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Preface

This thesis is written as a final closure for my master degree program in Offshore Technology; Industrial Asset Management. The thesis was conducted during the spring, from January to June, 2012 at the University of Stavanger. The thesis is an individual assignment, and is about the integrity problems regarding marine drilling riser system.

There are several people I would like to thank. First of all I will start to thank my girlfriend, Tonje G. Strand, for the support and understanding during this assignment. Second I will like to thank my friend Anders Eliesen for motivation and several good advices.

I would also like to thank my supervisors at UiS Tore Markeset and at Sub Sea Services Atle Kvamme.

This assignment has brought me a broader understanding drilling operations and deepwater development, and enlightened the need for further technical development and maintenance handling.

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Alexander Iversen

Summary

The main concerns during drilling operations are riser integrity and maintaining well control. This thesis has mainly been focusing on the problems and challenges faced with the marine riser system to illuminate high risk areas related to riser integrity.

A marine riser system consists generally of four main elements; the upper marine riser package, riser joints, lower marine riser package, and the blowout preventer, each playing an important part in the marine riser system. The marine riser function is to supports and guide the auxiliary lines used to control the well, and connect and provide for fluid communication between the drilling vessel and the wellhead.

Failure to the marine riser is related to technical problems associated with old design and lack of correct operating procedure and maintenance method. Elements like the telescopic joint haven't change the design since the 1960's and are exposed to problems like unplanned discharge caused of premature war to the packer element. Problems with the telescopic joint are not unique there are also experienced failure with tensioner system, flex joint and blowout preventer. Studies show that blowout preventer failure cases the longest downtime and most expensive repairs. Over 50% of blowout preventer failures are related to the control system and are caused by failure to the hydraulic components.

Exploration activity forces the drilling contractor further out and into deeper water depths, like the Gulf of Mexico or outside the Coast of Brazil. Greater water depths challenge the riser system on many places. Deepwater operations means harsher environment and problems in the forms of large waves, strong currents and increased pressure from the water column, all affecting the operations and riser pipe in several ways. The environmental issues causes the riser to fail due to increased tensile load, vortex induced vibrations, environmentally induced cracks and increased corrosion attacks. The increased tensile load on the riser pipe place importance on the top tension capacity of the rig and the riser pipe wall thickness. Moving into deeper ground, many rigs reach their tension capacity and must use buoyancy modules to provide sufficient tension to the riser.

Many of the problems could be addressed using simple solution, like implementing correct maintenance program or address the issues in the design phase. But economical impetus holds the development back. Solutions like redesign of the telescopic joint and blowout preventer is advised by operators, but some of the solution are proven to be economical unprofitable.

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List of Abbreviations

UMRP	Upper Marine Riser Package
LMRP	Lower Marine Riser Package
BOP	Blowout Preventer
SPE	Society of Petroleum Engineers
IADC	International Association of Drilling Contractors
E&P	Exploration and Production
FPSO	Floating, Production, Storing and Offloading
API	American Petroleum Institute
GPS	Global Position System
BCRT	Buoyancy Can Riser Tensioner
TTR	Top Tension Riser
TLP	Tension Leg Platform
O_2	Dioxide
CO_2	Carbon Dioxide
H_2S	Hydrogen Sulfide
H_2CO_3	Carbon Acid
SCC	Stress Corrosion Cracking
SINTEF	Scientific and Industrial Research at the Norwegian Inst. of Technology
BSR	Blind Shear Ram
JIP	Joint Industry Project
MUX	Multiplex
VIV	Vortex Induced Vibrations
FIFO	Flow In, Flow Out
MRS	Mud Recovery System
ISO	International Organization of Standardizations

Table 1 List of abbreviations

1. Introduction

1.1 Introduction

The purpose of this thesis is to show which areas of the marine drilling riser system that need to be looked into to enhance performance and keep the integrity of the drilling riser system. It also takes a brief look at deepwater challenges in relation to marine drilling risers.

This thesis is divided into nine chapters. Chapter one is the introduction and contains the introduction, project scope and task, the background, and methodology of the thesis. In chapter two we take a look at the concept of the two main elements of this thesis, marine drilling riser and deepwater operations. Chapter three is dedicated to and overview of the marine drilling riser system. Here we will go into detail about the main components of a marine riser system, and their individual parts and functions. In chapter four the thesis brings up the challenges and problems faced with selected parts and main components of the marine drilling riser system. Deepwater challenges will also be addressed in this chapter. Chapter five is dedicated to examples on solution to the problems identified in chapter four. In chapter six there will be a discussion about the identified problems and the evaluation of them. At the end come the conclusion, reference and appendixes.

1.2 Project scope and task

Main Objective: *Identifying and evaluating high risk areas and challenges on marine drilling riser system, in relation to deepwater problems.*

This is a theoretical thesis where the marine drilling riser system is evaluated and high risk areas are identified. Deepwater issues are addressed and evaluated in relation and its effect on the riser system.

This thesis is limited to the system of marine drilling risers and operation of deepwater drilling. The main object of this thesis is to identify some of the main challenges and problem related to the marine drilling riser system. The secondary part of the thesis is to identify challenges related to deepwater operations, with connection to marine drilling risers.

This is exclusively a theoretical thesis. Written based on information collected from different sources and systemized. The scope of this thesis is only to illuminate different problems areas connected with marine drilling riser system and deepwater operations.

1.3 Background

Since the first discovery of oil in the North Sea sea-soil, in 1969, the oil and gas reservoir have had a huge impact on the Norwegian wealth and economy. Since the beginning, petroleum production on the shelf has added more than NOK 9000 billion to the country's GDP. [Norwegian Petroleum Directorate, 2012] Statistics shows that the oil and gas industry in Norway contributed in 2011 with a value creation of approximately 610 billion NOK to the government, and employment of approximately 220 000 people divided all over the country. Norway is the world fourth largest oil exporter, and the third largest exporter of gas. The earnings from the oil and gas industry contribute to one third of the government incomes, and are the corner stone of Norwegian economy.

Oil and gas is Norway most important industry, and contributes the most to the Norwegian economy. The petroleum sector contributes with 26% of the state's revenue. This is way it is in the highest interest for the Norwegian, as people and government, and oil companies to deliver operations that are cost efficiency and with high performance, to avoid accidents and deliver on time.

The offshore drilling and oil companies highly depends on the drilling system and equipment to operate and keep on drilling under any circumstances, when exploring for oil and gas reservoir in the North Sea. Drill companies will always be looking for new solution or new equipment to keep the downtime low or to improve their performance. Identifying high risk areas and develop new systems or perform preventive maintenance will be of high significance the next decades. As the oil and gas industry worldwide is changing due to the introduction of new technology as well as exploitation in deeper water depths. The industry is always striving to exploit reservoir the best way, and to reduce the economical and capital expenses in new development.

One important part of the drilling operation system is the marine riser, connecting the vessel or rig to the sea bottom and wellhead. The marine riser system is highly exposed to load stress, currents, salt, waves and motion from the vessel. Oil companies will always try to improve their performance, and to achieve this, oil companies need to avoid downtime and high maintenance cost of the riser system. A failure on the Blowout preventer is one of the most expensive, and leads to the longest downtime one the drilling riser system.

Exploration wells are one of the main activities in the North Sea, and are a necessary action to find oil or gas reservoir. During the start of 2012 is has already been drilled 9 exploration wells and 36 production wells. Increased drilling activity in the North Sea, and combined with new development, high complexity, and large investment makes up the need for more efficient and safe drilling system. The main concern during exploratory drilling is maintaining well control. From the standpoint of maintaining well control is the integrity of the riser very important. This thesis is based on the need to have efficient drilling operations, improved performance and riser integrity for marine drilling risers.

During a study, conducted in 2003 for Society of Petroleum Engineers (SPE) and International Association of Drilling Contractor (IADC) on dropped BOP stacks, they revived and evaluated 32 total incidents of dropped objects and near misses. The study showed that over a third of all problems could be categorized as riser system problems. [Sattler, J.P., 2003]

1.4 Methodology

The methodology used in this thesis is strictly theoretical. I have used literature as reports, published papers, experienced, companies, and friends to collect and systemize the information. The information is used to underlie the theory and be the reason for the conclusion.

2. Concept

2.1 Drilling Riser System

Offshore drilling is the process where a wellbore is drilled through the seabed and into a reservoir for production of hydrocarbons. The drilling riser system houses the drill string and the returning drilling mud, and also connects the Blowout Preventer (BOP) with the drilling vessel or drill rig. The BOP is generally placed on top of the wellhead on the seabed, but in some few cases the BOP is also placed up on the drill deck on the vessel. There are mainly two types of drilling risers system; full-bore drilling riser and marine drilling risers. Marine drilling riser generally has a small diameter pipe and includes external choke and kill, booster and auxiliary lines. The full-bore riser does not feature any external lines. A marine drilling riser system, which this thesis is limited to, generally consists of four main segments; Upper Marine Riser Package, The Riser Joints, Lower Marine Riser Package, and The Blowout Preventer. All segments consist of many other different individuals part, which all have specified and unique functions. Further down in this thesis we will go in to closer detail of each part.

2.2 Deepwater

Deepwater drilling is by definition the process of oil and gas exploration and production in water depths from 300 meters (984 feet) to 1,500 meters (4921 feet). Wells located in water depths higher than 1,500 meters are classified as ultra deepwater wells. [Rocha, P. et al, 2003] Deepwater drilling operations are mainly conducted in the Gulf of Mexico or the coast of Brazil. Very few wells on the Norwegian continental shelf are deepwater wells. This is because The North Sea is very shallow water, with the mean depth of approximately 100 meter (328 feet). The exception is the Norwegian trench, in the northern part of the North Sea. Here there is experienced a maximum water depth of 725 meters (2379 feet) and will be classified as deepwater drilling. Technologies used in shallow water are no longer adequate for water depths over 1000 meters (3280 feet). [Armstrong, L.J., et al, 2002] The environmental consequences for some of the newer deepwater technologies are not well understood. This has required the standard assessment of drilling system to be revisited.

2.2.1 Norwegian continental shelf

The Norwegian continental shelf is the sea-bed and sea-soil outside the Norwegian coastline. It reaches all the way alongside the Norwegian coast line and stretches 200 nautical mil out in the ocean. Above the sea-bed, the Norwegian continental shelf is divided into three main seas; North Sea, Norwegian Sea, and Barents Sea. Even though the water depth in the North Sea is relatively shallow the drilling condition is very hard. Rough weather, high sea and strong currents are to affect the drilling condition. During the winter the average air temperature is between 0 to 4 degrees Celsius, and gales and storms frequently appears. When drilling in the Norwegian trench with a maximum depth of 700 meter, drilling operators reach the definition of deepwater drilling. This makes the drilling even harder.

Figure 1 Offshore oil platform 'Gullfaks C' stands up to a fierce, North Sea storm [Husmo, A., 2012.]

2.2.2 Gulf of Mexico

The Gulf of Mexico is a sea located in the southeastern corner of North America. The gulf measure approximately 1,600 kilometer from east to west, and 900 kilometers from north to south. This gives the Gulf of Mexico a surface of 1.5 billion square kilometers. Deep and ultra-deep water represent approximately 40% of the gulf. It is estimated that 1.4 to 7.2×10^8 barrels of petroleum and 4.4 to 22.3×10^{10} cubic meters of natural gas are present beneath the seafloor. [Gulfbase, 2012]

2.2.3 Coast of Brazil

The Coast of Brazil is together with the Gulf of Mexico one of the world largest deepwater development locations. In 2009 Brazil was the 9th largest oil producer in the world. But exploration and drilling outside the coast of Brazil is more technological challenging than other places. 72% of all exploration and production (E&P) activities involves depths of 1000 meters and further, and the distance from shore and the demands for special transport care makes. Due to the long distance from the coast the main type of platform used in the Brazilian deep oil fields is the Floating, Production, Storing and Offloading (FPSO). Petrobras, Brazilian state company, is the largest FPSO operator in the world.

3. Overview

The marine drilling riser system connects the vessel or rig to the Blowout Preventer, mounted on top of the wellhead on the sea-bed. The riser system has many different functions. The primary function for the marine riser system is to houses the drilling bore and the returning mud from the well. It also functions as a guide for tools in the well, and supports the kill and choke, booster, and auxiliary lines used to control the well. Generally a drilling riser consists of five main elements, the Upper Marine Riser Package (UMRP), Riser Joints, Lower Marine Riser Package (LMRP), and the Blowout Preventer (BOP). Each main element is made up from other smaller parts which will be discussed in greater detail further down in this chapter.

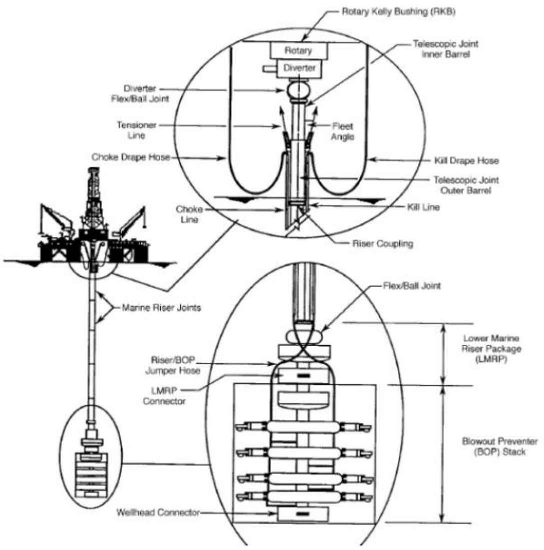


Figure 2 Marine Drilling Riser System and Associated Equipment [API 16F, 2004]

3.1 Upper Marine Riser Package (UMRP)

The upper marine riser package (UMRP) is the upper portion of the riser string, including the riser tensioner system.

The upper marine riser package includes:

- Diverter assembly
- Upper flex joint
- Riser rotation bearing joint
- Self-tensioned slip joint (telescopic joint)

3.1.1 Diverter Assembly

The diverter assembly is mounted on top of the upper marine riser package, but is not according to API 16F considered to be a part of the marine drilling riser system. Typically the diverter assembly includes an annular sealing device and control system. [API RP 16Q, 1993] The diverter system provides for safety for the personnel and equipment by providing low pressure well-flow control system. The well-flow control system directs controlled or uncontrolled wellbore fluids from the well away from the immediate drilling area. [Lim, J.S., and Pfeifler, J.R., 1986] The diverter assembly is often used when drilling top hole without casing and BOP.

3.1.2 Upper flex/ball Joint

The upper flex/ball joint is positioned typically between the diverter system and telescopic joint in the UMRP. The UPMR can either use a flex joint or a ball joint. Flex/ball joint permits the angular movement of a riser element, and permits the riser to accommodate roll, pitch, and offset of the vessel. [API 16F, 2004] The rotational stiffness of flex-joint makes them more effective than ball-joints in controlling riser angles. Typical rotational stiffness for a flex-joint, ranges from 10,000 to 30,000 foot-pounds per degree angle. [API RP 16Q, 1993] In the UMRP the loads is transferred through the upper flex/ball joint from the telescopic joint too the diverter. [Lim, J.S., and Pfeifler, J.R., 1986]

3.1.3 Riser Rotation Bearing Joint

The rotation bearing joint allows the vessel to rotate about the riser vertical axis. The bearing joint is mounted on the bottom of the telescopic joint. A typically bearing element consists of roller bearing system, built in locking device, and hydraulic motors. The roller bearing system minimizes the torque transferred from the riser to the telescopic joint. The hydraulic motors and the built in locking device is used for precise rotational control and preventing inappropriate rotation of the riser. [Lim, J.S., and Pfeifler, J.R., 1986]

3.1.4 Telescopic joint

The telescopic joint, also called Slip Joint, is a part of the upper marine riser package. A telescopic joint generally consist of an inner and outer barrel, packer system, seals and tension ring. The outer barrel is typically used to connect with the upper riser joint, and the inner barrel connects with the flex joint at the base of the surface diverter.

The telescopic joint function is to compensate for the heave and offset to the drilling vessel achieved by sea motion, by continuously adapt the riser length. This way it’s allowing the riser system to compress and extend and the movement is achieved through constant stroking movement of the inner and outer barrel. The secondary functions of the telescopic joint are to serve as a transmitter for the mud/fluid as it returns from the well. The packer system is under severe stress most of time and functions as a seal between the inner and outer barrel, preventing mud and fluid leakage from the telescopic joint.

3.2 Riser Joints

The riser joint is positioned between the telescopic joint and the lower marine riser package. The riser joint has no other function than extend the riser system to the sea floor, and guide the kill and choke, booster, and auxiliary lines down to the lower marine riser package and BOP.

3.2.1 Riser Pipes

The riser joint is basically an assembly of many riser pipes. Each riser pipe has a flange attached at both ends. The marine riser joint also have kill and choke, booster and hydraulic lines mounted on the outside of the riser, supported by brackets or other guiding devices. The riser pipe houses the drill string and the returning mud from the wellhead. The flange on each end of the riser joint makes up the joining point and is where the riser joints are connected with each other. There exist many different riser connection system on the market, some more reliable than other. The lines mounted on the outside of the riser body, is joint together with simple pin-box construction.

3.2.2 Tension System

All floating drill rigs use tension devices to keep the rigs steady and in position. A floating drill rig can be connected to the sea floor through pipes or cables called tension legs, or they can float freely and be maintained in location by a global positioning system (GPS). A drilling platform connected with tension legs can keep stability through a ballast system. The ballast system uses ballast tanks filled with air and water to keep stability. But the ballast system cannot keep control of the riser pipe tension. Tension in the riser pipe is developed through tensile load from underlying riser joint and BOP stack. To prevent the riser from buckling and collapse special tension system are being used. Tension systems are used to provide continuous, reliable axial tension to the marine riser pipe during drilling operations. Typical tension systems are Wire Line Tension System and Buoyancy Can Riser Tension System (BCRT). The wire line, or hydro-pneumatic, tension system is the most common, but for deepwater development are BCTR typically used.

3.2.2.1 Wire line Tension system.

Riser tension is maintained through tensioners applying tension at or near the top of the marine drilling riser. Tensioners are connected by wire rope over sheave to a tension ring attached to the slip joint. Through large piston/cylinder arrangements tension is applied to prevent the riser from buckling. The flexibility of the rope minimizes the effects of yaw that would otherwise be transmitted to the riser.

A wire line riser tension system usually consists of:

- Tension cylinders and sheave assembly
- Hydro pneumatic accumulators/air pressure vessel
- Control panel and Mani folding

A riser tension system is basically multiple hydraulic cylinders with wire lines sheaves. The wire line is reeved around the sheaves with one end and attached to the outer barrel of the riser telescopic joint. The tension on the wire lines is directly proportional to the pressure of stored air. The design principle behind the tension system is that when a rig heave upwards, fluid is forced out of the hydraulic cylinders, compressing the air. As the rig heaves downwards, the hydraulic cylinder is allowed to stroke the opposite direction, forced by the compressed air. [NOV, 2012] These tensions ensure that the lines remain fully taut, even under the most severe rig motion condition. The tension must respond to the maximum velocity of rig heave, not the average speed. [NOV, 2012]

3.2.2.2 Buoyancy Can Riser Tension system

Buoyancy equipment may be attached to the riser joints to reduce top tension requirements by decreasing the submerge weight of riser joint, typically used on deepwater operations. Buoyancy Can Riser Tension System (BCTR) is one design solution for buoyancy equipment. The BCRT is designed to give tension for the marine drilling risers, as well on drilling-vessels using Top Tension Risers (TTR). A TTR is vertical flexible risers that terminates directly below the facility and are fixed at the seafloor. The TTR keeps the drilling vessel steady and only allows for vertical displacement. The BCRT system is mounted on the outside of the riser giving tension to the riser using the buoyancy principle.

The BCTR is a passive tensioning system and are designed to transfer horizontal loads at hull connections. The BCTR system consists of three main segments; upper stem, buoyancy can, and lower stem.

The buoyancy can section is composed of many individual chambers filled with air or nitrogen gas. The BCTR system is installed at the top of the riser system and experiences the same elevation change as the riser. This way when the BCTR moves, the buoyancy provided by each buoyancy-can chamber, changes. This way the buoyancy can provide the tension required by the riser system to prevent buckling and instability.

Figure 3 Drilling Riser Buoyancy Module [Floating Technologies, 2012]

The upper stem mounted on the top of the buoyancy can transfers the tension provided by the BCTR to the riser. Attached to the bottom of the buoyancy can, the lower stem shields the riser from hydrodynamics forces. [Karayaka, M., 2003]

3.3 Lower Marine Riser Package (LMRP)

The lower marine riser package is an assembly located at the bottom of the drilling riser, but above the BOP. The LMRP provides releasable interface between the riser and BOP stack.

Typical component in a LMRP are:

- Lower Riser Adapter
- Flex/ball joint bypass lines
- Lower flex/ball joint
- Hydraulic connectors for mating the riser to the BOP stack

[API 16F, 2004]

3.3.1 Lower Riser Adapter

The lower riser adapter is the connection between the lower most riser joint and the lower flex/ball joint mounted on the lower marine riser package. [API 16F, 2004]

3.3.2 Flex/Ball joint bypass lines

The bypass lines are mounted on kick outs on the riser adapter. They bypass the flex/ball joint and terminate in the BOP. [API 16F, 2004]

3.3.3 Lower flex/ball joint

See Flex/ball joint for UMRP. The lower flex/ball joint is the same as the upper. It permits angular displacement for the riser.

3.4 Blowout Preventer

The Blowout Preventer (BOP) is the last and largest element attached to the riser system, and is in many ways the most important equipment in the drilling riser system. The BOP sits on top of the wellhead and is basically a specialized valve used to control and monitor the oil and gas flow from the well. There exist many different types and variations of BOP's, but very often several different blowouts preventer are installed on top of each other on top of the wellhead.

The goal of a exploration drilling operation is to find reservoir of oil and natural gas. On top of the reservoir, water and rock creates an enormous pressure inside making the oil and gas to burst out once the reservoir is punctured. To prevent the oil and gas from bursting out drilling mud is being used to stabilize the pressure. The drilling mud is a natural part of the drilling operation and is always circulating under pressure inside the riser pipe. This pressure opposes the pressure of the oil that wants to come out.

Figure 4 A Blowout Preventer, Credit: Cameron-Nautronix [The Encyclopedia of Earth, 2012]

Sometimes the pressure in the reservoir is too high and the pressure can blow all the mud right back up the well, commonly known as "kick" or "blowout". In case of these situations the blowout preventer is there to handle the situation and prevent the "kick". The Blowout preventer has many different approaches to these situations. The typical selection between BOP systems is annular BOP and Ram BOP.

3.4.1 Annular Blowout Preventer

The annular BOP closes around the drill string and seals it of at the top of the BOP. If no part of the drill stem is in the hole, the annular blowout preventer closes around the open hole, and uses the principle of a wedge to shut in the wellbore and seal it. This type of system requires that the drill string is out of the well. For other situations operators can use ram BOP system.

3.4.2 Ram Blowout Preventer

A ram BOP has the same principle as a gate valve. The difference is that the BOP uses a pair of opposing steel plungers. The ram BOP function as a extension from each side towards the center of the wellbore, to prevent mud-flow returning from the well. The rams, or ram blocks, comes in four different types; pipes, blind, shear, and blind shear, all with special abilities.

The pipe rams [Figure 5, b] closes around the drill pipe, preventing flow in the annulus, between the drill pipe and wellbore. The pipe rams do not obstruct the flow within the drill pipe.

Blind rams [Figure 5, a] have no opening for the drill pipe and can close well that does not contain a drill string by moving towards the center and seal it. A blind shear ram can cut through the drill pipe and seal the well.

The shear ram [Figure 5, c] can cut through the drill pipe with hardened steel shears.

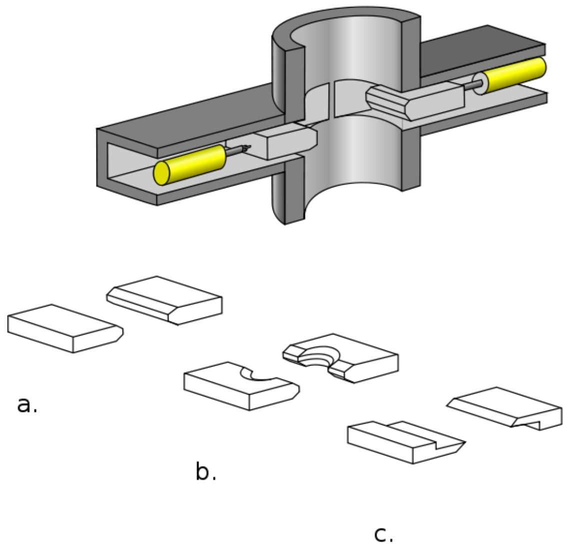


Figure 5 Blowout Preventer diagram showing different types of rams. (a) Blind ram (b) Pipe ram and (c) Shear ram. [Wikipedia, 2012]

3.4.3 BOP control system

The BOP control system talks with the BOP. It basically sends a signal down to the BOP subsea control system where the signal is decoded and performed. A BOP control system consist generally of two elements; electrical and hydraulic elements. The BOP system is controlled from a two completed control pods. Each pod is capable of performing all necessary function on the BOP. [Shanks, E., et al, 2003]

4. Challenges

After the identification and overview of the main- and sub-elements of the marine drilling riser system, will this thesis focus on identifying the challenges and problems faced with some of the selected elements and systems. The elements that is most exposed and chosen to be evaluated for the identification of high risk areas is the telescopic joint, riser pipes, tension system, lower flex/ball joint, and the Blowout Preventer with the control system.

4.1 Upper Marine Riser Package

4.1.1 Telescopic Joint

The design of the telescopic joint is old and has not been changed significantly since the introduction in the early 1960`s. [Upton, T.L., 2009] Fifty year old design combined with increased number of deepwater wells, new technology and harsher weather condition makes the telescopic joint exposed. The telescopic joint is associated with several problems-areas, and are known to adversely affect the well cost and well control. Discharging events attended with the packer system is a common problem, but there are also recorded incidents of packer housing bolts failed, new telescopic joints to fail, cracks developed at welds, and inner barrel shoe that could not support weight of riser and stack. [Sattler, J.P., 2003]

During the period of 2000 to 2008 there was conducted a review of discharge incidents that occurred during offshore operations, and the review related that on average approximately 2.5 unplanned fluid discharges or near miss events had occurred each year. All events where associated with marine riser slip joint packing-elements leaks. [Upton, T.L., 2009]

68% of telescopic joint failures were the result of failure of the primary packer element. [Upton, T.L., 2009] The remaining failures were the result of either insufficient air pressure or the total loss of air pressure required to activate the secondary packer element. Packer-wear was the main failure event causing the element to fail, but corrosion pitting on the surface of the inner barrel was a highly contributing factor.

The survey revealed that there were some correlations between equipment maintenance practice and packer elements failure. In all but one case, the seal failures were the result of premature wear to the slip joint packer element. A typically packer-elements replace frequency is between 1,800 and 3,600 operating ours. [Upton, T.L., 2009]

Figure 6 Eccentric wear to the packer element [Upton, T.L., 2009]

But insufficient maintenance intervals and premature wear had the packer elements failure occur in as few as 750 operating hours in some cases.

Failure with the packer element is the common failure with the telescopic joint, but studies have shown that the telescopic joint packer housing bolts have failed during lifting operation of the BOP stack. Closer examination revealed that worn threads and incorrect operation procedure was the main reason for these kind off accidents. [Sattler, J.P., 2003] The lack of preventing measures and correct operating and handling procedure have been shown to lead to the development of crack growth in welds, telescopic joint adapter to fail due to uncompleted welding procedure, and that the inner barrel shoe could not support the weight of riser and stack. [Sattler, J.P., 2003]

Figure 7 Detail of Failed Bolt [Upton, T.L., 2009]

The secondary function of the telescopic joint is to serve as a transmitter for the mud and drilling fluid as it returns from the well. One of the main problems associated with the telescopic joint concern the effect that it has on the return-flow of drilling mud. As the telescopic joint reciprocates due to the heave motion, a change in internal volume of the returning drilling mud will occur. The change in internal volume will causes the return mud-flow to subject to considerable variations of flow rate. This phenomenon has a number of adverse effects on well control. [Baker, R.J., 1991]

An influx of formation fluids, commonly known as “Kick”, has the potential to lead to blowouts. Therefor it’s important to have early detections of influx of formation fluids in the mud. The earliest detectable warning comes from accurately measuring the flow rate of the returning mud stream in the telescopic joint, and detecting an increase. But due to the widely fluctuating heave induced on floating drill rigs, it has been proven to be impossible to accurately measure the returning mud flow rate. The telescopic joint have in this way an adversely effect on the well control.

The widely fluctuating flow rate that appears in the telescopic joint could lead to increased well cost. The fluctuating flow rate makes it hard to maintain efficient operations of the shale shakers. To prevent liquid mud to be lost across the shakers scree, it becomes necessary to install screens that are coarse enough to handle the maximum flow rate.

The Telescopic joint is an important part in the riser system. It plays an important role for riser motion compensation and well control. But it is also highly exposed and vulnerable for damage and problems. The problems known for the telescopic joint is overall related to poor, insufficient and old design. The lack of renewal and upgrade makes the telescopic joint a weak link in the riser system. Deepwater challenges are not really an issue for the telescopic joint du the location, almost on the top of the riser system. Therefore the problems are more a technical challenge that could have been solved on a much earlier stage.

4.2 Riser Pipes and Tension system

4.2.1 Tension System

The tension system should provide a constant force to the slip joint to prevent the riser from buckling and instability, but real time motion of the slip joint due to vessel-motion cause's inertia and viscous effect. This means that tension system force will be time dependent and directly a function of the slip joint motion. [Kozik, T.J., 1975] Because of this, a study of load transmittal and variation in the riser tension system becomes an important and necessary to the detailed analysis of riser string motion and stresses.

The hydro-pneumatic wire rope tension system is the most common system used to maintain tension to the riser. The main concern regarding the wire rope tension system is the wire line life time. The wire line life is a function of a several parameters including sheave diameter, applied tension, operating circumstances and rope construction. But the common problem to the wire rope is that when approaching greater depths the drill rigs reaches their tension capacity. The solution to this is to use buoyancy can riser tension system to provide for sufficient tension to the riser.

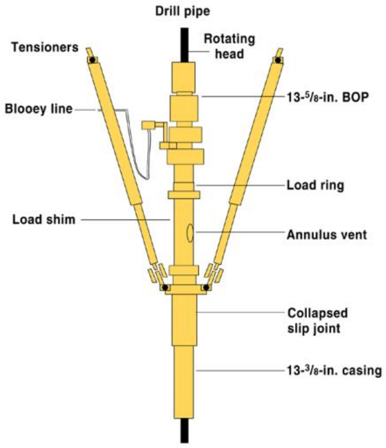


Figure 8 Riser tensioner system [Furlow. W., 2012]

The buoyancy can riser tension system (BCRT) is designed for Top Tension Risers (TTR). TTR are often used on Tension Leg Platform (TLP) or Spars, and are completely vertical riser system that terminates directly below the platform and are fixed to the seafloor. Due to the fixed point on the seafloor will vertical displacement occur between the top of the riser, and its connection point on the facility. [Rigzone, 2012] A typical solution to this issue is buoyancy can deployed around the outside the riser, decreasing the submerge weight of the riser.

For deepwater application there are some issues to address with the BCTR system. Typical deepwater TTR issues are material, pressure, water depth and number of casings. Increases in water depth and high reservoir pressure are primary parameters that influence the riser weight.

The increased riser weight have adversely influence on tension requirement for BCTR system. [Walters, D., Thomas, D., and Hatton, S., 2004] Increased tension requirements means to increase the hydro-pneumatic tension requirements, meaning larger air accumulator, and buoyancy can size.

Larger aircan volume, achieved through increasing the length or diameter, will have several adversely impact on the riser system. Increasing the aircan length will result in complex hydrodynamic loading with increased susceptibility to fatigue of the aircan, riser and mooring system. [Walters, D., Thomas, D., and Hatton, S., 2004] On deepwater will the aircan's have direct influence on the vortex induced vibrations, likely to lead to detrimental influence on the riser.

The enlarged buoyancy will also have a direct impact on installation of the BCTR system and vessel motion. Large aircan's will result in larger drag loading on the spar, increasing the vessel offset. Increased offset increases the bending loads on the lower joint at the base of the riser. [Walters, D., Thomas, D., and Hatton, S., 2004] This affects the riser material and the flex-angel on the lower flex joint.

The tensioner system provides stability for the riser. The tension requirements are no problem when operating in shallow water. The wire lines are designed to be capable to provide sufficient tension based upon the maximum rated water depth and maximum expected mud weight. Exceeding these limitations exposes the wire line and reduces the life time. The usage of enlarge buoyancy cans only add more adversely effects to the riser system.

4.2.2 Riser pipes

Over the last two decades, drilling activity has moved into deeper water. Deepwater represents a wide variety of technical and environmental challenges that has resulted in more stringent drilling riser design. Deepwater developments are typically characterized by environmental waves, high currents and dynamic loading leading to accelerated fatigue damage. [Hariharan, M. and Thethi, R., 2007]

The riser pipes are the "shell" protecting the drill string and houses the returning mud and drilling fluid. Due to their position in the riser system, riser pipes are highly exposed to several problems and challenges. The main challenges are corrosion, tension stress, currents, waves, curvature and offset from the wellhead position due to vessel motion. To prevent or minimize the possibility of riser downtime, the riser pipes must resist environmental wave and current loading, and maintain small flex-joint angles. [Howells, Dr. H., and Bowman, J., 1997] Riser pipe problems are mainly environmental, but they could be categorized into two areas; technical, from tensile load and internal & external pressure, and second; corrosion, both internal and external.

4.2.2.1 Technical

Heave motion from the vessel and improper functioning from the telescopic joint or tension system could lead to high tension in the riser pipe. Tension is caused from underlying riser joints and the BOP stack, and could leads to fatigue crack growth, Stress Corrosion Cracking, in the riser pipe. [Howells, Dr. H., 2000] High tension and the growth of cracks on the riser pipe place increased importance on wall thickness of the riser pipe.

Wall thickness is not only important for increased tension, but also for hoop stress resistance from mud head and collapse resistance from water column. [Hariharan, M., and Thethi, R., 2007] Normal wall thickness of a riser pipe is approximately 1 inch. The material the riser pipe is made of generally has the material quality of min 80Kpsi. [Hariharan, M., and Thethi, R., 2007] Minimum 80Kpsi gives minimum yield strength of 550 MPa. With a wall thickness of 1 inch the riser pipe can tolerate a tensile load of 14940kN. A normal tensile load from the riser joints, LMRP and the BOP stack are approximately 5500kN. [Appendix A]

Together with tensile load from the riser joints, LMRP and BOP, place internal pressure from mud head an increased importance on wall thickness regarding hoop stress resistance. Using the same dimension as before (previous section) we can check the maximum internal pressure resistance by using the highest utilization of hoop stress in a riser pipe. Maximum hoop stress is given by internal pressure of 38.8 MPa (5626 psi). The Normal working pressure from drilling fluid and mud is 3.44 MPa (500 psi). [Appendix A]

Riser pipes are exposed for collapse due to external pressure from the water column. Collapse resistance has great relation with wall thickness of the riser pipe. A riser pipe with wall thickness of 1 inch and material minimum yield of 550 MPa can tolerate an external pressure of theoretical 13.6 MPa before buckling. This is comparable to approximately 1300 meter water depth. [Appendix A] Some of the internal pressure prevents the pipe from buckling, so taking that into consideration, a theoretical water depth will be around 1600 meter. 1600 meter is also above the deepwater definition limit.

The riser pipe itself is fully dimensioned and resistance for deepwater application. But a fully dimensioned riser pipe faces challenges regarding the weight. Heavy riser pipes increases the tensile load on the cross-surface, meaning increased wear and top tension capacity on the rig. These issues are addressed further in the deepwater section.

4.2.2.2 Corrosion

Riser pipes are not only influenced by problems like tension, internal and external pressure. But the location, between the wellhead and vessel surrounded by seawater, makes the riser pipes exposed to corrosion, both inside and outside. Internal and external corrosion is the dominant integrity issues for riser pipes. Seawater penetration, CO_2 and H_2S corrosion have the possibility of corrosion fatigue, metal loss and even stress corrosion cracking. [Marsh, J., et al, 2009]

There exist many different types of internal corrosion, but the dominant corrosion issues, where water are in contact with steel, are of electrochemical nature; O_2, CO_2 and H_2S corrosion. The crude oil and natural gas from the oil/gas reservoir usually contains some level of Carbon Dioxide (CO_2) and Hydrogen Sulfide (H_2S).

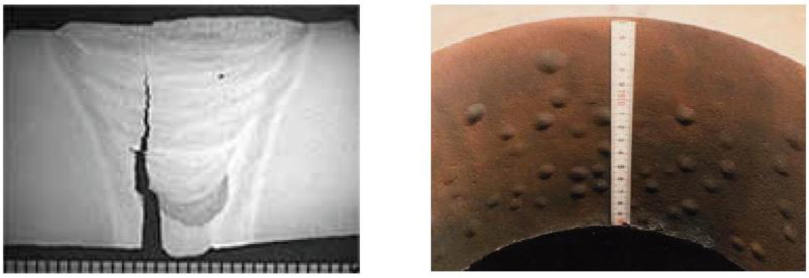
Figure 9 Heavy pitting and general wall loss [Hatton, S., 2010, HTHP]

During a study in the 1970's on industrial failures, corrosion (all types) was the mean cause of 33% of all failure, and the CO_2 and H_2S was the most common type. [King, G.E., 2009] Most often the corrosion pattern is in form of pits, craters or more uniform wall thinning.

Dioxide (O_2) corrosion is the most damaging corrosion mechanism. Small amounts of oxygen, water and chlorides can ruin a chrome tubing completion in a few months. O_2 corrosion is most common where seawater is being used, for example injection wells. [King, G.E., 2009]

When Carbone dioxide is dissolved in water it forms Carbon acid (H_2CO_3). Carbon acid is highly corrosive to carbon steel or low alloy steel. The CO_2 corrosion appears as pitting corrosion, holes in the metal, and has adversely effect on the wall thickness. CO_2 corrosion affect differently under varying condition of pressure, temperature, pH and oil water fractioning.

Hydrogen sulfide naturally exists with oil and gas in well reservoir, and does like CO_2 dissolve in water. When H_2S dissolves in water it produces hydrogen H- ions. H- Ions are relatively small and can diffuse through the grain boundaries or any defect openings in the steel materials. When two H- atom combines and form H_2 molecule, which is a gas, the molecules accumulates and gets trapped inside the material. This could cause highly localized pressure build up and initiate a crack.



Under the right condition the H_2S corrosion process can be very rapid leading to structural failure.

Figure 10 H_2S Corrosion crack and pressure build up [Hatton, S., 2010, HTHP]

The most common phenomenon below the water line is the electrochemical nature of anode depletion, leading to external corrosion. [Marsh, J., et al, 2009] But in addition to metal loss corrosion damage can also Environmentally Induced Cracking occur. These are typically Stress Corrosion Cracking (SCC), Hydrogen Embritllement and fatigue corrosion. [Roche, M., 2005] Environmentally induced cracking generally occur in the event of disbonded coatings. Disbonded coating is with time the major threat encountered with riser corrosion. External and internal corrosion impacts every aspect of a development from design, material specification, manufacture, installation, and operation. [Hatton, S., 2010] Corrosion is known as a key driver; it influences every aspect of a project.

The general dimension of a riser pipe does not face any menace regarding hoop stress, tensile load, or internal and external pressure. The riser wall thickness is proven to be sufficient enough. But in the case of corrosion attacks resulting in cracks and wall thinning the riser, wall thickness is to be an issue. Corrosion attacks could be dangerous causing damage fatigue, and are more likely to occur without an efficient corrosion prevention system. Two common prevention systems are cathodic protection and surface coating.

4.3 Lower Marine Riser Package

4.3.1 Lower Flex/ball Joints

The lower and upper Flex/ball joint compensate for the vessel or drill rig offsets relative to the wellhead location. During the late 70's there was conducted a study to determine the effect of water depth, vessel offset, mud weight, top tension and buoyancy modules on the riser stresses lower and upper flex/ball joint [Azar, J.J., and Soltveit, R.E., 1978]. The report concluded that the mud weight, vessel offset and buoyancy modules affected the bending moment in the riser and the riser angel provided by the flex joint.

On the rig today, the most common is to use flexible joint with a flexible element. Some flexible joint is based on the ball joint principle. Compared to the ball joint principle, failures in the flexible joint is rare. Due to the observation of several failures of the ball joint in the North Sea during the 1980's, it can be concluded that flexible joint is more reliable than the ball joint principle. A study conducted by SINTEF during the 80's and the 90's shows that five of twenty-six rigs had ball joints. The drill rigs using the ball joint principle represented 18, 5% of the BOP's-days in service. [Holand, P., 2001]. During the survey, flexible joint was observed with a failure. But the failure was in flex joint using the ball joint principle. The cause of the failure was an external leakage and not the flexible principle.

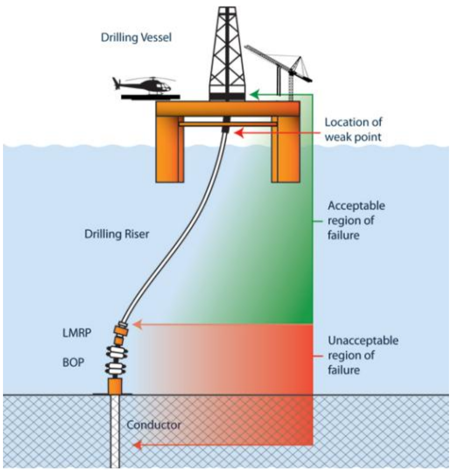


Figure 11 A riser failure assessment [Sonawane, M., Koska, R., and Campbell, M., 2012]

Large currents associated with deepwater drilling operations, makes the vessel drive off and give the vessel an offset in relation to on station position. Vessel offset affects the flex joint rotation. For drilling operations the flex joint rotation limit is mean 2 degrees, and max 4 degrees. Flex joint rotation near the max limit makes the material to reach below the yield limit of 67%. [Middleditch, B., 2011]

Drilling downtime is likely to be incurred if mean riser angle exceeds 2 degrees. [Westlake, A.S., Uppu, K., 2007] Downtime in the marine drilling riser or BOP is one of the main activities drilling contractor trying to prevent from happening. Limiting the mean drilling angel to 1 degree is a more stringent requirement placed by the drilling contractors to prevent downtime. This angular limitation is designed to reduce wear in the system, particularly in the lower flex joint, and prevent riser downtime. The limitation is also designed to give the needed free passage of the retrieval of tools with no damage. The limit on the lower flex-joint angle fulfills the requirement that the rig must be maintained in a position where emergency disconnect can be carried out. [Howells, Dr. H., and Bowman, J., 1997] The design also gives some margin against wellhead not being perfectly vertical when installed.

The flex joint is together with the telescopic joint one of the most important element in the marine riser system. They both compensate for vessel motion and allow displacement of the riser. But their functions make them important in preventing failure and downtime. In deepwater operations long risers are exposed for curvature and angular rotation. But research shows that flexible joints are less exposed for failure than ball joint. This would make the flex joint more poplar selection than the ball joint.

4.4 BOP

A reliable blowout preventer (BOP) is important for safe offshore drilling operations. Unexpected BOP failure can lead to in worst case a blowout and loss of life, and in best case significant downtime on drilling operations. In many countries regular scheduled BOP testing is a regulatory requirement for the contractors. Drilling contractors rely on the BOP to maintain its function and reliability. For offshore drilling operations the most expensive downtime event is associated with having to pull and retrieve the marine riser and the BOP because of a failure. To pull the BOP the result in cost will approximately be $1.00 MM per event. [Shanks, E., et al, 2003]

Due to the need for high reliability on the BOP system there was during the 1980's, to the late 1990's, conducted several reliability studies on subsea BOP system on the behalf of various oil companies. The studies where carried out of the Scientific and Industrial Research at the Norwegian Inst. of Technology (SINTEF). The studies where based on data from the wells drilled in the North Sea, Brazilian waters and the Gulf of Mexico Outer Continental Shelf.

The survey reviled several problems area with the BOP system.

- Approx. 4% drilling time is lost due to BOP failure in deepwater drilling
- Problem with locking system; “fail to open”
- Opening of the LMRP connector
- Backup control system
- BOP testing and test time.

The increased downtime for deepwater vs. shallow water can be explained by the increased handling time to repair each failure. Water depth seems to have no influence on the occurrence and frequency of failure. [Holand, P., 2001] There was discovered that some new design caused major problem with the locking system for new types of rams. The failure mode was not observed in BOP studies with older equipment.

Because many well sections are drilled without riser margin the opening of the LMRP connector is far more important during deepwater drilling. In the case of a non-functioning LMRP connector the control of the BOP is lost. Another problem related to where well sections are being drilled without riser margin is if the BOP accidentally disconnect. If an unintentional disconnect happens there is very important for deepwater operations to have backup of BOP control systems. On average a BOP test time consumes 5% of drilling time. [Holand, P., 2001]

During the survey they identified several main failures to specified component of the BOP system. Table 1 shows the number of failure and associated total downtime with BOP component.

BOP Subsystem	BOP-Days in Service	Total Days in Service	Total Lost Time (Hours)	No. of Failures	MTTF (BOP-Days)	Avg. Downtime %	Avg. Downtime per BOP-Day (Hours)
Annular preventer	4,009	7,449	336.50	12	334	0.35	0.08
Connector*	4,009	8,018	117.75	10	401	0.12	0.03
Flexible joint **	4,009	4,009	248.50	1	4,009	0.26	0.06
Ram preventer	4,009	16,193	1,505.25	11	364	1.56	0.38
Choke/kill valve	4,009	31,410	255.50	13	308	0.27	0.06
Choke/kill lines, all	4,009	4,009	36.50	8	501	0.04	0.01
Main control system	4,009	4,009	1,021.50	60	67	1.06	0.25
Dummy item†	4,009		116.00	2	2,005	0.12	0.03
Total	4,009		3,637.50	117	34.3	3.78	0.91

* Lost time for one LMRP connector failure unavailable because of missing daily drilling reports. Two to three days were lost.
** For the flexible joint failure, 250 hours more time was used to work on stuck pipe/fishing problems after the flexible joint failure was repaired. This work was most likely a result of the flexible joint failure.
† Includes two BOP failures that were impossible to link to a specific BOP item. Both failures occurred when preparing to run the BOP and were poorly described.

Table 2 Overview of BOP failures [Holand, P., 2001]

From the table we can see that more than 50% of the failure was observed in the main control system. The connector, annular preventers, ram preventers, choke and kill lines, and choke and kill valves each represented 7 to 11 % of the failures.

On the annular preventer system the most common failure was leaks through the closed annular. Another typical failure mode was “failed to fully open”, which seems to be a typical failure on new equipment. This means that the annular system refuse to fully retract preventing operators from pulling large-diameter tools through the annular preventer.

With Ram type preventer the most common failure is with the blind shear ram (BSR). Typical failure observed with the BSR is “failed to close” and “failed to open”. This kind of failures is hazards because an access to the wellbore is restricted.

All the failure observed with respect to the annual and ram preventing system was due to internal leakage from shuttle valve. The various valves contained in a BOP control system is a significant factor affecting the BOP reliability. Failures with the annular and ram preventing system is time consuming to fix. During the survey from SINTEF all the observed failures took approx. several hours to repair.

4.4.1 BOP control system

The more common causes for pulling the marine riser and subsea BOP is associated with the BOP control system and not the BOP itself.

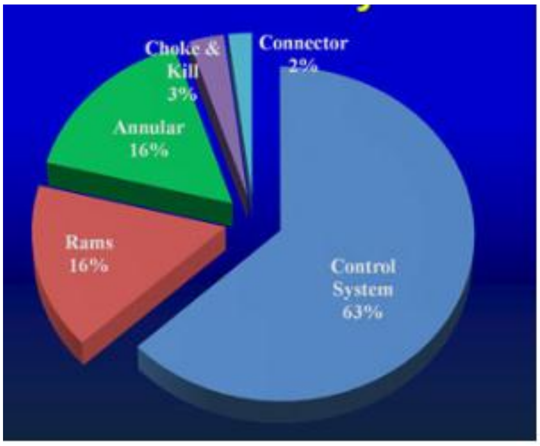


Figure 12 Control systems are where the majority of subsea BOP failures occur, according to an industry study. [Drilling Contractor, 2009]

In the period 2000 - 2004 there was conducted a joint industry project (JIP) where the goal was to examine BOP equipment and reliability. The study was conducted in the Gulf of Mexico, and the results from the JIP identified that 63% of BOP failure happened in the control system. [Drilling Contractor, 2009]

Historically the control systems hydraulic components have had the most problems that have required the riser and BOP stack to be pulled, and the main cause have been hydraulic leaks.. The hydraulic components represented 45% of the control system failure, and Multiplex (MUX) control accounted for 55% of the failures. [Drilling Contractor, 2009]

Transocean have conducted a survey for basic design and requirements for deepwater BOP control system. [Shanks, E., et al, 2003] The scope of the survey was to study deepwater BOP control system and take a look at reliability issues and determine period between maintenance. BOP problems can be extremely expensive and unexpected problems or failure can lead to significant downtime. Proper maintenance of rigs BOP is critical to ensure reliability and safety of offshore drilling operations. [Chapman, F.M., and Brown, R.L., 2009]

Transocean found out that the best time to perform major maintenance on complicated BOP control system was during the ship yard time. This means that the BOP has to function for a five-year interval to prevent unnecessary pulling of the marine riser and cause major downtime. Therefore it was necessary to have a look at some of the reliability issues associated with the BOP control system

When reviewing the reliability issues relative to the BOP control system they revealed that there was rarely any equipment performance requirement given by the vendors. The system requirements where develop between contract engineers, operators, and vendors, and reliability was assumed to be as good as the previous one. Or in the case of new design, it was assumed better than before. [Shanks, E., et al, 2003] The survey also revealed that the operating reliability was maintained through regular maintenance intervals, rather than specifying reliability of a system or component to minimize maintenance. The solution was to actively pursuing improvements in BOP reliability at all levels during the equipment life time, including design stage.

Keeping the reliability and active pursuing improvements in all levels are important to avoid failure and disaster. Consequences provided by BOP failure or well control problems could be highly expensive and cause environmental catastrophe. Accidents like Ekofisk Bravo blowout and Piper Alpha explosion are accidents operators trying to avoid. [Visser, R.C., 2011] Therefore it is important to make BOP system that are reliable, and maintenance program that achieve and maintain that level of reliability.

4.5 Deepwater

Deepwater drilling represents more challenges and problems than ever faced before. Drilling in deepwater is associated with increased water depth, harsher environments and larger currents affecting the riser system. In difference to the North Sea, exploring in the Gulf of Mexico and offshore Brazil is moving into water depths of over 2000 meter (6561 feet). The increased water depth and severe currents place more importance on design requirements for the drilling riser system. The deepwater development faces two kinds of challenges; the environmental and the technical, where the technical could be seen as a result of the environmental challenges.

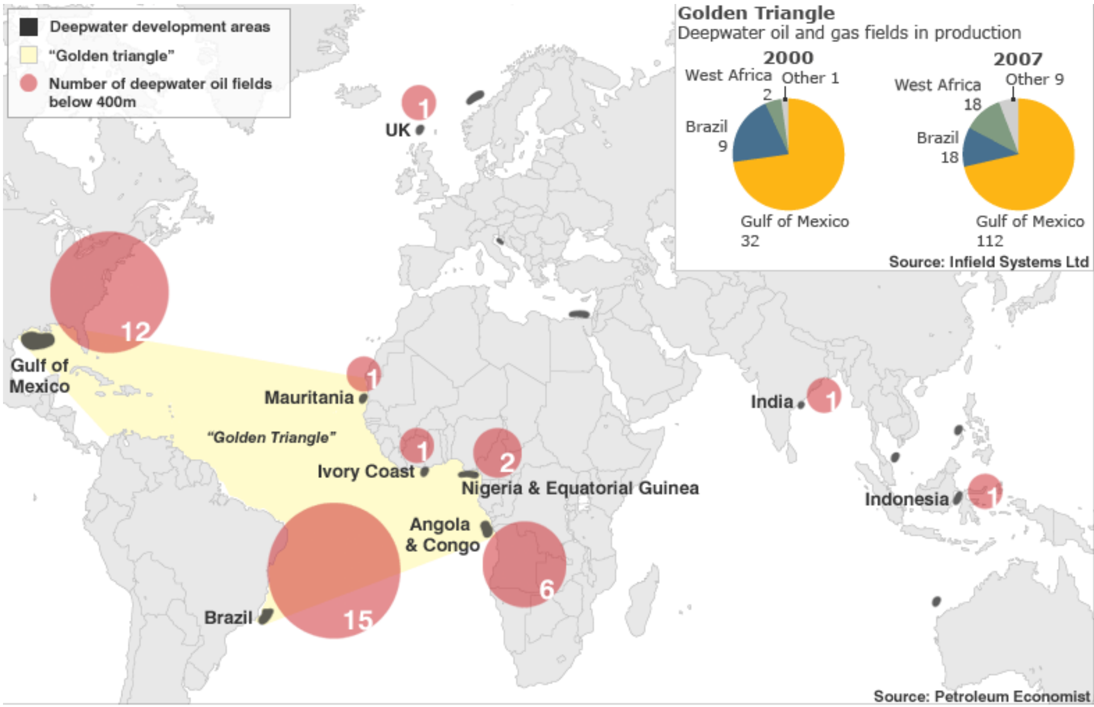


Figure 13 Global drilling map. Map of the world showing deepwater drilling and development. [BBC News: US & Canada, 2012]

In 2002 deepwater drilling consist of 3% of overall production, 2007 – 6%, and today it is 10% of all drilling operations. By 2015 deepwater is the only sector likely to continue to grow. [Hatton, S., 2010] From the global drilling map it could be stated that the Gulf of Mexico and coast of Brazil is the most important development areas for the future.

4.5.1 Technical

Technical challenges are mainly design challenges faced when scaling a shallow water riser to deepwater operations. The main focus is to identify the main difference between deepwater and shallow water drilling operations, and evaluate how they affect the marine riser system.

The main difference between deepwater and shallow water is:

- Increased tension
- Increased internal and external pressure
- Longer, heavier riser joints
- Exposure to severe currents
- Subjected to Vortex Induced Vibrations (VIV)
- Large Curvature

[Howells, Dr. H., 2000]

This means that the design requirements for drilling risers are not applicable for deepwater drilling, because they do not address the deepwater issues. The main different is to make the riser system functional for higher top tension requirements, meaning that the rig need to exceed their top tension capacity. When scaling a riser string for deepwater tension capacity there is some series of items that need to be considered.

Increased water depth results in longer drill string, and several longer and heavier riser joints. Longer and heavier riser joints lead to increase tension on the riser string. Increased tension need to be compensated by increased top tension from the tensioner system in the riser. High tension results in increased wear at the top of the riser and may accelerate fatigue crack growth in the riser. [Howells, Dr. H., 2000] Fatigue damage and crack growth in riser pipe is further mentioned in the riser pipe section in this thesis.

Longer riser joints natural increase the volume of drilling mud inside the riser pipe, which increase the internal pressure from the mud on the riser wall. Increased internal pressure affect the riser wall as consequence of increased hoop stress. Associated with greater water depth development, higher external pressure, resulting from the water column, is expected. The external pressure is increasing for every 10^{th} meter below sea level. Meaning that riser pipe should be design for operations on maximum water depth. Collapse of the riser wall is a consequence of the external pressure on the riser pipe.

The combination of increased internal and external pressure place increased importance on riser wall thickness. Wall thickness is like discussed earlier important for hoop load resistance, dimensional tolerance and collapse resistance. These challenges should be addressed during the design phase of the riser system, because changing the wall thickness could be some difficult when installed on the rig.

High tension, increased external and internal pressure, and large mean flex-angles or riser curvature are all contributing factor for increased wear at deepwater. Typical wear hotspots is on the lower flex joint, upper flex joint and telescopic joint, making them weak point in the riser system. Drilling in deepwater areas is generally associated with extended wear of the equipment. To prevent increased wear during deepwater drilling, it is important to have god wear control. Wear control could be achieved through controlling the triggering factor, like minimizing the flex-joint angle limits to 1 degree, have water depths limits, and conducting seasonal drilling. Limiting the drilling operations to seasonal drilling could be seen as an extreme action, regarding revenue loss and continuous rig cost.

4.5.2 Environmental

Deepwater challenges are not only riser technical specified; there are also experienced challenges with the environment, natural for deepwater areas. Increased water depth, higher waves and larger current loading all have significant influence on riser system response. Water depth has direct impact on the riser length, leading to increased curvature over the entire length of the drilling riser. Large wave heights increases the loading on the telescopic joint and UMRP, and vessel heave and pitch motions. Al together these issues have influences on the running and retrieval operations, and resulting in reduced weather - window for well testing and operations. [Howells, Dr. H., and Bowman, J., 1997]

Large currents leading to vortex induced vibrations (VIV) is common phenomenon in great water depths. VIV is one of the main concerns with deepwater development regarding the riser system. The concern is about the effect the currents have on riser joints. Large currents speed typical for deepwater give rise to vortex induce vibrations. The in-line current causes the bodies to vibrate at a natural frequency in the cross-flow direction. Constant vibration from VIV causes stress cycling in the riser. VIV can generate high levels of fatigue damage along the entire riser length, which can cause the raiser to fail. Typically riser failure from increased VIV is fatigue damage, increased curvature and the possibility of crack growth in the riser pipe. VIV generally requires more frequent inspection of the riser or use of a suppression device. [Howells, Dr. H., 1998]

Other aspects of deepwater drilling are the effect from buoyancy equipment. It's proven that the buoyancy effectiveness is reduced at increased water depth. [Howells, Dr. H., 1998] Due to reduced buoyancy effect, there is advisable that the lower part of deepwater riser should use slick joints to maximize effective use of buoyancy and maintain satisfactory level of tension during disconnect, hang-off and retrieval. [Howells, Dr. H., 1998]

There have been proven to be some relation between the water depth and the downtime of BOP system, as we can see from Figure 14 and 15. The trend of higher downtime in deeper water is caused by the BOP and LMRP handling time in deep water, and not from failure rate. There is not proven any relation between water depth and BOP failure rate. As mention before, risers used in deepwater are longer and heavier than those used in shallow water. This results in longer running and retrieval time when faults occur.

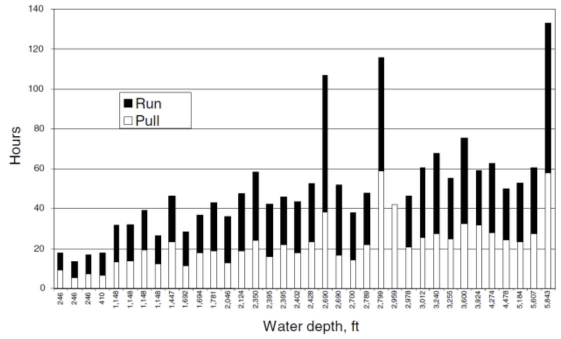


Figure 15 BOP/LMRP running and pulling times sorted on water depths [Holand, P., 2001]

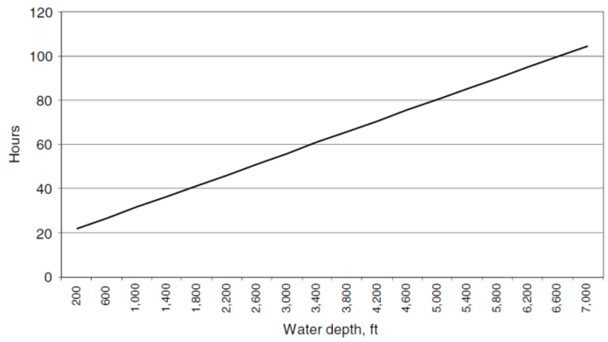


Figure 14 Regression line for BOP/LMRP running and pulling times vs. water depth. [Holand, P., 2001]

As the industry moves towards locations with greater water depth, will the always be continuously development of new technologies. The drilling technologies are always advancing to allow more efficient drilling operations. But going from shallow to deepwater drilling has reviled some new environmental question. The question is regarding dispersion, discharge of drill cuttings, drilling muds, storage, handling and discharge of chemicals and drilling mud. [Armstrong, L.J., 2002]

The search for new and bigger oil and gas reservoir takes the exploration companies to deeper water depths. Great water depths have a tendency to be located a long way from the shore. Deepwater drilling results therefor in longer traveling distance from the coast to the drilling vessel. This little detail has some impact on the vessel and drilling operations efficiency.

One major issue considering deepwater drilling is emergency response time due to unplanned discharge and oil spill to the sea. Throughout the world, response time is a part of regulatory framework for most countries, and almost every nation have national oil spill response plan in place. [Armstrong, L.J., 2002] Reacting quickly and efficient to pollution is very important, and the increasing distance to the shore can make this difficult in some cases. Long distance from the shore could delay emergency response and consume considerable time traveling. Where there is possible for shallow water operators to store anti-pollution on shore, deepwater operators must have enough equipment on board the platform or vessel to react on a discharging accident.

Oil weathering differs from shallow water to deepwater. Due to the difference in composition will crude oil from deepwater fields have different weathering and buoyancy characteristic than crude oil generated in shallow water. Consider deepwater drilling its possible for deep leaks to never reach the surface, due to the formation of gas hydrates. Research shows that some gas hydrates dissolve in the water column, preventing the plume to never reach the surface.

5. Solutions

To improve the operating window and resist the effects of VIV's, optimization of the riser and wellhead system may be necessary. This chapter will give a short introduction to the solution for some of the challenges addressed in chapter 4.

Maintain good well control and having a correct functioning telescopic joint is important. The telescopic joint contributes to improper well control with the phenomenon of reciprocates flow, due to the heave motion. Other relevant problems with the telescopic joint are the packer housing bolts, and packer elements leakage leading to unwanted discharge.

To compensate for fluctuating flow many different methods have been investigated. One method is the flow in, flow out (FIFO) principle. [Baker, R.J., 1991] The principle behind this method is to install a pump below the telescopic joint allowing it to pump the returning mud out of the marine riser. This then allows the returned mud to be accurately measured by flow meters. Accurately measure will give correct feedback on the influx of formation fluids.

The packer system is based on an old design, and hasn't change or renewed since the 1960's. Drilling operators believe that an evaluation of the currently available slip joint design is advisable to determine if new design would improve the sealing reliability. The selection of new design should consider new materials, new technology or a complete redesign of the sealing mechanism. One possible solution for the unplanned discharge from the telescopic joint, due to improper packer system, is a Mud Recovery System (MRS). The basic principle behind MRS is a mud-bucket mounted on the outer barrel, catching discharge fluid from the telescopic joint and then reusing it by pumping it back to the well. The main different between this and the FIFO principle is that with the mud-bucket the operators can add different fluids into the returning mud, optimizing the well control.

It is proven that in environment with high currents, like in deepwater developments, higher riser top tension is needed to reduce the curvature and limit the flex-joint angle preventing the fatigue damage incurred in the riser. For water depths below 500 meter (1640 feet), many rigs are at their rig tensioning capacity, making it hard to provide the needed tension for riser stability. The solution to this is buoyant joints used to increase the riser tension by decrease the submerge riser weight. [Howells, Dr. H., and Bowman, J., 1997] But increased tension and improved riser response are being reacted through the conductor, leading to increased wellhead fatigue damage. Riser tension and buoyancy must therefore be configured to meet a balance between riser and wellhead system fatigue damage preventing damage to the conductor.

Using buoyancy can to address riser tension issues provides new challenges. Large aircans could result in large drag loading, and have influence on the VIV. As a solution for top tension riser issues regarding increased aircan volume, reduction in wall thickness is a possible solution. Reduction in wall thickness lightens the riser joint, and has a corresponding effect of reducing the top tension requirements. Reducing the wall thickness could on the other side lead to other problems like hoop and collapse resistance, and corrosion resistance. Other possible solution should be taken into consideration, like further savings could be achieved through the uses of alternative material for the aircans [Walters, D., Thomas, D., and Hatton, S., 2004]

Riser pipes used in deepwater applications are often longer and heavier. This results in increased tension on the riser. To prevent the riser from buckling under the tension, the rig needs to increase the top tension provided from the wire line tensioner system. Another solution to minimize the tensile strength reacting on the riser is to increase the wall thickness, creating a large cross-section area in the riser pipe. Larger wall thickness provides also for hoop load and collapse resistance. The wall thickness plays an important role on riser pipes addressing deepwater issues, especially corrosive attacks. Corrosion attacks may lead to crack growth and wall thinning in the riser pipe.

To deal with the increased corrosion on risers and pipelines generally acceptance requirements for the prevention of external an internal corrosion have been introduce in the ISO 13623 and ISO TC67/SC2. But to have a complete and efficient corrosion prevention policy, drilling operators need to have Corrosion Management. A Corrosion Management policy is based on a few basic principles. [Roche, M., 2007]

The first principle is based on simple prevention actions. Operators can prevent corrosion by effective implementing internal and external corrosion prevention systems, including material selection, corrosion allowances, cathodic protection, external and internal coating, and injections of chemicals. In corrosive environments, most steel structures can be saved by coating and/or cathodic protection.

Cathodic protection and coating is the far most common corrosion prevention method being used. Cathodic protection is most often achieved through using sacrificial aluminum anode-bracelet. The principle is that the anode-bracelet is more easily corrode than the riser metal. Cathodic protection can in some cases also protect against Stress Corrosion Cracking. Coating is basically a covering applied to exposed surface on the riser to improve surface properties for corrosion resistance.

Second principle is about Corrosion Monitoring. Operators have to ensure that the corrosion prevention systems are actually applied correct and working sufficiently. The third principle is the inspection operation. Inspection provides information about the condition with respect to corrosion or mechanical damage.

Old equipment used in shallow water, water depth less than 300 meters (984 feet), does not address deepwater issues. Deepwater issues like increased top tension, increased internal and external riser pressure, longer and heavier riser joints, and increased VIV are some problems not meet by the old rigs and old equipment. The solution to face new and demanding condition are new larger capacity rigs. Rigs with larger tensioner system, to deal with the problem of little tension capacity, and greater deck capacity to handle larger and heavier riser joints are recommended.

Larger and heavier riser joints bring up the problem of increased VIV and fatigue damage. Vortex induced vibrations is a major design issue for all deepwater riser system where severe current can be expected. For top tensioned riser (TTR) increased top tension or suppression devices are used to limit the fatigue damage induced by VIV. [Liam, Dr. F., and Howells, Dr. H., 2000] There are mainly two type of suppression system that provides high level of suppression and that are strakes and fairings. Both strakes and fairings could reduce VIV fatigue damage by over 80%. [Howells, Dr. H., and Bowman, J., 1997] Problem with these two systems is that they provide handling difficulties. But the handling difficulties could be limited if the suppression devices could be implemented over a short length only.

6. Discussion

Moving drilling operations into deeper water like in the Gulf of Mexico, coast of Brazil and some places in the North Sea means a complete new environment and challenging drilling condition. The environmental condition varies between the different geographical locations, and the technical challenges vary with them. Drilling in deepwater faces challenges like low temperature, high salt level in seawater, large wave and currents, high corrosion possibilities, increased pressure (internal & external), increased top tension, and environmentally caused failures.

In this thesis we have identified several problems-areas and challenges faced with the marine riser system overall, and in relation with deepwater problems. The search for the worlds "next" large oil or gas reservoir forces drilling operators into new ground. Facing new challenges and drilling conditions. This makes drilling contractors looking for new solutions, new technology, and efficient development methods to keep up. There is no secret that most oil companies, contractor, and operators are driven by the economic profit from the exploitation of oil and gas. With today's regulations, cost of labor and rig rate, drilling equipment must be reliable, even under severe conditions. Operators need to avoid huge maintenance cost, long downtime leading to huge loss of revenue, and in worst case environmental disaster.

Keeping the riser integrity is the main concern for many drilling operators, and the marine riser system is the most important part in any drilling operations using a riser system. The equipment need to work and be reliable for maintaining and keeping an efficient operation and well control. This thesis has revealed some main problems with several components in the marine riser system. Most of them can be avoid by addressing the issues at an early stage, or in the design face. But several component, although they are new, are based on old design, and proven to be insufficient.

There are many ways to maintain reliability and riser integrity, but the key problem is to know when to stop doing "fix when broken" maintenance, and start doing preventing maintenance instead. Preventing maintenance is done by implementing a correct maintenance program based on failure rate, cost, performance, efficiency and availability. Correct maintenance and correct handling procedure can be the key solution to many problems, but in some cases will a new and complete redesign of the equipment be necessary. The solution is to find the balance between correct maintenance programs for existing equipment, or do a total redesign. The key is to know what is most economical profitable in the long run for the operator.

Looking at the marine riser system the main risk lies with the BOP system. BOP failures cause the drill contractor long downtime and huge expenses in repair and loss of revenue. This is due to the long handling time related to running and retrieval of the BOP stack and riser joints, especially on deepwater development. BOP is based on an old design, they are heavy, hard to control, but they represent a key component in a drilling operation, necessary to have and necessary to use. Why hasn’t the design of the BOP changed in the last decades, as the operations have been more and more challenging and dangerous? The problem can be looked at from two sides; from the user side, and from the manufacturer side. The user looks at the cost of the component failing and being repaired or replaced versus the cost of doing a new design of the BOP, designing for new reliability. From the manufacturer sides of view; there are a few companies around the world providing the industry with BOP system. Are they interested in changing the equipment and a functioning system that is making them a lot of money in spare parts, the answer is probably no. It all comes down to what is most economical profitable. It will also never be possible to

Including the BOP, are the lower and upper flex joint and telescopic joint a weak point in the marine riser system. These are typical hotspots for increased wear fatigue when exposed to waves and vessel offset, making the riser an angular displacement. Especially the lower flex joint is exposed for increased bending moment due to huge offset from vessel motion. By limiting the flex-angle to 1 degree, will the auto disconnect sequence activate when exceeding the limit. The telescopic joint is an overall important part in the riser system for well control and compensation for riser motion. Concerns for the telescopic joint is mainly technical and could be avoided by updating the design or apply correct maintenance program, but something needs to be done in order to keep risk as low as reasonable practicable and avoid environmental damage.

7. Conclusion

Main Objective: *Identifying and Evaluating High Risk areas and challenges on marine drilling riser system, in relation to deepwater problems.*

Based on the need for maintain riser integrity this thesis has identified and evaluated problem areas on the marine drilling riser system and evaluated them in relations to deepwater problem. Some problems and challenges are a direct consequence of deepwater environmental problems; other problems are related to technical challenges associated with old design and lack of correct operating procedure and maintenance method.

Identified high risk areas and challenges:

- Failure to packer element
- Old and unpractical design
- Packer housing bolt failed
- Lack of preventing measures and operating procedure
- Crack growth in riser pipe
- Adversely well control and well cost
- Fluctuating Flow-rate
- Reaching rigs tension capacity
- Increased focus on wall thickness
- Increased Corrosion attacks
- More registered failure to the ball joint principle than flex joint
- Increased flex-angel, limiting the flex-angle
- Several problems with the BOP and the BOP control system
    - Hydraulic connectors
    - Multiplex control
    - Reliability issues with BOP

Identified deepwater problems:

- Increased tension
- Increased hoop load
- Increased internal and external pressure
- Longer and heavier riser joints
- Environmentally induced cracks
- Vortex induced vibrations
- Reduced buoyancy effect
- Severe currents
- Large curvature
- Increased emergency response
- Longer distance from shore
- Increase emergency response time

There have been identified several problem areas and issues regarding marine riser system integrity in deepwater operations. Most of them are natural due to de fact that deepwater drilling is longer and are more exposed to harsh condition. But others are problems cause by wrong handling procedure, incorrect maintenance program and neglected design. There exist several easy solutions to correct these problems, but many of them is still today proven to be economical unprofitable. And economical profit margin is what drives today's contractor and operators.

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9. Appendix

9.1 Appendix A

Calculations for Riser Pipes

1.0 Inndata

Material	$\delta f := 550MPa$
Outer Diameter	$OD := 533.4mm$
Inner Diameter	$ID := 482.6mm$
Maximum material yield	$\delta f1 := 0.67 \cdot \delta f = 368.5MPa$
Internal Pressure	$pM := 500psi$
Elestic Modulus	$E_y := 200GPa$

2.0 Checking Tensile Load Resistance

Area: $A1 := \frac{OD^2}{4} \cdot \pi - \frac{ID^2}{4} \cdot \pi = 0.041m^2$

Maximum allowable Tensile Load $F1 := \delta f1 \cdot A1 = 1.494 \times 10^7 \cdot N$

F1 is approximately 1500 tonn

3.0 Checking Hoop Resistance

Thickness: $t_3 := \frac{OD - ID}{2} = 25.4mm$

Inner radius: $r_I := \frac{ID}{2} = 241.3mm$

Outer radius: $r_O := \frac{OD}{2} = 266.7mm$

Hoop stress at 500psi: $\sigma_\theta := \frac{pM \cdot r_I}{t_3} = 32.75 MPa$

Internal Pressure at Max Hoop stress $pM_{max} := \frac{\delta f1 \cdot t_3}{r_I} = 5.626 \times 10^3 \cdot psi$

$pM_{max} = 38.789 MPa$

4.0 Checking Collapse Resistance
ref: ASME 2007 Boiler & Pressure Vessel Code, section 4.4

Minimum Wall thickness $t := 25.4mm$

Length
Length of one Riser Pipe (50 feet) $L_1 := 15240mm$

$$M_x := \frac{L_1}{\sqrt{r_O \cdot t}} = 185.164$$

$$C_h := 0.55\left(\frac{t}{OD}\right) = 0.026$$

Predicted Elastic Buckling Stress $F_{he} := \frac{1.6 C_h \cdot E_y \cdot t}{OD} = 399.093 MPa$

Predicted Buckling Stress $F_{ic} := 0.7 \cdot \delta f1 \cdot \left(\frac{F_{he}^{0.4}}{\delta f1^{0.4}}\right) = 266.312 MPa$

Design Factor $FS := 2.407 - 0.740\left(\frac{F_{ic}}{\delta f1}\right) = 1.872$

$$F_{ha} := \frac{F_{ic}}{FS} = 142.245 MPa$$

Allowable External pressure $P_a := 2 \cdot F_{ha} \cdot \left(\frac{t}{OD}\right) = 13.547 MPa$

Approximatley depth d = 1300 meter