RISK ASSESSMENT OF SURFACE VS. SUBSURFACE BOP'S ON MOBILE OFFSHORE DRILLING UNITS

by

Jorge Melendez, Texas A&M University
Graduate Assistant Research
Jerome J. Schubert, Ph.D. PE, Texas A&M University
Assistant Professor
Mahmood Amani, Ph.D., Texas A&M University Qatar
Visiting Assistant Professor

Final Project Report
Prepared for the Minerals Management Service
Under the MMS/OTRC Cooperative Research Agreement
1435-01-04-CA-35515
Task Order 39226
MMS Project Number 540

August 2006

OTRC Library Number: 8/16A172

For more information contact:

Offshore Technology Research Center
Texas A&M University
1200 Mariner Drive
College Station, Texas 77845-3400
(979) 845-6000

or

Offshore Technology Research Center
The University of Texas at Austin
1 University Station C3700
Austin, Texas 78712-0318
(512) 471-6989

A National Science Foundation Graduated Engineering Research Center

Risk Assessment of Surface vs. Subsurface BOP's on Mobile Offshore Drilling Units

Jorge Melendez, Jerome J. Schubert, and Mahmood Amani, Texas A&M University

Executive Summary

Introduction

In an attempt to mitigate many of the problems associated with deepwater drilling, some operators such as Woodside Energy Ltd., Shell, TOTAL, and Unocal have either considered using or have used surface Blowout Preventers, BOP, with small diameter, high pressure risers in floating drilling operations. The myriad of problems associated with drilling in deep water have been extensively covered in the literature. Some of the problems that this technology can help to alleviate are directly associated with the large diameter marine risers currently being utilized.

As water depth increases, the weight of conventional risers increases to a point that only a very few fifth generation floating rigs have the capability to drill in ultra-deep water. The deck loads increase tremendously, the volume of mud required to fill the riser increases, and the choke line friction increases to a point to where successfully circulating a kick from the well becomes almost impossible. The small diameter, high pressure riser can alleviate the deck load requirements, reduce the volume of mud required, and eliminate the high choke line friction pressure experienced with conventional marine risers. This will also, minimize the problems associated with riser gas.

However, this is relatively new technology, and there is inherent risk in applying any new practices. Even though this technology is relatively new, it has been successfully applied in a number of international locations, mostly in calm waters, where currents are low, and storms are not common. Now, some operators would like to apply this technology to waters that are susceptible to high currents, and storms.

The Harold Vance Department of Petroleum Engineering at Texas A&M University was contracted by the U.S. Minerals Management Service through the Offshore Technology Research Center to conduct a comparative risk assessment of the use of Surface Blowout Preventer Systems and High Pressure Risers vs. conventional Subsea Blowout Preventer Systems and drilling risers in the Gulf of Mexico Environment.

Tasks

The tasks that we agreed to perform are as follows:

Phase I (Year 1)

1. A literature review to assess the state of the art in the use of surface BOPs on Mobile Offshore Drilling Units, MODUs. We will study the equipment that is currently being utilized by these operators and drilling contractors; where this technology is being applied; as well as sea conditions (e.g. current, wave height, and storm frequency and severity). We will compare the sea conditions where surface BOPs are utilized on MODUs to those in the Gulf of Mexico.
2. We will perform an analysis of the frequency of riser failures for both conventional large diameter risers as well as the smaller diameter high pressure risers. We will also review the causes of the failures. However, we do not intend to perform the failure analysis ourselves, just review the analysis performed by others.

3. Based on this failure analysis, we will determine the proper risk evaluation tools that are available today and analyze the risk of utilizing a surface BOP system in deep water on a MODU.

<u>*Phase II (year 2)*</u>

4. Based on the above risk analysis, we will determine the value and/or need for subsea shear rams (shut-in device, SID) to be used with high pressure risers and surface BOP systems. We will finish this task with a shorter analysis of the risk involved with utilizing the subsea shear rams.
5. We will document the results of this work in a final report that will be provided to the OTRC and the MMS. The final report will include all M.S. thesis written on the project.

We have completed tasks 1-4 and this executive summary and attached thesis entitled "Risk Assessment of Surface vs. Subsea Blowout Preventers (BOPS) on Mobile Offshore Drilling Units Focusing on Riser Failure and the Use of Subsea Shear Rams" constitutes the completion of task 5 the writing of the final report.

Results and Conclusions

In our study, we have identified 13 elements that affect the reliability and risk of failure of the riser system and seven elements that affect the reliability and risk of failure of the Subsea BOP system.

In our study we defined risk as the product of frequency of occurrence and the consequence. The risk assigned to each element for a conventional marine riser system can be found in Table 4.1 and Table 4.2 for the High Pressure Riser system. Of these thirteen elements in the riser system, there were five elements where the risk of failure was significantly lower for the High Pressure Riser than the conventional marine riser. Since there are no boost lines or choke and kill lines in the High Pressure Riser, they cannot fail as they can with the conventional system. Failure of the riser due to Drillstring Induced Vibration, DIV, Riser Wear, and Vortex Induced Vibration, VIV, is considerably lower for the High Pressure Riser simply due to the fact that the High Pressure Riser is used on only one well as a drilling riser. On the next well, this riser is cemented in the wellbore as an intermediate casing string.

Tables 4.1 and 4.2 show no difference in the risk of Burst/Collapse between the two systems simply because of the very low frequency. However, this comparison ignores two vital facts. One, the conventional marine riser is not designed as a pressure containment vessel, and, two, the rig crews are trained to never allow gas to enter the riser during well control operations, or to let the riser become emptied. Since the high pressure riser is designed to withstand much higher burst and collapse pressures than the conventional marine riser, the probability of failure due to burst and collapse should be much lower.

The reliability of the Surface BOP system as compared to the Subsea BOP system was determined to be nearly equal in our comparison, even though the Subsea BOP system utilized more redundant elements than the Surface BOP system. This is simply done because of the extreme difficulty in repairing the BOP stack when it is located on the seafloor.

Based on the data that we were able to acquire on BOP and Riser Failures and our subsequent risk analysis, we have determined the following:

- The qualitative analysis in determining the risk of SBOP operations when comparing these operations to the conventional system with the specific metocean conditions encountered in the GOM, showed acceptable values.
- Addition of the Shut-In Device, SID, improved the system reliability and maintained a failure rate within the acceptance risk envelope independently from the type of dataset used; thus it should be considered for deepwater operations in the GOM.
- This evaluation was done with a generic description of the drilling riser components and the pressure control equipment, thus it serves as a starting point for operators and contractors when planning the use of SBOPs in the GOM.

From the work presented in this study we can conclude the following:

1. Preliminary analysis of the simulations suggests that the risk of failure of the entire system can be acceptable and operations can be carried out safely.

2. A risk assessment can aid one to understand the high-pressure riser system through the identification of the critical components and their interaction with the overall pressure control equipment.

3. Specific location and equipment planned to be used can drastically change the outcome of the overall risk analysis, since some areas are more susceptible than others to be hit by harsh metocean conditions.

4. Results from the quantitative interpretation have a degree of uncertainty on their reliability, because of the nature of the dataset used. However, the work done allows the setting of upper and lower boundaries to understand the system behavior.

Data Utilized

Our study utilized information on riser and BOP failures from four separate data sets. These data sets are:

1. Reports of incidents made to the U.S. Minerals Management Service.
2. The Corrosion and Damage Database (CODAM) maintained by the Norwegian Petroleum Safety Authority
3. The Pipeline and Riser Loss of Containment database maintained by the U.K. Health and Safety Executive
4. A study conducted by SINTEF.

There is some uncertainty in the data due to potential and probably non-reporting of minor failures or problems with equipment. Also, the four datasets did not categorize failures consistently, which could effect the uncertainty of our results.

Limitation to Our Study and Recommendations for future work

Only primary failures from each component were taken into consideration for this study, because the purpose was to have a preliminary assessment of whether it would be positive or not to implement a high-pressure riser. Future work should include secondary and tertiary failures to take into account chain events and their consequences.

The riser system and pressure control equipment models were simplified into their main components; a more detailed analysis can be performed during the evaluation of a particular arrangement to determine the specific risk of the system.

A similar study could be performed to evaluate the risk of installing a high-pressure riser and an SBOP in fixed deepwater production units like spars and tension leg platforms as an alternative for well control measurements.

Awareness should be brought to the MMS regarding data quality to better assess risk analyses, since reported failures do not include a consequence level.

Summary of Thesis

The following is a brief summary of the contents of the attached thesis.

Chapter 1 – Introduction, provides a concise description of the BOP systems currently in use in floating drilling operations. This description not only describes the BOP equipment but also the conventional Marine Risers in use today. This chapter provides a brief summary of the history of the use of Surface BOP equipment on floating operations to date.

Chapter 2 – Background, describes the objective of the study, expected contribution to the industry and a description of the High Pressure Riser and Pressure Control System.

Chapter 3 – Risk Models, describe the risk analysis process, fault tree analysis and it's required input parameters.

Chapter 4 – Failure Rates, describes the failure rates that were used in this study, the source of the data, and how these failure rates were utilized in our study.

Chapters 5 and 6 describe the results and conclusions of our study while Appendix B contains the fault tree models that were built for our study. Appendix C is an Excel spreadsheet containing the assembly of the incidents reported to the MMS from 1999 to 2005. Appendix D is another Excel spreadsheet where the failure rates used in our risk analysis were calculated. This spreadsheet also contains the results from all the simulation runs for the qualitative analyses performed on each dataset

Acknowledgement

The authors would like to thank the U.S. Minerals Management Service and the Offshore Technology Research Center for providing funding and data to complete this project.

Disclaimer

This risk assessment and the conclusions stated are based on the data that was available to us at the time that the work was performed. Additional failure data could change the risk assessment as well as our conclusions.

RISK ASSESSMENT OF SURFACE VS SUBSEA BLOWOUT PREVENTERS (BOPS) ON MOBILE OFFSHORE DRILLING UNITS FOCUSING ON RISER FAILURE AND THE USE OF SUBSEA SHEAR RAMS

A Thesis

by

JORGE LUIS MELENDEZ

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2006

Major Subject: Petroleum Engineering

RISK ASSESSMENT OF SURFACE VS SUBSEA BLOWOUT PREVENTERS (BOPS) ON MOBILE OFFSHORE DRILLING UNITS FOCUSING ON RISER FAILURE AND THE USE OF SUBSEA SHEAR RAMS

A Thesis

by

JORGE LUIS MELENDEZ

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Approved by:

Chair of Committee,	Jerome J. Schubert
Committee Member,	Hans C. Juvkam-Wold
	Thomas R. Lalk
Head of Department,	Stephen A. Holditch

May 2006

Major Subject: Petroleum Engineering

ABSTRACT

Risk Assessment of Surface vs. Subsea Blowout Preventers (BOPs) on Mobile Offshore Drilling Units Focusing on Riser Failure and the Use of Subsea Shear Rams.

(May 2006)

Jorge Luis Meléndez, B.S., University of Zulia, Vemezuela

Chair of Advisory Committee: Dr. Jerome J. Schubert

The use of a slim, high-pressure drilling riser for surface blowout preventer operations in the deepwater Gulf of Mexico was assessed as an alternative to conventional drilling procedures from floating units. Comparison of the low- and high-pressure system was accomplished through a detailed qualitative (assigned frequency) and quantitative (reported incidents) risk analysis using generic fault tree models to statistically determine the reliability of the system based on metocean conditions from the Gulf of Mexico.

It is hoped that this investigation will serve as a starting point for drilling companies and regulatory agencies to understand the risk of implementing a high-pressure riser for surface blowout preventer applications in the Gulf of Mexico, because specific failure events and conditions of the area were considered. Despite the generic description of the drilling riser and pressure control system, the models are flexible enough to be modified and adapted to a specific rig configuration and location.

Results from the qualitative comparison suggest an acceptable risk and high reliability for high-pressure riser systems and surface preventers. The quantitative portion of the study is influenced by the data quality of the high-pressure system, however it provides a range of possible reliability values with an acceptable overall risk.

DEDICATION

I would like to dedicate this work to my family who have always supported and inspired me in my journeys thank you: Mom, Dad, Gina, Luisa and Malena.

This new step in my life could not have been possible without the love from Sacha, the sacrifices we both made will be rewarded in the future, thank you.

ACKNOWLEDGEMENTS

I would like to thank my committee chair and adviser, Dr. Jerome J. Schubert, for giving me the opportunity to develop this project; by trusting my work and judgment, and supporting me since the beginning.

Dr. Hans C. Juvkam-Wold, thank you for being part of my committee and sharing your vast knowledge of drilling through your classes. Also, thank you for always having the time to answer questions and discuss topics of many natures.

I would like to thank Dr. Thomas R. Lalk for agreeing to be part of my committee and being keen on the quality of the project.

My gratitude to Dr. Ann Jochens for her helpful insights concerning the Gulf of Mexico characteristics.

I would like to thank my trustful sponsors (Mom and Dad) for investing in my education.

Special thanks to the Minerals Management Service through the Offshore Technology Research Center whose funds made this work possible.

Thank you Texas A&M University for providing me a unique learning experience. To the faculty and staff of the Petroleum Engineering department; thank you for all your support and help.

To the friends I made, and the ones that have always been there, thank you for sharing great moments and experiences. Gig’em Ags!

TABLE OF CONTENTS

Page

Page

LIST OF FIGURES

FIGURE Page

LIST OF TABLES

1. INTRODUCTION

Deepwater drilling operations (> 1,000 ft) call for blowout preventers (BOPs) to be installed at the seabed, and then connected to a large-diameter drilling riser to control the well and transport fluids. Placing the BOP stack at the surface would reduce the requirements in pipe diameter of the riser, allowing the use of a slim high-pressure system capable of handling well pressures and controlling kick inflows. Surface BOPs (SBOPs) eliminate the downtime spent on lowering the large-diameter drilling riser and installing the BOP stack at the seabed, optimizing rig time. SBOPs also reduce the length of the kill and choke lines, and the pumping power required to overcome frictional pressure losses through the lines.[1]

The increase of top-tension loads and high-angle doglegs created by the large diameter riser creates additional problems for deepwater operations resulting in a permanent bend or collapse of the pipe. Harsh metheorological and oceanic (metocean) conditions create fatigue stresses in the tubing through the interaction of winds and currents, contributing to the vortex-induced vibration[2] phenomenon. A great advantage of the SBOP system is that the high-pressure string is used once as a riser, and then is set below the mudline on the following well, reducing long-term fatigue design requirements.

The objective of this study is to determine the feasibility of installing a slim, high-pressure drilling riser for SBOP operations in deepwater Gulf of Mexico (GOM), by comparing the reliability of the riser and overall well control system to the conventional subsea BOP configuration. The comparison follows current guidelines[3] and incorporates specific metocean conditions of the GOM, serving as a reference for regulatory agencies and drilling contractors for approval and planning of future wells.

This thesis follows the style and format of *SPE Drilling and Completion.*

Reliability studies have been conducted with the use of fault-tree analysis to model failure events from other industries[4] for some years in order to reduce incident occurrences by determining critical elements and their importance to the system. Fault-tree models represent each system configuration and allow comparisons based on similar situations to determine risk and reliability[5] of the drilling riser and BOPs. The models in this study use a numerical integration and a stochastic simulation to estimate the operability of each system with assigned frequency values and specific element failure rates from historical behavior in deepwater GOM.

The first section of the report introduces the blowout preventer and drilling riser concepts, along with a brief history of SBOP operations and the metocean conditions observed in the locations that have implemented this technology, focusing on the GOM.

The second section describes the objective and the contribution of this research; it also sets the background terminology of the elements mentioned in the assessment.

Section three explains the overall risk process. The methodology is introduced first, then the fault-tree analysis models and finally, the basis of the calculations and methods.

Section four illustrates the failure rate calculations for both the quantitative and qualitative analyses, with the various datasets used and the changes made to incorporate them into the risk models.

Results are presented in section five, along with a discussion on the findings from the assessment.

Section six contains additional discussion of the results, the conclusions and recommended future work.

1.1 BOP Systems

Blowout preventers act as a safety barrier in emergencies or undesired events by controlling reservoir pressures and fluids in the well. In the absence of BOPs well control is achieved solely by the water column imposed by the sea, allowing the possibility for shallow underground blowouts to occur without any possibility of controlling them.

The number of components and the capacity a BOP has varies widely within the industry depending on its application and requirements of the well. [6] However, deepwater drilling usually has the highest rated equipment due to the conditions at which they operate. The BOP system stack is made up of a series of pipe rams and annular preventers in charge of sealing and shearing the drillpipe. Normally, subsea stacks are larger and have more components than a surface stack, because there repairs and maintenance are more complicated.

A common subsea stack is shown in **Fig. 1.1.** It consists on two sets of annular preventers, three pipe rams, a single shear ram, and two sets of kill and choke lines. The redundancy in the system allows for the BOP to be very reliable. The size of the stack requires the rig to handle significant deck loads, limiting operations to fourth- or fifth-generation rigs. A typical SBOP arrangement consists of a single annular preventer, two pipe rams, a shear ram, and a single set of kill and choke lines. [7] The SBOP system is a simplified version of the subsea stack, in which the different components are easy to access, thus eliminating the redundancy required for minimal reliability and availability. An example of an SBOP array is shown in **Fig. 1.2.**

The top BOP manufacturers and their products are presented in Appendix A, which includes the description and advantages of each competitor.

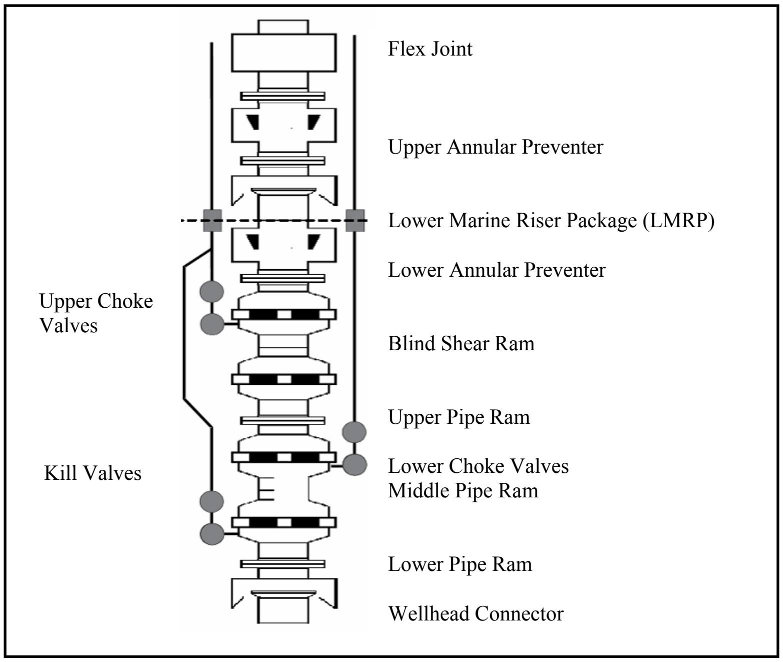


Fig. 1.1 - Typical subsea BOP stack.[8]

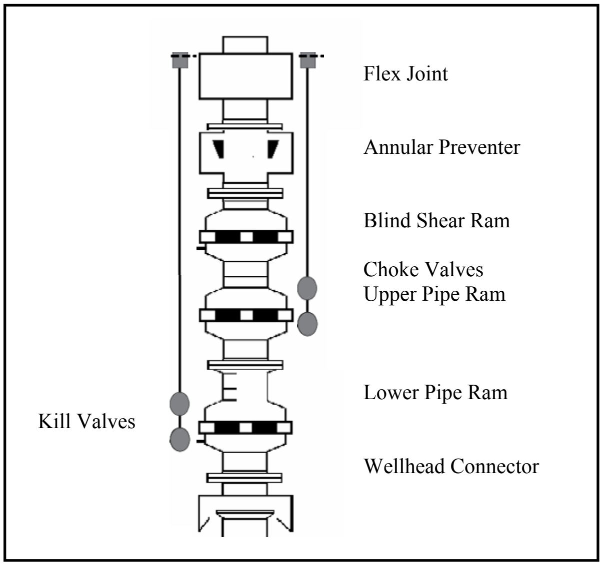


Fig. 1.2 - Typical surface BOP stack.[8]

1.2 Drilling Riser

The drilling riser is a large-diameter steel pipe used in offshore operations as a means of communication between the rig and the seafloor, as a guide to the drillpipe, and as a pathway for the mud and cuttings to be brought back to the surface. The riser also has attached to its body kill and choke lines used for BOP operations, and any additional boost lines required, increasing the complexity of the system.

The design requirements for the riser are aimed at maintaining its integrity, by considering the top tension necessities, external pressures imposed by the water, and its long term life as it will be used multiple times during its lifetime.

Deepwater drilling risers interact with the passing of currents, which create turbulence vortices (**Fig. 1.3**) causing the riser to vibrate; this phenomenon is called vortex induced vibration (VIV). The effect can be devastating if the excitation reaches the natural frequency of the system; but most importantly it shortens the life of the riser by the constant vibration. Studies[9-11] have shown that this effect can be minimized by the addition of VIV suppressors, which orient the path of the fluid as it crosses the riser; however such an alternative increases operational costs.

Other studies[12] and operators have found that the effect becomes less of a problem when the diameter is reduced and the surface is smoothed.

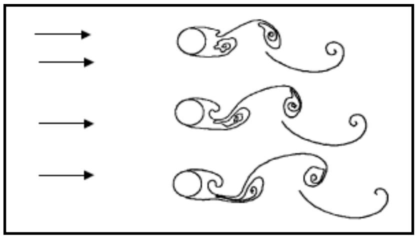


Fig. 1.3 – Turbulence created by the passing of a current resulting into VIVs. [10]

Recent technology has pushed the development of a composite riser, [13] in which fiber-composite joints are alternated between the metal ones. This arrangement greatly reduces the overall weight of the riser and allows it to withstand higher pressures, because of the specialized metal-to-composite connections. However, this configuration has only been applied to prototypes and production risers.

Other elements of the riser system are the diverter, telescopic joint, and the marine riser package. These will not be described because they are beyond the scope of this study.

1.3 SBOP History

Placing the BOPs below the moonpool or near the surface (below the splash zone) is not a new concept. In the early 1960's the technique was used in shallow waters (≈100 ft) in Southeast Asia. [14] Similar developments were made in West Africa in greater depths. In addition, fixed drilling units such as Jack-Ups and compliant towers have implemented SBOPs in water depths of up to 400 ft, [15] due to their stability by being in direct contact with the seabed.

In 1996, SBOPs were used in shallow waters and normally pressured formations from mobile units, [16] achieving remarkable savings ranging from 20% to 70% of the total cost to develop wells compared to the conventional approach of subsea BOPs. [17]

Current water depth record for SBOP applications was set in 2003 offshore of Brazil[18] at 9,472 ft in the Campos Basin area, setting a milestone in the implementation of this technology in harsh environments. The well was drilled with the use of a third-generation rig that was upgraded to drill in 10,000 ft of water and included a seabed isolating device.

To help understand the SBOPs concept **Fig. 1.4** illustrates current deepwater options regarding BOP placement.

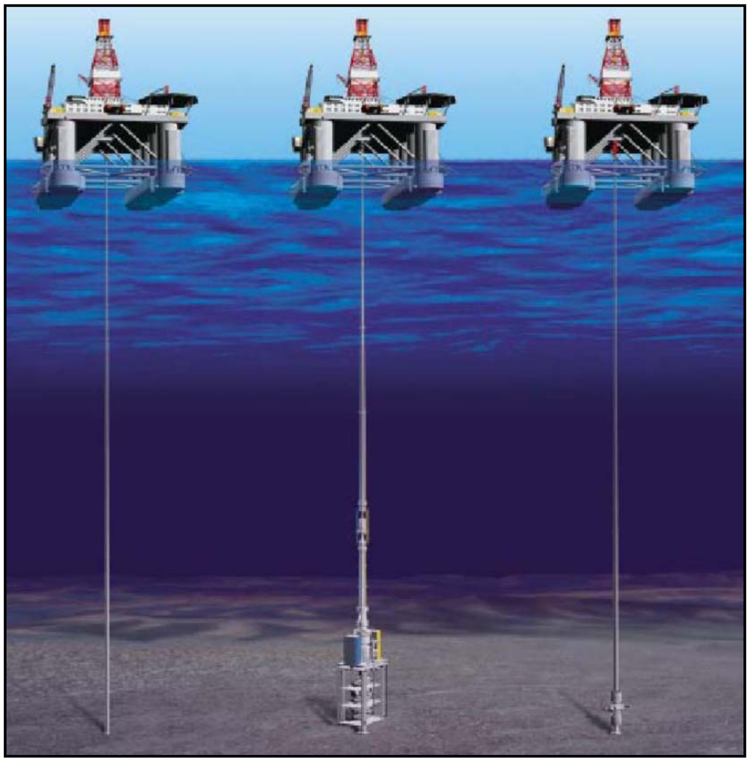


Fig. 1.4 – Deepwater drilling with SBOP, subsea BOP, and SBOP with SID. [19]

1.4 Metocean Conditions

Meteorological and oceanographic (metocean) conditions are a major challenge for every offshore activity. In the case of deepwater drilling operations, these conditions become critical in the selection of the rig and the equipment to operate it safely. Depending on the location, metocean conditions can vary greatly and change in a seasonal mode within the same region. Elements such as ocean currents, winds, significant wave height, and period are the main metocean characteristics one must consider when planning an offshore well.

SBOPs started to be implemented in calm metocean conditions, and then progressively moved to rougher parts and deeper zones like offshore Brazil. [20] Listed below is a summary of the metocean profile from the locations that have successfully applied the SBOP concept and the average conditions encountered in the GOM in various return periods.

1.4.1 West Africa – Angola

The Angola Current forms the eastern section of a large, cyclonic current in the Gulf of Guinea; where typical deepwater speeds are less than 0.6 knots (0.3 m/s). The current has been described[21] as a fast, narrow, and stable flow that reaches 700 to 900 ft depths and covers both the shelf regions and the continental slope.

1.4.2 Offshore Brazil – Campos Basin

Currents east of Brazil are influenced by two streams; one affects the surface movement and the other the bottom one. [21] The surface currents extend to a depth of 3,300 ft (1,000 m) and are influenced by the Antarctic Intermediate Water Mass; below this mark, the currents are moved by the North Atlantic Deep Water Mass in the opposite direction. Although speeds for these currents are low (<1 knot), they still need to be monitored for their effect on flow direction.

1.4.3 Southeast Asia - Indonesia

Currents offshore Indonesia travel at relatively low speeds (< 1 knot) in an almost uniform pattern creating little or no disturbance to the offshore units installed in shallow depths. Wind speeds only reach highs during typhoon season, when speeds can be up to 60 mph.

1.4.4 Gulf of Mexico

Due to its natural flowing currents, hurricane season, and subsurface currents, the Gulf of Mexico experiences a series of harsh environmental conditions.

The vertical structure of currents in the Gulf of Mexico shows intense flows at or near the surface, decreasing flows with depth to a minimum at approximately 3000 ft., and possible bottom-intensified flows near the sea floor (**Fig. 1.5**). The speed profile varies depending on location in the Gulf. The eastern part of the Gulf has greater maximum speeds recorded than the central and western part. The central part also has higher currents near the bottom, which reflects a stronger bottom intensification possibly associated with excitation from the Loop Current System. The sources of energy that drive this structure are largely two: the Loop Current System and energetic atmospheric events.

The Loop Current of the Gulf of Mexico is a major source of energy that drives the current system in the Gulf.[22] At the subsurface level between 3000 and 6000 ft., the Loop Current brings in waters from the world's oceans, including two major water masses: the Antarctic Intermediate Water and the Upper North Atlantic Deep Water.

The Loop Current originates from water that enters the Yucatan Channel (where it is called the Yucatan Current) from the Caribbean Sea. It enters as a northward-flowing, westward-intensified current. It then turns eastward in the eastern Gulf and exits through the Florida Straits, where it becomes part of the Gulf Stream System. The Loop Current is energetic, with near-surface flows that can exceed 4 knots. [22] It may also trigger currents in the waters below 3000 ft. particularly along the continental slope.

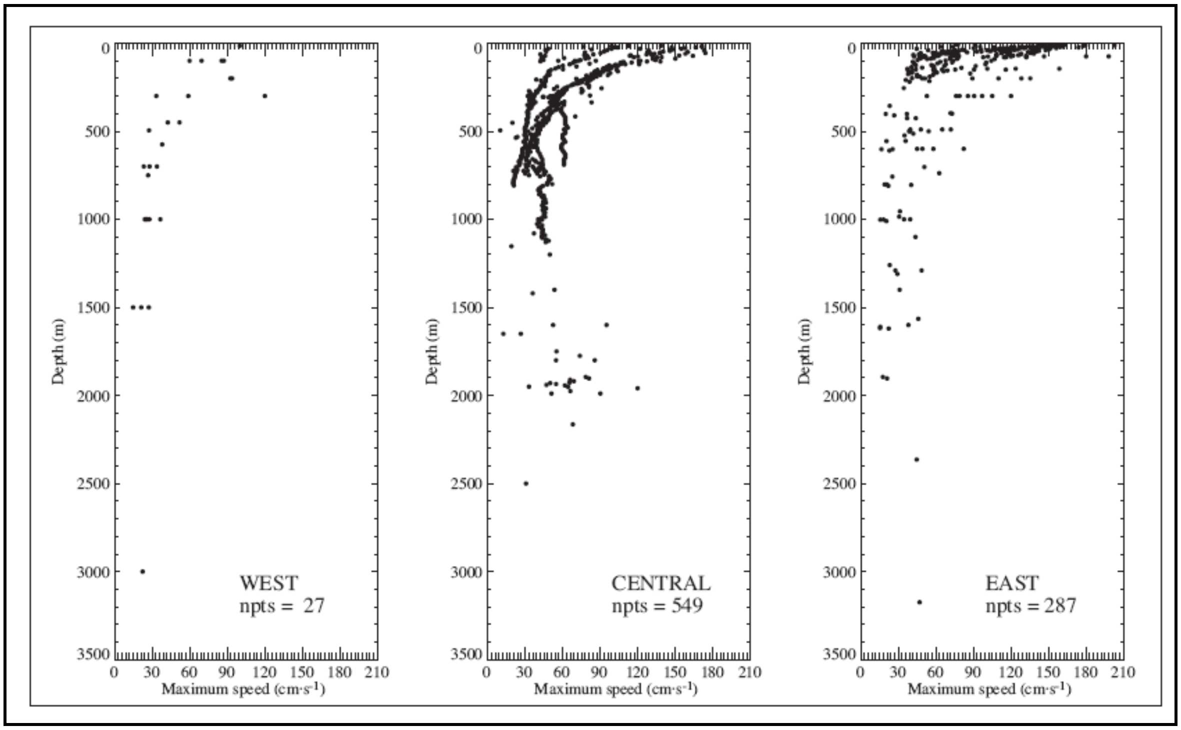


Fig. 1.5 – GOM maximum currents profile vs. depth. [22]

The northward penetration of the Loop Current into the Gulf of Mexico varies over time. When the penetration extends far enough into the Gulf, the Loop Current becomes unstable and a Loop Current Eddy (LCE) can separate (**Fig. 1.6**). The frequency of separation is irregular. LCEs are anticyclonic (clockwise circulating) rings, with surface intensified speeds of up to 4 knots. LCE currents extend down to approximately 3000 ft., with speeds decreasing from the surface with depth to ~0.2 knot at about 2000 ft. [22] LCEs also move westward into the western Gulf at average drift speeds of ~10 miles/d. The lifetimes of LCEs are up to one year.

Smaller eddies also exist in the Gulf. These include both anticyclonic eddies not from the Loop Current and cyclonic (counter-clockwise circulating) eddies. These eddies also have surface-intensified currents and can extend to about 3000 ft. depth. But they are generally less energetic than LCEs. Current speeds have been reported of up to 1 knot. [22]

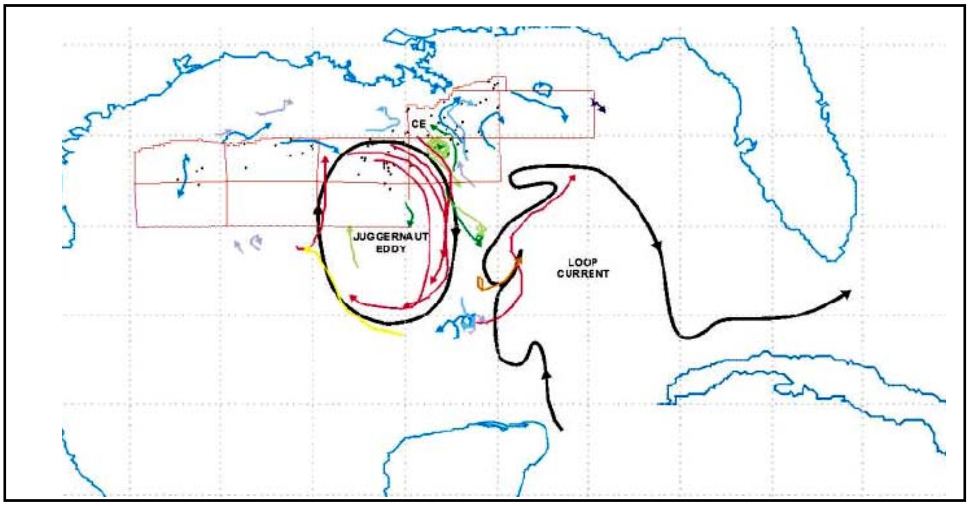


Fig. 1.6 – Loop and Eddie currents in the GOM. [23]

High-speed, subsurface-intensified current jets also are present in the Gulf, and may possibly be associated with the eddies. [24] These jets have durations of up to one day and maximum speeds that can exceed 4 knots, with the core of the high speed current occurring at 500-1200 ft.

The second major source of energy for the Gulf is atmospheric forcing, particularly energetic events such as hurricanes and wintertime extratropical cyclones. [22] Hurricane season in the GOM begins in May or June and lasts until October or November. The strong winds create high currents that may exceed 3 knots of surface speed. When combined with wave orbital velocities, the hurricane-induced currents can travel at speeds of as much as 6 knots.

During the colder months (November through April), a continental dry air flow enters the Gulf and can form extratropical cyclones. These atmospheric cyclones can generate energetic currents over the continental shelf and upper continental slope. On average, ten to twelve extratropical cyclones occur per year generating surface currents of 1 knot.

Specific conditions experienced in the GOM are listed in **Table 1.1.** Interpretation of the return periods can be done as follows:

1-year: used for concept study conditions.
5-year: winter storm conditions.
10-, 50-, and 100-year: hurricane conditions.

Table 1.1 – GOM metocean conditions in various return periods. [25]

Metocean Conditions		1-year	5-year	10-year	50-year	100-year
Winds, knots		40	62	70	100	112
Waves, ft	**Max Height**	30	43	50	75	85
	Sig. Height	16	24	28	42	48
	Period, s	10.3	11.7	12.3	14.3	14.9
Currents, knots	**Surface**	0.8	1.2	2.5	3.9	4.5
	Submerged	0.2	0.2	0.2	0.5	0.5
	Subsea	0.2	0.2	0.2	0.2	0.2

Fig. 1.7 shows various sea current profiles from worldwide locations. A summary of the values from **Fig. 1.7** are listed in **Table 1.2** along with other locations.

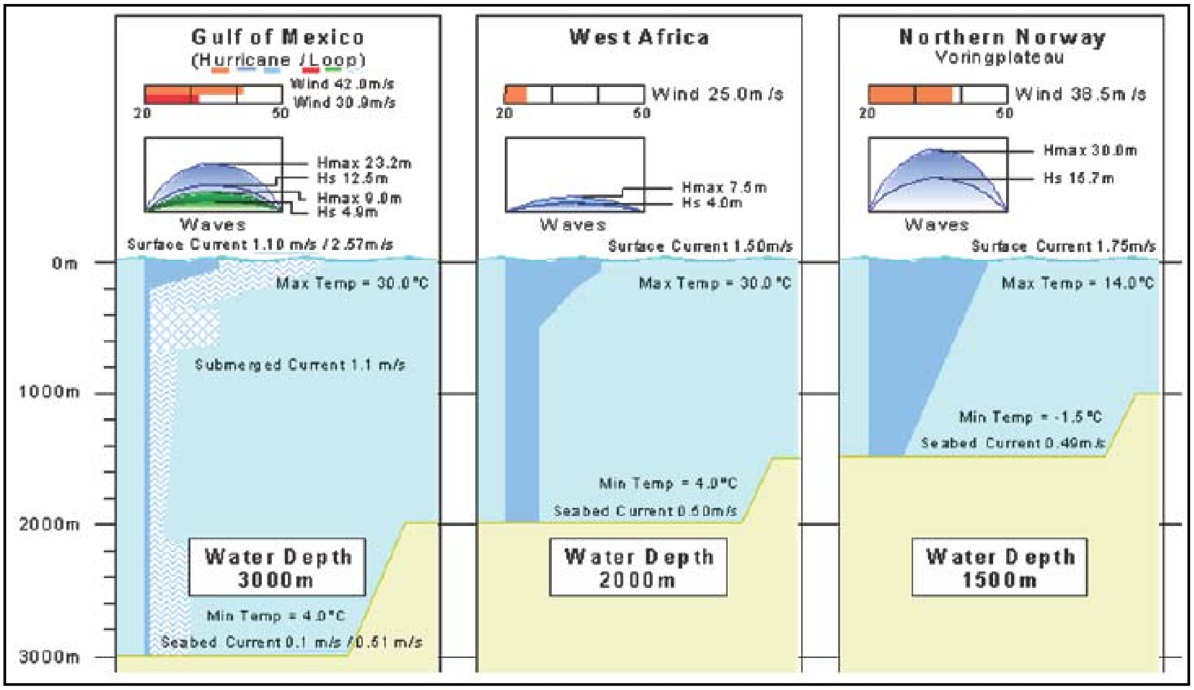


Fig. 1.7 – GOM, West Africa, and Northern Norway metocean conditions. [13]

Table 1.2 – 100-year return period comparison to the GOM. [13, 26]

Metocean Conditions		GOM	W. Africa	Norway	Brazil	Atlantic
Winds, knots		112	49	87	60	78
Waves, ft	**Max Height**	85	25	100	40	108
	Sig. Height	48	12	53	25	60
Currents, knots	**Surface**	4.5	3	3	2.5	3.5
	Submerged	0.5	--	--	1.1	--
	Subsea	0.2	1.1	0.9	--	1.1

2. BACKGROUND

In 2002 the Minerals Management Service (MMS) challenged the drilling industry by sponsoring a task force to develop a set of guidelines for SBOPs on mobile units [3] as a means to standardize practice and reduce accidents. The group consisted of operators, service companies, independent contractors, and regulatory agencies; each one with a specific contribution to the development of the project. The final version of the guidelines was published in 2004.

The study presented here follows the guidelines mentioned above, specifically bearing in mind the recommendations on the assessment process. This section covers the objectives and contribution of the research and explains the elements considered for the assessment.

2.1 Objective of the Study

The objective of this study is to determine the feasibility of installing a slim, high-pressure drilling riser for SBOP operations in deepwater Gulf of Mexico, by comparing the reliability of the drilling riser and overall well control system against the traditional low-pressure system. The assessment is done in two parts: first, a qualitative analysis is performed based on engineering judgment to provide an initial sense (preliminary diagnosis) on how the system behaves and to validate the risk models.

The second part of the study uses the same risk models previously built, but incorporates specific failure data from the GOM related to deepwater riser operations and the weather conditions experienced from 1999 to 2005. This quantitative analysis is done by screening reports filed by the MMS and other worldwide incident database to estimate high-pressure riser failures.

2.2 Expected Contribution

This paper should serve as a starting point for drilling companies and regulatory agencies to understand the risk of implementing a high-pressure riser for SBOP applications in the GOM, given that it includes specific failure events and conditions of the area. Despite the fact that the risk models are based on generic systems, they are flexible enough to be modified and adapted to a specific rig configuration and location.

The assessment also defines critical elements which might fail in the system allowing understanding of how each element interacts with one another and what can be modified or substituted to lower the overall risk. A relative ranking of the critical elements and their potential impact upon the overall system is provided.

2.3 System Description

The functional description of the system highlights individual elements to determine the reliability of the system. **Fig. 2.1** illustrates most of the equipment or parts of deepwater operations associated with the riser and pressure control systems used in this study.

The system description is divided into two parts; the first part lists the elements related with the drilling riser. Part two describes the elements associated with the overall pressure control system.

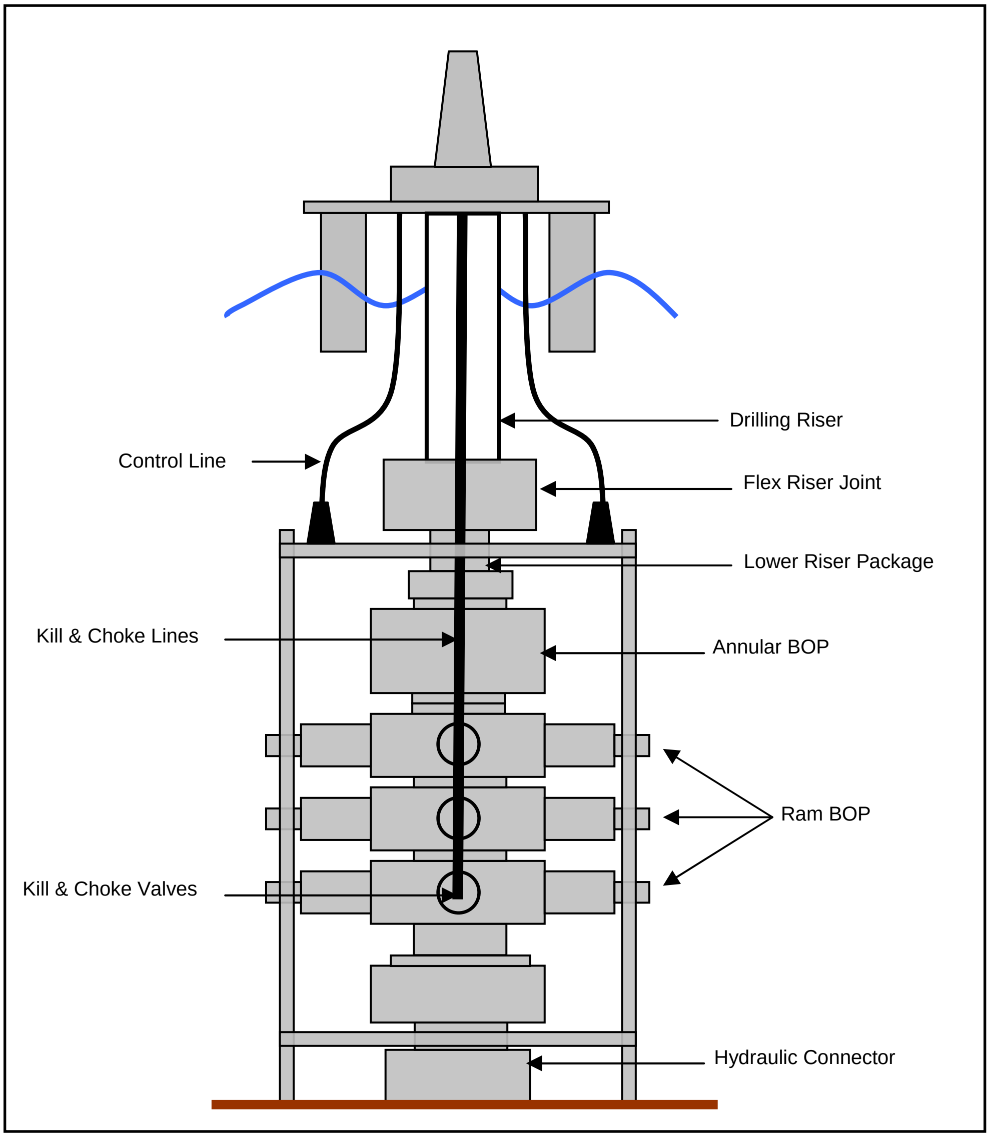


Fig. 2.1 – Overall deepwater drilling system.

2.3.1 Riser System

The description of the drilling riser led to the identification of thirteen general elements that affect the reliability of the system.

Boost Lines

Auxiliary lines attached to the riser to increase mud volume and sweep efficiency.

Burst/Collapse

Failure of the structure body of the riser due to internal or external forces applied to it.

Collision

Direct impact on the structure of the riser by an external factor (i.e. work boat, ships, another rig) that can interrupt drilling activities.

Connection Leakage

Leaks in the riser connections that can cause failure of the system.

Control System

Failures related to the automated control system that oversees riser operations.

Drillstring Induced Vibration, DIV

Riser wear caused by the rotation of the drillstring in the annulus.

Extreme Weather

Metocean conditions that cause the drilling riser to fail, such as winds, currents, waves, and hurricanes.

Human Error

Mistakes allocated to the operator when all systems are working properly but a wrong decision is made that compromises the drilling activity.

Kill and Choke Lines

Attached lines to the low-pressure riser used to circulate a kick and mud in well control operations.

Loss of Position

Refers to the failures in the positioning system attributed to a single or several mooring lines or, if the system is dynamically positioned to the servo motors that maintain the rig in place.

Loss of Support

Support system in charge of maintaining proper riser load and tension. This failure can be attributed to the heave compensator or the top tensioning system.

Riser Wear

Failures of the drilling riser due to cumulative long-term problems like corrosion and fatigue.

Vortex Induced Vibration, VIV

Vibrations that can cause fatigue stress in the riser attributable to the passage of sea currents.

2.3.2 Pressure Control System

The pressure control equipment and its main elements are described below. Note that the seabed isolating device (SID) shares the same elements as a BOP, but only operates in case of an emergency disconnection.

Annular Preventer

BOP stack upper element in charge of sealing the annular space to start well control operations.

Control System (BOP and SID)

Failures related to the automated control system that oversees BOP or SID operations.

Flex/Ball Joint

Top and bottom connections of the riser that permit its relative movement compared to the rig. Since each drilling unit can have a flex or a ball joint, no distinction of failure cause was made in this study.

Human Error (BOP and SID)

Mistakes allocated to the operator when all systems are working properly but a wrong decision is made that compromises the BOP or SID response.

Hydraulic Connector

Connectors attached to the ends of the riser to join the overall pressure control system; such as the lower and upper marine riser packages, the universal connection to the wellhead, and any transition joint.

Kill and Choke Control Valves (BOP and SID)

Valves that activate the BOP or SID functions; failures referred to these valves are local.

Pipe Ram (BOP)

BOP elements that can shear, hold, and close the borehole or drillpipe.

Pipe Ram (SID)

SID elements that can shear, hold, and close the borehole or drillpipe.

3. RISK MODELS

Using the correct tool ensures adequate approach when comparing systems; this section outlines the risk assessment process by describing the risk models, fault-tree analysis and risk calculations.

3.1 Risk Procedure

In order to properly assess the risk in a system, simple but important steps should be followed to ensure reliability of the analysis. **Fig. 3.1** outlines the general process to analyze risks. [27] Detailed information, such as the assumptions and considerations from each of the steps followed in the assessment are discussed ahead.

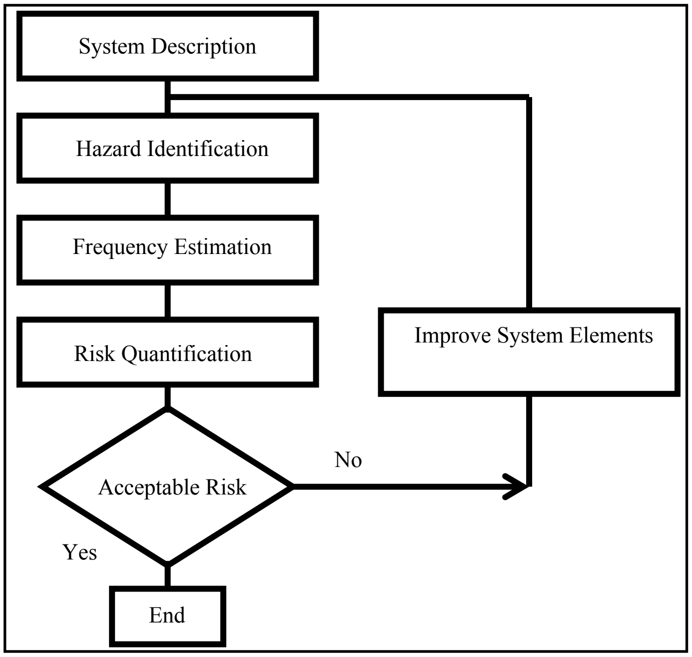


Fig. 3.1 – Risk assessment process.

To evaluate risk in this study, three fault tree models were built to represent each configuration (subsea BOP, SBOP, and SBOP with seabed isolating device) based on a functional description of the elements in relationship with the overall system.

3.2 Fault Tree Analysis

Fault tree analysis (FTA) is a statistical tool that can be used to determine the probability of an outcome of a single event based on logical element interaction through a graphical representation. The structure of the tree is based on a *top event* that would be the undesired outcome traced back to a series of *basic events* that can influence the outcome of the tree; these *basic events* are connected to a *gate symbol* which determines their relation to the failure. [28] The most common elements are shown in **Fig. 3.2**. The *event symbols* describe each element based on their nature and relation to the *top event*. A more detailed description of each element is presented in Appendix B.

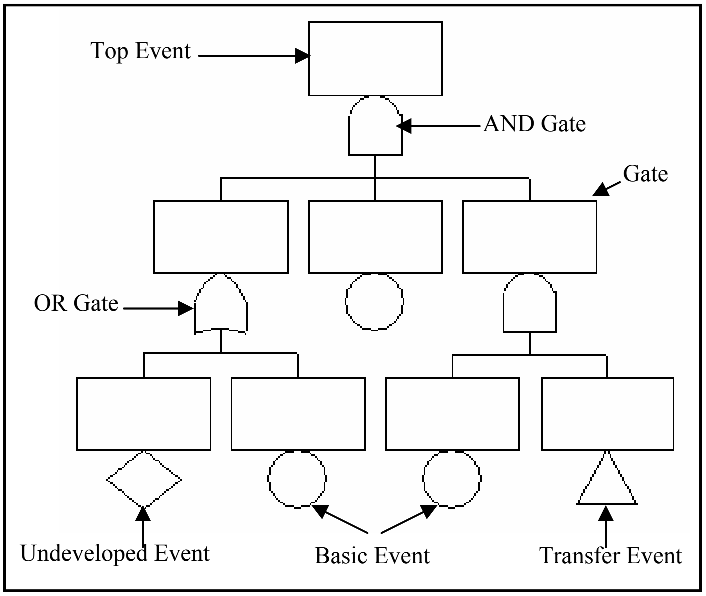


Fig. 3.2 – Common FTA elements. [29]

The *cut set* of the fault tree is the array of *basic event* such that if all these *basic events* occur then the t*op event* will happen; becoming a critical set if the path has the minimum number of elements to occur.

3.2.1 Fault Tree Models

The risk models can be used for either the quantitative or qualitative analysis, given that their functional structure is the same. An illustration of the trees is shown in **Fig. 3.3**. The complete fault tree models evaluated are shown in Appendix B, which are different from the models in this section due to limitations on the number of pages that could be used, which forced to accommodate a large number of *basic events* in a single page.

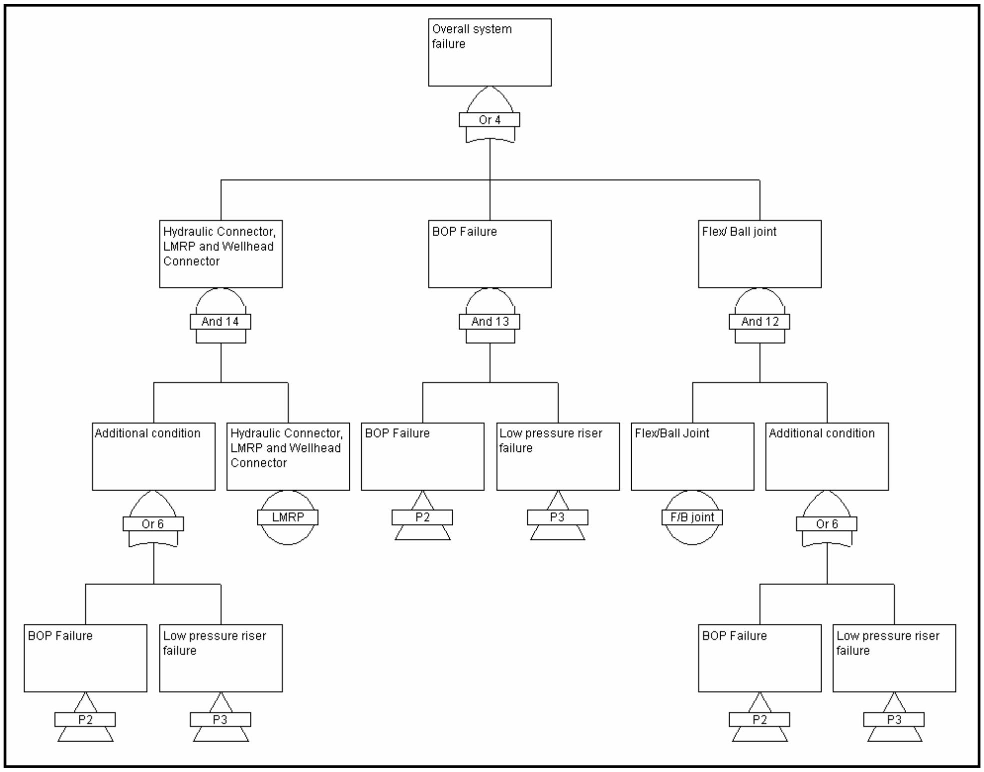


Fig. 3.3 – Simplified overall system fault tree.

The *top event* for the fault tree was the failure of the overall riser system connected to the pressure control equipment. Only important or relevant elements were considered. **Fig. 3.3** is supported by **Figs. 3.4 to 3.8.**

Fig. 3.4 describes the interaction of the general elements associated with the BOP failures, the SBOP model has all the elements as the subsea system except for the kill and choke lines.

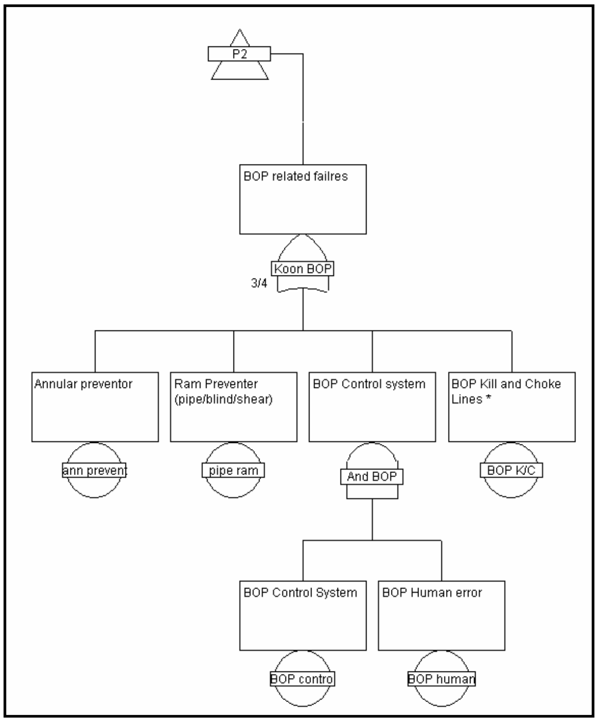


Fig. 3.4 – BOP related failures.

Fig. 3.5 describes the interaction of the riser elements related to the overall failure of the drilling riser. The model is based on failures related to external parameters (**Fig. 3.6**) and failures associated with internal conditions (**Fig. 3.7**).

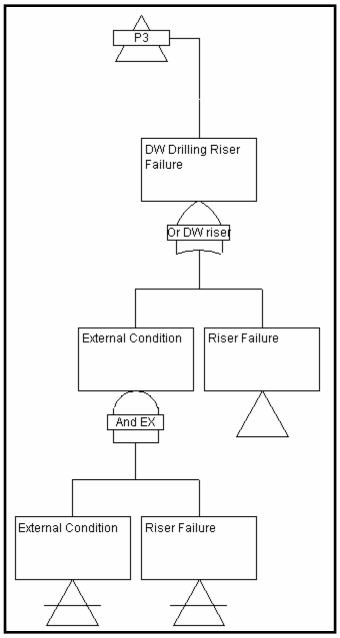


Fig. 3.5 – Drilling riser overall related failures.

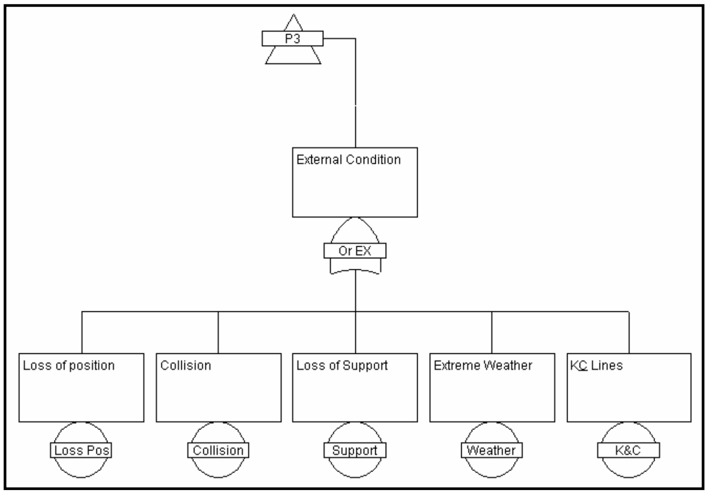


Fig. 3.6 – Drilling riser external elements.

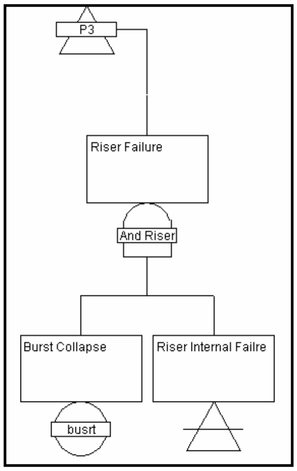


Fig. 3.7 – Drilling riser failure.

Fig. 3.8 describes the internal elements in the riser failure model. The SBOP array does not include the boost line element.

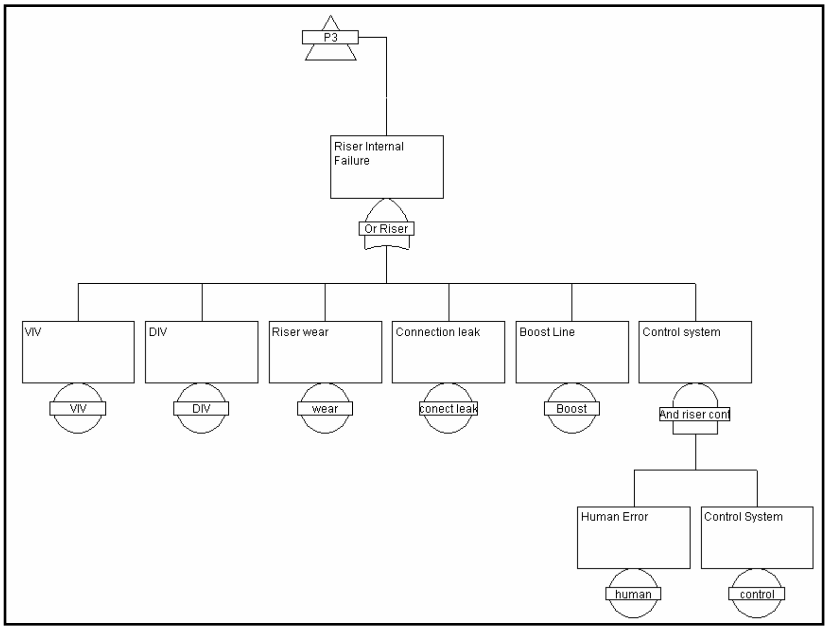


Fig. 3.8 – Drilling riser internal elements.

3.3 Risk

For this study, the term probability will be used to express the chance of an event to occur over a period of time; and reliability as "the ability of an item to perform a required function under given environmental and operational conditions for a stated period of time". [5]

A general risk definition can be expressed as "a term which combines the chance that a specific hazardous event will occur and the severity of the consequences of the event" [30] (ISO 13702). Mathematically speaking it can be represented as:

$R = f(p,C)$……………………………………………3.1

p = probability
C = Consequence

A graphical interpretation of risk is shown in **Fig. 3.9.**

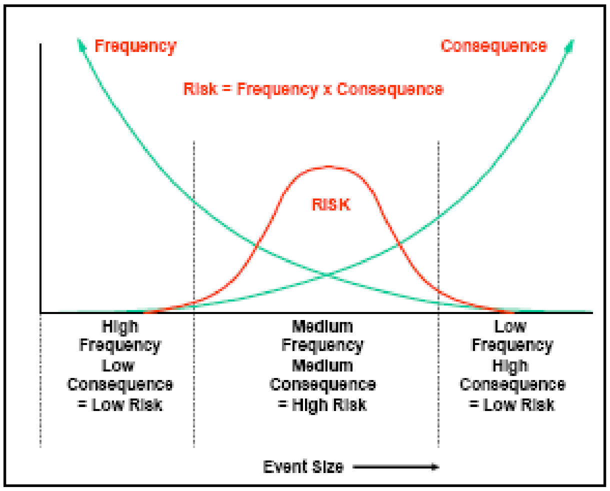


Fig. 3.9 – Example of a normal risk distribution. [3]

3.4 CARA Fault Tree

The software used for the risk assessment was the academic version of Cara Fault Tree Ver. 4.1. [28] This program is capable of determining the statistical parameters required for a detailed evaluation of the reliability of the system. A summary of the theory behind the calculations is presented below.

The type of data used for this study is considered to be *non-repairable*, which is used for elements that are not repaired when a failure occurs.

3.4.1 Input

The input used for the fault-tree model analysis is the conditional failure intensity ($\lambda_{(t)}$), which states that "t*he probability that the element fails per unit of time at time t, given that it is in the normal state at time zero and is normal at time t.*" [31]

The failure intensity and the failure rate are the same when elements are non-repairable.

3.4.2 Parameters Calculated

$Q_0(t)$

$Q_0(t)$ is the probability that the overall *top event* occurs at time *t*. If the state of each element is known at time *t*, then the state of the *top event* can also be determined regardless of what has happened up to time *t*.

$R_0(t)$

$R_0(t)$ is the probability that the *top event* has not occurred in the time period from 0 to *t*., depending on what has happened in the time interval. When all elements have failure data of *non-repairable* unit category, we have:

$$Ro(t) = 1 - Qo(t) \text{……………………….…………}3.2$$

Mean Time to Failure (MTTF)

MTTF is the mean time to the first occurrence of the *top event*, by assuming that all elements are functioning at time *t*. The MTTF can be represented by **Eq. 3.3, w**here T_i is the time of the first *top event* to occur.

$$MTTF = \frac{\sum_i T_i}{No.\text{ of runs with at least one top event}} \text{…..}3.3$$

The MTTF can also be expressed as the inverse of the failure rate (**Eq. 3.4**), when all elements have *non-repairable* data.

$$MTTF = \frac{1}{\lambda} \text{…………………………………………}3.4$$

3.4.3 Type of Statistical Analysis

$R_0(t)$ Survival Probability

The survival probability is a function of the non-occurrence of the *top event*, by always having that $R_0(t) < 1 - Q_0(t)$, unless all the inputs from elements are *non-repairable* in which case they are the same. The simulation is performed by a numerical integration since in most cases The Monte Carlo Simulation gives inaccurate values for very reliable systems. [28]

The numerical integration model is based on the kinetic tree theory [4] to establish an upper bound approximation for $Q_0(t)$. By denoting the minimal cut sets $k_1, k_2, ..., k_k,$ the probability of occurrence for the cut set k_j is:

$$\overset{u}{Q}_j(t) = \prod_{iek_j} q_i(t) \text{ ……………………….…………..3.5}$$

Now introduce:

$w_i(t)$ = failure frequency of the i'th element
$wk_j(t)$ = failure frequency of cut set k_j
$w_0(t)$ = unconditional failure frequency

The system unconditional failure frequency, which expresses the probability that the *top event* occurs per unit of time at time *t* can now be obtained by:

$$w_o(t) = \sum_{j=1}^{k} \frac{\partial Q_o(t)}{\partial \overset{u}{Q}_j(t)} wk_j(t) \text{ ………………………..…3.6}$$

Where the sensitivity of the probability of failure to the probability of failure of the j'th element can be approximated to:

$$\frac{\partial Q_o(t)}{\partial \overset{u}{Q}_j(t)} \approx 1-\sum_{\substack{i=1\\ i\neq j}}^{k} \overset{u}{Q}_i(t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.7$$

And

$$w_{k_i}(t)=\sum_{j=1}^{k}\frac{\partial \overset{u}{Q}_j(t)}{q_i(t)}[1-q_i(t)]\lambda_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.8$$

The system failure rate is defined by:

$$\lambda_o(t)=\frac{w_o(t)}{1-Q_o(t)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.9$$

Assuming that the failure rate remains constant through time, we can obtain by numerical integration:

$$R_o(t)=e^{-\int_0^{\infty}\lambda_o(x)dx} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.10$$

$$MTTF=\int_0^{\infty}R_o(t)dt \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.11$$

The above formulas **(Eq. 3.5 to 3.11)** only apply to very reliable systems, which in most cases describe the ideal system conditions or work with generic models. For unreliable or real systems, the formulas are inaccurate; therefore the assumptions are not valid and stochastic simulation must be considered.

Frequency of the top event

The frequency of the *top event* is the expected number of occurrences the *top event* has over a time period, determined by the probabilities P(X=0), P(X=1), P(X=2) etc., the expected value of X is given by:

$E(X)=\sum_{i=0}^{\infty} i*P(X=i)$ ……………………………..……3.12

If the times between consecutive occurrences of the *top event* are exponentially distributed (constant failure rate), then the number of failures X, in a unit period of time will be a Poisson distribution [5, 28] with parameter χ = 1/E(X) and the distribution of X is given by:

$P(\chi=i)=\frac{\lambda^{i}}{i!}e^{-\lambda}$ ………………………………….…...3.13

Probability of the top event

$Q_0(t) = P$……………………………………….....…3.14

The probability that the *top event* occur follows an upper bound approximation, by assuming the independence of each input event. The probability that all input events in the minimal cut set K_j occur, is:

$\overset{u}{Q}_j(t)=\prod_{iek_j} q_i(t)$ …………………………………..…3.15

If the cut sets were separate, then they would be stochastically independent and we would have:

$$Q_o(t)1-\prod_{j=1}^{k}(1-\overset{u}{Q}_j(t))\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ldots 3.16$$

In general, however, the minimal cut sets are not disjointed. In this case it may be shown that we always have:

$$Q_o(t)\leq 1-\prod_{j=1}^{k}(1-\overset{u}{Q}_j(t))\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots...\ldots\ldots 3.17$$

Uncertainty Analysis

The uncertainty analysis is used to model uncertainties of the input parameters by a log-normal distribution (**Fig. 3.10**). The input for each parameter is their mean value or the median *m*, and an error factor *k* to express confidence over the value *m*. If the failure rates are estimated from available failure data, then *m* may be set to the value of some point for the true failure rate, and a confidence interval for the failure rate may be used to compute *k*.

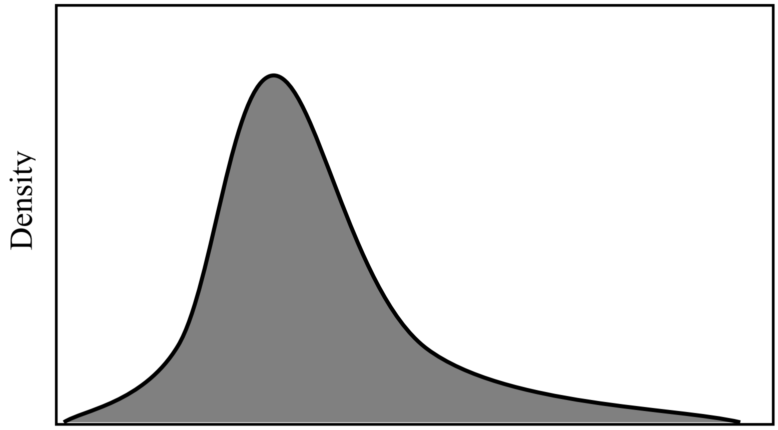


Fig. 3.10 – Example of log-normal distribution.

The uncertainty of $Q_0(t)$ is represented by the probability distribution of $Q_0(t)$ using a Monte Carlo Simulation to approximate the distribution of $Q_0(t)$. The simulation calculates the event probability $Q_0(t)$ by the upper bound approximation, giving a random set of values for $Q_0(t)$, from which the mean value, the variance and the standard deviation of $Q_0(t)$ are estimated. To save computational time, the ten input parameters to have the largest impact on $Q_0(t)$ are taken from the log-normal distribution of the system, and the remaining parameters use their mean/median values. The results are then presented in a histogram of the frequency distribution (**Fig. 3.11**).

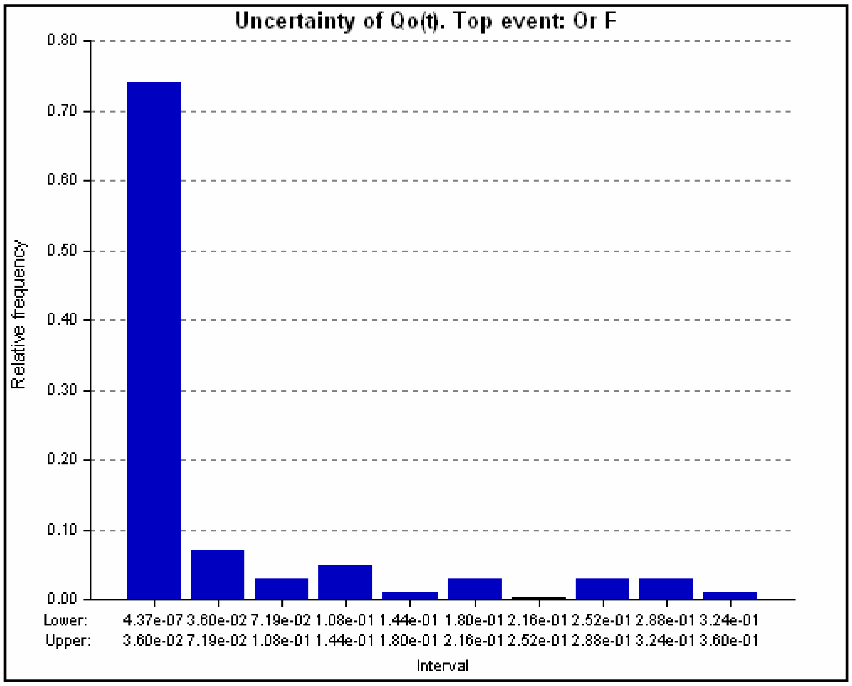


Fig. 3.11 – Example of frequency distribution.

4. FAILURE RATES

In order to evaluate the risk models, failure rates of each element must be determined to be input in the fault tree arrays. Both the qualitative and the quantitative analyses require a set of individual values to estimate the overall risk associated. The failure rates for the qualitative analysis were estimated using engineering judgment to test the fault trees and to understand the interaction of each element with the system. The qualitative failure rates were obtained by compiling incidents reported to the MMS in the GOM and other worldwide incidents in deepwater to create a generic dataset for this study. The development of the database is the most critical task when performing the risk assessment, in view of the fact that it determines the credibility of the results.

4.1 Qualitative Failure Rates

The failure rate and consequence level of each element was assigned based on experiences reported in the literature, and an educated guess to estimate the overall risk through **Eq. 3.1**.

The use of a risk matrix allows graphical interpretation of what the risk is and its location in relationship with the acceptance level. For this study an acceptable risk is considered an event that either has a low chance of occurring and high consequence, or an event that has a high chance of occurring and a low consequence, as seen in **Fig. 3.9**. Events with a mixed combination are described in the caution zone, and events with high probability and high consequence are considered unacceptable. **Fig 4.1** shows the risk matrix for the qualitative analysis and the acceptance limits for this study. **Tables 4.1 and 4.2** list the failure rate estimates and the calculated risk.

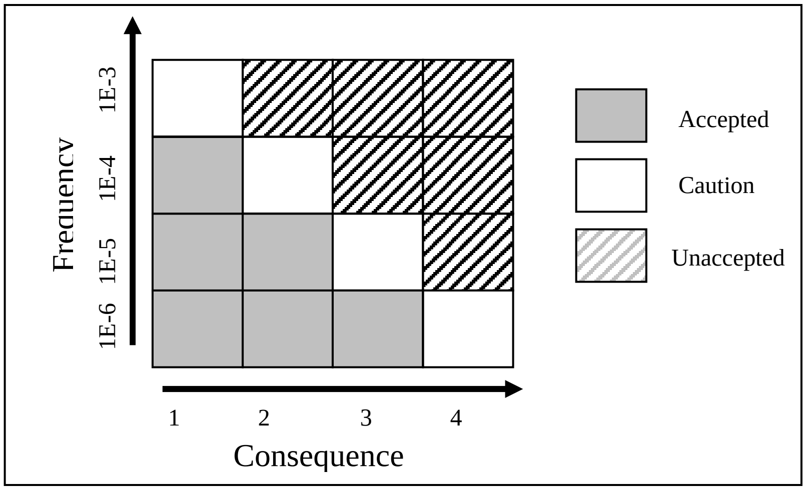


Fig. 4.1 – Risk matrix criteria.

Table 4.1 – Low-pressure riser and subsea BOP qualitative failure frequency.

Riser Element	Frequency	Consequence	Risk
Boost Lines	1.0E-04	2	2.0E-04
Burst/Collapse	1.0E-06	4	4.0E-06
Collision	1.0E-05	2	2.0E-05
Connection Leakage	1.0E-05	2	2.0E-05
Control System (riser)	1.0E-05	3	3.0E-05
DIV	1.0E-04	3	3.0E-04
Extreme Weather	1.0E-03	3	3.0E-03
Human Error (riser)	1.0E-03	4	4.0E-03
Kill & Choke Lines	1.0E-04	2	2.0E-04
Loss of Position	1.0E-05	3	3.0E-05
Loss of Support	1.0E-05	3	3.0E-05
Riser Wear	1.0E-04	4	4.0E-04
VIV	1.0E-04	3	3.0E-04
BOP Element			
Annular Preventer	1.0E-05	2	2.0E-05
Control System (BOP)	1.0E-05	3	3.0E-05
Flex/Ball Joint	1.0E-06	4	4.0E-06
Human Error (BOP)	1.0E-03	4	4.0E-03
Hydraulic Connector	1.0E-05	4	4.0E-05
Kill & Choke Control Valves	1.0E-05	3	3.0E-05
Pipe Ram	1.0E-04	2	2.0E-04

Table 4.2 – High-pressure riser, SBOP, and SID qualitative failure frequency.

Riser Element	Frequency	Consequence	Risk
Boost Lines	---	---	---
Burst/Collapse	1.0E-06	4	4.0E-06
Collision	1.0E-05	2	2.0E-05
Connection Leakage	1.0E-05	2	2.0E-05
Control System (riser)	1.0E-05	3	3.0E-05
DIV	1.0E-05	3	3.0E-05
Extreme Weather	1.0E-03	3	3.0E-03
Human Error (riser)	1.0E-03	4	4.0E-03
Kill & Choke Lines	---	---	---
Loss of Position	1.0E-05	3	3.0E-05
Loss of Support	1.0E-05	3	3.0E-05
Riser Wear	1.0E-05	4	4.0E-05
VIV	1.0E-05	3	3.0E-05
BOP Element			
Annular Preventer	1.0E-04	2	2.0E-04
Control System (BOP)	1.0E-05	3	3.0E-05
Flex/Ball Joint	1.0E-06	4	4.0E-06
Human Error (BOP)	1.0E-03	4	4.0E-03
Hydraulic Connector	1.0E-05	4	4.0E-05
Kill & Choke Control Valves	1.0E-05	2	2.0E-05
Pipe Ram	1.0E-04	2	2.0E-04
SID Element			
Control System (SID)	1.00E-05	3	3.0E-05
Human Error (SID)	1.00E-03	4	4.0E-03
Kill & Choke Control Valves (SID)	1.00E-05	2	2.0E-05
Pipe Ram (SID)	1.00E-04	2	2.0E-04

4.2 Quantitative Failure Rates

Failure rate calculations for the quantitative analysis were based on the development of a specific dataset from incidents related to deepwater riser systems. The complete failure set can be found in Appendix C.

In order to determine the failure rate of each element, it is necessary to establish the reference base time. For this study the time frame considered is operational MODUs drilling days in deepwater GOM. A summary of the total time all units worked in the past years is listed in **Table 4.3.**

Table 4.3 – MODUs drilling days in the GOM. [32]

Year	Drillships	Semisubmersibles
1999	18	697
2000	1666	6654
2001	2448	8339
2002	2310	6223
2003	2276	6206
2004	2257	4887
2005* (Aug.)	1025	3686
Total	48,692	

The element day in service is the product of the MODUs time and the number of times each element is run, or used in relationship with the reference time, **Eq. 4.1.**

$$t_{elem} = N \, x \, t_{MODU} \quad \ldots\ldots 4.1$$

N = number of times an element is used in relationship with a reference time.
t_{MODU} = operational MODU time.

Incidents reported to the MMS were used to build a failure database to accommodate for the specific conditions and situations that had occurred in the GOM in the past five years to estimate the element failure rates. Even though the dataset from the MMS is very reliable, there still might be some minor incidents that have not been reported or not published to date, thus there is some uncertainty in its reliability. A summary of the screening of the incidents reported to the MMS is presented in **Table 4.4**. In **Table 4.5** is a list of the main causes of riser related incidents in deepwater GOM.

Table 4.4 – Incidents reported to the MMS 1999-2005. [33]

MMS Database	Num.
Total Incidents	1,254
Deepwater	139
DW-Riser Related	15

Table 4.5 – Deepwater GOM riser related incidents. [33]

Main Cause	Num.
Equipment	7
Human Error	5
Weather	3

Since SBOP operations have not been yet implemented in the GOM deepwater region, it is impossible to estimate the failure rate of the high-pressure riser elements with MMS reports. Therefore, other databases were consulted to estimate more precisely the failure of slim risers in harsh metocean conditions. The Petroleum Safety Authority Norway (PETROLEUMSTILSYNET) keeps track of offshore incidents in its Corrosion and Damage Database (CODAM), which is available to the public, and dates from 1975. A summary of the riser incidents that CODAM has is listed in **Table 4.6.** In order to incorporate the CODAM failure rates into the models, the riser failure tree had to be modified to accommodate for the details of the data. See **Fig. 4.2.**

Table 4.6 – CODAM riser related incidents 1975-2005. [34]

	Diameter Size	
Type of Failure	< 16"	> 16"
Major	30	29
Minor	88	128
Insignificant	200	418
Total	893	

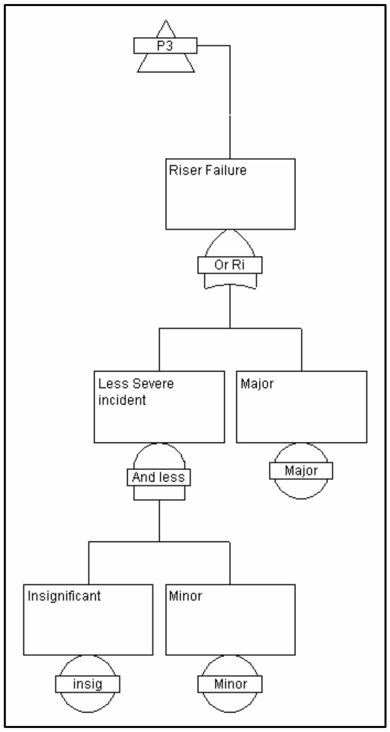


Fig. 4.2 – Modified riser fault tree for CODAM dataset.

Another database consulted to estimate slim riser failures is the one kept by the United Kingdom Health and Safety Executive (HSE) called Pipeline and Riser Loss of Containment (PARLOC), which keeps track of pipeline incidents reported in offshore areas of the North Sea. A summary of the riser related incidents reported in the 2001 report is listed in **Table 4.7**. Note that this is the latest version available to the public at the time of this study.

Table 4.7 – PARLOC riser related incidents 2001 report. [35]

Riser Diameter	Time, days	Num. Failures
9 to 16 – in	1,882,670	30

To include the PARLOC riser failure rate, the riser fault tree had to be simplified, see **Fig 4.3.**

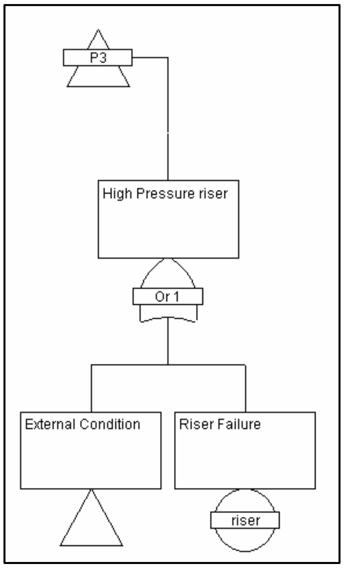


Fig. 4.3 – Modified riser fault tree for PARLOC dataset.

To estimate the failure frequency of the SBOP elements, generic values from a study in the GOM by SINTEF [8] were used as reference. Despite the fact that the work was done in subsea BOPs, the values can be used as a starting point to analyze SBOP behavior since there is no change in the elements themselves; only in the number each stack has. A summary of the values obtained from the study is listed in **Table 4.8.**

Table 4.8 – SINTEF BOP failure rates. [8]

BOP Element	BOP Days	Service Days	Num. Failures	Failure Rate
Annular Preventer	4,009	7,449	12	1.61E-03
Hydraulic Connector	4,009	8,018	10	1.25E-03
Flex/Ball Joint	4,009	4,009	1	2.49E-04
Pipe Ram (Generic)	4,009	16,193	11	6.79E-04
Kill & Choke Control Valves	4,009	35,419	21	5.93E-04
Control System (BOP)	4,009	4,009	60	1.50E-02

Since the riser failure rates were estimated from locations different from the GOM region, it is necessary to combine the data with reports from the MMS to obtain a generic dataset valid for the GOM. The same procedure is used for the SINTEF BOP estimates. The combination of data is based on Bayes' weighed estimation, [30] **Eq. 4.2.**

$$\lambda_{weighed} = \frac{N_{specific} + N_{generic}}{t_{specific} + t_{generic}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.2$$

N = number of occurrences.
t = observation time.

This estimation is possible by assuming that the failures follow a Poisson distribution and the failure rate remains constant, which is the case for *non-repairable* events.

A summary of the calculated failure rates for both the low-pressure subsea BOP system and the high-pressure SBOP is listed in **Tables 4.9 to 4.13**, including the generic dataset created to estimate riser failures.

Table 4.9 – Low-pressure riser and BOP quantitative failure rates: MMS.

Riser Element	MODUs Days	Service Days	Num. Failures	Failure Rate
Boost Line	48,692	97,384	2	2.05E-05
Burst/Collapse	48,692	48,692	1	2.05E-05
Collision	48,692	48,692	0	0
Connection Leakage	48,692	146,076	0	0
Control System (riser)	48,692	48,692	0	0
DIV	48,692	48,692	0	0
Extreme Weather	48,692	48,692	5	1.03E-04
Human Error (riser)	48,692	48,692	4	8.21E-05
Kill & Choke Lines	48,692	97,384	0	0
Loss of Position	48,682	48,682	2	4.11E-05
Loss of Support	48,692	48,692	0	0
Riser Wear	48,692	48,692	0	0
VIV	48,692	48,692	1	2.05E-05
BOP Element				
Annular Preventer	48,692	97,384	1	1.03E-05
Control System (BOP)	48,692	48,692	2	4.11E-05
Flex/Ball Joint	48,692	48,692	0	0
Human Error (BOP)	48,692	48,692	2	4.11E-05
Hydraulic Connector	48,692	97,384	0	0
Kill & Choke Control Valves	48,692	146,076	1	6.85E-06
Pipe Ram	48,692	194,768	0	0

Table 4.10 – High-pressure riser, SBOP, and SID quantitative failure rates: MMS.

Riser Element	MODUs Days	Service Days	Num. Failures	Failure Rate
Boost Line	48,692	---	---	---
Burst/Collapse	48,692	48,692	0	0
Collision	48,692	48,692	0	0
Connection Leakage	48,692	146,076	0	0
Control System (riser)	48,692	48,692	0	0
DIV	48,692	48,692	0	0
Extreme Weather	48,692	48,692	5	1.03E-04
Human Error (riser)	48,692	48,692	0	0
Kill & Choke lines	48,692	---	---	---
Loss of Position	48,682	48,682	0	0
Loss of Support	48,692	48,692	0	0
Riser Wear	48,692	48,692	0	0
VIV	48,692	48,692	0	0

Table 4.10 – Continued.

BOP Element	MODUs Days	Service Days	Num. Failures	Failure Rate
Annular Preventer	48,692	48,692	0	0
Control System (BOP)	48,692	48,692	0	0
Flex/Ball Joint	48,692	48,692	0	0
Human Error (BOP)	48,692	48,692	0	0
Hydraulic Connector	48,692	97,384	0	0
Kill & Choke Control Valves	48,692	97,384	0	0
Pipe Ram	48,692	146,076	0	0
SID Element				
Control System (SID)	48,692	48,692	0	0
Human Error (SID)	48,692	48,692	0	0
Kill & Choke Control Valves (SID)	48,692	48,692	0	0
Pipe Ram (SID)	48,692	97,384	0	0

Table 4.11 – Combined CODAM riser failure rates.

Diameter < 16"	Num. Failures	Failure Rate
Major	30	7.86E-04
Minor	88	3.46E-04
Insignificant	200	1.18E-04

Table 4.12 – Combined PARLOC riser failure rates.

Riser Diameter	MODUs Days	CODAM Days	Num. Failures	Failure Rate
9 to 16 - in	48,692	1,882,670	30	1.55E-05

Table 4.13 – Combined SINTEF BOP failure rates.

BOP Element	BOP Days	Service Days	Num. Failures	Failure Rate
Annular Preventer	4,009	56,141	12	2.14E-04
Hydraulic Connector	4,009	105,402	10	9.49E-05
Flex/Ball Joint	4,009	52,701	1	1.90E-05
Pipe Ram	4,009	162,269	11	6.78E-05
Pipe Ram (SID)	---	113,577	11	9.69E-05
Kill & Choke Control Valves	4,009	132,803	21	1.58E-04
Kill & Choke Control Valves (SID)	4,009	132,803	21	1.58E-04
Control System (BOP)	4,009	52,701	60	1.14E-03

4.3 Confidence Limits

In order to set the reliability of the dataset it was necessary to test different confidence limits that would serve as boundaries to the range of possible values when performing the random sampling of the values (stochastic) because specific values for the region were not found for the high-pressure system.

The approximation of the upper and lower confidence limits is based on the use of a Chi-square distribution, [30] which can estimate values even when there is no recorded failure of a particular event, as shown in **Eq 4.3 and 4.4.**

$$\text{Lower \% limit} = \frac{\chi^{\alpha/2}\, 2N}{2H} \quad \text{………………..………4.3}$$

$$\text{Upper \% limit} = \frac{\chi^{1-\alpha/2}\, 2N+2}{2H} \quad \text{…………………...4.4}$$

Where:

N = Number of Fatalities
H=Total Time

Failure rates estimated from the MMS reports were given a 90% confidence interval; and rates calculated from the CODAM and PARLOC datasets were given values of 70%, 80%, and 90% to perform a sensitivity analysis of their impact on the results. The complete dataset with the confidence limits can be found in Appendix D. As a example of the graphical representation of the confidence interval **Figs. 4.4 and 4.5** show the values from **Table 4.10** with an 80% confidence limits.

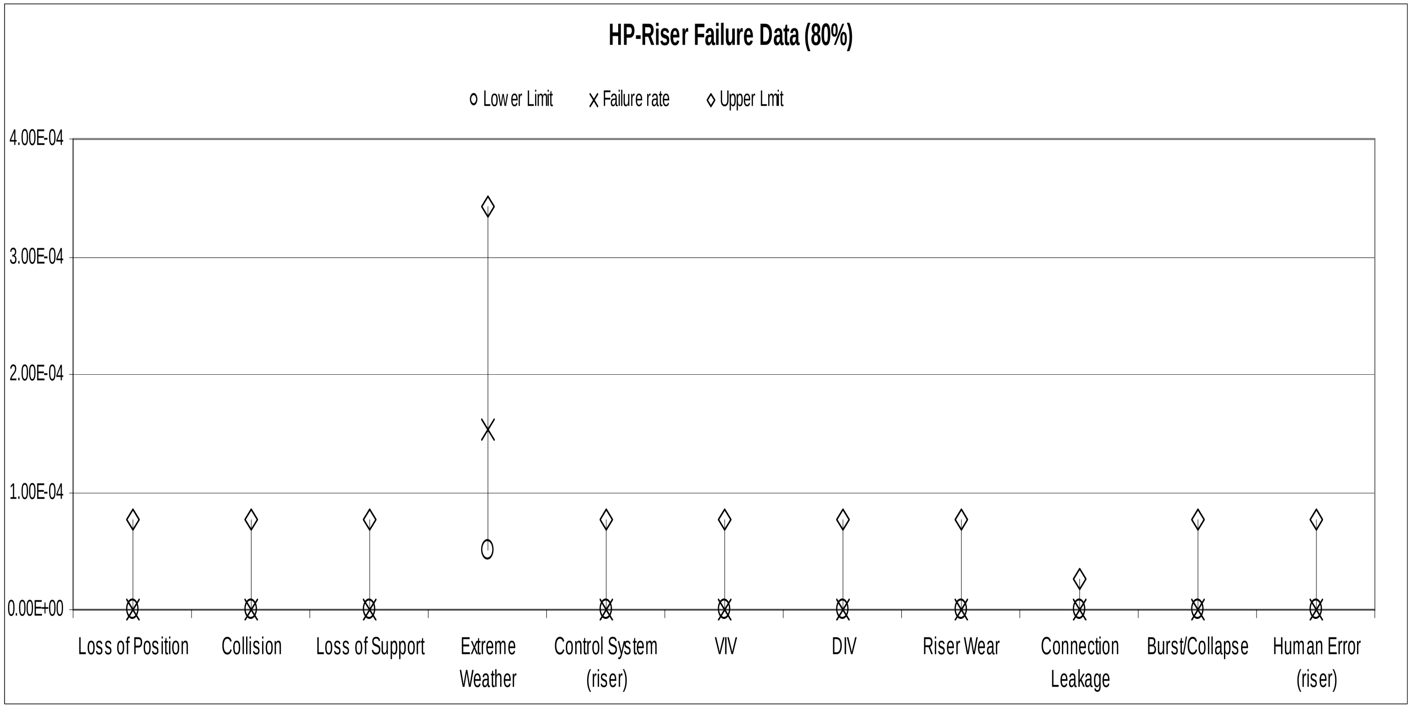


Fig. 4.4 - HP riser data from table 4.10.

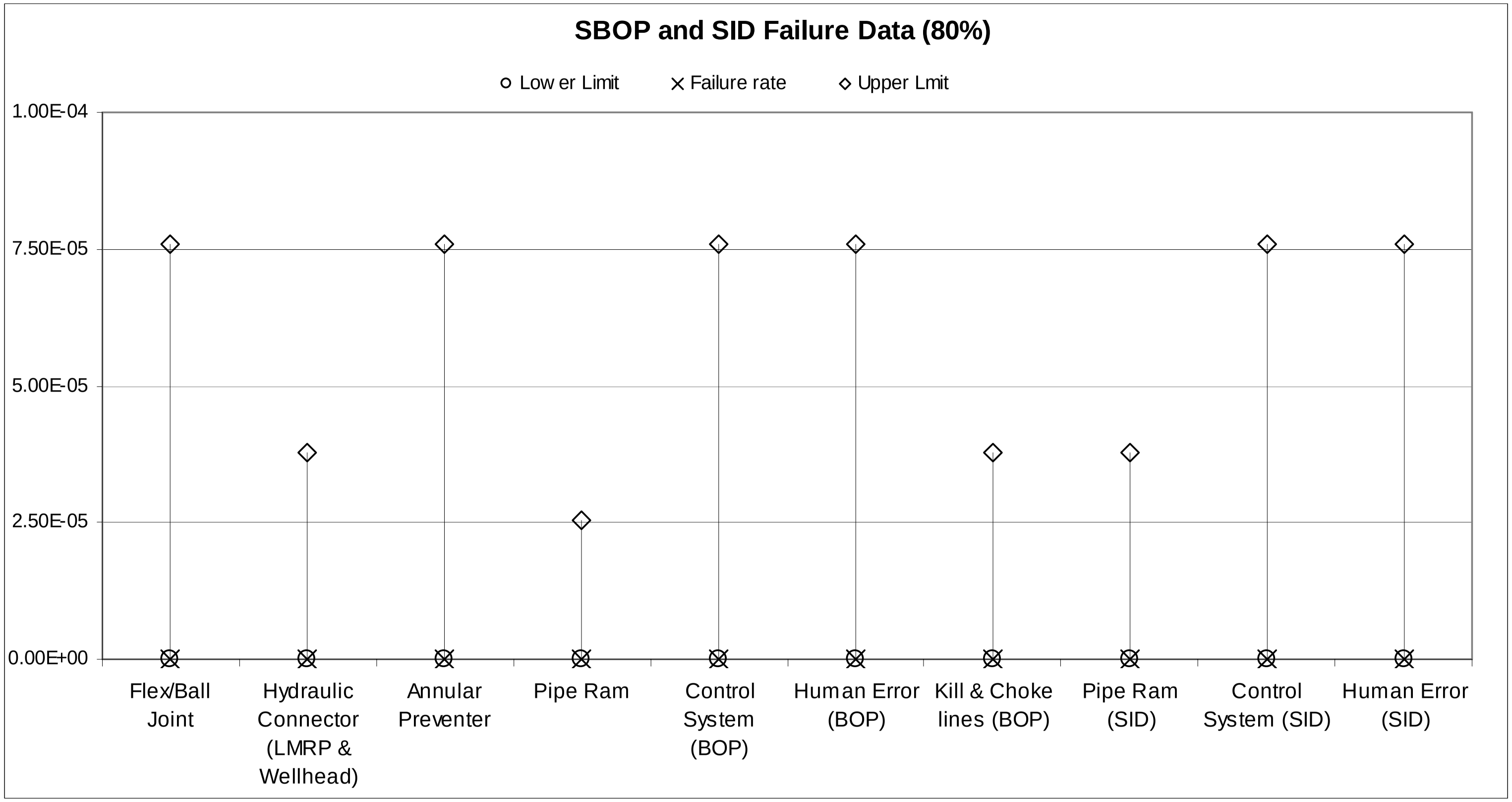


Fig. 4.5 – SBOP and SID data from table 4.10.

5. RESULTS

Results from the most significant runs are presented in this section; the rest can be found in Appendix D. In both analyses: qualitative and quantitative, the riser system response was compared first, and then the entire pressure control array. Every model was tested with the same statistical tool and time interval. The testing time was set to guarantee complete drilling activity in a single well under any condition.

Two criteria were used to compare the systems: Ro(t) (probability that the *top event* does not occur) and failure rate (λ); which estimates the number of failures that will occur over a specific time, and identifies the level of the risk calculated and the MTTF through **Eq. 3.4.**

5.1 Qualitative Analysis Results

The qualitative analysis was tested in two time intervals: 1-year (8,760 hours) and 0.5-year (4,380 hours) of continuous work to observe the risk models behavior through time. The results are listed in **Tables 5.1 and 5.2**.

Table 5.1 – Qualitative riser comparison: Monte Carlo simulation.

Riser Type	Ro(t), 8,760 h	λ # fail/time	Ro(t), 4,380 h	λ # fail/time
Low-pressure	84 %	3.42×10^{-05}	87 %	2.74×10^{-05}
High-pressure	90 %	2.05×10^{-05}	88 %	2.97×10^{-05}

Table 5.2 – Qualitative overall system comparison: Monte Carlo simulation.

System Type	Ro(t), 8,760 h	λ # fail/time	Ro(t), 4,380 h	λ # fail/time
Subsea BOP	96 %	1.14×10^{-05}	96 %	1.26×10^{-05}
SBOP	90 %	2.63×10^{-05}	88 %	3.08×10^{-05}
SBOP + SID	92 %	2.97×10^{-05}	98 %	9.13×10^{-06}

The results from this analysis show that the high-pressure riser has a reliability very close to that of the conventional system; and its failure rate is located within the acceptable risk zone determined from the risk matrix in both time intervals.

When comparing the overall systems, we notice that the addition of the seabed isolating device (ISD) increases the reliability of the system; however, it gives the highest failure rate, because of the lack of redundancy of the pressure control elements.

The reliability of the surface array without the SID decreases at a lower time interval, inferring an error on the assigned frequency or consequence of the elements. For a better understanding of the system, a relative critical ranking is listed in **Table 5.3**, showing what elements are more likely to fail in relationship with the influence they have upon the overall system reliability (subsea BOP, SBOP, and SBOP with SID).

Table 5.3 – Relative critical ranking of elements in qualitative comparison.

Subsea BOP		SBOP		SBOP + SID	
Rank	**Element**	**Rank**	**Element**	**Rank**	**Element**
0.87	Human Error (riser)	**0.86**	Human Error (riser)	**0.66**	SID Human Error
0.87	Riser Control	**0.75**	Flex/Ball Joint	**0.66**	SID Control
0.41	Flex/Ball Joint	**0.70**	Riser Control	**0.66**	SID Ram
0.41	Hyd. Connector	**0.19**	Hyd. Connector	**0.23**	Hyd. Connector
0.10	Burst	**0.07**	Burst	**0.23**	Human Error (riser)
				0.23	Riser Control

Table 5.3 – Continued.

Subsea BOP		SBOP		SBOP + SID	
Rank	Element	Rank	Element	Rank	Element
				0.03	Burst
				0.02	Flex/Ball Joint

5.2 Quantitative Analysis Results

The qualitative analysis was tested in three time intervals: 1-year (8,760 hours), 0.5-year (4,380 hours), and 0.25-year (2,190 hours) of continuous work, to see the influence of the different datasets used. The simulations showed no significant difference from the confidence interval chosen for the stochastic simulations. Below is the result of the intermediate level (80 %). **Tables 5.4 to 5.7** summarize the results of the simulations with the various datasets (MMS, CODAM, and PARLOC) and the methods used.

Table 5.4 – Quantitative dataset effect on riser: Monte Carlo simulation.

Riser Type	Ro(t), 8,760 h	λ # fail/time	Ro(t), 4,380 h	λ # fail/time	Ro(t), 2,190 h	λ # fail/time
LP (MMS)	90 %	2.05×10^{-05}	95 %	2.28×10^{-05}	99 %	9.13×10^{-05}
HP (CODAM)	30 %	1.14×10^{-04}	48 %	1.99×10^{-04}	71 %	2.79×10^{-04}
HP (PARLOC)	91 %	1.87×10^{-05}	98 %	1.14×10^{-05}	98 %	1.37×10^{-05}

Table 5.5 – Quantitative dataset effect on riser: Numerical Integration.

Riser Type	Ro(t), 8,760 h	λ # fail/time	Ro(t), 4,380 h	λ # fail/time	Ro(t), 2,190 h	λ # fail/time
LP (MMS)	78 %	7.28×10^{-05}	87 %	8.54×10^{-05}	93 %	9.33×10^{-05}
HP (CODAM)	44 %	1.12×10^{-04}	63 %	1.95×10^{-04}	81 %	2.58×10^{-04}
HP (PARLOC)	95 %	1.45×10^{-05}	98 %	1.50×10^{-05}	99 %	1.52×10^{-05}

Table 5.6 – Quantitative dataset effect on overall system: Monte Carlo simulation.

System Type	Ro(t), 8,760 h	λ # fail/time	Ro(t), 4,380 h	λ # fail/time	Ro(t), 2,190 h	λ # fail/time
Subsea BOP (MMS)	100 %	---	100 %	---	100 %	---
SBOP (MMS)	---	---	---	---	---	---
SBOP (CODAM)	67 %	7.53 x 10^{-05}	89 %	6.39 x 10^{-05}	97 %	5.94 x 10^{-04}
SBOP (PARLOC)	92 %	2.63 x 10^{-05}	98 %	1.60 x 10^{-05}	99 %	4.57 x 10^{-06}
SBOP + SID (SINTEF)	76 %	5.82 x 10^{-05}	92 %	5.02 x 10^{-05}	99 %	2.74 x 10^{-05}
SBOP + SID (CODAM)	60 %	9.42 x 10^{-05}	83 %	9.82 x 10^{-05}	94 %	7.76 x 10^{-05}
SBOP + SID (PARLOC)	79 %	6.39 x 10^{-05}	90 %	5.02 x 10^{-05}	99 %	1.83 x 10^{-05}

Table 5.7 – Quantitative dataset effect on overall system: Numerical Integration.

System Type	Ro(t), 8,760 h	λ # fail/time	Ro(t), 4,380 h	λ # fail/time	Ro(t), 2,190 h	λ # fail/time
Subsea BOP (MMS)	89 %	3.81 x 10^{-05}	94 %	3.98 x 10^{-05}	97 %	4.07 x 10^{-05}
SBOP (MMS)	77 %	8.11 x 10^{-05}	86 %	9.50 x 10^{-05}	92 %	1.03 x 10^{-04}
SBOP (CODAM)	71 %	9.88 x 10^{-05}	87 %	1.03 x 10^{-04}	97 %	6.87 x 10^{-05}
SBOP (PARLOC)	94 %	3.37 x 10^{-05}	99 %	1.46 x 10^{-05}	99 %	5.27 x 10^{-06}
SBOP + SID (SINTEF)	56 %	3.53 x 10^{-04}	77 %	2.31 x 10^{-04}	89 %	1.82 x 10^{-04}
SBOP + SID (CODAM)	58 %	2.89 x 10^{-04}	80 %	1.92 x 10^{-04}	93 %	1.35 x 10^{-04}
SBOP + SID (PARLOC)	70 %	1.60 x 10^{-04}	88 %	1.20 x 10^{-04}	97 %	7.70 x 10^{-05}

The results obtained after stochastic and numerical method analysis showed that the type of dataset used influences greatly the outcome of the analysis of the SBOP system. It must be pointed out that all the surface preventer models used the SINTEF BOP reliability data, to evaluate only the behavior related to the drilling riser failures, and stay focused on the objective of the study.

The CODAM dataset gave a pessimistic result, unlike the PARLOC dataset, whose results were optimistic. Although neither of the results might be correct, they can provide a range for the actual value of reliability. The failure rates from each dataset were located within the acceptance or caution zone when estimating the impact from the risk matrix used for the qualitative analysis. An important observation is that both the CODAM and PARLOC datasets have recorded failures from areas different from the GOM, and not all of the incidents are guaranteed to be from high-pressure systems.

The critical elements for the subsea system were the same as in the qualitative analysis. In the case of the SBOPs, they differed depending on the type of dataset used. **Table 5.8** shows the relative ranking of the critical elements for the SBOP system.

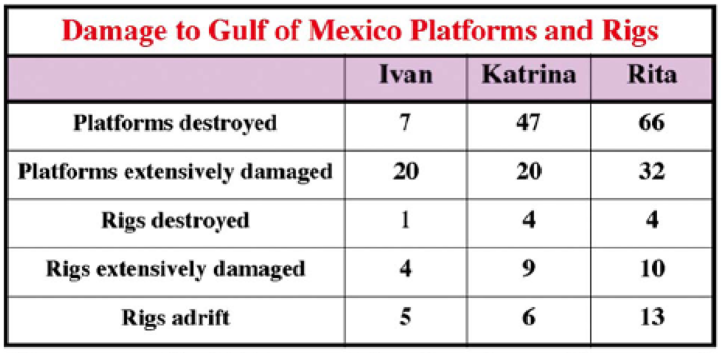
Table 5.8 – Relative critical ranking of elements in quantitative comparison.

SBOP CODAM		SBOP + SID CODAM		SBOP + SID PARLOC	
Rank	**Element**	**Rank**	**Element**	**Rank**	**Element**
0.75	Riser Failure	**0.99**	Riser Failure	**0.55**	Hyd. Connector
0.42	Hyd. Connector	**0.76**	Hyd. Connector	**0.45**	Insignificant Riser Failure
0.20	Annular Preventer	**0.11**	Flex/Ball Joint	**0.45**	Minor Riser Failure
0.20	BOP K&C Valves			**0.21**	Major Riser Failure
0.17	Ram Preventer			**0.06**	Flex/Ball Joint
0.05	Flex/Ball Joint				

Variations on the ranking of the elements for the SBOPs configuration are the consequence of the modifications made to the riser fault trees to accommodate the description of each dataset, making some systems more critical than what they would normally be.

6. DISCUSSION AND CONCLUSIONS

No one can predict how the metocean conditions in the GOM will change in the years ahead; like the past 2005 hurricane season, which had an unusual number of storms which left severe damages on the oil and gas industries operating in the gulf. This unexpected weather pattern has led operators and contractors to question the minimum conditions and regulations floating units should comply with. Current API standards[36] suggest the design conditions to be from 5 to 10-years for MODUS and 100-years for fixed platforms. **Fig. 6.1** shows the statistics from the past three major hurricanes that hit the GOM region and the damages they caused to the units operating in it.



Damage to Gulf of Mexico Platforms and Rigs

	Ivan	Katrina	Rita
Platforms destroyed	7	47	66
Platforms extensively damaged	20	20	32
Rigs destroyed	1	4	4
Rigs extensively damaged	4	9	10
Rigs adrift	5	6	13

Fig. 6.1 – Past major hurricanes in the GOM. [37]

Currently, the MMS is revising code standards and regulations on MODUS, [38] by sponsoring joint projects from operators, contractors, and universities to understand new working environments and conditions in the GOM, to reduce incidents and casualties.

An important point to mention is that SBOP applications do not solve the entire drilling problems encountered in deepwater environments, because the slim high-pressure riser system has its own limitations, such as: the number of casing strings that could be set after the installation of the drilling riser, the reduction of the operating envelope (**Fig. 6.2**), and the initial investment and time spent to bring the rig up to specifications. SBOP technology benefits from other applications like the use of expandable tubulars, and dual-gradient drilling; whose combination can increase their acceptance in the drilling industry. Old generation rigs would be the ones to benefit the most from this technology for the expansion of their operating field environment and active life.

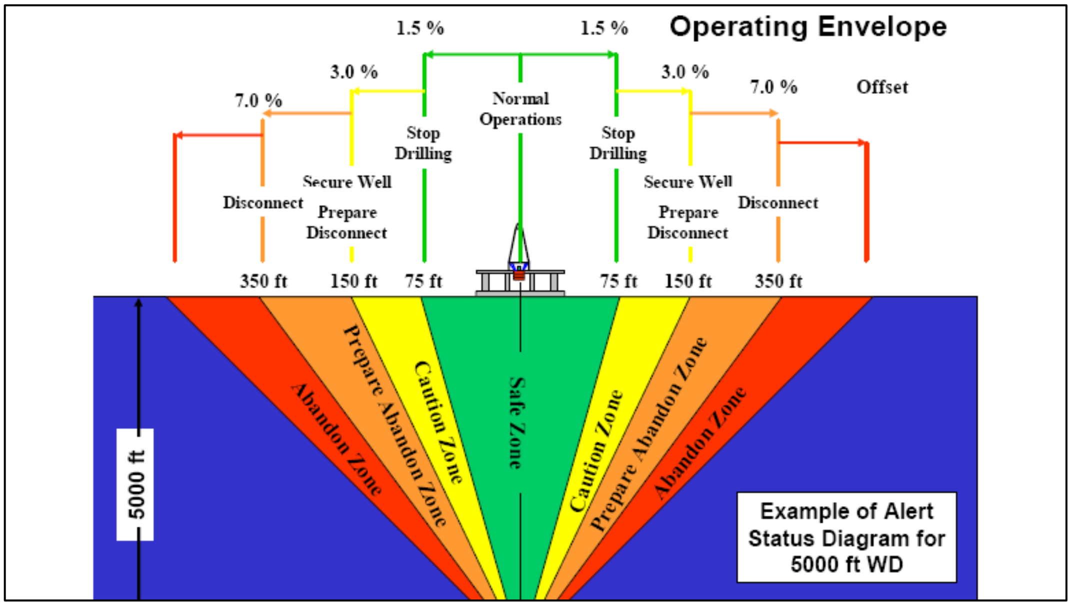


Fig. 6.2 – Operating envelope example for SBOP applications. [3]

A comparison between moored vs. dynamically positioned systems was performed to see which station keeping alternative was more reliable and what failures are associated with each one. Lack of reported incidents did not allow the evaluation of the system model. Another limitation on this analysis was that the dataset used to calculate operational time in the GOM could only distinguish the type of rig used and not its positioning system, an important requirement when estimating the failure rate of each component.

Out of the fifteen incidents associated with drilling risers in deepwater GOM, eleven rigs had a dynamically positioning system and the other four were moored. This comparison is not enough to conclude which system is better, since factors like: water depth, location, and seasonal time can influence the outcome despite the positioning system used.

The following findings may be useful in understanding the results of this study.

- The qualitative analysis was conclusive in determining the risk of SBOP operations when comparing these operations to the conventional system with the specific metocean conditions encountered in the GOM, which showed acceptable values.
- Addition of the SID improved the system reliability and maintained a failure rate within the acceptance risk envelope independently from the type of dataset used; thus it should be considered for deepwater operations in the GOM.

- This evaluation was done with a generic description of the drilling riser components and the pressure control equipment, thus it serves as a starting point for operators and contractors when planning the use of SBOPs in the GOM.

6.1 Conclusions

From the work presented in this study we can conclude the following:

1. Preliminary analysis of the simulations suggests that the risk of failure of the entire system can be acceptable and operations can be carried out safely.

2. A risk assessment can aid understand the high-pressure riser system through the identification of the critical components and their interaction with the overall pressure control equipment.

3. Specific location and equipment planned to be used can drastically change the outcome of the overall risk analysis, since some areas are more susceptible than others to be hit by harsh metocean conditions.

4. Results from the quantitative interpretation have a degree of uncertainty on their reliability, because of the nature of the dataset used. However, the work done allows the setting of upper and lower boundaries to understand the system behavior.

6.2 Suggested Future Work

Only primary failures from each component were taken into consideration for this study, because the purpose was to have a preliminary assessment on whether it would be positive or not to implement a high-pressure riser. Future work should include secondary and tertiary failures to take into account chain events and their consequences.

The riser system and pressure control equipment models were simplified into their main components; a more detailed analysis can be performed during the evaluation of a particular arrangement to determine the specific risk of the system.

A similar study could be performed to evaluate the risk of installing a high-pressure riser and an SBOP in fixed deepwater production units like spars and tension leg platforms as an alternative for well control measurements.

Awareness should be brought to the MMS regarding data quality to better assess risk analyses, since reported failures do not include a consequence level.

NOMENCLATURE

API	American Petroleum Institute
BOP	Blowout Preventer
C	Consequence
CODAM	Corrosion and Damage
DPS	Dynamically Positioning System
DW	Deepwater
FTA	Fault Tree Analysis
GOM	Gulf of Mexico
H	Total time
HP	High Pressure
HSE	Health and Safety Executive
LCE	Loop Current Eddies
MMS	Minerals Management Service
MTTF	Mean Time to First Failure
N	Number of failures
p	Probability
PARLOC	Pipeline and Riser Loss of Containment
Qo(t)	Probability that the *top event* occurs
R	Risk
Ro(t)	Probability that the *top event* does not occur
SBOP	Surface Blowout Preventer
SID	Seabed Isolation Device
SINTEF	Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology
t	time
VIV	Vortex Induced Vibration

$wi(t)$	Failure frequency of the i’th component
$wK_j(t)$	Failure frequency of cut set K_j
$w_o(t)$	System failure frequency
$\lambda(t)$	Failure rate, failures/time
χ	Chi-square function

REFERENCES

1. Simondin, A. *et al*.: “A Deepwater Well Construction Alternative: Surface BOP Drilling Concept Using Environmental Safe Guard,” paper SPE 87108 presented at the 2004 IADC/SPE Drilling Conference, Dallas, 2-4 March.
2. Farrant, T. and Javed, K.: “Minimizing the Effect of Deepwater Currents on Drilling Riser Operations,” paper presented at the 2001 Deepwater Drilling Technologies Conference, Aberdeen, 30-31 January.
3. *Surface BOP Guidelines for Floating MODUS*, revision 071604, IADC, Houston (2004).
4. Henley, E. J. and Kumamoto, H.: *Probalistic Risk Assessment, Reliability Engineering, Design, and Analysis*, IEEE Press, New York (1992).
5. Høyland, A. and Rausand, M.: *System Reliability Theory, Models and Statistical Methods*, John Wiley & Sons, New York (1994).
6. Grace, R. D.: *Advance Blowout and Well Control*, Gulf Publishing Company, Houston (1994).
7. Holand, P.: *Offshore Blowouts, Causes and Control*, Gulf Publishing Company, Houston (1997).
8. Holand, P.: “Reliability of Subsea BOP Systems for Deepwater Application, Phase II DW,” unrestricted version, Report No. STF38-A99426, MMS, New Orleans (November 1999).
9. Lim, F. and Howells, H.: “Deepwater Riser VIV, Fatigue and Monitoring,” paper presented at the 2000 Deepwater Pipeline and Riser Technology Conference, Houston, 6-9 March.
10. Howells, H. and Walters, D.: “Deepwater Drilling Riser Integrity – Fatigue, Wear, Inspection and Monitoring,” paper presented at the 2000 Offshore Mechanics and Artic Engineering Conference, New Orleans, 14-17 February.
11. Maksoud, J.: “Improved Strake Design Reduces Spar VIV,” http://ogj.pennnet.com/articles/article_display.cfm, 17 June 2005.

12. Lustosa, E., Hatton, S., and Walters, D.: “Small Bore Drilling Risers Offer Reduction in Drilling Costs,” paper presented at the 2003 Energy Wise Workshop Technology Options for Deepwater Brazil, Rio de Janeiro, 26-27 March.
13. Howells, D.: “Deep Water Drilling Riser Technology, VIV & Fatigue Management,” paper presented at the 1998 4th Quarter Meeting Drilling Engineering Association, Paris, 19 November.
14. DeLuca, M.: “BOPs Breaking the Surface,” *Offshore Engineering* (January 2003).
15. DeLuca, M.: “SBOPS Best Practice Guide Sets Scene for Wider Take Up,” *Asian Oil & Gas* (April 2005).
16. DeLuca, M.: “SBOP Maintaining its Niche,” *Offshore Engineering* (February 2005).
17. Ryan, P.: “Surface BOP Proves to be Efficient Drilling Technique,” *Drilling Contractor* (July/August 2003).
18. Brander, G. *et al*.: “Drilling in Brazil in 2887 m Water Depth Using a Surface BOP System and a DP Vessel,” paper SPE 87113 presented at the 2004 IADC/SPE Drilling Conference, Dallas, 2-4 March.
19. Touboul, N. *et al*.: “New Technologies Combine to Reduce Drilling Costs in Ultradeepwater Applications,” paper SPE 90830 presented at the 2004 SPE Annual technical Conference and Exhibition, Houston, 26-29 September.
20. Shanks, E. *et al*.: “Surface BOP for Deepwater Moderate Environment Drilling Operations From a Floating Drilling Unit,” paper OTC 14265 presented at the 2002 Offshore Technology Conference, Houston, 6-9 May.
21. “Surface Currents in the Atlantic Ocean,” Ocean Currents, http://oceancurrents.rsmas.miami.edu/atlantic, 10 October 2005.
22. Nowling, W. *et al*.: “Deepwater Physical Oceanography Reanalysis and Synthesis of Historical Data,” synthesis repot, Contract 1435-01-98-CT-30910, U. S Department of the Interior, MMS, New Orleans (August 2001).
23. “Gulf of Mexico Deepwater Operations and Activities, Environmental Assessment,” MMS-2000-001, New Orleans (2000).

24. DiMarco, S. *et al*.: “Subsurface, High-Speed Current Jets in the Deepwater Region of the Gulf of Mexico,” final repot, Contract 1435-01-99-CT-31026, U. S Department of the Interior, MMS, New Orleans (July 2004).
25. Ghoneim, A. and Colby, C.: “GOM Offshore Structures Design Criteria,” paper presented at the 2005 Soc. of Naval Architects and Marine Engineers Texas Section Meeting, Houston, 13 December.
26. Huang, K.: “Mooring System Design Consideration for FPSOs,” report 2000-KTM-04, American Bureau of Shipping, Houston (2000).
27. *Guidelines for Hazard Evaluation Procedures*, second edition, Center for Chemical Process and Safety, New York (1992).
28. *Cara Fault Tree Applications*, Vers. 4.1 SRI, Sydvest Software (2000).
29. Wang, Y.: “Development of a Computer-Aided Fault Tree Synthesis Methodology for Quantitative Risk Analysis in the Chemical Process Industry,” PhD dissertation, Texas A&M U., College Station, Texas (2004).
30. Vinnem, J.: *Offshore Risk Assessment, Principles, Modeling and Applications of QRA Studies*, Kluwer Academic Publishers, Dordrecht, The Netherland (1999).
31. Koller, G.: *Risk Assessment and Decision Making in Business and Industry, A Practical Guide*, CRC Press LLC, Boca Raton, Fl. (1999).
32. “Rigs – USGOM-DW,” Rig Zone, www.rigzone.com/data/, 15 September 2005.
33. “OCS – Related Incidents,” MMS, www.mms.gov/incidents/index.htm, 16 September 2005.
34. “CODAM database,” Petroleum Safety Authority Norway, www.ptil.no/English, 25 September 2005.
35. MacDonald, M.: *PARLOC:2001, The Updated Loss of Containment Data for Offshore Pipelines*, Energy Institute, London (2003).
36. Pelley, D.: “Discussion of Hurricane Mooring Issues for Moored Semisubmersibles MODUs,” paper presented at the 2005 IADC Drilling Gulf of Mexico Conference and Exhibition, Houston, 30 November – 1 December.
37. “Post Hurricane Symposium,” Benfield Corporate Risk, Houston (2006).

38. Howard, D.: “Severe Weather Preparedness” paper presented at the 2005 IADC Drilling Gulf of Mexico Conference and Exhibition, Houston, 30 November – 1 December.
39. “BOP Market Share,” Rig Zone, www.rigzone.com/data/, 15 September 2005.
40. “Drilling Products and Systems,” Cameron, www.coopercameron.com, 15 September 2005.
41. “Pressure Control Line,” Hydril, www.hydril.com/, 11 September 2005.
42. “Pressure Control,” Varco, www.natoil.com/pdf/c3shafer.pdf, 15 September 2005.

Other Sources Consulted

“DEOS Spar Buoy and Mooring Design,” preliminary draft report, Deep Oil Technology Inc. (1999).

“Reliability of Blowout Preventers Tested Under Fourteen and Seven Days Time Interval,” Tetrahedron, Inc., New Orleans (December 1996).

Gallagher, K. T. and Bond, D. D.: “Redefining the Environmental Envelope for Surface BOPs on a Semi-Submersible Drilling Unit,” paper SPE 67709 presented at the 2001 IADC/SPE Drilling Conference, Amsterdam, 27 February -1 March.

Henley, E. J. and Kumamoto, H.: *Reliability Engineering, Design, and Analysis*, IEEE Press, New York (1981).

Koller, G.: *Risk Modeling for Determining Value and Decision Making*, CRC Press LLC, Boca Raton, Fl. (2000).

Oynes, C.: “Deepwater Ocean Current Monitoring on Floating Facilities,” notice to lessees and operators, NTL No. 2005-G05, MMS, New Orleans (April 2005).

Quilici, M. D.: “DP System Reliability – Quantitative vs. Qualitative Analysis,” paper presented at the 1999 Dynamic Positioning Conference, Houston, 12-13 October.

Schaudt, K. J.: “Using Oceanographic Data to Maximize Operational Efficiency in the Gulf of Mexico,” paper presented at the 2003 Dynamic Positioning Conference, Houston, 16-17 September.

APPENDIX A

BOP MANUFACTURERS

The main BOP system manufacturers are: Cameron, Hydril, and Shaffer[39] (**Fig. A.1**). Because of their individual experience and range of products for every specific need, these three companies control a great part of the current worldwide market, SBOPs commonly use land or Jack-Up type components, but they can also incorporate parts from a subsea stack; thus no specialized designs or parts have been made by the top manufacturers.

The stack design varies from application to application and drilling company, depending on the available equipment and the specific pressure requirements to safely maintain control of a well. Some of the latest models from each company are detailed below.

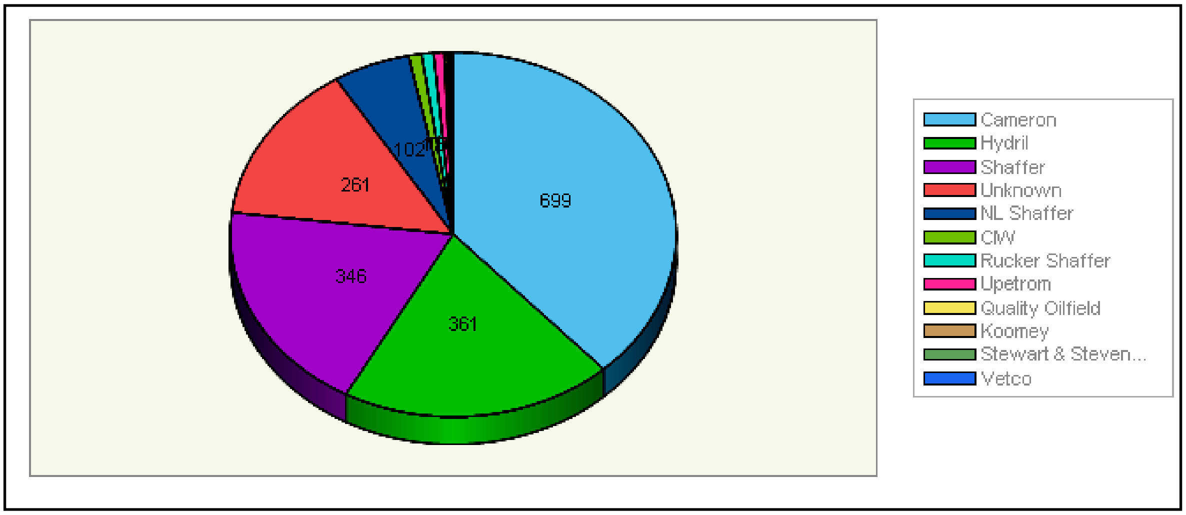


Fig. A.1 – BOP manufacturers worldwide. [39]

A.1 Cameron

Cameron offers a variety of rams for subsea applications which can be adapted to SBOPs scenarios. Their high-pressure system (15,000 psi) is available in sizes up to 13 5/8-in, and the low-pressure system can be up to 26-in size. Some of the products offered are U- and UM-type rams (**Fig. A.2**), the T and TL series which come in a single, double, or triple layout (**Fig. A.3**), and the DL annular preventer.

The U ram is the most used preventer worldwide [40] for both land and offshore applications, due to its versatility in size and pressure ratings. This ram is capable of withstanding pressures during hydraulic losses by sealing its system. The UM is a lightweight version designed for easy maintenance and long life.

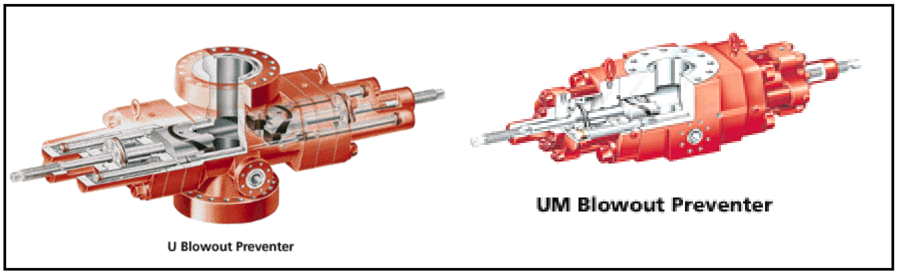


Fig. A.2 –Cameron’s U and UM ram preventers. [40]

The T and TL series allow removal and maintenance through side access, reducing stack height and cutting rig time. The stacks come in a modular form for flexible arrangement and configuration, in sizes up to 18 3/4-in and working pressures of 15,000 psi.

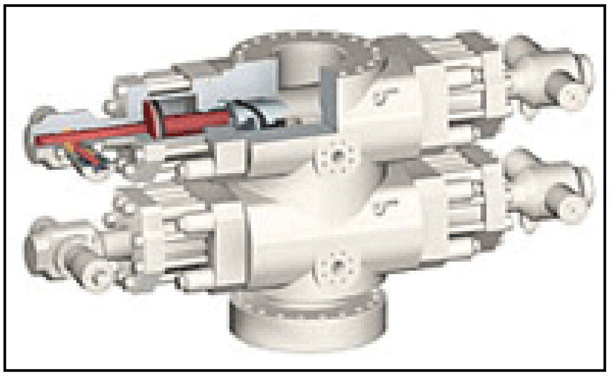


Fig. A.3 – Cameron TL ram preventer. [40]

The DL annular preventer (**Fig. A.4**) is a high performance compact size preventer capable of working at pressures of up to 20,000 psi, and ranges from 7 to 21–in diameter. It is designed to operate in sour environments and has the ability to strip pipe, and to close and seal almost any size or shape of object located in the wellbore.

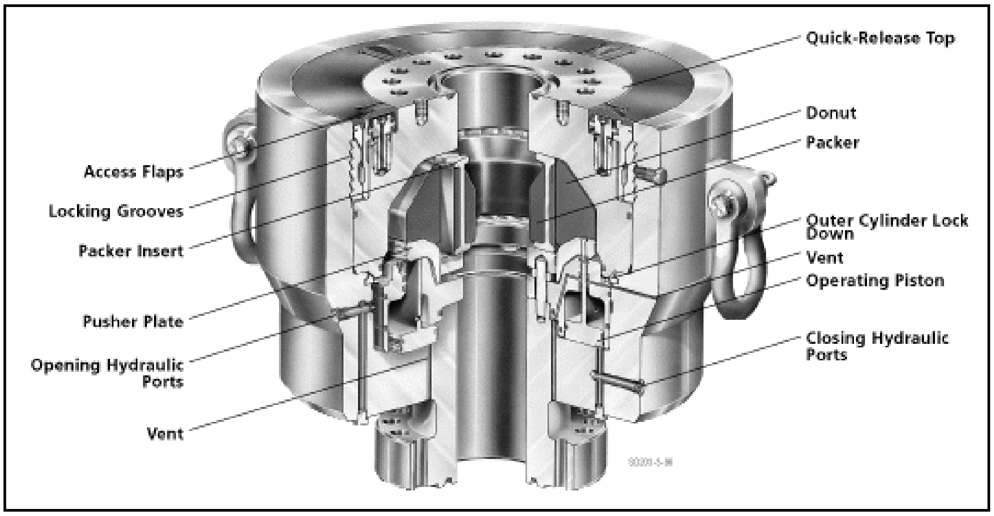


Fig. A.4 – Cameron DL annular preventer. [40]

A.2 Hydril

Hydril is known for its line of annular preventers, manufactured in the GX and GLseries (**Fig. A.5**). All of them are capable of withstanding working pressures of up to 15,000 psi and can close on a drillpipe or an open hole. Most of Hydrill's preventers can be installed in either a subsea or surface stack. The MSP/SVX series combines BOP and diverter functions with working pressures ranging from 500 to 2,000 psi, and sizes from 12 1/4 to 30-in.

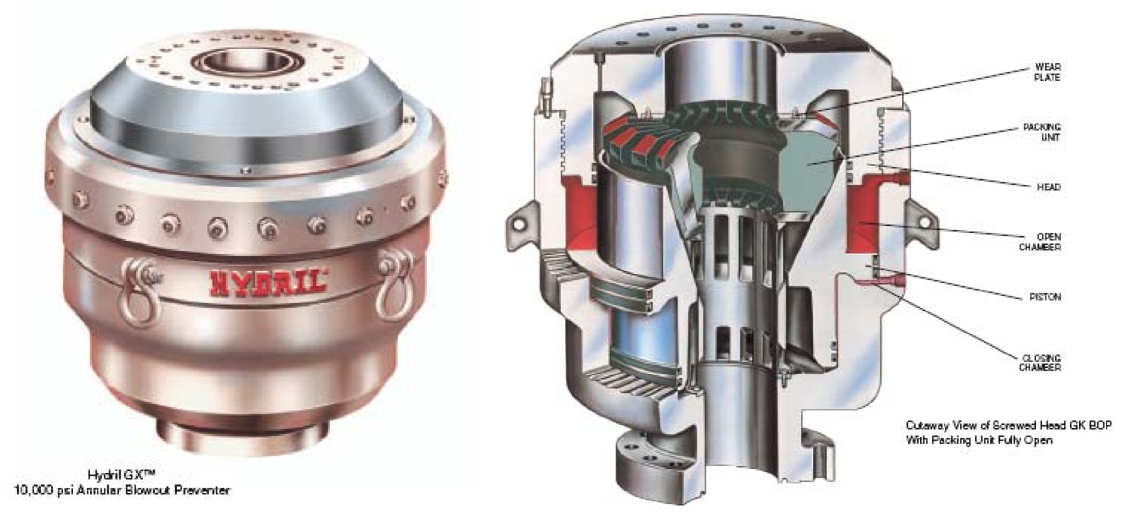


Fig. A.5 – Hydril GX and GK annular preventers. [41]

The Hydril dual compact ram series maintains the performance of larger stacks with a reduction on height, as illustrated in **Fig. A.6.**

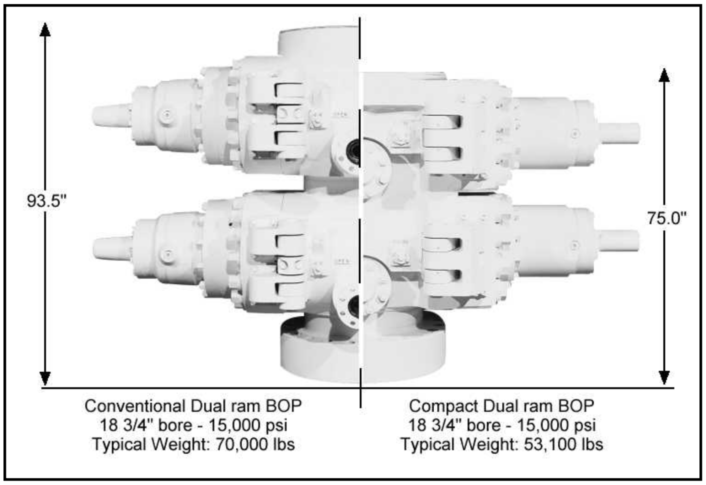


Fig. A.6 – Hydril compact ram preventer series. [41]

A.3 Shaffer

Shaffer currently offers three basic models of ram preventers: the NXT, the SL/SLX, and the LWS series, with variations in each series depending on the size and pressure requirements. The NXT series (**Fig. A.7**) is designed for tough and demanding tasks making it a great candidate for high-pressure applications. The SL/SLX series is designed for critical services, and the LWS series is used for smaller boreholes. Most of the rams can be installed in either land or offshore applications.

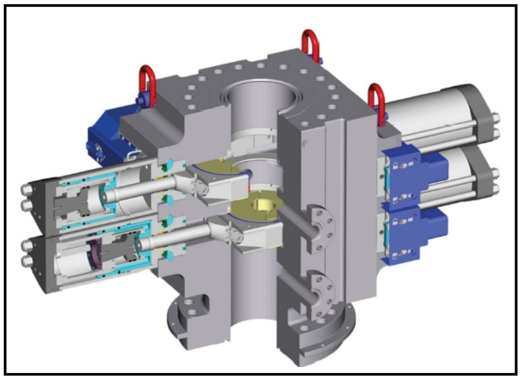
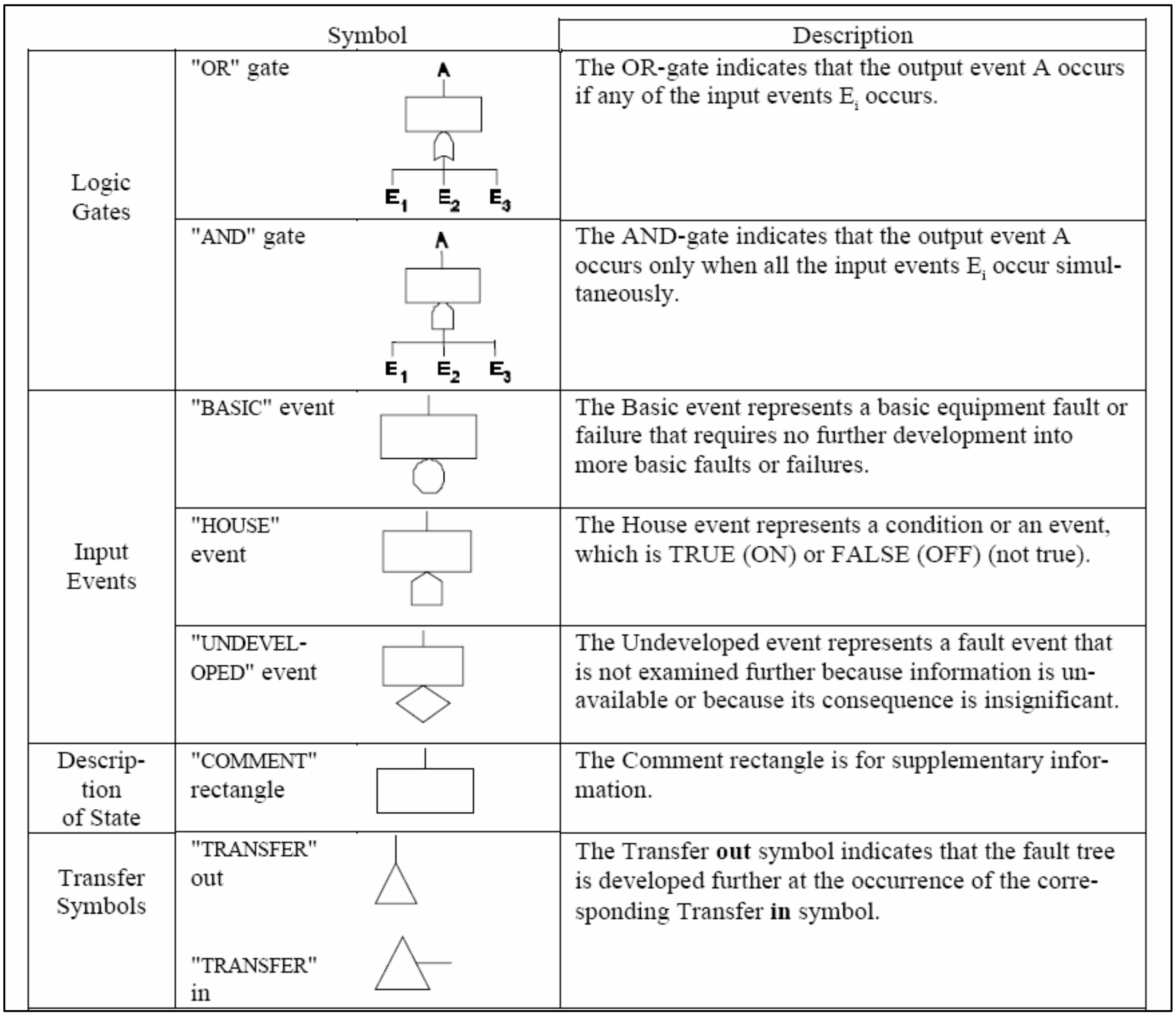


Fig. A.7 – Shaffer NXT high-pressure ram series. [42]

APPENDIX B
FAULT TREES MODELS

Common fault tree symbols are described in **Fig.B-1.**



Symbol		Description
Logic Gates	"OR" gate	The OR-gate indicates that the output event A occurs if any of the input events E_i occurs.
	"AND" gate	The AND-gate indicates that the output event A occurs only when all the input events E_i occur simultaneously.
Input Events	"BASIC" event	The Basic event represents a basic equipment fault or failure that requires no further development into more basic faults or failures.
	"HOUSE" event	The House event represents a condition or an event, which is TRUE (ON) or FALSE (OFF) (not true).
	"UNDEVELOPED" event	The Undeveloped event represents a fault event that is not examined further because information is unavailable or because its consequence is insignificant.
Description of State	"COMMENT" rectangle	The Comment rectangle is for supplementary information.
Transfer Symbols	"TRANSFER" out "TRANSFER" in	The Transfer **out** symbol indicates that the fault tree is developed further at the occurrence of the corresponding Transfer **in** symbol.

Fig. B.1 – Fault tree symbol description. [7]

The fault trees used in this study are presented as they were input to software.

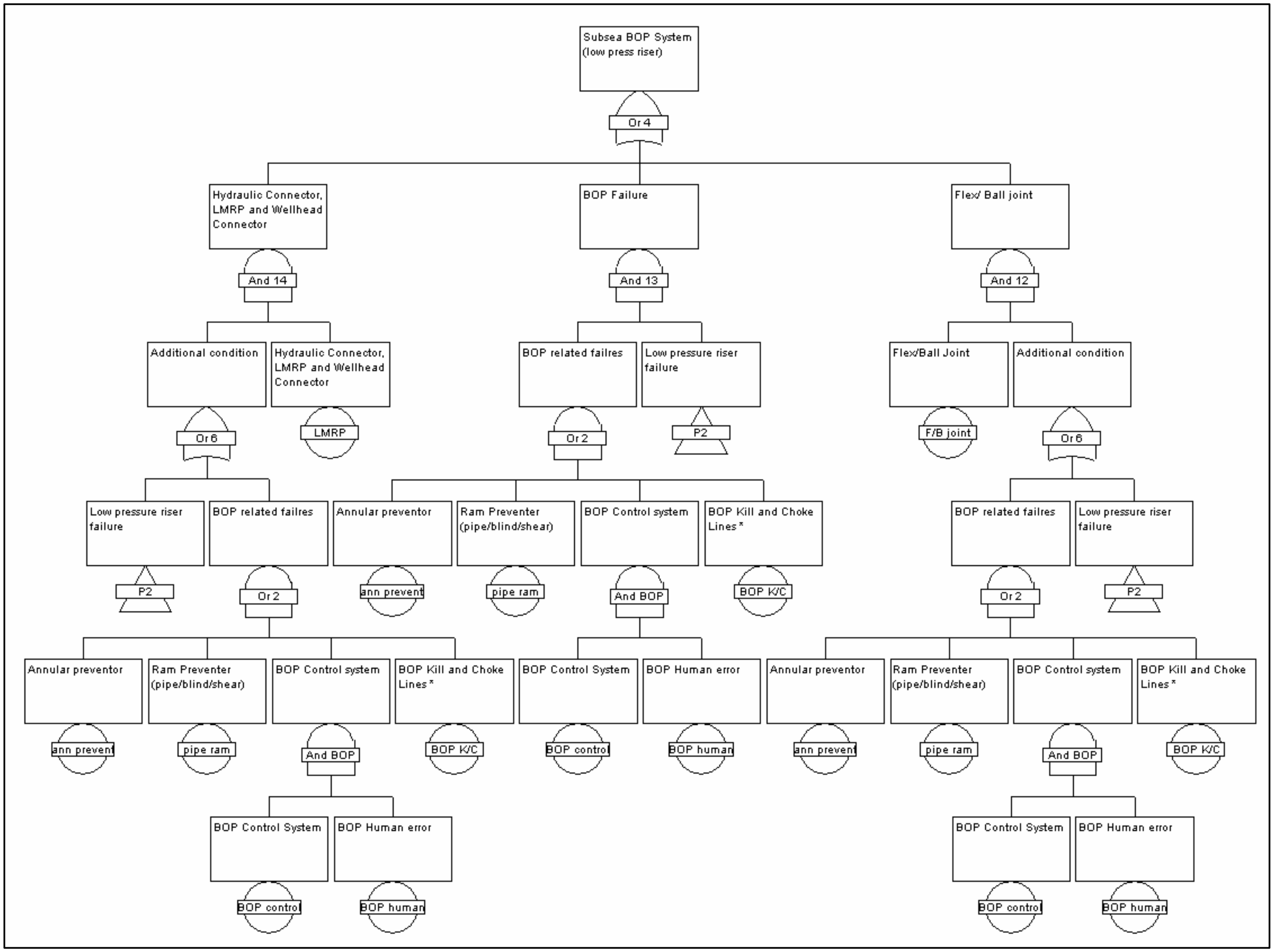


Fig. B.2a– Subsea fault tree model.

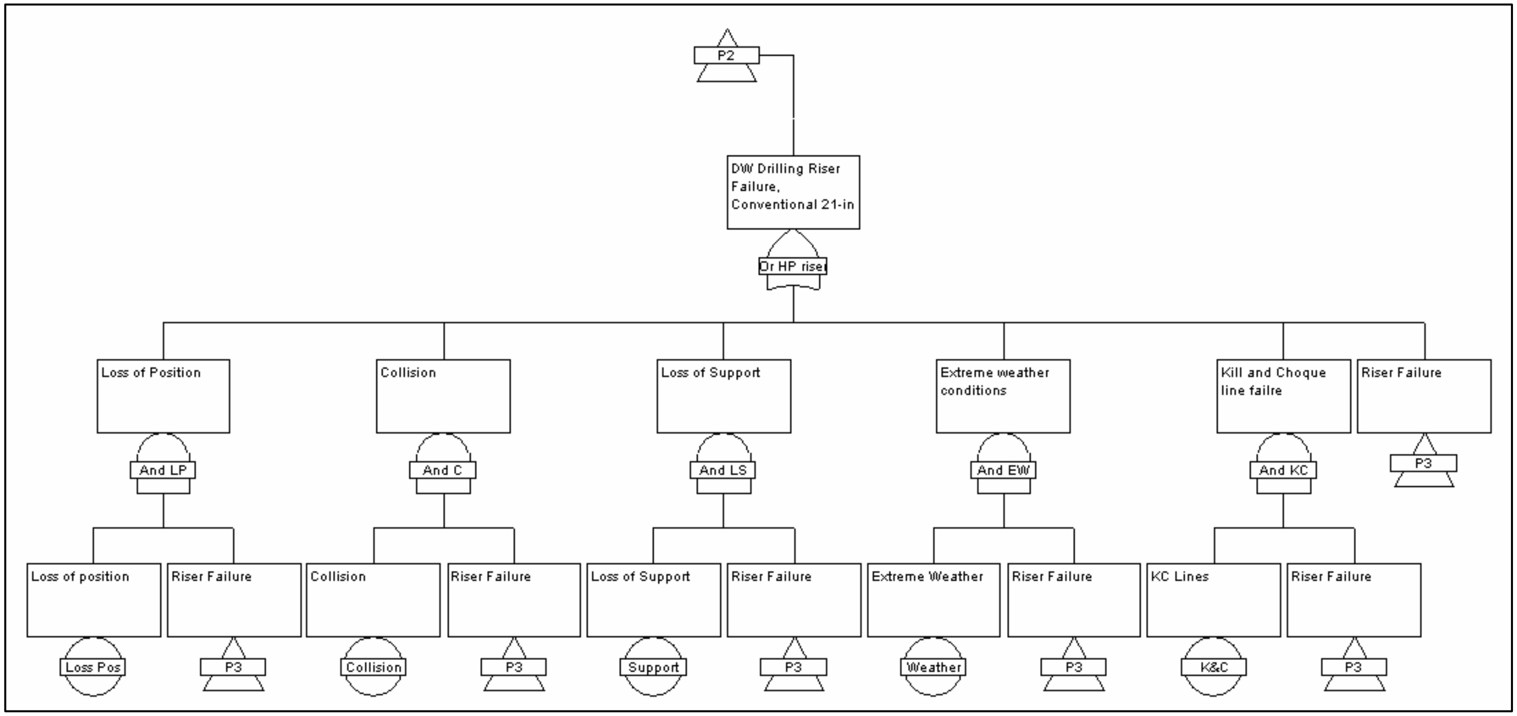


Fig. B.2b– Subsea fault tree model.

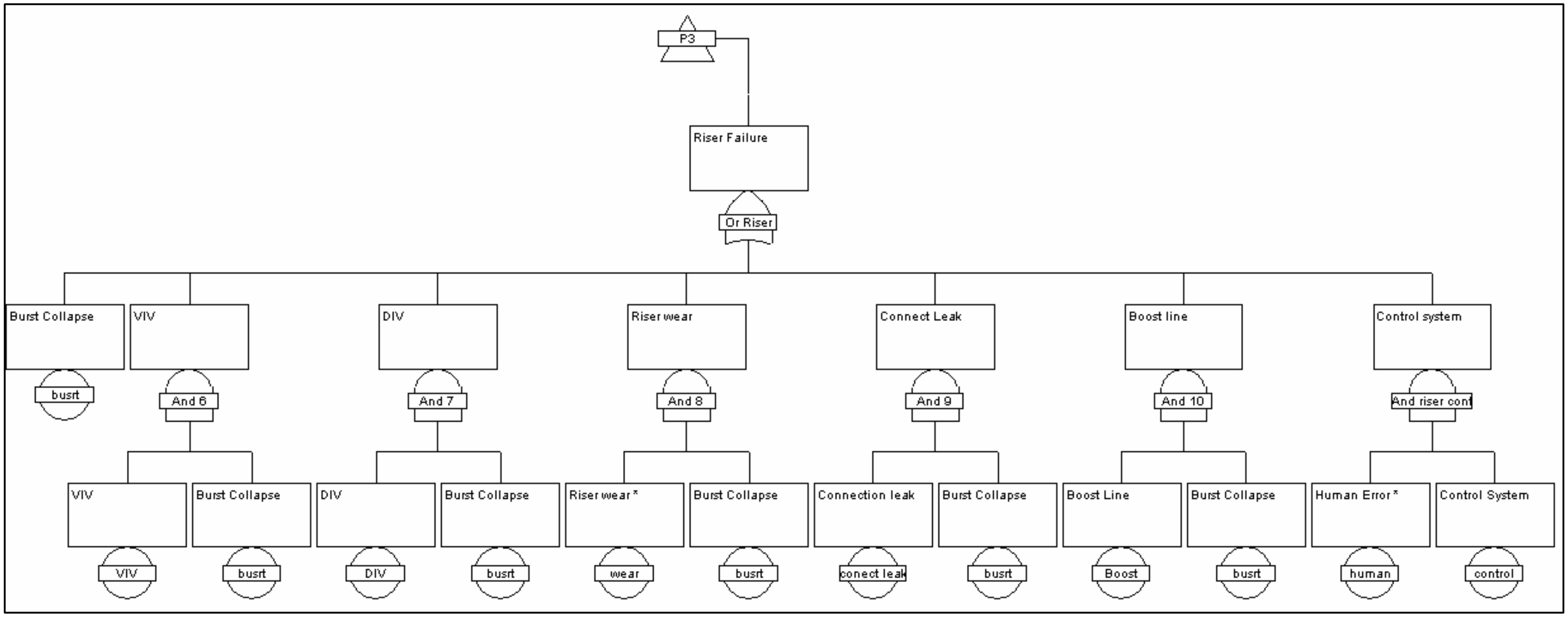


Fig. B.2c– Subsea fault tree model.

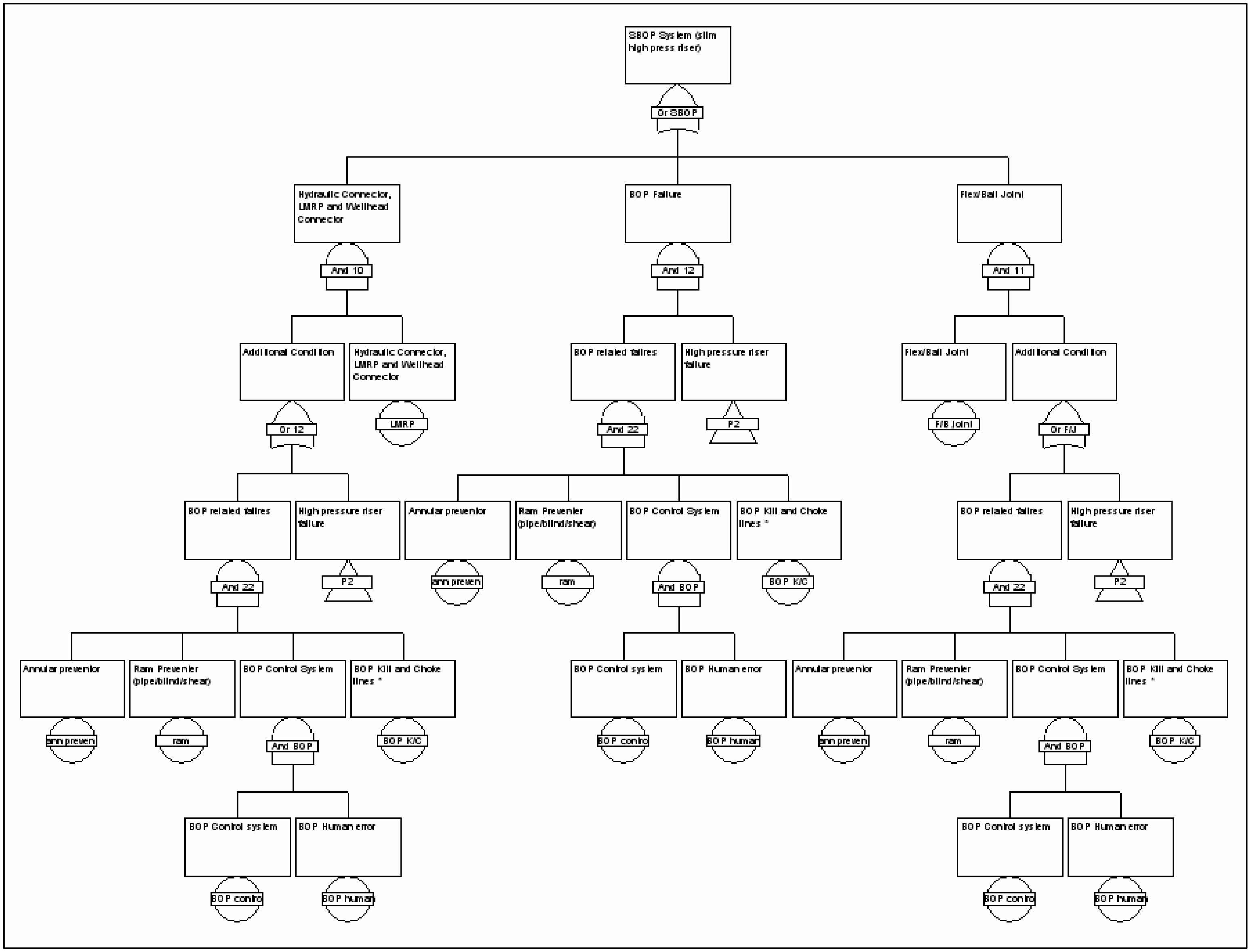


Fig. B.3a– SBOP fault tree model.

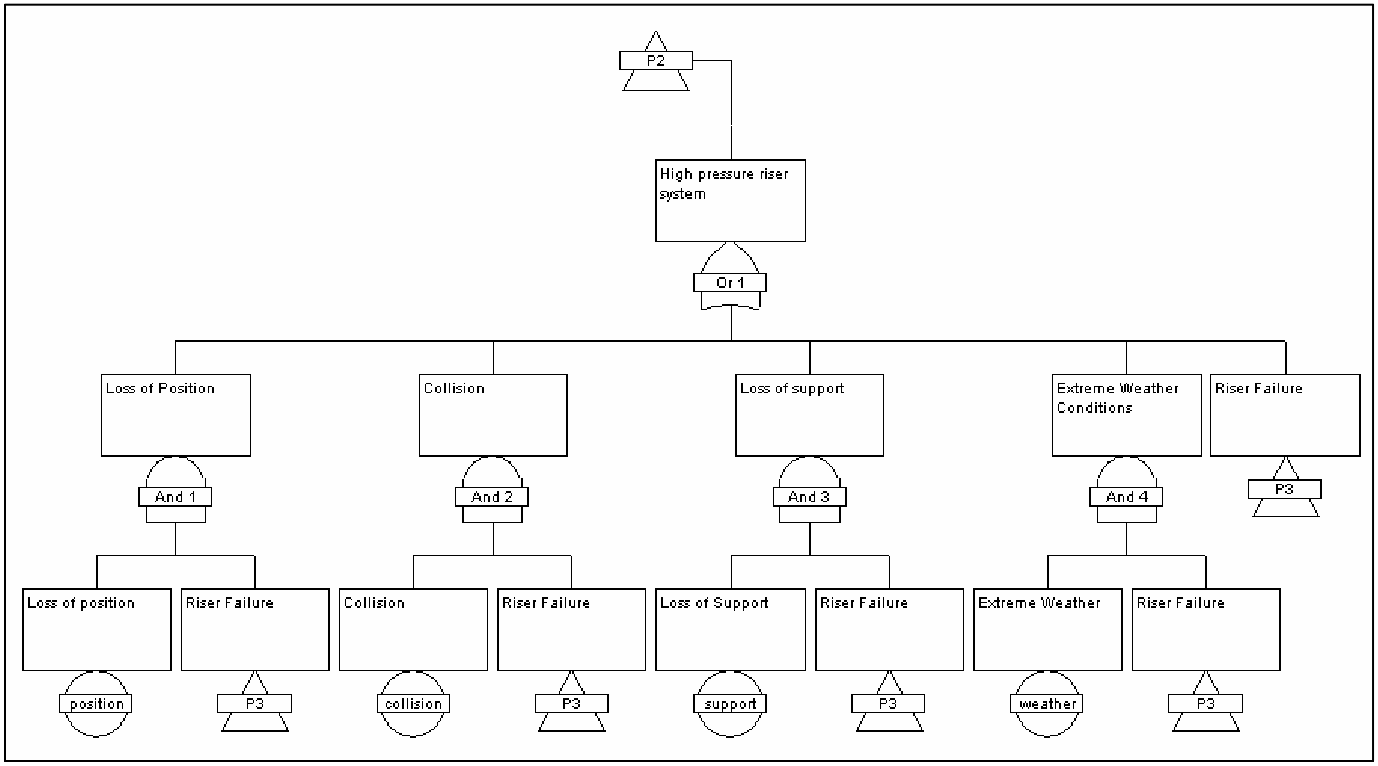


Fig. B.3b– SBOP fault tree model.

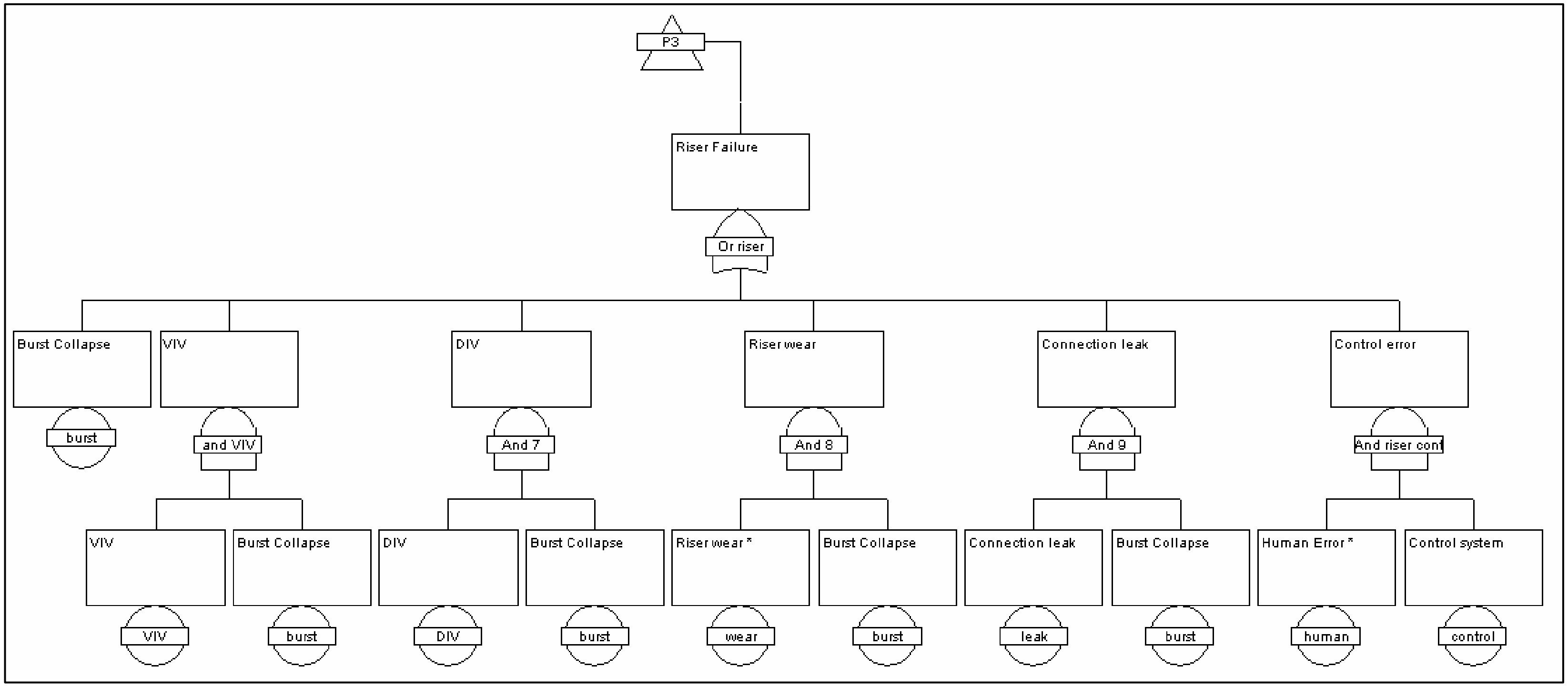


Fig. B.3c– SBOP fault tree model.

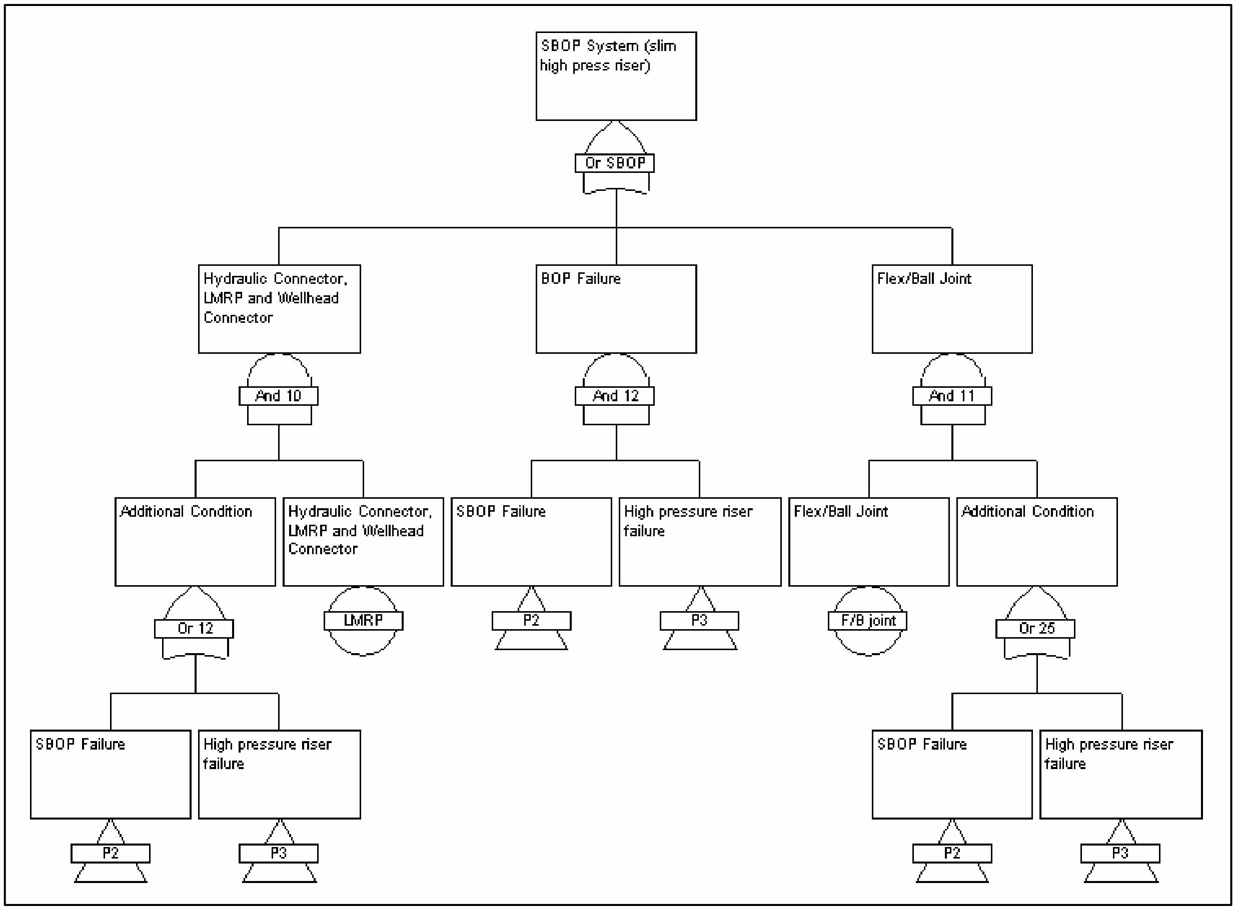


Fig. B.4a– PARLOC SBOP fault tree model.

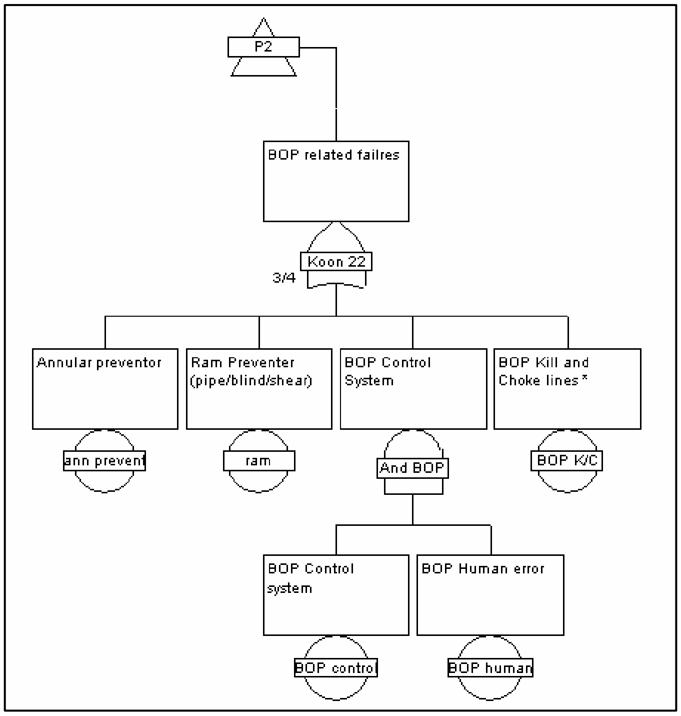


Fig. B.4b– PARLOC SBOP fault tree model.

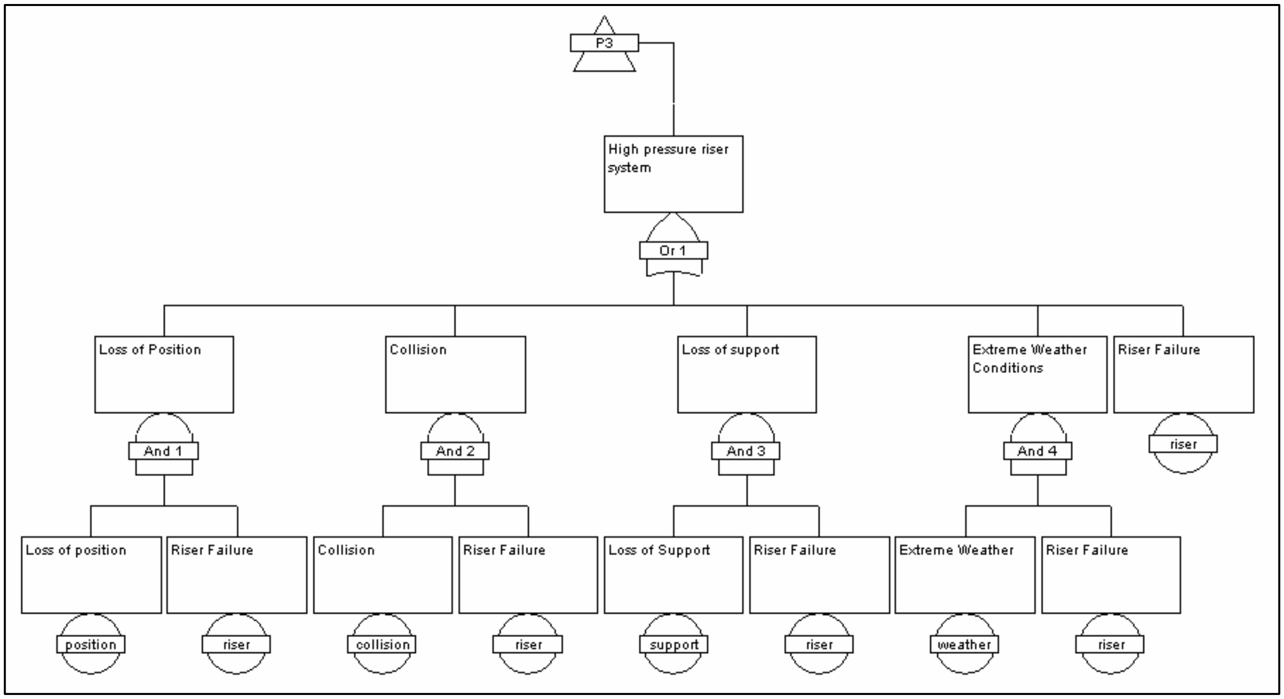


Fig. B.4c– PARLOC SBOP fault tree model.

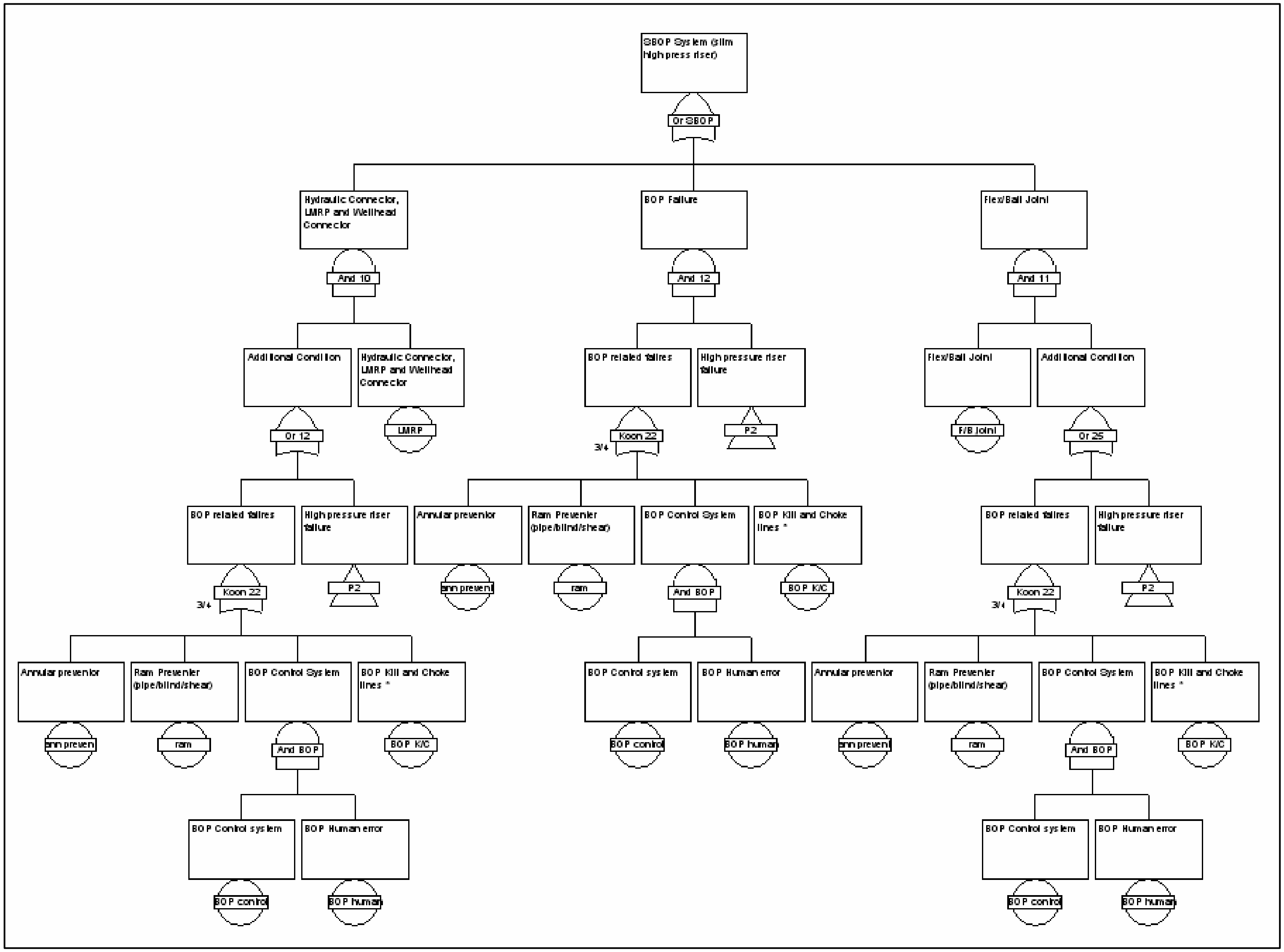


Fig. B.5a– CODAM SBOP fault tree

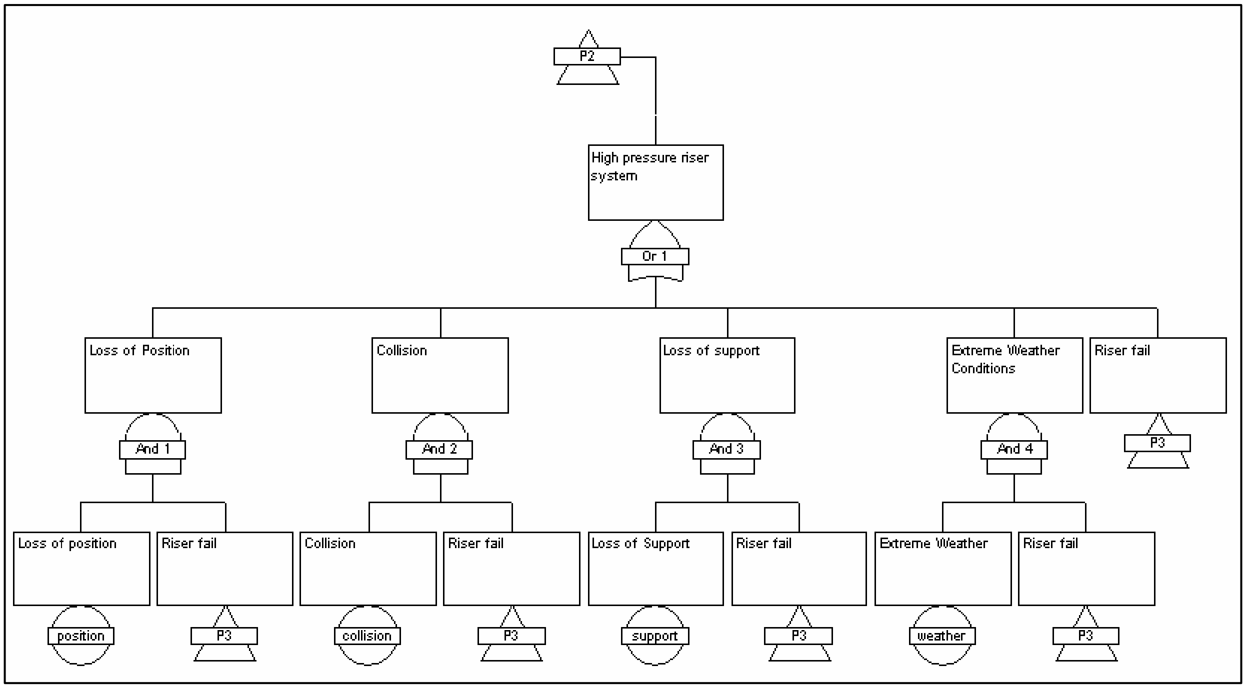


Fig. B.5b– CODAM SBOP fault tree model.

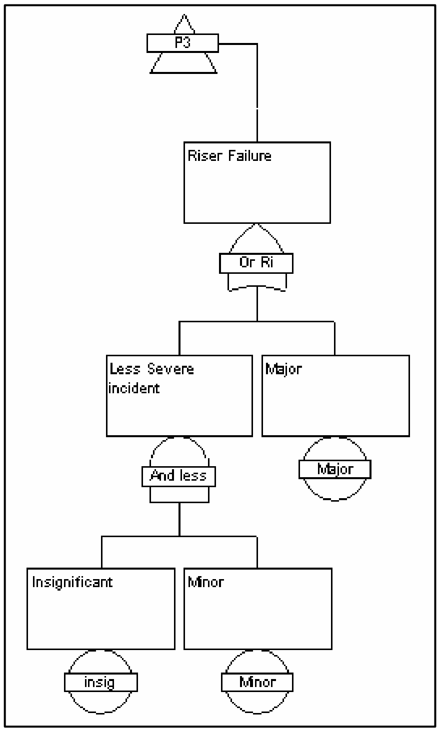


Fig. B.5c– CODAM SBOP fault tree model.

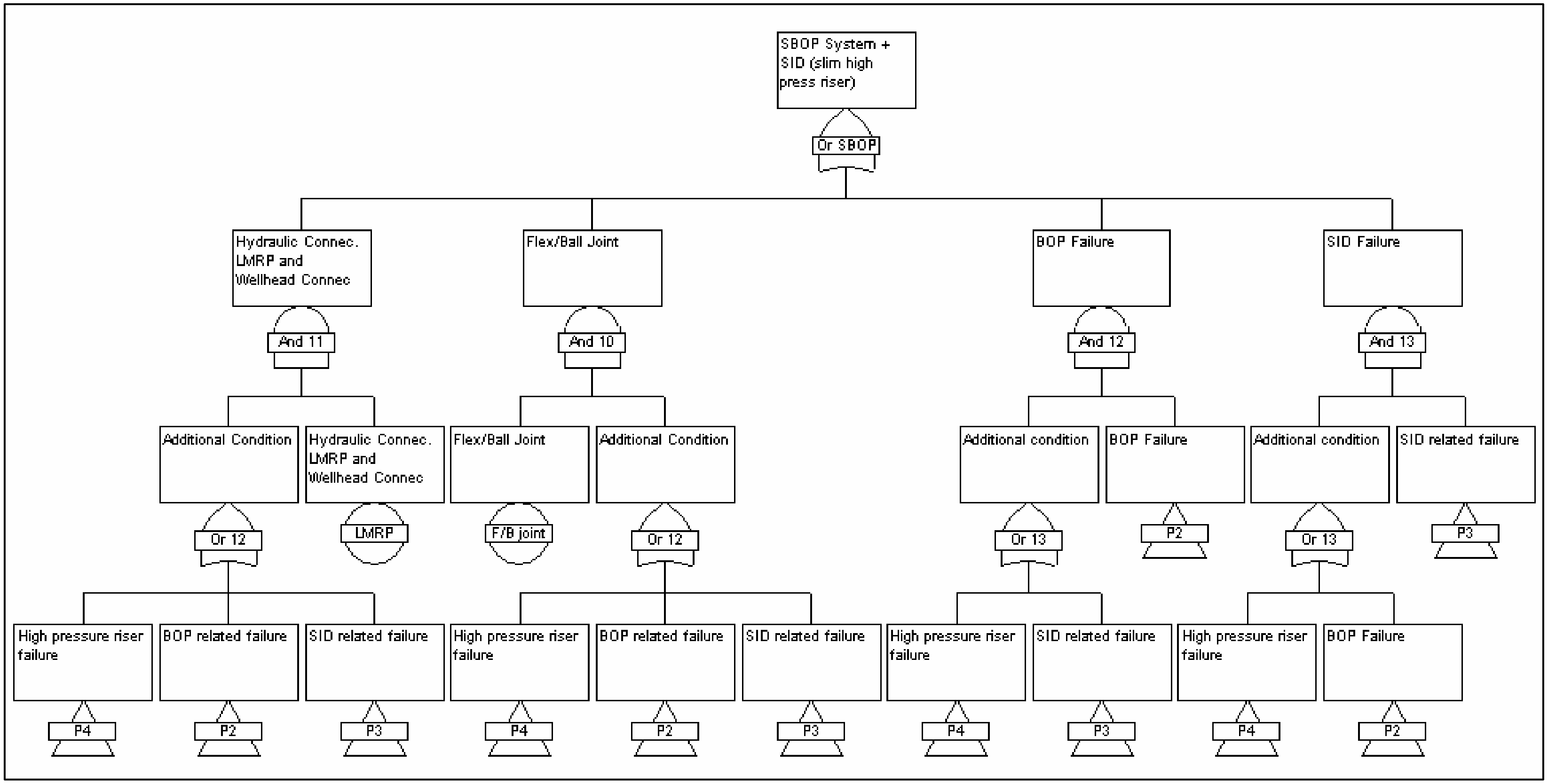


Fig. B.6a– SBOP + SID fault tree model.

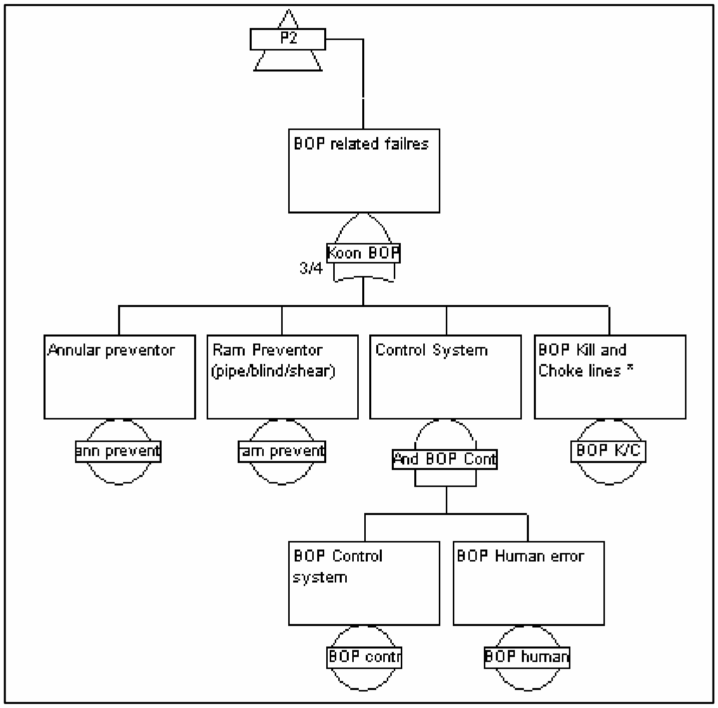


Fig. B.6b– SBOP + SID fault tree model.

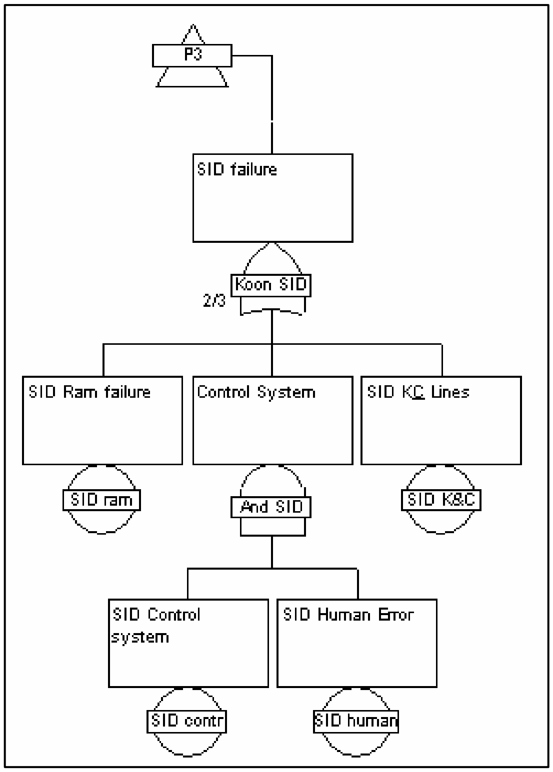


Fig. B.6c– SBOP + SID fault tree model.

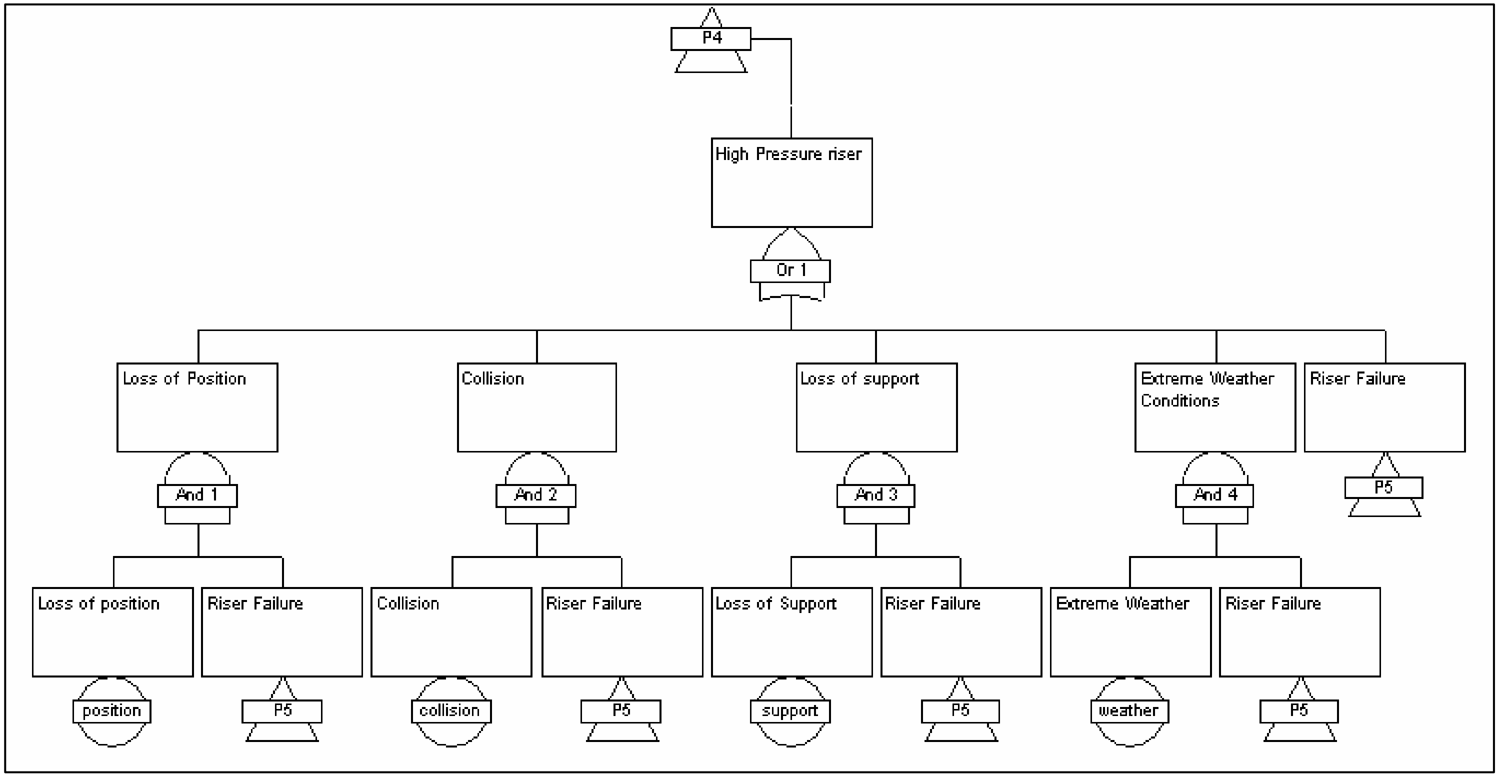


Fig. B.6d– SBOP + SID fault tree model.

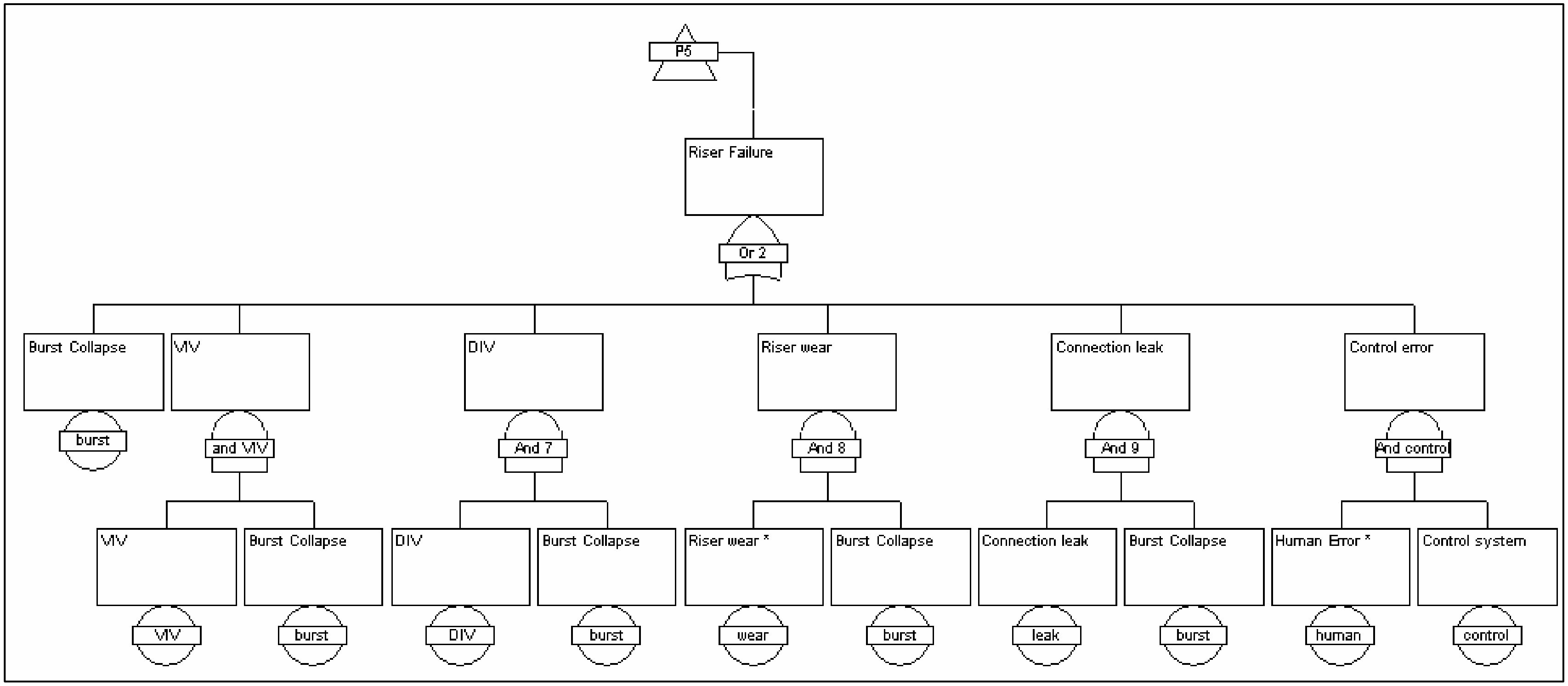


Fig. B.6e– SBOP + SID fault tree model.

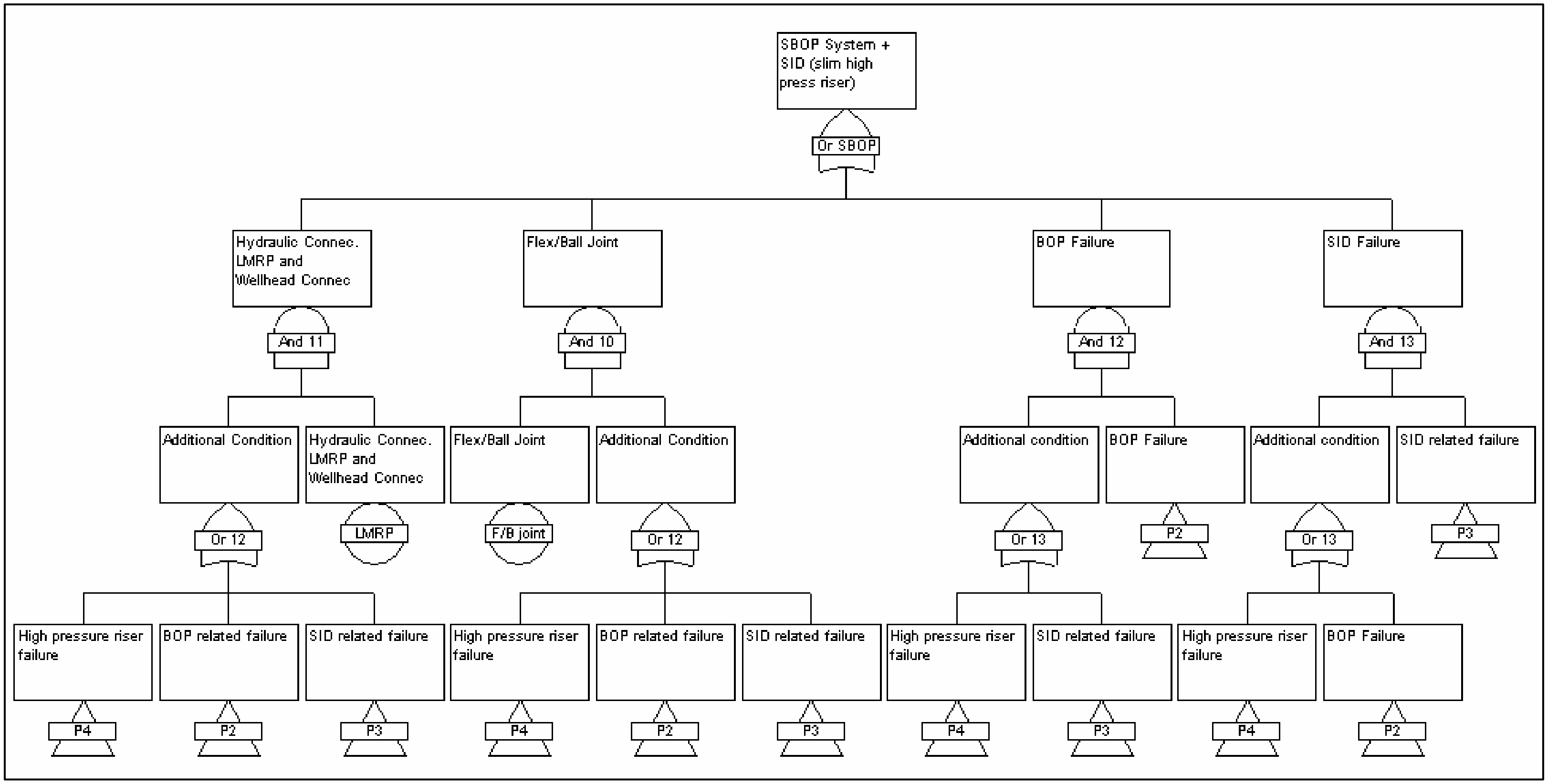


Fig. B.7a– PARLOC SBOP + SID fault tree

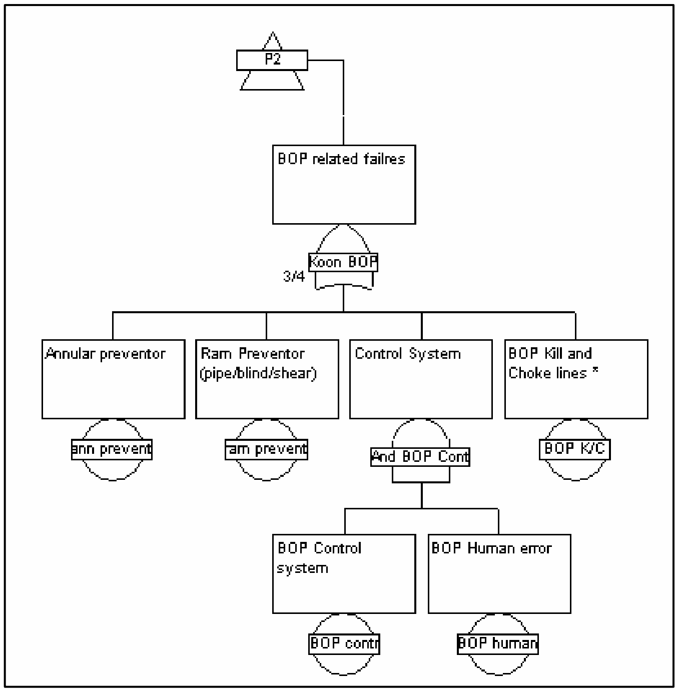


Fig. B.7b– PARLOC SBOP + SID fault tree model.

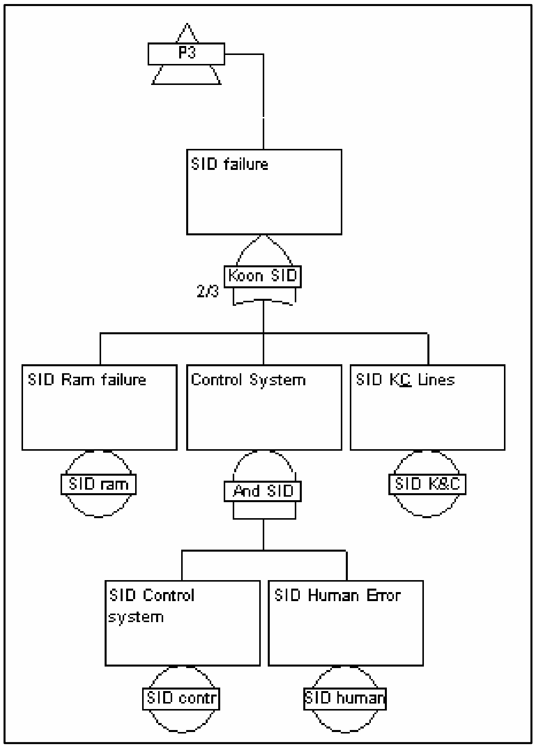


Fig. B.7c– PARLOC SBOP + SID fault tree model.

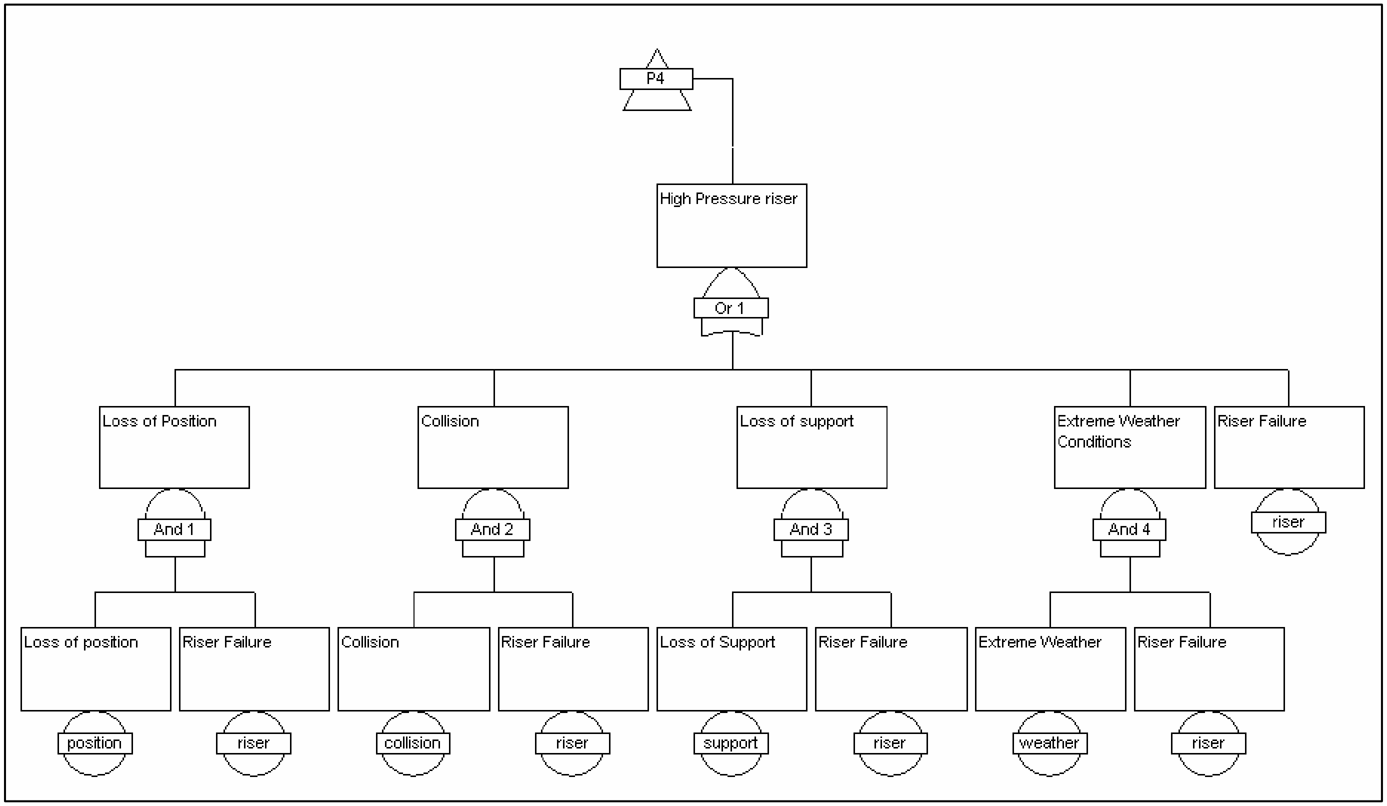


Fig. B.7d– PARLOC SBOP + SID fault tree

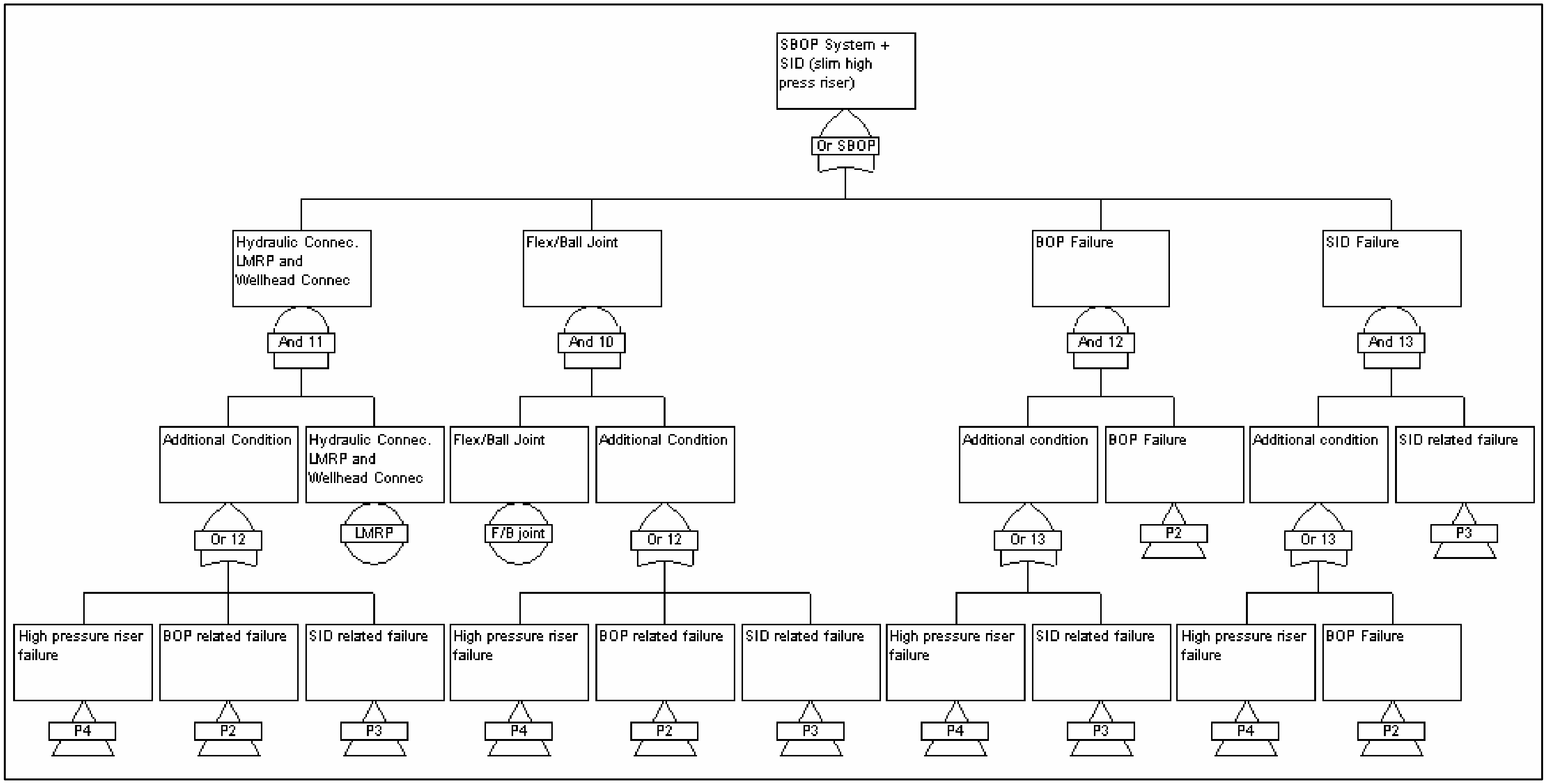


Fig. B.8a– CODAM SBOP + SID fault tree

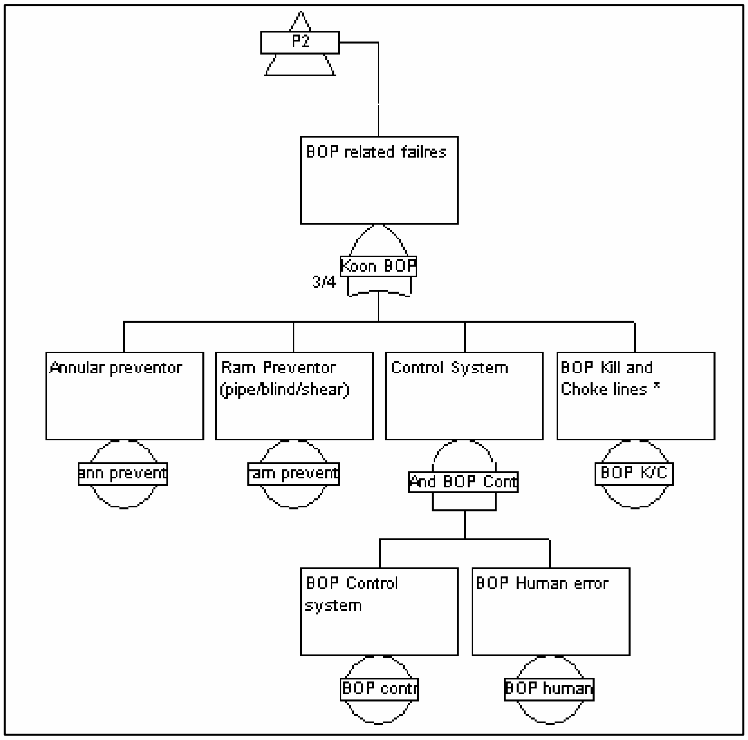


Fig. B.8b– CODAM SBOP + SID fault tree model.

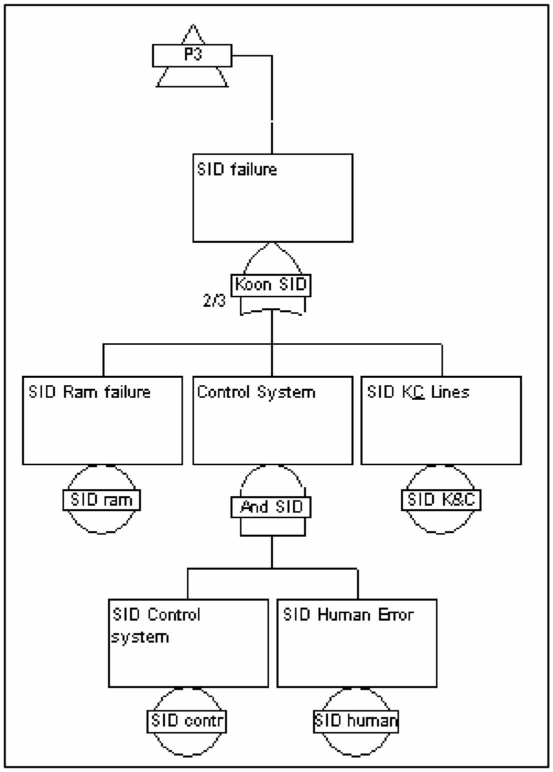


Fig. B.8c– CODAM SBOP + SID fault tree model.

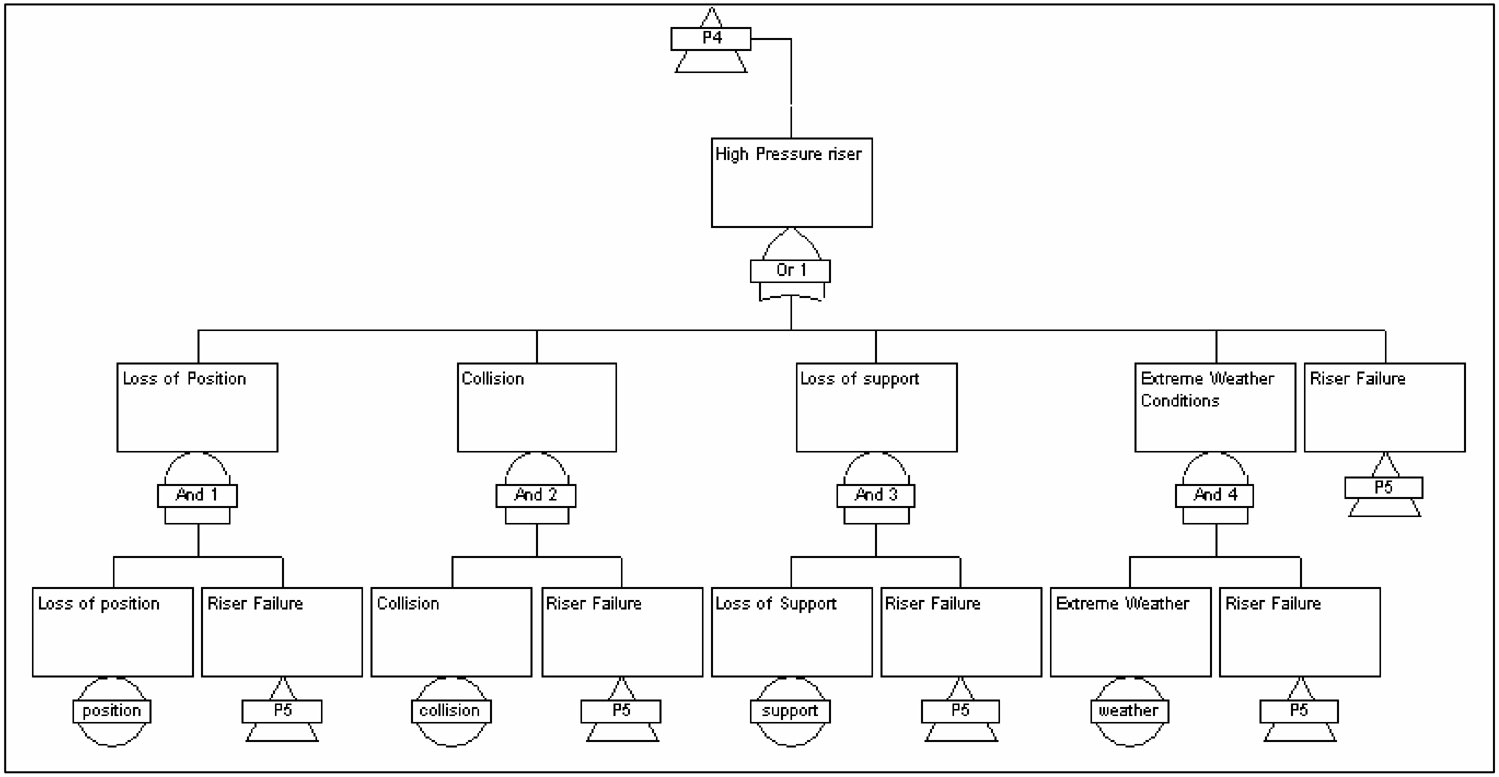


Fig. B.8d– CODAM SBOP + SID fault tree

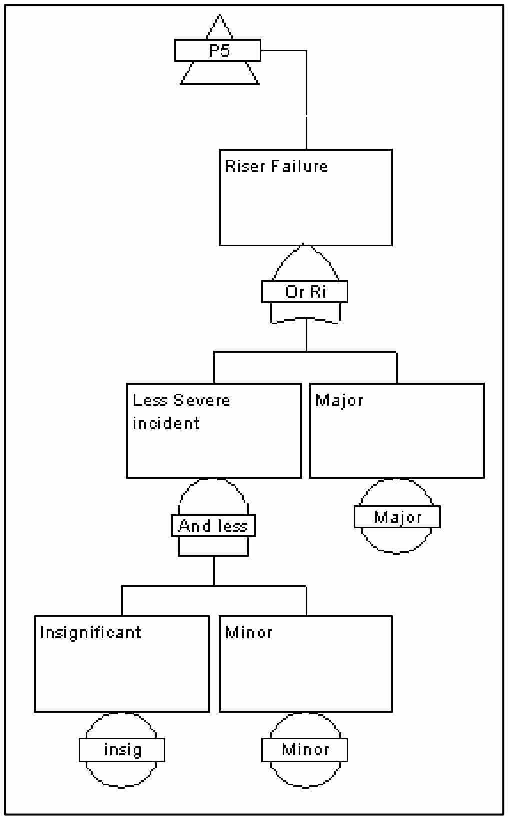


Fig. B.8e– CODAM SBOP + SID fault tree model.

APPENDIX C

MMS GOM DEEPWATER INCIDENTS: 1999 TO 2005

In the attached files there is an Excel spreadsheet named “Appendix-C.xls”. The file contains the dataset assembly made to screen the deepwater incidents reported to the MMS from 1999 to 2005, and has sorted the incidents related to the drilling riser.

APPENDIX D

QUALITATIVE FAILURE RATES AND RESULTS

In the attached files there is an Excel spreadsheet named “Appendix-D.xls”. The file contains the calculations of the failure rate for each component along with the confidence level estimates.

Additionally, the results from all the simulation runs for the qualitative analysis are included with the different datasets assembled.

VITA

Name:	Jorge Luis Melendez
Address:	Calle 58 Num. 6-45 Edif. Costa Brava Apt. 3-C Maracaibo, Estado Zulia, Venezuela 4002
Email Address:	melendezj@tamu.edu
Education:	University of Zulia Venezuela, B.S. – Mechanical Engineering, 2003
	Texas A&M University USA, M.S. – Petroleum Engineering, 2006