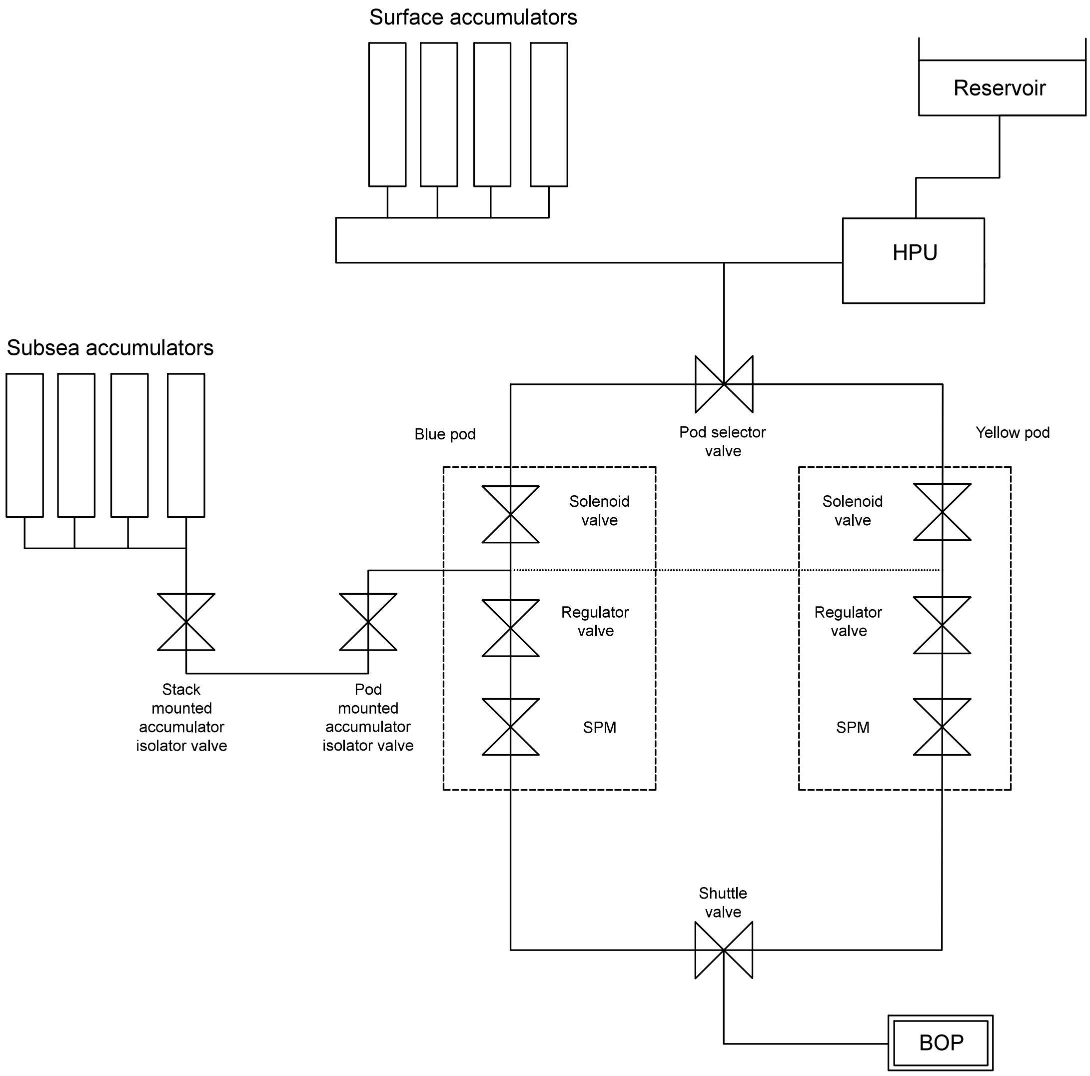


FIGURE 16: HYDRAULIC FLUID SYSTEM

The main objective of the accumulators, both topside and subsea, is to provide the BOP functions with closing force in terms of pre-charged hydraulic fluid, allowing them to close rapidly upon demand.

There are strict rules and regulations, as specified in Section 3.5, regarding calculation of accumulator capacity, depending on water depth for the drilling operation. Larger depths demand larger accumulator capacity, and often additional depth compensating measures. It is required to have three sources of accumulator capacity, as listed below. The bottles are 'charged' by the HPU.

1. Topside
2. On the LMRP
3. On the BOP stack

The accumulators on the seabed are required to have enough pressure to operate the shear ram and cut through the drill string, after having closed a pipe ram preventer even if the umbilical connection to the rig is lost. It should also have enough pressure left to disconnect the LMRP after cutting through the drill string (NORSOK, 2012).

The requirements specify a time limit for these functions, typically 30, 45 or 60 seconds. The subsea accumulator bottles work as batteries with hydraulic fluid to fulfil these requirements. If the umbilical is broken or disconnected, the LMRP functions are activated from either acoustic control or ROV operation, which is described in Section 5.1.4. The accumulator bottles on the BOP stack is the only 'battery source' available in case of an emergency disconnect.

The accumulators also have other functions. Firstly, they increase the response time of the system. Secondly they act as shock absorbers of 'shock waves' that are created due to high flow and high pressure when a function is activated.

The supply system is arranged so that the accumulator bottles, both topside and stack mounted ones, are charged to the required pressure, and then automatically recharged when the stored fluid is depleted by activation of BOP functions. The accumulator bottles are common for the blue and yellow control pods, meaning that a leak in the accumulators will affect both pods. However, the hydraulic supply system is equipped with accumulator isolation valves topside, in each pod and on the BOP stack. The valves can be closed and the BOP functions operated directly from the topside. This will however have a significant impact on the closing time for each preventer.

5.1.4 Back-up Control System

If the primary control system is incapable of activating the BOP functions, a back-up system is needed. Acoustic control and ROV activation are two such back-up systems. Brief descriptions of these systems are given below.

Acoustic control

The acoustic control system is a redundant receiver/transmitter for communication with the rig through acoustics. It is interfaced to the BOP control pod so that different sets of emergency functions can be activated if the regular umbilical is broken and normal communication with the BOP is not possible.

An acoustic control system by Kongsberg Maritime is shown in Figure 17. The surface equipment consists of a portable Acoustic Command Unit and a Dunking transducer with hand operable cable winch. The subsea equipment consists of a Subsea Control Unit (SCU), two transducers with cables and waterproof connectors, and an interface cable for BOP solenoid pack connection.

The SCU holds the subsea electronics. It includes two transceivers with transducers, which makes it redundant. The SCU is powered from internal lithium batteries.

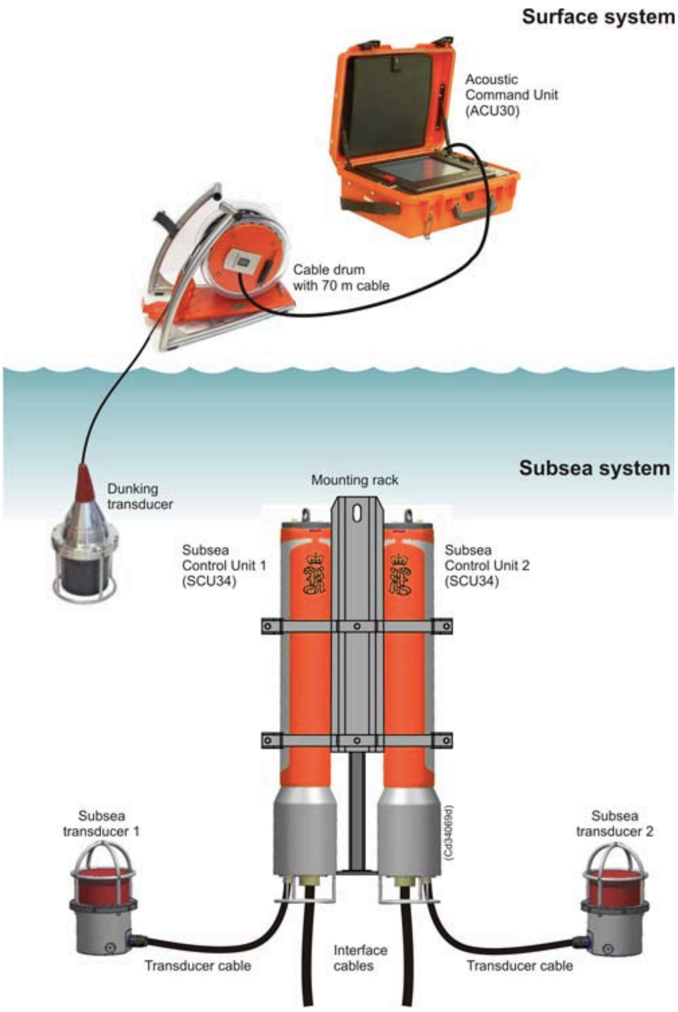


FIGURE 17: ACOUSTIC CONTROL SYSTEM (KONGSBERG MARITIME, 2014)

ROV activation

The BOP can also be operated with the use of a remotely operated vehicle (ROV). ROV panels are mounted on the lower BOP stack, and are used to permit ROV-initiated disconnect of the lower stack from the subsea wellhead and other necessary emergency functions.

5.2 DEEPSEA STAVANGER

Deepsea Stavanger (DSS) is a sixth generation deepwater and harsh environment semi-submersible. The unit is owned and managed by Odfjell Drilling and is a state-of-the-art dual derrick, dynamic-positioned unit of enhanced GVA 7500 design. Currently, the unit operates in west Angola on contract with BP.

TABLE 4: KEY DATA DEEPSEA STAVANGER (ODFJELL DRILLING)

Construction Yard	DSME South Korea	**Accommodation**	190
Construction Year	2010	**Derrick**	Dual 1000ton/500ton
Classification	DNV	**Drawworks**	Dual AHD + Single AHD
Water Depth Capacity	10,000 ft. (3,000 m.)	**Mud Pumps**	4 x 14-P-220, 7,500psi
Station Keeping	DP	**Top Drive**	HPS-1,000
VDL (Moored)	7,500 (6,000) mt.	**BOP**	Shaffer MUX 6 ram

The unit is designed for operations in harsh environments and at water depths of up to 3,000 m. It is equipped with a full conventional mooring spread for operations in water depths of 70 to 500 metres. The 7,500 mt loading capacity in all operating conditions ensures efficiency, with a reduced need for supply. Additionally, full winterization may be provided for improved working conditions in an arctic environment.

The rig has a modern, highly efficient drilling system, which includes a dual derrick with a main and an auxiliary work centre to facilitate a number of simultaneous operations. The drilling system has dual active heave compensating drawworks for increased performance, efficiency, safety and redundancy. The rig is designed for worldwide operation and is especially suitable for development drilling. The rig meets the latest regulatory requirements of Norwegian Maritime Authority (NMA), PSA/ UK-HSE and NORSOK (Odfjell Drilling).

5.2.1 SHAFFER BOP

The 18 ¾", 15,000 psi (1,034 bar) electro-hydraulic Shaffer BOP installed on DSS is one of the most commonly used subsea BOPs in the world today. The BOP installed on DSS is illustrated in Figure 18 on the next page.

The total height of the combined BOP stack and LMRP is 15.473 metres, and the total weight is estimated to 371,728 kg. All functions on the LMRP and BOP stack are electro-hydraulically controlled from control panels located topside on the unit. The BOP system consists of two annular preventers (Spherical BOPs) and six ram preventers, as shown in Table 5.

TABLE 5: DSS BOP, MODIFIED FROM BOP USER'S MANUAL (NOV)

<table>
<tr><td>Upper Spherical BOP 18 ¾",
10,000 psi (690 bar),
Wedge-Cover</td><td>The annular seals on almost any shape or size of kelly, tool joint, drill pipe, drill collar, casing and wireline that may typically be run through the preventer. The annular can also close completely over an open hole.</td><td>LMRP</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Lower Spherical BOP 18 ¾",
10,000 psi (690 bar),
Wedge-Cover</td><td>Similar to the upper annular.</td><td rowspan="7">BOP stack</td></tr>
<tr><td>Pipe Shear Ram BOP 18 ¾",
15,000 psi</td><td rowspan="3">The top triple on the lower BOP stack is equipped with pipe shear rams and casing shear rams. These rams are normally used when a sudden kick occurs while drill pipe is in the hole.</td></tr>
<tr><td>Casing Shear Ram BOP 18 ¾",
15,000 psi</td></tr>
<tr><td>Pipe Ram #1 BOP 18 ¾",
15,000 psi</td></tr>
<tr><td>Multi-Pipe Ram #2 BOP 18 ¾",
15,000 psi</td><td rowspan="3">The bottom triple on the lower BOP stack is equipped with pipe rams (Figure 13). The ram-type preventers equipped with pipe rams are used to close off the annulus around the drill pipe. These rams are normally used when a sudden kick occurs while pipe is in the hole. At times they may be used to hang off the drill string.</td></tr>
<tr><td>Multi-Pipe Ram #3 BOP 18 ¾",
15,000 psi</td></tr>
<tr><td>Pipe Ram #4 BOP 18 ¾",
15,000 psi</td></tr>
</table>

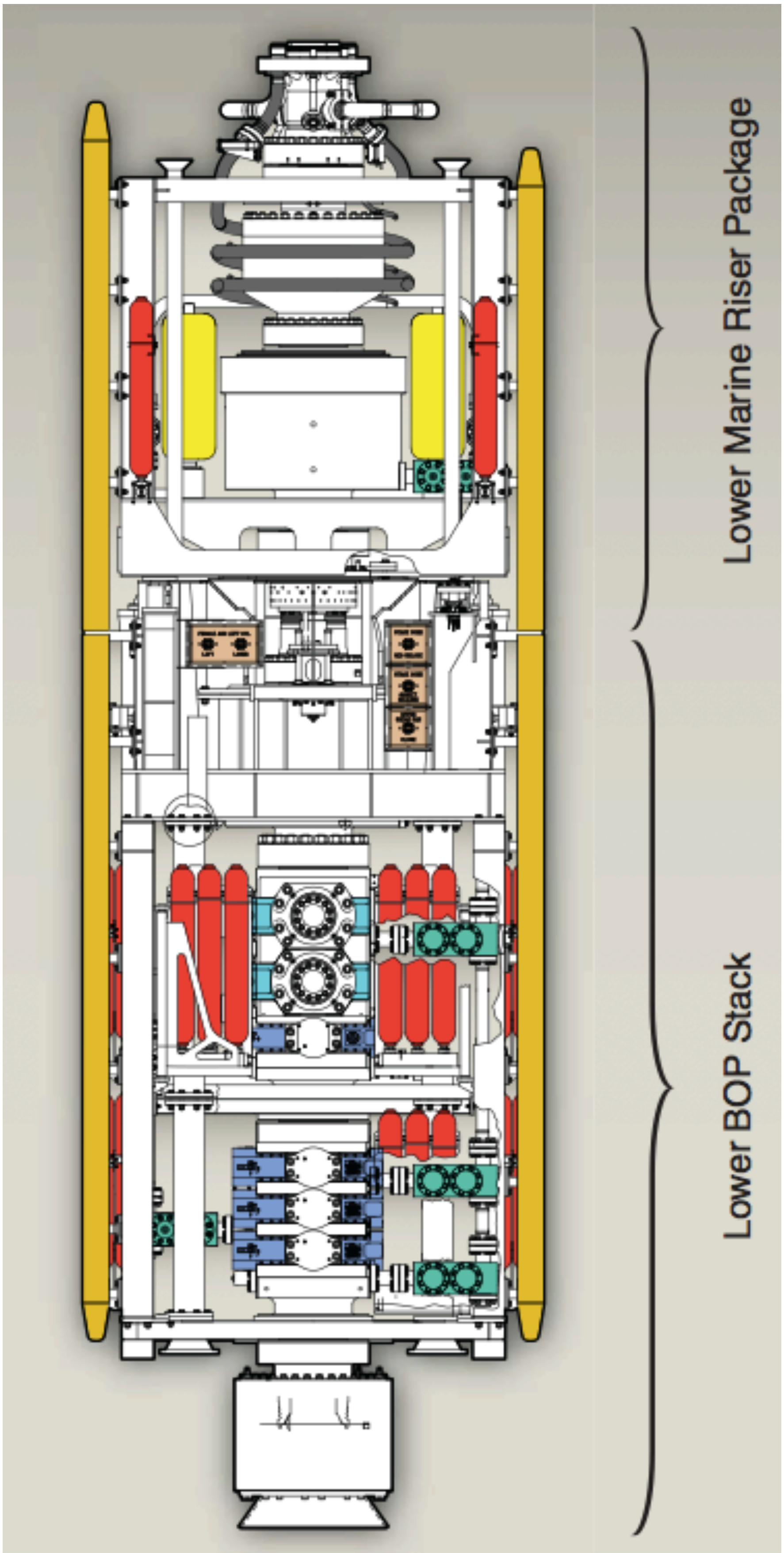


FIGURE 18: DSS BOP (NOV)

There are a total of 141 15-gallon (3.78 litre) accumulator bottles used to store the hydraulic operating fluid for the functions of the LMRP and BOP stack. 16 are mounted on the LMRP and 124 on the stack. These accumulator bottles are mounted in bottle rack assemblies bolted to the BOP frame.

In addition to Shaffer (Acquired by National Oilwell Varco (NOV)), only two other BOP companies are market leaders; Cameron and Hydril (Acquired by General Electric (GE)). These companies are all American and located in Huston TX. China is currently on track with a number of BOP manufacturers, but the industry is conservative and it will probably still take a long time before they are accepted in the market.

5.2.2 Limitations and Challenges

The equipment delivered by any of the three big BOP manufacturers worldwide today is considered to be conservative, not very user- or service-friendly and fitted with somewhat old and out-dated technology and solutions. Some examples from DSS are listed below, based on experience input from the Workshop (Stautland, Hope , Eriksen, Rød, Grøtheim, & Hellenes, 2014).

- Many screwed fittings on the hydraulic system, rather than welded and bent tubes – each fitting represents a possible leak point. On the DSS BOP stack, there are many hundreds of possible flaws in fittings and hoses. A small leak could mean that the whole BOP must be recovered to the surface for reparations and testing. Expected delay/downtime during such a repair is 4-5 days, if not more.
- Heavy use of hoses instead of bent and welded tubes. A ‘ bird nest’ of hoses is prone to damage and further leaks, and is appearing as messy and chaotic. The users on board DSS wish that bent tubes made of stainless steel were used instead, with welded connection points. Such a solution enables a pressure test to be performed to confirm that the tubes are tight – almost ‘for ever ‘.
- Gnarled placement of typical service points on the BOP stack makes access difficult. This may extend the required service and repair time. When the BOP is on deck between well maintenance, all parties involved aim for a quick return of the BOP into the sea.
- Not enough spare parts on stock/ on board and long delivery time on spare parts from BOP suppliers. Missing spare pars are solely the rig owner’s responsibility, but still a fairly widespread problem in the industry.
- Hydraulic fluid is subject to contamination in subsea applications. Contamination causes a ripple effect as it moves through the system and damages multiple components, each of which may need to be repaired or replaced.

Other factors resulting in increased downtime of BOP equipment during drilling is deeper waters and wells with higher pressures and temperatures.

Additionally, problems with subsea BOP control systems are a significant contributor to the non-productive time of drilling rigs. Despite several advantages with the MUX system, several limitations and weaknesses have been noticed in the aim towards improved safety, reliability, performance and cost optimization of the system. One of the potential causes for these problems may be the fact that today's BOP control systems function with hydraulic technology.

The accumulators have a key function in the BOP control system. Rajabi & Amani (2010) describe how the current accumulator design methods are inadequate for deepwater drilling. Usable fluid, which is declared as the amount of pressurized liquid that an accumulator can hold, decreases with water depth so that a larger number of accumulator bottle is needed to store hydraulic oil required to close and open BOP functions. This behaviour of accumulators is in part because of non-ideal behaviour of compressed gas, usually nitrogen, in high ambient pressure at the sea floor where the accumulators are mounted on the BOP stack. But, even if nitrogen behaves like an ideal gas, the volume of usable fluid decreases, since the hydraulic fluid exhausts to the seawater to reduce the length of umbilical and pressure drop. So, the calculation of usable fluid should compensate for the hydrostatic pressure of water depth where hydraulic fluid is supposed to exhaust. Figure 19 shows how the volume of usable fluid decreases as water depth increases. This graph is plotted for a 15-gallon bladder accumulator (Vac = 13.7 gal.) with a maximum working pressure of 5,000 psi, minimum working pressure of 2,000 psi, and a pre-charged pressure of 1,800 psi.

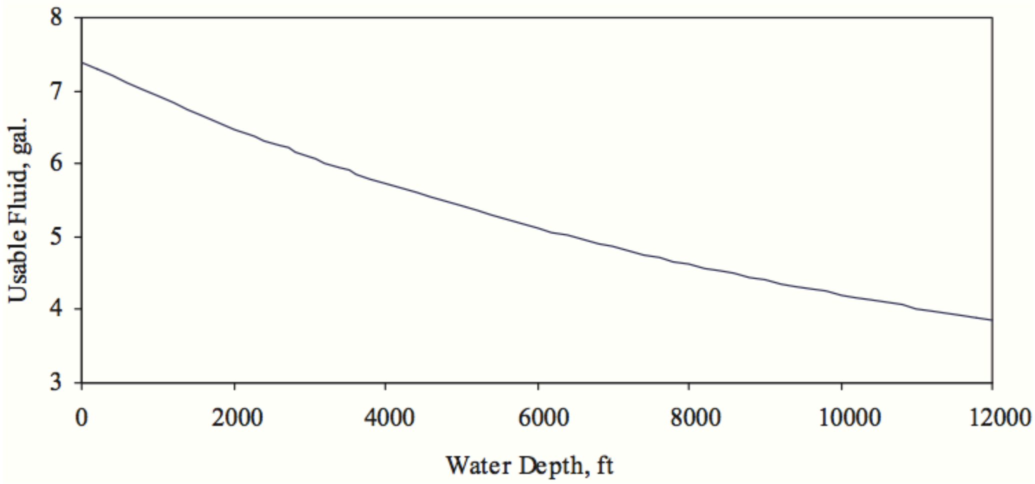


FIGURE 19: USABLE FLUID VS. DEPTH, IDEAL GAS (RAJABI & AMANI, 2010)

Research has been done to find a way to transfer all the BOP equipment to the surface. Replacing conventional accumulators by another kind of accumulators, whose functionality is not affected by the hydrostatic pressure, may provide a better solution for deepwater drilling. Problems with leakage, contaminated hydraulic fluids, seal failures, shuttle valve failures, etc. will than still be an issue. Spring-loaded accumulators and weighted accumulators are discussed as additional alternatives in Rajabi and Amani's article (2010).

In order to reduce downtime due to BOP failures, Odfjell Drilling consider installing two BOPs on board their deepwater drilling units. This is a huge investment, but will reduce the risk for downtime a great deal. This solution will also allow better time for maintenance and control when the BOP is on deck. Several new drillships delivered nowadays are designed and delivered with dual BOP.

Another alternative is a BOP technology concept with electrical actuation and control. This concept can improve water depth capability, safety features and decrease release of hydraulic fluid to the environment. The concept involves subsea batteries instead of accumulators. The HPU topside will be replaced with a battery charger. The company ESD is currently working on developing such an electrical system, and this technology is thoroughly described in Section 5.3.

5.3 ALL-ELECTRIC BOP TECHNOLOGY

Electrical Subsea & Drilling AS (ESD) is working on developing an all-electric BOP technology concept. The main focus for ESD is development of a light concept, with electrical actuation and control. Additionally, the emphasis is on improved water depth capability, safety features and no release of hydraulic fluid to the environment. The secondary focus is on technology elements for future riserless drilling and utilisation of technology elements in current systems.

The focus in this thesis is on ESD's BOP technology. The company has developed the following all-electrical concepts that are interesting in this context:

- Actuator concept for ring piston devices (annular preventers and connectors)
- Ram actuator concept (ram preventers)
- All-electric actuated valves

The goal for ESD is to make these devices compatible for existing electro-hydraulic systems, only by replacing the hydraulics with electrical power. The mechanical construction of the BOP system (sealing/ cutting devices, etc.) is, in other words, (almost) similar to the description in Section 5.1 of existing systems. The main difference will be the actuation element on each preventer that is run by an electric motor, and subsea batteries instead of accumulators. The concept is based on the same topside infrastructure, communication systems and back-up control as an existing electro-hydraulic control system.

The main market driver for an all-electric BOP is to reduce rig downtime, with secondary benefits related to deepwater use, as described in this thesis. There are two possible market segments;

1. New BOPs with all-electric controls and actuation
2. Retro-fit of all-electric controls and actuators on existing BOPs

Figure 20 illustrates the different electrical devices working together in a BOP system. The utilization of the mechanical components will be low during operation. The power overview in Figure 20 reflects the maximum electrical power consumption for each function, which is an instantaneous maximum load, or an accidental load. Mostly, the actuators will run idle, with some degree of final loading upon torque-up in end position. The shear-ram mechanical components are only fully utilized in the accidental scenario.

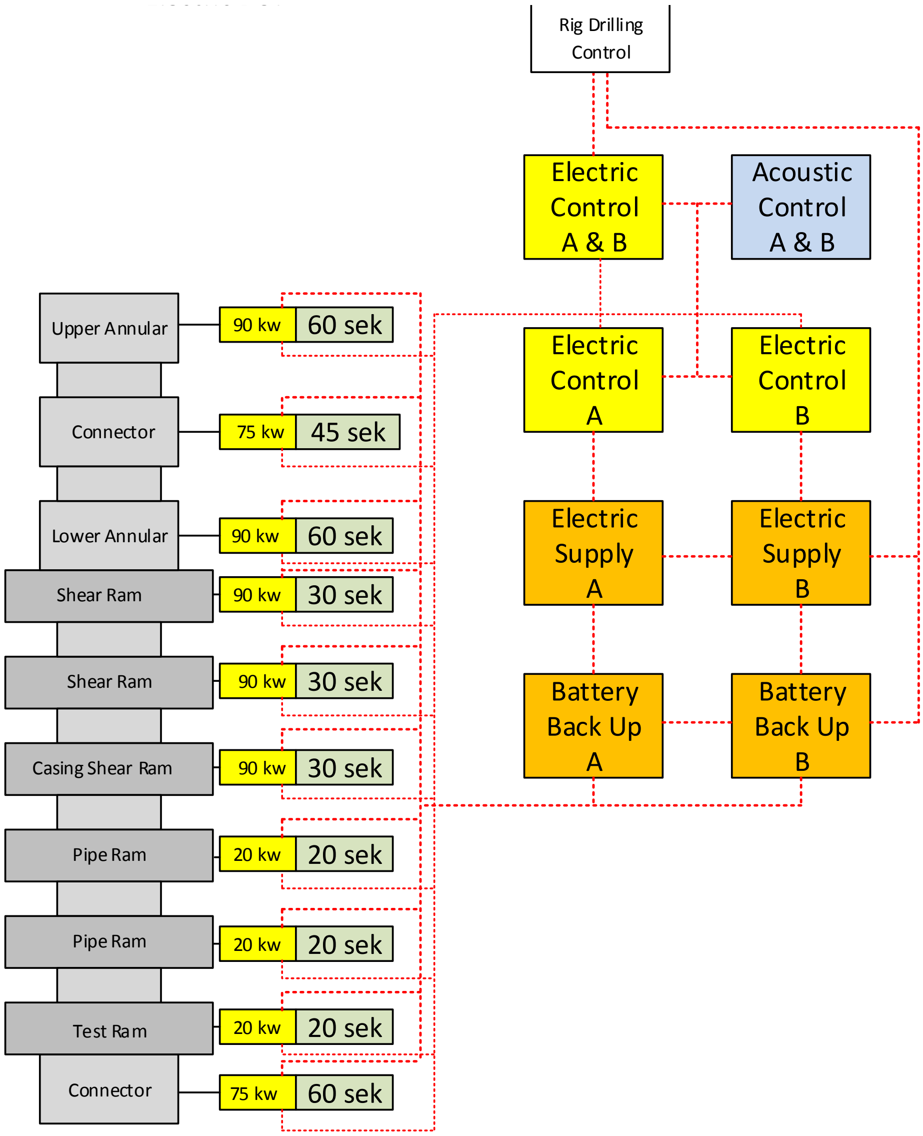


FIGURE 20: BOP CONCEPT (ESD, 2013)

ESD describes how the system can control charging of the batteries, both subsea and topside, by turning the charger on and off when necessary. Further, the power actuator will be provided with a position sensor for accurate feedback of gear turns which, when connected to a control system, will show the exact, relative position of the actuation element in the power actuator, at any given time. This, in combination with control of the motor with regard to position, provides double position control. It is also possible to control the actuating power that the motor exerts against the actuating element by means of applied power. An operator thus may control both power and the relative position of the actuating element in the actuator, from the surface (Eriksen, 2013). The all-electric concept thus offers more detailed and reliable monitoring than what is present in today's MUX systems.

Simplified, the all-electric actuation devices developed to run a BOP system comprises of the following:

- Transmission element
- Electric motor
- Actuation element
- Actuator nut

5.3.1 Actuator Concept for Ring Piston Devices

ESD has several electrical actuator solutions in various stages of patenting. This section will present the actuator concept to be used for ring piston devices – Norwegian patent 333966 – (approved 04.11.2013), PCT application approved, international patenting in 2014. The same internal mechanism principle is used in both annular preventers and connectors. The term actuator is used in order to emphasise that the device is particularly suitable for use where relatively large actuator forces are required.

The transmission element and the electric motor is arranged to move an actuation element between at least a first position and a second position. The rotor of the electric motor surrounds and is connected to the actuator nut which is in threaded engagement with the actuation element. The internal ring motor, activating nut and threaded rollers can be seen in the split view of the connector in Figure 21. The motor rotates the ring nut, which engages the rollers. The rollers drive a ring formed activating element that is connected to the activation ring for the locking segments (shown in red).

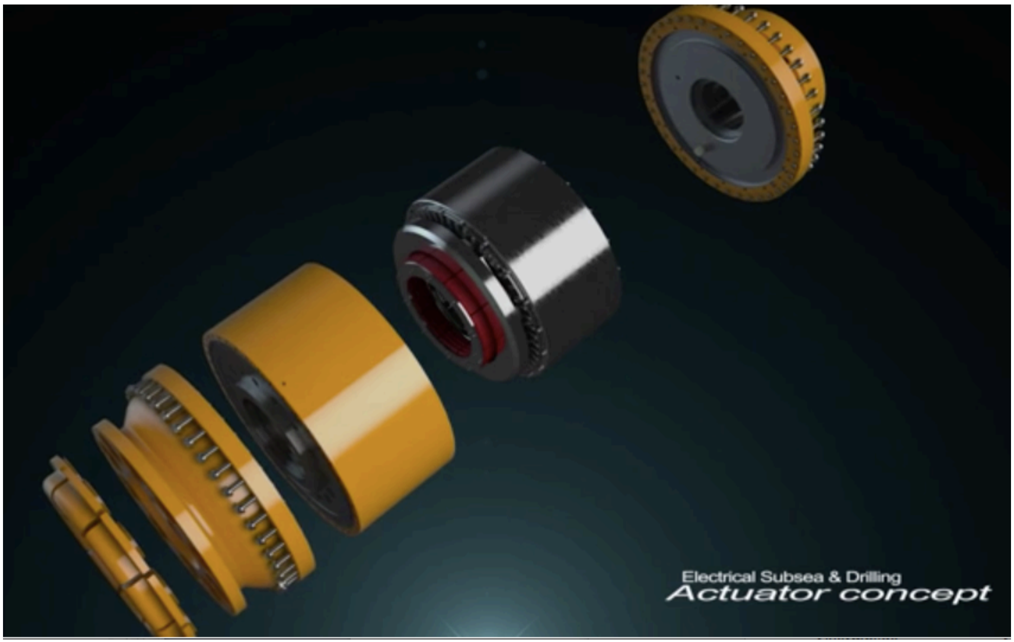


FIGURE 21: MAIN COMPONENTS, CONNECTOR (ESD, 2013)

The individual actuator parts and the mechanical override feature at the top, are shown in Figure 22. A single override transmission element is shown, but the override may be further developed with several transmission elements to achieve redundancy.

FIGURE 22: ACTUATOR PARTS (ESD, 2013)

In addition to electrical control, the actuator is arranged to enable manoeuvring by means of an external motor, for instance an ROV. Drawings of the annular preventer and the connector are given in Figure 23 and Figure 24 on the next page.

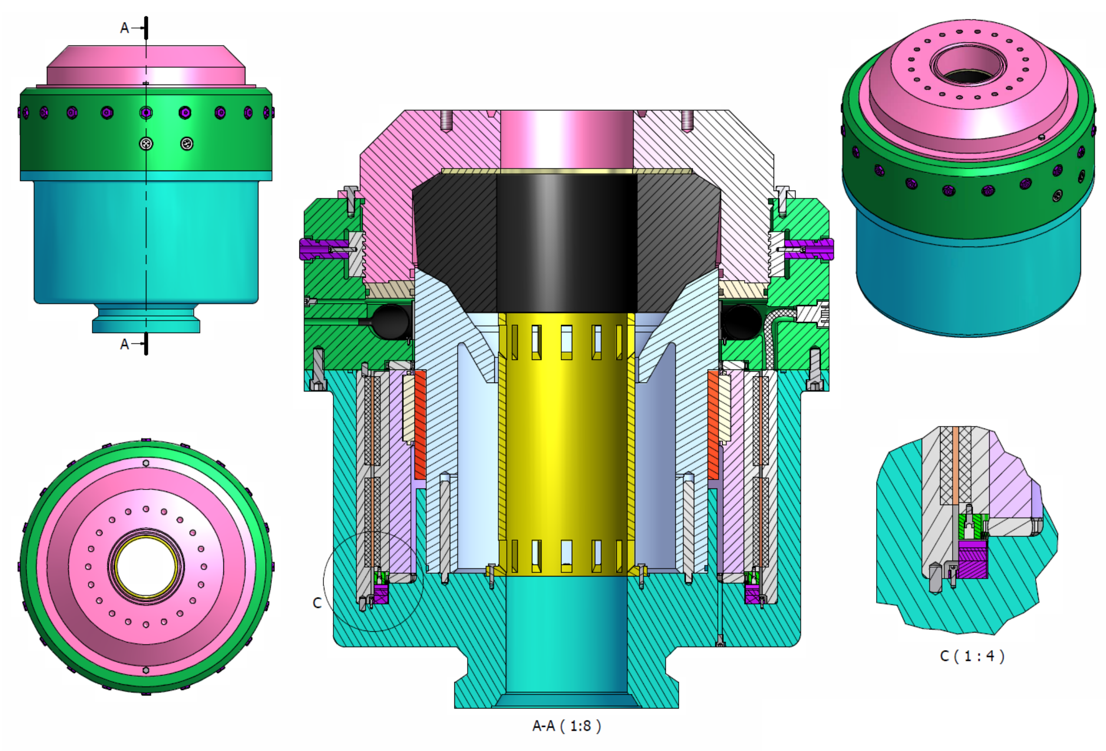


FIGURE 23: ANNULAR BOP (ESD, 2013)

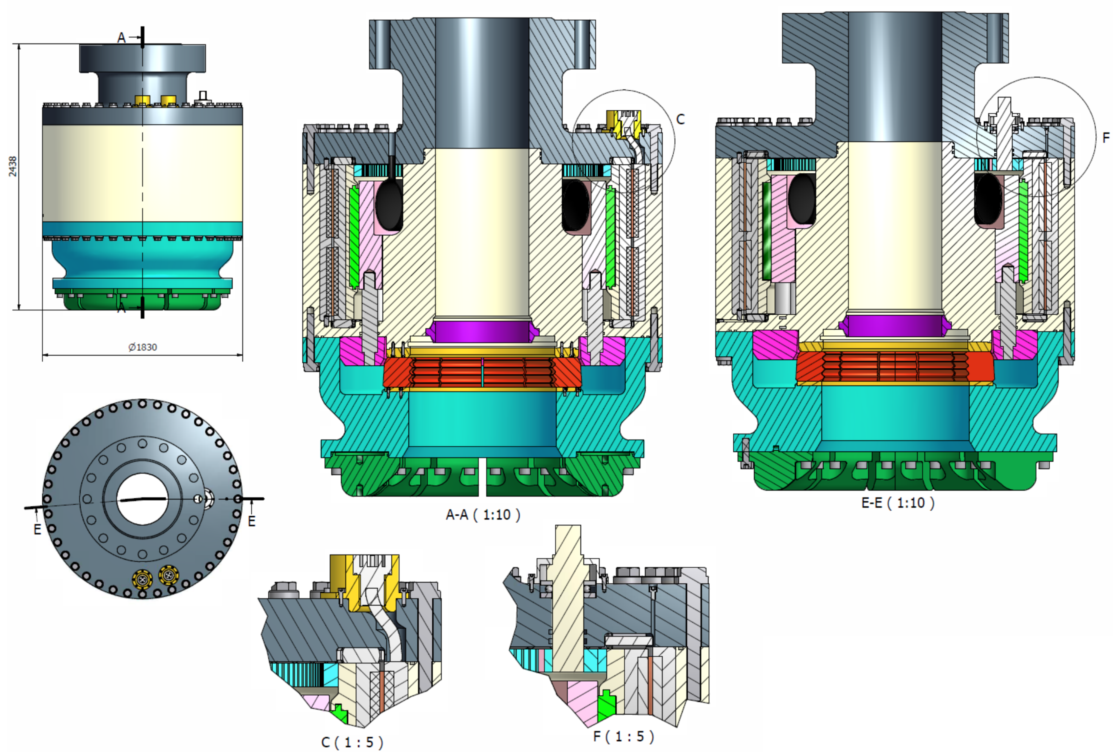


FIGURE 24: CONNECTOR (ESD, 2013)

The external diameter of the actuator nut corresponds to the internal diameter of the rotor. The moving direction of the actuation element may be parallel to the rotational axis of the motor. The solution shown in Figure 23 is an exemplary embodiment where the actuator has been built into a sealing device for a BOP.

The same figure demonstrates that axial displacement of the actuation element may be provided with relatively small constructional dimensions. The actuation element may also surround a central through-going opening which may constitute a fluid path and which may also be adapted for passage of tools.

The actuator is in a pressure-compensated actuator housing in which the pressure is compensated relative to the surroundings by means of an elastic compensator communicating with the ambient pressure.

The motor may include at least two individual sets of windings to provide the necessary redundancy.

5.3.2 Ram Actuator Concept

The power actuator device can also be developed for use in a ram preventer – Norwegian 'patent pending', PCT application approved, international patenting in 2014. A ring motor, with internal planetary gear, drives the ram. The output torque is transferred to a drive shaft, which is engaged with four activation wheels. The drive wheels turn the activation screws so that the ram activation plate, with the nuts, moves forward towards the end barriers. The actuation spindle is transferring the axial load from the actuating plate to the cutting device. The activation plate with nuts, the screws and the spindle is illustrated together with the cutting device in Figure 25. External dimensions and interfaces shall as far as possible be adapted to existing BOP technology.

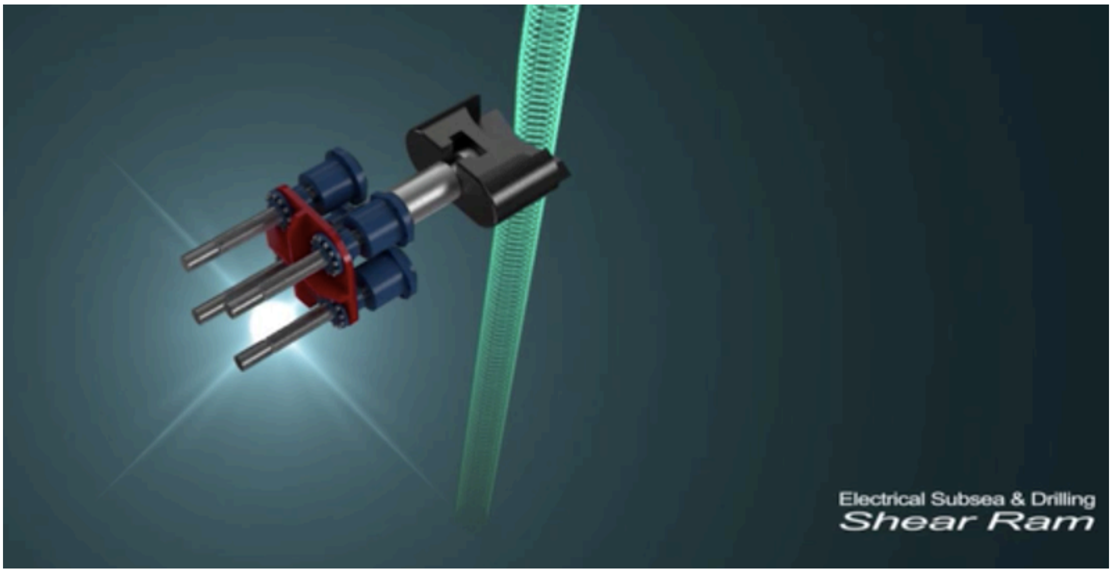


FIGURE 25: RAM ACTUATOR CONCEPT (ESD, 2013)

Figure 26 gives a perspective view of two power actuators that are connected to a BOP. Figure 27 shows a cross section of the same device in a larger scale.

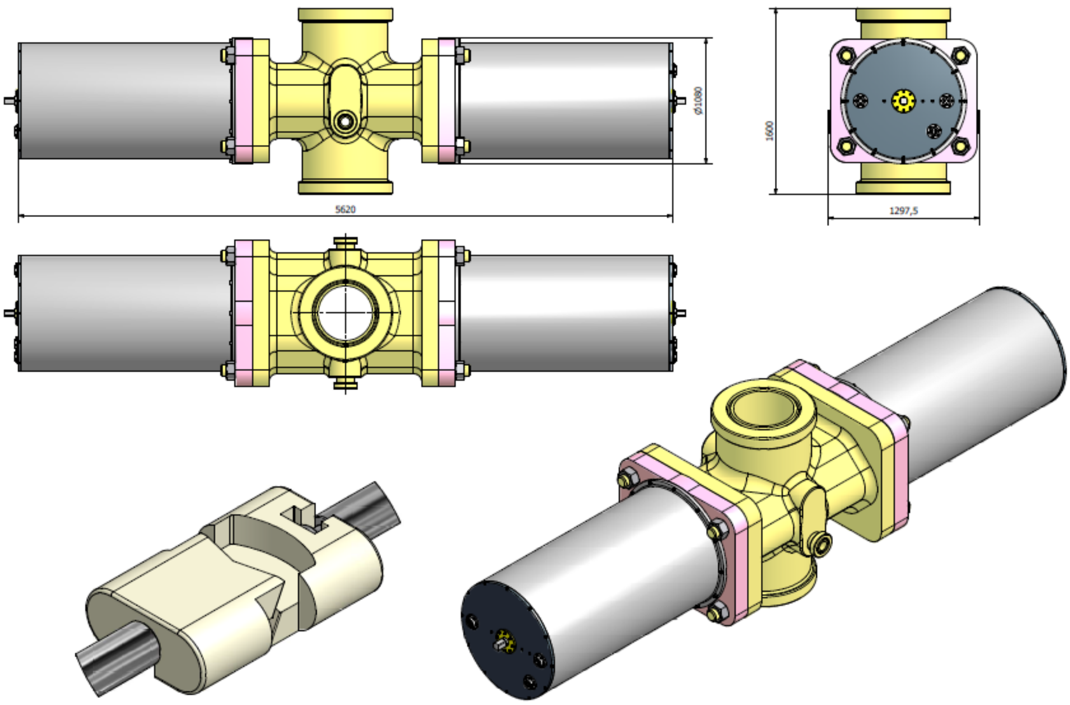


FIGURE 26: RAM PISTONS (ESD, 2013)

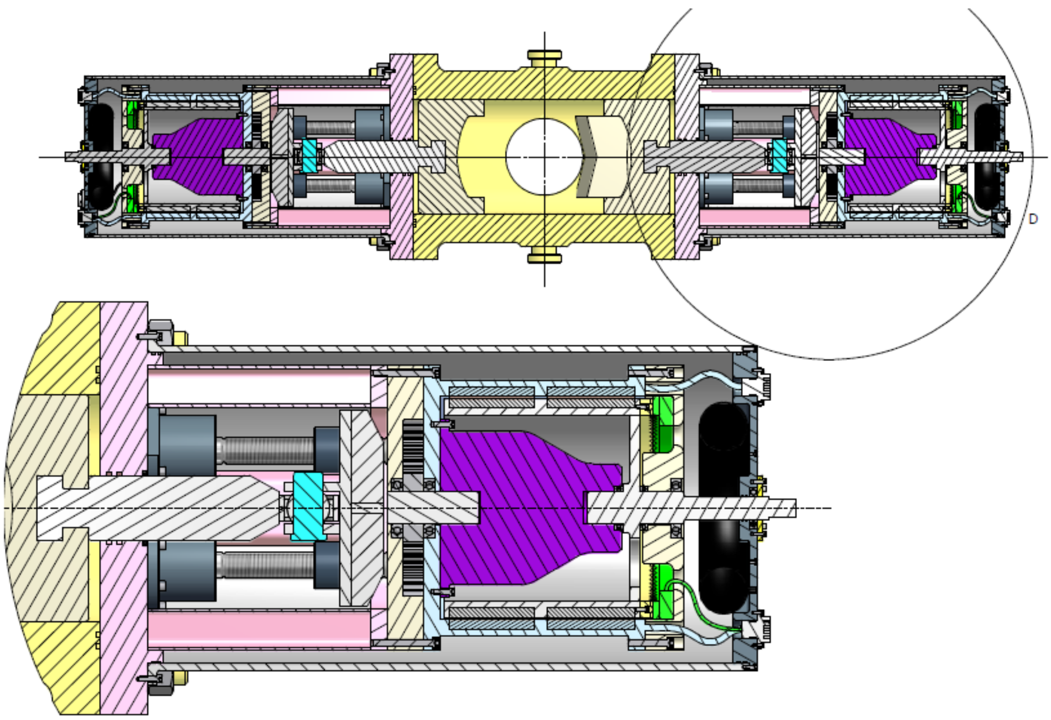


FIGURE 27: CROSS SECTION (ESD, 2013)

Cutting capacity for a shear ram preventer shall be at least 900 metric tonnes – which according to ESD can be achieved with standard industry components. The next development step will be to look at higher capacity, up to 1500 tonnes. Also here, the motor comprises at least two individual sets of windings.

5.3.3 ALL-ELECTRIC ACTUATED VALVES

ESD is in a patent processes with all-electrically actuated valves. The main advantage with electrical valves is that they can be operated and stopped in between positions, while hydraulic valves are limited to 'on or off'.

- Choke actuator – Norwegian patent confirmed NO 331659. National patenting is ongoing in selected countries.
- Actuator with spring return – Norwegian patent confirmed, 333570. National patenting is ongoing in selected countries.

The subsea choke actuator is developed by ESD in the Statoil and Aker Solutions SBB (Subsea Building Blocks) Project. One important aspect of the project was well construction and reduced rig time for drilling, completion and intervention of subsea wells. An illustration of the subsea choke actuator is given in Figure 28, which among others features the following:

- 3" retrievable valves for subsea BOP.
- Extremely fast closure.

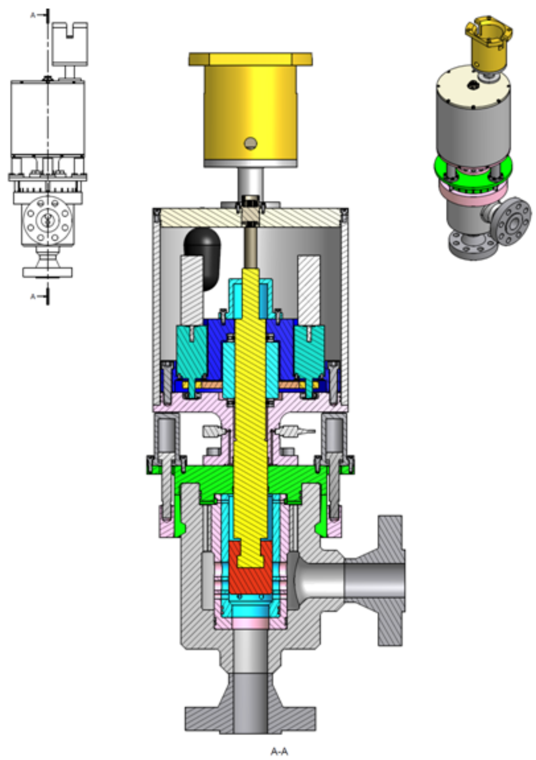


FIGURE 28: SUBSEA CHOKE ACTUATOR (ESD, 2013)

5.3.4 BENEFITS

According to ESD, the main benefits with the new approach are as follows;

- Elimination of non-productive downtime of drilling equipment caused by contaminated hydraulic fluids, seal failures, shuttle-valve failures, and other hydraulic components on the BOP.
- Reduced weight of the BOP stack due to replacement of hydraulic accumulators with batteries, pipework, replacement of electro-hydraulic control modules, etc. This will further provide increased water depth capability.
- Electrical batteries. No hydraulic accumulators, lower weight, no loss of efficiency due to deepwater, adiabatic discharge and low temperature.
- Saving space and cost topsides – no surface HPU, electrical cable instead of umbilical, simplified monitoring.
- Accurate monitoring facilities of equipment function and diagnostics. The inherent design features of the electro-mechanical actuation will provide exact position of the actuating device.
- Same actuation force in both directions. The power density of hydraulic actuation is largely dependent upon the pressure of their systems, and for safety and cost reasons these pressures have plateaued over the past decade. On the other hand, the power density of electric motors has substantially increased over the same time frame because of advances in magnetic materials, ball screw efficiency, construction, manufacturing techniques and electronics. One of the most significant benefits is the ability to deliver substantially more power while maintaining high levels of efficiency. Additional improvements have come in the power transmission, largely through gearbox designs.
- High reliability of components.
- Dual redundant actuator and subsea controls, as opposed to current shuttle valves between electro-hydraulic pods.
- Secondary mechanical override of all actuators can easily be implemented.
- No discharge of hydraulic fluid to sea during testing and operation.
- Easy to interface to existing BOP designs and control features.

5.4 EXISTING ELECTRICAL SUBSEA SYSTEMS

K5F Gas Field, Netherlands

Cameron has designed an all-electrically actuated subsea production system, which was installed on gas wells off the Netherlands in 2008. The project included a three-well combined template/manifold installed in 40 m of water. The initial installation included two template/manifold-mounted trees with the option for two more trees in the future, one of which would be a satellite tree (Akker & Burdick, 2008).

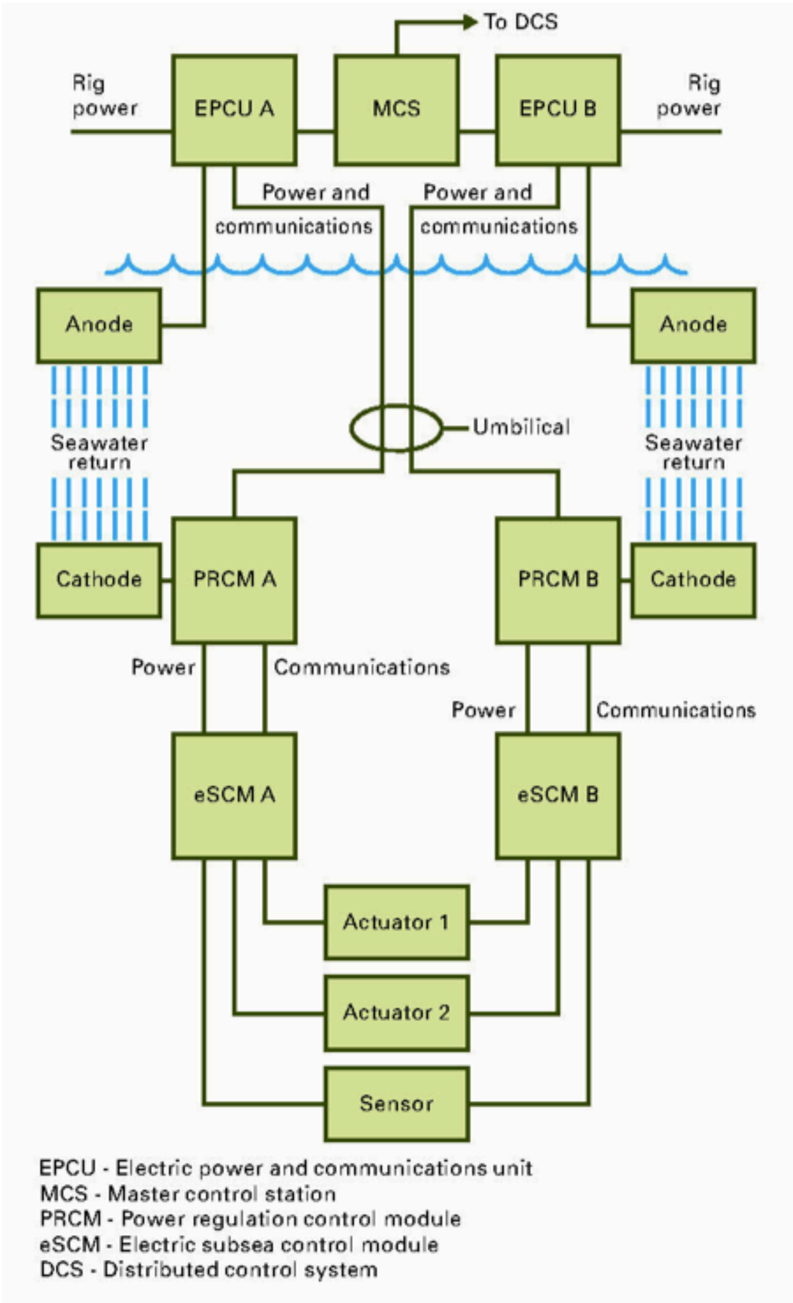


FIGURE 29: MAIN COMPONENTS (AKKER & BURDICK, 2008)

The keynote of the K5F project is that it marks the first worldwide implementation of an all-electrical Christmas tree. The system, powered by direct current (DC), has no batteries or accumulators and much of the conventional electro-hydraulic equipment has been simplified or eliminated. The main components in the production system are shown in Figure 29.

The system includes an electric subsea control module, a power-regulation and communications module, all-electric actuated chemical-injection valves, annulus and production gate valves, and an all-electric actuated choke.

North Sea

FMC Technologies has developed a variety of all-electrical technologies. Statoil's Statfjord field got its first electric actuators from FMC Technologies in 2001. The actuators were used to control the ROV-operated choke valves on the manifold. This system is battery-based and consists of a subsea control module and multiple electric actuators. The control module includes the electronic devices and batteries (NiCad batteries). For Statoil's Norne field a new generation of actuators was developed and deployed in 2005 using Li-ion batteries. Further, Statoil's Aasgard Subsea Gas Compression project has recently ordered 82 electrical actuators to operate process and manifold valves in varying sizes (Rokne, 2013).

CHAPTER 6

RELIABILITY ANALYSIS

This chapter addresses the BOP system boundaries for the reliability analyses, system functions and potential failures modes of the two concepts. The analyses are given in detail, with results, in Chapter 7.

6.1 SYSTEM SELECTION AND DEFINITION

In principle, a reliability analysis would benefit from a thorough study of all parts of the BOP systems. With limited resources one must, however, make priorities. The following criteria are used to prioritize components for the analysis:

- The failure effects of potential component failures must be significant in terms of system reliability and downtime
- Reliability data or operating experience from the actual part, or similar parts, must be available

Thorough descriptions of both BOP concepts are given in Chapter 5. The system boundaries for the analytical part are defined as;

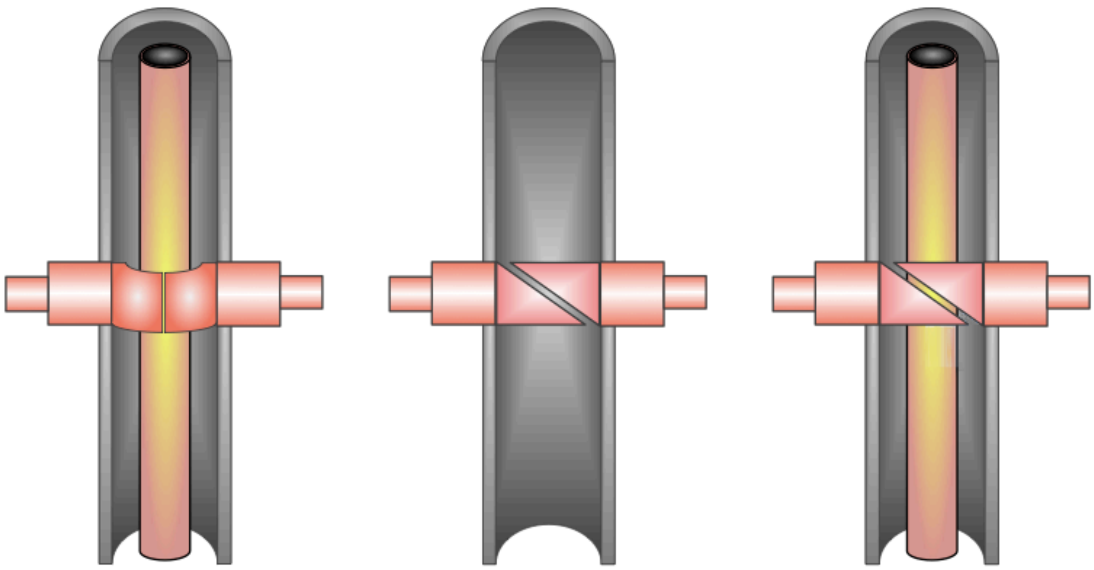
- The panels necessary to activate a required BOP function
- The signal transmission and hydraulic/ electrical power necessary
- The individual valves and equipment of the BOP

6.2 IDENTIFICATION OF SYSTEM FUNCTIONS

The most essential functions of a BOP system are prevention of blowouts and prevention of well leaks, i.e. the ability to shut in or *isolate a well*. The BOP is designed to be able to fulfil this function in a variety of ways, depending on the nature of the process demand and on operational conditions present when the process demand takes place.

The Guidelines for the Application of IEC 61508 and IEC 61511 in the petroleum activities on the continental shelf (Norwegian oil and gas, 2004) specify three functions in terms of the BOP's ability to act as a safety barrier, as listed and illustrated in Figure 30. Together, these three functions must fulfil the requirements for the BOP as a well barrier.

1. Seal around drill pipe
2. Seal an open hole
3. Shear drill pipe and seal off well



Function 1 Function 2 Function 3

FIGURE 30: BOP FUNCTIONS. MODIFIED FROM (KLAKEGG, 2012).

Function 1 above is the most commonly used. The BOP has annular preventers and pipe ram preventers for the purpose. There can be limitations to when the pipe rams work properly, such as closing on drill collars, tool joints, perforation guns, etc.

For function 2, the blind shear ram will be the means to seal the well. This scenario is only relevant when the drill pipe is not running through the BOP. It is claimed by manufacturers that the annular preventers can be used to seal on an open hole. However, according to Holand (1999) this is rarely done and little reliability data exists for such application of annular preventers. Closing the annular preventer on an open hole is therefore not included in further analyses.

For function 3, the drill pipe has to be sheared before the well can be sealed off. Historically this has been an event where the well has blown out through the drill string and stabbing the top drive and/or the kelly valve on the drill floor has failed (Norwegian oil and gas, 2004). This thesis only concerns closing of the annular and ram preventers in response to a kick, and does not consider internal closing of the drill pipe. Shearing the drill pipe to seal off the well is considered as the 'last line of defence' in a scenario where the well control is lost.

The ability of a BOP system to isolate a well can be divided into four sub-functions. These sub-functions are equal whether the system is hydraulically or all-electrically operated, but the component(s) that fulfil each function will vary. A generic function tree for a subsea BOP system is given in Figure 31. Notice that redundancies in a system are not illustrated in a function tree. For example, the control pod function may be realized with two redundant pods. In the function tree this is represented as one function (convert electrical signals to power input), while a physical break down structure gets two elements, one for each pod. Reliability block diagrams illustrate this in Section 7.3.

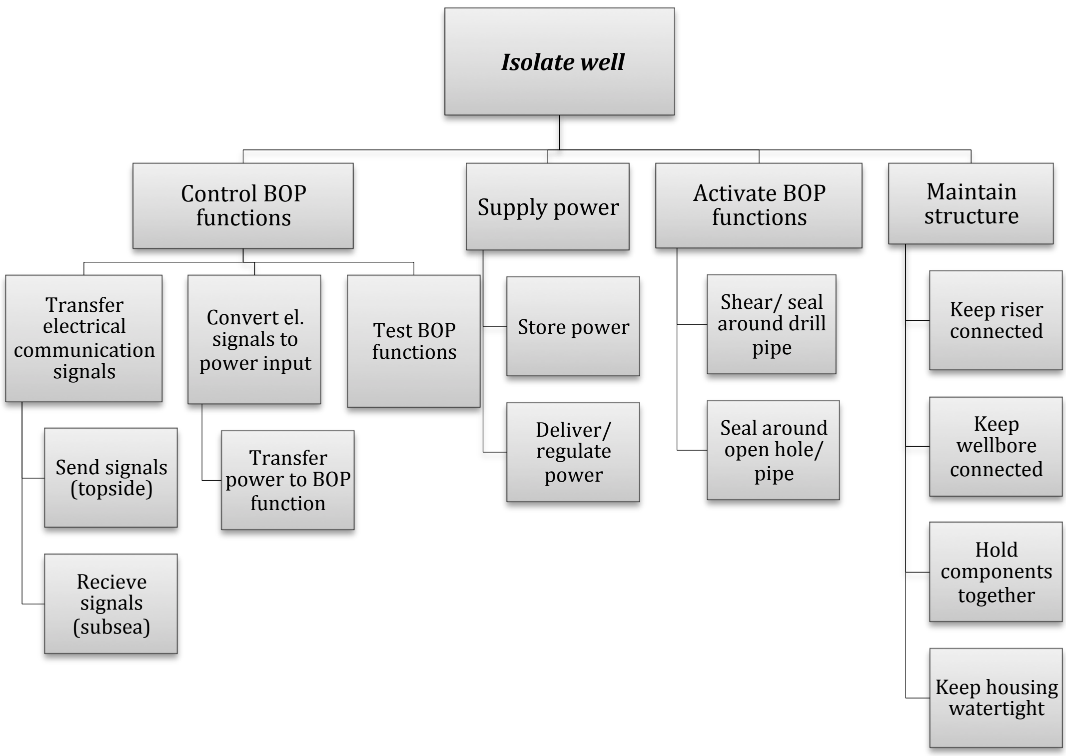


FIGURE 31: GENERIC FUNCTION TREE

A BOP system is a technical system that is operated, controlled and maintained by humans. The reliability of the system will depend in its interfaces with the rest of the world. Some of these interfaces are assessed in Chapter 5, and BOP failures are studied in this chapter. Important aspects are also summed up and included in the discussion in Chapter 8.

Functional block diagrams for the electro-hydraulic and the all-electric BOP concepts are given in Figure 32 and Figure 33 on the next page. The functional block diagrams illustrate how the functions in the system must interface in order to achieve the overall function *Isolate well*, by closing one or more of the preventers (i.e. performing one or more of the functions 1, 2 or 3 defined on page 60). Each functional block represents a function in the given system, with inherent sub-functions, which is linked to a specific component.

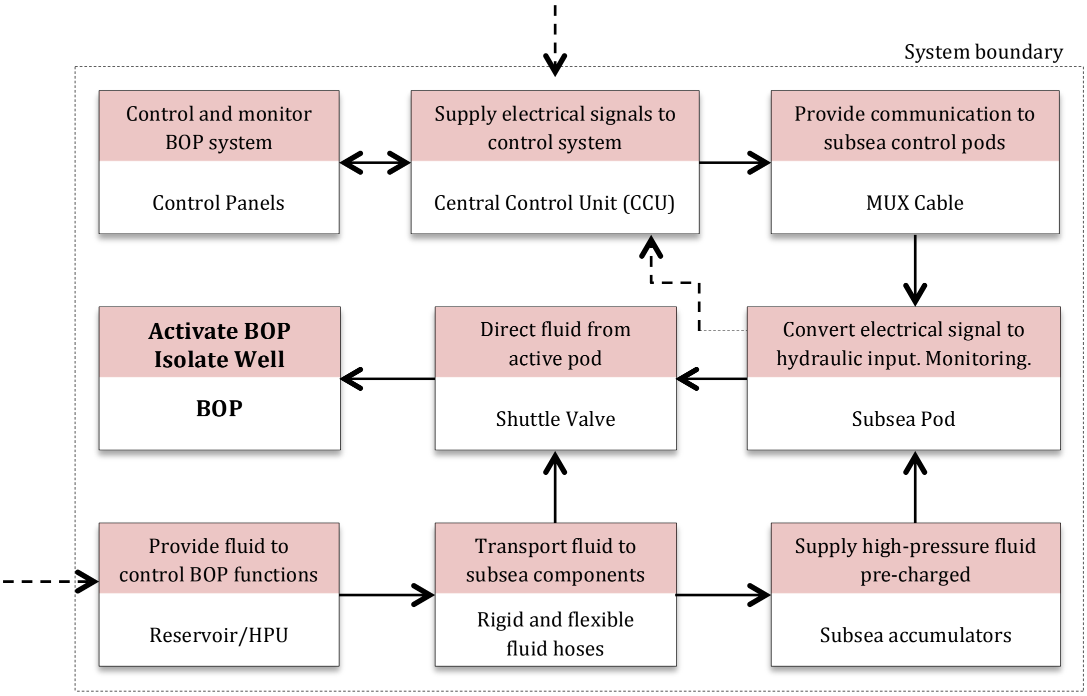


FIGURE 32: FUNCTIONAL BLOCK DIAGRAM ELECTRO-HYDRAULIC SYSTEM

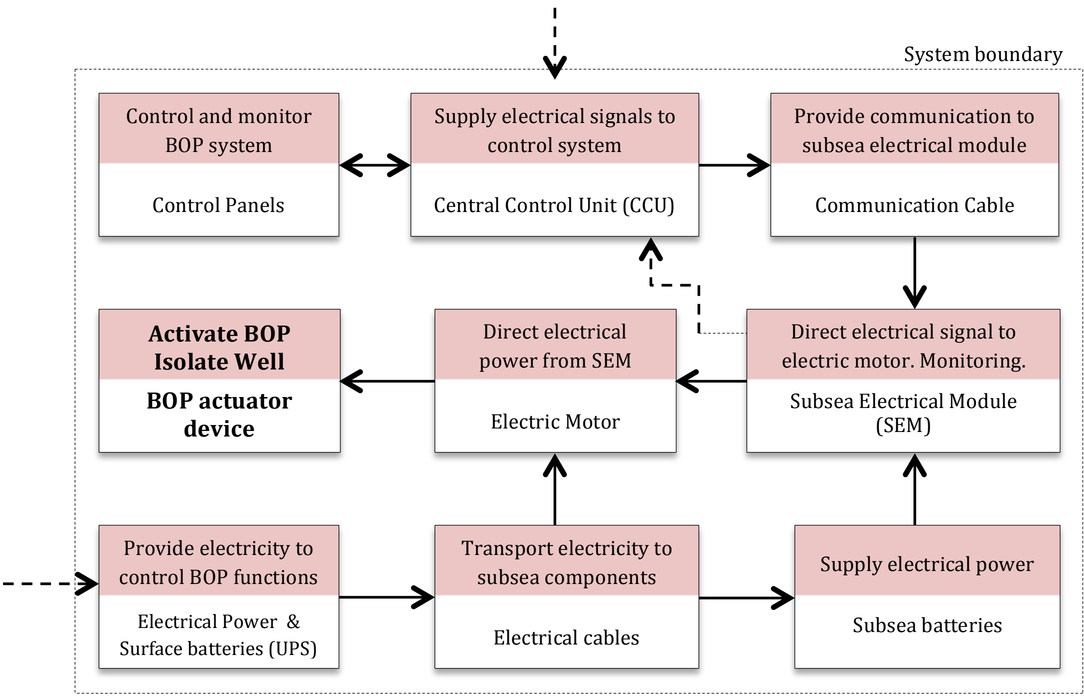


FIGURE 33: FUNCTIONAL BLOCK DIGRAM ALL-ELECTRIC SYSTEM

The inputs to the electro-hydraulic BOP system are electrical power to the CCU and hydraulic fluid to the fluid system. The shuttle valve is the last component that the fluid flows through before it enters the BOP.

The input to the all-electric BOP concept is electricity, both for communication and power. The subsea electrical module (SEM) receives electrical signals and transfer electrical power from subsea batteries to the electric motor, which runs the BOP actuator device.

6.3 BOP FAILURES

6.3.1 TYPICAL BOP COMPONENT FAILURES

Holand (1999) and Holand & Skalle (2001) outline the BOP system specific reliability in their studies. The most frequently observed failures for the different BOP components are briefly discussed below.

Flexible joint
Today, most rigs have flexible joints with a flexible element. Failures in these are rare. Worn joints can, however, lead to internal or external leakage.

Annular preventer
The main failure modes for the annular preventer are internal leakage (leakage through a closed annular) and failure to fully open. In Holand's study two of the 12 annular preventer failures caused the BOP stack or LMRP to be pulled.

Hydraulic connector
The LMRP connector and the wellhead connector are in principle identical, but usually the wellhead connector is rated to a higher pressure. Typically the wellhead connector is rated to the same pressure as the ram preventers, and the LMRP connector is rated to the same pressures as the annulars. It is observed that the main failure modes for the connectors are external leakage (leakage to environment) and failure to unlock.

Ram preventers
The most frequent failure modes for ram preventers are internal leakage and failure to open. Other failure modes observed are premature closure, failure to close and to keep closed, in addition to external leakage. Out of the 11 failures registered by Holand, six occurred in the BSR and five occurred in the pipe rams.

Choke and kill lines and valves
The choke and kill lines were not significant contributors to BOP downtime in Holand's study. External leakage is still the dominant failure mode, followed by bursted/plugged lines. The valves are prone to internal and external leakage, as well as failure to close and open.

NB: Well killing operations are not considered in further analyses. The reliability of choke and kill lines and valves during testing (normal operation of the BOP) are, however, considered.

Subsea control pods and accumulators
The MUX control system can experience loss of either one or all functions of the subsea control pod. The bladder accumulators are prone to corrosion, bladder burst and leakage. The bladder may leak at the connection point to the valve/ piping in the bottom of 'the bottle' or may puncture, which is quite common. By use of piston accumulators, internal leakage across the seal on the piston provides a similar problem as burst bladder.

No monitoring of nitrogen loss/leakage is possible with current bladder accumulator systems. Piston accumulators may be fitted with piston position monitoring in order to monitor nitrogen, but this is normally only done on topside accumulators.

Topside
Topside failure modes are related to loss of control of topside panels and malfunction of measure instruments.

6.3.2 Deepsea Stavanger

The Shaffer BOP installed on board DSS has been pulled up during operation 11 times over the last three years (2011, 2012, 2013). Pulling the BOP stack normally causes downtime. The experienced failure modes are listed below, in ascending order with respect to downtime influence.

1) Leaks in piping / tubing / hoses
2) Poor design of rubber seals that had to be replaced due to damage / wear
3) Improper operation of equipment. Human errors of operators on board

6.3.3 Electrical Component Failures

The main differences between the all-electric BOP concept and existing hydraulic BOP systems can briefly be summarized as follows:

- Electric actuator, powered by an electric motor with double sets of windings - full redundancy down to the actuator (no shuttle valve)
- Subsea batteries (instead of accumulators)
- Electrical valves and lines (instead of hydraulic change-over)

Although the actuators and belonging BOP technology are new, the proposed all-electric system is made up of known components. To assess possible failures and establish reliability data for the BOP concept, one can therefore assess potential failures on the inbound equipment. Unless other information is given, are the potential failure modes assessed in this section based on the engineering judgements from the workshop (Stautland, Hope , Eriksen, Rød, Grøtheim, & Hellenes, 2014) and comparable components in OREDA.

Electric actuator

ESD has done initial work with possible suppliers of the electric actuator. Standard equipment from the industry portfolio can be modified and used for a cutting case up to 900 mt, if not even more. Special versions in alternative materials can be provided if required in order to further enhance the capacity, with a moderate cost increase.

The mechanical parts of the actuator will generally be very reliable. Low utilization of the actuators helps to minimize wear and maintain a high reliability. However, potential failure modes due to material/component production error, or assembly errors that are not picked-up during quality control and function test cannot be ruled out. External leakage is also a potential failure mode.

Electric motor

The basic technology for the electric motor control is available from the car industry and maritime sector. There are several possible suppliers that can make special motors for the applications. According to ESD, ring motors with sufficient size are most suitable for the BOP concept.

Possible failure modes for a topside motor are listed in OREDA. The three most critical modes are summarized in Table 6 below. One can experience the same failures subsea, in addition to possible external leakage. The OREDA data can therefore be used as a decent estimate for a subsea electric motor.

TABLE 6: ELECTRIC MOTOR FAILURES

Critical failure mode	Failure rate (per 10^6 hours)
Breakdown	2.25
Fail to start on demand	6.73
Low output	9.34

Subsea batteries

An A123 battery cell is considered suitable for the subsea batteries. A123's nano-phosphate exhibits superior abuse tolerance and is not explosive, which is a huge advantage both with respect to safety and reliability (A123 Systems, 2012).

Another aspect of safety is the amount of excess lithium in the system. In contrast to the conventional lithium ion technologies, A123's nanophosphate technology has no excess lithium. If the A123 cell is overcharged, it will cause the cell to vent, due to the generated gas that is created from breakdown of the electrolyte (A123 Systems, 2012). This makes the batteries protected against human errors.

A battery charger placed topside will charge the batteries continuously as they are depleted. The 'charger' will be similar the existing power supply unit in the MUX control system, and will charge and monitor each cell individually. A shared accumulator bank for a system can be emptied by an external leakage since it is connected, while electrical batteries are not connected in the same way.

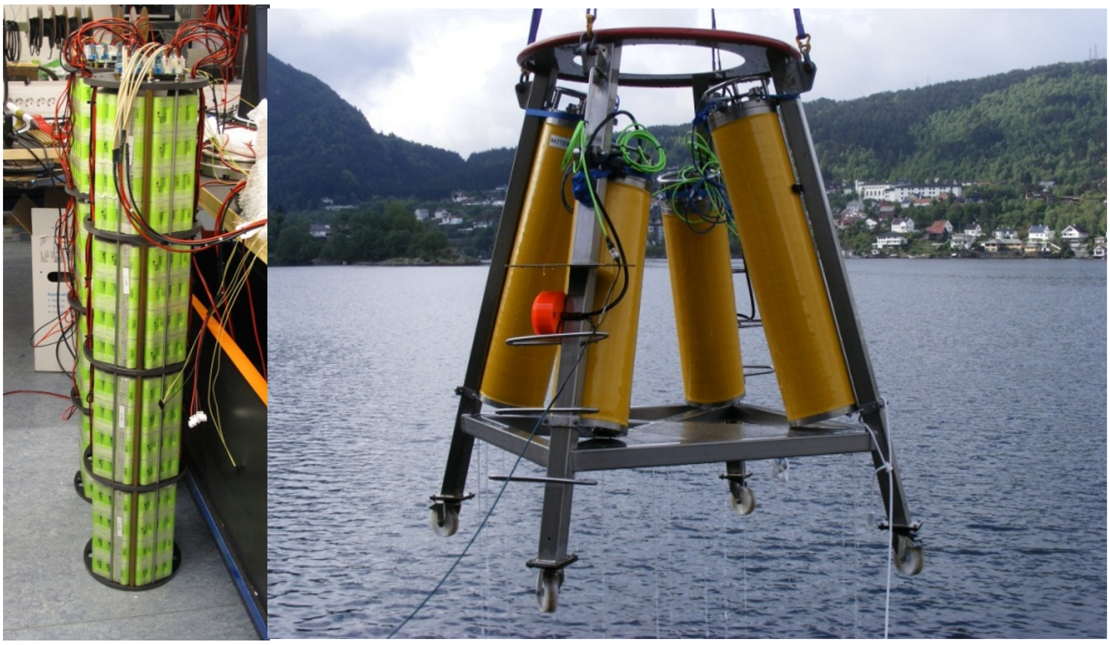


FIGURE 34: SUBSEA BATTERIES (A123 SYSTEMS, 2012)

Gylling Teknikk AS is a possible supplier of A123 batteries. According to their experience data on these batteries installed subsea, MTBF is calculated to just over one billion hours (by converting the 35 registered defects to installed hours) (Løvlie, 2014).

TABLE 7: SUBSEA BATTERY

Critical failure mode	Failure rate (per 10^6 hours)
Failure of battery	0.001

Electrical valves and lines

There are no control valve features in the all-electric concept since there are no hydraulics. The new technology is therefore not prone to valve failures.

The electrical power line from topside to subsea equipment will be the same type of cable that is used in the MUX system for communication signals – but will transfer more power. OREDA data for a power/signal line can be used as a decent estimate, as listed in Table 8 below.

TABLE 8: ELECTRICAL POWER CABLE

Critical failure mode	Failure rate (per 10^6 hours)
Transmission failure	0.27

The electrical power lines on the BOP stack form a simpler system than the equivalent hydraulic cables. Each line is directed straight from a subsea distribution box (initiated from the SEM) to the electric engine and the given BOP actuator. OREDA failure data for a power/signal jumper is given in Table 9, which shows that the electrical jumpers are considered as very reliable.

TABLE 9: BOP ATTACHED JUMPERS

Critical failure mode	Failure rate (per 10^6 hours)
Short circuit	0.02
Transmission failure	0.03

CHAPTER 7

RESULTS

7.1 FUNCTIONAL ANALYSIS

Norwegian Oil and Gas (2004) specify three functions in terms of the BOP's ability to act as a safety barrier, as specified in Section 6.2. Thus the guideline differentiates between two main functionalities in order to maintain the most essential function of the BOP – to isolate the well;

- The annular preventer/pipe ram function (function 1)
- The shear ram function (function 2 and 3 combined)

A generic function tree is established for the two BOP concepts, containing four sub-functions required to isolate the well. These sub-functions are equal whether the system is hydraulically or all-electrically operated, but the component(s) that fulfil each sub-function may vary. The components required to fulfil the activation function and the maintain structure function are similar for both concepts. The components involved in the control function and the supply power function, however, are not identical.

In the functional block diagrams in Figure 32 and Figure 33 are the top boxes, representing the activation of the preventer, similar for both concepts. The bottom boxes, representing supply of power, are however not similar. The boxes in the middle, representing the control functions of the BOP, are neither similar for the two concepts.

The emphasis in a comparison of the two BOP concepts should be placed on the parts and the components of the systems that vary the most. Both the generic function tree and the functional block diagrams justify that the emphasis should be placed on the control function and the supply power function.

7.2 FMECA

Based on the system description in Chapter 6 and input from the workshop performed together with Odfjell Drilling and ESD (Stautland, Hope , Eriksen, Rød, Grøtheim, & Hellenes, 2014) the two BOP systems are broken down into 25-30 components for further analyses. Additionally, failure modes and reliability data are gathered from Holand (1999), OREDA (SINTEF, 2009) and previous master thesis work (Januarilham, 2012), (Klakegg, 2012) & (Pinker, 2012).

7.2.1 ELECTRO-HYDRAULIC MUX SYSTEM

All components and its corresponding potential failure mode(s) are identified and given a unique number, as listed in Table 10 for the electro-hydraulic system. FMECA sheets are given in Appendix B.

TABLE 10: POTENTIAL FAILURE MODES FOR ELECTRO-HYDRAULIC SYSTEM

COMP. NUMBER	COMPONENT	POTENTIAL FAILURE MODE	
Sub-function 1: Control BOP functions			
1.1	Power supply unit (topside)	**F-1.1.1**	Erratic output
		F-1.1.2	Transmission failure
1.2	Electrical panel (topside)	**F-1.2.1**	Erratic output
1.3	Electric power battery back-up	**F-1.3.1**	Insufficient power
1.4	MUX cable reel	**F-1.4.1**	Transmission failure
1.5	Batteries inside subsea pods	**F-1.5.1**	Insufficient power
1.6	Electrical power and communication unit	**F-1.6.1**	Control/ signal failure
		F-1.6.2	Erratic output
		F-1.6.3	Fail to function on demand
		F-1.6.4	Spurious operation
1.7	Pod selector valve	**F-1.7.1**	Fail to move (stuck in position)
1.8	Solenoid valve	**F-1.8.1**	Fail to move
1.9	SPM valve	**F-1.9.1**	Fail to open/close. Fail between positions.
1.10	Shuttle valve	**F-1.10.1**	Fail to move (stuck in position)
1.11	Choke and kill valve	**F-1.11.1**	Fail to open/close. Fail between positions.
		F-1.11.2	External leakage
		F-1.11.3	Internal leakage
Sub-function 2: Supply power			
2.1	Subsea accumulators	**F-2.1.1**	Burst bladder
		F-2.1.2	Internal leakage
2.2	Fluid reservoir	**F-2.2.1**	Contamination of hydraulic fluid
		F-2.2.2	Rupture of reservoir
		F-2.2.3	Too low volumetric capacity
2.3	HPU	**F-2.3.1**	Hydraulic pump not running as intended
		F-2.3.2	Fail to make the required fluid
2.4	Hydraulic line from HPU to BOP	**F-2.4.1**	Combined/ common cause
		F-2.4.2	External leakage
		F-2.4.3	Internal leakage
		F-2.4.4	Plugged/ choked line
2.5	Regulator valve	**F-2.5.1**	Fail to move (stuck in position)
2.6	Pod/ stack mounted accumulator isolation valve	**F-2.6.1**	Fail to open/close
2.7	Hydraulic lines on BOP stack	**F-2.7.1**	Internal leakage

Sub-function 3: Activate BOP functions			
3.1	Ram preventer (fixed/variable bore ram/ blind shear ram)	**F-3.1.1**	Premature closure
		F-3.1.2	Fail to close
		F-3.1.3	Fail to shear pipe
		F-3.1.4	Fail to open
		F-3.1.5	Fail to keep closed
		F-3.1.6	External leakage
		F-3.1.7	Internal leakage
3.2	Annular BOP	**F-3.2.1**	Not able to close (around tubular)
		F-3.2.2	Not able to fully open
		F-3.2.3	Fail to keep closed
		F-3.2.4	External leakage
		F-3.2.5	Internal leakage
Sub-function 4: Maintain structure			
4.1	Riser/ wellbore connector	**F-4.1.1**	External leakage
		F-4.1.2	Unable to connect /disconnect
4.2	Ram preventer housing	**F-4.2.1**	External leakage
4.3	Annular preventer housing	**F-4.3.1**	External leakage
4.4	Flange and gasket	**F-4.4.1**	External leakage

All components required to fulfil the sub-function control of BOP functions are assigned with a low criticality, except the shuttle valve. This part of the BOP system is equipped with a great amount of redundancy, as specified in the FMECA sheets in Appendix B, and the consequences of a failure in either of the encompassed components are therefore considered as low or limited. Also, OREDA data and engineering judgement show, with great consensus, that the possibility for component faults in this part of the system is low. The shuttle valve, however, has no redundancy and is prone to corrosion and other types of mechanical damage. Hence, the criticality is ranked as tolerable. Historically, the shuttle valve has not been subject to many failures, but it is still very critical if a failure occurs (Stautland, Hope , Eriksen, Rød, Grøtheim, & Hellenes, 2014).

For the supply power sub-function, the subsea accumulators, the fluid reservoir and the hydraulic lines on the BOP stack stand out as the most critical components, based on experience data from DSS. Based on OREDA and engineering judgements (Workshop, 2014) are the remaining components ranked with an acceptable criticality.

Failure modes and reliability data for the sub-function activation of the BOP are based on Holand’s reliability study (1999). Failure to shear drill pipe is considered to be the most critical failure mode. The Macondo accident speaks for itself regarding the consequences of such a failure, reference is given to Section 3.4.

Flanges and gaskets are the most critical components with respect to maintaining the structure. Experience data from DSS shows that external leaks are a considerable problem leading to downtime, and the criticality with respect to reliability is therefore listed as tolerable.

TABLE 11: CRITICALITY MATRIX, ELECTRO-HYDRAULIC SYSTEM

CONSEQUENCE (IMPACT)	PROBABILITY (LIKELIHOOD)				
SEVERITY RATING	A (1) 0-20%	B (2) 20-40%	C (3) 40-60%	D (4) 60-80%	E (5) 80-100%
5 (75) SEVERE					
4 (25) MAJOR	F-1.10.1				
3 (10) CONSIDERABLE	F-2.4.2 F-3.2.1 F-4.1.1 F-4.1.2 F-4.2.1 F-4.3.1		F-3.1.3	F-2.7.1	
2 (5) LIMITED	F-1.6.1 F-1.6.2 F-1.6.3 F-2.4.1 F-3.1.1 F-3.1.2	F-1.1.1 F-1.1.2 F-1.6.4 F-1.7.1 F-1.11.1 F-1.11.2 F-1.11.3 F-2.2.3 F-2.4.4 F-3.1.4 F-3.2.2	F-2.1.1 F-4.4.1		
1 (1) LOW	F-2.4.3 F-3.1.5 F-3.1.6 F-3.2.4	F-1.2.1 F-1.3.1 F-1.4.1 F-1.5.1 F-2.1.2 F-2.3.2 F-3.1.7 F-3.2.3 F-3.2.5	F-1.8.1 F-1.9.1 F-2.2.1 F-2.2.2 F-2.3.1 F-2.5.1 F-2.6.1		

The critical failure modes are in the tolerable (yellow) region of the risk matrix. The most critical failure modes with respect to reliability to the electro-hydraulic BOP system are listed in Table 12.

TABLE 12: POTENTIAL CRITICAL FAILURE MODES, ELECTRO-HYDRAULIC SYSTEM

PRIORITY	COMPONENT	POTENTIAL FAILURE MODE	
1	Hydraulic lines on BOP stack	**F-2.7.1**	Internal leakage
2	Blind shear ram preventer	**F-3.1.3**	Fail to shear pipe
3	Shuttle valve	**F-1.10.1**	Fail to move (stuck in position)
4	Subsea accumulators	**F-2.1.1**	Burst bladder
	Flange and gasket	**F-4.4.1**	External leakage

7.2.2 ALL-ELECTRIC CONCEPT

The all-electric components and their corresponding potential failure mode(s) are identified and listed in Table 13.

TABLE 13: POTENTIAL FAILURE MODES FOR ALL-ELECTRIC CONCEPT

COMP. NUMBER	COMPONENT	POTENTIAL FAILURE MODE	
Sub-function 1: Control BOP functions			
1.1	Power supply unit (topside)	**F-1.1.1**	Erratic output
		F-1.1.2	Transmission failure
1.2	Electrical panel (topside)	**F-1.2.1**	Erratic output
1.3	Electric power battery back-up (topside)	**F-1.3.1**	Insufficient power
1.4	Electrical communication cable reel	**F-1.4.1**	Transmission failure
1.5	Subsea batteries inside SEM	**F-1.5.1**	Insufficient power
1.6	Electrical power and communication unit	**F-1.6.1**	Control/ signal failure
		F-1.6.2	Erratic output
		F-1.6.3	Fail to function on demand
		F-1.6.4	Spurious operation
1.7	Electric motor	**F-1.7.1**	Insufficient power
		F-1.7.2	External leakage
		F-1.7.3	Erratic output
		F-1.7.4	Breakdown
1.8	Choke and kill valve	**F-1.8.1**	Fail to open/close. Fail between positions.
		F-1.8.2	External leakage
		F-1.8.3	Transmission failure
1.9	Subsea electric module (SEM)	**F-1.9.1**	Erratic/ spurious output
Sub-function 2: Supply power			
2.1	Surface/subsea batteries	**F-2.1.1**	Obsolete battery
		F-2.1.2	Short circuit
2.2	Electrical lines on BOP stack	**F-2.2.1**	Transmission failure
2.3	Electric supply/ battery charger	**F-2.3.1**	Transmission failure
		F-2.3.2	Insufficient power
2.4	Electrical power line from topside to subsea equipment	**F-2.4.1**	Transmission failure
		F-2.4.2	Insufficient power
2.5	Electrical regulator valve (solenoid control valve)	**F-2.5.1**	Fail to function on demand
Sub-function 3: Activate BOP functions			
3.1	Ram preventer (fixed/variable bore ram/ blind shear ram)	**F-3.1.1**	Premature closure
		F-3.1.2	Fail to close
		F-3.1.3	Fail to shear pipe
		F-3.1.4	Fail to open
		F-3.1.5	Fail to keep closed
		F-3.1.6	External leakage
		F-3.1.7	Internal leakage
3.2	Annular BOP	**F-3.2.1**	Not able to close (around tubular)
		F-3.2.2	Not able to fully open

		F-3.2.3	Fail to keep closed
		F-3.2.4	External leakage
		F-3.2.5	Internal leakage
3.3	Actuator element	**F-3.3.1**	Fail to move
Maintain structure			
4.1	Riser/ wellbore connector	**F-4.1.1**	External leakage
		F-4.1.2	Unable to connect /disconnect
4.2	Ram preventer housing	**F-4.2.1**	External leakage
4.3	Annular preventer housing	**F-4.3.1**	External leakage
4.4	Flange and gasket	**F-4.4.1**	External leakage

Most of the components that are required to fulfil the sub-function control of BOP functions are similar for the all-electric and the electro-hydraulic system. The electric motor (replacing the shuttle valve) and the SEM (replacing the pod) are the two exceptions. The electric motor together with the actuation element is more redundant and considered as more reliable than the shuttle valve (Stautland, Hope , Eriksen, Rød, Grøtheim, & Hellenes, 2014). The SEM is less complex than the electro-hydraulic pod, which also makes it less prone to failures. All the components listed under the first sub-function are therefore assigned with a low criticality. The consequences of a failure in either of these components are again considered as low or limited.

The largest advantage with replacing hydraulic components with electric components is elimination of pumps, hoses and valves. Further are the size, weight, noise and vibrations reduced. For the supply power sub-function, the hydraulic components are replaced with corresponding electrical components. The power line from topside to subsea is still ranked with tolerable criticality, while the subsea batteries, the electrical lines, the power supply unit and the regulator valve are all ranked with an acceptable criticality, based on reliability data from OREDA.

Over the last years electric actuators have benefited from improved reliability of all electronic and electrical products. Consisting solely of a motor, gearbox and screws, electric actuators are much simpler than their hydraulic counterparts. Based on highly reliable electronic technology and with minimized possible points of failure, the reliability of electric actuators has improved in recent years to the point that in the vast majority of applications they will outlive the equipment they are installed in (Stautland, Hope , Eriksen, Rød, Grøtheim, & Hellenes, 2014).

Additionally, electric actuators provide true maintenance-free operation and are less prone to fail due to lack of maintenance. Maintenance with hydraulic systems begins with changing the fluid and filter on a regular basis and ensuring that the system always has sufficient fluid. Hydraulic fluid is always subject to contamination in tough subsea applications. Contamination causes a ripple effect as it moves through the system and damages multiple components, each of which may need to be repaired or replaced. Another concern is that when a hydraulic system is lost such as in a line rupture, there is no way to manually actuate the affected axes. In contrast, today's electric actuators require zero maintenance - not even lubrication. Electric actuators run independently with every axis being powered by a different motor, so a failure in an electric application affects only that single actuator, which makes it much easier to troubleshoot and repair.

As mentioned earlier, external dimensions and interfaces in the power actuator device can be adapted to existing BOP technology. Failure modes and reliability data for the sub-function activation of the BOP are therefore, as for the electro-hydraulic BOP system, based on Holand's reliability study (1999). Failure to shear drill pipe is again considered to be the most critical failure.

As for the electro-hydraulic system, flanges and gaskets are the most critical components with respect to maintaining the structure. Experience data from DSS show that external leaks are a considerable problem, and the all-electric concept has the same safeguards against leakage as the excising technology. The criticality for flanges and gaskets is therefore listed as tolerable also for the all-electric concept.

TABLE 14: CRITICALITY MATRIX, ALL-ELECTRIC CONCEPT

CONSEQUENCE (IMPACT)	PROBABILITY (LIKELIHOOD)				
SEVERITY RATING	A (1) 0-20%	B (2) 20-40%	C (3) 40-60%	D (4) 60-80%	E (5) 80-100%
5 (75) SEVERE					
4 (25) MAJOR					
3 (10) CONSIDERABLE	F-1.6.3 F-2.1.1 F-2.1.2 F-3.2.1 F-4.1.1 F-4.1.2 F-4.2.1 F-4.3.1	F-3.3.1	F-3.1.3		
2 (5) LIMITED	F-1.6.1 F-1.6.2 F-1.7.2 F-3.1.1 F-3.1.2	F-1.1.1 F-1.1.2 F-1.5.1 F-1.6.4 F-1.7.1 F-1.7.3 F-1.7.4 F-1.8.1 F-1.8.2 F-1.8.3 F-1.1.9 F-2.2.1 F-2.4.2 F-2.5.1 F-3.1.4 F-3.2.2	F-2.4.1 F-4.4.1		
1 (1) LOW	F-1.4.1 F-3.1.5 F-3.1.6 F-3.2.4	F-1.3.1 F-2.3.2 F-3.1.7 F-3.2.3 F-3.2.5	F-1.2.1 F-2.3.1		

Again, the critical failure modes are in the tolerable (yellow) region of the risk matrix. The most critical failure modes with respect to reliability of the all-electric BOP system are listed in Table 15.

TABLE 15: POTENTIAL CRITICAL FAILURE MODES, ALL-ELECTRIC CONCEPT

PRIORITY	COMPONENT	POTENTIAL FAILURE MODE	
1	Blind shear ram preventer	**F-3.1.3**	Fail to shear pipe
2	Actuator element	**F-3.3.1**	Fail to move
3	Electrical power cable	**F-2.4.1**	Transmission failure
	Flange and gasket	**F-4.4.1**	External leakage

7.3 Reliability Block Diagrams

Reliability block diagrams (RBDs) give a graphical representation of the BOP systems' logic and an extensive understanding of how the components interact to fulfil the functions of the systems. As justified in Section 6.2, there are three functions in terms of the BOP's ability to isolate a well;

1. Seal around drill pipe
2. Seal an open hole
3. Shear drill pipe and seal off well

Each of these three functions must be considered individually, and separate reliability block diagrams have to be established for each BOP system.

7.3.1 Electro-hydraulic BOP

Control system

For the electro-hydraulic BOP, the control system will act in the same way for all three functions, as illustrated in Figure 35 on the next page.

As described in Section 5.1, all subsea BOP control systems include two pods for redundancy purposes. The BOP can be fully controlled by each of these pods. The pod selector valve on the rig is common for the pods. Further, the hydraulic hard line and the shuttle valve located on each preventer are common.

For the control function, the RBD starts with a signal to activate the desired preventer (annular, shear or pipe ram), either all-electric (push bottom on electrical panel on the oil rig) or manually (from an ROV). The acoustic back-up control is left out from the diagrams.

If the BOP is activated via an electrical signal, the pod selector valve sends the signal to either of the pods via the MUX cable. Next, the solenoid valve releases pressurized hydraulic energy being stored in either of the accumulators or the HPU by use of the regulator valve. Further, the hydraulic fluid travels through the sub plate mounted (SPM) control valve and finally through the shuttle valve and into the preventer.

The block *preventer* will vary; depending on which function that is required. RBDs of the closing process for the three functions are given in Figure 36, Figure 37 and Figure 38.

Most of the components in the electro-hydraulic BOP system are modelled in series. The control pod power source is modelled as parallel because the electricity can come from the rig or batteries mounted inside the BOP structure. The hydraulic fluid has a double redundancy in accumulators at the surface and subsea – in addition to the HPU. All other components are modelled in series.

Critical components in the control system, based on minimum cut set (one component), are listed below:

- Pod selector valve
- Hydraulic hard line
- Shuttle valve
- Annular or ram preventer

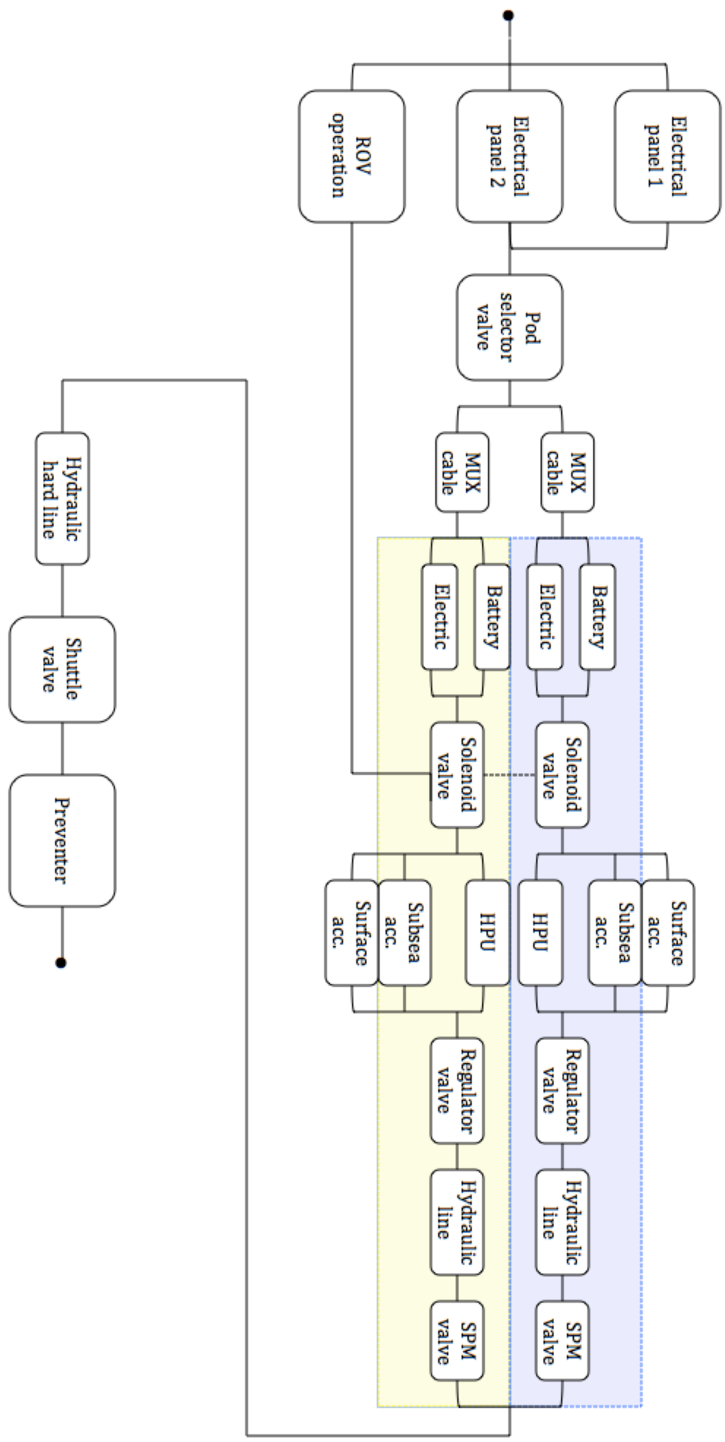


FIGURE 35: CONTROL SYSTEM, ELECTRO-HYDRAULIC BOP

Function 1: Seal around drill pipe
The annular preventer is the main component used to seal around drill pipe. RBD for this function is given below.

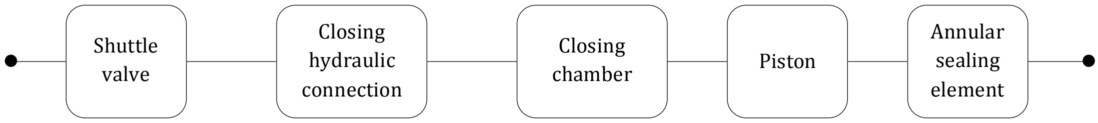


FIGURE 36: RBD ANNULAR PREVENTER, CONVENTIONAL BOP

The diagram is based on Figure 12. Based on minimum cut sets, all of the components in the diagram are critical. The wedge locks help to prevent the pistons from moving back, but they are not critical components for the seal function, and are therefore left out from the diagram above.

Function 2: Seal an open hole
Both the ram preventer and the annular preventer can be used to seal an open hole to seal off the well. RBD for the annular preventer is given in Figure 36. RBD for the ram preventers is given below.

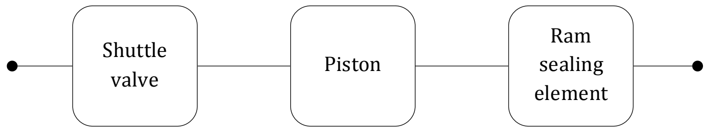


FIGURE 37: RBD PIPE RAM PREVENTERS, CONVENTIONAL BOP

The diagram is based on Figure 14. All of the components in the diagram are critical, and the wedge locks are, as for function 1, left out from the diagram.

Function 3: Shear drill pipe and seal off well
The BSR and the CSR preventers are used to shear drill pipe and seal off the well. RBD for the shear ram preventers are given below.

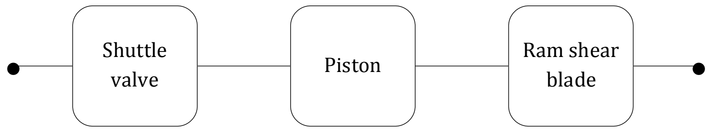


FIGURE 38: RBD SHEAR RAM PREVENTERS, CONVENTIONAL BOP

The diagram is based on Figure 14. Again, all of the components in the diagram are critical, and the wedge locks are left out from the diagram.

7.3.2 ALL-ELECTRIC BOP

Control system

Also for the all-electric BOP concept, the control system will act in the same way for all three functions, as illustrated in Figure 39.

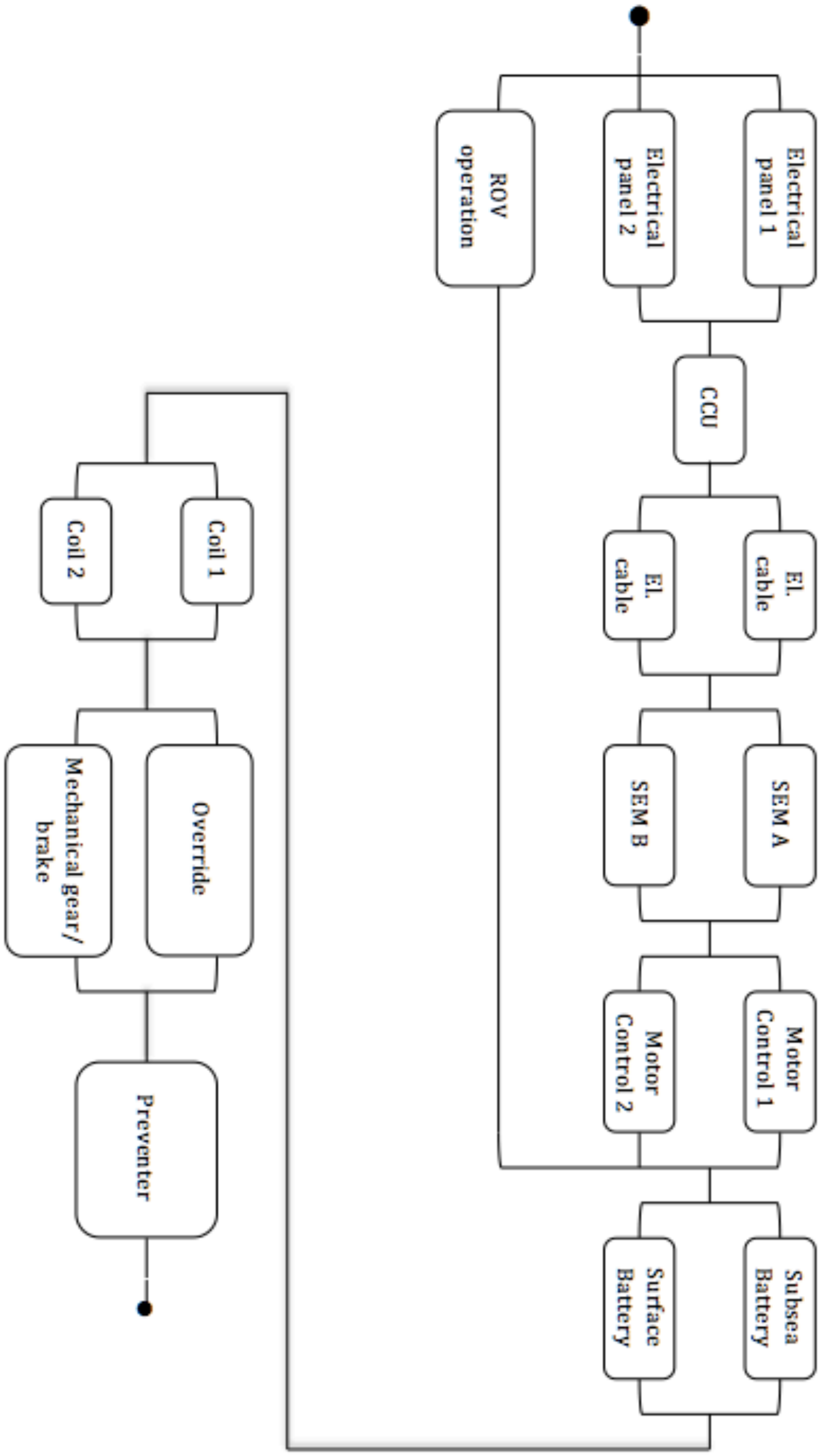


FIGURE 39: RBD CONTROL SYSTEM, ALL-ELECTRIC BOP

The RBD starts with a signal to activate the desired preventer (annular, pipe or shear ram), either all-electric from electrical panels on the unit or manually from an ROV. Also for this system, the acoustic back-up control is left out from the diagrams.

If the BOP is activated via an electrical signal, the CCU passes the electrical communication through an electrical cable to either of the subsea electrical modules (SEMs), which activate the motor control. Next, electrical power is released from subsea or surface (back-up) batteries. Further, the power travels to either of the coils in the electric motor that closes the preventer.

Depending on which BOP function that is required, the block *preventer* will vary. RBDs of the closing process for the three functions for the all-electric BOP concept are show in Figure 40, Figure 41 and Figure 42.

In contrast to the electro-hydraulic system, few of the components are modelled in series in Figure 39, most act in parallel. Critical components in the control system, based on minimum cut set (one component), are listed below:

- CCU
- Annular or ram preventer

Function 1: Seal around drill pipe
Again, the annular preventer is the main component used to seal around drill pipe. RBD for this function with electric actuation is given below.

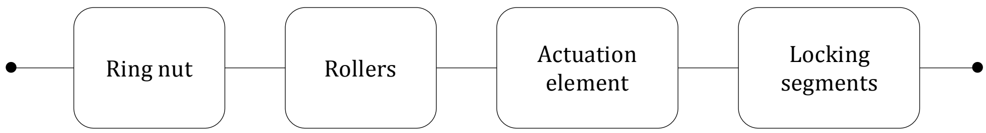


FIGURE 40: RBD ANNULAR PREVENTER, ALL-ELECTRIC BOP

The diagram is based on descriptions and figures given in Section 5.3.1. Based on minimum cut set, all of the components in the diagram are critical. The wedge locks are left out from the diagram.

Function 2: Seal an open hole
Also for the all-electric concept, both the ram preventer and the annular preventer can be used to seal an open hole. RBD for the annular preventer is given in Figure 40. RBD for the pipe ram preventers is given below.

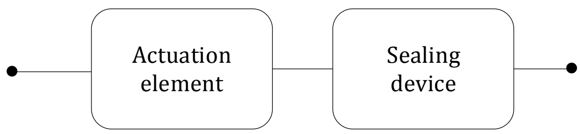


FIGURE 41: RBD PIPE RAM PREVENTER, ALL-ELECTRIC BOP

Function 3: Shear drill pipe and seal off well

Ram preventers are used to seal and open hole and to shear drill pipe and seal off the well. RBD for the ram preventers are given below.

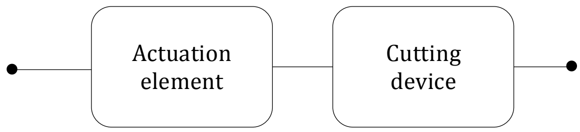


FIGURE 42: RBD SHEAR RAM PREVENTER, ALL-ELECTRIC BOP

Figure 41 and Figure 42 are based on descriptions and figures given in Section 5.3.2. The wedge locks are left out from the diagrams for both functions. The figures presented above illustrate that all of the components mentioned are critical.

7.4 FAULT TREES

Failure to shear pipe and seal off the well is found to be among the most critical failures in the FMECA, for both systems. The BSRs failing to fully close and seal was also identified as the primary cause of failure in the Macondo accident (ref. Section 3.4). This possible event is therefore analysed further in fault trees for both BOP concepts, as shown in Figure 43 and Figure 44. For detailed tree construction and data input see Appendix C.

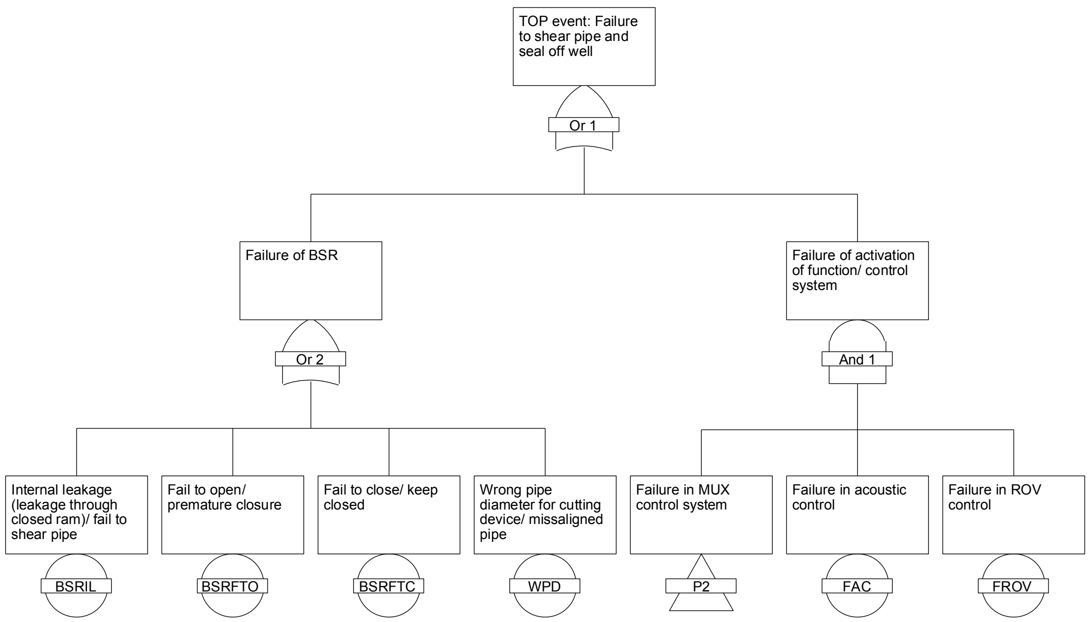


FIGURE 43: FAILURE TO SHEAR PIPE AND SEAL OFF WELL, ELCTRO-HYDRAULIC

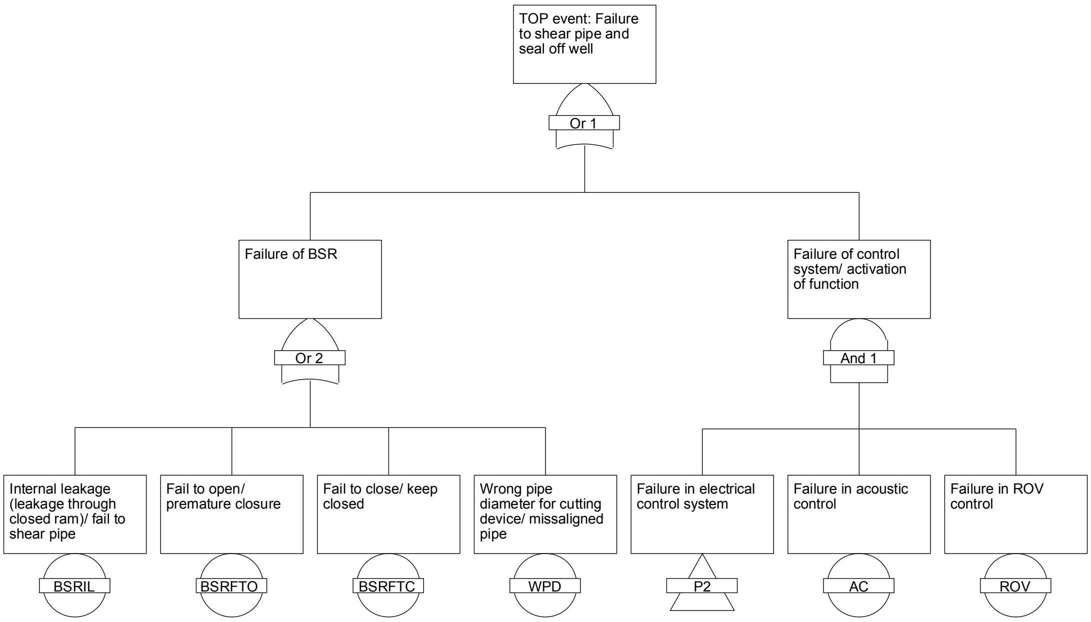


FIGURE 44: FAILURE TO SHEAR PIPE AND SEAL OFF WELL, ALL-ELECTRIC

7.4.1 QUALITATIVE EVALUATION

A qualitative evaluation of the fault trees may be carried out on the basis of minimal cut sets. The criticality of a cut set obviously depends on the number of basic events in the cut set (i.e., the order of the cut set). A cut set of order 1 is usually more critical than a cut set of order 2, or more (Rausand & Høyland, System Reliability Theory, 2004).

Both BOP concepts have the same cut sets of order 1 (1 component), as listed below;

{BSRIL}
{BSRFTO}
{BSRFTC}
{WPD}

Since these cut sets are common for both systems, they are not valuable for the comparison analyses.

None of the systems have cut set(s) of order 2 or higher than order 4. Cut sets of order 3 and 4 for both systems are listed in Table 16 on the next page.

TABLE 16: CUT SETS OF ORDER 3 AND 4

Cut set order	Electro-hydraulic system:	All-electric system:
3 **(3 components)**	{FAC,FROV,Line 1} {FAC,FROV,Line 2} {FAC,FROV,BOPL} {FAC,FROV,SHV}	{AC,ROV,BOPJ} {AC,ROV,EL}
4 **(4 components)**	{FAC,FROV,Panel 1,Panel 2} {FAC,FROV,PSU,BUB} {FAC,FROV,MUX 1,MUX 2} {FAC,FROV,Pod 1,Pod 2} {FAC,FROV,HPU,FSACC}	{AC,ROV,Panel 1,Panel 2} {AC,ROV,PSU,BUB} {AC,ROV,C-cable 1,C-cable 2} {AC,ROV,SEM 1,SEM 2} {AC,ROV,P-cable 1,P-cable 2} {AC,ROV,ElW 1,ElW 2}

7.4.2 QUANTITATIVE EVALUATION

The basic events in the fault trees must be updated with reliability data in order to perform a quantitative evaluation. The overall goal with such an evaluation is to see if the expected frequency of failure of BSR to shear and seal off well is different for the two systems.

Results from the quantitative evaluation of the fault trees are listed in Table 17 below. Input data to and explanation of the basic events are given in Appendix C3.

TABLE 17: FAULT TREE CALCULATIONS WITH BACK-UP CONTROL

	Electro-hydraulic system:	All-electric system:
MTTF **[Hours / Years]**	37,006.9 / 4.23	46,405.2 / 5.30
Frequency of Top event **[Occ. per Hours]**	2.686e-005	2.115e-005

The probability of failure of the ROV system and the acoustic control system will be the same for both systems. Furthermore, the probability of failure in either of the back-up control systems is considered as low (Workshop, 2014), which will make their reliability 'dominate' the results.

In comparing the systems, the emphasis should be placed on the parts that actually vary, i.e. the activation and control of the preventers. Failure of the ROV system and the acoustic control system is therefore left out from further analyses. Trees without back-up control systems are given in Figure 45 and Figure 46 on the next page.

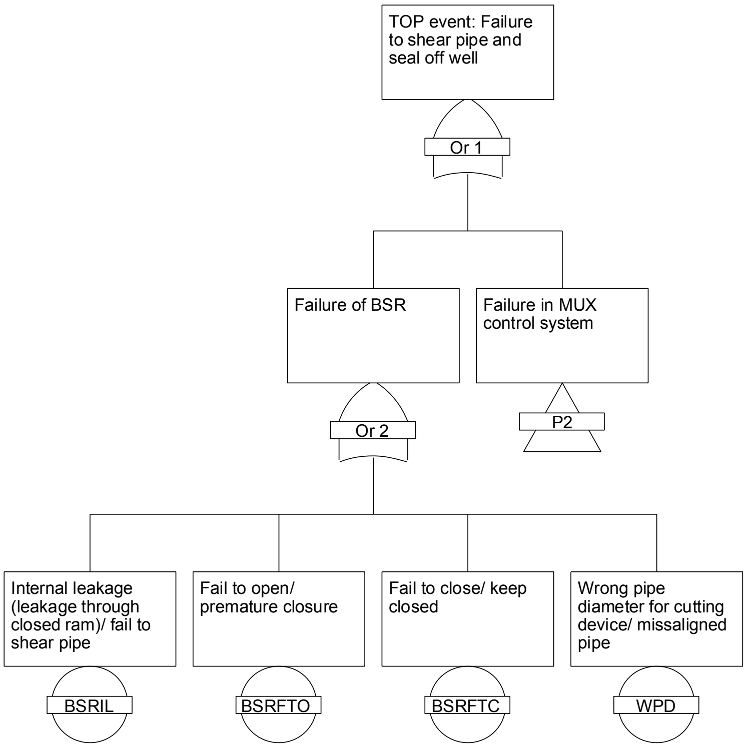


FIGURE 45: FAULT TREE WITHOUT BACK-UP CONTROL, ELECTRO-HYDRAULIC

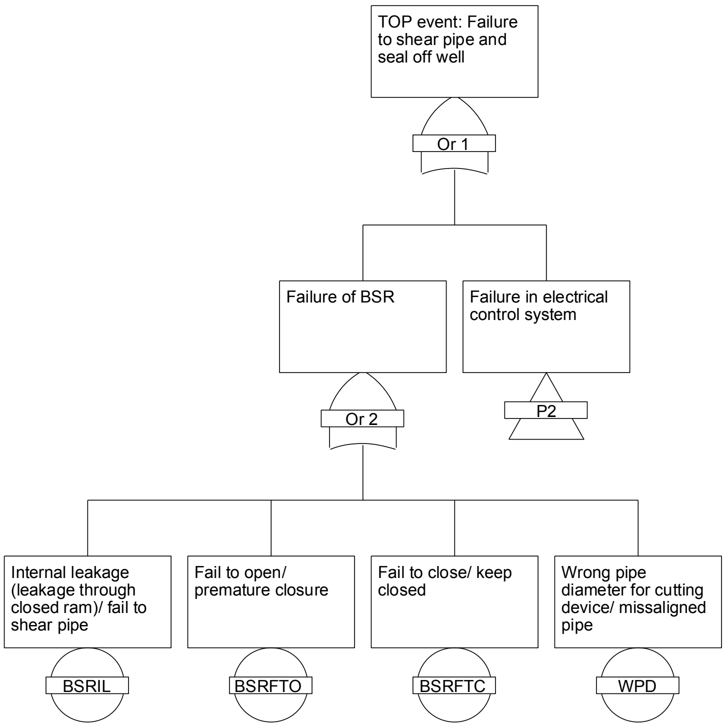


FIGURE 46: FAULT TREE WITHOUT BACK-UP CONTROL, ALL-ELECTRIC

The probability of failure of the BSR is known from Holand's reliability studies. The basic events related to the BSR are considered to be similar for both systems, with one exception – wrong pipe diameter for cutting device/ misaligned pipe. With reference to the Macondo blowout this event is considered as very topical. For the electro-hydraulic system it is estimated that such a failure may occur once every 10th year. The all-electric concept allows better and more detailed monitoring of the pipe and it is therefore estimated that such a failure may occur once every 20th year (Workshop, 2014).

OREDA is the main source for reliability data for the control systems. Reference is given to Section 6.3 and Appendix C3 for details. Results from the quantitative evaluation without back-up control systems are given in Table 18.

TABLE 18: FAULT TREE CALCULATIONS WITHOUT BACK-UP CONTROL

	Electro-hydraulic system:	**All-electric system:**
MTTF [Hours / Years]	10,173.2 / 1.16	41,348.4 / 4.72
Frequency of Top event [Occ. per Hours]	9.94885e-005	2.40284e-005

CHAPTER 8

DISCUSSION

The results from the reliability analyses yield that the all-electric BOP concept *is* more reliable and less prone to failures than existing electro-hydraulic MUX BOP systems. However, this is a result based on a single case study, with numerous assumptions involved. There are also other factors, in addition to reliability, which are important to consider when assessing a BOP system.

The overall function for a BOP system is to act as a safety barrier. The BOP is mainly a second barrier (after the mud column) – but act as the primary barrier when the LMRP is disconnected. The functional analysis justifies that the emphasis when comparing the two concepts is placed on the control function and the supply power function. In a reliability analysis, however, it is important to look at the system as a whole – and all sub-functions identified in the functional analysis are therefore included in the FMECA. Also, exclusion of two of the system sub-functions early in the reliability analysis can result in loss of valuable information later on.

For the electro-hydraulic system, the results from the FMECA designate the hydraulic lines on the BOP stack, the blind shear ram and the shuttle valve as the most critical components with respect to reliability. Also the subsea accumulators and flanges and gaskets are in the tolerable region of the risk matrix. For the all-electric concept, the blind shear ram is considered as the most critical component, followed by the actuator element, electrical power cable and flanges and gaskets.

The obvious part of the FMECA results is that the hydraulic components, which are listed as critical for the electro-hydraulic system, are not present on the all-electric list. Reliability data shows that electrical components required for the control function and the supply power function of the BOP, i.e. the SEMs, batteries, jumpers, cables and actuators are more reliable than their hydraulic counterparts. Hence, the all-electric concept comprises of fewer and more reliable components, making it simpler than the electro-hydraulic system. Additionally, contamination and internal leakage of fluid is not a concern. Mechanical override is also an argument in favour of all-electric operation.

The FMECA results also yield that there are fewer potential failure modes in the tolerable region of the risk matrix for the all-electric system than for the electro-hydraulic one. Perhaps less obvious is the fact that many of the critical components represent similar system functions, implying that the most critical potential failure modes are common for the two systems, but represented by different components. There are however two important exceptions. The function of the shuttle valve and the subsea accumulators do not represent potential critical failure modes in the all-electric concept.

The electric motor (replacing the shuttle valve) and the SEMs (replacing the pods) are the only components associated with control of the BOP that are not similar for the electro-hydraulic and the all-electric system. Elimination of the shuttle valve, in favour of electric actuation, allows the all-electric concept to have full redundancy down to the preventer. This is a great advantage for the all-electric control function, which avoids having any of its potential failure modes ranked as higher than acceptable in the FMECA risk matrix.

Subsea batteries, instead of accumulators, are another advantage of the all-electric concept. Firstly, power can be stored more compactly in electric batteries than in hydraulic accumulators and the capacity is unaffected by the water depth. This contributes to weight savings in many parts of the system, i.e. the HPU, the umbilical, control modules, lines and valves. Secondly, batteries are less prone to failure than the accumulators. Burst and damaged bladders is a significant contributor to downtime on the BOP on board DSS. Batteries cannot be ‘overcharged’ and damaged by human errors and are easier to monitor than the accumulators.

In addition to the subsea accumulators, the hydraulic lines on the BOP stack stand out as the most critical components for the supply power sub-function in the FMECA, based on experience data from DSS. For the all-electric concept, the hydraulic components are replaced with corresponding electrical components, and ranked with lower criticalities. This is an assumption based on comparable electrical components in OREDA and the configuration of the all-electric system. The electrical lines on the BOP stack are connected directly from the SEM to the preventer – without passing valves or gaskets, making them protected against transmission failures and mechanical errors. The power line from topside to subsea is ranked with tolerable criticality for both concepts, based on reliability data on a signal line in a dynamic umbilical in OREDA.

When looking at comparable electrical components in OREDA there are many precautions and assessments in terms of uncertainty that have to be made. First of all it must be addressed how alike the components actually are, both with respect to function, operational time and maintenance. Secondly, the uncertainty as to whether or not the amount of power to be transmitted and stored will affect the reliability must be thoroughly considered. It is a gross assumption to consider electrical communication signals as equal to high power signals. This assumption contributes in giving the all-electric system a slightly exaggerated reliability.

Although a unit in OREDA proves to be a good comparative component for the BOP concept, there are still uncertainties related to the reliability data. OREDA is based on many years of data collecting and is thus never 100 % accurate. There is also uncertainty related to the failure modes – grouping and descriptions might be inaccurate, or there might exist other failure modes than those listed in the literature.

For both concepts failure modes and reliability data for the sub-function activation of the BOP are based on Holand's reliability studies. Failure to shear drill pipe is considered to be the most critical failure mode. The Macondo blowout speaks for itself regarding the consequences of such a failure. Holand does not associate his work with drilling of high pressure/ high temperature wells or deepwater drilling. One can therefore argue that this reliability data is old and out-dated. But, in fact, the technical mode of operation of the BOP has not changed – although drilling has moved to deeper waters and more complicated wells. Holand's reliability studies are therefore still topical. Additionally, out-dated BOP technology is an argument in itself for the need for new solutions for subsea BOPs.

Flanges and gaskets are the most critical components with respect to maintaining the structure for both concepts. Experience data from DSS shows that external leaks are a considerable problem. There is, however, great uncertainty associated with external leaks for the all-electric system. Firstly, experience data for subsea hydraulic components is available in a much larger scale than for electrical components. Secondly, the consequences of leakage might escalate differently for the two concepts. E.g., the consequences of a short circuit in the all-electric system during a kick are hard to predict. Reliability data for electrical components is often based on 'waterproof' operation. Still, potential failure modes due to material/component production error, or assembly errors that are not picked-up during quality control and function test cannot be ruled out. The weighting of the probability of external leaks will therefore have a huge impact on the proposed reliability for the all-electric concept.

Blowout accidents have major consequences. Although failure of the BOP is rarely the only cause of a blowout, it is necessary to discuss why none of the critical failure modes in the FMECA are assigned with a higher criticality than tolerable (yellow) in the risk matrix. Firstly, the analysis is performed on a component level. Although most components are ranked with an acceptable (green) risk, the system reliability as a whole will depend on how the components act together – and might have a higher total risk. Secondly, 'safeguards' in the systems have been considered and taken into account for each component when setting the criticality. I.e., if there are redundancy or other safety barriers in the system, the criticality of a potential failure mode of a component decreases. Thirdly, the equipment involved is in use on subsea equipment today. It is therefore unrealistic to assign many of the components with a high risk of failure when operational data tells otherwise.

The reliability block diagrams for the electro-hydraulic system show that there is a greater amount of redundancy in the control system than in each specific preventer. All three functions in terms of the BOP's ability to isolate the well depend on the control system. Still, the pod selector valve, hydraulic lines and the shuttle valve do not have any redundant components, and two of these are ranked as critical in the FMECA. Hence, in order to increase the reliability of the BOP system the emphasis should be placed on these specific parts of the control system rather than on each preventer. This is an interesting finding, as there is a tendency in the industry towards wanting to increase the number of preventers in the stack as a measure towards increasing the reliability. It can be argued, based on these findings and previous reliability studies by Holand, that the focus should rather be on increasing the redundancy of the control system. This also supports the findings in the functional analysis; to emphasize the control systems when comparing the two BOP concepts.

Redundancy in the control system is a great improvement with the all-electric concept. The shuttle valve has already been discussed, in addition to mentioning strengths of the electrical lines over the hydraulic hoses and the possibility for mechanical override to control the preventer.

In the qualitative fault tree evaluation, the electro-hydraulic system has more cut sets of order 3 than the all-electric concept, and fewer cut sets of order 4. Given that a cut set of order 3 is more critical than a cut set of order 4, the results imply that the electro-hydraulic system has more critical cut sets than the all-electric concept.

Another important factor when assessing cut sets is the type of basic events the cut sets contain. Failure in acoustic and ROV back-up control are basic events in all the sets. Hydraulic lines and the shuttle valve are basic events in cut sets of order 3 for the electro-hydraulic system, while electrical lines and the electric motor are basic events for the all-electric concept. These results are in accordance with the results from the FMECA.

The quantitative fault tree evaluation shows that the expected frequency of failure of BSR is higher for the electro-hydraulic BOP system than for the all-electric concept. When excluding the back-up control systems from the trees, the differences between the two systems are more clearly outlined, but the expected frequency of the top event to occur is also higher than for a realistic system.

The emphasis in the fault tree analyses has not been on the numbers. Expected frequency of failure to shear pipe and seal off well of respectively 4.3 years and 5.4 years for the electro-hydraulic and the all-electric concept is very high. The fact that the BOP does not shear the pipe and seal off the well on regular basis must be taken into account. Therefore, these numbers only represent estimates of reliability of the two systems, with respect to each other. Additionally, failures are usually discovered through monitoring, and failure modes then lead to downtime instead of a blowout.

The all-electric concept offers better monitoring and more detailed control than the electro-hydraulic system. This is a great advantage, both during regular testing and in a well-control situation – e.g. if the drill pipe needs to be cut, as in the Macondo blowout. The exact position and size of the pipe can then be controlled ahead of cutting. Detailed monitoring makes it easier to trouble shoot and control all functions of the BOP.

Hydraulic components may entail spills of considerable amounts of hydraulic fluid into the surroundings. During BOP testing there is always pollution to the sea, to a greater or lesser extent. This pollution can be avoided with the all-electric concept.

Maintenance and repair time also influence the downtime for a BOP system. These topics are only briefly examined in this thesis. It is formed a basis to argue that electrical components demand less maintenance and are less prone to fail due to lack of maintenance than hydraulic ones, but with great uncertainty. The all-electric concept demands for new training of subsea personnel, which might cause great variations in the reparation times.

Another aspect that may weigh against the all-electric concept is the existing electrical subsea systems. Although the subsea production system off the Netherlands is considered successful, the technology has not been implemented elsewhere. Whether this is due to technological challenges or commercial interests is not answered in this thesis. It does, however, seem likely that the latter point plays an important role. The aspect of costs with the all-electric concept is associated with great ambiguity.

Holand outlines that it is important to be aware of the human controlled environments a BOP system is relying on. Although human errors are the third largest contributor to downtime on the BOP on board DSS, human impacts are only briefly assessed in the analyses in this thesis. Again, this substantiates the uncertainty in the analyses results.

Hydraulic technology has been used in the offshore industry for decades and the industry has become familiar with its pros and cons, both on a component and system level. Hydraulic components have also historically enjoyed a lead in power density over their electric counterparts, which enhance their performance in the most difficult applications. Many people working in the industry may be unaware of the improvement of electrical components, and might be sceptical to new, all-electric solutions.

A promise of high reliability is not enough to drive the development forward and create success. Existing BOP suppliers don't have the incentive to develop new technology, since they are already in the market with their electro-hydraulic solutions. Some companies might be sceptical of a technology shift from electro-hydraulic control to all-electric control. This does not only apply to BOPs, but to all-electric subsea solutions in general. For suppliers of hydraulic equipment an 'electrical revolution' can have undesired effects. Still, the subsea system suppliers are large companies and have a great degree of influence on the development of new technology.

An all-electric BOP concept can solve many of the challenges the drilling industry is facing in the years to come, but there are still questions to be answered in order to prove that the concept is both technically and financially profitable.

CHAPTER 9

CONCLUSIONS

9.1 SUMMARY AND CONCLUSIONS

Traditionally, BOP systems have been hydraulically operated. The response time for a hydraulic system increases with water depth, and to overcome signal delays electro-hydraulic systems are used for deepwater drilling. Deepwater operations experience new challenges compared to drilling in more shallow depths. For the BOP this involves increased loads from the riser system, higher pressure and temperature in the well and energy loss in subsea accumulators. Improved technology and new solutions for subsea BOPs are believed to be a necessity for future deepwater drilling.

This thesis compares the electro-hydraulic BOP system with a new, all-electric BOP concept, with respect to reliability. The purpose of the comparison is to see if any of the recurring failures Odfjell Drilling experiences on the BOP on board Deepsea Stavanger are less likely to occur if the BOP is all-electrically operated.

To compare the two BOP concepts, a reliability analysis is performed on each system. The reliability analyses is performed in four steps:

1. Functional analysis
2. FMECA
3. Reliability block diagram analysis
4. Fault tree analysis

The results from the reliability analyses yield that the all-electric BOP concept is more reliable and less prone to failures than the electro-hydraulic BOP system, as listed in Table 19 below.

TABLE 19: RESULTS

	Electro-hydraulic system:	All-electric system:
MTTF [Hours / Years]	10,173.2 / 1.16	41,348.4 / 4.72
Frequency of Top event [Occ. per Hours]	9.94885e-005	2.40284e-005

This is, however, a result based on a single case study with numerous assumptions and with a great amount of uncertainty involved. Reliability data is gathered from experience data on board Deepsea Stavanger, engineering judgment input from a workshop performed with Odfjell Drilling and ESD, previous reliability studies by Holand and comparative components in OREDA.

The results from this thesis give no clear answers to which BOP concept that contributes the least to downtime. Nevertheless, in addition to reliability, there are many arguments in favour of the all-electric concept. An electric system contains fewer and more reliable components than an electro-hydraulic one, making the all-electric concept simpler than existing BOP systems. No shuttle valve and subsea batteries instead of accumulators are the most obvious advantages with the all-electric concept. In addition, the concept is weight saving, has a greater amount of redundancy in the control system, offers better and more precise monitoring and is less polluting. Still, there is considerable uncertainty associated with the new technology, both with respect to human impacts, maintenance, repair hours and costs.

Hydraulic technology has been used in the offshore industry for decades and the industry has become familiar with its pros and cons. Over the past decade the power density and roughness of electrical components have substantially improved, while in hydraulic components the improvements have been much smaller or non-existent. Many people working in the industry may be unaware of the improvement of electrical components, and might be sceptical to new, all-electric subsea solutions.

For new technology to be developed and implemented there must exist some market drivers. A promise of high reliability is not enough to create success. An all-electric BOP concept can solve many of the challenges the drilling industry is facing in the years to come, but time will show whether or not the concept proves to be both technically and financially profitable.

9.2 Recommendations and Suggestions for Further Work

There are many arguments in favour of the all-electric BOP concept relative to the electro-hydraulic system – and many of these are discussed in this work. Still, there is considerable uncertainty associated with new BOP technology, and there are more issues to be examined before a certain conclusion can be drawn.

The impact of human errors along with the maintenance and repair requirements for the all-electrical concept have not been properly assessed in this thesis, and should be subject to more research. The costs also need to be further assessed. Additionally, the reliability source data, both for the electro-hydraulic and the all-electric BOP system should be investigated in more detail.

Also, research should be done on other possible solutions for future deepwater BOPs. Subsea HPUs and dual BOP technology are mentioned briefly in this work, and are candidates for such research.

The main stakeholders, the oil companies and drilling companies are the parties that really can benefit from a more reliable BOP solution. Some of these may be motivated to support new developments with funding and pilot projects. ESD is currently in a process to establish a Joint Industry Partnering Project for development of all-electric BOP controls and is seeking financial and other support from such companies.

References

A123 Systems. (2012). *A123 Systems Presentation May 2012.*

Akker, J. v., & Burdick, J. (2008, March 17). All-electric actuated subsea system qualified, implemented. *Oil&Gas Journal* , 44-50.

API. (2012). *Standard 53 - Blowout Prevention Equipment Systems for Drilling Wells.* American Petroleum Institute.

Bjørkhaug, M., Danielsen, U., Håverstad, T., Jacobsen, Ø., & Pedersen, K. S. (1985). *Årsaksforhold ved utvikling av brann of eksplosjon ombord i boreriggen West Vanguard natt til den 7.oktober 1985.* http://nbl.sintef.no/publication/lists/docs/STF25_A85013.pdf.

Det Norske Veritas. (2011). *Forensic Examination of Deepwater Horizon Blowout Preventer.*

Eriksen, E. (2013). *Patent No. WO 2013/119126 A1.* NO.

ESD. (2013). New drilling BOP technology. *Huston presentation.*

gCaptain. (2013). *www.gCaptain.com*. Retrieved February 2014

Gröndahl, M., Park, H., Roberts, G., & Tse, A. (2010, June). Investigating the Cause of the Deepwater Horizon Blowout. *The New York Times* .

Hals, T., & Molnes, E. (1984). *Reliability of Subsea BOP Systems - Phase II Control Systems.* Trondheim: SINTEF.

Holand, P. (1997). *Offshore Blowouts Causes and Control.* Houston, Texas, USA: Gulf Publishing Company.

Holand, P. (1996). *Offshore Blowouts Causes and Trends.* Trondheim, Norway: Doctoral Dissertation, Norwegian Institute of Technology, Department of Production and Quality Engineering .

Holand, P. (1987). *Reliability of Subsea BOP Systems - Phase IV.* Trondheim: SINTEF.

Holand, P. (1997). *Reliability of Subsea BOP Systems for Deepwater Application & Fault Tree Analysis.* Trondheim: SINTEF.

Holand, P. (1999). *Reliability of Subsea BOP Systems for Deepwater Application, Phase II DW.* SINTEF.

Holand, P. (1989). *Subsea BOP Systems, Reliability and Testing - Phase V.* Trondheim: SINTEF.

Holand, P., & Molnes, E. (1986). *Reliability of Subsea BOP Systems - Phase III Testing and Maintenance, Main Report.* Trondheim: SINTEF.

Holand, P., & Rausand, M. (1987). Reliability of Subsea BOP Systems. *Reliability Engineering* , 263-275.

Holand, P., & Skalle, P. (2001). *Deepwater Kicks and BOP Performance.* Trondheim: SINTEF.

IEC 60300-3-11. (2009). *Dependability management - Part 3-11: Application guide - Reliability centred maintenance.* standard.no.

Ireland, R. D. (1991). *Determination by R.D. Ireland in Fatal Accident Inquiry Into the Death of Timothy John Williams on Board Ocean Odyssey.* Sheriff Clerk.

Januarilham, Y. (2012). *Analysis of Component Criticality in the Blowout Preventer.* University of Stavanger (UiS). Faculty of Science and Technology.

Klakegg, S. (2012). *Improved methods for reliability assessments of safety-critical systems: an application example for BOP systems.* NTNU, Department of Peoduction and Quality Engineering. Faculty of Engineering Science and Technology.

Kobbacy, K. A., & Murthy, D. P. (2008). *Complex System Maintenance Handbook.* Springer.

Kongsberg Maritime. (2014). *Acoustic control system for BOP operation - ACS 500*. Retrieved April 28, 2014 from http://www.km.kongsberg.com

Løvlie, J. (2014, May). Ingeniør Batterisystemer Gylling Teknikk AS.

Leffler, W. L., Pattarozzi, R., & Sterling, G. (2003). *Deepwater Petroleum Exploration & Prodution: A nontechnical guide.* PennWell Corporation.

McCrae, H. (2003). *Marine risers and subsea blowout preventers.* The University of Texas at Austin.

NORSOK. (2012). *D-001 Drilling facility.* www.standard.no.

NORSOK. (2013). *D-010 Well integrity in drilling and well operations.* www.standard.no.

Norwegian Oil and Gas. (n.d.). Retrieved April 2, 2014 from http://www.norskoljeoggass.no/en/About/

Norwegian oil and gas. (2004). *070 - Application of IEC 61508 and IEC 61511 in the Norwegian petroleum industry.* http://www.norskoljeoggass.no.

NOV. (2013). Retrieved February 23, 2014 from Shaffer Spherical BOP: https://www.nov.com/uploadedFiles/Business_Groups/Rig_Solutions/Drilling_Pressure_Control/Blowout_Preventers_BOPs/Spherical_BOPs/D392004080-MKT-001-Shaffer%20Spherical%20BOP.pdf

NOV. *User's Manual .* National Oilwell Varco.

Odfjell Drilling. (n.d.). (Odfjell Drilling AS) Retrieved February 17, 2014 from http://www.odfjelldrilling.com/Business-Areas/Mobile-Offshore-Drilling-Units/Fleet-of-semis--drillships/

Odfjell Drilling. (2013). Risk Matrix.

Petroleum Safety Authority Norway, PSA. (2013, February 2). *www.ptil.no*. Retrieved April 14, 2014 from Operator Statoil lost control of well 34/10-C-6 A on the Gullfaks C platform in the Norwegian North Sea during 19 May 2010.: http://www.ptil.no/articles-in-safety-status-and-signals-2012-2013/gullfaks-c-2010-article9128-1095.html

Petroleumstilsynet. (2005). *Gransking av gassutblåsning på Snorre A, brønn 34/7-P31 A 28.11.2004. .*

Pinker, R. (2012). *Improved methods for reliability assessments of safety-critical systems: an application example for BOP systems.* NTNU, Department of Production and Quality Engineering. Faculty if Engineering Science and Technology.

PSA. (2013). *Saga 2/4-14: A tough fight*. Retrieved February 2014 from http://www.psa.no/articles-in-safety-status-and-signals-2012-2013/saga-2-4-14-a-tough-fight-article9139-1095.html

Rajabi, M. M., & Amani, M. (2010). Possible Alternatives for Deep-Water Gas Charged Accumulators. *CSCanada , 3* (2,2012), 31-41.

Rausand, M. (1983). *Reliability of Subsea BOP Systems.* Trondheim: SINTEF.

Rausand, M., & Høyland, A. (2004). *System Reliability Theory* (2nd Edition ed.). New Jersey: John Wiley & Sons.

Rausand, M., Holand, P., Husebye, R., Lydersen, S., Molnes, E., & Ulleberg, T. (1985). *Reliability of Subsea BOP Systems - Phase II, Main Report.* Trondheim: SINTEF.

Rees, A., & Daniel, M. (2011). Blowout Preventer Stack and Control Systems . *16th Lillehammer Energy Claims Conference March 3, 2011.* http://www.energyclaims.net/assets/BOP-and-control-system.pdf.

Rokne, Ø. (2013). Deepwater developments can benefit from all-electric controls. *Offshore , 73* (11).

SINTEF. (2011). *Deepwater Horizon-ulykken: Årsaker, lærepunkter og forbedringstiltak for norsk sokkel.*

SINTEF. (2009). *Offshore Reliability Data Handbook* (5th Edition ed.). OREDA Participants.

SINTEF. (2014, January 22). *SINTEF Offshore Blowout Database*. Retrieved February 18, 2014 from http://www.sintef.no/home/Technology-and-Society/Projects/Projects-SINTEF-TS-2001/SINTEF-Offshore-Blowout-Database/

Stautland, T., Hope , K. A., Eriksen, E., Rød, M., Grøtheim, J., & Hellenes, A. (2014, April 10). Workshop.

Steve Devereux, C. (2012). *Drilling Technology in a Nontechnical Language.* PennWell Corporation.

The Bureau of Ocean Energy Management, Regulation & Enforcement. (2011). *Report Regarding the Causes of the April 20, 2010 Macondo Well Blowout.*

US Chemical Safety Board. (2013, April 1). Statement of CSB Chairperson Dr. Rafael Moure-Eraso on Court Decision in Deepwater Horizon/Macondo Investigation Case. http://www.csb.gov/statement-of-csb-chairperson-dr-rafael-moure-eraso-on-court-decision-in-deepwater-horizonmacondo-investigation-case/.

Vinnem, J.-E. (2014). *Offshore Risk Assessment* (3rd Edition ed., Vol. II). Springer.

APPENDIX

A. Problem Description

NTNU
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Faculty of Engineering Science and Technology
Department of Marine Technology

MASTER THESIS
Spring 2014

for

M.Sc. student Elisabeth Drægebø
Department of Marine Technology

Reliability Analysis of Blowout Preventer Systems

Pålitelighetsanalyse av BOP-systemer

The background for this thesis is Odfjell Drilling's experience with excessive downtime on the blow out preventer (BOP) during drilling operations. This is a well-known problem also for other drilling companies worldwide, which causes increased costs and delays in a drilling project. All BOPs on board drilling units owned by Odfjell Drilling are hydraulically operated.

The downtime and associated cost due to failure on the BOP increases with the water depth of a drilling project, because the time it takes to recover and re-install the BOP stack will increase. In a deepwater operation, the unproductive downtime from a problem that requires the BOP stack to be recovered to the surface may be 1-2 weeks. The magnitude of the resulting daily loss, both for the owner and the client involved, illustrates how important reliability of the BOP is.

Deepwater drilling operations may also experience new challenges compared to operations in more shallow depths. Examples are increased loads on the riser system, higher pressure and temperature in the well, energy loss in subsea accumulators, etc. Today, drilling companies worldwide have a strong focus on reducing BOP downtime. Improved technology and new solutions for subsea BOPs are therefore believed to be a necessity for future deepwater drilling.

This master thesis is a case study of the electro-hydraulic BOP on board Deepsea Stavanger, a drilling unit owned and managed by Odfjell Drilling. The first focus is to analyse BOP failures that have led to downtime on this rig, and to relate them to the technical mode of operation on the BOP.

The company Electrical Subsea & Drilling AS (ESD) is working on developing an all-electrically operated BOP. They claim that their new technology can provide many benefits versus the electro-hydraulic BOP systems, both with respect to environmental and operational safety, as well as cost reduction for drilling- and oil companies. Additionally, they claim that their BOP technology is more reliable and less prone to excessive downtime. The second focus is therefore to establish a thorough system description of this concept, to analyse potential failures and to compare them with the failures experienced on board Deepsea Stavanger.

The thesis should compare the conventional electro-hydraulic BOP system with the all-electric BOP concept developed by ESD, with respect to reliability. The purpose of such a comparison is to see if any of the recurring failures Odfjell Drilling experiences on board Deepsea Stavanger are less likely to occur if the BOP is all-electrically operated.

Summed up, this thesis shall address the following:

1. BOP reliability literature study, including relevant previous blowout accidents, standards for BOP operations, and basic BOP principles applied in drilling.
2. Description of the technical mode of operation of the BOP, covering both the electro-hydraulic system and the all-electric concept.
3. Assessment of potential BOP failure modes, and how these relate to the technical mode of operation.
4. Qualitative analysis of potential faults.
5. Comparison of the electro-hydraulic BOP system and the all-electric operated system.
6. Conclusions and recommendations for further work.

All necessary input data is assumed to be provided by Odfjell Drilling Technology AS and Electrical Subsea & Drilling AS.

The work scope may prove to be larger than initially anticipated. Subject to approval from the supervisors, topics may be deleted from the list above or reduced in extent.

The thesis must be written like a research report, with an abstract, conclusions, contents list, reference list, etc.
During preparation of the thesis it is important that the candidate emphasizes easily understood and well-written text. For ease of reading, the thesis should contain adequate references at appropriate places to related text, tables and figures. On evaluation, a lot of weight is put on thorough preparation of results, their clear presentation in the form of tables and/or graphs, and on comprehensive discussion.

The thesis is to be handed in electronically. Also a .pdf-version of the final thesis is to be submitted to the supervisor by email.

Starting date: 15th January 2014
Completion date: 10th June 2014

B. FMECA SHEETS

B.1 ELECTRO-HYDRAULIC BOP SYSTEM

COMP NUM	COMPONENT Function	OPERATIONAL MODE	POTENTIAL FAILURE MODE		POTENTIAL CAUSES	POTENTIAL FAILURE EFFECTS LOCAL VS. GLOBAL		DETECTION METHOD	CURRENT CONTROL/ SAFEGUARDS	C	P	RISK (PxC)	COMMENT
Sub-function 1: Control BOP functions													
1.1	Power supply unit (topside) **Function:** deliver power to el.panels and CCU	Shall be available at all times	**F-1.1.1**	Erratic output	Failed electrical cable Obsolete unit	No significant effect	No global effect due to safeguard	Monitoring	Redundancy: back-up battery	Limited	20 - 40 %	Acceptable risk	OREDA: Failure rate: 15.63 per 10^6 hours
			F-1.1.2	Transmission failure	Mechanical/ electrical failure Obstruction	No electrical output	No global effect due to safeguard	Monitoring	Redundancy: back-up battery	Limited	20 - 40 %	Acceptable risk	OREDA: Failure rate: 3.32 per 10^6 hours
1.2	Electrical panel (topside) **Function:** send activation signals to CCU	Used for all operational modes, shall be available at all times	**F-1.2.1**	Erratic output	Electric failure Failed MUX cable Human error	No initiation of valves or BOP function	No global effect due to safeguard	Flow meters and pressure gauges	Redundancy: two separate panels Maintenance/ operational procedures	Low	20 - 40 %	Acceptable risk	Engineering judgement
1.3	Electric power battery **Function:** deliver power to el.panels and CCU (back-up)	Shall be available at all times	**F-1.3.1**	Insufficient power	Failed electrical cable Obsolete battery	No significant effect	No global effect due to safeguard	Indicator alarms	Redundancy: generator is main power source Maintenance/ operational procedures	Low	20 - 40 %	Acceptable risk	Engineering judgement
1.4	MUX cable reel **Function:** transfer electrical communication signals from CCU to subsea pod	Used for all operational modes, shall be available at all times	**F-1.4.1**	Transmission failure	Worn cable Short circuit No signal sent from electrical panel Mechanical failure	Unable to initiate BOP functions	Worst case: no commands can be initiated from the control panel	Visual Feedback from hydraulic system Flow meter, pressure gauge	Redundancy: the other MUX cable can be used Maintenance/ operational routines	Low	20 - 40 %	Acceptable risk	Engineering judgement

1.5	Batteries inside subsea pods **Function:** enable pod to convert el. signals to hydraulics	Shall be available at all times	**F-1.5.1**	Insufficient power	Obsolete battery Corrosion Thermal variations	Solenoid valve not functioning	In case of emergency: the blind shear ram will not be activated Reduced effect due to redundancy	No hydraulic/ electrical communication with pod	Redundancy: batteries in other pod and acoustic back-up Maintenance/ operational routines	Low	20 - 40 %	Acceptable risk	Engineering judgement
1.6	CCU **Function:** send/ receive communication signals. Monitoring	Shall be available at all times	**F-1.6.1**	Control/ signal failure	Mechanical/ electrical failure Thermal variations	Routing failure of electrical signals	Worst case: no BOP function due to lack of electrical signals causing high probability of blowout	Monitoring	Redundancy: ROV operation and acoustic back-up	Limited	0 - 20 %	Acceptable risk	OREDA: Failure rate: 3.52 per 10^6 hours
			F-1.6.2	Erratic output	Mechanical/ electrical failure Human error	Routing failure of electrical signals	Worst case: no BOP function due to lack of electrical signals causing high probability of blowout	Monitoring	Redundancy: ROV operation and acoustic back-up	Limited	0 - 20 %	Acceptable risk	OREDA: Failure rate: 1.08 per 10^6 hours
			F-1.6.3	Fail to function on demand	Mechanical/ electrical failure Worn cables	No signal output	Worst case: no BOP function due to lack of electrical signals causing high probability of blowout	Monitoring	Redundancy: ROV operation and acoustic back-up	Limited	0 - 20 %	Acceptable risk	OREDA: Failure rate: 1.59 per 10^6 hours
			F-1.6.4	Spurious operation	Mechanical/ electrical failure Worn cables	Routing failure of electrical signals	Worst case: no BOP function due to lack of electrical signals causing high probability of blowout	Monitoring	Redundancy: ROV operation and acoustic back-up	Limited	20 - 40 %	Acceptable risk	OREDA: Failure rate: 4.20 per 10^6 hours

1.7	Pod selector valve **Function:** direct electrical signals to pod	Shall be available at all times	**F-1.7.1**	Fail to move (stuck in position)	Mechanical failure Obstruction Corrosion	Routing failure of the hydraulic fluid	In case of failure in one of the pods, the hydraulic fluid cannot be routed into another pod. Worst case: no BOP function causing high probability of blowout	Monitoring of valve position.	Regularly testing. Maintenance/ operational routines	Limited	20 - 40 %	Acceptable risk	Engineering judgement. Not very critical all though there is no redundancy
1.8	Solenoid valve **Function:** convert electrical signals to hydraulics	Used for all operational modes, shall be available at all times	**F-1.8.1**	Fail to move	Mechanical/ electrical failure Contamination Obstruction	Affected solenoid cannot be operated from panels	No consequence due to safeguards Still possible to operate BOP functions manually	Valve monitoring Flow meter and pressure transmitter monitoring	Maintenance/ operational routines Regularly function testing of BOP	Low	40 - 60 %	Acceptable risk	Engineering judgement
1.9	SPM valve **Function:** convert electrical signals to hydraulics	Shall be available at all times	**F-1.9.1**	Fail to open/close. Fail between positions.	Hydraulic leakage, worn/ degrade parts, corrosion, stuck, mechanical failure.	Affected SPM will not close/open - delays in hydraulic fluid system	No consequence due to safeguards	Monitoring of valve Flow meter and pressure transmitter monitoring	Redundancy: use the other SPM valve Maintenance/ operational routines Regularly function testing of BOP	Low	40 - 60 %	Acceptable risk	Engineering judgement

1.10	Shuttle valve **Function:** transfer hydraulics to BOP function	Shall be available at all times	**F-1.10.1**	Fail to move (stuck in position)	Mechanical failure Corrosion (shuttle valve is exposed)	Shuttle valve cannot move	Loss of redundancy with regards to shear ram functions Worst case: delayed or no shearing	Monitoring of valve position.	Maintenance/ operational routines Regularly function testing of BOP	Major	0 - 20 %	Tolerable risk	Engineering judgement. Ref. ram closing principle.
1.11	Choke and kill valve **Function:** test BOP functions (Well killing operations are left out from the analysis)	Shall be available at all times	**F-1.11.1**	Fail to open/close. Fail between positions.	Plugged line. Mechanical failure. Corrosion	Not able to perform testing as intended. Wrongly performed tests.	No consequence due to redundancy	Monitoring. Test procedures	Redundancy: Other choke and kill valve	Limited	20 - 40 %	Acceptable risk	Engineering judgement
			F-1.11.2	External leakage	Worn/ degraded parts (ring gasket and flange) Human error (improper valve connection installation)	Not able to perform testing as intended. Wrongly performed tests.	No consequence due to redundancy	Monitoring. Test procedures	Redundancy: Other choke and kill valve	Limited	20 - 40 %	Acceptable risk	Engineering judgement
			F-1.11.3	Internal leakage	Worn/ degraded parts (ring gasket and flange) Human error (improper valve connection installation)	Not able to perform testing as intended. Wrongly performed tests.	No consequence due to redundancy	Monitoring. Test procedures	Redundancy: Other choke and kill valve	Limited	20 - 40 %	Acceptable risk	Engineering judgement

Sub-function 2: Supply power													
2.1	Subsea accumulators **Function:** store hydraulic fluid	Used for all operational modes, shall be available at all times	**F-2.1.1**	Burst bladder	Wear due to ageing Human errors Damage from valve in the bottom of bladder	Gas in system Reduced accuracy of flow meter Affected bladder will not function Lack of pressure	Some reduced capacity Particles from burst bladder in hydraulic system BOP functions will still be upheld due to overcapacity	Maintenance and inspection procedures	Redundancy: min. 25% overcapacity of bottles Routines for control of charge pressure + training of personnel Regularly function testing of BOP	Limited	40 - 60 %	Tolerable risk	Ref. Workshop
			F-2.1.2	Internal leakage	Poor quality of accumulator valve Mechanical damage	Affected accumulator has reduced capacity/ lack of pressure/ does not function	No consequence due to safeguards BOP functions will still be upheld due to overcapacity	Topside: visual if a big leakage Subsea: pressure testing and inspection procedures	Redundancy: min. 25% overcapacity of bottles Routines for leak check Regularly function testing of BOP	Low	20 - 40 %	Acceptable risk	OREDA Failure rate: 0.15 per 10^6 h
2.2	Fluid reservoir **Function:** Deliver hydraulics	Used for all operational modes, shall be available at all times	**F-2.2.1**	Contamination of hydraulic fluid	Failure in reservoir cover allowing dirt and other contaminants to reservoir fluid	Hydraulic fluid quality is inadequate. Damage on valves	Clogging of hydraulic pumps. Fine particles may pass through and increase wear on pumps	Sampling of hydraulic fluid done according to operation/ maintenance procedures	Strainers on suction side of pumps will remove large particles. The strainers are monitored	Considerable	40 - 60 %	Tolerable risk	Ref. Workshop. Engineering judgement

			F-2.2.2	Rupture of reservoir	Too small or clogged vent on hydraulic reservoir	Leakage of hydraulic fluid	No consequence due to safeguards	Level transmitter Visual	Vent is designed with overcapacity Redundancy: accumulators store enough fluid to ensure BOP operation	Low	40 - 60 %	Acceptable risk	Engineering judgement
			F-2.2.3	Too low volumetric capacity	Reservoir volume too small/ too low level in reservoir Level transmitter fails to read correctly	Tank will be emptied, or reservoir may overflow if there are more fluid in the system and accumulators than the capacity of the reservoir	Potential for spills of hydraulic fluid to the environment	Level transmitter Visual	Environmental friendly fluid. Low level alarm. Maintenance/ operational routines	Limited	20 - 40 %	Acceptable risk	Engineering judgement
2.3	HPU **Function:** Deliver hydraulics	Used for all operational modes, shall be available at all times	**F-2.3.1**	Hydraulic pump not running as intended	Electrical/mechanical errors Poor quality linings in electrical motor	Affected pump does not run	No global effect. System will still operate due to redundancy	Pumps are monitored with alarms if not running	Redundancy: 100% with regards to pump capacity Accumulator banks Maintenance/ operational procedures	Low	40 - 60 %	Acceptable risk	Engineering judgement

			F-2.3.2	Fail to make the required fluid	Inadequate mixture Human error Leakage	Might need more powerful pump to transfer into accumulator Might damage accumulator	Improper opening/closing of SPM valve Improper opening/closing of preventers	Pump stroke reading	Quality control of hydraulic fluid from mixing system	Low	20 - 40 %	Acceptable risk	Engineering judgement
2.4	Hydraulic line from HPU to BOP **Function:** deliver hydraulics	Used for all operational modes, shall be available at all times	**F-2.4.1**	Combined/ common cause	Mechanical failure Corrosion Fatigue	Spillage to environment Potential for personnel injury	No consequence due to redundancy	Visual Low level/pressure alarms Excessive running of pumps	Environmental friendly fluid. Low level alarm. Maintenance/ operational routines	Limited	0 - 20 %	Acceptable risk	OREDA Failure rate: 0.08 per 10^6 h
			F-2.4.2	External leakage	External forces Vibration Failure in fittings, gaskets, etc.	Spillage to environment Potential for personnel injury	Worst case: drain all hydraulic fluid in the bottle racks Potential loss of individual BOP functions or loss of the complete surface volume of hydraulic fluid through burst hose	Visual Low level/pressure alarms Excessive running of pumps	Environmental friendly fluid. Low level alarm. Maintenance/ operational routines	Considerable	0 - 20 %	Acceptable risk	OREDA Failure rate: 0.07 per 10^6 h

			F-2.4.3	Internal leakage	External forces Vibration Failure in fittings, gaskets, etc.	Reduced fluid delivery	No consequence due to redundancy	Visual Low level/pressure alarms Excessive running of pumps	Environmental friendly fluid. Low level alarm. Maintenance/ operational routines	Low	0 - 20 %	Acceptable risk	OREDA Failure rate: 0.03 per 10^6 h
			F-2.4.4	Plugged/ choked line	Mechanical failure. Contamination of hydraulic fluid	Spillage to environment Potential for personnel injury	Potential loss of individual BOP functions	Visual Low level/pressure alarms Excessive running of pumps	Environmental friendly fluid. Low level alarm. Maintenance/ operational routines	Limited	20 - 40 %	Acceptable risk	OREDA Failure rate: 0.14 per 10^6 h
2.5	Regulator valve **Function:** regulate hydraulics	Used for all operational modes, shall be available at all times	**F-2.5.1**	Fail to move (stuck in position)	Mechanical/electrical failure Corrosion Solenoid valve failure	Cannot operate the regulator from the panels	No consequence due to safeguards	Visual Pressure transmitters	Can be operated manually or can be bypassed. Maintenance/ operational routines	Low	40 - 60 %	Acceptable risk	Engineering judgement

2.6	Pod/ stack mounted accumulator isolation valve **Function:** regulate hydraulics	Used for all operational modes, shall be available at all times	**F-2.6.1**	Fail to open/close	Corrosion, mechanical failure	Fail to open: unable to flow the hydraulic from the valve Unable to close: the flow can still be stopped by second accum. Isolation valve	No consequence due to redundancy	Monitoring of valve Flow meter and pressure transmitter monitoring	Redundancy: use the other isolation valve Maintenance/ operational routines	Low	40 - 60 %	Acceptable risk	Engineering judgement
2.7	Hydraulic lines on BOP stack **Function:** transfer hydraulic fluid	Used for all operational modes, shall be available at all times	**F-2.7.1**	Internal leakage	Corrosion, mechanical failure	Unable to operate BOP function.	Environmental leakage	Monitoring of valve Flow meter and pressure transmitter monitoring		Considerable	60 - 80 %	Tolerable risk	Ref. Workshop

Sub-function 3: Activate BOP functions													
3.1	Ram preventer (fixed/variable bore ram/ blind shear ram) **Function:** seal/ shear pipe	Shall be available at all times	**F-3.1.1**	Premature closure	Mechanical failure of ram sealing element/ ram pistons Hydraulic failure Human error	Affected ram not able to operate	No global effects due to redundancy and safeguards	Flow meter, pressure gauges Feedback from hydraulic system	Redundancy: other pipe rams Maintenance/ operational routines Regularly function testing of BOP	Limited	0 - 20 %	Acceptable risk	Data from Holand.
			F-3.1.2	Fail to close	Mechanical failure of ram sealing element/ ram pistons Hydraulic failure Corrosion/ deformation	Affected ram not able to operate	No global effects due to redundancy and safeguards	Flow meter, pressure gauges Feedback from hydraulic system	Redundancy: other pipe rams. Possible to close annular Maintenance/ operational routines Regularly function testing of BOP	Limited	0 - 20 %	Acceptable risk	Data from Holand.
			F-3.1.3	Fail to shear pipe	Hydraulic failure, mechanical failure of shearing blades, human error, too high wellbore pressure Pipe not in centre position Potential for tubular dimensions outside the shear ram specifications	No shearing	Potential for need to drop string or tubular before closing shear ram Worst case: influx might enter the riser up to the surface and endanger personnel	Visual Known ram specifications	Maintenance/ operational routines Pressure testing	Considerable	40 - 60 %	Tolerable risk	Data from Holand. Ref. Macondo.

			F-3.1.4	Fail to open	Mechanical failure Hydraulic failure Human error	Affected ram not able to operate	No global effects due to redundancy and safeguards	Flow meter, pressure gauges Feedback from hydraulic system	Maintenance/ operational routines Regularly function testing of BOP	Limited	20 - 40 %	Acceptable risk	Data from Holand.
			F-3.1.5	Fail to keep closed	Wrong ram with regards to tubular diameter/ geometry Failure of subsea wedge lock: worn parts, wrong closing pressure	Unable to lock/unlock rams in closed position	Unwanted amounts of fluids or gas influx into the wellbore, and also possibility for influx to surface for the amount of time it takes from trying to close the first ram until the next one is closed	Unstable pressures	Redundancy: other pipe rams Maintenance/ operational routines Regularly function testing of BOP	Low	0 - 20 %	Acceptable risk	Data from Holand. Ref workshop
			F-3.1.6	External leakage	Loosen bolts Loosen ram housing flange Worn parts	Fluid leakage to environment	In worst case: influx can deteriorate the seal and bolt causing massive environment spill	Visual Reduction in hydraulic pressure	Redundancy: other pipe rams Maintenance/ operational routines Regularly function testing of BOP	Low	0 - 20 %	Acceptable risk	Data from Holand.

			F-3.1.7	Internal leakage	Worn parts	Some influx into wellbore	In worst case: influx can deteriorate seal and packers causing failure in ram function. It allows influx to reach surface and endanger personnel	Visual Flow meter, pressure gauges Reduction in kill mud pressure	Redundancy: other pipe rams Maintenance/ operational routines Regularly function testing of BOP	Low	20 - 40 %	Acceptable risk	Data from Holand.
3.2	Annular BOP **Function:** seal around open hole/ pipe	Shall be available at all times	**F-3.2.1**	Not able to close (around tubular)	Failure of annular sealing element/ ring piston Wrong closing pressure	Unable to seal off well during well control situations	Possibility for influx to surface for the amount of time it takes from trying to close the annular until the other rams with suitable size is closed	Unstable shut-in pressures	Redundancy: Shear ram and other rams available Maintenance/ operational routines Regularly function testing of BOP	Considerable	0 - 20 %	Acceptable risk	Data from Holand
			F-3.2.2	Not able to fully open	Mechanical failure Hydraulic failure Human error Worn elements	Annular not able to operate	No global effects due to redundancy and safeguards	Flow meter, pressure gauges Feedback from hydraulic system	Redundancy: other annular Maintenance/ operational routines Regularly function testing of BOP	Limited	20 - 40 %	Acceptable risk	Data from Holand

Sub-function 4: Maintain structure													
4.1	Riser/ wellbore connector **Function:** keep riser/ wellbore connected	Shall be available at all times	**F-4.1.1**	External leakage	Leakage in wellhead gasket Damage seal ring Over pressure	Leakage of drilling fluid into environment	Delays in well control operations	Visual	Regularly BOP function testing Maintenance/ operational routines	Considerable	0 - 20 %	Acceptable risk	OREDA Failure rate: 0.10 per 10^6 h
			F-4.1.2	Unable to connect /disconnect	Failure in wellhead connector Failure in LMRP connector Connector stuck Hydraulic failure	Damage to wellhead connector during drift off	Possibility if major leakage to environment if not handled properly	No hydraulic communication	Redundancy: two connectors, Regularly BOP function testing Maintenance/ operational routines	Considerable	0 - 20 %	Acceptable risk	OREDA Failure rate: 0.07 per 10^6 h
4.2	Ram preventer housing **Function:** keep components together	Shall be available at all times	**F-4.2.1**	External leakage	Excess pressure, thermal variation, corrosion, fatigue	Hydraulic fluid not contained, leakage of hydraulic oil	Failure on rams function	Visual. Monitoring		Considerable	0 - 20 %	Acceptable risk	Data from Holand
4.3	Annular preventer housing **Function:** keep components together	Shall be available at all times	**F-4.3.1**	External leakage	Excess force, corrosion, thermal fatigue	Hydrocarbon influx not contained, leak	Failure on annular prevention function	Visual. Monitoring		Considerable	0 - 20 %	Acceptable risk	Data from Holand
4.4	Flange and gasket **Function:** keep housing watertight	Used for all operational modes, shall be available at all times	**F-4.4.1**	External leakage	Poor quality of gaskets. Wrong torque applied when fastening bolts. Insufficient or wrong support, vibration Human error Misalignment	Spillage	Worst case: drain all hydraulic fluid in the bottle racks	Visual. Monitoring		Limited	40 - 60 %	Tolerable risk	Engineering judgement. Ref workshop

B.2 All-electric BOP Concept

COMP NUM	COMPONENT Function	OPERATIONAL MODE	POTENTIAL FAILURE MODE		POTENTIAL CAUSES	POTENTIAL FAILURE EFFECTS LOCAL VS. GLOBAL		DETECTION METHOD	CURRENT CONTROL/ SAFEGUARDS	C	P	RISK (PxC)	COMMENT
Sub-function 1: Control BOP functions													
1.1	Power supply unit (topside) UPS. **Function:** deliver power to el.panels and control unit	Shall be available at all times	**F-1.1.1**	Erratic output	Failed electrical cable Obsolete unit	No significant power supply	No global effect due to safeguards	Monitoring	Redundancy: back-up battery. Double both UPS and batteries	Limited	20 - 40 %	Acceptable risk	OREDA: Failure rate: 15.63 per 10^6 hours. Same as for MUX sys
			F-1.1.2	Transmission failure	Mechanical/ electrical failure Obstruction	No electrical output	No global effect due to safeguards	Monitoring	Redundancy: back-up battery	Limited	20 - 40 %	Acceptable risk	OREDA: Failure rate: 3.32 per 10^6 hours. Same as for MUX sys
1.2	Electrical panel (topside). **Function:** send signals. Monitoring	Shall be available at all times	**F-1.2.1**	Erratic output	Electrical failure Human error Loss of power supply	No initiation of valves or BOP function	No global effect due to safeguards	Monitoring	Redundancy: extra panels	Low	40 - 60 %	Acceptable risk	Engineering judgement. Same as for MUX sys. (can also be a laptop)
1.3	Electric power battery back-up (topside). Double back-up **Function:** deliver power to el.panels	Shall be available at all times	**F-1.3.1**	Insufficient power	Failed electrical cable Obsolete battery	No significant effect	No global effect due to safeguards	Monitoring	Redundancy: power supply unit is main power source. Extra battery capacity - double back-up.	Low	20 - 40 %	Acceptable risk	Engineering judgement, estimated to have the same reliability as subsea batteries from Gylling.

1.4	Electrical communication cable reel **Function:** send/ receive electrical signals	Shall be available at all times	**F-1.4.1**	Transmission failure	Worn cable Short circuit Mechanical/ electrical failure	Unable to initiate BOP functions	Worst case: no commands can be initiated from the control panel	Monitoring	Redundancy: other cable can be used	Low	0 - 20 %	Acceptable risk	OREDA: Failure rate: 0.36 per 10^6 hours. Same as MUX sys. A production control system can have one common cable for power and communication
1.5	Subsea back-up batteries inside SEM **Function:** operate SEM	Shall be available at all times	**F-1.5.1**	Insufficient power	Obsolete battery Corrosion Thermal variations	Not able to operate given SEM	No effect due to redundancy	Monitoring	Redundancy	Limited	20 - 40 %	Acceptable risk	Engineering judgement, ref workshop.
1.6	Electrical master control/ communication unit. (CCU) **Function:** send/ receive signals. Monitoring	Shall be available at all times	**F-1.6.1**	Control/ signal failure	Mechanical/ electrical failure Thermal variations	Routing failure of electrical signals	Worst case: no BOP function due to lack of electrical signals causing high probability of blowout	Monitoring	Redundancy: ROV operation and acoustic back-up	Limited	0 - 20 %	Acceptable risk	OREDA: Failure rate: 3.52 per 10^6 hours
			F-1.6.2	Erratic output	Mechanical/ electrical failure Human error	Routing failure of electrical signals	Worst case: no BOP function due to lack of electrical signals causing high probability of blowout	Monitoring	Redundancy: ROV operation and acoustic back-up	Limited	0 - 20 %	Acceptable risk	OREDA: Failure rate: 1.08 per 10^6 hours

			F-1.6.3	Fail to function on demand	Mechanical/ electrical failure Worn cables	No signal output	Worst case: no BOP function due to lack of electrical signals causing high probability of blowout	Monitoring	Redundancy: ROV operation and acoustic back-up	Considerable	0 - 20 %	Acceptable risk	OREDA: Failure rate: 1.59 per 10^6 hours
			F-1.6.4	Spurious operation	Mechanical/ electrical failure Worn cables	Routing failure of electrical signals	Worst case: no BOP function due to lack of electrical signals causing high probability of blowout	Monitoring	Redundancy: ROV operation and acoustic back-up	Limited	20 - 40 %	Acceptable risk	OREDA: Failure rate: 4.20 per 10^6 hours
1.7	Electric motor **Function:** transfer power to BOP function	Shall be available at all times	**F-1.7.1**	Insufficient power	Mechanical/ electrical failure Corrosion	BOP function cannot be operated from control panel	Worst case: delayed or no BOP activation from topside	Monitoring	Redundancy	Limited	20 - 40 %	Acceptable risk	Engineering judgement. Motor instead of shuttle valve
			F-1.7.2	External leakage	Mechanical error Human error	Motor parts may be broken/ unable to operate	Worst case: delayed or no BOP activation from topside	Monitoring (insulating resistance)	Double seals Pressure-compensated (oil) inside the motor	Limited	0 - 20 %	Acceptable risk	Ref external leakage on preventers, Holand and workshop
			F-1.7.3	Erratic output	Mechanical/ electrical failure Corrosion	BOP function cannot be operated from control panel	Worst case: delayed or no BOP activation from topside	Monitoring	Redundancy	Limited	20 - 40 %	Acceptable risk	Engineering judgement. Motor instead of shuttle valve

			F-1.7.4	Breakdown	Mechanical/ electrical failure Corrosion	BOP function cannot be operated from control panel	Worst case: delayed or no BOP activation from topside	Monitoring	Redundancy	Limited	20 - 40 %	Acceptable risk	Engineering judgement. Motor instead of shuttle valve
1.8	Choke and kill valve. All-electric valves.	Shall be available at all times	**F-1.8.1**	Fail to open/close. Fail between positions.	Plugged line. Mechanical failure. Corrosion	Not able to perform testing as intended. Wrongly performed tests.	No consequence due to redundancy	Monitoring	Redundancy: Other choke and kill valve	Limited	20 - 40 %	Acceptable risk	Ref. 5.4 Existing electrical subsea systems
			F-1.8.2	External leakage	Worn/ degraded parts (ring gasket and flange) Human error (improper valve connection installation)	Not able to perform testing as intended. Wrongly performed tests.	No consequence due to redundancy	Monitoring	Redundancy: Other choke and kill valve	Limited	20 - 40 %	Acceptable risk	
			F-1.8.3	Transmission failure	Worn/ degraded parts (ring gasket and flange) Human error (improper valve connection installation)	Not able to perform testing as intended. Wrongly performed tests.	No consequence due to redundancy	Monitoring	Redundancy: Other choke and kill valve	Limited	20 - 40 %	Acceptable risk	
1.9	Subsea electric module (SEM)	Shall be available at all times	**F-1.9.1**	Erratic/ spurious output	Electrical/ mechanical failure Worn/ degraded parts (ring gasket and flange)	Not able to route electrical signals/ power as intended	No consequence due to redundancy	Monitoring	Redundancy: other SEM	Limited	20 - 40 %	Acceptable risk	OREDA Failure rate: 4.42 per 10^6 h. Critical failures, subsea electronic module p. 60 (S)

Sub-function 2: Supply power													
2.1	Surface/subsea batteries. **Function:** store electrical power	Shall be available at all times	**F-2.1.1**	Obsolete battery	Wear due to ageing Mechanical fault	Delayed/ no BOP function Affected battery will not function	BOP functions will still be upheld due to redundancy	Monitoring	Redundancy (as for bottles: min. 25% overcapacity)	Considerable	0 - 20 %	Acceptable risk	Ref. A123 solutions - Gylling Teknikk AS
			F-2.1.2	Short circuit	Sea water ingress Electrical damage	Affected battery has reduced capacity/ does not function	No consequence due to safeguards BOP functions will still be upheld due to overcapacity	Monitoring	Redundancy: min. 25% overcapacity of bottles Routines for leak check Regularly function testing of BOP	Considerable	0 - 20 %	**Acceptable risk**	Ref. A123 solutions - Gylling Teknikk AS
2.2	Electrical lines on BOP stack **Function:** transfer electrical power	Shall be available at all times	**F-2.2.1**	Transmission failure	Corrosion, mechanical/ electrical failure	Unable to operate BOP functions	Short circuit of whole system.	Monitoring	Redundancy - two independent systems from each SEM	Limited	20 - 40 %	Acceptable risk	OREDA: Failure rate: 0,27 per 10^6 - ref. workshop.
2.3	Electric supply/ battery charger. (Power supply unit) **Function:** Deliver hydraulics	Shall be available at all times	**F-2.3.1**	Transmission failure	Electrical/mechanical fault Human error	Unable to initiate valves and other function of BOP from topside	No global effect. System will still operate due to redundancy	Monitoring	Redundancy: battery back-up topside + subsea	Low	40 - 60 %	Acceptable risk	Engineering judgement, ref. Workshop.

			F-2.3.2	Insufficient power	Inadequate operation	Unable to initiate valves and other function of BOP from topside	Improper opening/closing of preventers	Monitoring	Redundancy: battery back-up topside + subsea	Low	20 - 40 %	Acceptable risk	Engineering judgement
2.4	Electrical power line from topside to subsea equipment. **Function:** deliver electric power	Shall be available at all times	F-2.4.1	Transmission failure	Mechanical/ electrical failure Corrosion Fatigue/ external forces/ vibration	Unable to initiate valves and other function of BOP from topside	Delayed or no activation of BOP. Problems to disconnect. Reduced effect due to safeguards	Monitoring	Redundancy: ROV operation and acoustic back-up	Limited	40 - 60 %	Tolerable risk	Engineering judgement, same as MUX/ communication cable
			F-2.4.2	Insufficient power	Mechanical failure. Contamination of hydraulic fluid	Unable to initiate valves and other function of BOP from topside	Delayed or no activation of BOP. Problems to disconnect. Reduced effect due to safeguards	Monitoring	Redundancy: ROV operation and acoustic back-up	Limited	20 - 40 %	Acceptable risk	Engineering judgement, same as MUX/ communication cable
2.5	Electrical regulator valve (solenoid control valve). **Function:** regulate electrical power	Shall be available at all times	F-2.5.1	Fail to function on demand	Mechanical/electrical failure Corrosion	Cannot operate the regulator valve from the panels	No consequence due to safeguards	Monitoring	Can be operated manually or can be bypassed. Maintenance/ operational routines	Limited	20 - 40 %	Acceptable risk	OREDA Failure rate: 0.17 per 10^6 h

Sub-function 3: Activate BOP functions. Main differences: secondary override and more detailed monitoring.													
3.1	Ram preventer (fixed/variable bore ram/ blind shear ram) **Function:** seal/ shear pipe	Shall be available at all times	**F-3.1.1**	Premature closure	Mechanical failure Electrical failure Human error	Affected ram not able to operate	No global effects due to redundancy and safeguards	Monitoring	Redundancy: other rams	Limited	0 - 20 %	Acceptable risk	Data from Holand.
			F-3.1.2	Fail to close	Mechanical failure of ram sealing device Electrical failure	Affected ram not able to operate	No global effects due to redundancy and safeguards	Monitoring	Redundancy: other rams	Limited	0 - 20 %	Acceptable risk	Data from Holand.
			F-3.1.3	Fail to shear pipe	Hydraulic failure, mechanical failure of shearing blades, human error, too high wellbore pressure Pipe not in centre position Potential for tubular dimensions outside the shear ram specifications	No shearing	Potential for need to drop string or tubular before closing shear ram Worst case: influx might enter the riser up to the surface and endanger personnel	Visual Known ram specifications	Maintenance/ operational routines Pressure testing	Considerable	40 - 60 %	Tolerable risk	Data from Holand. Ref. Macondo.
			F-3.1.4	Fail to open	Mechanical failure Electrical failure Human error	Affected ram not able to operate, delays in project	No global effects	Monitoring		Limited	20 - 40 %	Acceptable risk	Data from Holand.

			F-3.1.5	Fail to keep closed	Wrong ram with regards to tubular diameter/ geometry Failure of subsea wedge locks: worn parts, wrong closing pressure	Unable to lock/unlock rams in closed position	Unwanted amounts of fluids or gas influx into the wellbore, and also possibility for influx to surface for the amount of time it takes from trying to close the first ram until the next one is closed	Unstable pressures	Redundancy: other pipe rams Maintenance/ operational routines Regularly function testing of BOP	Low	0 - 20 %	Acceptable risk	Data from Holand. Ref workshop
			F-3.1.6	External leakage	Loosen bolts Loosen ram housing flange Worn parts	Fluid leakage to environment	In worst case: influx can deteriorate the seal and bolt causing massive environment spill	Monitoring	Redundancy: other pipe ram	Low	0 - 20 %	Acceptable risk	Data from Holand.
			F-3.1.7	Internal leakage - spindle motor	Worn parts	Some influx into wellbore	In worst case: influx can deteriorate seal and packers causing failure in ram function. It allows influx to reach surface and endanger personnel	Monitoring	Redundancy: other rams	Low	20 - 40 %	Acceptable risk	Data from Holand.

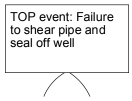
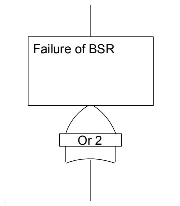
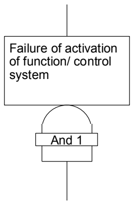
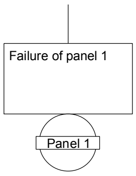
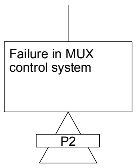
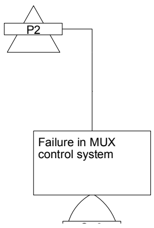
3.2	Annular BOP **Function:** seal around open hole/ pipe	Shall be available at all times	**F-3.2.1**	Not able to close (around tubular)	Failure in ring nut (engage the rollers), rollers (drive ring formed act.element), actuator element (activate locking seg.) or locking segment. Wrong closing pressure	Unable to seal off well during well control situations	Possibility for influx to surface for the amount of time it takes from trying to close the annular until the other rams with suitable size is closed	Monitoring	Redundancy: Shear ram and rams available	Considerable	0 - 20 %	Acceptable risk	Data from Holand
			F-3.2.2	Not able to fully open	Mechanical failure Electrical failure Human error Worn elements	Annular not able to operate	No global effects due to redundancy and safeguards	Monitoring	Redundancy: other annular	Limited	20 - 40 %	Acceptable risk	Data from Holand
			F-3.2.3	Fail to keep closed	Failure of annular locking wedge. Thermal variation in combination with excess force Galling, seizure, misalignment, impact failure	Unable to lock/unlock annular in closed position	No consequence due to safeguards	Unstable pressures	Redundancy: other annular Maintenance/ operational routines Regularly function testing of BOP	Low	20 - 40 %	Acceptable risk	Ref. Workshop
			F-3.2.4	External leakage	Loosen bolts Loosen ram housing flange Worn parts	Fluid leakage to environment	In worst case: influx can deteriorate the seal and bolt causing massive environment spill	Monitoring	Redundancy: other annular	Low	0 - 20 %	Acceptable risk	Data from Holand

			F-3.2.5	Internal leakage	Worn parts	Some influx into wellbore due to leakage through a closed annular	In worst case: influx can deteriorate seal and packers causing failure in ram function. It allows influx to reach surface and endanger personnel	Monitoring	Redundancy: other annular	Low	20 - 40 %	Acceptable risk	Data from Holand
3.3	Actuator element **Function:** activate BOP function	Shall be available at all times	**F-3.3.1**	Fail to move	Corrosion, galling, seizure, misalignment, pitting Thermal variation Electric motor break down	Shear ram not operational	Worst case: influx might escalate and escape into surface	Monitoring	Inside an enclosed environment with oil around. Protected. The mechanics are operating in a protected environment.	Considerable	20 - 40 %	Tolerable risk	Ref workshop.

Sub-function 4: Maintain structure													
4.1	Riser/ wellbore connector **Function:** keep riser/ wellbore connected	Shall be available at all times	**F-4.1.1**	External leakage	Leakage in wellhead gasket Damage seal ring Over pressure	Leakage of drilling fluid into environment	Delays in well control operations	Visual	Regularly BOP function testing Maintenance/ operational routines	Considerable	0 - 20 %	Acceptable risk	OREDA Failure rate: 0.10 per 10^6 h
			F-4.1.2	Unable to connect /disconnect	Failure in wellhead connector Failure in LMRP connector Connector stuck Hydraulic system failure	Damage to wellhead connector during drift off	Possibility if major leakage to environment if not handled properly	No hydraulic communication	Redundancy: two connectors, Regularly BOP testing Maintenance/ operational routines	Considerable	0 - 20 %	Acceptable risk	OREDA Failure rate: 0.07 per 10^6 h
4.2	Ram preventer housing **Function:** keep components together	Shall be available at all times	**F-4.2.1**	External leakage	Excess pressure, thermal variation, corrosion, fatigue	Hydraulic fluid not contained, leakage of hydraulic oil	Failure on rams function	Visual		Considerable	0 - 20 %	Acceptable risk	Data from Holand
4.3	Annular preventer housing **Function:** keep components together	Shall be available at all times	**F-4.3.1**	External leakage	Excess force, corrosion, thermal fatigue	Hydrocarbon influx not contained, leak	Failure on annular prevention function	Visual		Considerable	0 - 20 %	Acceptable risk	Data from Holand
4.4	Flange and gasket **Function:** keep housing watertight	Used for all operational modes, shall be available at all times	**F-4.4.1**	External leakage	Poor quality of gaskets. Wrong torque applied when fastening bolts. Insufficient or wrong support, vibration Human error Misalignment	Spillage	Worst case: drain all hydraulic fluid in the bottle racks	Visual		Limited	40 - 60 %	Tolerable risk	Engineering judgement. Ref workshop

C. Fault Trees

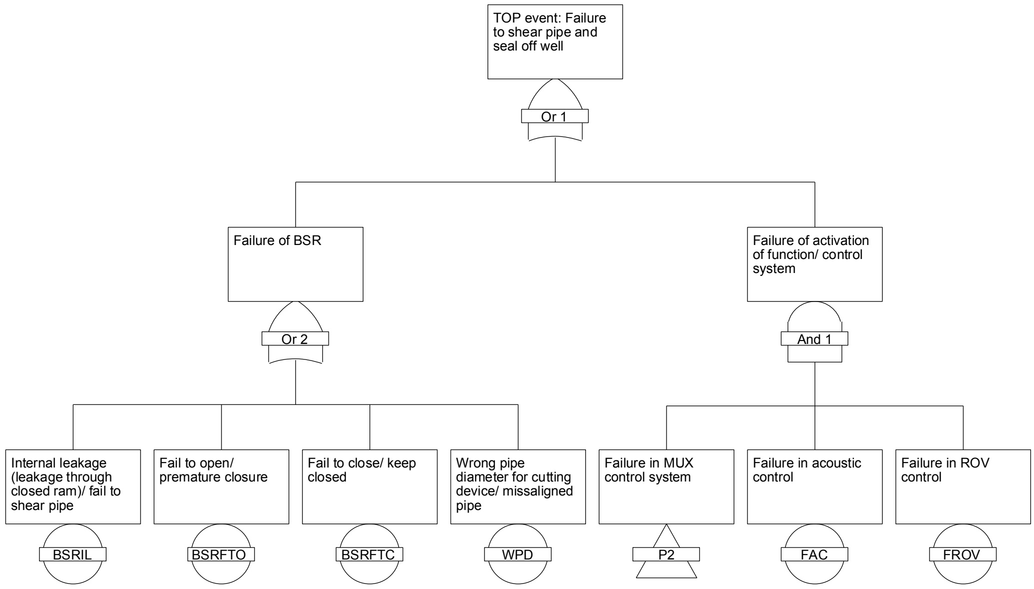
C.1 Fault Tree Symbols

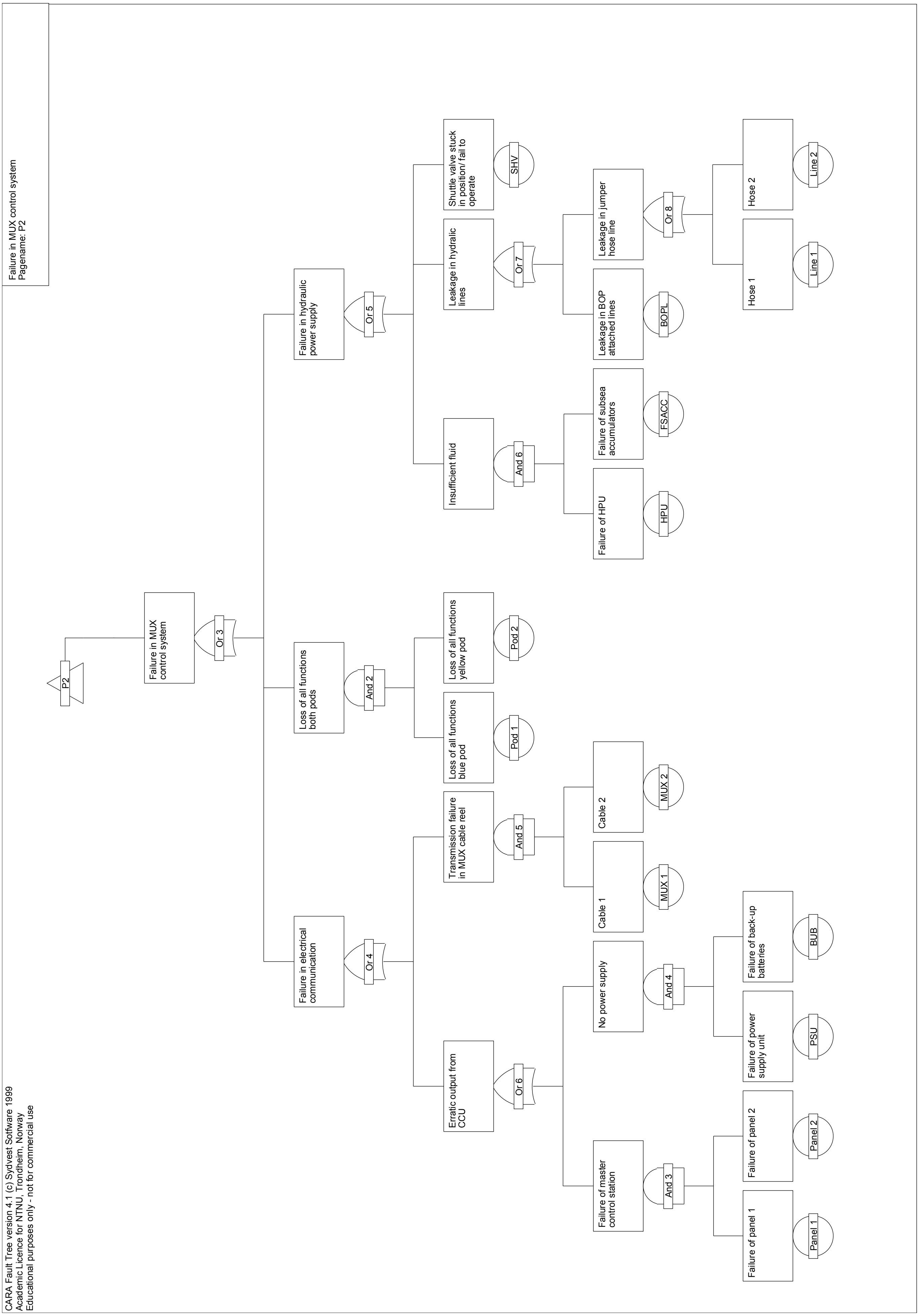
	Symbol		Description
Start Event	Top event		The TOP event represents a potential system failure.
Logic Gates	OR gate		The OR-gate indicates that the output event occurs if any of the input events occur.
	AND gate		The AND-gate indicated that the output event occurs only when all the input events occur simultaneously.
Input Event	BASIC event		The Basic event represents a basic event equipment failure or failure that requires no further development into more basic faults or failures.
Transfer Symbols	TRANSFER out		The **Transfer out** symbol indicated that the fault tree is developed further at the occurrence of the corresponding **Transfer in** symbol
	TRANSFER in		

C.2 Fault Trees

The fault trees utilised for the analyses are presented in the following pages. Fault tree input data is listed in Section C.3.

Failure to shear pipe and seal off well [Electro-hydraulic system]
Pagename: TOP




Failure in MUX control system
Pagename: P2
CARA Fault Tree version 4.1 (c) Sydvest Sotfware 1999
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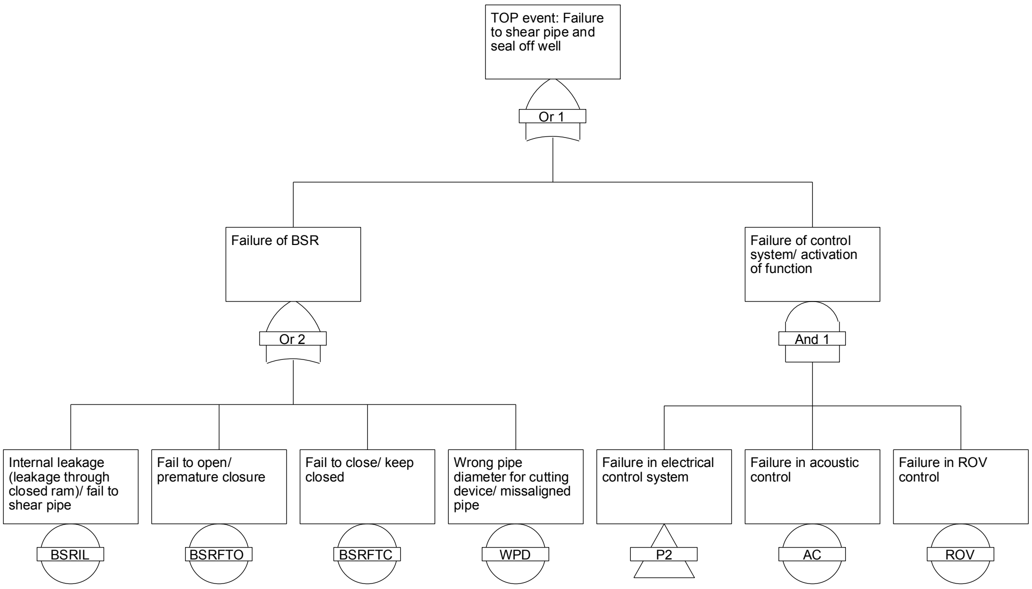
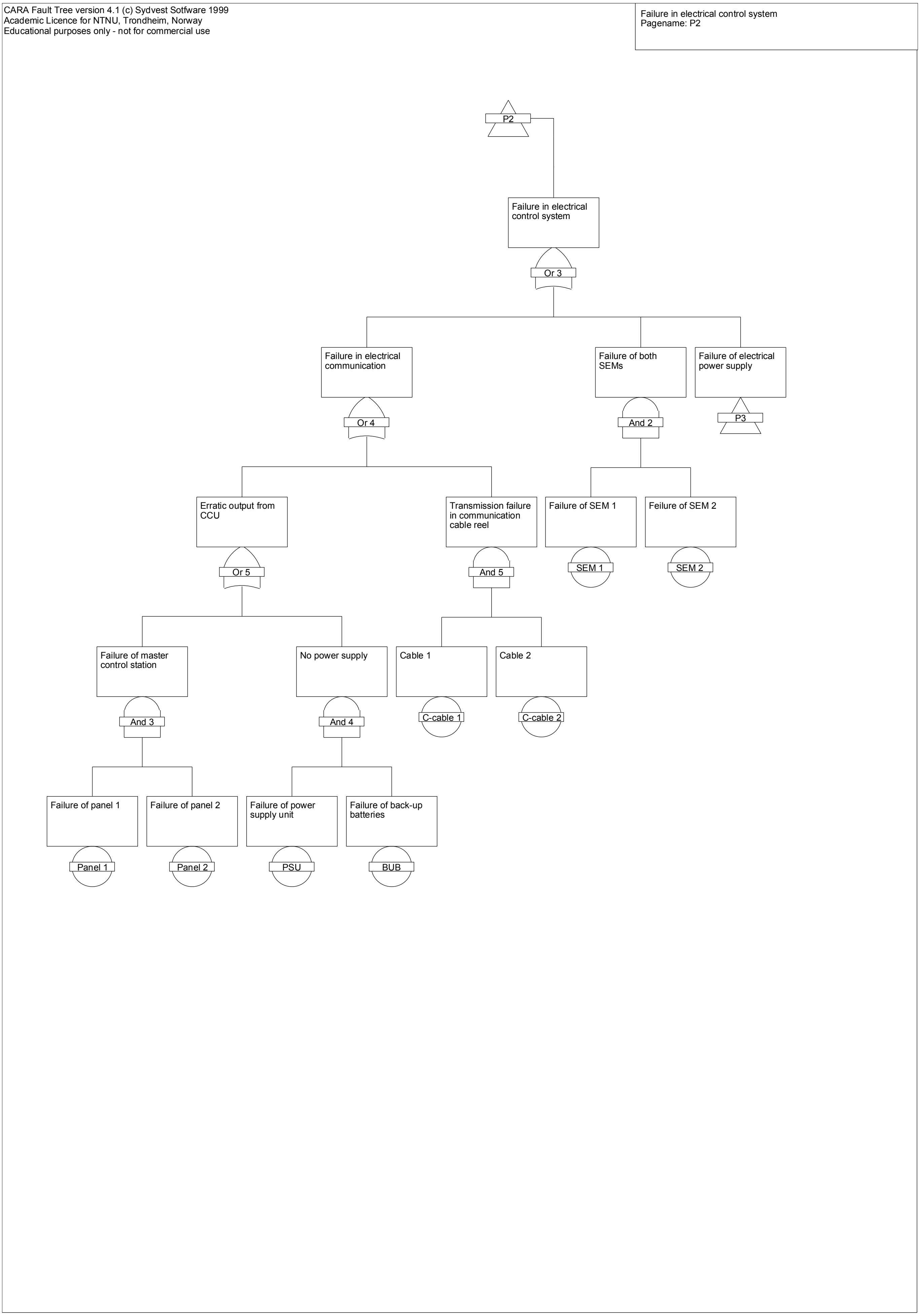
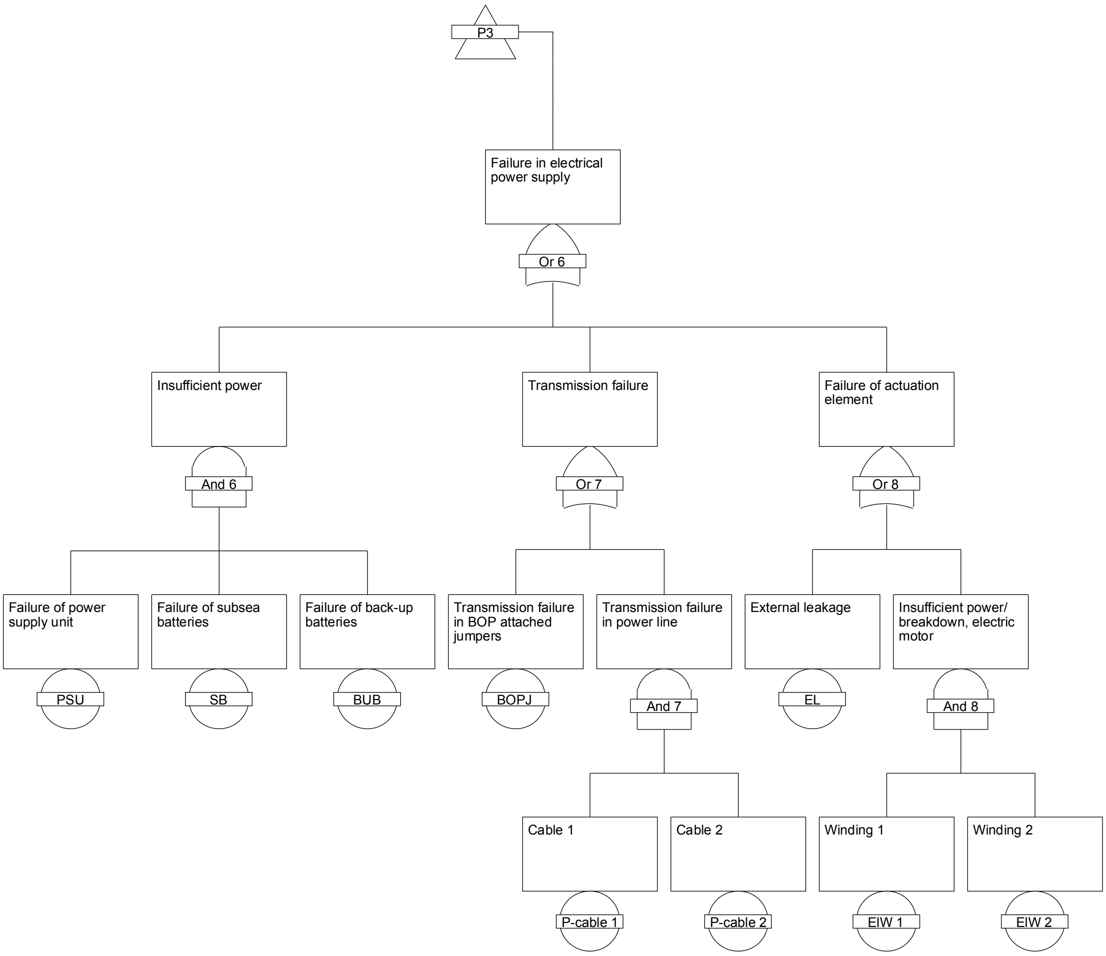
P2
Failure in MUX control system
Or 3
Failure in electrical communication
Or 4
Loss of all functions both pods
And 2
Failure in hydraulic power supply
Or 5
Erratic output from CCU
Or 6
Transmission failure in MUX cable reel
And 5
Loss of all functions blue pod
Pod 1
Loss of all functions yellow pod
Pod 2
Insufficient fluid
And 6
Leakage in hydralic lines
Or 7
Shuttle valve stuck in position/ fail to operate
SHV
Failure of master control station
And 3
No power supply
And 4
Cable 1
MUX 1
Cable 2
MUX 2
Failure of HPU
HPU
Failure of subsea accumulators
FSACC
Leakage in BOP attached lines
BOPL
Leakage in jumper hose line
Or 8
Failure of panel 1
Panel 1
Failure of panel 2
Panel 2
Failure of power supply unit
PSU
Failure of back-up batteries
BUB
Hose 1
Line 1
Hose 2
Line 2

Failure to shear pipe and seal off well [Fully-electrical system]
Pagename: TOP




CARA Fault Tree version 4.1 (c) Sydvest Sotfware 1999
Academic Licence for NTNU, Trondheim, Norway
Educational purposes only - not for commercial use
Failure in electrical control system
Pagename: P2
P2
Failure in electrical control system
Or 3
Failure in electrical communication
Failure of both SEMs
Failure of electrical power supply
Or 4
And 2
P3
Erratic output from CCU
Transmission failure in communication cable reel
Failure of SEM 1
Feilure of SEM 2
Or 5
And 5
SEM 1
SEM 2
Failure of master control station
No power supply
Cable 1
Cable 2
And 3
And 4
C-cable 1
C-cable 2
Failure of panel 1
Failure of panel 2
Failure of power supply unit
Failure of back-up batteries
Panel 1
Panel 2
PSU
BUB

Failure in electrical power supply
Pagename: P3



Electro-hydraulic BOP system

CARA Fault Tree version 4.1 (c) Sydvest Software 1999
Academic Licence for NTNU, Trondheim, Norway
Educational purposes only - not for commercial use
Date: 28.05.2014 Time: 19:28:07

File: Electro-hydraulic - Failure of BSR.CFT

Maximum cut size: 9 Top event: Or 1

Cut set(s) with 1 component (Total: 4)
{BSRIL}
{BSRFTO}
{BSRFTC}
{WPD}

Cut set(s) with 2 components (None found)

Cut set(s) with 3 components (Total: 4)
{FAC,FROV,Line 1}
{FAC,FROV,Line 2}
{FAC,FROV,BOPL}
{FAC,FROV,SHV}

Cut set(s) with 4 components (Total: 5)
{FAC,FROV,Panel 1,Panel 2}
{FAC,FROV,PSU,BUB}
{FAC,FROV,MUX 1,MUX 2}
{FAC,FROV,Pod 1,Pod 2}
{FAC,FROV,HPU,FSACC}

Cut set(s) with 5 components (None found)

Cut set(s) with 6 components (None found)

Cut set(s) with 7 components (None found)

Cut set(s) with 8 components (None found)

Cut set(s) with 9 components (None found)

Total number of cut sets up to order 9: 13

Calculation of MTTF - mean time to first failure
Method: Numerical integration

Maximum cut size: 5 Top event: Or 1

Specifications:

Mission time: t= 87600
Number of intv.: 10

MTTF=Mean time to first failure: 37006,9

Calculation of Freq(Top event: Or 1)

Method: Hand calculation - Upper bound approximation

Maximum cut size: 5 Top event: Or 1

Mission time t=87600

Frequency of Top event (Or 1):
2,686e-005 [Occ. per Hours]

All-electric BOP system

CARA Fault Tree version 4.1 (c) Sydvest Software 1999
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Educational purposes only - not for commercial use
Date: 28.05.2014 Time: 19:39:56

File: Fully-electrical - Failure of BSR.CFT

Maximum cut size: 9 Top event: Or 1

Cut set(s) with 1 component (Total: 4)
{BSRIL}
{BSRFTO}
{BSRFTC}
{WPD}

Cut set(s) with 2 components (None found)

Cut set(s) with 3 components (Total: 2)
{AC,ROV,BOPJ}
{AC,ROV,EL}

Cut set(s) with 4 components (Total: 6)
{AC,ROV,Panel 1,Panel 2}
{AC,ROV,PSU,BUB}
{AC,ROV,C-cable 1,C-cable 2}
{AC,ROV,SEM 1,SEM 2}
{AC,ROV,P-cable 1,P-cable 2}
{AC,ROV,EIW 1,EIW 2}

Cut set(s) with 5 components (None found)

Cut set(s) with 6 components (None found)

Cut set(s) with 7 components (None found)

Cut set(s) with 8 components (None found)

Cut set(s) with 9 components (None found)

Total number of cut sets up to order 9: 12

Calculation of MTTF - mean time to first failure
Method: Numerical integration

Maximum cut size: 5 Top event: Or 1

Specifications:

Mission time: t= 87600
Number of intv.: 10

MTTF=Mean time to first failure: 46405,2

Calculation of Freq(Top event: Or 1)

Method: Hand calculation - Upper bound approximation

Maximum cut size: 5 Top event: Or 1

Mission time t=87600

Frequency of Top event (Or 1):
2,115e-005 [Occ. per Hours]

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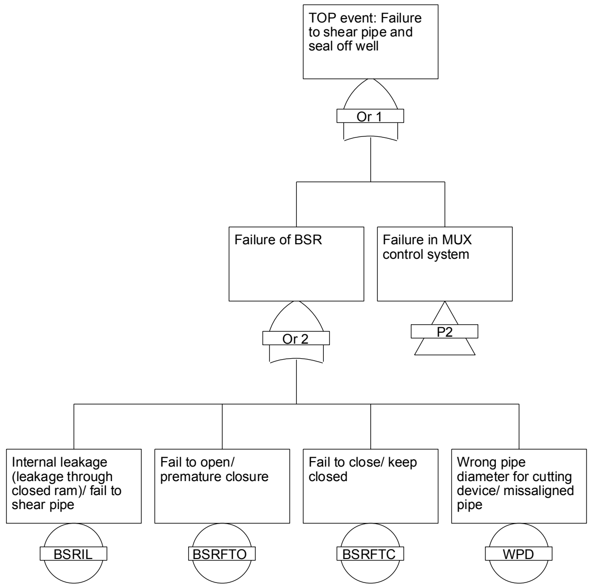
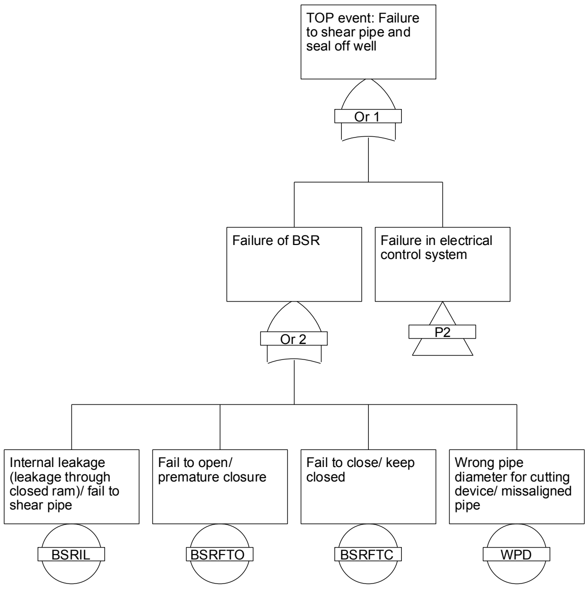
Failure to shear pipe and seal off well [Electro-hydraulic system]
Pagename: TOP



Failure to shear pipe and seal off well [Fully-electrical system]
Pagename: TOP



Electro-hydraulic BOP system without back-up control system

CARA Fault Tree version 4.1 (c) Sydvest Software 1999
Academic Licence for NTNU, Trondheim, Norway
Educational purposes only - not for commercial use
Date: 28.05.2014 Time: 19:45:07

File: Electro-hydraulic - Failure of BSR without ROV and AC.CFT

Maximum cut size: 9 Top event: Or 1

Cut set(s) with 1 component (Total: 8)
{BSRIL}
{BSRFTO}
{BSRFTC}
{WPD}
{Line 1}
{Line 2}
{BOPL}
{SHV}

Cut set(s) with 2 components (Total: 5)
{Panel 1,Panel 2}
{PSU,BUB}
{MUX 1,MUX 2}
{Pod 1,Pod 2}
{HPU,FSACC}

Cut set(s) with 3 components (None found)

Cut set(s) with 4 components (None found)

Cut set(s) with 5 components (None found)

Cut set(s) with 6 components (None found)

Cut set(s) with 7 components (None found)

Cut set(s) with 8 components (None found)

Cut set(s) with 9 components (None found)

Total number of cut sets up to order 9: 13

Calculation of MTTF - mean time to first failure
Method: Numerical integration

Maximum cut size: 5 Top event: Or 1

Specifications:

Mission time: t= 87600
Number of intv.: 10

MTTF=Mean time to first failure: 10173,2

Calculation of Freq(Top event: Or 1)

Method: Hand calculation - Upper bound approximation

Maximum cut size: 5 Top event: Or 1

Mission time t=87600
Frequency of Top event (Or 1):
9,94885e-005 [Occ. per Hours]

All-electric BOP system without back-up control system

CARA Fault Tree version 4.1 (c) Sydvest Software 1999
Academic Licence for NTNU, Trondheim, Norway
Educational purposes only - not for commercial use
Date: 28.05.2014 Time: 19:49:46

File: Fully-electrical - Failure of BSR without ROV and AC.CFT

Maximum cut size: 9 Top event: Or 1

Cut set(s) with 1 component (Total: 6)
{BSRIL}
{BSRFTO}
{BSRFTC}
{WPD}
{BOPJ}
{EL}

Cut set(s) with 2 components (Total: 6)
{Panel 1,Panel 2}
{PSU,BUB}
{C-cable 1,C-cable 2}
{SEM 1,SEM 2}
{P-cable 1,P-cable 2}
{EIW 1,EIW 2}

Cut set(s) with 3 components (None found)

Cut set(s) with 4 components (None found)

Cut set(s) with 5 components (None found)

Cut set(s) with 6 components (None found)

Cut set(s) with 7 components (None found)

Cut set(s) with 8 components (None found)

Cut set(s) with 9 components (None found)

Total number of cut sets up to order 9: 12

Calculation of MTTF - mean time to first failure
Method: Numerical integration

Maximum cut size: 5 Top event: Or 1

Specifications:

Mission time: t= 87600
Number of intv.: 10

MTTF=Mean time to first failure: 41348,4

Calculation of Freq(Top event: Or 1)

Method: Hand calculation - Upper bound approximation

Maximum cut size: 5 Top event: Or 1

Mission time t=87600
Frequency of Top event (Or 1):
2,40284e-005 [Occ. per Hours]

C.3 Fault Tree Input Data

Electro-hydraulic system:

Basic event	Failure	Failure rate [per 10^6 h]	MTTR [hours]	Source	Comment
IL	Ram preventer, internal leakage (leakage through a closed ram)	7,72E+00	45,17	Holand	
FTO	Ram preventer, failed to open	5,15E+00	391,38	Holand	
FTC	Ram preventer, failed to close	2,57E+00	475,50	Holand	
WPD	Wrong pipe diameter for cutting device, misaligned pipe	1,14E+01	-		Ref. Workshop/ Macondo
AC	Failure in acoustic control	1,00E-06	-	Eng.judgement	Not necessary to include
ROV	Failure in ROV control	1,00E-06	-	Eng.judgement	Not necessary to include
Panel 1	Failure of master control station 1, panel 1	1,16E+01	9,60	OREDA	Critical failure, master control station p. 57 (S)
Panel 2	Failure of master control station 2, panel 2	1,16E+01	9,60	OREDA	Critical failure, master control station p. 57 (S)
PSU	Failure of power supply unit	1,77E+01	9,80	OREDA	Critical failures, power supply unit p. 55 (S)
BUB	Failure of back-up batteries (topside)	1,00E-03	-	Eng.judgement	As for subsea batteries
MUX1	Transmission failure in MUX cable 1	2,70E-01	-	OREDA	Dynamic umbilical, power/signal line p. 55 (S)
MUX2	Transmission failure in MUX cable 2	2,70E-01	-	OREDA	Dynamic umbilical, power/signal line p. 55 (S)
Pod1	Loss of all functions pod 1	9,08E+01	0,413	Holand	For Multiplex system
Pod2	Loss of all functions pod 2	9,08E+01	0,413	Holand	For Multiplex system
HPU	Failure of HPU	2,03E+01	6	OREDA	p. 56 Subsea
Acc	Failure of subsea accumulators	1,50E-01	-	OREDA	p. 60 Subsea
SHV	Shuttle valve stuck in position/ fail to operate	1,00E+01	8,00		Engineering judgement
Line1	Leakage in jumper hose line 1	2,08E+01	4,75	Holand	Jumper Hose Line
Line2	Leakage in jumper hose line 2	2,08E+01	4,75	Holand	Jumper Hose Line
BOPL	Leakage in BOP attached lines	2,08E+01	8,00	Holand	BOP attached line

All-electric system: (listed on the next page)

Basic event	Failure	Failure rate [per 10^6 h]	MTTR [hours]	Source	Comment
IL	Ram preventer, internal leakage	7,72E+00	45,17	Holand	
FTO	Ram preventer, failed to open	5,15E+00	391,38	Holand	
FTC	Ram preventer, failed to close	2,57E+00	475,50	Holand	
WPD	Wrong pipe diameter for cutting device, misaligned pipe	5,71E+00	-		Ref. Workshop/ Macondo
AC	Failure in acoustic control	1,00E-06	-	Holand	
ROV	Failure in ROV control	1,00E-06	-	Holand	
Panel 1	Failure of master control station 1, panel 1	1,16E+01	9,60	OREDA	Critical failure, master control station p.57 (S)
Panel 2	Failure of master control station 2, panel 2	1,16E+01	9,60	OREDA	Critical failure, master control station p.57 (S)
CCable 1	Transmission failure in communication cable 1	2,70E-01	-	OREDA	Dynamic umbilical, power/signal line p. 55 (S)
CCable 2	Transmission failure in communication cable 2	2,70E-01	-	OREDA	Dynamic umbilical, power/signal line p. 55 (S)
SEM 1	Failure of SEM 1	4,42E+00	6,4	OREDA	Critical failures, subsea electronic module p. 60 (S)
SEM 2	Failure of SEM 2	4,42E+00	6,4	OREDA	Critical failures, subsea electronic module p. 60 (S)
PSU	Failure of power supply unit	1,77E+01	9,80	OREDA	Critical failures, power supply unit p. 55 (S)
SB	Failure of subsea batteries, type A123	1,00E-03	-	Gylling	Mail sent to Gylling
BUB	Failure of back-up batteries (topside)	1,00E-03	-	Eng.jud gement	
BOPJ	Transmission failure or short circuit in BOP attached jumpers	2,70E-01	21,5	OREDA	Power/signal jumper, subsea distribution module p. 62 (S)
PCable1	Transmission failure in power cable 1	2,70E-01	-	OREDA	Dynamic umbilical, power/signal line p. 55 (S)
PCable2	Transmission failure in power cable 2	2,70E-01	-	OREDA	Dynamic umbilical, power/signal line p. 55 (S)
ElW1	Insufficient power or breakdown, electric motor winding 1	1,83E+01	13,00	OREDA	Electric motor, top side p. 265
ElW2	Insufficient power or breakdown, electric motor winding 2	1,83E+01	13,00	OREDA	Electric motor, top side p. 265