



Universidade Federal
do Rio de Janeiro

Escola Politécnica

INTEGRITY OF DRILLING RISERS IN EXTREME ARCTIC CONDITIONS

Fernanda Moreira Pedó

Graduation project submitted to the teaching staff of the Petroleum Engineering Department of Federal University of Rio de Janeiro as part of the necessary requirements to obtain the degree of Petroleum Engineer.

Advisors: Arnfinn Ivar Nergaard
Paulo Couto

Rio de Janeiro, RJ
October, 2016

INTEGRITY OF DRILLING RISERS IN EXTREME ARCTIC CONDITIONS

Fernanda Moreira Pedó

GRADUATION PROJECT SUBMITTED TO THE TEACHING STAFF OF THE
PETROLEUM ENGINEERING DEPARTMENT OF FEDERAL UNIVERSITY OF
RIO DE JANEIRO AS PART OF THE NECESSARY REQUIREMENTS TO
OBTAIN THE DEGREE OF PETROLEUM ENGINEER.

Evaluated by:

Professor Arnfinn Ivar Nergaard

Professor Paulo Couto

Professor Carlos Antonio Levi

RIO DE JANEIRO, RJ – BRAZIL

OCTOBER, 2016

Pedó, Fernanda Moreira

Integrity of Drilling Risers in Extreme Arctic Conditions/ Fernanda Moreira Pedó, - Rio de Janeiro: UFRJ/ POLYTECHNIC SCHOOL, 2016.

X, 93 p.: il.; 29,7 cm.

Advisors: Arnfinn Ivar Nergaard and Paulo Couto

Graduation Project – UFRJ/ Polytechnic/ Petroleum Engineering, 2016.

Bibliographic References: p. 94-100

1. Integrity Analysis 2. Drilling Risers 3. Arctic Conditions. I. Ivar Nergaard, Arnfinn; Couto, Paulo. II. Federal University of Rio de Janeiro, Polytechnic, Petroleum Engineering. III. Integrity of Drilling Risers in Extreme Arctic Conditions.

Acknowledgements

I would like to thank my advisor Arnfinn Nergaard from the University of Stavanger where I developed the main part of this project during five months of my exchange programme there. He has provided me useful ideas, excellent feedbacks and support for the development of this monograph. I would also like to thank my professor and UFRJ coordinator Paulo Couto for the great assistance and help both during my stay in Norway and after my return to Brazil. Without their advices and patience, the project development would have been much tougher.

To my parents and sister, my special thank for the fulltime support that always helped me to keep me confident to achieve my life goals and follow my dreams.

Abstract of Undergraduate Project presented to POLI/UFRJ as a partial fulfilment of the requirements for the degree of Petroleum Engineer.

INTEGRITY OF DRILLING RISERS IN EXTREME ARCTIC CONDITIONS

Fernanda Moreira Pedó

October/2016

Advisors: Arnfinn Nergaard and Paulo Couto

Course: Petroleum Engineering

As the world demand for oil and gas continues growing and the main discovered reserves are depleting, the Arctic is becoming even more a potential area to explore this energy resource. Drilling in Arctic offshore conditions is very challenging and with the increase of operations there, drilling riser requirements and limits have become more critical due to all the uncertainties in this harsh environment.

In this monography, the Arctic conditions, critical issues and operations as well as the description of drilling riser system, its functions and the loadings it is susceptible to are presented. The main objective of this project is to evaluate how the drilling riser structure can withstand with static and dynamic loadings considering the Arctic environment challenges.

Table of Contents

1	INTRODUCTION	1
1.1	BACKGROUND.....	1
1.2	OBJECTIVES	3
1.3	ORGANIZATION OF THE THESIS	4
2	RULES AND REGULATIONS (R&R), CODES AND STANDARDS	6
2.1	API RP 16Q	7
2.2	DNV-OS-F201	7
2.3	DNV-OSS-302	8
2.4	ISO 13624	8
2.5	POLAR CODE	8
3	ARCTIC CONDITIONS.....	10
3.1	GEOGRAPHY	10
3.2	CLIMATE	11
3.3	CURRENTS.....	12
3.4	WIND	13
3.5	PRECIPITATION.....	13
3.6	SEAS.....	14
3.6.1	<i>Barents Sea</i>	14
3.6.2	<i>Norwegian Sea</i>	15
3.6.3	<i>Beaufort Sea</i>	16
3.6.4	<i>Chukchi Sea</i>	16
3.6.5	<i>Greenland Sea</i>	17
3.6.6	<i>East Siberian Sea</i>	18
3.6.7	<i>Kara Sea</i>	18
4	STATE OF THE ART	19
4.1	HISTORICAL OPERATIONS.....	19
4.2	GENERAL DRILLING CONCEPTS AND APPLICATION IN ARCTIC CONDITIONS.....	22
4.2.1	<i>Rigs</i>	22
4.2.2	<i>Risers</i>	33
4.2.3	<i>BOP</i>	35
5	CHALLENGES AND CRITICAL ISSUES FOR ARCTIC DRILLING	38
5.1	CRITICAL ISSUES	38
5.1.1	<i>Sea Ice and icebergs</i>	38
5.1.2	<i>Marine and atmospheric icing</i>	40
5.1.3	<i>Temperature, visibility and snow</i>	41
5.1.4	<i>Waves</i>	42
5.1.5	<i>Wind and polar lows</i>	42
5.1.6	<i>Permafrost</i>	42
5.1.7	<i>Ecosystem in case of oil spills</i>	43
5.2	CRITICAL OPERATIONS	43
5.2.1	<i>Long distances from shore</i>	43
5.2.2	<i>Working environment and emergency preparedness</i>	44
6	MARINE DRILLING RISER SYSTEM	46
6.1	FUNCTIONS	46

6.2	RISER DESIGN AND COMPONENTS FUNCTIONS	47
6.2.1	<i>Tensioner system</i>	48
6.2.2	<i>Diverter System</i>	50
6.2.3	<i>Telescopic Joint (Slip Joint)</i>	51
6.2.4	<i>Riser Joints</i>	53
6.2.5	<i>Choke/kill and auxiliary lines</i>	55
6.2.5.1	Flexible choke and kill lines	57
6.2.6	<i>Flex and ball joints</i>	57
6.2.7	<i>Riser running equipment</i>	58
6.2.8	<i>Lower Marine Riser Package (LMRP)</i>	60
6.2.9	<i>Buoyancy equipment</i>	61
6.2.10	<i>Specialty equipment</i>	62
6.2.10.1	MUX lines	62
6.2.10.2	Latch (pin connector)	63
6.2.10.3	Riser hang-off system	63
6.3	BLOWOUT PREVENTER	64
7	LOADINGS ON THE RISER SYSTEM AND THE WEAKNESS POINTS	67
7.1	STATIC LOADINGS	67
7.1.1	<i>Internal forces in a submerged body</i>	67
7.1.2	<i>Stresses in Risers</i>	70
7.1.3	<i>Radial, Hoop and Axial stresses</i>	70
7.1.4	<i>Shear stress</i>	72
7.1.5	<i>Bending stress</i>	72
7.1.6	<i>Minimum top tension</i>	73
7.2	DYNAMIC LOADINGS	76
7.2.1	<i>Currents</i>	76
7.2.2	<i>Waves</i>	78
7.2.3	<i>Vessel motions</i>	79
7.2.4	<i>Dynamic forces in the riser system due to the vessel motion</i>	80
7.2.5	<i>Structural dynamic of the riser</i>	81
7.3	WEAK POINTS ANALYSIS	83
8	SOLUTION PROPOSAL FOR OPERATIONS IN THE ARCTIC SEA	85
8.1	OPERATING UNDER ARCTIC CONDITIONS	85
8.2	ICE MANAGEMENT	86
8.3	WINTERIZATION	87
8.4	HEAT TRACING	87
8.5	STEEL SELECTION	89
	REFERENCES	94

List of figures

FIGURE 1. 1 PROVINCES WHERE MEAN ESTIMATED UNDISCOVERED GAS ARE LOCATED	2
FIGURE 1. 2 PROVINCES WHERE MEAN ESTIMATED UNDISCOVERED OIL ARE LOCATED	2
FIGURE 3. 1 ARCTIC GEOGRAPHY	10
FIGURE 3. 2 ARCTIC SEAS' WATER DEPTHS.....	11
FIGURE 3. 3 CURRENTS IN ARCTIC SEAS (AMAP, 2007)	12
FIGURE 3. 4 ARCTIC SEAS (LLOYD'S, 2011)	14
FIGURE 3. 5 BARENTS SEA REGION (USGS, 2003).....	15
FIGURE 3. 6 CHUKCHI SEA CIRCULATION SYSTEM.....	17
FIGURE 4. 1 WEST VENTURE SEMI-SUBMERSIBLE (SEADRILL, 2016).....	23
FIGURE 4. 2 TRANSOCEAN BARENTS SEMI-SUBMERSIBLE	24
FIGURE 4. 3 POLAR PIONEER SEMI-SUBMERSIBLE	24
FIGURE 4. 4 HUISMANN JBF ARCTIC DRILLING UNIT (HUISMAN, 2015).....	25
FIGURE 4. 5 WEST TELLUS DRILLSHIP	26
FIGURE 4. 6 WEST NAVIGATOR DRILLSHIP (SEADRILL, 2016)	26
FIGURE 4. 7 INOCEAN ARCTIC DRILLSHIP IN-ICE (INOCEAN, 2016)	27
FIGURE 4. 8 CAT I DRILLSHIP DESIGN (INOCEAN, 2016)	27
FIGURE 4. 9 AKER ARCTIC DRILLSHIP	27
FIGURE 4. 10 SEVAN BRASIL (MARINE, SEVANDRILLING, 2013).....	28
FIGURE 4. 11 SEVAN 1000 FPSO FOR GOLIAT.....	29
FIGURE 4. 12 KULLUK RIG	30
FIGURE 4. 13 JACK-UP CJ70 (GUSTOMSC, 2016)	30
FIGURE 4. 14 ARKTICHESKAYA JACK-UP	31
FIGURE 4. 15 GUSTOMSC SEA 15000 ICE SERIE JACK-UP (WASSINK & VAN DER LIST, 2013).....	32
FIGURE 4. 16 NEW CONCEPT OF JACK-UP (URYCHEVA & GUDMESTAD, 2014)	32
FIGURE 4. 17 GENERAL VIEW OF A DRILLING RISER SYSTEM (SCHLUMBERGER, 2016)	34
FIGURE 4. 18 LOADS ON THE DRILLING RISER SYSTEM(DNV, 2011).....	35
FIGURE 4. 19 SCHEMATIC DIAGRAM OF A BOP STACK (LLOYD'S, 2011)	37
FIGURE 5. 1 MAXIMUM AND MINIMUM EXTENSION OF ICE DURING THE YEAR	38
FIGURE 5. 2 ICE BELOW THE WATER MAY DIG THE SEAFLOOR AND DAMAGE THE PIPELINE IF IT IS NOT POSITIONED DEEP ENOUGH (THE PEW CHARITABLE TRUSTS, 2013)	39
FIGURE 5. 3 ARCTIC PIPELINE DUE TO PERMAFROST	40
FIGURE 5. 4 VESSEL ICING FROM SEA SPRAY (THE PEW CHARITABLE TRUSTS, 2013).....	41

FIGURE 6. 1 MARINE RISER SYSTEM AND ASSOCIATED EQUIPMENT (API RP 16Q, 1993)	46
FIGURE 6. 2 KEY COMPONENTS IN A DRILLING RISER SYSTEM (MCCRAE, 2003)	47
FIGURE 6. 3 WIRELINE TENSIONER SYSTEM (HAZIRI & DYNGVOLD, 2011)	48
FIGURE 6. 4 HYDRAULIC TENSIONER SYSTEM (OR DRT).....	50
FIGURE 6. 5 DIVERTER SYSTEM (JVS ENGINEERS, 2013).....	51
FIGURE 6. 6 SCHEME OF THE DIVERTER SYSTEM (MCCRAE, 2003)	51
FIGURE 6. 7 TELESCOPIC JOINT (MCCRAE, 2003)	52
FIGURE 6. 8 SERIES OF RISER JOINTS BEING LIFTED FOR TRANSPORTATION	53
FIGURE 6. 9 COMPONENTS THAT MAKE A RISER ASSEMBLY (MCCRAE, 2003)	54
FIGURE 6. 10 FLANGED-TYPE COUPLING DESIGN (MCCRAE, 2003)	55
FIGURE 6. 11 DOG-STYLE COUPLING DESIGN (MCCRAE, 2003).....	55
FIGURE 6. 12 RISER MAIN TUBE AND AUXILIARY LINES (2B1ST, 2016)	55
FIGURE 6. 13 RISER HANDLING TOOL (FIRST SUBSEA, 2016)& (CAMERON, 2016)	59
FIGURE 6. 14 RISER SPIDERS (CAMERON, 2016).....	59
FIGURE 6. 15 LOWER MARINE RISER PACKAGE (LMRP)	60
FIGURE 6. 16 BUOYANCY EQUIPMENT - FOAM MODULES (TRELLEBORG, 2016).....	61
FIGURE 6. 17 BOP STACK ARRANGEMENT (GCAPTAIN, 2010).....	65
FIGURE 7. 1 INTERNAL FORCES ACTING ON SEGMENT BODY (SPARKS, 2004).....	67
FIGURE 7. 2 FORCES AND PRESSURES ACTING ALONG THE RISER SYSTEM (SPARKS, 2004)	69
FIGURE 7. 3 THREE MAJOR STRESSES	70
FIGURE 7. 4 PIPE SECTION (SPARKS, 2004).....	71
FIGURE 7. 5 BEAM ILLUSTRATING THE BENDING STRESS.....	73
FIGURE 7. 6 CURRENTS IN A SUBMERGED CYLINDER.....	76
FIGURE 7. 7 RELATION BETWEEN C_D AND RE	77
FIGURE 7. 8 SUBMERGED CYLINDER UNDER WAVE ACTION.....	78
FIGURE 7. 9 SIX DEGREES OF FREEDOM IN A VESSEL	79
FIGURE 7. 10 LOADINGS ON RISER SYSTEM (LARSEN, C. M., 2008)	80
FIGURE 7. 11 TENSION EFFECT ON A SLENDER BEAM (LARSEN, C. M., 2008).....	81

List of tables

TABLE 1 POLAR CLASS DESCRIPTION (IACS, 2016).....	6
TABLE 2 RIG TYPE SELECTION	33
TABLE 3 ELECTRIC HEAT TRACING (EHT) TYPE (BRAZIL, CONACHEY, GARY SAVAGE, & BAEN, 2013)	88
TABLE 4 MECHANICAL PROPERTIES OF STRUCTURAL STEEL PLATES (EL-REEDY, 2012).....	92

1 Introduction

1.1 Background

As demand for oil and gas continues growing around the world and the main known and discovered reserves are depleting, scientists and companies are trying to find new places to supply this need. The decrease of the ice cap in the Arctic due to the ice melting caused by the global warming is calling the attention of oil and gas companies. This area is responsible to hold the world's largest untapped reserves of oil and gas with an evaluated potential of 90 billion barrels of oil, 1.669 trillion cubic feet of natural gas and 44 billion barrels of natural gas liquids by the U.S Geology Survey in 2008 (Cleveland, 2011). From this amount, more than 70% of the undiscovered natural gas is probably concentrated in just three provinces (West Siberian Basin, East Barents Basins and Arctic Alaska) and, in a widely distributed situation, more than 70% of oil is thought to occur in five provinces (Arctic Alaska, Amerasia Basin, East Greenland Rift Basins, West Greenland – East Canada and the East Barent Basins) (Figures 1.1 and 1.2). As 84% of the reserves are estimated to be located offshore, under water less than 500 meters deep, these open waters are potential treasure chests for the hydrocarbon's exploration. However, it is still a big challenge for the offshore developments due to the low temperatures, usually below 0° F, limited sunlight with seasonal darkness that generally lasts nine months, extended periods of heavy fog, week-long storms, different forms and thickness of ice and remoteness areas that characterize the Arctic as a short productive season zone. The drilling and exploratory seismic period is usually from June to October when the sea ice begins to retreat northwards. As a harsh territory to work in and its distance from where response capacity is located, can take days or weeks to respond to an oil spill. Also, it can take many decades for Arctic regions to recover from habitat disruption (WWF, 2014) as an example, the Exxon Valdez case in 1989 that 11 million gallons of oil were spilled into Alaska's Prince William Sound and after spending \$2 billion trying to clean up, less than 7% of the oil spilled were recovered. Considering the very long distances from the Arctic seas to the markets for oil and gas products and all the peculiarities of this harsh environment, drilling riser requirements and limits have become more critical due to uncertainties involved in response prediction. So, the transport from the sea to the coast will represent

a substantial part of the capital and operational costs of the development. Considering the transportation step from the seabed to the platform, the drilling risers in shallow waters will be studied in this project, aiming a successful production in a peculiar and challenging environment like Arctic.

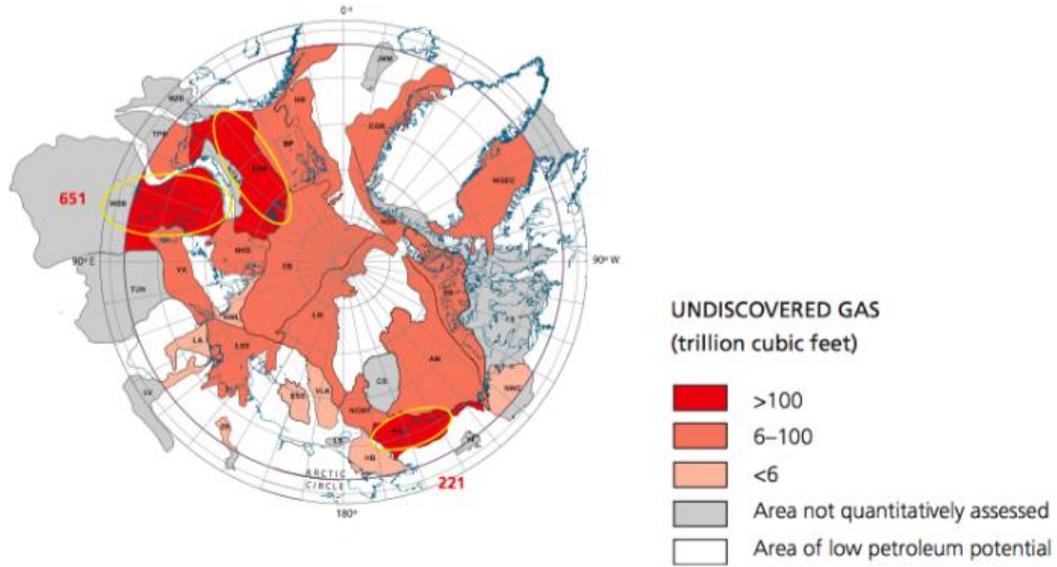


Figure 1. 1 Provinces where mean estimated undiscovered gas are located

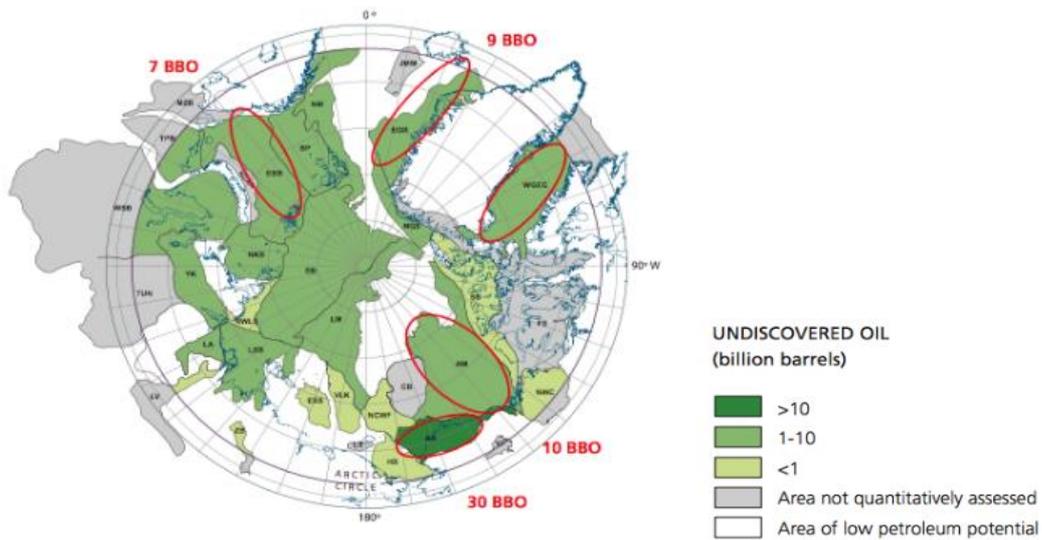


Figure 1. 2 Provinces where mean estimated undiscovered oil are located

1.2 Objectives

The objectives of this thesis are related to the analysis of the integrity and design of drilling risers in Arctic conditions. Also, it will be taken into account besides the riser system, the BOP and control system involved for the operations considering that those parts are also exposed to very low temperatures and it is of the utmost importance for a safe and successful production. The following main objectives are then set:

- Develop a critical review of system integrity for arctic subsea drilling identifying the critical issues and challenges for such a harsh environment.
- Identify the very critical operations and systems in the Arctic.
- Different concepts, modifications and adaptations for risers in the Arctic environment.
- Discussion of weakness points for drilling risers and development of potential improvements.
- Present the best geometry, steel selection and anchoring type to resist the ice loadings and extremely low temperatures.

1.3 Organization of the thesis

- Chapter 2: Description of some rules and regulations related to design and use of risers for petroleum exploration offshore. Also, the polar code and polar class required for ships when operating under Arctic conditions.
- Chapter 3: Description of the Arctic singular conditions englobing the Arctic ocean and surrounding lands that comprise this region; the climate on summer and winter time; currents system in the different seas as well as a brief description of them (Barents Sea; Norwegian Sea, etc.). Moreover, the wind and precipitation changes over the different Arctic areas.
- Chapter 4: This chapter presents a chronology of (some) historical operations and the different challenges according to each Arctic region conditions. It also includes the general drilling concepts and its applications in Arctic. The rig types, riser and BOP were comprised as the three “big systems” located from the seabed to the sea surface.
- Chapter 5: Combine the information of the two previous chapters relating how the Arctic conditions influence the drilling systems. This analysis is divided into two sections: critical issues, specifying the possible events caused by the severe environment and what the crew must be aware of in order to avoid problems, and the other section is related to the critical operations. The last one englobe the remoteness, lack of infrastructure and the work environment faced when experiencing the Arctic conditions.
- Chapter 6: Describe the marine drilling riser functions and give detailed description of the riser components and the associated functions.
- Chapter 7: This chapter takes into consideration the loadings, both static and dynamic, that a riser is submitted to and how the components as waves, currents, riser weight, pressure, etc. influence on the riser performance and lifetime.

- Chapter 8: As the Arctic presents severe environment characteristics and some conditions out of the “conventional” ones, solutions were proposed to work in such challenge place. Those solutions include techniques to keep the vessel, drilling structures and personnel under safe conditions.

2 Rules and Regulations (R&R), Codes and Standards

All offshore leasing and operations are governed by a variety of laws and regulations that set requirements for petroleum exploration and services companies according to local governmental regulations in the field area. For preparation of the vessels as the design of equipment, the companies should follow the principles given by the codes and standards that are applied according to governmental regulations all around the globe. When designing the ships, different class notations are given to the vessels that differs its applicability, operation's type, navigation places, etc. For the ones operating in the Arctic, beside other classes, the Polar Class notation is required (Table 1). The Norwegian Det Norske Veritas (DNV) together with Lloyds Register and American Bureau of Shipping are the world's biggest classifying societies for petroleum vessels and platforms.

Those documents are periodically updated to reflect and follow the advances in technology and new information as the different operational conditions around the world. Therefore, the selection, design, maintenance and operation of marine drilling riser system for mobile offshore units (MODU's) are specified in the international standards, such as API RP 16Q, DNV-OS-F201, DNV-OSS-302 and ISO 13624.

Polar Class	Ice descriptions (based on WMO Sea Ice Nomenclature)
PC 1	Year-round operation in all polar waters
PC 2	Year-round operation in moderate multi-year ice conditions
PC 3	Year-round operation in second-year ice which may include multi-year ice inclusions.
PC 4	Year-round operation in thick first-year ice which may include old ice inclusions
PC 5	Year-round operation in medium first-year ice which may include old ice inclusions
PC 6	Summer/autumn operation in medium first-year ice which may include old ice inclusions
PC 7	Summer/autumn operation in thin first-year ice which may include old ice inclusions

Table 1 Polar Class description (IACS, 2016)

When operating in the Arctic, the safety of ships for the harsh, remote and vulnerable polar areas. The International code of safety for ships operating in polar waters (Polar Code) covers the full range of design, construction, equipment, operational, training, search and rescue and environmental protection matters relevant to ships operating in the inhospitable waters surrounding the two poles (IMO, 2016).

2.1 API RP 16Q

Under the description of “*Recommended Practice for Design, Selection, Operation and Maintenance of Marine Drilling Riser Systems*” was first issued in 1993 and focus on the way of design and operation of drilling risers to ensure safety and integrity in deepwater environment. The three primary strands associated to this regulation are: Analysis Guidelines, Operations Guidelines and Integrity Guidelines (OTC, 2012)

Other API regulations related to drilling risers are:

- API SPEC 16F: “*Specification for Marine Drilling Riser Equipment*”
- API STD 2RD: “*Dynamic Risers for Floating Production Systems*”
- API SPEC16R: “*Specification for Marine Drilling Riser Couplings*”

2.2 DNV-OS-F201

This R&R is about “*Dynamic Risers*” and comprises the criteria, requirements and guidance on structural design and analysis of riser systems exposed to static and dynamic loading for use in the offshore petroleum and natural gas industries. The major benefits in using this standard comprise in provision of riser solutions with consistent safety level based on flexible limit state design principles; application of safety class methodology linking acceptance criteria to consequence of failure; provision of state-of-the-art limit state functions in a Load and Resistance Factor Design (LRFD) format with reliability-based calibration of partial safety factors. guidance and requirements for efficient global analyses and introduce a consistent link between design checks (failure modes), load conditions and load effect assessment in the course of the global analyses; allowance for the use of innovative techniques and procedures, such as reliability-based design methods (DNV, Dynamic Risers, 2010).

2.3 DNV-OSS-302

This R&R is about “*Offshore Riser System*” providing criteria and guidance for technical advice/assistance research and development systems, design verification/product certification in a way for either complete dynamic riser systems, or for separate/self-contained components of riser systems (DNV, Offshore Riser Systems, 2010).

2.4 ISO 13624

ISO 13624 has been developed under the title “*Petroleum and natural gas industries – Drilling and production equipment*” and comprises the following two parts:

- Part 1: “*Design and operation of marine drilling riser equipment*”
- Part 2: “*Deepwater drilling riser methodologies, operations and integrity technical report*”

For the purpose of this part of ISO 13624, a marine drilling riser system includes the tensioner system and all equipment between the top connection of the upper flex/ball joint and the bottom of wellhead conductor outer casing, excluding the diverter. Also, the applicability is limited to operations with a subsea BOP stack deployed at the seafloor (NS-EN ISO 13624-1:2009, 2009).

2.5 Polar Code

The Polar Code includes mandatory measures covering safety part (part I-A) and pollution prevention (part II-A) and recommendatory provisions for both (parts I-B and II-B).

The Code requires ships intending to operating in the defined waters of the Antarctic and Arctic to apply for a Polar Ship Certificate, which would classify the vessel as:

- Category A ship - ships designed for operation in polar waters at least in medium first-year ice, which may include old ice inclusions;
- Category B ship - a ship not included in category A, designed for operation in polar waters in at least thin first-year ice, which may include old ice inclusions;
- Category C ship - a ship designed to operate in open water or in ice conditions less severe than those included in Categories A and B.

The issuance of a certificate would require an assessment, taking into account the anticipated range of operating conditions and hazards the ship may encounter in the polar waters. The assessment would include information on identified operational limitations, and plans or procedures or additional safety equipment necessary to mitigate incidents with potential safety or environmental consequences (IMO, 2016).

3 Arctic conditions

3.1 Geography

The Arctic covers 14.5 million square kilometres and it is a single, highly integrated system comprised of Arctic ocean and surrounding lands that occupies one-third of the total area, including all of Greenland and the northern parts of Alaska, Canada, Iceland, Norway, Finland, Sweden and Russia. Also, this region can be defined in many different ways with regard of its boundary (figure 3.1): by the northern limit of stands trees on land; by the line of average July temperature of 10°C or by the Arctic Circle, an imaginary line located at 66° 34' N of latitude.



Figure 3. 1 Arctic geography

The Arctic Ocean is an enclosed ocean, connected to the Pacific Ocean through the Bering Strait and the Bering Sea, and to the Atlantic Ocean through Fram Strait and the Barents Sea via the Greenland and Norwegian seas as well as through the Canadian Arctic Archipelago via Baffin Bay (Norsk Polar Institutt, 2001). The main seas of the Arctic Ocean are the Beaufort, Chukchi, East Siberian, Kara, Greenland and Barents seas and its water depths can vary from shallow to deep waters as can be seen in figure 3.2.

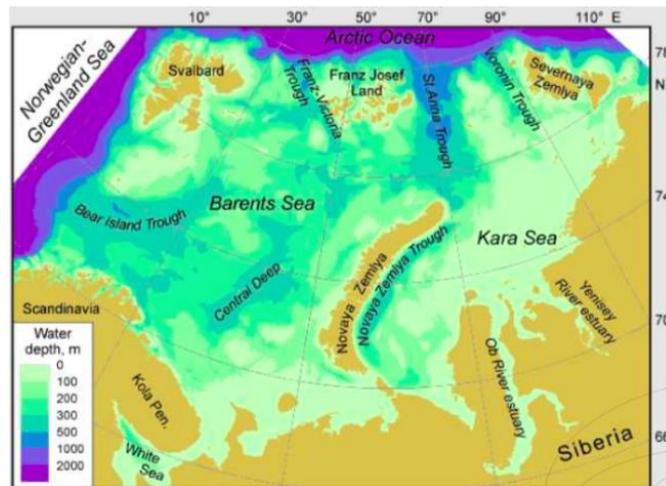


Figure 3. 2 Arctic seas' water depths

3.2 Climate

The Arctic is a unique place for weather and climate because of the special factors that influence it. Sunlight is perhaps the most important of those factors. Above the Arctic Circle, the sun disappears in the winter, leaving the region dark and cold. In between the North Pole and Arctic Circle, the number of days of continuous night decreases the closer you get to the Arctic Circle. During the summer, the sun shines during the most part of the day, bringing warmth and light. The number of days of continuous daylight also decreases as you get closer to the Arctic Circle. Scientists separate the Arctic into two major climate types: near the ocean, the maritime climate and away from the coasts, the continental climate. For the first type, in Alaska, Iceland, and northern Russia and Scandinavia, the winters are stormy and wet, with snow and rainfall reaching 60 cm to 125 cm each year. For the summers, the tendency is to be cold and cloudy; average temperatures hover around 10 degrees Celsius. For the second type, the weather is dryer, with less snow in the winter and sunny summer days. Winter weather can be severe, with frigid temperatures well below freezing. In some regions of Siberia, average January temperatures are lower than -40 degrees Celsius. In the summer, the long days of sunshine thaw the top layer of permafrost and bring average temperatures above 10 degrees Celsius. At some weather stations in the interior, summer temperatures are warmer than 30 degrees Celsius.

3.3 Currents

The Arctic temperature can also change from the ocean circulations and the amount of sea ice can alter how cold the poles are. Heat can come from the South with ocean currents and airstreams. One branch of the Gulf Stream, called the North Atlantic Current, flows along the coast of Norway and continues all the way to the Arctic Ocean and it represents almost 60% of the water entering in the Arctic Ocean. However, some water also flows in through the Bering Strait and some fresh water enters from the big Russian and Canadian rivers, which explains why the topmost 45 metres of the Arctic Ocean are less saline than the water below.

The Fram Strait between Greenland and Svalbard is therefore an important route for seawater to and from the polar area. Warm Atlantic Ocean water flows north along the west coast of Svalbard, and cold water flows south along the coast of East Greenland, and out into the Barents Sea along the east side of Svalbard (Norwegian Polar Institute). An exemplification of this currents system is in the picture below (figure 3.3).



Figure 3. 3 Currents in Arctic seas (AMAP, 2007)

3.4 Wind

Winds in the Arctic can vary a lot in strength, but they are typically light. Winds tends to be stronger in the Russian Arctic, where there are more storms, than in the Canadian Arctic, for example. Although, winds can be strong gales that can reach hurricane strength and last several days. In the winter, these strong winds scour the snow from exposed areas and form large snow drifts in sheltered areas (NSIDC, 2016).

3.5 Precipitation

The precipitation levels are low in the Arctic. Some areas are called polar deserts and receive as little precipitation as the Sahara Desert. However, the Atlantic sector of the Arctic, between Greenland and Scandinavia is an exception. Storms forming in the Atlantic Ocean bring moisture up into this area, especially in winter.

Almost all precipitation in the central Arctic and over land falls as snow in winter. However, rain can occur on rare occasions during winter in the central Arctic ocean when warm air is transported into this region. Snow also falls in summer. More than half of the precipitation events at the North Pole are snowfall. Over the Atlantic sector, snow is very rare in summer (NSIDC, 2016).

3.6 Seas



Figure 3. 4 Arctic seas (Lloyd's, 2011)

3.6.1 Barents Sea

The Barents Sea region is located in the extreme northeast of Europe between the latitudes 82°N and 59°N and from 68°E to 15°E of longitude. Its open water area is approximately 1.5 million km² and it lies almost entirely within the boundaries of Russia and in the extreme southwest, a smaller part that belongs to Norway and Finland. More than 50% of the area have depths of 200 to 500 meters with an average of 230 meters. However, it can reach a depth of 2500 meters nearby the Norwegian Sea (figure 3.5).

The main climate influence is from the ocean currents. Northwards-flowing ocean currents transport Atlantic water eastwards and northwards, and southward-flowing

ocean currents transport Arctic water southwards. The supply of Atlantic water helps to make parts of the area stand out from other Arctic seas at a similar latitude, and it also means that these areas are comparatively easily accessible for most of the year (Norwegian Polar Institute, 2014). The average sea temperature in January is close to 0°C and in summer time it can vary from 30°C over the costal water mass to 24°C at the boundary of Atlantic and Arctic water masses (Global International Waters Assessment, 2004).

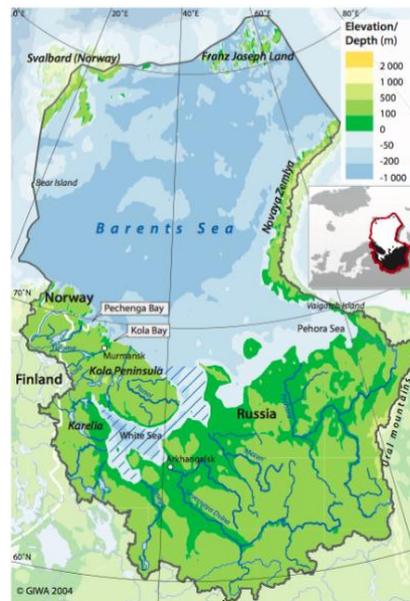


Figure 3. 5 Barents Sea region (USGS, 2003)

3.6.2 Norwegian Sea

The Norwegian Sea is bounded by Greenland and Barents Sea from northwest through northeast; Norway on the east side; the North Sea and the Atlantic Ocean on south part and Iceland on west. The sea reaches a maximum depth of approximately 3970 m. The warm Norway currents enters the Norwegian Sea from north of Scotland and flows northeastward along the coast of Norway before flowing into the Barents Sea. With subsurface temperatures ranging from 8°C in the south to 4° C in the north, the current exerts a moderating influence on the climate of Norway and northern Europe giving the all year ice-free characteristic to this sea.

3.6.3 Beaufort Sea

The Beaufort Sea is located north of Alaska and western Canada. It extends northeastward from Point Barrow, Alaska, toward Lands End on Prince Patrick Island, and westward from Banks Island to the Chukchi Sea. Its surface area is about 476 000 km². The average water depth is around 1000 meters and the deepest part is situated 4682 meters down the surface line (Encyclopedia Britannica, 2011).

The Beaufort Sea just have an ice break up in August and September and only nearby the coasts; the rest of the year it is under ice conditions. The surface water mass ranges in temperature from -1.4°C in summer to -1.8°C in winter. The subsurface water mass is formed by the Pacific Ocean and Bering Sea waters and has much warmer temperatures. The deep Atlantic water is the warmest with temperatures ranging from 0°C to 1°C. Deeper than this, the bottom water that has temperatures from -0.4°C to 0.8°C. The currents in Beaufort Sea are majority thus westwards or southward. Only close to the mouth of Mackenzie river that an eastward current was recorded.

One business feature part of the sea is the Prudhoe Bay, Alaska, where is located the centre of petroleum production on the costal lowland known as the North Slope.

3.6.4 Chukchi Sea

The Chukchi Sea has an area of 582 000 km² and it is bounded by the Wrangel Island on the west part, part of Siberia and Alaska on the south, the Beaufort Sea on east and the Arctic continental slope on north. It is fed from the south by the Pacific water flow through the Bering Strait. Patterns of ice melt suggest the mean flow is split into four main outflows (figure 3.6) - one through Barrow Canyon in the east, one through the Central Gap in the Central Chukchi Sea, one through Herald Canyon, just east of Wrangel Island, and one through Long Strait, between Wrangle Island and the mainland of Russia. There is also a seasonal current, the Siberian Coastal Current, present some years, flowing south through the Long Strait (Polar Science Center, University of Washington , 2003). The average water depth is 77 meters and has an open water season when navigation is possible between July and October.

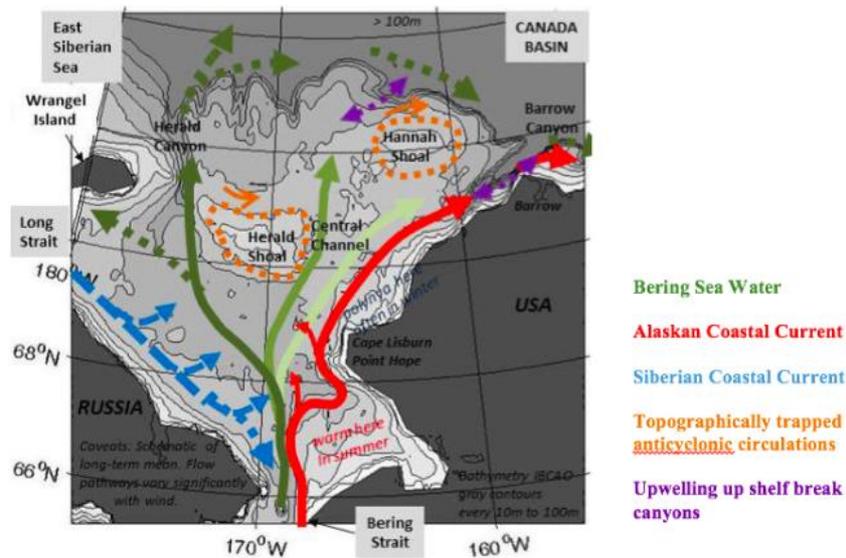


Figure 3. 6 Chukchi Sea circulation system

3.6.5 Greenland Sea

The Greenland Sea cover an area of 1 205 000 km² and it is bordered by Greenland in the west, Svalbard in the east, the main Arctic Ocean in the north and the Norwegian Sea and Iceland in the south. The water depth can vary significantly with the deepest point at 4 800 meters and an average of 1 450 meters.

The north and northeast winds cool the sea surface and drive the cold waters southward. Air temperatures reach as low as -49°C off west of Svalbard and as high as 25° C off Greenland. Averages are -10° C in the south and -26° C in the north for February, the coldest month. In August, the warmest month, the averages range from 5° C in the south to 0° C in the north. The number of frosty days ranges from 225 (south) to 334 (north). The surface water temperatures range from -1° C in the north, in February, to 6° C in the south, in August.

The East Greenland Current brings ice down from the north and bifurcates near the central ridge. Branches of warm Atlantic currents push floating ice northward. The ice season lasts from October to the following August, and the ice includes Arctic pack ice (several yards thick), sea ice (about a yard thick), and freshwater ice in the form of towering icebergs (Encyclopedia Britannica, 2013).

3.6.6 East Siberian Sea

The East Siberian Sea has an area of 936 000 km², situated between the New Siberian Islands in the west and Wrangel Island in the east. To the west it is connected to the Laptev Sea by the Dmitrya Lapteva, Eterikan, and Sannikov straits; to the east Long Strait connects it with the Chukchi Sea. The water depths can from 9 to 20 meters in the western and central parts to its greatest depth, 155 meters.

Covered by ice most part of the year, the East Siberian Sea has surface temperatures in winter varying from -0.2 to -0.6°C on the river deltas to -1.7 to -1.8°C in the northern sea. From November to March, the weather is dominated by the cold continental air masses moving northwestward from Siberia resulting in temperatures of -30°C.

3.6.7 Kara Sea

The Kara Sea has an area of 880 000 km², located located off western Siberia, between the Novaya Zemlya islands in the west, Franz Josef Land in the northwest, and the Severnaya Zemlya islands in the east. It is connected with the Arctic Basin in the north, the Barents Sea in the west, and the Laptev Sea on the east part.

The Kara Sea lies on the Siberian Shelf; thus, about 40 percent of it is less than 50 meters deep, and only 2 percent is over 500 meters deep with a maximum depth of 620 meters and an average of 127 meters.

Air temperatures below 0° C prevail in the north 9 to 10 months a year and in the south 7 to 8 months. The average temperature in January is from -28° to -20° C, and the minimum is -46° C. In July, averages are from -1° to 6° C, with a maximum of 16° C. Winter brings frequent gales and snowstorms, while summer brings snow, snow squalls, and fogs. For most of the year the sea is covered with ice.

The water masses of the Kara Sea are extremely cold and stratified. In the winter the water temperature averages -1.6° C; in the summer. it reaches 6° C in the south-western part of the sea and 2° C in the north. Currents move in two slow, counter-clockwise rotations in the south-western and north-eastern parts of the sea. (Encyclopedia Britannica, 2014)

4 State of the art

4.1 Historical operations

The “Arctic countries” can be subdivided into regions according to the different operational challenges in each sea or basin around the Arctic sea. To simplify this analysis, this region will be divided into sub regions:

- Annual ice covered sea as the case of Beaufort Sea, Chukchi Sea, Northern Greenland, Kara Sea and East Siberian Sea;
- Occasional ice covered sea as it is possible to find in southern Greenland, Northern Barents Sea, Sakhalin and Sea of Okhotsk;
- Environments with extreme low temperatures as in Southern Barents Sea.

The oil and gas development in Canadian and Alaska areas began really early in 1919 with the oil discovery at Norman Wells by Imperial Oil Limited. However, the exploration activity in the Makenzie Delta/Beaufort Sea region just began in 1957 with onshore activities with early reconnaissance-level ground and air studies by the British American Oil Company, Chevron Canada Limited, Dome Petroleum Limited, Imperial, Shell Canada Limited, and others (Lin Callow, LTLC Consulting, 2012). In the early 1970s began the Canadian offshore drilling in the Beaufort Sea with 92 wells drilled in the region according to the National Energy Board (NEB) records. For the next decade, in the 1980s, the Union Oil Company, in partnership with Shell and Amoco, drilled two exploration wells at the Hammerhead prospect, which since has been renamed Sivulliq. Although oil was discovered, the prospect was uneconomic to develop at that time, and the leases were relinquished in 1998 (Interior, U.S. Department of, 2013). From 1944 through 2008, 506 exploration wells were drilled on the North Slope. During this period, the number of exploration wells drilled annually has ranged from 0-35. Recently, in 2012 Chevron undertook an exploratory seismic program there.

Still in the North Slope subarea, the federal waters in the Chukchi Sea have a more limited history of exploration than the Beaufort Sea. Between 1989 and 1991, Shell drilled four exploration wells in the Chukchi Sea at its Burger, Klondike, Crackerjack, and Popcorn prospects. Chevron drilled a fifth exploration well at the Diamond prospect. All of the wells resulted in the discovery of hydrocarbons, although none was considered commercial for development at the time (U.S Department of Interior, 2008). In 2008,

Shell obtained the license to drill in the area. After spending \$7 billion with one disappointing dry well and not being able to drill to depths where oil could be found because of spills response system failed during a test, the company decided to end with the exploratory project.

The Barents Sea is “shared” basically between Norway and Russia. In the 1970s, the Soviet Union began seismic surveying and in the 1980s a systematic exploration effort took place revealing gas fields in the north-western part of the Russian Barents Sea. The Norwegian Barents Sea began very optimistic in the mid 1980s but contrary of expectations, the results of the exploration were not very impressive. Several minor discoveries have been made in Barents Sea, but only one, the gas field *Snøhvit* (Snow White) discovered in 1984, came on stream being developed in the fall of 2007. The second substantial discovery, the *Goliat* oil field, was made in 2000 by Agip. Nowadays this sea has two main exploration programmes in progress: the Statoil one (2013-2014) that started with five wells in the proximity of Johan Castberg and then three more in the Hoop area during the summer which confirmed a working petroleum system in Hoop. The other one is the Goliat, presumed to contain 174 million barrels of oil, and Eni Norge as the main operator is planning to invest NOK 28 billion in the field development. The field is located southeast of the Snøhvit and it is expected to produce for at least 15 years. According to Roald Sæter, geologist in the Norwegian Petroleum Directorate, this field is considered as a “fairly large field” being significant for the development of new oil discoveries in the surrounding areas.

The region of the Greenland Sea can be divided into three distinct geological provinces: The North Danmarkshavn basin, the South Danmarkshavn basin, and the Thetis basin. The North and South Danmarkshavn basins are very similar to petroleum-bearing sequences in the Norwegian Sea with potential source rocks and petroleum traps (The Arctic Institute, 2014). The first scientific investigations in the region were carried out in 1876–78 with Norwegian, Icelandic, and Soviet vessels. However, the oil exploration in the Greenland shelf started in the 1970s, though with the decline of the oil prices, the companies lost the interest in the area. In 1989, Denmark granted a prospecting license to a consortium of companies to conduct initial petroleum exploration in areas offshore of western Greenland. The consortium was known as the Kanumas project and consisted of ExxonMobil, Statoil, BP, Japan National Oil Company, Texaco, Shell and NUNAOIL.

(The Arctic Institute, 2014). In the early 2000s, additional licences were offered, but there was not much demand from companies. In 2006, with the oil prices rising again, the demand was bigger but there was not revealed any promising prospects. In 2010, the British company Cairn Energy established the presence of oil and gas in the region and for now, the future plan is for 2017 with the licensing round for exploration and exploitation of hydrocarbons in offshore areas in Baffin Bay, North West Greenland (NAALAKKERSUISUT, Government of greenland, 2016).

4.2 General drilling concepts and application in Arctic conditions

4.2.1 Rigs

The rigs or MODUs (mobile drilling units) can generally be divided into three major types: Jack-ups, Semi-submersible and Ship-shaped. For their utilization, some factors need to be considered as water depth limitations and drilling capabilities. When talking about Arctic conditions some several environmental challenging characteristics can greatly affect the operations. Those are mainly sea ice, ridges and icebergs, fog, gusty winds, long periods of darkness and very cold temperatures. In response to these environmental conditions, the drilling procedures and equipment must be adjusted to withstand and work safely in ice. Some of the adjusts are: double-ended hull, ice management systems, station-keeping technologies, ice protection for drilling components such as riser systems and subsea equipment, cold- weather materials must be selected to ensure the structural integrity of the drilling equipment, multi-layer well control system and early detection measures with sophisticated sensors.

- **Semisubmersible concept**

The semi-submersibles are units designed with a platform-type deck that contains drilling equipment and other machinery supported by pontoon-type columns that are submerged into the water during operations. This combined with hull mass displacement and the possibility for wave to pass between the pontoons, makes it handle harsh environment very well, minimizing roll, pitch, sway, surge, heave and yaw. Additionally, dynamic positioning as well as mooring lines are used to keep the rig in place. Semi submersibles are capable of carrying less equipment than drill ships, making them more dependent of re-supplement during drilling operation. They are capable of drilling in water depths between 30-3000m with some restriction in extremely shallow waters because the collision risk between the pontoons and lower hulls with the subsea BOP when marine riser is disconnected. To illustrate a semi-submersible rig, the West Venture from SeaDrill is showed below in figure 4.1. The design water depth for it is 1800m and the minimum safe water depth is 70m; its dimensions are 117m long x 69m wide; and the riser minimum ID is 19^{3/4}in nad 75in length joints.



Figure 4. 1 West Venture semi-submersible (Seadrill, 2016)

The semisubmersibles are the most stable floating drilling rigs and the most used for Arctic operations. Though, it faces challenges regarding to the exposure of equipment in the splash zone, where sea ice interact with the equipment; and also in terms of sea ice loading due to ice clogging between the columns. Special skirts or rounded shape (spaced in the centre) columns that extend below the ice zone can be effective in protecting risers and exposed equipment.

- **Semisubmersible designs for Arctic**

Some already built designs from Transocean were developed to operate in harsh environment such as: the Transocean Barents, that is shown in figure 4.2, Henry Goodrich, Polar Pioneer, Transocean Spitsbergen, Transocean Leader, Transocean Arctic and Paul B. Loyd Jr.

The most recent designed of the list above are Transocean Barents and Transocean Spitsbergen that started operations in 2009. Both of them has a maximum design water depth of 10 000ft. and the maximum drilling depth is 30 000 ft. The main deck for both has 295ft. long x 230ft. wide. The marine risers used are 21in. OD and riser joints 75ft. long (Transocean, 2014).



Figure 4. 2 Transocean Barents semi-submersible

Another one is the Polar Pioneer, shown in figure 4.3. It was designed by Sonat/Hitachi and owned by Transocean as a high specification harsh environment semi-submersible in 1985. The dimensions are: 400ft long x 292ft wide x 137ft deep. The maximum water depth is 1 640ft and the maximum drilling water depth is 25 000ft. The marine riser is a 21in OD with 3^{1/2}in choke and kill lines and working pressure of 15 000psi. This rig had a contract with Shell to operate in Alaska in 2015. Though, due to the company's announcement of little oil and gas reserves in the area and further cancelation of operation, the contract was cancelled earlier.



Figure 4. 3 Polar pioneer semi-submersible

Some designs are being projected in the recent years as the JBF Arctic drilling unit (figure 4.4) designed by Huisman. The design combines the advantages of a conventional semi-submersible and a heavily strengthened ice resistant unit. It is designed to drill wells in Arctic, moored in ice infested waters with ice thickness up to approximately 2.0 meters. It consists of a strengthened round floater used for transit through broken ice, eight

columns and a conical shaped deck-box also heavily strengthened at waterline level to deflect and break the ice. When operating in ice, the unit will ballast to ice draft (partly submerged deck-box) to protect the riser against level ice (up to 1,5 to 2,0 meters' ice thickness), rubble and ice ridges. In ice occasion, a heavy 12-point mooring system is used to improve stability. The unit can operate in water-depths between 50 and 1500 meters (Huisman, 2015).

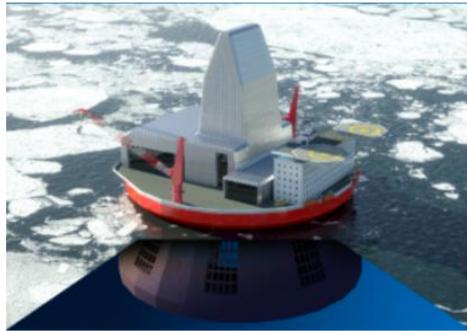


Figure 4. 4 Huisman JBF Arctic drilling unit (Huisman, 2015)

- **Drillships concept**

Drillships are monohull vessels equipped with a drilling derrick and a moon-pool where the drilling equipment pass through and is connected to the well equipment via drilling risers. This type of rig can proper itself and easily move from one location to another. Another advantage regards to the deck space and possibility to carry a larger amount of equipment (high variable deck load – VDL) on it, what minimize the necessity of re-supplement during drilling. However, it has disadvantages about its rental cost that is quite expensive and also a higher susceptibility to be shaken by waves, wind and currents.

To minimize those movements and help to keep the rig in place, dynamic positioning system and mooring lines are used. Drillships are typically employed in deep and ultra-deep water with water depths ranging from 610 to 3050 meters. To exemplify this drilling unit with dimensions, water depth limitations and some drilling equipment used, the West Tellus from SeaDrill is presented in figure 4.5. It was built in 2013 with a design water depth of 3600m., a minimum water depth of 500m. and the drilling depth of 11400m. The ship is 228m. long x 42m. wide and has a riser system operating with a 19^{1/4}:in. minimum ID and riser joints of 90ft. long.



Figure 4. 5 West Tellus drillship

- **Drillship designs for Arctic**

When operating in the Arctic, the high variable deck load (VDL) is one characteristic that highlight this MODU when compared to semi-submersibles. Another advantage in this environment is regarding to the protection of drilling equipment in the moonpool area. As the drillships are more susceptible to motions due to the high waterplane area and the hull shape, weather and ice vaning are needed when operating in Arctic. It is used to minimise the environment loads that can be extreme and beyond the mooring system or DP capacity to keep the vessel in place.

The West Navigator drillship (figure 4.6) has been operating in Norway, UK, West of Shetland, Ireland, Greenland, Canada, Faeroes, Egypt and Mauritania in water depths ranging from 280 m to 1920 m. The maximum rated water depth is 2500 meters and the drilling depth is 9000 meters. The dimensions are 253m long and 42m wide. The minimum ID for the riser system is 19^{1/4}in and the length of the joints are 75ft.



Figure 4. 6 West Navigator drillship (Seadrill, 2016)

Inocean has developed an Arctic drillship (not built) that has been named as IN-ICE (Inocean, 2015) (figure 4.7). The ship is completely enclosed and winterized, is environmentally friendly, and has enhanced logistics / storage facilities. The ice class is Polar Class 4 that is for a substantially extended drilling season (Proactima, 2015). They also won the CAT I drillship design contract from Statoil (figure 4.8) that is now being developed for Arctic operations (Inocean, 2016).



Figure 4. 7 Inocean Arctic drillship IN-ICE (Inocean, 2016)



Figure 4. 8 CAT I drillship design (Inocean, 2016)

Aker Solutions and Aker Arctic have developed (not built) an Arctic drillship concept design for a MODU (figure 4.9) with capabilities to perform extended season drilling in waters with sea ice (Bruun et al., 2015). The objective of the drillship design is to propose a concept that may extend the drilling season in areas with limited open water season by having capability to perform drilling operations during interaction with sea ice.

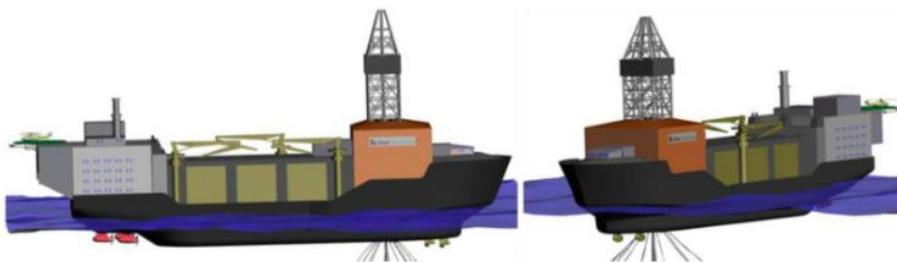


Figure 4. 9 Aker Arctic drillship

- **Round-shaped rigs concepts:**

The cylindrically shaped hull is designed for obtaining good performance both in harsh open water wave conditions as well as in drifting ice (Proactima, 2015). The design is particularly suitable in drifting ice as it faces the ice with the same shape in all directions.

To exemplify this rig type, the Sevan Brasil is showed in figure 4.10. It was first constructed at Cosco Qidong Shipyard in China and started operating in Brazil in July 2012. The maximum rated water depth is 3000 meters and a rated drilling depth of 12000 meters. The deck area is 5700m², a variable deck load (VDL) of 20000 mT and an oil storage capacity of 150000bbl (Marine, SEVANDrilling, 2013).



Figure 4. 10 Sevan Brasil (Marine, SEVANDrilling, 2013)

- **Round-shaped rigs designs for Arctic:**

Mobile units able to withstand thick sea ice, however, require appropriate specification and design for year-round drilling operations. Historically, drilling units specially designed for Arctic waters often have a cylindrical body with a conical shape structure at the level of the ice-water line for breaking ice.

The advantages of the round-shape rigs under Arctic conditions are: protected moonpool (centred for drilling); large load carrying capacity, so the need for supply during operations is minimized; permanent mooring with protected mooring chains/wires; quick release mechanism for mooring chains/wires. In case of extended operational season, just few modifications from the standard concept are needed. However, it has some implications for drilling as the requirement for permanent mooring to resist ice loads; handle with rapidly drift direction of drifting ice and move off in case of icebergs or

severe ice condition (Marine, Understanding the key challenges of FPSOs in Arctic conditions, 2013)

Sevan Marine has developed a cylindrical floating drilling unit for Arctic environments, the Sevan 1000 FPSO for Goliat, in the Norwegian Barents Sea (figure 4.11). The oil production capability is 100 000 bbls/day, a gas production of 3,9 million m³/day and an oil storage capacity of 1 million bbls. The rated water depth is 380-400 meters and the deck area has 9 000m². The unit use a spread mooring system with 14 lines to maintain it stable.



Figure 4. 11 Sevan 1000 FPSO for Goliat

Another cylindrical shaped unit is the Kulluk rig (figure 4.12) built in 1983 by the Japanese Mitsui Company and nowadays owned by Shell. Until 1993 this rig was used to exploration drilling in the Barents Sea. The operating water depths range from 18.3 to 183m., drilling depth up to 6096m. and the VDL is 7000t. The rig has two BOP systems for redundancy. The unit is also designed with an inverted conical hull that minimizes the icebreaking and clearance forces. The capacity of the mooring system allows the rig to operate in ice up to 1.2m.



Figure 4. 12 Kulluk rig

- **Jack-ups concepts:**

Jack-up rigs usually have three or four legs that are lowered down and stationed on ocean floor and then the hull is jacked up to the required elevation. When their legs are not deployed, jack-ups float, what makes possible the transportation from one drilling location to another. The jack-ups can operate in a water depth up to 150m. To exemplify this drilling unit with dimensions, water depth limitations and some drilling equipment used, the CJ70 from GustoMC is presented in figure 4.13. It is specifically designed for all year use in water depths up to 150 meters on the Norwegian Continental Shelf. It provides a significantly less motion during the harsh winter months due to the fixed nature of a jack-up. The deck size is 88,88 x 102,5 meters; the deck load in operation is up to 12000mt and the mud capacity up to 9800 bbls.



Figure 4. 13 Jack-up CJ70 (GustoMSC, 2016)

In the Arctic seas, due to the high sea ice loads and resulting overturning moment, a practical upper limit of 50 to 80 meters is found for jack-up type solutions. Although deeper water is theoretically possible by enlarging the unit, it is not economically attractive (Wassink & Van der List, 2013). To cope with these expected high local loads, the use of circular protective legs has been purposed. In addition, a change in design from 3 to 4 legs with greater distance between the legs will make the structure more stable and able to better resist overturning momentum. This give greater deck space and minimise the chance of ice becoming trapped between the legs.

- **Jack-ups designs for Arctic:**

One of the concepts proposed for Arctic conditions is the jack-up “Arkticheskaya” constructed in Zvezdochka shipyard for Gazprom (figure 4.14). The jack-up hull comprises the rectangular pontoon and three trapezoidal outriggers. Drilling and production equipment and power unit are located in the pontoon. The water depth design ranges from 7-100meters, can support currents of 0,5m/s, temperatures ranging from +30 to -30°C and brash ice conditions.



Figure 4. 14 Arkticheskaya jack-up

The GustoMSC developed the SEA ICE series of jack-ups (not built) that comprises a four circular leg configuration with a hydraulic jacking system. It is fully winterized, has a downwards sloped hull to reduce ice loads in floating mode. The SEA ICE series are in three types with different particular characteristics: SEA 5000 ICE, SEA 11000 ICE and SEA 15000 ICE (figure 4.15)



Figure 4. 15 GustoMSC SEA 15000 ICE serie jack-up (Wassink & Van der List, 2013)

ConocoPhillips and Keppel Offshore and Marine Technology Centre, have jointly developed a basis of design and specifications for a self-elevating Arctic MODU for use in water depths from 10 to 50 meters for drilling a wide range of wells (Shafer et al., 2013). The MODU will not be designed for the highest possible ice load. In the event an ice feature is forecasted to result in loads that exceed the MODU's capabilities, the MODU will be moved.

Another new concept of jack-up was studied by University of Stavanger and Gubkin University. Its concept is a hull with icebreaking capabilities, which makes it ideal as a standby for relief well drilling in case of a blowout, and with four outrigger arms: two in each side of the hull. Also, it should have four tubular legs (instead of an open-truss design) with individual mud mats mounted on the outrigger arms (figure 4.16). It is designed to extend the drilling season with between 4-5 weeks in ice areas like Pechora and Kara Sea. This will have a major impact of the work that can be done in one season.



Figure 4. 16 New concept of jack-up (Urycheva & Gudmestad, 2014)

Summarizing, the selection of the major types of units for the different Arctic seas is illustrated in table 2.

Area	Jack-up	Semi-submersible	Ship-shaped
Beaufort, Chukchi, Northern Greenland, Kara, East Siberian	✓	✗	✓✓
Seasonal high arctic and periodic ice infested - Southern Greenland and Barents	✓	✓	✓✓
Harsh environment	✓	✓✓	✓

Table 2 Rig type selection

4.2.2 Risers

In this section, a brief overview of the riser system will be given. More details of the riser functions, components and the loadings on the riser system are given in the chapters 6 and 7.

The risers can be used for four main purposes: drilling, completion/workover, production/injection and export. For the objective of this thesis, the focus will be given to the drilling risers. During offshore drilling operations, the riser is used to connect the surface equipment on the MODU to the BOP Stack and the well. A general view of this system is presented in figure 4.17.

Some of the main functions of the drilling riser are to provide a fluid communication from the seabed to the rig in both ways; guide tools from the drilling rig to the wellhead; support auxiliary line as the choke and kill lines. The basic “body” of the riser is made of a number of riser joints, typically 50-70 ft long, normally comprises a central tube of 20 or 21 inch outside diameter (OD) diameter and a 18^{3/4}inch inside diameter (ID).

The drilling risers can be subdivided into low-pressure and high-pressure risers. The standard drilling riser today is a low pressure riser, open to atmospheric pressure at the top end. Thus, the internal pressure is basically dictated by the drilling-mud weight. The other type, the high-pressure risers are used when the BOP is located at the surface. This riser has a much simpler architecture than does a low-pressure riser, since it does not require the kill and choke lines. Since the BOP is located at the surface, it is immediately

accessible on the drilling rig in case of a kick. Thus, the riser has to be designed to take the full well pressure.

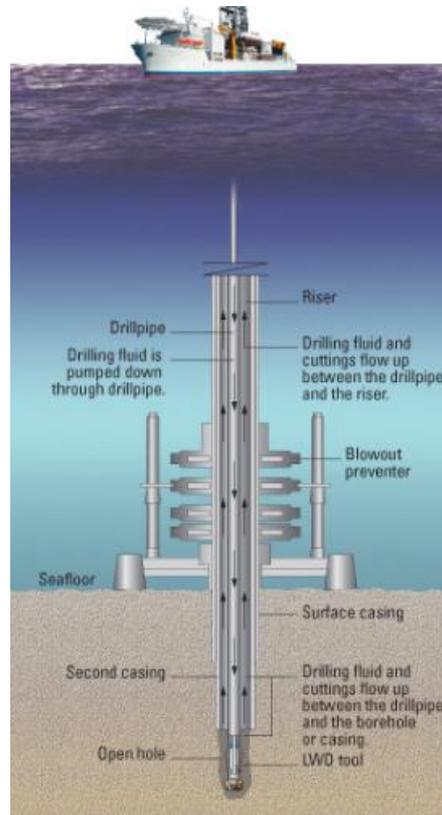


Figure 4. 17 General view of a drilling riser system (Schlumberger, 2016)

Before the production of the riser and test of material, first there must be a preliminary judging standard of material properties index, then amend this standard based on test results and finally establish standards of performance index of riser material (Tubular Goods Research Center of CNPC, 2010). Also, points as cost, resistance to corrosion effects, weight requirement and weldability need to be judged.

This key component of the drilling system is subjected to various loadings, both static and dynamic, as a result of the internal and external pressures, vibrations, tensions, currents, variation of temperatures, and many others. A scheme of the loadings that a riser suffers is presented in figure 4.18. Thus, the connection points between pipes and the upper and down connections with the MODU and seabed equipment, respectively, are considered weakness points and some extra attention should be given. The riser string is made up of a large number of joints that are connected on the drilling rig prior to deployment. There are mainly three types of connection at the market: bolted flange type,

dog type and clip type. The most common one is the bolted flange type (Husøy, 2010). The top tension in the connection between the drilling riser and the rig is, according to API RP 16Q, the minimum tension required to ensure the stability of the risers. The tension setting should be sufficiently high so that the effective tension is always positive in all parts of the riser even if a tensioner should fail.

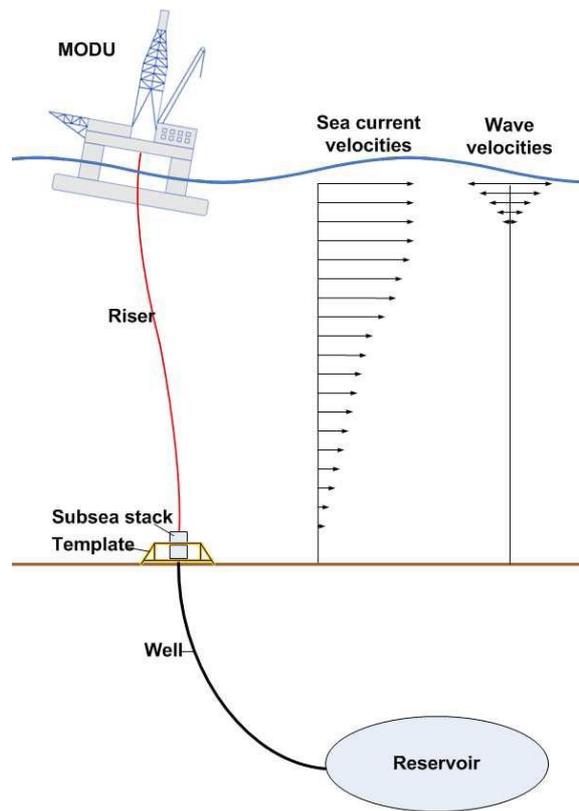


Figure 4. 18 Loads on the drilling riser system(DNV, 2011)

The Arctic environment conditions bring besides the regular loadings, the presence of massive ice features. Hence, the riser planning phase is extremely important to define the right riser in terms of size, material type and grade in order to define an operational window that a riser can tolerate from environmental and applied loading without being failed.

4.2.3 BOP

In this section, a brief overview of the BOP system will be given. More details are given in section 6.3.

The Blowout Preventer (BOP) is a structure with a large set of valves and rams placed on the top of the wellhead that can be closed when drilling crew have uncontrolled flow of formation fluids. It is also used to hold erratic pressures of a flow that comes from a well during drilling. During well killing, BOP also allows the drill pipe to be laid into down hole while maintaining the sealing of the well. The BOP is incorporated with LMRP on the top, to enables quick disconnection between marine riser and BOP in emergency situation (Januarilham, 2012). It is in the LMRP that the control pods are located, choke and kill lines connected, and upper and lower annular can be located. A schematic diagram of a BOP stack is presented in figure 4.19.

The main tool to keep a well under control is by equalising the pressure with the weight of the drilling mud. In case of an uncontrolled flow and if the primary barrier failure (mud column), a formation influx takes place during drilling, one or more BOPs are activated to seal off the annulus, or wellbore, in order to “shut-in” the well. Afterwards, the required mud weight to balance the pressure from a kick will be circulated into the well through kill line and the flow of fluid in the well will be circulated through choke flow line into mud pit. Once the well is filled with a “kill mud” from the bottom to the top, the well is back in balance and has been “killed.” Operations may proceed with the integrity of the well re-established (Vafin, 2015).

A second solution is to use the annulars and rams to seal off the well when it is needed. Rams are hydraulically driven steel rams with rubber gaskets designed for different purposes, some seal off the flow around the drill pipe, while others can cut the drill pipe and seal the flow by completely shutting the area. Annular uses pistons to push an elastic rubber material into place, which can seal around a pipe or seal the empty area.

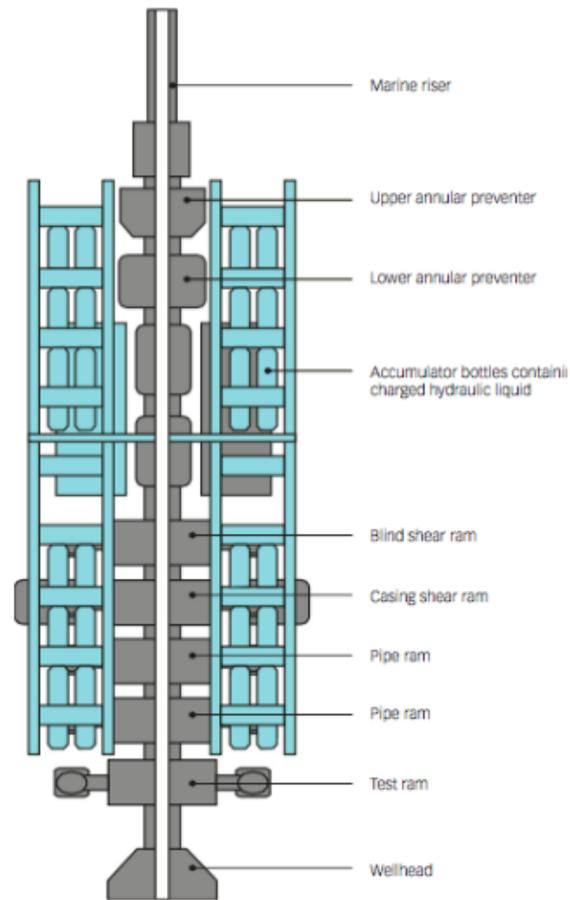


Figure 4. 19 Schematic diagram of a BOP stack (Lloyd's, 2011)

5 Challenges and critical issues for Arctic drilling

5.1 Critical Issues

5.1.1 Sea Ice and icebergs

The Arctic sea is characterized by the presence of ice which can occur in four main forms: pack-ice (frozen salt-water), icebergs, permafrost or ice accretion. The level of ice changes during the year with the maximum extension in winter and the minimum in summer as can be seen in figure 5.1. The interaction between the rig and ice will cause loads in the structure and can exceed the mooring/DP system capacity. In order to keep those loads under the systems capacity, ice management is needed to break the ice into smaller pieces.

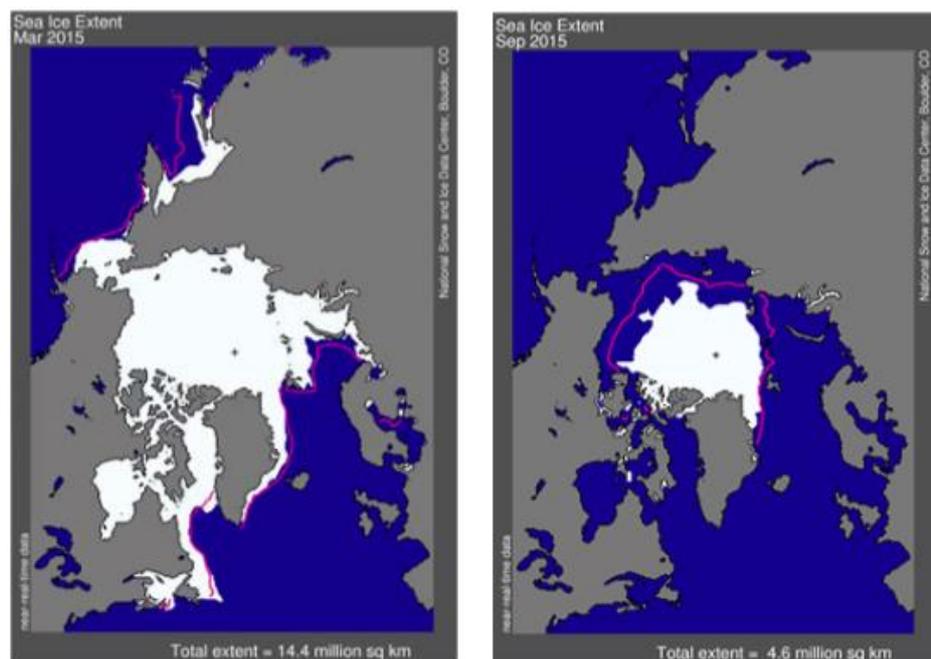


Figure 5. 1 Maximum and minimum extension of ice during the year

- **Pack-ice:**

Pack-ice is a floating layer of ice of variable age and thickness. It begins forming in late summer and early autumn. Going through several stages, it starts as individual ice crystals appearing in the water and ends as very hard irregular shaped “floes¹” that can reach up

¹ Floe: any relatively flat piece of ice which is more than 20m across.

to 4m. thick. During the summer, pack-ice composed of multi-year ice covers approximately 7 million km² of the ocean. In the winter as temperatures drop and new ice forms, this area increases to approximately 14 million km². This ice layer can extend southward as far as latitude 48°N with exception of Norwegian and Barents Seas that remain ice-free because of the influence of the North Atlantic drift as mentioned in section 3.6. (OGP, 2013).

- **Iceberg:**

Iceberg is frozen freshwater from land-based glacial sources specially along the Greenland coast and Ellesmere Island. In a less extension, can also include Svalbard, Franz Joseph Land, Severnya Zemlya and Novaya Zemlya. Also, what characterize an iceberg is its protrusion of more than 5m, with possibility to extend to more than 200m, above the sea level. Once broken off, they become ice islands and enter the Arctic current systems where they can circulate for years before moving down the coast of Greenland and into the Atlantic Ocean, where they progressively melt (OGP, 2013). Some icebergs can reach hundreds meters long with deep keels what can be a hazard to offshore installations, subsea equipment and pipelines figure 5.2). Ice management programs need to make sure icebergs don't collide with the installations.

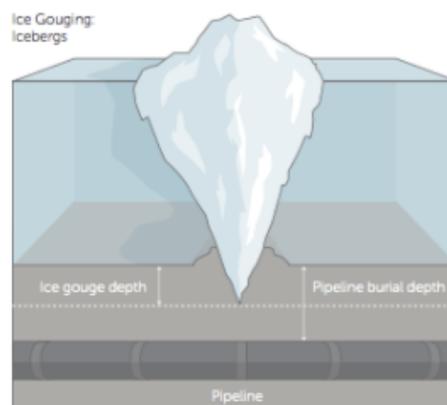


Figure 5. 2 Ice below the water may dig the seafloor and damage the pipeline if it is not positioned deep enough (The PEW charitable trusts, 2013)

- **Permafrost:**

It is found in shallow waters (up to 3m deep) primarily along the northern Russia coastline, where land permafrost extends into the sea. Arctic pipelines must be designed

to withstand bending stresses on the pipeline due to permafrost thaw subsidence (figure 5.3).

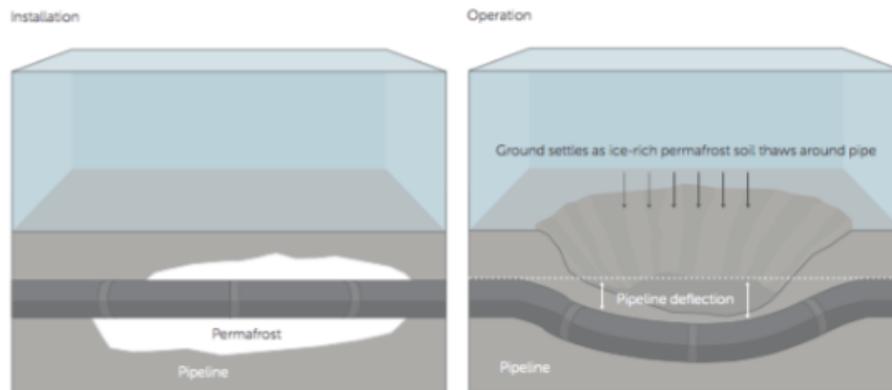


Figure 5. 3 Arctic pipeline due to permafrost

- **Ice accretion:**

Ice accretion can be caused both from atmospheric icing and sea spray. The extent of ice accretion must be considered in the design and operability of the structure.

5.1.2 Marine and atmospheric icing

Atmospheric icing is related to precipitation and its most common forms are super-cooled droplets as frost smog, super-cooled fog or freezing rain. Atmospheric icing can occur in arctic and cold region seas throughout the year when air temperatures are between 0°C and -20°C and in presence of wind speed less than 10 m/s. By itself, atmospheric icing does not necessarily cause major structural consequences, though severe operational ones. If atmospheric icing occurs together with sea spray icing, it can accelerate the build-up of icing in a phenomenon called mixed icing (ISO , 2010).

Marine icing caused by sea spray is the most frequent and most important form of icing in the sea. Sea spray can be formed from the vessel or structure interaction with waves or from droplets of water blown by the wind. It begins to occur at wind speeds of 8 to 10m/s (ISO , 2010). Another cause of marine icing is shipped water that enters the deck of a vessel over the bow or sides. Significant amounts of superstructure icing can accumulate

(figure 5.4) when air temperature is below the sea water freezing point ($\sim -1,8^{\circ}\text{C}$); wind speed is more than 10m/s and seawater colder than 8°C . (Solberg, 2014).

Arctic icing and ice accretion caused by atmospheric icing and sea spray can cause problems on outdoor facilities, installations and structures. Effects are both in terms of increased weight on the installation, resulting in stability loss due to change of the centre of gravity upwards, and access to and workability of critical facilities. The rate of ice accumulation depends on the structure height above the water, the geometry, wind speed and air temperature.



Figure 5. 4 Vessel icing from sea spray (The PEW charitable trusts, 2013)

5.1.3 Temperature, visibility and snow

As explained in section 3.2, the Arctic experience severe low temperatures what may affect the regularity/reliability of equipment and the human working environment. Material fatigue and cracking can be an issue in such low temperatures. During the open water months, warmer air interacts with the cold water forming the fog what can be a concern regarding the reduction of visibility. Also, precipitation in form of snow impact the visibility and when combined with wind, sea ice spray and extremely low

temperatures can cause a solid hard layer on the surfaces that are difficult to remove. Another point that impacts the visibility is the darkness that Arctic experiences during winters. Reduced visibility affect helicopter transportation, emergency response, ice management, resupplies, marine operations and oil clean up response (Stephen Potter, 2012).

5.1.4 Waves

The interaction of waves and ice is particularly complex, because ice can suppress waves by scattering and dissipating wave energy, while the waves simultaneously break up the ice (Jim Thomson, 2014). Ocean wind and swell waves are generated by the wind blowing over the availability fetch length that can vary from zero winter time with full ice cover to many hundred kilometres during open water season. The wave conditions imply in vessel motions (section 7.2.3), more drift ice, restriction on marine operations and clean-up of oil spills.

5.1.5 Wind and polar lows

Polar lows are defined as a maritime mesoscale cyclone in polar air. They are associated with the rapid change in the weather conditions where the wind speeds may rise and the direction changes rapidly. The wind in Arctic can vary intensity a lot, as mentioned in section 3.4. The rapidly change in wind direction is hazard to drillships due to weathervaning. Also, the increase in wind speed and the polar lows contribute to vessel icing, thunderstorms and snowstorms.

5.1.6 Permafrost

Permafrost is the term for the permanently frozen ground status. Large areas of Arctic are underlain by permafrost ground. At higher latitudes where the mean annual air temperature is -8° C, continuous permafrost (that may have existed for thousand years) can be found. Further south, where the air temperature ranges from -8° C to 0° C, discontinuous permafrost can be found. Permafrost generally occurs in the upper 500 m of the Earth's surface but has been found as deep as 1500 m, especially in areas with low air temperature and thin snow cover. This event can also occur offshore as mentioned before in this chapter (OGP, 2013).

Permafrost causes problems in multiple phases during drilling and completion. When drilling through a zone that can contain permafrost it is vital to keep drilling mud temperature as low as possible. If the temperature gets too high, it can cause bore hole instabilities and bore hole collapse. For the cementation step, there is a need for specialized slurries that can build compressive strength also below water's freezing point. Another issue during cement jobs is melting the permafrost, this can happen since the cement hydration is an exothermic reaction. If the permafrost is melted the cement support is lost and this will cause the cement job to fail and the casing string will have no support.

5.1.7 Ecosystem in case of oil spills

The Arctic Ocean's weather conditions present a challenge to oil and gas operators and emergency response workers (The PEW charitable trusts, 2013). It is probably one of the most vulnerable ecosystems on earth for oil spills. The presence of ice, cold temperatures and long periods of darkness can greatly reduce the spreading and weathering of spilled oil. Also, the freezing temperatures will make the oil more viscous, making it stick to birds and animals (Solberg, 2014). Sea ice offers one advantage, though, oil that is encapsulated in ice during freeze-up is typically returned to the surface during spring thaw through the processes of migration. Because this oil is found in the same state of weathering as before encapsulation, it is possible to remove this oil by in situ burning (OGP, 2013). The impacts of an oil spill and the likely difficulties of cleaning it up makes the exploration in this region highly controversial. To try to minimize the emission to this sensitive environment, the rigs must be designed to minimize the waste from the drilling operations such as mud, cuttings, emissions, etc.

5.2 Critical Operations

5.2.1 Long distances from shore

In addition to the severe environment conditions, the Arctic remoteness and lack of infrastructure both onshore and offshore is another problem in the Arctic oil & gas campaign. The onshore infrastructure has limited number of roads, ports, airports and some places satellite communication is precarious. The offshore primary consideration

when planning for infrastructure and support services is the distance of the field from established bases onshore. Also, the satellite coverage is lowered north of 75 degrees, being a challenge for drilling units using Dynamic Positioning system and for the communication with the rest of the world. In addition, the rigs must be self sufficient and carry additional equipment and supplement as drill pipes, mud, fuel supplies, possibly two BOP systems, etc. In critical situations, the remote location areas also make evacuation of personnel more time consuming and difficult, and delays start of medical treatment. Helicopter reach is limited and under large concern (Gudmestad & Quale, 2011). In case of an oil spill, the distance from where response capacity is stationed mean it can take days or weeks, even during ice-free periods (WWF, 2014).

5.2.2 Working environment and emergency preparedness

There will be need for practical solutions for the working environment, related to darkness, cold climate and distances. Work in low temperatures, which often are enhanced by the wind chill effect, implies new requirements to personal safety equipment and ergonomics. Winterisation and weather protection of personnel and facilities contribute to sheltered areas avoiding damage due to ice and freezing temperatures. With activities distant from land, far outside the reach of helicopters, there will be lack of options for shore bases and helicopter-landing sites, being a logistics and rescues preparedness challenge. Considering the lack options of external assistance, the rigs and vessels must have specially designed lifeboats that handle with the ice conditions. Another important task for the working environment is about clothing. It must be warm and at the same time be flexible for execution of work tasks and be suitable for survival actions (Gudmestad & Quale, 2011)

The most effective measure to prevent unwanted incidents to happen is education and training in the proper use of available winterisation technology, and defensive behaviour regarding the possible falling loads, slippery work areas and access ways (Gudmestad & Quale, 2011). In case of oil spills, some techniques can be used as mechanical recovery with (or without) ice management and in-situ burning. A clean-up operation would combine all those methods. However, as operating in presence of ice and leading with all the difficulties about this harsh environment, the success rate of oil removal operations is

highly uncertain and limited. If considering the spill during an ice season, this rate is even smaller, reaching zero success in some cases.

6 Marine drilling riser system

6.1 Functions

The marine riser system forms an extension of the well bore from the Blowout Preventer (BOP) Stack to the drilling vessel (Figure 6.1). The functions of the marine riser system are:

- Provide a fluid conduit to and from the wellbore, that is, it extends the wellbore from the subsea BOP stack to the drilling rig. This communication can be set in the riser annulus under normal drilling conditions or through the choke and kill lines when the BOP stack is being used to control the well;
- Support for hydrostatic pressure due to the fluid column used as a primary well barrier.
- Guide tools such as the drilling bit and the bottomhole assembly (BHA) from the drilling rig to the wellhead on the seabed;
- Serve as a running and retrieving string for the BOP stack;
- Support auxiliary lines, such as choke and kill lines, mud booster lines, hydraulic conduits and air injection lines

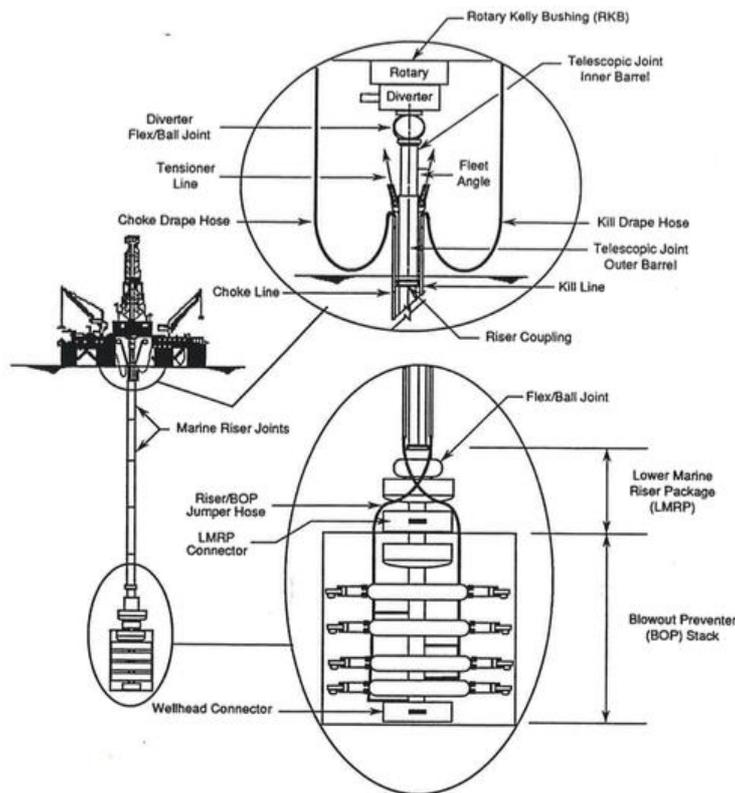


Figure 6. 1 Marine riser system and associated equipment (API RP 16Q, 1993)

6.2 Riser design and components functions

Efficient deployment and retrieval systems of the riser and BOP stack are integral parts of the marine riser design. The design includes not only normal procedures, but also emergency disconnect and hang-off procedures. These conditions may dominate the design criteria.

A typical marine drilling riser system consists of a surface tensioner system; a surface diverter system; a telescopic (or slip) joint; individual riser joints; high pressure choke and kill lines; hydraulic conduit lines; a mud booster line; a riser fill-up valve; a termination spool; flex and ball joint; a BOP stack; and a lower marine riser package (LMRP). The key components of the drilling riser system can be seen in figure 6.2.

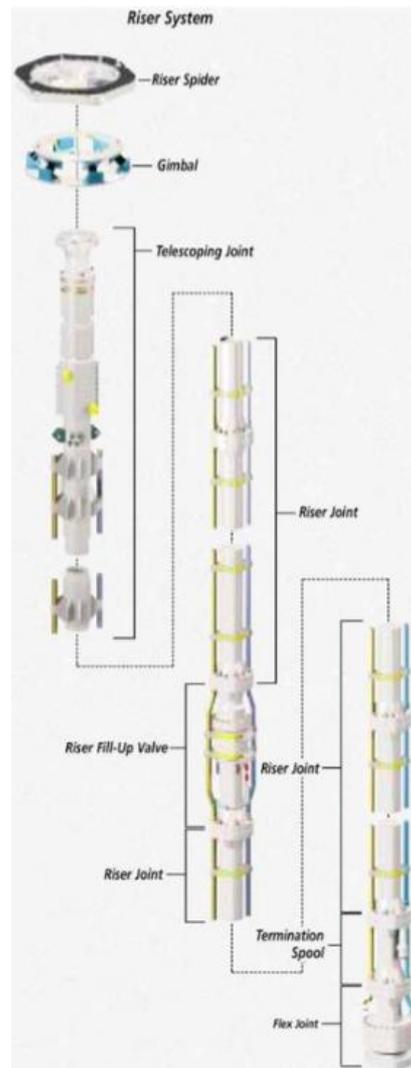


Figure 6. 2 Key components in a drilling riser system (McCrae, 2003)

6.2.1 Tensioner system

A riser tensioning system must ensure a certain tension is maintained in the marine riser and also support the weight of the longest riser string at the rig's deepest operating water depth. So, tensioner units apply vertical force to the top of the marine drilling riser to control its stresses and displacements. They aim to provide constant axial tension to the riser while the vessel moves vertically and laterally in response to environment elements as wind, waves and currents. The tension required is determined by many variables besides the vessel motion, as rated water depth, mud weight inside the riser, and buoyancy effects.

There are two types of tensioner system: the traditionally used one, the wire-based system (figure 6.3) and the new developed concept, the hydraulic system or as known in the market, Direct Riser Tensioners (DRT) (figure 6.4).

Wire-based system: Tensioner units use a hydraulic ram, air-filled accumulator to maintain near constant the pressure/tension in the line. It is usually located on the drilling vessel near the periphery of the drill floor and its substructure. One end of the line, which may be wire rope or chain, is attached at the tensioner and the other is attached to a padeye on the outer barrel of the telescopic joint. Normally, a four-part line reeving system is used, what means that the effective wire travel is four times the piston travel.

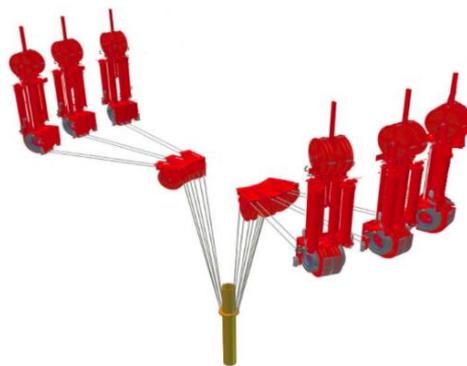


Figure 6. 3 Wireline tensioner system (Haziri & Dyngvold, 2011)

Some important considerations for designing an effective tensioner system are: the fleet angle; accumulators and air pressure vessels; dynamic tension limit (DTL); maximum

tension setting; velocity limiting device. (For a better understand of some descriptions below, go back to the scheme in figure 6.1)

- The fleet angle: is the angle between the vertical axis and a riser tensioner line at the point where the line connects to the telescopic joint. It should be minimized in order to maximize the vertical component of tension, minimize the horizontal component, and increases wireline life.
- Accumulators² and air pressure vessels: each tensioner unit have an accumulator to store a large enough volume of hydraulic fluid. Large air pressure vessels reduce the change in air pressure caused by the ‘in and out’ tensioner stroke.
- Dynamic Tension Limit (DTL): is defined differently by each tensioner manufacturer. The tensioner system should be designed to continue operating normally even without one unit in case of maintenance or repair need. All components in a riser system installation should be designed for the maximum allowable pressure.
- Maximum tension setting: should not exceed 90% of the DTL.
- Velocity limiting device: in case of failure of a tensioner wireline, the flow control device (located in the line between the fluid port on each tensioner and the air/oil interface bottle) should immediately interrupt or reduce the fluid flow into the tensioner.

The traditional system has some disadvantages compared with the new one such as wire and sheaves limit access to areas where other drilling operations are conducted; maximum capacity is limited from a practical point of view by wire and sheave diameters; handling the wire while doing cut and slip operations is difficult, especially for the larger wire sizes. Because of those reasons, the direct hydraulic technology was developed.

Hydraulic system (DRT): consists of six direct acting tension cylinders with 50 to 65 ft stroke, pulling on the marine riser. Supported from the structure underneath drill floor and connected to the telescopic joint load ring, it generates a nearly constant pull on the

² Accumulator is a pressure vessel charged with gas over liquid that is pressurized on the gas side from the tensioner high-pressure gas supply bottles and supplies high pressure hydraulic fluid to energize the riser tensioner cylinder.

riser. The riser tensioning cylinders are located in the moonpool area, while the rest of the equipment is placed on deck. The main component is the cylinder that generates a tensioning force on the riser that is generated by hydraulic pressure in a closed volume. Each cylinder has a positioning system to determine position, speed and direction of the rod movement.



Figure 6. 4 Hydraulic tensioner system (or DRT)

The cylinder rod side is connected to a high pressure accumulator via a shut off valve that gradually choke and stop the hydraulic supply to the tensioner cylinders in the event of disconnect or a riser failure to eliminate or minimize the effect of riser recoil³.

Control of the riser tensioner system is centralized at one local control cabinet and drillers control screen. All information and commands about controlling and adjusting the tensioner system is done through these panels/screens.

6.2.2 Diverter System

Diverter system (figure 6.5) directs an uncontrolled flow from a shallow zone (shallow gas kicks) away from the rig floor. Such gas flows can occur when drilling the top hole through the 30-inch conductor casing. At this stage the riser may be deployed enabling

³ Riser recoils system is a means of limiting the upward acceleration of the riser when a disconnect is made at the riser connector.

the use of weighted mud to provide overbalance if needed. As the BOP stack is not in place at this time, in case of an unexpected flow, the riser will direct it to the diverter system aboard the rig. During normal drilling operations, the diverter directs the flow of mud returning from the marine riser into the rig's return flow line.



Figure 6. 5 Diverter system (JVS Engineers, 2013)

A surface diverter system is usually installed directly below the rotatory table. It generally consists of a permanently fixed housing, which is bolted to large support beams below the rotatory table. The mud flow line and overboard vent lines are permanently attached to the side outlets of the fixed diverter housing (figure 6.6) (McCrae, 2003).

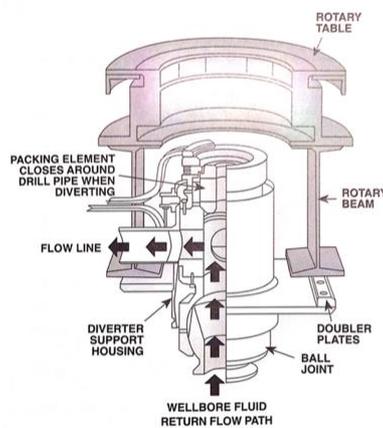


Figure 6. 6 Scheme of the diverter system (McCrae, 2003)

6.2.3 Telescopic Joint (Slip Joint)

The telescopic joint is installed at the top of a marine riser system. The main basic function is to compensate for the relative translational movement between the vessel and the riser. Also, it provides a means of connecting the diverter assembly to the riser,

provides terminations for the riser auxiliary lines to flexible hoses at the drilling vessel and provides attachment points for the riser tensioning system.

A telescopic joint is made of an outer barrel which is connected to the drilling riser, an inner barrel that is connected to the drilling vessel (passing through the diverter assembly), and a tensioner ring that transmits loads from the tensioner system to the outer barrel of the riser. The stroke length of the telescopic joint can be from 45ft (for shallow water and mild environment) to 65ft (for deepwater and harsh environment).

The riser tensioner lines typically attach to a hydraulic tensioner ring, near the top of the telescopic joint outer barrel providing the structural interface between the marine riser and the tensioner system. Moreover, this tensioner ring should be rated for the maximum load capacity of the telescopic joint and also allows the running, latching the ring to the outer barrel, and retrieving, latching the ring to the diverter housing, of the telescopic joint without removing the tensioner lines. Padeyes on the tensioner ring accommodate pinned connections at the ends of the tensioner lines (figure 6.7).

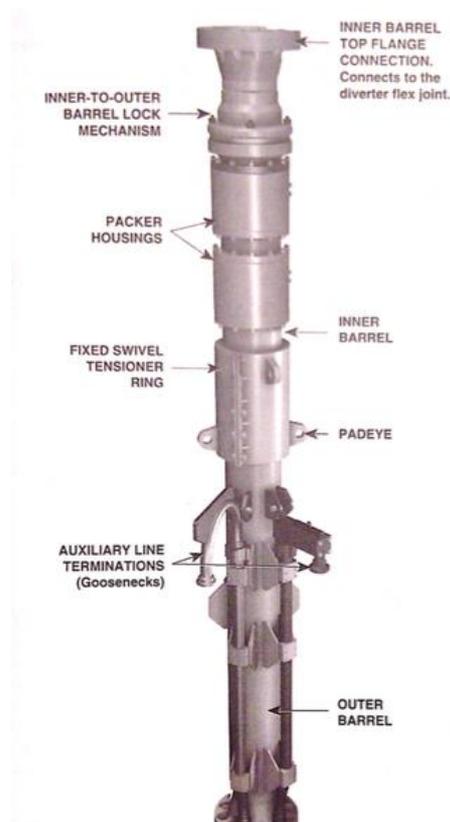


Figure 6. 7 Telescopic joint (McCrae, 2003)

Locking devices on the telescopic joint lock the inner barrel to the outer barrel in a fully retracted position. This is the required position during the running or retrieving the BOP assembly. In both, retracted and extended positions, the telescopic joint should support the weight of the riser and BOP stack.

6.2.4 Riser Joints

A riser joint is a large diameter, high-strength pipe, either seamless or electric welded, that has connectors at each end. A series of individual riser joints are coupled together (figure 6.8) on the drill floor level and lowered vertically into the water. The string of riser joints represents the principal component of the riser system. The coupling at the upper end of the riser joint usually has a riser support shoulder that supports the loads of the marine riser and BOP stack when it is suspended from the riser spider (see section 6.2.7). It also provides support for the choke, kill and auxiliary lines to the pipe and load reaction for buoyancy devices (API RP 16Q, 1993) (figure 6.9).



Figure 6. 8 Series of riser joints being lifted for transportation

The typical riser joints lengths for deepwater drilling is 70ft (21,34 m) and for shallow waters, 50ft (15,24m). There are riser pup joints that are shorter lengths of risers to accommodate riser space-out. For the selection of the pup joints, the crew should be sure the telescopic joint is positioned in the mid-stroke position, so that it can accommodate the increased riser length. If either the extension or retraction limits of the telescopic joint are exceeded, the riser and associated equipment can be damaged.

The riser main tube should have adequate strength to withstand combined loads from waves, current, applied tension, motion of the rig, and drilling fluid weight mud. The

strength characteristics of the main tube are dictated by its diameter, wall thickness, and steel grade. The typical riser's outside diameter (OD) are 20 or 21 inch, inside diameter (ID) of 18^{3/4} inch and wall thickness of 1^{1/4} inch. The steel grades commonly used are X-52, X-65 and X-80, where the numbers refer to the minimum yield strength in ksi of each grade.

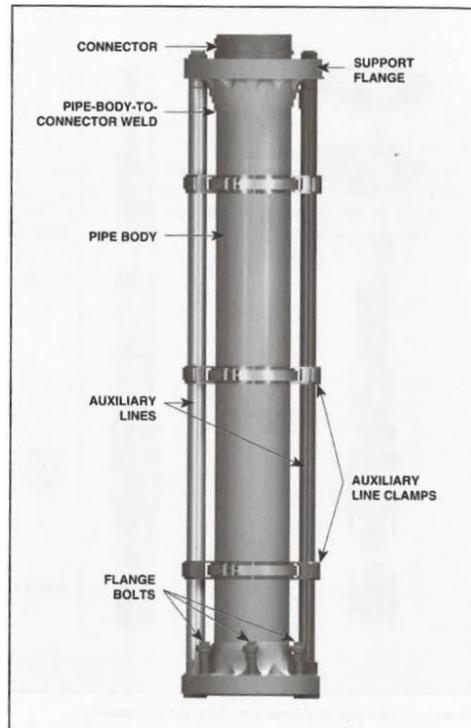


Figure 6. 9 Components that make a riser assembly (McCrae, 2003)

There are four basic riser coupling designs: dog-type, flanged, threaded union and breech-block. The two main used types are the flanged-type followed by the dog-type (figures 6.10 and 6.11). Because the riser joint multi-bore connectors operate under extreme conditions, it is made stronger than the riser pipes and the selection should be based on the strength; load rating of support ring; fatigue resistance; reliability; speed of make-up; preload for make-up; maintenance requirements; main tube dimensions; strength to weight ratio.

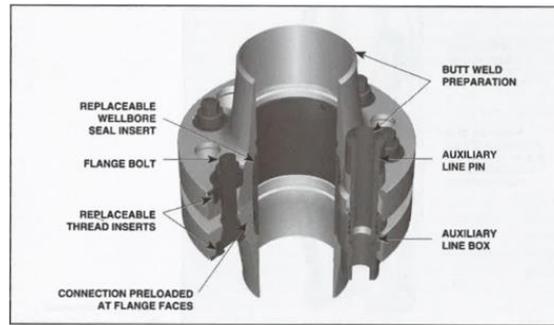


Figure 6. 10 Flanged-type coupling design (McCrae, 2003)

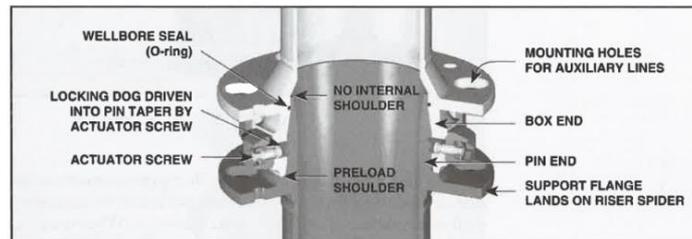


Figure 6. 11 Dog-style coupling design (McCrae, 2003)

6.2.5 Choke/kill and auxiliary lines

Beside the choke and kill lines, the auxiliary lines include: mud booster, air injection (if any) and hydraulic supply lines. All those lines carry fluids along the length of the riser and in the most part of the cases, they are attached on the outside of the riser main tube by support brackets as an integral part of each riser joint (figure 6.12). The brackets also prevent buckling when the lines are pressurized.



Figure 6. 12 Riser main tube and auxiliary lines (2B1st, 2016)

Choke and kill lines: high pressure lines (pressure rating should be the same as that of the BOP stack) that are used to provide a controlled flow of oil, gas or drilling fluid from the wellbore to the surface when the BOP stack is closed on a well kick. During well killing operations, well fluids normally return to the surface through the choke line and, if required, mud can be pumped down the kill line.

Those lines are held to the riser joints by support brackets that prevent buckling when the lines are pressurized. Those brackets are spaced depending on the rated pressure of the choke/kill lines and the buckling characteristics of the pipe.

Generally, the ID of those lines is 3in and can be up to 4^{1/2}in for deep water operations and the steel grade is usually X52, X65 or X80.

Mud booster lines: used as conduits for drilling fluid which is pumped into the riser just above the BOP stack to increase annular circulating velocities. The pressure rating should be suitable for the mud circulating system rating. The ID is generally 3in and the steel grade used, X52 or X65.

Hydraulic supply lines: carry hydraulic operating fluid to the BOP subsea control system. It can be used either as a primary or secondary supply line. Most BOP systems incorporate a flexible hydraulic fluid supply line inside the control line hose umbilical. Some systems have two hydraulic conduit lines, one for each BOP control pod. Others have just one, which supplies both pods. The working pressure rating should be compatible with the working pressure rating of the BOP control system.

The hydraulic supply line's ID is generally 2 or 3in and constructed of corrosion-resistant material to prevent rust particles from clogging hydraulic operator ports and damaging seals and sealing surfaces. The typical material used for those lines is stainless steel, so that, proper galvanic protection is provided.

Air injection lines: used to supply air to increase riser buoyancy for risers which use air-chamber buoyancy systems.

Important selection criteria should be considered when selecting, designing or specifying those lines. Some principles that are applied for all of them are:

- The lines couplings must be able to seal against full pressure while allowing for relative motion between the box and pin⁴ caused by temperature difference between the fluid in the main marine riser and the fluids in the choke/kill or auxiliary lines; bending loads imposed by deflections of the riser; Poison's effect (that creates motion between the box and pin on the auxiliary lines couplings) resulted from structural compression caused by pressure exerted on the end of the pins.
- To prevent accidental mismatching of the auxiliary lines when the riser is deployed, the couplings are oriented asymmetrically around the riser support ring. To prevent accidental over pressuring while testing, the test caps for the choke/kill lines are designed so that they cannot be installed on the mud booster or hydraulic conduit lines because those cannot tolerate the high pressures required for the choke/kill lines.

6.2.5.1 Flexible choke and kill lines

Flexible choke and kill lines allow relative movement at the telescopic joint and at the flex/ball joints in the riser system. Three basic designs are commonly used: flexible pipe, steel reinforced hoses, or flow loops with threaded, clamped, or flanged end fittings.

Flexible lines should be compatible with the rest of the choke and kill piping system and with the BOP stack, riser, and choke and kill manifold. Selection of flexible lines should take into account: length requirement and tolerance; end fitting compatibility; pressure rating; collapse; temperature rating; minimum bend radius; fluid compatibility; resistance to wear by abrasive fluids; corrosion resistance; fatigue resistance to bend and pressure cycling (API RP 16Q, 1993).

6.2.6 Flex and ball joints

A flex or ball joint is mounted between the annular preventer and the riser adapter on the LMRP. Both the flex and the ball joints are used to allow angular misalignment between

⁴ The box and pin are stab-in couplings to connect the auxiliary lines of one riser joint to to their counterparts. The box contains an elastomeric radial seal which expands against the smooth, abrasion-resistant sealing face of the pin when the line is pressurized. It also facilitates the fast make-up while deploying the riser

the riser and the BOP stack, thereby reducing the bending moment on the riser. They are also used at the top of the riser to allow the motion of the rig. In some instances they may also be installed at some intermediate level in the riser string below the telescopic joint to reduce stresses in the riser (API RP 16Q, 1993).

Directly on the top of the flex joint, a LMRP's riser adapter is commonly installed. The adapter adds height to the BOP – LMRP assembly and in some cases, the cellar deck in the rig is not big enough to handle this additional height. To overcome this problem, the rig can use a termination joint or spool, which is a standard riser joint with a side entry to allow connection of the mud booster line.

6.2.7 Riser running equipment

The three main equipment to be cited are: the handling tools, riser spiders and guidelines. All of them are based on some selection criteria such as maximum static loading capacity; dynamic loads induced by waves, currents, rig motions; bending loads during riser running operations; impact loads.

Handling tools: are used for hoisting and lowering the riser, telescopic joint and BOP stack. The riser handling tools make up to the top of the riser during deployment and retrieval. The connection at the top of the riser (top connection) is a short length of pipe that is supported by the hoisting equipment (figure 6.13). Another important tool is the diverter handling tool that is used to carry the entire riser system load prior to landing the BOP stack on the wellhead.

There are two types of handling tools: the mechanical and the hydraulic riser handling tool. The hydraulic type is operated hydraulically and reduce the time spent in making the connections.

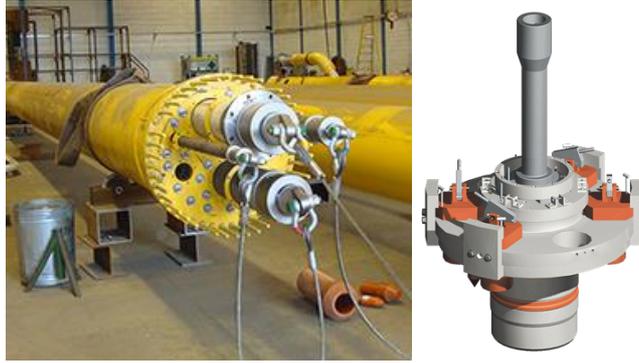


Figure 6. 13 Riser handling tool (First Subsea, 2016)& (Cameron, 2016)

Riser Spiders: provide support for the riser and BOP stack at the drill-floor while they are being run or retrieved. The spider consists of a base plate and top plate with a series of support arms between them. The arms support the riser joint under the riser joint's flange (figure 6.14).

There are also the shock-absorbing spiders that are used to reduce the impact loads on riser-support shoulders; and the gimbaling spiders that reduce bending moments on the shoulder.



Figure 6. 14 Riser spiders (Cameron, 2016)

Guidelines: When used, guidelines direct the riser and associated subsea equipment to their matching connections near the seafloor. Generally, four wire rope guidelines, forming the corners of a square, extend up from the temporary guidebase to the floating drilling vessel where each is tensioned by a guideline tensioner. Typically, the guideline attachment points are 6ft from the centre of the wellbore forming a square measuring 8,5ft on a side (NS-EN ISO 13624-1:2009, 2009).

6.2.8 Lower Marine Riser Package (LMRP)

The Lower Marine Riser Package (LMRP) provides interface between the riser and the BOP stack and also allows the disconnection between them in case of an emergency. In addition, it provides hydraulic control of BOP stack functions through the control pods. The package comprises a riser adapter; a flex or ball joint; an annular BOP; BOP control pods; a hydraulic connector; flexible choke and kill lines; and choke and kill stabs (figure 6.15)

The selection of the LMRP components are based on well-control considerations; BOP pressure rating and bore; guideline or guidelineless operations; overall height and weight limitations; operating environment and design loads; method of BOP control and operational fail-safe design features; operational water depth; method for running/retrieving control pods; methods for re-entry on guidelineless systems (if any); methods for emergency recovery.

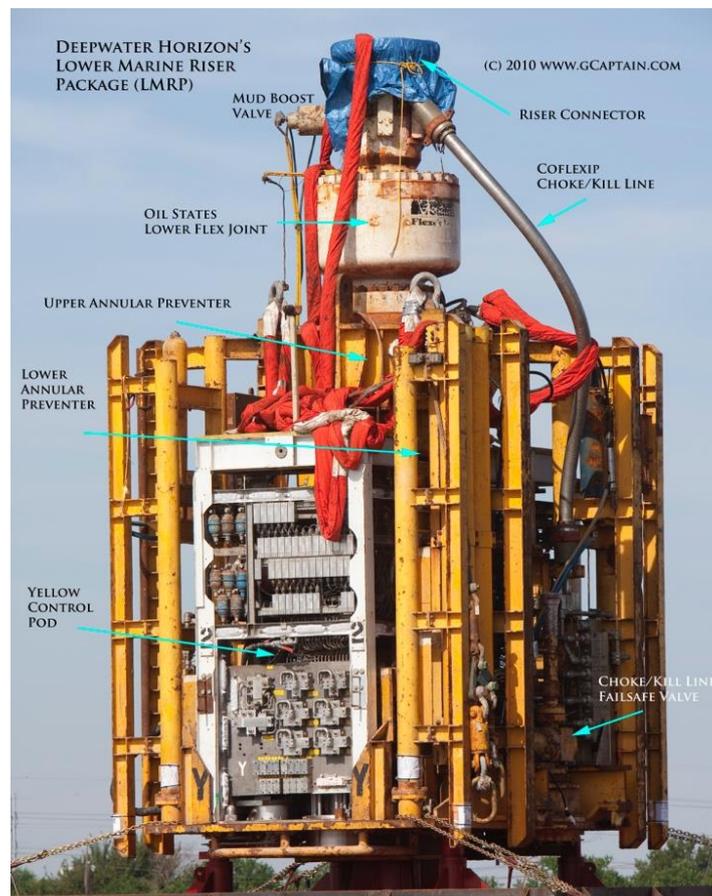


Figure 6. 15 Lower Marine Riser Package (LMRP)

6.2.9 Buoyancy equipment

Buoyancy equipment may be attached to riser joint to reduce the tension between the riser and the rig, the top tension, by decreasing the submerged weight of riser joints. It is even more useful for deepwater exploration as weight increases with water depth. Some benefits of using the buoyancy equipment are to reduce deck weight, increase rig operating depth and rig operating window in high current conditions.

The typical designs are foam modules and open-bottom air chambers:

Foam modules: Syntactic foam is typically a composite material of tiny glass microspheres in a matrix of thermo-setting plastic resin, often with larger microspheres of glass-fibre-reinforced plastic. In simpler words, it is a “plastic foam” that is hardened by heat and is full of small and round air bubbles that are encased in a hard shell.

The diameter of syntactic-foam modules depends primarily on the buoyancy requirements and the foam density. Depending on the design water depth, the foam density requirement changes: deeper water depths, denser materials are used to withstand higher collapse pressures. Also, the design should be such that they do not limit the bending of the riser tube and can be safely handled and stored.

The installation procedure is typically done in pairs of foam modules around the riser joint and with cut-outs to accommodate the auxiliary lines (figure 6.16). When installed correctly, buoyancy riser modules can reduce the effective weight of the riser string in water by 90% of its weight in air.



Figure 6. 16 Buoyancy equipment - foam modules (Trelleborg, 2016)

Open-bottom air chamber: Open-bottom air cans are typically attached to the riser coupling and provide an annular space around the riser. Air-injection and pilot lines provide the means to inject air at ambient hydrostatic pressure. Air displace seawater from the annular space to provide buoyancy and the water level is maintained at the preset level by a float valve in the injection line near the bottom of the chamber. Valves can be arranged and adjusted to provide the desired buoyancy level so that way, air can be removed from the system through a discharge valve actuated by the pilot line or dispose into the system supplied from compressors aboard the drilling vessel through the injection line.

Open-bottom air cans are relatively resistant to handling damage, but they can increase bending stresses at the riser coupling because of the added resistance of the air cans. (NS-EN ISO 13624-1:2009, 2009)

6.2.10 Specialty equipment

6.2.10.1 MUX lines

Every component in the subsea BOP assemble is hydraulic operated and a control system is used to operate them. Subsea control systems are indirect pilot-operated systems and can be either straight hydraulic type or multiplex type. As deeper the operation is, longer it takes for the pilot signal to travel through the pilot hose and then more time is needed to operate the BOP components. To compensate this delays, the multiplex electronic control (MUX) systems are used. The MUX reduce the signal time and therefore, the response from the BOP. Two subsea electronic MUX cables are deployed, connecting topside to the hydraulic control pods, one yellow and one blue.

Surface electronics transmit electronic command signal through the cable reels to the subsea electronic packages, which decode and deliver the commands to solenoid valves mounted in the subsea control pod. The solenoids are supplied with pressure from the hydraulic system. When energized, the solenoids deliver the pilot pressure to the

hydraulic control pod's SPM⁵ valves and regulators. The distance that the signal travels is shorter than using the straight hydraulic system, providing then a very quick signal.

Normally, two conduit lines are installed: one for the yellow pod supply and the other for the blue pod supply. At the surface, the operator selects them by means of conduit select valves.

6.2.10.2 Latch (pin connector)

Under some conditions, it is advantageous to have the riser deployed while drilling the top hole (24in or 26in). In that event, a 30in latch is used to connect the marine riser to the 30in conductor housing. The latch is normally controlled by a dedicated hydraulic hose bundle run from the surface diverter/BOP control system. It is usually fitted with a flex/ball joint and a riser adapter (NS-EN ISO 13624-1:2009, 2009).

6.2.10.3 Riser hang-off system

When environmental conditions exceed the limits for safe operations with the riser connected such as the case for this thesis, under Arctic conditions, the riser and LMRP may be disconnected from the BOP stack and hung-off until the weather conditions improve. The disconnected riser may be hung off from the hook, the spider, the diverter housing or specially designed beam structure and this operation is called hard hang-off method.

The soft hang-off method may be used to hang-off the riser from the tensioners and/or the motion compensator.

The dynamic loads of the riser (see chapter 7) should be considered to ensure that the system equipment provide the sufficient strength to support the axial and transverse loads transmitted by the suspended riser without damaging it or the vessel (NS-EN ISO 13624-1:2009, 2009).

⁵ The SPM valve is three-way, two-position directional control valve operated by a hydraulic pilot signal.

6.3 Blowout Preventer

The blowout preventer (BOP) stack is used to provide pressure control to the wells. In the event of the primary barrier failure (mud column), an influx takes place during drilling, one or more BOPs are activated to seal off the annulus, or wellbore, in order to stop the flow of fluids out of the wellbore (“shut-in” the well). The next step is to circulate denser mud into the wellbore, pumping it down the drill string, up the annulus and out through the choke line. When the well pressure is stabilized, the normal operations can restart. A typical stack arrangement, as shown in figure 6.17, has up to six ram preventers in the lower part, and the annular preventers in the LMRP (figure 6.15).

The ram preventers have the purpose to close around the drill pipe or on open hole to seal the hole. It can be pipe ram preventers that seals the annulus between the drill pipe and the wellbore below; blind ram preventers that close in the top of the open hole what are not normally installed in a subsea stack, however, blind-shear rams are installed and beside this characteristic, it can cut the drill pipe and form a seal to shut in the well. Also there are the casing-shear ram preventers that can be used in a BOP stack in addition to the blind-shear rams. The annular preventers are used to close and seal the wellbore and, at the same time, allow the drill stem to be moved through the closed preventer.

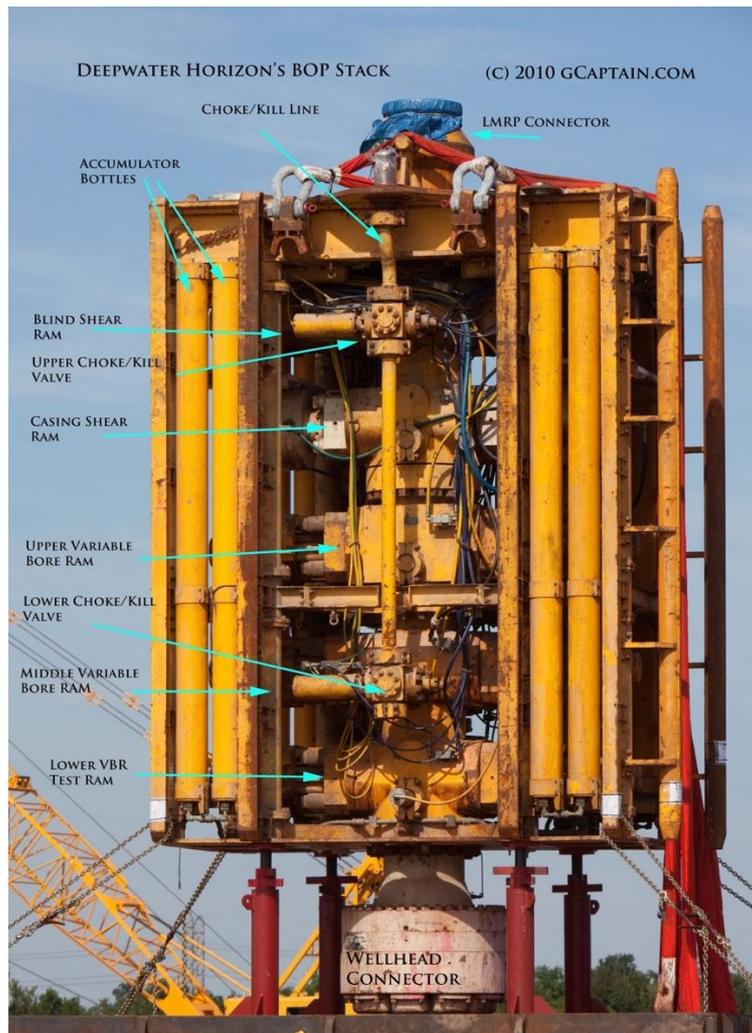


Figure 6. 17 BOP stack arrangement (gCaptain, 2010)

The configuration of the stack preventers is chosen so that to provide maximum pressure integrity, safety and flexibility in case of an emergency. Typically, emergency modes of the BOP system are:

- Blind-shear rams: the function (already mentioned above) is manually initiated by the rig crew and requires at least one operational control pod associated multiplex cable;
- Emergency disconnect sequence: Reduce the risk of losing containment due to a failure in the station keeping system, requiring the rig to move off the well site. The first step is to initiate the blind-shear ram and then the disconnection sequence where the LMRP is disconnected from the lower BOP stack. Hydraulic power is provided by accumulators on the BOP stack. The emergency disconnect sequence is initiated by the rig crew. It requires at least one operational control pod and associated MUX cable;

- Automatic mode function: If hydraulic, electrical power and communication with the BOP is lost, the emergency disconnect sequence is initiated automatically. This operation requires at least one operational control pod.

7 Loadings on the riser system and the weakness points

The riser system is exposed to pressure, tension and weight variations along its extension from the MODU to the seafloor. Its ability to resist environmental loadings and keep its structural stability is derived from the applied tensions. Based on the response to the environmental and hydrostatic loads, which may have impact on buckling and failure, the riser is designed and the top tension is selected. The following topics describe the loads associated to the tension calculations.

The Archimedes' Law is the basic principle to understand those calculations. Some important points of this law must be considered such as its application only to pressure fields that are completely closed; the possibility of resultant moment when combining the closed pressure field with the distributed weight of the displaced fluid; and that it must be applied for the whole submerged body, not only parts of it.

7.1 Static loadings

7.1.1 Internal forces in a submerged body

In a submerged body, the problem is to take into considerations the pressure field that is not closed. In order to apply the Archimedes' Law, it is necessary to add the missing pressure to close the pressure field. This extra part gives the system a force " $p_e A_e$ " that must be deducted from the forces on the original body segment. Figure 7.1 shows part of a submerged body with the forces acting on it (Sparks, 2004).

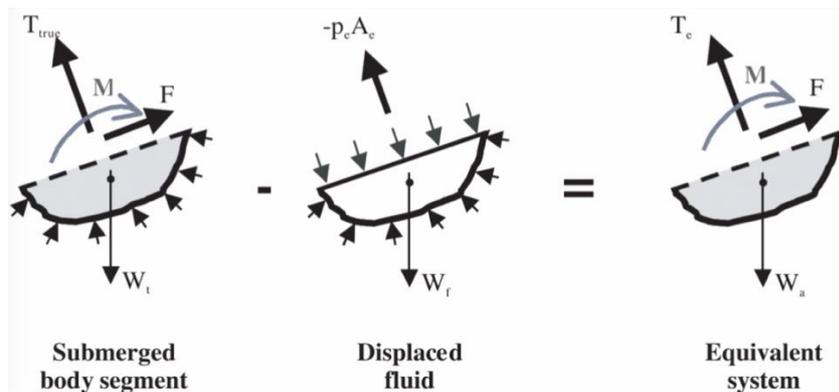


Figure 7. 1 Internal forces acting on segment body (Sparks, 2004)

The sketch in the middle shows the forces acting on the displacement fluid segment in a closed pressure field. Subtracting those forces from the ones on the body segment, the pressure field acting below the body is eliminated. Though, the “ $p_e A_e$ ” force (where p_e is the pressure in the fluid and A_e is the cross-section area of the section) linked to the pressure acting on the section, remains there.

The sketch on the right shows the equivalent system after the superposition application with acting forces and moment in equilibrium with the apparent weight W_a . The other force showed, the effective tension T_e , is the result of the sum of the true tension T_{true} and the additional force $p_e A_e$ (equation 7.1). The effective tension has a great importance in riser’s system because it is responsible to control the stability of the risers and must be always positive. The shear force “F” and the moment “M” are the same as in the body segment.

$$T_e = T_{true} - (-p_e A_e) = T_{true} + p_e A_e \quad (7.1)$$

The apparent weight (equation 7.2) can be defined as the difference between the weight of the submerged body W_t and the weight of the displaced fluid W_f :

$$W_a = W_t - W_f \quad (7.2)$$

Now, the object of study is not a random segment anymore, but a curved riser under the influence of its apparent weight, top tension, internal fluid column, and true tension.

The closed pressure field acting on the inside fluid column is in equilibrium with the internal fluid weight. The pressures acting around the riser wall has the same module but opposite direction than those in the internal part as the requisite for the system to stay in equilibrium. Using the same superposition logic than before but omitting the shear force and moment, the lateral pressures are eliminated in the final situation. However, the axial force $p_i A_i$ in the fluid column still remains (where p_i is the internal pressure and A_i is internal cross-section of the pipe). Thus, the relations for the effective tension and apparent weight of the equivalent system are (equations 7.3 and 7.4):

$$T_e = T_{true} + (-p_i A_i) \quad (7.3)$$

$$W_a = W_t - W_i \quad (7.4)$$

When considering the external and internal pressures together in the system, the same method can be used. This was, the pressures in the wall can be excluded when the forces of the internal fluid are added to the pipe segment system and then the external fluid forces are subtracted from the system (figure 7.2). Thus, the resulted effective tension and apparent weight are (equations 7.5 and 7.6):

$$T_e = T_{true} + (-p_i A_i) - (-p_e A_e) \quad (7.5)$$

$$W_a = W_t - W_i - W_e \quad (7.6)$$

Where:

W_a : apparent weight;

W_t : weight of the curved riser;

W_i : weight of the internal fluid;

W_e : weight of the displaced fluid column

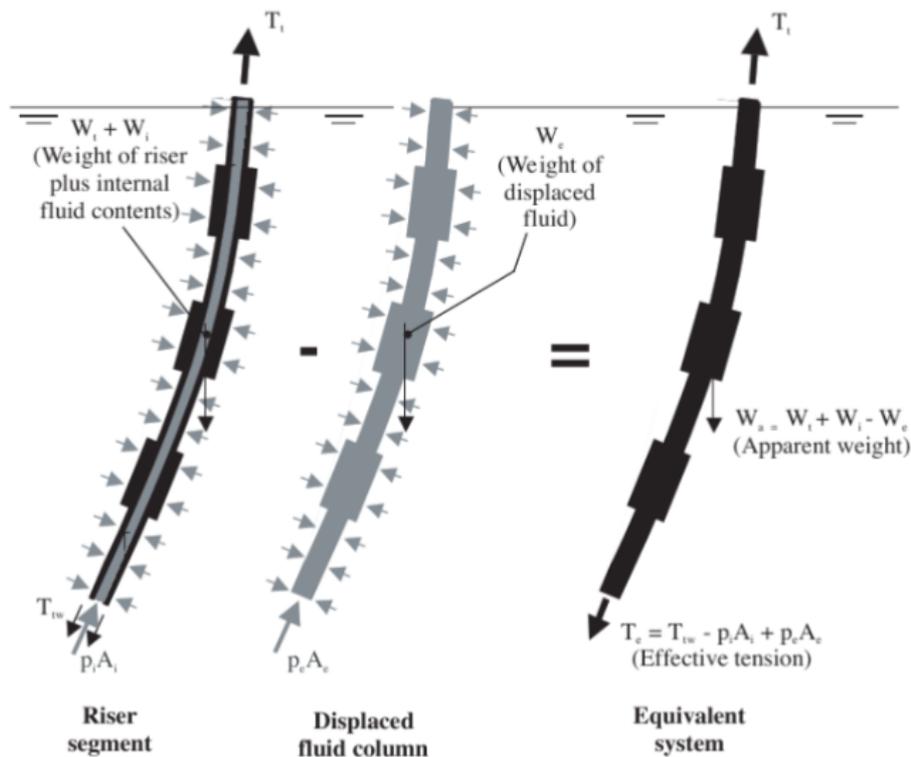


Figure 7. 2 Forces and pressures acting along the riser system (Sparks, 2004)

From this analyses, it is possible to conclude that the effective tension is independent of pressure and dependant only of the top tension and apparent weight. However, the true wall tension varies with pressure.

7.1.2 Stresses in Risers

To prevent structural deformation that can lead to failure, the stress analysis is required. This analysis is performed by ensuring that the riser is strong enough to support the maximum design loads while keeping the maximum stresses below the allowable stress. Nowadays, the most accurate and practical criterion for ductile materials is the Von-Mises stress failure criterion (equation 7.7), which is based on the maximum distortion energy criteria. This method combines the three major stresses (axial, radial, and hoop stress) (figure 7.3) and the shear stress induced by an applied moment. However, if there is no torque in the system, the shear stress can be omitted.

$$\sigma_{vm}^2 = \left\{ \frac{1}{2} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] + 3\tau^2 \right\} \quad (7.7)$$

Where:

- σ_{vm} : Von-Mises stress
- σ_1 : axial plus/minus bending stress⁶
- σ_2 : hoop stress
- σ_3 : radial stress
- τ : shear stress

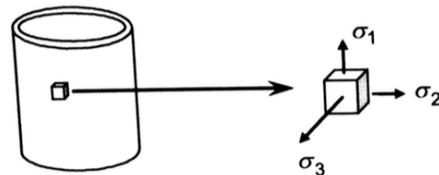


Figure 7. 3 Three major stresses

According to API 16Q and ISO 13624, there are two allowable stress criteria to be taken into consideration during design. One is generally applied for most water depth locations and says that the allowable stress during drilling mode is 40% of the minimum yield strength⁷ of the material. While the other one is mostly applied for deepwater locations and has an allowable stress of 67% of the minimum yield point.

7.1.3 Radial, Hoop and Axial stresses

In order to perform those stresses analysis and calculations, the pipe section, shown in Figure 7.4, is going to be used. It is pressurized with internal pressure P_i and with external

⁶ The riser will be in reality subjected to moments that causes the bending stress. The criterion is required to be verified at the outer surface with the maximum bending stress and at the inner surface, where the bending occurs at its minimum.

⁷ Yield strength is the point, if exceeded, deformations on the material start to be permanent and can cause failure in the system.

pressure P_e . The inner radius of the pipe is r_i , the external radius, r_e and the wall thickness is the difference between them ($r_e - r_i$) (to be considered as a thick wall cylinder, this difference must be $> 0,1r_e$). The infinitesimal cube scheme is the same showed in figure 7.3 with the three major stresses.

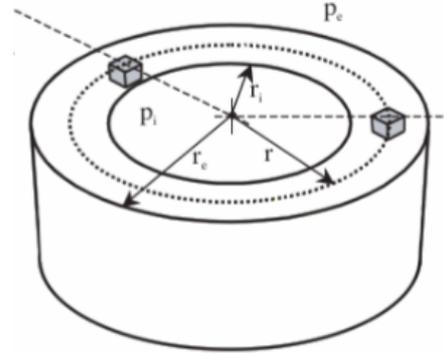


Figure 7. 4 Pipe section (Sparks, 2004)

Also, some conditions have to be considered in order to obtain the solution for those stresses distribution over the segment. Those are: the Newton Law about equilibrium, compatibility relations (geometrical relationship), constitutive relation of the stress-strain-temperature (Hooke's Law) and also suitable boundary conditions. To define the main stresses in a thick-walled cylindrical tube, the Lamé equations (equations 7.8, 7.9 and 7.10) are used:

- **Radial stress:**

$$\sigma_3 = \frac{p_i \times A_i^2 - p_e \times A_e^2}{A_e^2 - A_i^2} - \frac{A_i^2 \times A_e^2}{[(A_e^2 - A_i^2) \times r_i^2]} \times (p_i - p_e) \quad (7.8)$$

- **Hoop stress:**

$$\sigma_2 = \frac{p_i \times A_i^2 - p_e \times A_e^2}{A_e^2 - A_i^2} + \frac{A_i^2 \times A_e^2}{[(A_e^2 - A_i^2) \times r_i^2]} \times (p_i - p_e) \quad (7.9)$$

- **Axial stress:** applying an axial force F_a to the pipe (tension or compression), an axial stress appears.

$$\sigma_1 = \frac{F_a}{A} + \frac{p_i \times A_i^2 - p_e \times A_e^2}{A_e^2 - A_i^2} \quad (7.10)$$

Where:

p_i : internal pressure in the cylinder

p_e : external pressure in the cylinder

A_i : internal cross-sectional area of the cylinder

A_e : external cross-sectional are of the cylinder

r_i : inner radius of the cylinder

F_a : applied axial load

7.1.4 Shear stress

In a situation of a thin wall cylinder with applied torque, the induced shear stress can be approximated as (equation 7.11):

$$\tau = \frac{T}{[2\pi \times r_i^2 \times (r_e - r_i)]} \quad (7.11)$$

Where:

T: applied torque

r_e : external radius of the cylinder

r_i : internal radius of the cylinder (Aadnoy, 2006)

7.1.5 Bending stress

As the wells are drilled to increasingly longer reach at high inclination, buckling problems have become more important. If put into compression, for example, a tubular can easily be buckled and consequently will not be able to keep it installed at the desired location. The riser buckling can generate the bending stress and due to the curved shape, an external bending moment is in equilibrium with and internal strain moment. To illustrate and derive the expression for the bending stress (equation 7.12), a beam is going to be used (figure 7.5). The maximum stress occurs at the external part of the curved beam while the minimum stress in the internal part.

The bending stress can be expressed as:

$$\sigma_b = \frac{M}{I} y \quad (7.12)$$

Where:

I: inertia moment of the sectional area

y: distance from the considered point to the neutral surface

M: the bending moment

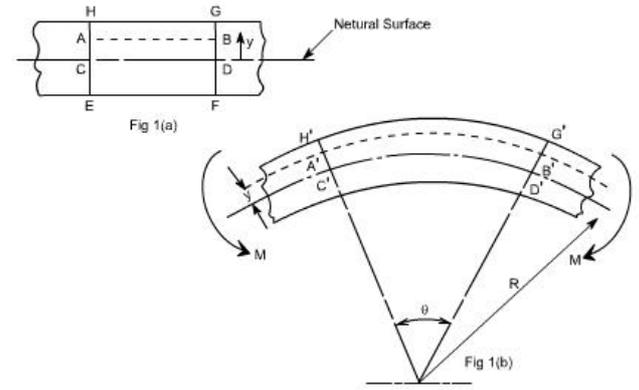


Figure 7.5 Beam illustrating the bending stress

7.1.6 Minimum top tension

The top tension was briefly mentioned before in section 6.2. However, as it is the minimum tension required to ensure the stability of the riser, it deserves a special chapter. The tension setting should be sufficiently high to keep the effective tension always positive in all parts of the riser and to prevent riser buckling in the event of a tensioner unit failure. For normal operations, the top tension is maintained at a safe level above the API recommended minimum tension to allow for variations in tension that can otherwise allow the riser tension to fail below the minimum top tension (equation 7.13). It can be expressed as (NS-EN ISO 13624-1:2009, 2009):

$$T_{min} = T_{Sr\ min} \times \frac{N}{[R_f(N-n)]} \quad (7.13)$$

Where:

N: number of tensioners supporting the riser;

n: number of tensioners subject to sudden failure;

R_f : reduction factor, relating vertical tension at the slip ring to tensioner setting to account for fleet and mechanical efficiency;

$T_{Sr\ min}$: minimum tension for the tensioner ring;

$$T_{Sr\ min} = W_s f_{wt} - B_n f_{bt} + A_i [\rho_m H_m - \rho_w H_w] \quad (7.14)$$

Where:

W_s : submerged riser weight above the point of consideration;

f_{wt} : submerged weight tolerance factor;

B_n : the net lift of buoyancy material above the point of consideration;

f_{bt} : buoyancy loss and tolerance factor;

A_i : internal cross-sectional area of the riser (including auxiliary lines);

ρ_m : drilling fluid density;

ρ_w : seawater density;

H_m : Height of the drilling fluid columns to the point of consideration;

H_w : Height of the seawater column to the point of consideration.

Expanding the term of the submerged riser weight, it is easier to see the effect of buoyancy in the system:

$$W_s = W_{sd} - (A_o - A_i)\rho_w H_w \quad (7.15)$$

If W_{sd} is the dry steel weight and A_o , the external cross sectional area, it is clear that the buoyancy is represented by the term: $-(A_o - A_i)\rho_w H_w$ (attention for the minus before it) contributing to reduce the weight of the riser when submerged. This element has extremely importance to reduce the required top tension as can be seen below with the expanded terms included (equation 7.16):

$$T_{Sr \min} = [W_{sd} - (A_o - A_i)\rho_w H_w]f_{wt} - B_n f_{bt} + A_i[\rho_m H_m - \rho_w H_w]$$

$$T_{Sr \min} = [W_{sd} - A_o \rho_w H_w + A_i \rho_w H_w]f_{wt} - B_n f_{bt} + A_i \rho_m H_m - A_i \rho_w H_w$$

To simplify, the correction factors can be removed:

$$T_{Sr \min} = W_{sd} + A_i \rho_m H_m - A_o \rho_w H_w \quad (7.16)$$

Showing that the minimum top tension to avoid buckling at a certain point is the dry weight of the pipe plus the weight of the internal fluid minus the weight of the external fluid displaced by the pipe, all of it above the considered point.

Also, the design analysis includes the recommended settings according to the drilling fluid weight. The minimum riser tension increases as fluid weight in the riser is increased. This occurs because the tensioners must support the additional weight of the drilling fluid

applied on the system. Riser-tension operating envelopes provide the basis for riser-tension increases as drilling progresses and drilling fluid weight is increased (ISO 13624, 2009).

A numerical example is given below for a better idea of the concepts listed above:

The usual outside diameter (OD) for a riser is 21 inch and this value will be considered for this example. For the internal diameter (ID), 20 inch. As most part of the Arctic seas are located in shallow water depths, the height of seawater column of the point in consideration will be 500meters. And height of mud column of this point, 520 meters. For those calculations, the dry steel weight is needed; so we can assume 26,7 kN (6000 lb). With those information, it is already possible to calculate the minimum tension for the tensioner ring:

(Ps: Convert kN to kg! 1kN = 101,97kg)

$$T_{Sr\ min} = W_{sd} + A_i\rho_m H_m - A_o\rho_w H_w$$

$$T_{Sr\ min} = 26,7 \times 101,9 + 0,2078 \times 1300 \times 520 - 0,2234 \times 1025 \times 500$$

$$T_{Sr\ min} \approx 28701\ \text{kg}$$

To calculate the minimum top tension required, the number of tensioners supporting the riser and the number of those sudden to failure are needed. Let's consider 10 tensioners supporting the riser and unforeseen 2 of them to failure. Also, the reduction factor for the vertical tension at the slip-ring tensioner setting during drilling that is 0,95.

$$T_{min} = T_{Sr\ min} \times \frac{N}{[R_f(N - n)]}$$

$$T_{min} = 28701 \times \frac{10}{[0,95(10 - 2)]}$$

$$T_{min} = 37\ 764,5\ \text{kg}$$

7.2 Dynamic loadings

Since the sea is not static, it is important to study the impact of this motion on the submerged bodies.

7.2.1 Currents

Firstly, a situation of submerged cylinder into water with no waves, but currents with constant velocity, c_0 is considered. The figure 7.6 shows firstly an almost symmetric current on both sides of the body. Then, eddy currents start to form after the body due to friction between the cylinder and the flow. After this, the third picture shows the moment when the eddy currents get so large that they leave the cylinder. At this point, parallel and perpendicular forces are acting on the body (Gudmestad, 2015).

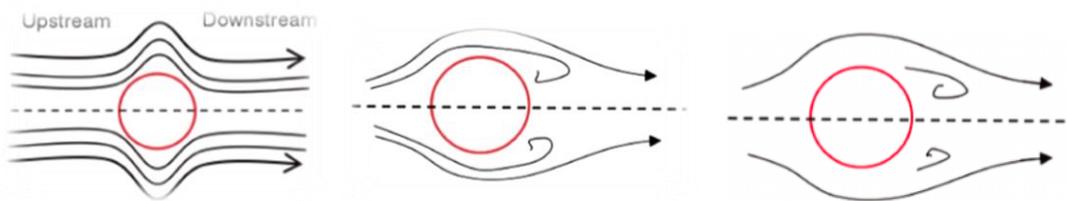


Figure 7. 6 Currents in a submerged cylinder

Certain conditions will create large vibrations, due to the induced vortex induced vibration⁸ (VIV) of the cylinder. The resulting forces along the flow are called drag forces, f_D (eq. 7.17), and the perpendicular ones are called lift forces, f_L (eq. 7.18). Those forces are caused by friction between the fluid and the cylinder, causing eddy currents; difference in pressure between the side before the cylinder (upstream) and the side after the cylinder (downstream); and when water flow back into a stagnation point behind the cylinder.

$$f_D = \frac{1}{2} \rho C_D D u^2 \quad (7.17)$$

and

$$f_L = \frac{1}{2} \rho C_L D u^2 \quad (7.18)$$

⁸ The VIV are motions caused anytime on a abrupt body, which is subjected to an external flow of fluid producing vortices around this body at its natural frequency.

Where:

ρ : density of the water

u : water particle velocity

C_D : drag coefficient (function of Reynolds number, Re , for the flow and the roughness, k , for the cylinder surface)

C_L : lifting coefficient ~ 0.3

D : diameter of the cylinder

For currents in the ocean, "u" usually ranges from 1-10m/s and the $Re \sim 10^6$ - 10^7 . Figure 7.7 illustrates how Re and C_D are connected.

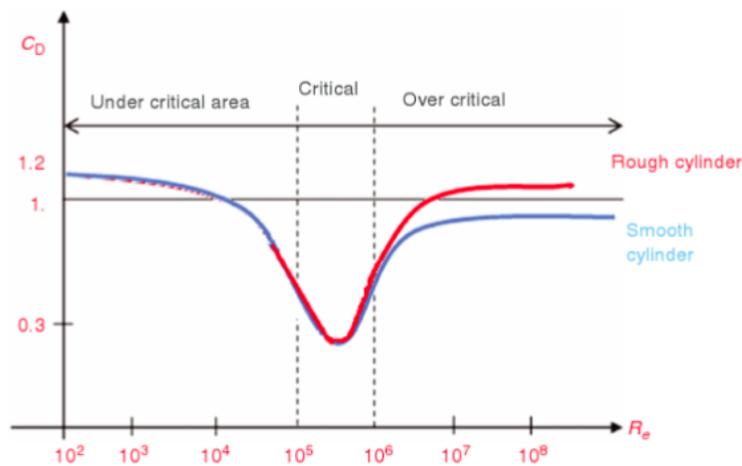


Figure 7. 7 Relation between C_D and Re

Now, a new situation is presented: a cylinder submerged in a water with no waves but currents with constant acceleration. The pressure against the surface of the cylinder results in a force that is sufficient to provide the mass acceleration. This force is called Froude Krylov (equation 7.19) and can be expressed as:

$$f_{FK} = \left(\frac{\rho\pi D^2}{4}\right)\dot{u} \quad (7.19)$$

Where:

$\frac{\rho\pi D^2}{4}$: mass of a unit length of the cylinder

\dot{u} : acceleration

If the relation between the diameter of the cylinder and the length of the wave (D/L) is smaller than 0,2, the fluid near the cylinder will be dragged along the flow. When adding

an accelerated mass to the system, the total mass force acting on the cylinder is (equation 7.20):

$$f_M = f_{FK} C_M \quad (7.20)$$

Where:

$$C_M: \frac{1+m_A}{m} \text{ (mass coefficient)}$$

m_A : additional mass

When C_M remains constant over time ($C_M \sim 2$), the mass force is also called inertia force.

7.2.2 Waves

In case of waves, a combination of velocities and accelerations from the water particles actuate on the cylinder body. Morison's equation shows that the force the body suffers in case of $D/L < 0,2$ is the sum of the mass force and the drag force. However, the force actuating in the entire body must be the integral of this force between the point of analysis until the surface (equation 7.21 and figure 7.8) (Gudmestad, 2015):

$$F(t) = \int_{-d}^{surface} f(z, t) dz = \int_{-d}^{\xi} f_M(z, t) dz + \int_{-d}^{\xi} f_D(z, t) dz \quad (7.21)$$

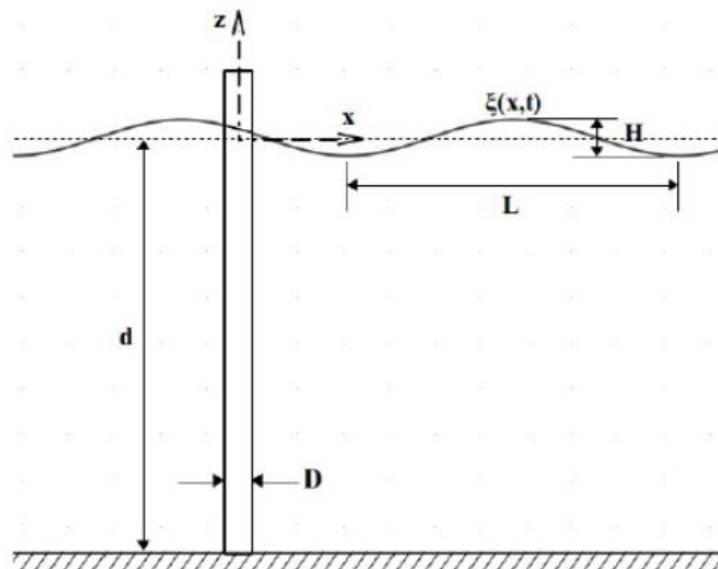


Figure 7. 8 Submerged cylinder under wave action

Different from the currents, there is usually no sufficient time for eddies to form in the case of waves. So, the drag force is something questionable in the equation. However, if many vortices are created for each half-wave period, the drag force will be important. Otherwise, the situation is similar than with current in a constant acceleration.

7.2.3 Vessel motions

The action of winds, currents and waves generates horizontal and vertical forces to the vessels. The action of waves generate motion in six degrees of freedom (DOF). Those six DOF include three translational (heave, surge, and sway) and three rotational motions (roll, yaw, and pitch) (figure 7.9).

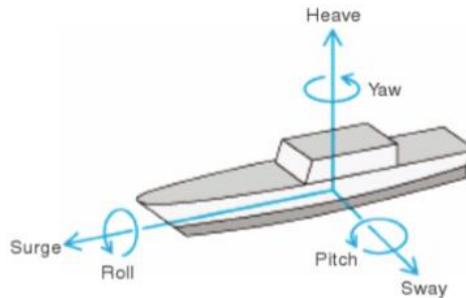


Figure 7. 9 Six degrees of freedom in a vessel

Those loads generate forces and stresses in systems and equipment such as the anchor system and the marine riser structure. For the loads on the marine riser, the Morison force equation (eq. 7.22) can also be used:

$$F_{unit\ length} = \rho C_M \nabla \dot{u}_w + \frac{1}{2} \rho C_D A |u_w + u_c| (u_w + u_c) \quad (7.22)$$

Where:

ρ : density of the water

C_M : mass coefficient

C_D : drag coefficient

u_w : wave velocity

u_c : current velocity

$\nabla \dot{u}_w$: gradient of wave acceleration

7.2.4 Dynamic forces in the riser system due to the vessel motion

As described in the previous sections, the vessels are exposed to the currents, waves and wind influence. Those effects when combined to the dynamic position system (DP) response, provide motion to the vessel affecting the drilling riser system (figure 7.10).

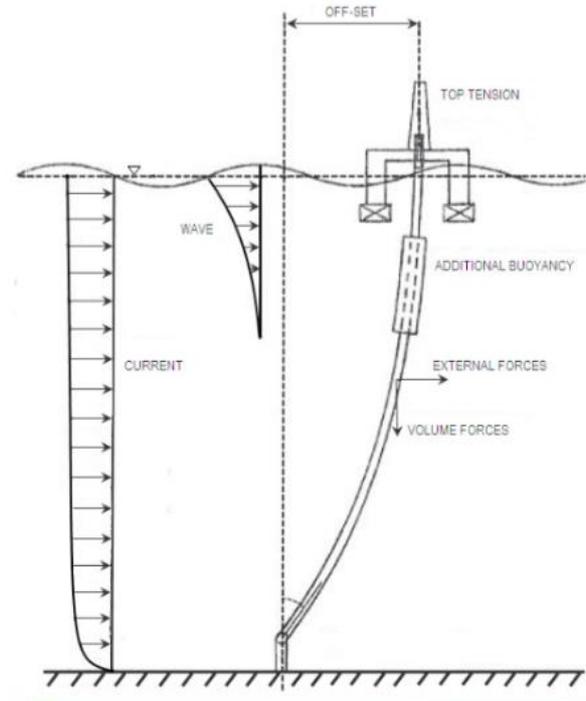


Figure 7. 10 Loadings on riser system (LARSEN, C. M., 2008)

The vessel vertical motion due to wave effects will create a tension variation on the riser. The tension itself varies along the depth for the marine riser, so when this system contains a lot of buoyancy elements, the tension applied on the top of the riser will be close to the tension on the end, above the LMRP. However, if the riser consists of joints without buoyancy and contains heavy mud, a higher top tension is required to carry the weight of the riser and give enough tension at the LMRP connector (Grønevik, 2013).

To avoid large bending moments on the riser due to the vertical motion, a tensioner system (as described in section 6.2.1) must be used. The top tension helps to increase lateral stiffness and the riser experience less displacements when exposed to lateral forces, as the action of currents. The stiffness increases because the lateral components of the tension counteract the lateral forces the riser is subject to. To illustrate this, a comparison between the riser and a slender beam is presented in figure 7.11.

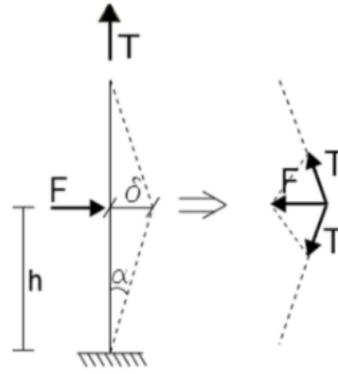


Figure 7. 11 Tension effect on a slender beam (LARSEN, C. M., 2008)

Where F is the resulting lateral force, T is the top tension and α is the deflection angle

So F can be expressed as,

$$F = 2T \sin \alpha \quad (7.23)$$

if α is sufficiently small,

$$F \approx 2T \alpha \quad \text{and} \quad \alpha = \frac{\delta}{h} \quad (7.24)$$

7.2.5 Structural dynamic of the riser

For this analysis, the comparison between the riser and a vertical beam will still be valid. In this case, a cantilever beam on the top and fixed on the bottom will be considered. The movement on the upper part of the riser (beam) will be given due to the vessel motion, as introduced in the two previous sections. An important consideration for this is that the angle (α) will not exceed 10 degrees from the vertical direction. The Bernoulli-Euler equation rightly describe the behaviour of the riser in the transversal direction, in other words, the movement the system is submitted when exposed to currents. The application of this equation for a beam is better detailed by YOUNG and FOWLER, and the resultant equation is (R.D. YOUNG; J.R. FOWLER, 1978):

$$f_y = M\ddot{y} + EIy'''' - \frac{dT_{ef}}{dx}y' - T_e y'' \quad (7.25)$$

Where:

f_y : loading over the transversal axis of the riser

M: riser mass, including additional hydrodynamic mass and internal fluid

x: riser axial axis

y: riser transversal axis

$$\ddot{y}: \frac{d^2 y}{dt^2}$$

$$y': \frac{dy}{dx}$$

$$y'': \frac{d^2 y}{dx^2}$$

$$y''''': \frac{d^4 y}{dx^4}$$

E: steel elasticity modulus

I: inertia momentum of the transversal section of the riser

T_e : riser effective tension

The equation shows that y'' when applied to the riser analysis is the effective tension suffered on the top of the structure.

For the axial analysis, the longitudinal motion of the riser due to the waves influence, can be described as (AZPIAZU & NGUYEN, 1984):

$$f_x = -M\ddot{u} + (EAu')' - C(\dot{u})$$

Where:

f_x : loading over the axial axis of the riser

M: riser mass, including additional hydrodynamic mass and internal fluid

x: riser axial axis

u: riser shift range in the axial axis

E: steel elasticity modulus

A: riser transversal section area

$$\dot{u}: \frac{du}{dt}$$

$$\ddot{u}: \frac{d^2 u}{dt^2}$$

$$u': \frac{du}{dx}$$

C: function that returns the damping force to the system in function of \dot{u} .

The boundary conditions for the lower part of the riser is equal to zero as it is considered a simply supporter. The boundary conditions for the upper part consider the movement

absorbers and clamps between the riser and the vessel (those systems are detailed in chapter 6), so the sum of the applied forces by the tensioner system is:

$$\sum k_c(u_o - h) + \sum C_c(\dot{u}_o - \dot{h}) - \dot{E}Au'_o = 0$$

Where:

k_c : tensioners stiffness

C_c : tensioners damping

u_o : riser shift range in the connection point with the tensioners

h : vertical motion of the vessel where the tensioners are installed

$$\dot{u}_o: \frac{du_o}{dt}$$

$$\dot{h}: \frac{dh}{dt}$$

$$u'_o: \frac{\partial u_o}{\partial x}$$

The first term represents the stiffness of the tensioner system; the second, the tensioner system damping and the third term represents the elastic force on the top of the riser in static conditions, the applied top tension.

Those equations define a general response of the drilling riser. However, it is not possible to obtain the precise solution for the riser-vessel system due to the non-linearity of the involved functions. For that, the use of a software is needed.

7.3 Weak points analysis

The weak points are the most probable points of failure in the riser/wellhead system. A selection of casing and wellhead equipment is necessary to ensure the wellbore containment.

Based on the probability of occurrence of certain environmental event, the analysis of the forces required to transmit the necessary load for failure can be done. Moreover, this analysis is also used to define the potential weak points and the procedures to prevent the failure.

A sequence of events must happen in order to the wellbore containment be a concern.

There are:

- Failure in dynamic position or mooring system;
- Failure of emergency disconnect system;
- Environmental conditions severe enough to overcome the restoring force from the riser and thus allow sufficient offset of the vessel to impose the loads to end in a failure;
- Operations in a critical stage that the riser disconnection implies significant environmental damage.

There is one type of analysis, often static, that is related to an elastic analysis and predicts the first component to reach its yield limit. However, the first component that reaches the yield limit is not necessarily the first to fail; it can, for example, deform and relieve some loads while others are increasing. Typically, the first components that reach the yield limit are the telescopic joint immediately below the tensioner ring and the structural casing followed by the tensioners bottom out. If dynamic, this analysis allows coupling of the rig to the riser, includes environmental forces and take into consideration the inertia in the system.

Another type of analysis that can be taken is the plastic analysis using actual material properties. This type regards for reduction in loads due to yielding and allows analysis of the components using their actual yield and maximum strengths.

These types of analysis do not include separation of components but can predict some failure events as a result from environmental loads and, therefore, dynamic impacts on the system.

8 Solution proposal for operations in the Arctic sea

Materials for fixed and floating structures in Arctic environment must be designed for low ambient temperature. So, to conclude this project, some proposals will be given in this chapter in order to improve the oil & gas exploration in the Arctic regarding safe work conditions both for equipment and crew.

8.1 Operating under Arctic conditions

The materials strength, ductility and durability resistance are challenged. Structural steels and steel for piping and pressure vessels for operating temperatures down to -60°C are being tested.

The selection of materials for advanced heating, ventilation and air conditioning (HVAC) systems need to be developed for systems operating in Arctic environment where conditions as sea spray, ice accretion and snow can be hazardous. Some strategies to cope with those issues are winterization as the construction shelter for process equipment and side walls to reduce sea spray; and electrical heat tracing (EHT) of critical components (Hauge, 2012)

The operations under those conditions should be really cautious because even the smallest ice pieces can cause severe damages for the structures. A moving ice sheet places can cause severe loadings on the drilling vessel and to the positioning system. The ice chunks can be so small in a way to do not be detected by radar, and those are particularly hazardous because it gets close to the vessel without detection and consequently, no extra precautions are taken.

A ship's hull tends to protect the riser from smaller, broken-up sheet ice. Though, it can be pushed under the vessel by stronger currents or wind. In the moonpool area, the concept of "ice-lip" that can be used as a border to deflect ice from entering this area.

When subject to very low air temperatures and sea ice effect, the riser operations can be compromised. Steel components exposed to temperatures below -20°C should be qualified for cold-temperatures applications. It means that before the operation stage, the steel used in the riser fabrication should be submitted to special processes such as the

thermo-mechanical controlled process (TMCP) and the Charpy V notch toughness, to satisfy appropriate requirements for those harsh conditions. Testing should be performed in accordance with ASTM A370 and ASTM E23. The operating range of elastomeric materials should also be consistent with cold weather operations.

Operation of a marine riser in sub-freezing temperatures can face to some problems, including:

- ice formation inside the exposed choke and kill lines, terminal fittings, hoses and surface piping;
- ice formation inside the control hoses for functions, such as energizing the telescopic joint packer;
- freezing of the telescopic joint packer lubricating fluid.

The problems can be avoided by:

- using ethylene glycol solutions for pressure testing, hydraulic control and lubrication;
- enclosing the moonpool and cellar deck space below the drill-floor with windwalls and sealable access doors, as permitted;
- introducing heated air into the enclosed spaces;
- allowing a small volume of drilling mud to flow past the telescopic joint packer (NS-EN ISO 13624-1:2009, 2009) .

8.2 Ice Management

As the Arctic areas has limited open water seasons, ice management programs are needed in order to extend the drilling seasons. The main aim of those programs is to minimise the load that sea ice and icebergs can inflict on installations, since DP and mooring systems are not capable of handling the great loads they can lay on the equipment (Pilisi, Maes, & Lewis, Deepwater drilling for Arctic Oil and Gas Resources Development: A conceptual study in the Beaufort Sea, 2011).

The different types of ice require different management measures, pack-ice needs to be broken into smaller pieces by icebreakers and large icebergs need to be towed away from collision course with the installation. Pack-ice management could be needed to extend drilling season in open-water areas or create drilling possibilities in areas that have year

round ice. In areas with year-round multi-year ice there is a limit on how thick and tough ice icebreakers are able to break up.

Iceberg management in open-waters involve at least two tugboats cooperating. The boats use synthetic lines between them to “catch” the iceberg and tow it off collision course with the installation. Some arctic areas may need both tugboats and icebreaker to manage mixed ice conditions. In the event of icebergs or multi-year ice big or thick enough that is not possible to be managed, the production or drilling operation needs to be postponed.

8.3 Winterization

Winterization measures must be considered to ensure the safe operation of all system and equipment, thereby ensuring the safety of personnel and operation. Such measures shall ensure the crew protection from the extreme conditions in a way to be able to conduct the required tasks (ISO 19906, 2010).

Winterization usually involves topside working areas sheltering, topside modules design to minimize environmental effects as ice accretion and wind of supply, hull compartments heating, insulation of riser, pipelines and flow lines to keep mud and other fluids flowing. Winterization also involve changing steel materials and coatings, since the cold environment makes different steels and alloys brittle and make them fail under much smaller loads than at non-arctic conditions (Bjoern, 2014).

8.4 Heat tracing

When leading with extreme low temperatures, special care and attention must be given on the control of temperature to provide work conditions for both crew onboard and equipment. One of the techniques for that is the heat tracing concept, providing heat for pipes, tanks and instrumentation onboard vessels. It is a freeze protection, temperature maintenance and way to prevent the accumulation of snow and ice by melting it. Exposed surfaces as stairs, handrails and walkways require protection in such harsh environment and heat tracing is a way to reduce unsafe conditions during operations (Brazil, Conachey, Gary Savage, & Baen, 2013).

The integrity and expected performance of rigs, equipment and systems operating under Arctic conditions depend upon a good control of the temperature guaranteeing a minimum operational value and safety for both workers and equipment. Also, the temperature control for production and utility fluids, ensuring the proper viscosity or preventing water from freezing, must be considered. An electric heat tracing (EHT) may be installed to compensate the heat losses and to maintain a minimum temperature. In the traditional layout of EHT circuits for piping, tanks, and instrumentation, the objectives are to achieve a low installation cost by maximizing EHT circuit lengths and minimizing conduit, wiring, electrical distribution, and costs (Brazil, Conachey, Gary Savage, & Baen, 2013). The different types of EHT are addressed in table 3

Electrical Heat Trace Type	Application	Advantages	Limitations
Self-regulating (self-limiting)	Winterization/Freeze Protection Process Temperature Maintenance (Maintain to 300F/149C)	Easy to design, Flexible, Cut-to-length, Easy to terminate, Unconditional "T-Rating"	Sensitive to high temp exposure (generally <420F/215C), Start-up currents must be considered
Power-limiting	Winterization/Freeze Protection Process Temperature Maintenance (Maintain to 400F/204C)	Easy to design, Flexible, Cut-to-length, Built-in Cold Lead, High-temp exposure to 500F/260C	Higher run-away temperatures, T-rating determined by application, More care during circuit fabrication
Parallel (Zone) Constant Watt	Winterization/Freeze Protection Process Temperature Maintenance (Maintain to 400F/204C)	Easy to design, Flexible, Cut-to-length, Built-in Cold Lead, High-temp exposure to 500F/260C	Higher temperatures require control, T-rating determined by application, More care during circuit fabrication
Flexible Series	Winterization/Freeze Protection Process Temperature Maintenance (Maintain to 400F/204C)	Flexible, Easy to monitor current, Can be field fabricated, High-temp exposure to 500F/260C	Difficult to design, Circuit length affects power output (shorter lengths may require transformers), T-rating determined by application, More care during circuit fabrication
Mineral Insulated (MI) Series Heaters	Winterization/Freeze Protection Process Temperature Maintenance (Maintain to 932F/500C)	Durable and rugged sheath, Easy to monitor current, Custom fabricated heaters, Highest-temp ratings to 1100F/593C	Difficult to design, MgO dielectric susceptible to moisture, Field measurements required for factory fabrication (long lead times), Shorter lengths may require transformer, T-rating determined by application

Table 3 Electric Heat Tracing (EHT) type (Brazil, Conachey, Gary Savage, & Baen, 2013)

Special attention must be given to do not put down the efficiency and reliability of the unit (rigs, pipes, system) when considering the electric loads for high energy requirements and also installation of potentially sensitive electrical circuits exposed to rain, wind, ocean spray, etc. Because these installations can represent significant heat loads, there is also a need to address control technologies that include provisions for energy management.

Shipboard power is already limited, and arctic and polar vessels facing increased restrictions to exploration in those areas.

DNV defines the equipment and areas requiring attention into two categories:

- Category 1: equipment or areas necessary for navigation steering, propulsion, anchoring, and lifesaving;
- Category 2: equipment or areas comprising decks and superstructures, helicopter decks, railings, and cargo deck area.

Furthermore, the main mast deserves a special attention, considering that it is a very susceptible area to ice build-up (Brazil, Conachey, Gary Savage, & Baen, 2013).

The power capacity to prevent ice formation (anti-icing) and to melt ice already formed (de-icing) has some industrial values but can also be calculated using mathematical models. To calculate heat loads and make a thermal design it is important that the design conditions do not arbitrarily specify the coldest possible day with the highest possible wind speed. Also, the energy requirements for thermal insulation to retain the heat within the surface to be heated can be very high. Areas without provisions for thermal insulation as walkways, stair, helipads, etc. require even more energy. The calculations for heat losses from exposed surfaces is another important consideration. Preventing snow and ice accumulation, independent testing has to be done to estimate heating requirements. In addition, while there may be no thermal insulation in the system, there is no wind on the underside of the surface, and in some cases, there may be some residual heat from the compartment below. In this case, the heat loss is not released to the environment, but used to heat other equipment. Some common values for power capacity are 300 W/m^2 for open-deck areas, helicopter decks, stairways, etc.; 200 W/m^2 for superstructures and 50 W/m for railing/steel handrail (Brazil, Conachey, Gary Savage, & Baen, 2013).

8.5 Steel Selection

The material selection must have properties to comply with the functional requirements and be compatible with all anticipated internal and external fluids, temperatures and environments during all operations. Also, it must be suitable for operations associated

with dynamic risers for floating production systems, including the associated loadings. Another important point is to have the mechanical properties, including strength, toughness and fatigue performance, necessary to comply with design performance (API Standard 2 RD, 2013).

The biggest challenge for materials operating under Arctic conditions is the low ambient temperature. The structural steels will suffer from reduced fracture toughness at low temperatures being susceptible to fail in a shorter time than under warmer conditions. To resist specified accidental actions, extreme ice actions or other abnormal environmental action, arctic grade steel must be used to achieve the ductility and toughness required for proper performance (ISO 19906, 2010). Therefore, Class C steels are used when temperatures can reach -40°C . The steel itself should be tested by mechanical testing, such as tensile tests, bend tests, Charpy V-notch test (for Class C, the test is made under temperatures from -20°C to -40°C) and hardness tests. Impact testing frequency for Class C steels should be in accordance with the specification under which the steel is ordered; in the absence of other requirements, heat lot testing may be used. Some mechanical properties of Class C steel are given in table 4 (El-Reedy, 2012).

In order to make a comparison between the Steel Class H, used for services under temperatures above freezing, and the Steel Class C, the table 4 is presented.

Group	Class	Specifications and Grade	Yield Strength (MPa)	Tensile Strength (MPa)
I	H	ASTM A36, to 50mm thick	250	400-550
		ASTM A131 Grade A, to 12 mm thick	235	400-490
		ASTM A285 Grade C, to 19 mm thick	205	380-515
I	C	ASTM A131 Grades CS, E	235	400-490

II	H	ASTM A572 Grade 42, to 50mm thick	290	415 min
		ASTM A572 Grade 50, to 50mm thick [S91 required over 12mm]	345	450 min

II	C	API Spec 2H Grade 42	290	430-550
		Grade 50, to 62mm thick	345	483-620
		Grade 50, over 62mm thick	325	483-620
		API Spec 2W Grade 50, to 25 mm thick	345-517	448 min
		API Spec 2W Grade 50, over 25 mm thick	345-483	448 min
		API Spec 2Y Grade 50, to 25 mm thick	345-517	448 min
		API Spec 2Y Grade 50, over 25 mm thick	345-483	448 min
		ASTM A131 Grades DH32, EH32	315	470-585
		ASTM A131 Grades DH36, EH36	350	490-620
		ASTM A537 Class I, to 62mm thick	345	485-620
		ASTM A633, Grade A	290	435-570
		ASTM A633 Grades C,D	345	485-620

		ASTM A678 Grade A	345	485-620
III	C	ASTM A537 Class II, to 62 mm thick	415	550-690
		ASTM A678 Grade B	415	550-690
		API SPEC 2W Grade 60, to 25mm thick	414-621	517 min
		API SPEC 2W Grade 60, over 25mm thick	414-586	517 min
		API SPEC 2Y Grade 60, to 25mm thick	414-621	517 min
		API SPEC 2Y Grade 60, over 25mm thick	414-586	517 min
		ASTM A710 Grade A Class 3, quenched and precipitation heat to 50 mm	515	585
		ASTM A710 Grade A Class 3, quenched and precipitation heat -50 to 100mm	450	515
		ASTM A710 Grade A Class 3, quenched and precipitation heat - over 100mm	415	485

Table 4 Mechanical properties of structural steel plates (El-Reedy, 2012)

The three different groups that were presented, organize the steel selection according to its strengths level with group I considering mild steels, group II, intermediate-strength and group III high strength steels. From the table analysis, it is possible to see that just Class C participates of group III. Also, is possible to conclude that, considering same

groups from Class C and Class H, the average values for both yield strength and tensile strength are higher for Class C than H. Combining those two observations, we can say that Class C has a better resistance to applied tensions and has a better efficiency, what gives the riser conditions to work in an environment with more '*traps*' than usual as the Arctic area.

References

- 2B1st. *Riser*. Accessed in April, 2016, Available in <http://www.2b1stconsulting.com/riser/>
- Aadnoy, B. S. (2006). *Mechanics of Drilling*. Aachen: Shaker Verlag.
- AMAP. (December, 2007). *SURFACE OCEAN CURRENTS IN THE ARCTIC*. Accessed in March, 2016, available in <http://www.amap.no/documents/doc/surface-ocean-currents-in-the-arctic/566>
- API RP 16Q. (1993). *Design, selection, operation and maintenance of marine drilling riser system*. American Petroleum Institute. Washington: American Petroleum Institute.
- API Standard 2 RD. (2013). *Dynamic risers for floating production systems*.
- AZPIAZU, W. R., & NGUYEN, V. N. (1984). *Vertical dynamics of marine risers*. Houston.
- Bjoern, H. (2014). *Challenges with Arctic and Harsh Environment Exploration and Production*. University of Stavanger, Stavanger.
- Brazil, H., Conachey, R., Gary Savage, & Baen, P. (2013). *Electrical Heat Tracing for Surface Heating on Arctic Vessels and Structures to Prevent Snow and Ice Accumulation*. IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS.
- Cameron. (2016). *Drilling Systems* . Accessed in 2016, available in LoadKing 4.0 Riser System: <http://www3.c-a-m.com/forms/Product.aspx?prodID=90596928-7a52-4939-89ad-2a88021ba6ea>
- Canadoil Group . (2016). *High Yield Steel - PIPING SOLUTIONS*. Accessed in 2016, available in: <https://www.canadoilgroup.com/Files/PDF/High%20Yield%20Steel%20X65,80,100.pdf>
- Cleveland, C. J. (March, 2011). *The Encyclopedia of the Earth*. Accessed in 2 February, 2016, available in Offshore drilling in the Arctic: background and issues for the

future consideration of oil and gas activities:
<http://www.eoearth.org/view/article/163045/>

DNV. (2010). *Dynamic Risers*.

DNV. (2010). *Offshore Riser Systems*.

El-Reedy, M. A. (2012). *Offshore Structures : Design, Construction and Maintenance*. Gulf Publishing Company.

Encyclopedia Britannica. (November, 2013). Accessed in March, 2016, available in Greenland Sea: <http://global.britannica.com/place/Greenland-Sea>

Encyclopedia Britannica. (November, 2011). *Beaufort Sea*. Accessed in March, 2016, available in Sea, Arctic Ocean: <http://global.britannica.com/place/Beaufort-Sea>

Encyclopedia Britannica. (November, 2014). *Kara Sea*. Accessed in March, 2016, available in Sea, Russia: <http://global.britannica.com/place/Kara-Sea>

First Subsea. (2016). *Riser Handling and Tendon Tools*. Accessed in 2016, available in Riser handling tool: <http://www.firstsubsea.com/products/rht-tendon.html>

gCaptain. (2010). *Deepwater Horizon's BOP stack*. Accessed in April, 2016, available in <http://gcaptain.com/blowout-4-5-billion-surge-orders/>

Geoscience news and information. (2016). *Arctic Ocean Map and Bathymetric Chart*. Accessed in July, 2016, available in <http://geology.com/world/arctic-ocean-map.shtml>

Global International Waters Assessment. (2004). Accessed in March, 2016, available in Barents Sea - Regional Assessment 11: http://www.unep.org/dewa/giwa/areas/reports/r11/giwa_regional_assessment_11.pdf

Grønevik, A. (2013). *SIMULATION OF DRILLING RISER DISCONNECTION – RECOIL ANALYSIS*. Norwegian University of Science and Technology, NTNU, Department of Marine Technology, Trondheim.

Gudmestad. (2015). *Marine Technology and Operations: Theory & Practice*. WIT Press.

- Gudmestad, O. (2007). *Engineering Aspects Related to Arctic Offshore Developments*. St. Petersburg: LAN.
- Gudmestad, O. T., & Quale, C. (2011). *Technology and Operational Challenges for the High North*. Stavanger.
- GustoMSC. (2016). Source: Jack-ups designs: [http://www.gustomsc.com/our-designs?f\[0\]=field_markets_ref%253Aparents_all%3A15&f\[1\]=field_solutions_series_ref%253Aparents_all%3A34](http://www.gustomsc.com/our-designs?f[0]=field_markets_ref%253Aparents_all%3A15&f[1]=field_solutions_series_ref%253Aparents_all%3A34)
- Hauge, M. (2012). *Arctic Offshore Materials and Platform Winterisation*. Statoil.
- Haziri, S., & Dyngvold, Ø. (2011). *Development of simulation model for virtual testing and design of a riser tensioner system*. Master Thesis, University of Agder, Agder.
- Huisman. (2015). *JBF Arctic*. Accessed in March, 2016, available in http://www.huismanequipment.com/en/products/drilling/jbf_14000/jbf_arctic
- Husøy, K. (2010). *Design of Tool for Drilling Riser Connections*. (NTNU) Accessed in April, 2016, available in Design of Tool for Drilling Riser Connections
- IACS. (2016). *Requirements concerning POLAR CLASS*.
- IMO. (2016). *Shipping in polar waters*. Accessed in July, 2016, available in Adoption of an international code of safety for ships operating in polar waters (Polar Code): <http://www.imo.org/en/MediaCentre/HotTopics/polar/Pages/default.aspx>
- Inocean. (February, 2016). *Inocean won the CAT I drillship design contract from Statoil*. Accessed in March, 2016, available in <http://www.inocean.no/inocean-won-the-cat-i-drillship-design-contract-from-statoil>
- Interior, U.S. Department of. (March, 2013). Accessed in February, 2016, available in REVIEW OF SHELL'S 2012 ALASKA OFFSHORE OIL AND GAS EXPLORATION PROGRAM: <https://www.doi.gov/sites/doi.gov/files/migrated/news/pressreleases/upload/Shell-report-3-8-13-Final.pdf>

- ISO 19906:2010 *Petroleum and natural gas industries - Arctic offshore structures*. Geneva: International Organization for Standardization.
- ISO 19906. (2010). *Arctic offshore structures*. Norsk Standard.
- Januarilham, Y. (2012). *Analysis of Component Criticality in the Blowout Preventer*. UiS, Offshore Technology/ Risk Management, Stavanger.
- Jim Thomson, W. E. (May, 2014). Swell and sea in the emerging Arctic Ocean. *Geophysical Research Letters* .
- JVS Engineers. (2013). Accessed in 2016, available in Diverter System: <http://www.jvsengg.com/pressure-diverter-ball-valve.html>
- LARSEN, C. M. (2008). *Aspects of marine riser analysis*. NTNU, Department of marine structures, Trondheim.
- Lin Callow, LTLC Consulting. (April, 2012). *Beaufort Sea*. Accessed in February, 2016, available in Oil and Gas Exploration & Development Activity Forecast: <http://www.beaufortrea.ca/wp-content/uploads/2012/04/Beaufort-Sea-OG-activity-forecast-2012-2017.pdf>
- Lloyd's. (2011). *Drilling in extreme environments: Challenges and implications for the energy insurance industry*.
- Lund, K. H. (2011). *BOP Basic Safety Functions*. Scandpower AS.
- Macalister, T. (September, 2015). Shell abandons Alaska Arctic drilling. *The Guardian* .
- Marine, S. (2013). *SEVANDrilling*. Accessed in May, 2016, available in Sevan Brasil: <http://www.sevandrilling.com/section-9-27-sevan-brasil.html>
- Marine, S. (October, 2013). *Understanding the key challenges of FPSOs in Arctic conditions*. Accessed in May, 2016, available in Presentation for International forum Arctic Projects – Today and Tomorrow: http://www.sevanmarine.com/images/stories/Presentations/2013/other/Sevan_Marine_Presentation_Arkhangelsk_30_Nov_2013.pdf
- McCrae, H. (2003). *Marine riser systems and subsea blowout preventers*. Texas.

NAALAKKERSUISUT, Government of Greenland. (2016). Accessed in February, 2016, available in Government of Greenland: <https://www.govmin.gl/petroleum/exploration-a-exploitation/13-uncategorised/143-licensing-round-2017>

Norsk Polar Institutt. (2001). *Circulation in the Arctic Ocean*.

Norwegian Polar Institute. (September, 2014). Accessed in March, 2016, available in Barents Sea: <http://www.npolar.no/en/the-arctic/the-barents-sea/>

Norwegian Polar Institute. (s.d.). *The Arctic System*. Source: The sea and ocean currents: <http://www.arcticsystem.no/en/outsideworld/oceancurrents/>

NS-EN ISO 13624-1:2009. (2009). *Petroleum and natural gas industries - Drilling and production equipment - Part 1: Design and operation of marine drilling riser equipment*. Lysaker: CEN.

NSIDC. (2016). *National Snow & Ice Data Center*. Accessed in March, 2016, available in: All About Arctic Climatology and Meteorology: https://nsidc.org/cryosphere/arctic-meteorology/factors_affecting_climate_weather.html#geography

OGP. (2013). *Environmental management in Arctic oil and gas operations: Good practice guide*. International Association of Oil & Gas Producers.

OTC. (2012). *New Revision of Drilling Riser Recommended Practice (API RP 16Q)*.

Pilisi, N., Maes, M., & Lewis, D. (2011). *Deepwater drilling for Arctic Oil and Gas Resources Development: A conceptual study in the Beaufort Sea*. OTC.

Pilisi, N., Maes, M., & Lewis, D. (2011). *Deepwater Drilling for Arctic Oil and Gas Resources Development: A Conceptual Study in the Beaufort Sea*. OTC, Houston.

Polar Science Center, University of Washington . (2003). Accessed in 2016, available in: <http://psc.apl.washington.edu/HLD/Chukchi/Chukchi.html>

Proactima. (2015). *Petroleum Safety Authority Norway (on behalf of the Norwegian Ministry of Foreign Affairs)*.

- R.D. YOUNG; J.R. FOWLER. (November, 1978). *Mathematics of the marine riser*. Houston, Texas.
- Schlumberger. (2016). *Oil Glossary*. Accessed in 2016, available in Marine Drilling Riser: http://www.glossary.oilfield.slb.com/Terms/m/marine_drilling_riser.aspx
- Seadrill. (2016). *Our fleet*. Accessed in April, 2016, available in: <http://www.seadrill.com/our-fleet.aspx?=1>
- Sevan Marine. (October, 2013). Accessed in March, 2016, available in: Understanding the key challenges of FPSOs in Arctic conditions: http://www.sevanmarine.com/images/stories/Presentations/2013/other/Sevan_Marine_Presentation_Arkhangelsk_30_Nov_2013.pdf
- Sevan Marine. (2016). *Sevan 1000 FPSO for Goliat*. Accessed in April, 2016, available in: <http://www.sevanmarine.com/goliat>
- Solberg, S. B. (2014). *Evaluation of MODU concepts and subsea systems for Arctic drilling*. University of Stavanger.
- Sparks, C. P. (2004). *Fundamentals of Marine Riser Mechanics*. PennWell.
- Stephen Potter, I. B. (2012). *Spill Response in the Arctic Offshore*. Debra Scholz.
- The Arctic Institute. (January, 2014). Accessed in February, 2016, available in: Greenland's New Frontier: Oil and Gas Licenses Issued, Though Development Likely Years Off: <http://www.thearcticinstitute.org/2014/01/greenlands-new-frontier-oil-and-gas.html>
- The PEW charitable trusts. (2013). *Arctic Standards - Recommendations on Oil Spill Prevention, Response, and Safety in the U.S. Arctic Ocean*.
- The Research Council of Norway. (August, 2015). *Nanotechnology and advanced models*. Accessed in April, 2016, available in: Nanotechnology can double the lifetime of tensioning systems: http://www.forskningradet.no/prognett-nano2021/Nyheter/Nanotechnology_can_double_the_lifetime_of_tensioning_systems/1254011295759/p1253969916306

- Transocean. (2014). *Transocean Barents*. Accessed in April, 2016, available in <http://www.deepwater.com/Documents/RigSpecs/Transocean%20Barents.pdf>
- Trelleborg. (2016). *Drill Riser Buoyancy Module*. Accessed in April, 2016, available in <http://www.trelleborg.com/en/offshore/products/drill--riser--buoyancy/drill--riser--buoyancy--module>
- Tubular Goods Research Center of CNPC. (2010). *Material Properties Standard of Marine Drilling Riser*. Accessed in 2016, available in: <https://www.onepetro.org/download/conference-paper/SPE-130897-MS?id=conference-paper%2FSPE-130897-MS>
- U.S Department of Interior. (March, 2008). *REVIEW OF SHELL'S 2012 ALASKA OFFSHORE OIL AND GAS EXPLORATION PROGRAM*. Accessed in February, 2016, available in: <https://www.doi.gov/sites/doi.gov/files/migrated/news/pressreleases/upload/Shell-report-3-8-13-Final.pdf>
- Urycheva, M., & Gudmestad, O. T. (2014). Accessed in 2016, available in: A new jack-up unit concept to extend the arctic drilling season: <https://www.onepetro.org/download/conference-paper/OTC-24616-MS?id=conference-paper%2FOTC-24616-MS>
- Vafin, A. (2015). *Simulation - based assessment of drilling riser and its application for the Kara Sea region*. UiS, Petroleum Engineering/ Well Engineering, Stavanger.
- Wassink, A., & Van der List, R. (2013). Development of solutions for Arctic offshore drilling.
- WWF. (2014). *Arctic Oil and Gas*. Accessed in April, 2016, available in: http://wwf.panda.org/what_we_do/where_we_work/arctic/what_we_do/oil_gas/
- WWF. (December, 2014). *WWF*. Accessed in February, 2016, available in Arctic oil and gas: http://wwf.panda.org/what_we_do/where_we_work/arctic/what_we_do/oil_gas/