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Abstract

All oil and gas wells will require plugging and abandonment (P&A) at some point in their operating life. Considering the challenging nature of the Arctic weather, its remoteness and lack of infrastructures, and its ice conditions, conducting this operation in the High Arctic will have the potential to be more costly, time consuming, and challenging. In addition, Arctic weather and ice conditions are difficult to predict. For instance, drift ice cover varies from open waters in the summer to very close drift ice in the winter, but the drift pattern is difficult to predict because of influences from tidal currents and winds (Keinonen, A., et al., 2000). Therefore, it is very important to understand the High Arctic environment so as to get familiar with challenges that can be encountered during P&A operations in the environment. This will make it possible to develop means of conducting safe, and time and cost effective Arctic P&A operations.

The thesis presents the challenges and possible solutions for P&A operation in Arctic environments in terms of safety and cost effectiveness. In order to comply with the already established standards, NORSOK-D-10 rev-4 and UKOOA are reviewed.

- The study shows that the main challenges of Arctic subsea P&A are associated with the extreme weather condition of the Arctic, Arctic ice conditions such as sea ice and icebergs, and remoteness and lack of infrastructures in the Arctic. Others are spill management problems, P&A vessel challenges, permafrost, and cementing related challenges.

- Solutions suggested to these challenges from this study include the need to develop ship-shaped vessels that are enabled for high Arctic operations such as Category A vessels (or the Category I Arctic drilling vessel) with full capabilities for the three phases of well abandonment specified in the Oil and Gas UK standard for P&A operations (Oil and Gas, UK; 2011). Another possibility is to combine the Category A and Category I vessels such that jobs like logging and bullheading can be done by the Category A vessels, while heavier jobs such as cutting and pulling of tubing can be done by the Category I vessels. The study also suggests that before deciding on combining vessels for Arctic P&A operations, one must consider that increased cost of vessel mobilization would result and that it is likely that there will be limited number of Arctic-enabled vessels in existence.

- Other suggested solutions include the need for ice management to support the operations of the P&A vessels in the Arctic, use of batch campaigns to reduce vessel mobilization cost and to solve logistic challenges due to remoteness of Arctic offshore oil and gas fields, and use of PPEs customized to the weather

condition on each field location. Furthermore, the need for zero tolerance for spills in the Arctic, and the need for freeze protected cement slurry to prevent freezing of cement are also suggested.

- To reduce the time needed for Arctic P&A operations due to the short open water season, it is suggested to design Arctic wells such that milling and pulling of production tubing can be avoided during the P&A operations. This would help to increase the effectiveness of batch operations in the region, make it possible to use simpler P&A vessels, and reduce operations cost. Avoiding milling would also help to reduce chances of mud loss, thereby enabling environmentally friendly Arctic P&A operations.

Dedication

This work is dedicated to the memory of my beloved sister, Nebiat, who was my closest friend and great support until she passed unto eternal glory on 13.03.2014, during the course of this work.

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First and foremost, I thank God for giving me the strength to finish this thesis successfully.

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Finally, I want to thank my family for their care, love and unfailing support.

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Abbreviations

ACEX	Arctic Coring Expedition
ANWR	National Wildlife Refuge
AS	Arctic Slurry
AUs	Assessment Units
BBO	Barrels Of Oil
BOP	Blow Out Preventer
CARA	Circum Arctic Resource Appraisal
CBL	Cement Bond Logs
CT	Coiled Tubing
ECD	Equivalent Circulating Density
FPSOs	Floating, Production, Storage and Offloading Vessels
GHSZ	Gas Hydrate Zone
HSE	Health, Safety and Environment
HWU	Hydraulic Workover Unit
LOT	Leak Off Test
LWI	Light Well Intervention
MMS	Mineral Management Service
MODU's	Mobile Offshore Drilling Units
NCS	Norwegian Continental Shelf
NGLs	Natural Gas Liquids
NPD	Norwegian Petroleum Directorate
NPRA	National Petroleum Reserve of Alaska
NSIDC	National Snow and Ice Data Center
OCS	Continental Shelf
OCT	Outer Continental Shelf
P&A	Plug and abandonment
PP&A	Permanent Plug and Abandonment
PPE	Personal Protective Equipment
PWC	Perforate, Wash and Cement
RLWI	Riserless Well Intervention

SWAT	Suspended Well Abandonment Tool
TAPS	Trans Alaska pipeline system
Tcf	Trillion cubic feet
Tcm	Trillion cubic meter
TOC	Top of Cement
USGS	U.S. Geological Survey
VDL	variable density log
WBE	Well Barrier Element
WBS	Well barrier schematics
WL	Wireline
Xmas tree	Christmas trees

Chapter 1

Introduction

The aim of this thesis is to study challenges that may affect subsea P&A operations in the Arctic, with main focus on the High Arctic, and to present solutions that would make safe and cost effective operations possible in the environment. The Arctic environment in terms of its climate, weather patterns, and offshore ice conditions is studied in this thesis to gain understanding of what challenges they can pose to P&A operations. The thesis also presents the hydrocarbon potential of the Arctic, and offshore oil and gas activities in different parts of the Arctic. Mobile offshore drilling rigs are also reviewed, and their suitability for different parts of the Arctic is also studied. Study of the drilling rigs shows that while drillships are more suitable for high Arctic areas, semi submersibles and jack-up rigs are more suitable for sub-Arctic and harsh environments. Furthermore, a general overview of P&A operations, requirements of NORSOK D-010 rev- 4 and the Oil and Gas UK standard for P&A operations (UKOOA), and typical vessels for subsea P&A is also provided.

1.1 Background Study

The Arctic is regarded as one of the world's largest petroleum provinces, accounting for 13% of the world's undiscovered oil reserves and 30% of the undiscovered natural gas reserves distributed in numerous geological basins (Gautier, D. L., et al., 2009). 15% of the world's energy needs are presently supplied by onshore and offshore production in the Arctic, and the figure is expected to be doubled by 2050 (JIP, 2014). As global energy demand increases, there is increasing need to develop more oil and gas fields to meet the ever growing demands of the global market. As hydrocarbon resources in the conventional onshore and offshore areas of the world continue to decline, the need to further explore and produce the rich hydrocarbon resources of the Arctic becomes more necessary.

While the Arctic contains large oil and gas reserves, exploring the resources and developing fields in the Arctic is difficult as a result of the challenging nature of the Arctic environment and weather. Coupled with the fact that Arctic oil and gas operations are very expensive, the nature of the Arctic environment is such that zero tolerance level must be placed on spills and leakages. Extremely cold weather, ice cover, and limited amount of sunlight will make breakdown of spills very difficult in the environment. This means the region would require very expensive technology to be put in place if spills will be manageable in the area. Furthermore, the Arctic region is very remote and getting access to fields in the Arctic requires navigation through long distance of ice-covered water. This further makes response to spills slow in the Arctic and expensive as large amount of fuel will be consumed by the Arctic vessel while travelling to the spill location. This places very high importance on safe and cost effective performance of tasks such as drilling and P&A of wells in the Arctic.

Wells in the high Arctic will typically be subsea wells so as to make it possible to detach the drilling, production or P&A vessel from them and leave the field to avoid adverse ice features. Thus, this thesis focuses on the P&A of subsea wells in the Arctic, with main focus on the high Arctic region. The primary aim of P&A operations is to properly secure wellbores so as to isolate hydrocarbons from flowing either temporarily or permanently to prevent leaks into the well or from the well to surrounding environment.

Records from offshore fields in conventional areas of the world show that P&A of wells is a time consuming and expensive activity. According to Saasen, A., (2013), a significant part of the cost of drilling offshore exploration and production wells goes into P&A operations. For instance, it is written in the paper that as much as 25% of the total cost of drilling offshore exploration wells on the Norwegian Continental Shelf goes into P&A of the wells. Having this in mind in addition to the challenges of the Arctic environment makes it necessary to have cost effective systems for performing P&A operations in the Arctic.

To successfully conduct P&A operations in the Arctic, a good understanding of the Arctic environmental conditions such as its weather, ice features, permafrost, and water depth is necessary. It is also important to have an understanding of the distribution and variation of these Arctic phenomena in different parts of the Arctic. This will make it possible to develop P&A vessels and equipment that are suitable for the Arctic environment, and to develop procedures such as ice management to support the P&A vessels. Ice management would help to reduce ice interactions with P&A vessels to manageable levels and will also help to increase the length of open water season within which P&A operations can be conducted in the Arctic. Reduction in cost of Arctic P&A operations will also be achieved as an understanding of the environment will aid in choosing the correct vessels for jobs and will also aid in designing the vessels with the winterization requirements necessary for a particular Arctic location so as to avoid excessive complexities in the vessels. In addition, it will also help in designing the correct PPE for personnel with respect to weather conditions of the particular field in order to avoid excessively heavy weight PPEs which can interfere with work effectiveness.

1.2 Purpose and Scope

This thesis looks into the problems that can be associated with P&A operations in the Arctic (with main focus on the High Arctic), with the aim of presenting solutions to the identified problems. To do this, an extensive study of the Arctic environment is made to get an overview of the region's climatic factors and icing conditions, hydrocarbon resource distribution in the region, and drilling vessels suitable for the environment. In literature, there are no much field case studies, special standard and best practices documentations for the Arctic region. Therefore, this thesis reviews the already established standards (NORSOK-D10 rev-4 and the Oil and Gas UK standard for P&A operations (UKOOA)) and practices, whose experiences and possibilities can be extended to the Arctic region. A highlight of the tasks undertaken in this thesis is as follows:

- Chapter 2 provides an overview of the Arctic climatic factors and weather patterns, and ice conditions which include sea ice, icebergs, permafrost, spray sea icing and atmospheric icing.
- Chapter 3 discusses the distribution of hydrocarbon resources in Arctic geological basins, and oil and gas activities and hydrocarbon potentials of some of the countries that form part of the Arctic.
- Chapter 4 looks into mobile offshore drilling rigs with their features and what can be done to make them suitable for Arctic operations. Distinction is also made between drilling vessels suitable for high Arctic areas and those suitable for sub-Arctic areas.
- Chapter 5 presents what a P&A job entails, the requirements of NORSOK D-010 rev-4 and the Oil and Gas UK standard for well abandonment operations, and vessels typically used for P&A operations.
- Chapter 6 presents discussions on challenges of P&A activities in the Arctic with proposed solutions.
- Chapter 7 concludes with a summary of the solutions recommended to the P&A challenges in the Arctic.

Chapter 2

The Arctic Region

2.1 Definition and Geographical Extent

The Arctic lies in the northern polar region of the earth. It encloses about 6% of the earth's total surface and it is about 30 million km^2. The word Arctic comes from the Greek word "Arktikos" which means "near the bear".

There are many ways of drawing "Arctic boundary" on a map, but the most common one is by connecting the mean 10 °C July isotherm. According to Budzik, P., (2009), the size of the Arctic region is about the same size of the African continent, where one–third of it is above the sea level and another one-third is an offshore continental shelf, with depth less than 500 m. The remaining part of this region comprises deep ocean water with depth greater than 500 m. The Arctic water is covered with ice that has various thicknesses depending on the latitude.

Figure 2.1 is a geographical overview of the Arctic Region.

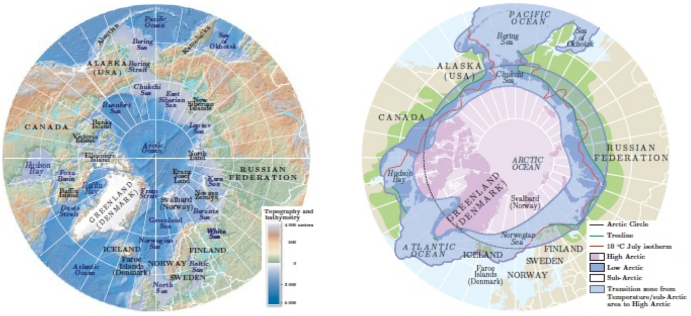

Figure 2.1: Overview of the Arctic Region (Burg, L., 2007)

Arctic can have different definitions even if it is considered to be as a single region.

Some of the definitions are:

- Budzik, P., (2009) stated that the Arctic is defined as the Northern hemisphere region located north of the Arctic Circle, the circle of latitude where sunlight is uniquely present or absent for 24 continuous hours on the summer and winter solstices, respectively.
- According to PSA, (2014), it is defined as the area marked by the northern tree line which coincides by and large with the isotherm for a mean July temperature of 10 °C.
- According to FNI and DNV, (2012), it is defined as all places in the north pole where the average temperature of the warmest month does not exceed 10 °C.
- Aronson, J. G. and Raykin, V., (2012) & IAOGS, (2013) defined the Arctic by the Arctic Circle which in 2012 was at 66 degrees, 33 minutes, and 44 seconds North, which is the approximate limit of the midnight sun (24 hour sunlight) and the polar night (24 hours of darkness).

The Landmass and marine environment of the Arctic region is divided among eight countries – Canada, Denmark/Greenland, Finland, Iceland, Norway, Russia, Sweden and the United States. About 78% of the landmass is shared by Canada, and Russia; around 18% by Denmark/Greenland, Finland, Iceland and Norway, whereas about 4% is claimed by the United State (IAOGS, 2002).

Figure 2.2 shows countries sharing the Arctic region.

Figure 2.2: *Countries sharing the Arctic region (TravelWild, 2014)*

Furthermore, the Arctic region can be divided into High Arctic and Sub-Arctic regions. According to Hamilton, J. M., (2011), deep water in high Arctic offshore is defined as water depth that exceeds about 100 m. High-Arctic region refers to the entire circumpolar Arctic, which is as represented in Figure 2.1.

Wassink, A. and v.List, R., (2013) states the subdivisions of arctic as:

- **High Arctic**: Suitable for areas with annual sea ice cover, with clear open water and ice seasons in an extended season or year round operational modus. This involves operations in areas such as the Beaufort Sea, Chukchi Sea, Northern Greenland, Kara Sea and East Siberian Sea.
- **Sub-Arctic**: Suitable for areas with occasional sea ice cover and/or high Arctic areas in a seasonal operational modus. This involves operations in areas such as southern Greenland. Northern Barents Sea, Sakhalin and Sea of Okhotsk.
- **Winterized/harsh environment**: Suitable for harsh environment areas with extreme low temperatures. This involves operations in areas such as Southern Barents Sea.

2.2 Arctic Climate Conditions

Just like in other parts of the earth, there are many factors that can influence the Arctic climate. The climate factors also interact with each other to create weather patterns in the Arctic (NSIDC, 2013c). These factors include temperature, atmospheric pressure, precipitation, latitude and sunlight, wind, humidity and clouds. According to IAOGS, (2013), maritime (influenced by ocean) and continental (influenced by large mass area) are the two main climate divisions in the Arctic. The maritime climate is found in Iceland, the Norwegian coast, Northern Russia, and the Alaska coast. The continental climate is characteristic of the Eurasia and the land-masses of North America. Some of the Arctic climatic factors are discussed in the section 2.2.1.

2.2.1 Temperature, Precipitation, Light, Wind and Wind Chill

2.2.1.1 Temperature

An article by NSIDC, (2013c) reports the Arctic temperatures tend to rise during the day when sunlight warms the ground and fall at night, like other regions of the earth. Arctic temperatures are warmer in summer, when there is more sunlight, and colder in winter, when the region is dark.

In the maritime climate division of the arctic, the air temperature is moderate and averages between 5 °C and 10 °C in summer. The temperature reaches up to minus 11 °C in some areas of this climate division during winter (IAOGS, 2013).

The continental climate division is colder in the winter with more extreme temperatures than the maritime climate division. In January, the temperature ranges between minus 20 °C and minus 60 °C (IAOGS, 2013). Long days of sunshine in the summer bring average summer temperatures in this region to 10 °C in this region. In addition, some weather stations in the interior parts of this climate division experience temperatures up to 30 °C for a short period of time during summer (NSIDC, 2013b) & (Briney, A., 2010).

Generally, the mean annual temperature in the Arctic region is getting warmer. In a report by Lindsey, R., (2013), it is stated that the Arctic has warmed with about 3.6 °F more than other regions for the past forty years as it also can be seen in figure 2.3. A significant warming took place between the 1930s and the 1950s when the mean winter temperatures were over 5 °C higher than in the early years of the century (IAOGS, 2013). In addition, the first twelve years of the 21st century have been warmer than the period at the end of the 20th century from 1971 to 2000 due to global warming (Perovich, D. K., et al., 2013).

Figure 2.3 shows the Arctic-wide annual difference from average temperature.

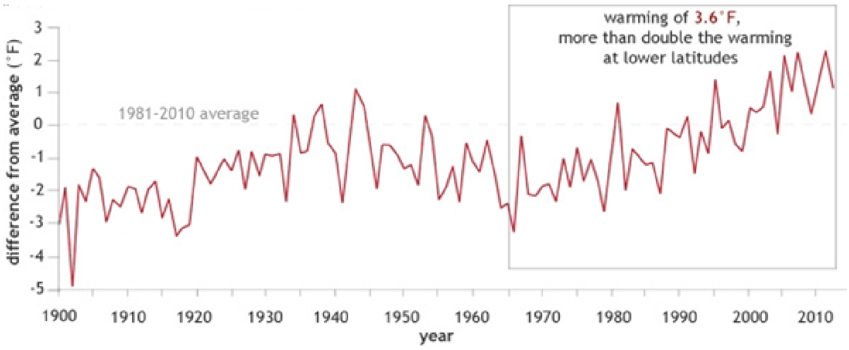

Figure 2.3: *Arctic-wide annual difference from average temperature for all stations north of 60 degrees North since 1900 (Lindsey, R., 2013)*

NSIDC, (2013a) wrote that the Arctic warming has resulted in changes in sea ice, snow cover, and the extent of permafrost in the Arctic. Satellite data show that snow cover over land in the Arctic has decreased, and glaciers in Greenland and northern Canada are retreating. In addition, frozen ground in the Arctic has started to thaw out. In support of this, Perovich, D. K., et al., (2013) further says that the snow cover extent in the Northern hemisphere in early 2013 was recorded to be lower than the average value for the period from 1967 to 2013.

2.2.1.2 Precipitation

Precipitation is very low over most parts of the Arctic. According to NSIDC, (2013e), some areas of the Arctic are called polar deserts and receive as little precipitation as the Sahara desert. The amount of precipitation is higher in the maritime climate division than in the continental climate division. The precipitation in the maritime climate areas is up to 1400mm per year (IAOGS, 2013). Storms forming in the Atlantic Ocean bring moisture up into these areas, especially in winter.

On the other hand, precipitation in the continental climate areas is around 70-200 mm per year (IAOGS, 2013). Almost all precipitation in these areas falls as snow in winter. Persistent winds drive up and blow fallen snow to create an appearance similar to constant snowfall (Columbia University Press, 2012). It is also explained in NSIDC, (2013e) that rain can occur on rare occasions during winter in these areas when warm air is transported into this region. Snow also falls in summer.

2.2.1.3 Light

A press release by Columbia University Press, (2012), shows that great seasonal changes in the length of days and nights are experienced north of the Arctic Circle, with variations that range from 24 hours of constant daylight (”midnight sun”) or darkness at the Arctic Circle to six months of daylight or darkness at the North Pole. The reason for this is the tilt of the earth on its axis. Figure 2.4 shows the seasonal daylight variation in a year in some Arctic areas. IAOGS, (2013) write that there is almost continuous darkness or semi-darkness that stretches from late autumn to early spring. The remaining part of the year experiences continuous or semi-continuous daylight. 24 hours of darkness occurs when high latitude areas such as the Arctic are turned away from the sun. On the other hand, 24 hours of sunlight occur when these areas are tilted towards the sun.

2.2.1.4 Wind and Wind Chill

Windy conditions in the Arctic are related to the pressure gradients in different parts of the region. U.S.A.C.O.E, (1987) writes that many areas in the Arctic and Subarctic with weak pressure gradient and temperature inversion experience fairly low surface winds (Temperature inversion means increase in temperature with height). Areas with high pressure gradient, such as areas near seacoasts and around mountains, are known to record strong winds, with the wind speed reaching up to hurricane velocities

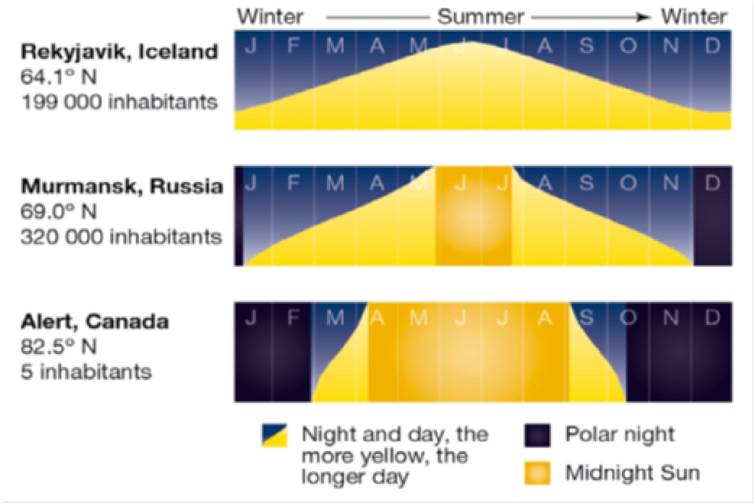

Figure 2.4: *Seasonal daylight variation in a year in some Arctic areas (IAOGS, 2013)*

sometimes. For instance, extreme wind gust in winter of 130 miles per hour has been recorded around Alaska.

Windy conditions in the Arctic blow up fallen snow, and reduce visibility in the winter months. As it is stated by Nuttall, M., (2005), winds of around 6 miles per hour will cause unconsolidated snow to drift along the ground surface. Wind speed of 12-17 miles per hour will lift snow into air, and drifting snow is referred to as blowing snow once it reaches a height of 6 feet. This is usually experienced for half of the winter days in many parts of the Arctic.

Table 2.1 shows effects of different levels of wind chill on persons working in outdoor areas of the Arctic. Wind chill increases with strong winds. According to NSIDC, (2013e), wind chill refers to the cooling effect of any combination of temperature and wind, expressed as the loss of body heat in watts per square meter of skin surface. It can also be expressed in Btu/ft^2hr or $kgcal/m^2hr$. The body has a very thin layer of still air immediately adjacent to it called the boundary layer that helps to insulate the body from heat loss. As wind speed increases, the thickness of the boundary layer diminishes, and the rate of sensible heat loss from the body increases. This decreases the efficiency of workers in the outdoor areas in the Arctic, especially in winter seasons. With the wind chill factor, it is possible to have an idea of the apparent temperature, thereby predicting and preventing the risk of frost bite.

2.2.2 Weather Patterns in the Arctic

The Arctic is characterized by a number of weather patterns which reappear in the region from year to year. Some of the weather patterns are also experienced in other

Table 2.1: *Stages of human comfort and the environmental effects of atmospheric cooling (Nuttall, M., 2005)* modified

Windchill factor		Relative Comfort
(Btu/ft^2hr)	$Kg\,(cal/m^2hr)$	
220	600	Conditions considered as comfortable when people are dressed in wool underwear, socks, mitts, ski boots, ski headband and thin cotton windbreaker suits, and while skiing over snow at about 3 mph(metabolic output about 200 $Kgcal/m^2 \cdot hr$
370	1000	Pleasant conditions for travel cease on foggy ant overcast days.
440	1200	Pleasant conditions for travel cease on clean sunlit (days)
520	1400	Freezing of human flesh begins, depending upon the degree of activity, the amount of solar radiation, and the character of the skin and circulation. Average maximum limit of cooling during November, December and January. At temperatures above ,5 °F these conditions are accompanied by winds approaching blizzard force.
590	1600	Travel and life in temporary shelter very disagreeable
700	1900	Conditions reached in the darkness of mid-winter. Exposed areas of face freeze in less than a minute for the average individual.Travel dangerous.
850	2300	Exposed areas of the face freeze less than $\frac{1}{2}$ minute for the average individual

parts of the world while the others are unique to the Arctic region only. In general, weather patterns that occur in the Arctic include cyclones, anticyclones, polar vortex, semi-permanent high and low pressures, the Arctic Oscillation and feedback loops, according to IAOGS, (2013) & NSIDC, (2013d). These weather patterns influence the variability of the weather in the Arctic.

Cyclones are low pressure systems that rotate in a counter clockwise direction. Air moves upward in a cyclone, bringing stormy wet weather. They are experienced all through the year in the Arctic, but with more intensity in some parts of the Arctic depending on the time of the year. On the other hand, anticyclones are high pressure systems that rotate in a clockwise direction. Examples of anticyclones in the Arctic are the Beaufort High recorded in winter and spring over the Beaufort Sea and Canadian Archipelago, and the Siberian High found in Siberia.

A polar low is a small, but fairly intense atmospheric low pressure system found in maritime regions, well north of the polar front (DNV GL Group, 2013). In mature stage, polar lows are seen from satellite pictures as large spiral cloud bands centered around an eye. This explains why they are also called Arctic hurricanes. Polar lows develop when cold Arctic air flows over relatively warm open water. The typical diameter of polar lows is from 100–500 km and they last for anything between 12 and 36 hours. Polar lows give severe weather in the form of strong and rapidly changing winds, and heavy precipitation composed of dense showers of snow or hail (NSIDC, 2013d) & (WeatherOnline, 2014). An interesting feature of polar lows is that they are quite unpredictable and develop rapidly. Breeze can develop to storm within minutes, while wave heights have been seen to increase up to 5 m in less than an hour due to polar lows (PSA, 2014).

DNV GL Group, (2013) wrote further that the average maximum wind speed is 46knots, which is a severe gale. 35-50% of the lows have storm force winds of 50 knot or more, and the strongest recorded since 2000 had a wind speed of 70 knots. Polar lows are mostly found in the Norwegian and Barents Seas, and most occurrences have being between observed at locations between 65 °N and 75 °N, from the 0 meridian to Novaya Zemlya. Other areas Polar lows have been observed include south of Iceland, southwest of Spitsbergen, and in the Hudson Bay. Most polar lows occur between December and March, though the polar lows season ranges from October to May. In a season, the Norwegian and Barents seas can witness about 10-20 fully developed polar lows.

Figure 2.5 shows a pictorial representation of Polar low.

Figure 2.5: *Polar low (Gudmestad, O. T., 2008)*

NSIDC, (2013d) refers Arctic oscillation as an opposing pattern of pressure between the Arctic and the northern middle latitudes. This implies when pressure is high in the Arctic, it is low in the middle latitudes and vice versa. Arctic Oscillation is in the negative phase when pressure is high in the Arctic and low in the mid-latitudes, while it is in the positive phase when vice versa. In the positive phase, Arctic Oscillations result in warmer and wetter weather in Alaska, the Scandinavia and Eurasia, and colder weather in Greenland. The negative phase brings warm weather to high latitudes, and cold, stormy weather to the more temperate regions where people live. According to IAOGS, (2013), the oscillations have tended towards the positive phase since the 1970s, resulting in lower air pressures and higher temperatures in much of the USA and Eurasia.

Figure 2.6 shows positive and negative phases of Arctic Oscillations.

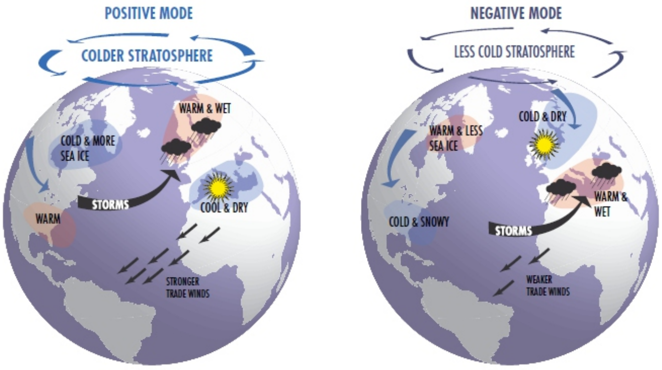

Figure 2.6: *Positive and negative phases of Arctic Oscillation (IAOGS, 2013)*

2.3 Ice condition in the Arctic offshore

Ice exists in different forms in the Arctic marine environment. These include permanent or seasonal pack-ice (generally called sea ice) and icebergs. Also, permanently frozen ground known as permafrost can be found under the surface in a large part of the Arctic. In addition, other important icing considerations in the Arctic waters are sea spray icing and atmospheric icing.

2.3.1 Permanent/ Seasonal Pack-ice

Pack ice is a floating layer of ice of variable age and thickness which results from freezing of the sea surface. The term “drift ice” is used to describe sea ice in motion under the influence of currents, waves and wind. “Landfast ice” refers to sea ice attached to the landmass. Landfast ice is typically about 1.5m to 2m thick by the end of winter, and it reaches out to about 18m depth from shore (PCT, 2013).

Understanding of sea ice is an important factor in the effectiveness and scheduling of activities in the High Arctic and Subarctic. For instance, sea ice occasionally blocks the north-west Russian port of Murmansk (PSA, 2014).

Figure 2.7 shows influence of seasonal ice cover on access to the Arctic.

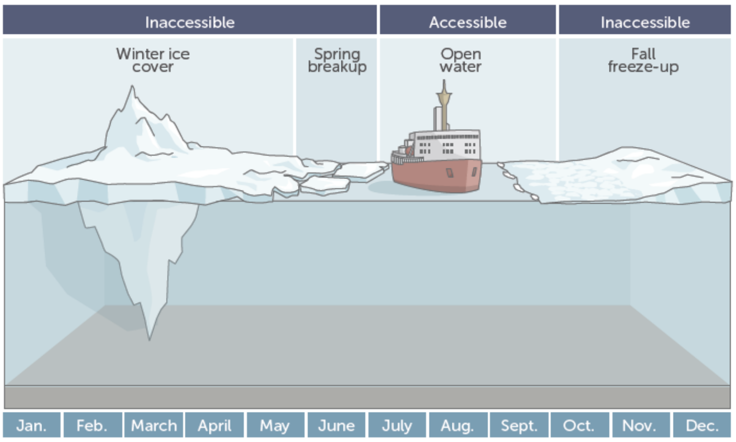

Figure 2.7: *Influence of seasonal ice cover on access to the Arctic (PCT, 2013)*

Attributes used to measure sea ice include sea ice extent, sea ice area, sea ice thickness and volume. Sea ice extent defines all areas with over 15% ice concentrations, including some ice-free water. IAOGS, (2013) illustrated that sea ice area on the other hand is the actual area covered by ice, excluding any open water. Sea ice extent is used as the basic description of the Arctic sea ice cover.

Over the past 30 years, there has been a decrease of maximum and minimum sea ice coverage (see figure 2.8 below). According to Perovich, D. K., et al., (2013), estimates produced from satellite records by the National Snow and Ice Data Center (NSIDC) show that the Arctic sea ice cover reached a minimum annual extent of 5.10 million km^2 in September, 2013. This was 1.69 million km^2 higher than the record minimum set in 2012 (3.41 million km^2). However, the 2013 summer extent was still 1.12 million km^2 below the 1981-2010 average minimum ice extent.

Although high confidence prediction of future trends in Arctic ice cover is not possible, figure 2.9 shows the thickness of Arctic ice cover in the 2050s is projected to be 54% of the value in the 1950s.

Age-wise, the following classes of sea ice exist (Arctic Council Report, 2009) and (Environment Canada, 2013):

- **New Ice**: This is a general term for recently formed ice which includes frazil ice, grease ice, slush and shuga. These types of ice are composed of ice crystals which are only weakly frozen together (if at all) and have a definite form only while they are afloat.
- **Nilas**: This refers to a thin elastic crust of ice which easily bends in a wave field. Under pressure, it grows in a pattern of interlocking "fingers" (finger rafting).

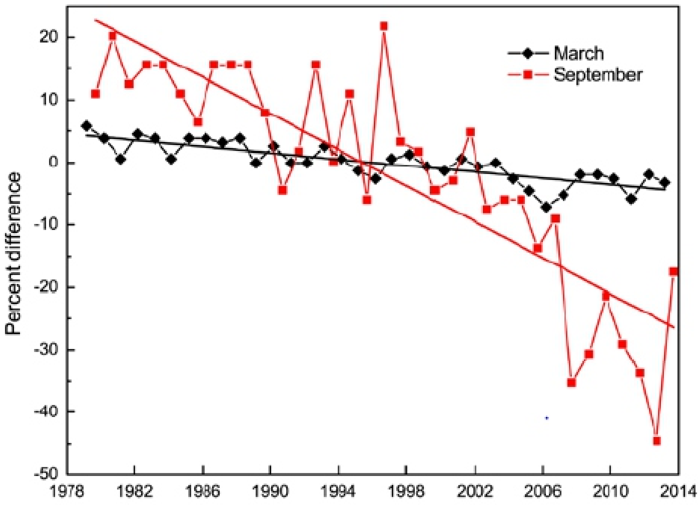

Figure 2.8: *Difference between sea ice extent of March and September, and the average value for the period 1981-2010. The black and red lines are least squares linear regression lines (Perovich, D. K., et al., 2013)*

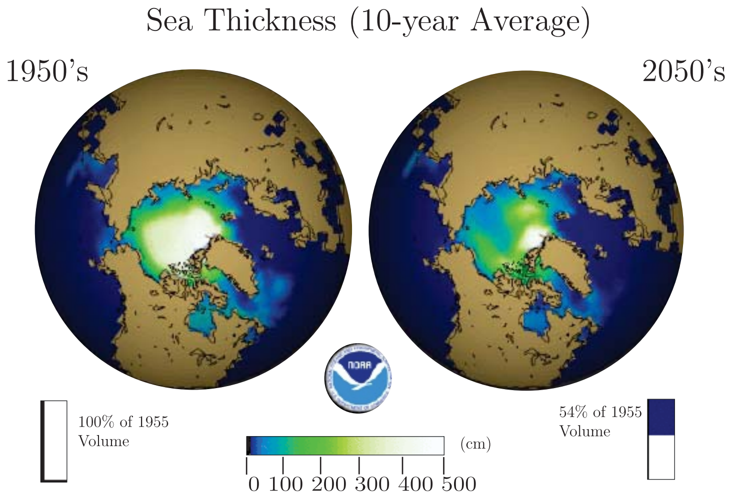

Figure 2.9: *Projected changes in Arctic sea ice from 1950 to 2050 (*modified *(Watts, A., 2012)*

Nilas is up to 10 cm in thickness and may be subdivided into dark nilas (0-5 cm in thickness) and light Nilas (greater than 5cm in thickness) (Eicken, H., 1999).

- **Young Ice**: This is ice that is thicker than Nilas, but thinner than mature first year ice. Its thickness is 10-30 cm, and it can be subdivided into grey ice and grey-white ice. Its formation period is in autumn as ocean surface temperature falls below freezing point. Young ice does not lead to significant safety problems for Arctic vessel. However, it can disturb the motion of the vessels when it is subjected to pressure by winds or currents.

- **First Year Ice**: This is sea ice of not more than one winter growth, and it develops from young ice. It has a thickness of 30 cm to 2 m (it can easily grow to 1m thickness but rarely grows to more than 2 m thickness by the end of winter). Due to the presence of air pockets and brine inclusions in it, first year ice is relatively soft. Hence, it will not generally prevent a well operated ice-strengthened ship from moving. However, it should be noted that under pressure from winds or currents, first year ice can hinder even powerful vessels for hours or days. First-year ice may be subdivided into thin first year ice, medium first year ice, and thick first year ice.

- **Old Ice**: This is sea ice that has survived at least one summer's melt. It can be subdivided into second-year ice and multiyear ice, and it is very hard. It is usually 1-5 m thick. Old ice forms after brine cells and air pockets in first year ice drain out during the summer melt season. This produces a harder than concrete, clear, solid ice mass. The hardness of old ice is such that it can hold down ice-strengthened vessels. Furthermore, the most powerful ice breakers can be stopped by under-pressure old ice.

Figure 2.10 Shows the floating sea ice on the Arctic ocean.

Figure 2.10: *Sea ice floating on the Arctic ocean (Daileda, C., 2014)*

According to IAOGS, (2013), the central Arctic Ocean is covered by multiyear ice averaging around 7 million km^2 (measured over the years 1979-2000) during summer. Temperature drops during autumn and winter; new ice forms and grows into first year ice which increases the ice covered area to 14 million km^2. This ice can extend southwards up to latitude 48 °N, with the exception of the Norwegian and the Barents Seas that stay ice-free because they get "warmed up" by the North Atlantic Drift. The ice span in the Arctic Ocean reduces during summer and spring through extensive melt and break-up. The thickest Arctic ice is obtained off the Canadian Archipelago.

2.3.2 Icebergs

Icebergs are large masses of floating ice which originate from land ice which forms from freezing of fresh water and compaction of snow into glaciers. They break off from the glaciers and drift off into the sea under the action of winds and currents. Icebergs are very hard because their source does not contain salt. As a result of this, they can cause great damage to Arctic offshore facilities like platforms, vessels and pipelines on collision with such. About 30000 icebergs form annually in different areas of the Arctic such as the Greenland coast (with the largest number of icebergs), Ellesmere Island, Svalbard, Franz Joseph land, Severnya, and Novaya Zemlya (IAOGS, 2013). These icebergs can weigh several millions of tonnes at the start of their lives, but they usually break into several pieces as the float southwards. It is on record that icebergs from Kong Karls Land (north-east of Svalbard) were seen as far south as the Finnmark coast in 1881, 1929 and 1939, and were also seen off Russia's Kola Peninsula in 2002 (PSA, 2014). IAOGS, (2013) writes further that It also reports about 1500 icebergs per year from the Arctic reach as far as 48 °N into the North Atlantic, where they progressively melt. Smaller pieces of icebergs are known as bergy bits and growlers (NOAA, 2014).

Figure 2.11 shows an illustration of an Iceberg.

2.3.3 Permafrost

Permafrost is ground that remains frozen (i.e. that does not thaw) for two or more years. Ahlenius, H. et al., (2005) writes that permafrost can reach up to 1000 m depth, as observed on the North Slope of Alaska. It has also been found in depths up to 1500 m, especially in areas with thin snow cover and low air temperature (IAOGS, 2013). Permafrost can also be found in water up to 3m deep, mainly along the coast in the north of Russia.

Permafrost has a surface active layer that thaws during summer and freezes again during autumn. On the average, the thickness of the active layer has increased in

Figure 2.11: *Iceberg (ATC, 2014)*

the Arctic over the past 16 years implying more permafrost is melting each summer (Perovich, D. K., et al., 2013). This makes permafrost unstable, resulting in difficulties in drilling activities, weakening of integrity of offshore structures, and bending of pipelines.

Figure 2.12 shows how thawing of permafrost can lead to pipe bending.

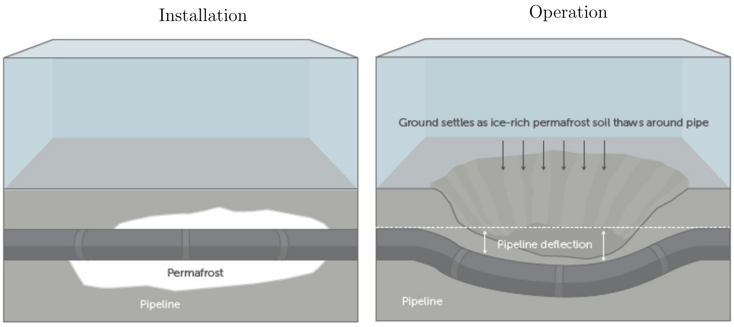

Figure 2.12: *How thawing of the active surface leads to pipe bending (PCT, 2013)*

In terms of percentage area coverage, Boyer, Y. and Szakolczai, C., (2011) classifies permafrost distribution in the Arctic as follows:

- **Continuous Permafrost**: This occupies 90-100% of the area where it is found. It is found at higher latitude areas of the Arctic, with its southern limit coinciding with the -8 °C mean annual air temperature isotherm(IAOGS, 2013).
- **Discontinuous Permafrost**: This covers 50-90% of the landscape, and is found between the -8 °C and the 0 °C isotherm (IAOGS, 2013).
- **Sporadic Permafrost**: It has a coverage of 10-50% of the landscape

- **Isolated Patches**: This occupies 0-10% of the landscape

Figure 2.13 illustrates distribution of permafrost in the Arctic.

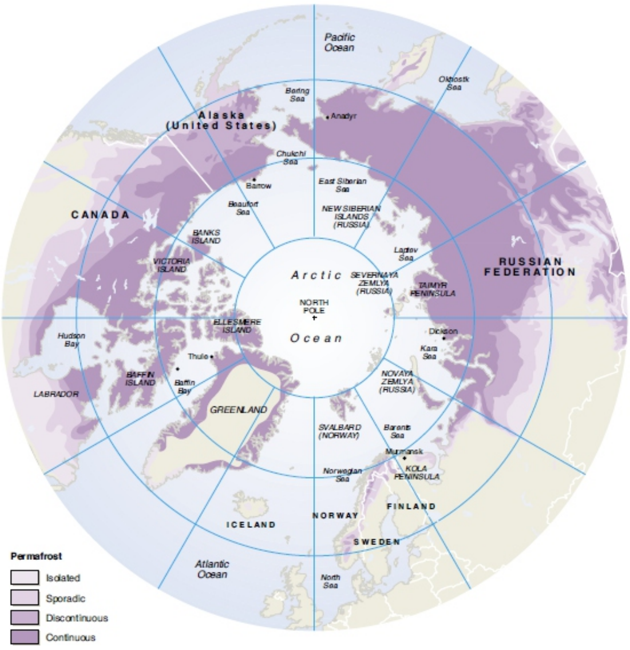

Figure 2.13: *Permafrost distribution in the Arctic (Ahlenius, H. et al., 2005)*

2.3.4 Sea Spray Icing and Atmospheric Icing

While pack ice and icebergs affect movement and usage of offshore structures in Arctic waters, sea spray icing and atmospheric icing lead to accumulations of ice and snow on the structures. These accumulations increase the gravity load of the structure and affect its stability.

Sea spray icing occurs when water (from waves) freezes on to surfaces of an offshore structure. Atmospheric icing is formation of ice on the surfaces of an offshore structure by freezing rain or drizzle, freezing fog, or snow (Løset, S., et al., 2006). Further, it is also demonstrated that the sea spray icing is the most important form of icing in the sea (Arctic and non-Arctic seas), and it also occurs more often than atmospheric icing. However, it should be noted that atmospheric icing can occur at any time of the year in Arctic seas because sub-zero temperatures are possible at any time. Atmospheric icing has been observed about 50 times per year in the Kara Sea and 80-90 times in the Laptev, East Siberian, and Chukchi Seas.

Figure 2.14 shows examples of ice accumulations on Arctic offshore structures.

Figure 2.14: *Examples of ice accumulations on offshore structures in the Arctic (Burg, L., 2007)*

Chapter 3

Hydrocarbon Potential in the Arctic

3.1 Hydrocarbon Basins and Reserves

The Arctic region contains nineteen geological basins. As stated by IAOGS, (2013), the hydrocarbon basins are distributed mainly on the continental shelf of Arctic ocean's marginal seas and on land. The Arctic Ocean basin lies within the Arctic Circle and it is the smallest of Earth's five Ocean basins. It contains a deep ocean basin, about 4500 m deep and the broad shelves of the Barents, Kara, Laptev, East Siberian, Chukchi and Beaufort Seas, the White Sea, the Lincoln Sea and the narrow shelf off Canadian Arctic Archipelago and Northern Greenland. The continental shelf contains the broad shelves of Eurasia, narrow shelves off North America and Northern Greenland, and occupies about 53% of the total area of the Arctic Ocean (Wlodraska-Kowalczuk, M., 2013).

Figure 3.1 shows the major oil and gas provinces and basins around the Arctic.

3.2 History of Oil and Gas Activity in the Arctic

Arctic is one of the world's large petroleum provinces. Around 1920s, the first Arctic onshore development started. The first oil well was drilled in Norman wells oil field in Canada. In 1958, the Mackenzie Delta was developed by Imperial Oil. Around 1960s, west Siberia fields started producing. According to IAOGS, (2013), the field is covering almost 90 percent of Russian gas production. Wendler, C. and Sharma, A., (2011) write that large oil and gas discoveries started around 1962 north of the Arctic

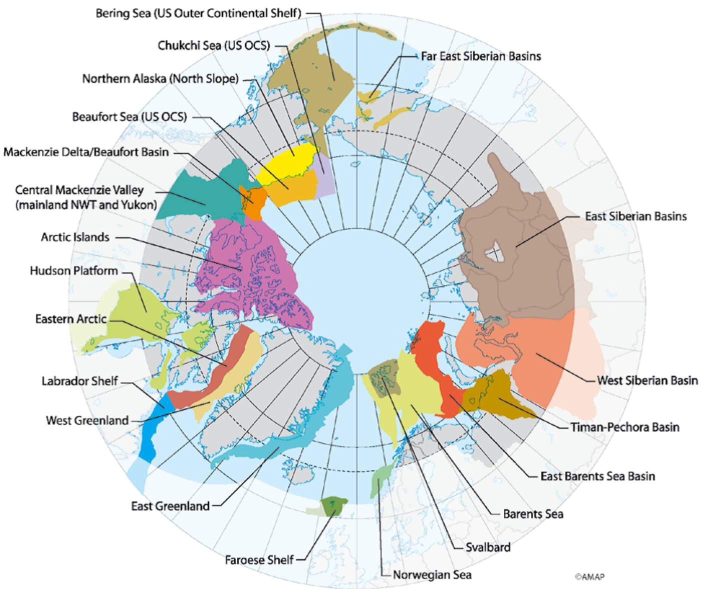

Figure 3.1: *Major oil and gas provinces and basins around the Arctic (IAOGS, 2013)*

Circle in Russia with Tazovskoye Field and in the United states around 1967, with the Alaskan Prudhoe Bay field.

By 2007 as mentioned by Gautier, D. L., (2011), the Arctic onshore developed more than 400 oil and gas fields, including 40 billion barrels of oil (BBO), 1136 trillion cubic feet (tcf) of natural gas, and 8 billion barrels of natural gas liquids in the north of the Arctic circle. Russia contains more than two-third of the onshore producing fields, mostly in the West Siberian Basin.

One-third of the Arctic circle is above sea level, the second one-third is under less than 500 m deep water in the continental shelves (Gautier, D. L., et al., 2009). The final one-third is in made up of the deep ocean basins historically covered by sea ice. Further, Gautier, D. L., (2011) document that large amount of undiscovered oil and gas of this region lies offshore under less than 500 m of water.

The first offshore development started in 1963, where the first well was drilled in the Cook Alaska. In the Arctic offshore, less than three hundred wells have been drilled, and these has indicated that this region holds a large oil and gas potential (Gautier, D. L., 2011). However, because of technical challenges, cost and remoteness, offshore development has been very slow.

Around sixty one large discoveries has been made in Russia, Alaska, Canada's Northwest Territories and Norway within the Arctic circle. Out of the sixty one fields, it is only fifteen of them that are yet to be developed (Budzik, P., 2009). While two of the fields are in Russia, eleven fields are in Canada's Northwest Territories and two fields are in Alaska. Russia has forty three fields out of the sixty one large hydrocarbon fields and thirty five of them are located in West Siberian Basin. Thirty three of the fields are natural gas fields whereas two of them are oil fields. The remaining five out of the eight large fields are in Timan-Pechora Basin, two are in the South Barents Basin, and one is in the Ludlov Saddle (Budzik, P., 2009).

Today, 15% of world's energy supply is covered by the Arctic onshore and offshore production. In the last decade, the global demand for energy increased considerably. By 2050, it is expected to be doubled and between 60%-70% of it is expected to be supplied by fossil fuels (JIP, 2014). Despite the global climate-friendly agenda, higher demand of energy is causing a further increase in exploration of Arctic oil and gas resources.

Figure 3.2 shows the Arctic region reserves on-stream from 2012-2018.

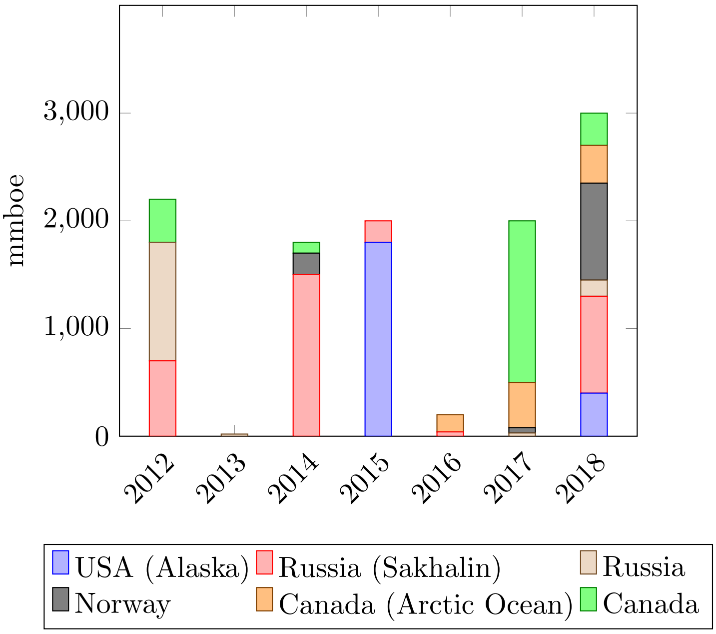

Figure 3.2: *Arctic Region Reserves On-stream 2012-2018 (Infield Systems, 2012)*

3.3 Undiscovered hydrocarbons

The Arctic region is a large unexplored area with significant recoverable conventional oil and natural gas potential. This region is expected to be one of the last and large hydrocarbon frontiers of the world. The U.S. Geological survey (USGS), and geological experts from Norway, Russia, Greenland, Denmark and Canada evaluated the Arctic hydrocarbon potential in what is known as Circum-Arctic Resource Appraisal (CARA).

The team grouped the region with at least 3km sedimentary rocks into 69 Assessment Units (AUs) (Nelder, C., 2009).

According to the USGS, the Arctic may probably have approximately 90 billion bbl of oil, 1.700 Tcf of natural gas, and 44 bbl of natural gas liquids (NGLs). Furthermore about 84% of undiscovered resources are expected to be found offshore (Ernst and Young, 2013).

Based on the USGS 2008 study estimation, the area north of the Arctic Circle is expected to hold 13% (90 billion barrels) of world's undiscovered oil reserves and 30% of undiscovered natural gas reserves mostly offshore under less than 500 m of water (Gautier, D. L., et al., 2009).

The Arctic undisvovered oil and gas reserves are distributed within few sedimentary provinces, as can be seen on the table 3.1 below. (Gautier, D. L., et al., 2009) wrote that billions BOE-plus reserves of oil and gas accomulations are estimated at 50% probability in the Kara Sea, Barents Sea, Offshore East and West Greenland, Canada and Alaska. Based on the USGS estimation, 87% of the Arctic resources which is equivalent to 360 billion barrel of oil is located into seven Arctic basin provinces, where each has 3km of sedeimetary strata. These are: West Siberian Basin, Arctic Alaska Basin, East Barents Basin, East Greenland Rift Basin, Yenisey-Khatang Basin, Amerasia Basin and the West Greenland East Canada Basin (King, H., 2014).

Table 3.1: *Arctic area mean estimated undiscovered technically recoverable, conventional oil and natural gas resources for the seven largest Arctic basin provinces, (King, H., 2014)* modified

Petroleum Province	Crude Oil (billion barrels)	Natural Gas (trillion cubic feet)	Natural Gas Liquids (billion barrels)	Total (oil equivalent in billions of barrels)
West Siberian Basin	3.66	651.50	20.33	132.57
Arctic Alaska	29.96	221.40	5.90	72.77
East Barents Basin	7.41	317.56	1.42	61.76
East Greenland Rift Basin	8.90	86.18	8.12	31.39
Yenisey-Khatanga Basin	5.58	99.96	2.68	24.92
Amerasia Basin	9.72	56.89	0.54	19.75
West Greenland-East Canada	7.27	51.82	1.15	17.06

In the Arctic marine area, offshore hydrocarbon activity is increasing very fast. Oil and Gas exploration in this region is becoming less challenging as the ice in the Arctic is melting down rapidly and thereby the water is open due to global warming. Alaska, Canada, Russia and Norway are some of the countries which already have experienced the offshore oil and gas exploitation developments.

Figure 3.3 shows an overview of the countries that share Arctic Circle.

Figure 3.3: *Overview of the countries that share Arctic Circle, (Børre, P. N. H., et al., 2014)*

3.3.1 Oil and Gas Activities in the U.S

Figure 3.4 shows the US share of the Arctic.

Alaska holds close to 25% of the US remaining proved oil reserves and 13% of the US proved gas reserves. The North Slope area of Alaska accounts for 10% of the current domestic oil production of the US (Eurasia Group).

Cohen, A., (2011) wrote that the North Slope is a region of Alaska which extends from the Canadian border on the east to the Chukchi Sea Outer Continental Shelf (OCS) on the west. Furthermore, Cohen, A., (2011) & Ernst and Young, (2013) write that Alaskan Arctic region is made up of 5 areas, and these are Chukchi Sea OCS, the Beaufort Sea OCS, the Arctic National Wildlife Refuge (ANWR), Central Arctic and the National Petroleum Reserve of Alaska (NPRA).

Between 1977 and 2004, 15 billion barrels of oil was produced in the Prudhoe Bay oil field on the North Slope. By 1988, more than 25% of the oil production of the U.S crude oil had been extracted from Prudhoe Bay oil field. However current production of this field has steeply declined (Cohen, A., 2011).

Cohen, A., (2011) further states that, the US Department of Energy report found

Figure 3.4: *U.S portion of the Arctic Circle, (Børre, P. N. H., et al., 2014):modified*

that the Alaska's North Slope has 36 billion barrels of oil potential and 3.8 trillion cubic metres (tcm), gas potential which is close to Nigeria's proven reserves. Also, the Chukchi Sea OCS and the Beaufort Sea OCS together accounts for 14 billion barrels of oil and about 2 tcm of gas.

Based on the US Mineral Management Service (MMS), the Alaska's outer continental shelf is estimated to hold around 27 billion barrels of oil and 132 tcf of natural gas. Since 1977, the production of North Slope has been around 15.5 billion barrels (IRN, 2014).

Most of the oil and gas activities in the Prudhoe Bay area are onshore. Alaska has three big important oil fields: Endicott, Point Macintyre and Northstar.

As stated by Koivurova, T. and Hossain, K., (2008), Endicott oil field is the third largest of the seven main North Slope oil fields and it is connected to the onshore Prudhoe Bay oil field via causeway to produce oil from artificial island. The second oil field, Point Macintyre is produced from the East Dock off of the Prudhoe Bay oil field. The North Star which is the third oil field is located in the Beaufort Sea. This field is at a distance of around 12 miles North West (NW) of Prudhoe Bay and 2 miles away from shore. The oil from here is transported through 10 km long first Arctic subsea pipelines to the shore.

65% of undiscovered Arctic oil and 26% of undiscovered Arctic gas is estimated to be located in the North American side of the Arctic. According to Ernst and Young, (2013), this region is specifically estimated to hold the largest undiscovered oil deposits which can be approximately about 30 billion barrels of oil.

The hydrocarbons deposits in Alaska area is estimated to have 40% of the remaining undiscovered crude oil and equivalent natural gas of this region according to IRN, (2014). From 60% to 70% of the estimated reserves are regarded to be located on offshore, beneath the shallow ice covered sea.

According to Ernst and Young, (2013), the first oil from Beaufort Sea which has a relatively shallow water and is close to existing infrastructure (i.e the Trans-Alaska pipeline system (TAPS)) is expected to come as early as 2020. The first oil from the Chukchi Sea where the water is deeper and is far from existing infrastructure is not expected to come any time before 2022.

Much of the Arctic's hydrocarbon reserves of this region have been untouched due to various reasons. However today, companies such as Royal Dutch Shell are there to run drilling exploration activities of this region.

3.3.2 Oil and Gas Activities in Russia

Figure 3.5: *Indication of Russian portion of the Arctic Circle, (Børre, P. N. H., et al., 2014)–modified*

Figure 3.5 shows the Russian share of the Arctic.

Russia's shelf and continental slope has an area of 6.2 million square kilometers, with a major part of this lying in the Arctic. Up to 80% of Russia‘s potential oil and gas reserves are concentrated on the Arctic shelf (Koivurova, T. and Hossain, K., 2008). Ninety-five percent of Russia's gas reserves and sixty percent of its oil reserves are believed to lie in the Arctic (Eurasia Group).

IRN, (2014) & Ernst and Young, (2013) write that twenty major oil and gas provinces and basins have been discovered on the Russian shelf. Ten of these provinces have proven oil and gas reserves. East Barents, South Kara, Laptev, East Siberian and Chukchi basins are the largest of the Russian Arctic sedimentary basins.

Cohen, A., (2011) adds that proven oil deposits in these large basins could be up to 418 million tons (3 billion barrels), and proven gas reserves could reach 7.7 tcm. Also, approximately 9.24 billion tons (67.6 billion barrels) of unexplored oil reserves and 88.3 tcm of unexplored natural gas reserves are expected to be present. In total, the areas are estimated to enclose up to 10 trillion tons of hydrocarbon deposits (equivalent to 73 trillion barrels of oil). Further is is reported that while most of the resources in the western part of the shelf have been found, the hydrocarbon potential of the eastern part (along the slope and in the deep Arctic basin) are contingent resources (Ernst and Young, 2013).

According to Eurasia Group, 252 wells have been drilled on the entire Russian continental shelf. While majority of the wells can be found in Barents and Kara seas in the west, Russia's shelf remains largely unexplored. Exploration in Russia's continental Arctic shelf is currently carried out by only 2 oil and gas companies: Gazprom and Rosneft (Ernst and Young, 2013). There is the chance, however, that more companies (including some smaller, private companies or subsidiaries of state-controlled companies) may have the opportunity to explore and produce oil and gas from the shelf, according to Russia's Arctic shelf development program. This would lead to increased oil and gas production from the area. Promising finds such as the supergiant Shtokman gas field and the Ledovoye and Ludlov fields in the Barents Sea, and the Rusanov and Leningrad gas fields in the Kara Sea have encouraged the Russian government and investors to pursue opportunities on the shelf (Eurasia Group).

3.3.3 Offshore Oil and Gas Activities in Canada

Figure 3.6 shows the Canadian share of the Arctic.

40% of Canada's landmass is located in the Arctic region as mentioned by (Harsem, Ø., et al., 2011). Sedimentary basins of this region have a large amount of hydrocarbon potential which makes the region more attractive.

Figure 3.6: *Indication of Canadian portion of the Arctic Circle, (Børre, P. N. H., et al., 2014)–modified*

According to Eurasia Group, Canadian Arctic is estimated to have considerable amount of undiscovered hydrocarbon reserves in in the Mackenzie Delta onshore, in the Canadian Beaufort offshore, in the Baffin Bay offshore, in the Sverdrup Basin and Arctic Islands, and in the Newfoundland and Labrador offshore.

The geological survey of Canada shows that two Arctic sedimentary basins of the regions i.e Cratonic and Arctic Margin holds around 16% of Canada's total conventional hydrocarbon resources. Significant amount of it is located in the Beaufort Sea and among the Arctic islands of the offshore region (IRN, 2014).

Eurasia Group writes that, the estimated volume of undiscovered recoverable oil to Canadian Arctic is 20.2 billion bbls of oil, 186.8 tcf of gas and 0.9 billion bbls of natural gas liquids (NGL). The area around Meckenzie delta onshore and Canadian Beaufort offshore is estimated to have a total of 8.1 billion bbls of oil, 67.1 tcf of gas, and 0.2 billion bbls of NGLs. Labrador-Newfoundland offshore estimated to hold 2.7 billion bbls oil and 57 tcf of gas. The remaining volumes are distributed in the Baffin Bay offshore, and the Sverdrup Basin and Arctic Island.

Records from (Ernst and Young, 2013) shows that between 1970s and 1980s, many important discoveries were made in Mackenzie Delta region, the Beaufort Sea basin and the Arctic islands as a result of increase in fuel price. The first offshore development of the Canadian Arctic offshore started in 1972. During this period around 90 offshore wells were drilled in Beaufort Sea, 34 offshore wells in Nunavut's High Arctic Islands and 3 offshore wells in Eastern Arctic offshore.

3.3.4 Oil and Gas Activities in Norway

Figure 3.7: *Indication of the Norwegian portion of the Arctic Circle, (Børre, P. N. H., et al., 2014)–modified*

Figure 3.7 shows the Norwegian share of the Arctic.

According to Kulander, C. and Lomako, S., (2010), one-third of mainland Norway and its coastline lie inside the Arctic Circle, thereby providing Norway a basis for its claim to portions of the Arctic.

The Norwegian sector of the high Arctic region holds the future hydrocarbon potential for Norway as the reserves in the North Sea and Norwegian Sea keep reducing. As stated by Harsem, Ø., et al., (2011), the estimate of the Arctic oil and gas reserves in this region is roughly 18.7 billion barrels of oil equivalent.

Oil and gas activities in the Norwegian Arctic are mainly located in the Barents sea (Koivurova, T. and Hossain, K., 2008). In the words of Ernst and Young, (2013), the Norwegian authorities opened the Barents Sea for exploitation in 1981, and the state-owned oil company (Statoil) discovered the huge Snøhvit field the same year. The 30-year period following this time saw Statoil and some other international players develop fields and strong foothold in the North, in part through drilling of over 80 exploration wells.

The Russia-Norway border agreement of 2010 which has allowed Norway to open up more parts of the Barents Sea has led increased interest in the area. Statoil hopes to produce one million barrels of oil equivalent per day from new Arctic wells by 2020 (Ernst and Young, 2013). Significant amount of resources (400-600 million billion barrels of recoverable oil) in Statoil's Havis and Skrugard discoveries have also generated increased interest in the Norwegian Arctic (Eurasia Group).

The Norwegian Petroleum Directorate (NPD) says the Barents Sea holds at least 345 million oil barrels of undiscovered resources (IRN, 2014).

3.3.5 Oil and Gas Activities in Greenland

Figure 3.8: *Greenland portion of the Arctic Circle, (Børre, P. N. H., et al., 2014):modified*

Figure 3.8 shows Greenland's share of the Arctic.

Based on geography, Greenland is part of North America continent and geopolitically it is counted as part of Europe, but nationally it is a part of Denmark (Ernst and Young, 2013). According to Eurasia Group, a large part of Greenland is located on the northern part of the Arctic Circle and 80% of the Island in this region is covered by ice sheet.

Late 1970's, the first exploration of offshore hydrocarbons in this region started in West Greenland and in 1976, 1977 and 1990, the result failed to indicate profitable potential of this region. However, all this changed in the summer of 2010 after the first hydrocarbon discovery was made by an independent British oil company (Ernst and Young, 2013).

East Greenland Rift basins is believed to hold the larges reserves, which is estimated to have 8.9 billion bbls of oil, 86.2 tcf of gas, and 8.1 billion barrels of NGLs. Greenland in total is estimated to hold 16.1 billion bbls of oil, 137.6 .6 tcf gas and 9.93 billion bbls of NGLs (Eurasia Group). According to USGS's 2008 appraisal, Greenland basins is estimated to hold around 17 billion barrels of oil and 138,000 billion cubic feet of natural gas (IRN, 2014).

Chapter 4

Drilling vessels for Arctic condition

The offshore drilling structures are divided into two main categories: mobile bottom supported and floating rigs, and Stationary production structures used exclusively for development wells. Floaters are classified as Semi-Submersible rigs and Drillships (Tanaka, S., et al., 2005).

The Arctic location and environment make vessel operation in this region more challenging. The offshore rigs are referred to as mobile offshore drilling units (MODU's). MODUs are mostly used for drilling exploration wells, development wells and most deep water wells. Factors that can influence the selection of rig types include cost, capability and limitation. Various types of rigs are designed to satisfy different needs. These rigs are designed to perform in unique conditions like shallow water, deep water and generally challenging weather conditions.

A lot of parameters are considered during selection of vessels for Arctic operations. These parameters are water depth (relatively shallow or deep), metocean conditions (waves, current, fog, gusty winds, wind), operating period (seasonal or year-round), very long period of darkness and very cold temperatures. In addition, operating in ice condition needs consideration of specific ice data such as main ice features (ridges, landfast ice, pack ice, icebergs, ice floes) and ice drift velocities (Pilisi, N., et al., 2011). The first category includes:

1. Jack-up rigs
2. Submersible rigs (swamp barges)
3. Anchor-stationed or dynamically positioned semisubmersible rigs
4. Anchor-stationed or dynamically positioned drillships

Drilling structures from stationary platforms used for developing offshore fields includes:

1. Self-contained platforms
2. Tender or jack-up assisted platforms or well-protector jackets

According to Hamilton, J., et al., (2011), water depth greater than 100 m is the major challenge when it comes to offshore development in High-Arctic region. Furthermore, Pilisi, N., et al., (2011) states that for deep water areas, passive design that can withstand all environmental conditions such as fixed structures that would need to resist ice sheets and ridge loads notably are not technically and economically feasible.

According to Tanaka, S., et al., (2005), the following guide line can be used as a rough basis for selection of offshore drilling rigs according to water depth, sea state and winds:

- Submersible rigs (swamp barges): for water at depth less than 25 m.
- Tender or jack-up assisted platforms: for water depth less than 50 m and calm sea.
- Self-contained platforms: for a water depth less than 400 m and mild sea:
- Jack-up rigs: for water depth from 15 m to 150 m.
- Anchored drillships or semisubmersible rigs: for water depth from 20 m to 2000 m.
- Drillships or semisubmersible rigs with dynamic positioning system: for water depth from 500 m to 3000 m.
- Drillships with dynamic positioning system: Isolated area with icebergs.
- Semisubmersible rigs or new generation: Severe sea conditions.

4.1 Jack-up Rigs

The first jack-up was built in 1954 and since then, they have become the most popular mobile offshore drilling unit (Rigzone, 2014a). A jack-up rig was defined by Harrall, J. W., et al., (1984) as any offshore platform with a hull, a jacking mechanism, legs, self-elevating and mobile. Jack-up rigs are the most common offshore drilling rigs nowadays and these types of platforms are designed specifically for the purpose of offshore exploration and development.

The jack-up rig is applied in shallow water (a water depth less than 150 m) and ice free sea. The hull of a jack-up rig is usually designed in triangular shape with three legs but other designs may have rectangular or other shapes (Tanaka, S., et al., 2005).

According to Tanaka, S., et al., (2005) & Petrowiki, (2012), there are two basic configurations of jack-up legs. The leg types are the independent-leg type and mat-supported leg type. The ocean seabed conditions and general weather conditions determine which configuration to apply.

The independent-leg type consists of three legs with lattice construction, and each leg has a spud can on its end. Greenberg, J., (2010) writes that this type of jack-up unit can be used in soft and hard seabed areas, and on sloping seabed. This leg type can also be used in areas with obstacles on the seabed, such as pipelines, boulders or other debris, which gives it an advantage over a mat supported leg type.

The mat-supported type usually has three cylindrical legs that are attached to a very large mat that rests on the ocean bottom. This type is suited to soft seabed. A main advantage of the mat-supported leg jack-up is that they are relatively inexpensive to build and leave no footprint at the drilling location. However, this jack-up unit has a number of disadvantages which include:

- It is prone to damage from objects on the seabed. They can be damaged by workboat propellers and tugs. Also, the large size of the mat and hull makes them to tow very slowly.
- Most jack-up units of this type have cylindrical legs and have structural limitations that restrict their use to shallow water depths, typically less than 75 m.
- The storage space on the open deck of the upper hull is limited.
- Sometimes, the legs can fail from wind-induced leg vibration at high winds.

Jack-up rigs is moderately stable during the process of towing. To move a jack-up rig to a location, legs are elevated. Once the rig is on location, the legs are lowered down to the bottom. For the independent leg-type, sea water is pumped into ballast tanks in the hull to pre-load the foundation of the platform, and this drives the legs into the seabed. For the mat-supported type, the mat is ”jacked down” to the seabed and the hull is ”jacked up” until it is above water, without the pre-load operation needed for the independent leg-type jack-up rig. The platform is ”jacked up” above the wave actions by means of hydraulic jacks (Petrocenter, 2014). During the operation of towing jack-up rigs, tugboat or heavy lift carrier are used. When dealing with such operation, it is very important to ensure that the weather conditions (sea state and winds) are not above the allowable parameter of that specific rig.

The advantages of a jack-up rig are as follows (Petrocenter, 2014) & (Petrowiki, 2012):

1. It is mobile.
2. It has a stable and relatively motion-free platform.
3. It has relatively low mobilization cost. Also, it is relatively quick and easy to mobilize.
4. It can operate on soft seabed.
5. It is easier to update and maintain in comparison with drillship and semisubmersible.

The disadvantages of a jack-up rig are as follows (Sheppard, D.M., 2001) and (Petrowiki, 2012):

1. It is difficult to tow.
2. It depends on weather windows for placement, and this requirement can become more challenging if much preloading sequence has to be carried out to install the legs.
3. Most jack-ups are limited to shallow water depths.
4. The rig can collapse because of soil fluidization if blowout occurs.

Figure 4.1 shows an example of a jack-up rig.

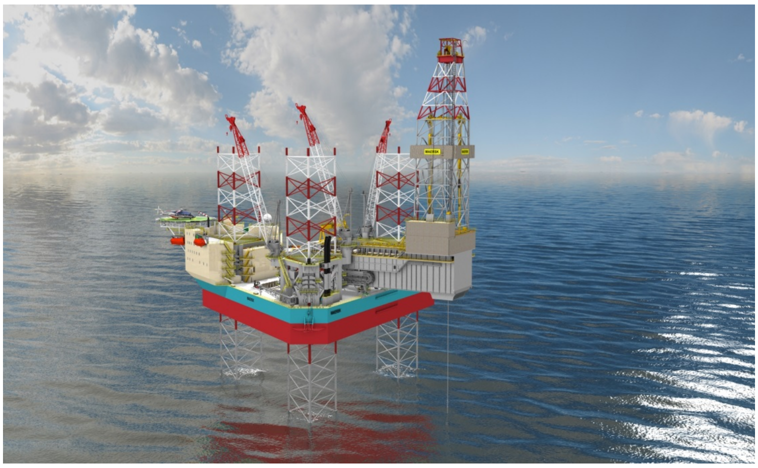

Figure 4.1: *Jack-up (OFT, 2011)*

4.2 Semi-Submersible Rig

The first semi-submersible rig, Blue water I, was developed around 1960 by Shell Oil Company from an existing four column submersible rig (OEC, 2011). Since this time, semi-submersible rigs have been characterized by many generations and today, they are the most common offshore drilling rig type.

Semi-submersible rig types are designed for exploration and production purposes. This type of drilling rig is mostly applied in water depth beyond the operational ability of Jack-up rigs. The operational water depth of Semi-Submersible rigs ranges from 70 m-1000 m, when anchoring system is used, and greater than 1000 m when the rig is kept in position using system (CAPP, 2006).

A large number of modern day semi-submersibles are rectangular and have a working platform supported by four or more vertical columns. The columns can be cylindrical, square with rounded corners or square with flat corners. The columns connect the working platform to two or more steel pontoons that float below sea level during drilling operations (Greenberg, J., 2010) & (CAPP, 2006).

Furthermore, the authors wrote that a semi-submersible can either be towed to a location or self-propelled by its own power. Once the rig is on location, the pontoons and columns are ballasted with sea water, and the rig is semi-submerged. The amount of sea water on ballast can be adjusted to lower or raise the platform here. When the pontoons are submerged, the rig will move less; the deeper the pontoons get, the less effect of wave actions will be on the rig. When the operation on the current location is over, the seawater on the pontoons and columns are deballasted, and the rig can be ready to move to another location.

Usually, semi-submersible rigs have an opening in the hull called a moonpool at the center or near to center of the rig. Drilling operation is run through the moonpool. Semi-submersible rig has several advantages. Some of these are:

1. It is less sensitive to water depth
2. It is easy to move using tug boats and has a high transit speed.
3. It has a large deck (working) area.
4. It has a good wave, wind and current resistance from any direction.

Some of the disadvantages of this type of rig are (Sheppard, D.M., 2001):

1. It has a high initial cost and high rig rate.
2. It has limited deck load capacity.
3. It is prone to structural fatigue.

4. It is difficult to handle mooring system and land BOP stack and riser system in a rough sea.
5. It is expensive to move it over a large distance

Figure 4.2 shows an example of semi-submersible rig.

Figure 4.2: *Semi-submersible rig (Staalesen, A., 2013)*

4.3 Drillships

Drillship is a marine vessel with physical, structural and functional modifications for drilling oil and gas wells, and drillships are the most mobile offshore unit. In the late of 1940s, the first drillship was developed by marine architects (Rigzone, 2014b).

According to Tanaka, S., et al., (2005), the first offshore drillship operation started in 1953, and in 1961 the first dynamic positioning system was mounted on the rig. Drillships are mounted with all drilling and completion equipment. Just like semi-submersible rigs, a drillship has a moonpool at the center of the hull, where drilling operations are conducted through the drilling derrick. Drilling equipment is lowered through the moonpool to the subsea well by passing it through a flexible riser that runs from the vessel to the well.

Drillships are able to operate in water depth far beyond the limit of jackups and semisubmersible rigs. The operational water depth of such types of rig ranges from 200 m-1000 m when using anchoring system, and more than 1000 m when using dynamic positioning as the station keeping system. Drillships are typically used in deep and ultra-deep water. They have a large storage volume for fuels, water and other supplies that can be useful during operation. This enables drillships to operate in remote areas for a long period with limited support (CAPP, 2006) & (Rigzone, 2014b).

Since they are basically ships, drillships do not need to be towed to and from the field i.e. they self-mobilize and self-demobilize. Drillship are mainly used for offshore drilling exploration, but they can also be used to perform well maintenance or completion works such as casing and tubing installation or subsea tree installation (QGOG, 2014).

Advantages of drillship are as follows (Day, H. and Springett, C., 2002) and (Sheppard, D.M., 2001):

1. It is mobile and has a higher transit speed (up to 16 knots)
2. It has higher load capacity than jack ups and semi submersible rigs
3. Its initial and operating costs are low, and it also has low cost of mobilization.
4. It has large storage volume

Disadvantages of drillship are as follows (Greenberg, J., 2010) and (Sheppard, D.M., 2001):

1. It is more prone to wave, wind and current than a semi-submersible rig
2. It has less stability in rough sea.
3. It has small deck area
4. It has low freeboard.

Figure 4.3 shows an example of drillship.

Figure 4.3: *Drillship (ICTMN, 2012)*

4.4 Usability of the Discussed MODUs in Arctic Conditions

4.4.1 Jack-up Rigs

Apart from water depth limitations, a challenge that can be faced by a jack-up rig is the exposure of equipment in the splash zone. Lattice type leg designs can also be subjected to very high local ice loads in addition to ice accumulation (from sea spray icing and atmospheric icing) on the jack-up structure, leading to very high bending load on the platform legs. High ice loads on the legs also imposes overturning moment on the jack-up structure; a challenge that increases as the water depth increases. Furthermore, horizontal loads from ice on the legs can lead to sliding of the jack-up unit. Considering that the rig is suited to shallow waters, solving these challenges will enhance its performance in shallow water areas of the Arctic.

4.4.2 Semi-Submersible Rigs

Just like a jack-up rig, exposure of equipment in the splash zone is a significant challenge for a semi-submersible rig. The space between the columns can also be clogged by sea ice, which can lead to high sea ice loading on the structure. A semi-submersible rig also has a relatively low deck load capacity which limits its storage capacity. It may also be challenging to move off the field to avoid unmanageable ice features since multiple point detachment of mooring lines, and single or multiple points detachment of risers may be required depending on how they are connected to the platform hull (Aggarwal, R. and D'Souza, R., 2011). These challenges make the rig unsuitable for high Arctic areas. However, considering that the semi-submersible rig has very good motion characteristic in harsh environments, it can be applied in sub-Arctic areas with restrictions.

4.4.3 Drillships

Unlike a jack-up rig and a semi-submersible rig, the ship-shaped construction of a drillship makes its moonpool to shield equipment from exposure in the splash zone. The drillship has high deck load capacity and good transit speed which make it suitable for use at distances far away from supply locations such as experienced in high Arctic areas. However, drillships can also be affected by sea ice if the hull is not sufficiently ice-strengthened. Furthermore, in harsh environments, a drillship is prone to more motions than a semi-submersible, but it will still be able to operate in such environments by applying appropriate station keeping systems.

4.4.4 Rig Selection Matrix for the Arctic

By considering the capabilities and limitations of the different rigs as discussed in the previous sections, the selection of rig types for different Arctic areas was summarized in Wassink, A. and v.List, R., (2013) as follows: Table 4.1 shows rig type selection matrix.

Table 4.1: *Rig type selection matrix (Wassink, A. and v.List, R., 2013)*

Area	Jack-up	Semi Submersible	Ship Shaped
High Arctic (Beaufort, Chukci, Northern Greenland, Kara, East Siberian)	+[1]	−	++
Sub Arctic (Seasonal High arctic and periodic ice infested such as southern Greenland, Barents)	+[1]	+	++
Winterized / Harsh Environment	+[1]	++	+

4.5 General Solutions to Improve Performance of Rigs in the Arctic

While different rigs have different specific challenges, there are some challenges that are common to all the rigs. Figure 4.4 illustrate two-stage ice management wherein ice breakers reduce ice floes to sizes manageable by a stationary drilling vessel.

The solutions to some of the common challenges are as follows (Aggarwal, R. and D'Souza, R., 2011) and (Wassink, A. and v.List, R., 2013):

- **Ice management**: This is necessary to protect the rigs from potential interaction with large ice features or icebergs. Ice management as "the process of protecting a stationary vessel in moving ice by using icebreakers working upstream of the vessel to create a continuous channel of thoroughly broken up floes" (Hamilton, J., et al., 2011). A good ice management program could help to reduce maximum ice loads within tolerable limits for the station keeping system and the vessel hull. The icebreakers can be used to break up drifting ice to sizes that exert reduced and tolerable loads on drilling rigs on site. They can also be used to clear away ice during tow away of drilling rigs. The performance of icebreakers has been enhanced recently with the use of modified bow design and azipod propulsion system. Efficient reduction of size of drifting ice is achieved usually by using multiple stages of ice breaking. For instance, a two-stage operation will involve using a first-stage or primary icebreaker to

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[1] Limitations in water depth apply

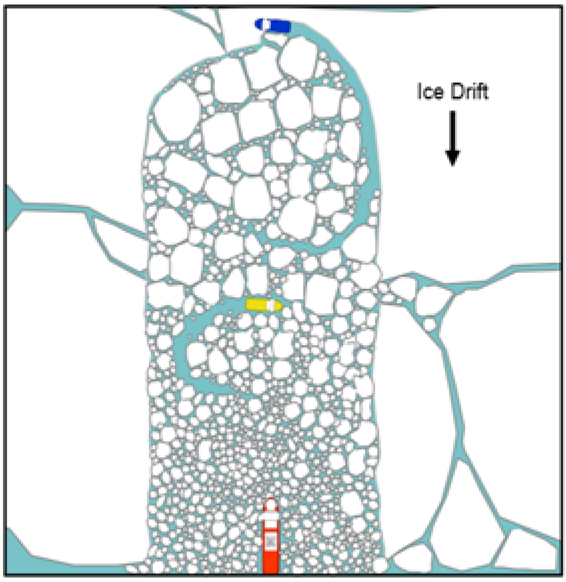


Figure 4.4: *Two-stage ice management (Hamilton, J., et al., 2011)*

break large drifting ice into sizes that can be further broken into smaller floes by the second-stage icebreaker. The two-stage ice management was applied in the 2004 Arctic Coring Expedition (ACEX). Two icebreakers; the nuclear powered Sovietsky Soyez and the Oden, were used to reduce floes to sizes manageable by the drilling vessel called Vidar Viking (Hamilton, J., et al., 2011).

In open water season, icebergs or ice ridges can be towed off to avoid collision with the drilling rig, by using one or several towing vessels with synthetic lines (Pilisi, N., et al., 2011).

- **Hull and leg structural design**: To operate effectively in high Arctic areas, the hull of drillships and jack-up rigs should be ice-strengthened to withstand ice loading. An inverted cone transition section can also be applied to the legs of jack up rigs and semi-submersible near the water line to break ice by bending downwards. This is because failure of ice sheet by crushing on a vertical surface generates significantly higher load than its failure by bending. The hull of a jack-up rig can also be made with a sloped design (like the inverted cone) to reduce ice loads when the unit is in floating mode.

Figure 4.5 shows downward breaking of ice by inverted cone-like shape.

- Winterization: Topsides and hulls of platforms in the Arctic should be designed with considerations to effects of very low temperatures. Winterization simply means enclosing working areas and equipment to prevent exposure of personnel to extremely cold temperature and to improve equipment reliability. It also

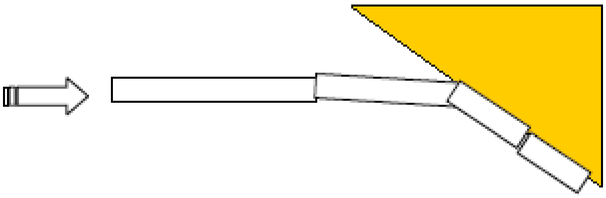


Figure 4.5: *Illustration of inverted cone design (Aggarwal, R. and D'Souza, R., 2011)*

helps to reduce reliance on anti-icing measures on the platform. In addition, it is important for flow assurance in risers, flowlines and exposed pipes. Apart from having enclosed topside, some other possible winterization measures include heating of hull compartment, and design of topside modules to reduce ice accumulation (Aggarwal, R. and D'Souza, R., 2011).

- Systems for detachment (during emergency abandonment) and reattachment (when the drilling rig returns to site) of risers and mooring lines must be fast.

4.6 Specific solutions to jack-up and drillship challenges in the Arctic

Wassink, A. and v.List, R., (2013) suggested some solutions to the specific challenges faced by jack-up rigs and drillships in the Arctic environment. They are as follows:

4.6.1 Jack-up Rigs

- Leg design: Since the braces of the lattice leg construction are prone to high ice loads, circular tubular legs can be considered.
- Overturning moment: The large overturning moment which results from ice loading as water depth increases can be countered by making jack-up platforms larger and with larger leg separation to make the units more stable. This has the additional advantage of increasing the deck area and reducing the chance of having ice floes clogged between the legs.
- Sliding resistance: The danger of sliding of the jack-up unit under the action of horizontal ice loads can be worsened by the soil condition at the drilling site

offers less resistance against sliding. Large skirted spud cans can be applied to the legs of the jack-up unit to improve its sliding resistance.

- Protection of drillstring in exploration mode: To prevent interaction of sea ice in the splash zone with the drillstring, a retractable protective sleeve can be used to shield the drillstring and subsea equipment in the splash zone.

Figure 4.6 illustrate a winterized jack up with circular legs.

Figure 4.6: *Winterized jack-up rig (Wassink, A. and v.List, R., 2013)*

4.6.2 Drillships

The choice of a good station keeping system helps to tackle most of the main challenges faced by a drillship. The three types of station keeping system that can be applied in drillships are dynamic positioning, spread mooring, and turret mooring.

Station keeping by means of dynamic positioning is provided by a number of thrusters and propellers on the vessel. A dynamic positioning system allows for fast start of operations on the field because no mooring lines are required. The system also makes it possible to weather vane or ice vane a drillship (i.e. to head the vessel into the prevailing direction of environmental conditions so as to keep the resulting motions and environmental loads with the limit of the vessel). However, the system is limited only to large water depths. It also consumes large amount of fuel and creates large emissions because high ice loads require large thruster power.

Spread mooring is achieved by anchors and mooring lines secured to winches on a fixed position on the drillship. This system fixes the drillship heading into a particular direction, thereby making it difficult to weather vane or ice vane it. This makes it challenging to reduce the vessel motions and mooring loads. This also limits the prevailing maximum ice thickness under which the vessel can operate. This means there must be means of detaching the mooring lines when necessary to prevent the occurrence of mooring loads (from sea ice) beyond the capacity of the mooring lines. However, advantages of the spread mooring include its ease of installation and the fact that it does not require power (hence no fuel consumption).

Turret mooring is provided by anchors and mooring lines attached to the turret of the drillship. Unlike spread mooring, turret mooring allows weather vaning and ice vaning of the drillship, thereby allowing it to take more mooring loads from sea ice, even in harsh sea ice conditions. It also makes it possible to reduce the vessel motions. In addition, thruster assisted mooring is possible with a turret mooring system, which improves the vessel operability. Turret mooring also reduces fuel consumption, just like spread mooring. However, it is more difficult to install than spread mooring, and also requires disconnection features to avoid mooring loads beyond the capacity of the mooring lines.

Considering the importance weather vaning and ice vaning, and the need to be able to leave the drilling site as fast as possible when the weather becomes very harsh, drillship station keeping in the Arctic should be based on dynamic positioning and turret mooring.

Chapter 5

Plug and abandonment (P&A)

This chapter will focus mostly on permanent plug and abandonment (PP&A) of subsea wells because the wells in the Arctic will typically be of this type.

5.1 Platform and Subsea P&A

The P&A technique applied on a field depends on the nature of wells present. A fixed installation with platform wells such as Statfjord would require platform P&A. Performing this operation on such an installation typically involves skidding the platform derrick to the relevant well slot. However, so as to sustain production, it is important that the derrick is dedicated to drilling of new wells. Hence, the focus of platform P&A operations should be to transfer operations to wireline (WL), coiled tubing (CT), and jacking units.

On the other hand, the number of subsea wells on the Norwegian Continental Shelf (NCS) keeps growing. Most of these wells are in subsea to shore developments (e.g. Ormen Lange) or tied back to existing platforms (e.g. Tordis to Gullfaks C platform). These wells would require subsea P&A and would have some unique challenges different from those of platform P&A. Subsea P&A typically involves the use of rigs with expensive day rates, such as semi-submersibles. Hence, there is large focus on moving parts of the subsea P&A work to cheaper light well intervention vessels (Vralstad, T., et al., 2014).

Due to water depth limitations and the need to be able detach from the well as ice load increases or as icebergs approach, fixed platforms are not ideal for Arctic activities. Mobile offshore units such as jack-up rigs, semi-submersibles, and Floating, Production, Storage and Offloading vessels (FPSOs) are more suitable for the Arctic. The need to be able to move off the field to avoid unmanageable ice features and adverse weather conditions means Arctic wells must be subsea wells. Therefore, this thesis will focus on subsea P&A.

Of all the mobile offshore units, FPSOs are the most suitable to Sub-Arctic and High Arctic areas. According to Rigzone, (2014c), FPSOs are ship-shaped which gives them characteristics such as weather vaning and ice vaning which allow for high mooring loads; moonpool which shields equipment in the splash zone, and ease of detachment of mooring and risers (especially for turret moored FPSOs) as ice load increases. Connection of FPSOs to the seabed by mooring lines means they are effective for operations in deepwater areas such as found in the Arctic. FPSOs also have storage space for produced hydrocarbons, an important feature in the Arctic environment where remoteness and lack of infrastructures such as pipelines for transferring products to shore are main challenges. FPSOs are connected to subsea wells by means of risers.

Figure 5.1 shows an example of a turret-moored FPSO.

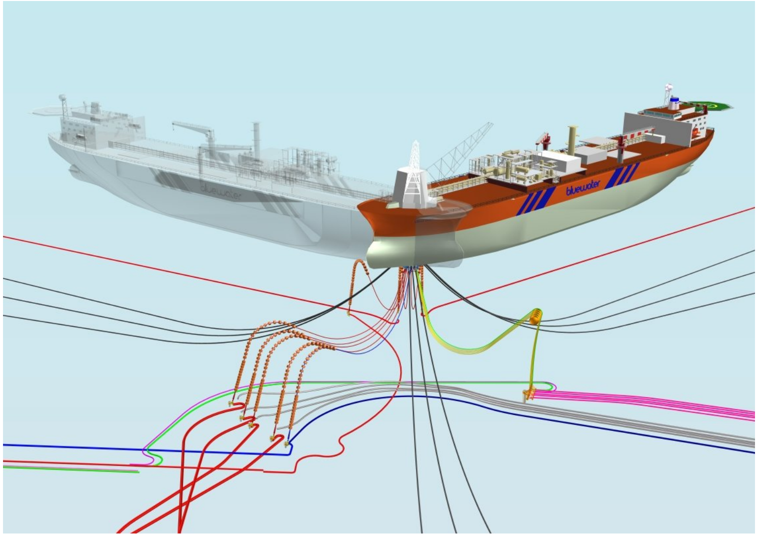


Figure 5.1: *Weather/ice vaning of turret-moored FPSO (Bluewater, 2013)*

5.1.1 Vessels for Subsea P&A

This section discusses the UKOAA classification of vessel technology and the categories of subsea P&A vessels.

5.1.2 Oil and Gas UK standard for well abandonment operations (UKOAA) classification of vessel technology versus P&A complexity and phases

Depending on the complexity of abandonment work for each of the well abandonment phases (see section 5.7) Oil and Gas UK standard for well abandonment operations Oil and Gas, UK; (2011) uses digits (0 to 4) to classify the work type and vessel requirements for P&A as follows:

TYPE 0: No work required – A phase or phases of abandonment work may already have been completed

TYPE 1: Simple Rig-less Abandonment - Using wireline, pumping, crane, jacks. Subsea will use Light Well Intervention Vessel and be riser-less

TYPE 2: Complex Rig-less Abandonment - Using CT, HWU, wireline, pumping, crane, jacks. Subsea will use Heavy Duty Well Intervention Vessel with Riser

TYPE 3: Simple Rig-based Abandonment - requiring retrieval of tubing and casing

TYPE 4: Complex Rig-based Abandonment – May have poor access and poor cement requiring retrieval of tubing and casing, milling and cement repairs

Table 5.1 from UKOOA can be used to record the complexity and methodology to be applied in each well abandonment phase:

Table 5.1: *Location, Abandonment Complexity Type and Abandonment Phase (Oil and Gas, UK; 2011)*

Location (Single Well, Field, or Platform) (Maybe offshore or onshore)			Abandonment Complexity				
			Type 0 No Work Required	Type 1 Simple Rig-less	Type 2 Complex Rig-less	Type 3 Simple Rig-based	Type 4 Complex Rig-based
Phase	1	Reservoir Abandonment					
	2	Intermediate Abandonment					
	3	Wellhead Conductor Removal					

5.1.2.1 Categories of Subsea P&A vessels

Subsea P&A operations can be conducted with a drilling rig or a rigless vessel. Vessels and rigs considered for subsea P&A are commonly categorized as Category

A vessels, Category B vessels, and Category C vessels. Figure 5.2 shows these vessel categories.

Category A Vessels

These are Light well intervention (LWI), or more precisely, Riserless Well Intervention (RLWI) vessels. They are of monohull construction and with use of WL, but with no use of risers. According to Vralstad, T., et al., (2014), these vessels have been in use on the Norwegian Continental Shelf (NCS) since the early 2000s and have been seen to be cost efficient for intervention activities of subsea wells. As a result of this, the future aim of subsea P&A is to perform full permanent abandonment with these vessels, without need of expensive semi-submersibles of the Category C vessel classification (Eshraghi, D. T., 2013). Significant cost and duration savings have already been recorded by transferring some subsea P&A tasks typically carried out by rigs to these vessels (Vralstad, T., et al., 2014). P& A Lecture Notes, (2013), writes that LWI vessels can be used to perform preparatory works such as anchor setting before the drilling rig comes to site, and some phase 1 tasks of well abandonment like logging, killing the well, setting temporary plugs, and removing xmas tree. These vessels can also be used for phase 3 tasks and have also been used for phase 2 job such as setting surface plug using the Suspended Well Abandonment Tool (SWAT).

An extension of Category A vessels was presented further, on P& A Lecture Notes, (2013). These are monohull vessels that use rigid risers, and can perform both WL and CT. They are also equipped with heavy lift cranes. All these make it possible for the vessels to perform more P&A tasks.

Category B Vessels

This is a semi-submersible type rig which will come on stream in 2015 and is intended to bridge the gap between Category A and Category C vessels. According to Eshraghi, D. T., (2013), Category A vessels are limited although they are cost effective and very effective for light intervention tasks, while Category C vessels are very expensive although they can carry out all forms of intervention tasks. The Category B vessel will have integrated equipment like WL and be able to perform heavy interventions like CT, and will be useful for some lifting operations.

Category C Vessels

These are traditionally semi-submersibles and can perform all operations needed to securely plug and abandon a well. However, they have limited availability, they are very expensive as they have high daily rates, and they move slower between different locations when compared with Category A vessels. With the use of Category A vessels for some of the tasks carried out by Category C vessels, it will be possible to release the latter to their originally intended purpose of drilling and completion of new wells and thereby increase oil recovery potential (Saasen, A., 2013).

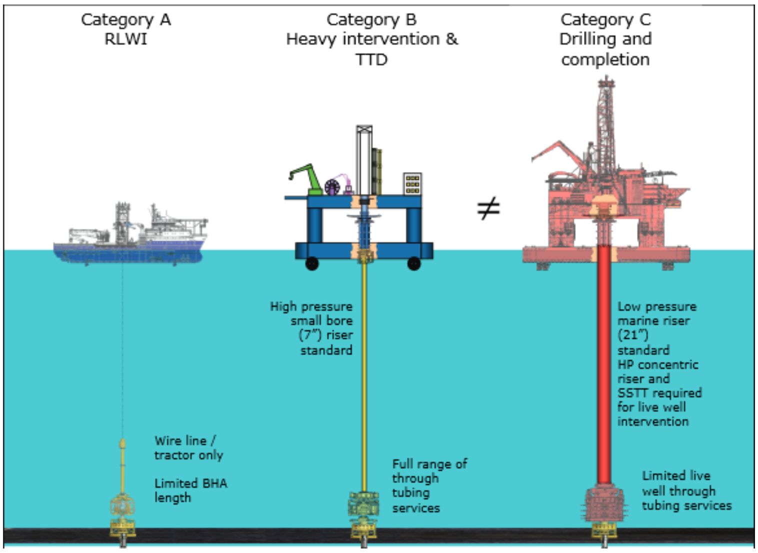


Figure 5.2: *Categories of Subsea P&A vessels (Fjaertoft, L. and Sonstabo, G., 2011)*

For Arctic operations, P&A with Category A vessels should be given utmost consideration. This is because in addition to being cost effective, these vessels are ships just like the drillships discussed in chapter 4. The vessels will have good ice vaning and weather vaning characteristics in the Arctic. P&A tools deployed through the moonpool of these vessels will be shielded in the splash zone, unlike in semi-submersibles. Ice accumulation as experienced between the columns of semi-submersibles is not a challenge for the vessels. Coupled with ice management and winterization, ice-strengthening the hull of the vessels will enhance their operability in the Arctic (Fjaertoft, L. and Sonstabo, G., 2011).

5.2 Terms and Definitions

P&A is an operation performed during process of exploration and exploitation of oil and gas, where the wells are plugged and abandoned for technical, economical and environmental reasons. P&A operations are complicated with severe consequences such as oil leakage and therefore require very detailed planning. Usually P&A operations are done on production wells that are no longer producing due to economic viability or "depletion" and wells that are intended for future use but need temporary closure for maintenance or other technical reasons. P&A operation can also be done during slot recovery and on exploration pilot holes. An oil and gas well can either be temporarily or permanently abandoned. Temporary abandoned wells are all wells/wellbores that are not on life stream or permanently abandoned. Live wells can be defined as production/injection wells that are under current injection or production operation. The purpose of plugging of a well is to isolate and protect all fresh and near fresh water zones and prevent, leaks into the well or from the well to surrounding environment (create a temporary or permanent seal).

The Norwegian Standards for the Petroleum Industry NORSOK D-010 rev-4 - Well Integrity in Drilling and Well operations defines terms related to P&A as follows:

1. Plug: A device or material placed in the well with intention to function as a foundation or as a qualified well barrier element.

2. Plugging: The operation of securing a well by installing required well barriers.

3. Temporary abandonment is defined as:

    - Temporary abandonment – with monitoring: Well status where the well is abandoned and the primary and secondary well barriers are continuously monitored and routinely tested. If the criteria cannot be fulfilled, the well shall be categorized as a temporary abandoned well without monitoring.

    - Temporary abandonment – without monitoring: Well status, where the well is abandoned and the primary and secondary well barriers are not continuously monitored and not routinely tested.

4. Permanent abandonment

    Well status, where the well is abandoned permanently and will not be used or re-entered again.

    Furthermore, Norsok D-010, (2013) states that the maximum abandonment period for temporary abandonment-without monitoring plugging shall be three years. The standard requires that a visual observation program will be set up for subsea wells without monitoring. Risk assessment shall be carried out to access the frequency of the program, and the frequency shall not exceed one year. For the one with monitoring, there is no maximum abandonment period.

    The future plan for a well to be temporarily abandoned and the planed abandonment duration shall be documented before abandonment process. Safe re-entrance into the well during temporary abandoned duration is required.

5.3 Well barriers

5.3.1 Definition and classification of well barrier

A well barrier function is to prevent, control or mitigate the risk of uncontrolled or undesired out flow to the external environment. Well barrier are defined as follows (Norsok D-010, 2013):

Well barrier : envelope of one or several well barrier elements preventing fluids from flowing unintentionally from the formation into the wellbore, into another formation or to the external environment.

Well barriers are applied in P&A operations and other active well operations as drilling, completion and production wells. The main objectives of well barriers are to:

- To prevent unexpected fluid flow from the formation to surrounding area, either during production phase or well operation.
- To shut in the well during emergency situations thereby preventing fluid flow from the well. A well can have one or several well barriers, and according to reference (Norsok D-010, 2013), well barriers are classified as follows:

Primary well barrier : first well barrier that prevents flow from a potential source of inflow

Secondary well barrier : second well barrier that prevents flow from a potential source of inflow

In places where there are two reservoir formation zones, a secondary well barrier for the first reservoir formation zone may work as a primary well barrier for shallower permeable formation zone when the well barrier element is designed to satisfy the requirements for both formation zones. In many cases, a well barer will consist of several barer elements which enevelope the hydroccarbons.

Well barrier element (WBEs) : a physical element which in itself does not prevent flow but in combination with other WBE's forms a well barrier.

Although temporary P&A and P P&A well barriers have the same functional requirements, consideration is given to abandonment time, the ability to re-enter the well, or resume after temporary abandonment when choosing WBEs.

5.4 Classifications of Well Barriers and Schematics

According to Norsok D-010, (2013), well barriers are classified based on their function and depth positions.

Table 5.2 shows the overview of the different types of well barriers with their function and depth positions.

Table 5.2: *Different well barriers with their function and depth position (Norsok D-010, 2013)*

Name	Function	Depth Position
Primary well barrier	To isolate a source of inflow, formation with normal pressure or over-pressured/impermeable formation from surface to seabed	The base of the well barriers shall be positioned at a depth where formation integrity is higher than potential pressure below.
Secondary well barrier	Back-up to the primary well barrier, against a source of inflow	As above
Cross flow well barrier	To prevent flow between formations (where crossflow is not acceptable). May also function as primary well barrier for the reservoir below.	As above
Open hole to surface well barrier	To permanently isolate flow conduits from exposed formation(s) to surface after casing(s) are cut and retrieved and contain environmentally harmful fluids. The exposed formation can be over-pressurized with no source of inflow. No hydrocarbons present.	No depth requirement with respect to formation integrity

5.4.1 Well barrier schematics (WBS)

Well barrier schematics are used to illustrate well barriers and they shall be prepared for each well activity and operation. Different colours are used to illustrate well barriers; primary well barriers are shown in blue and secondary well barriers are shown in red.

Figure 5.3 illustrate well schematics prior to P&A .

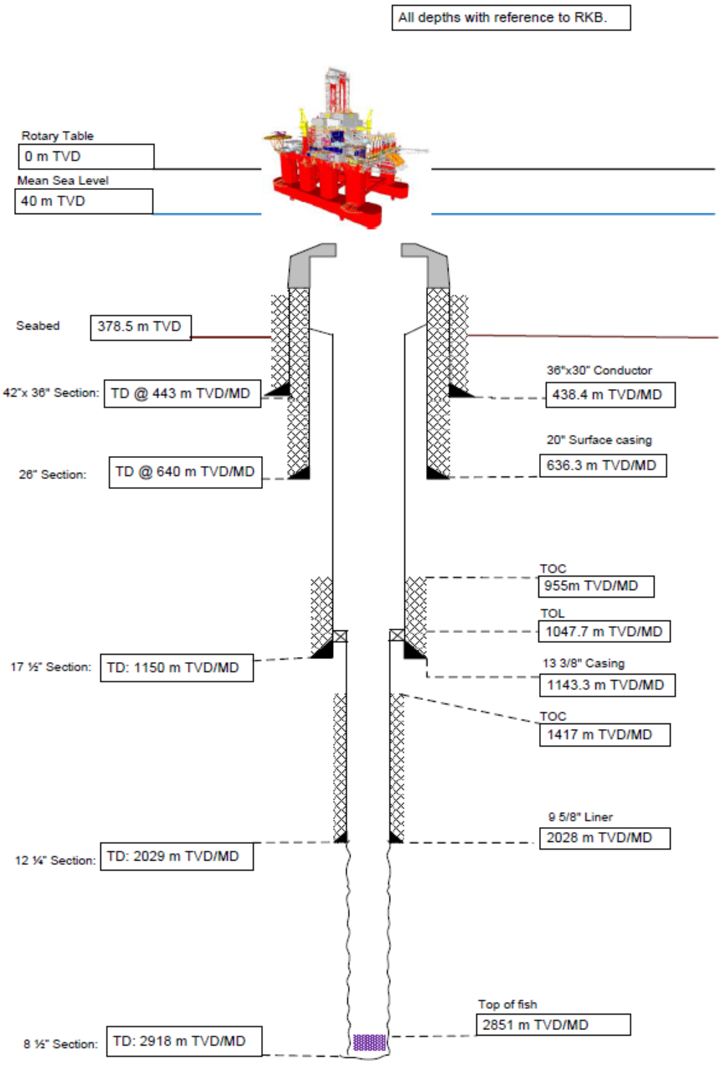
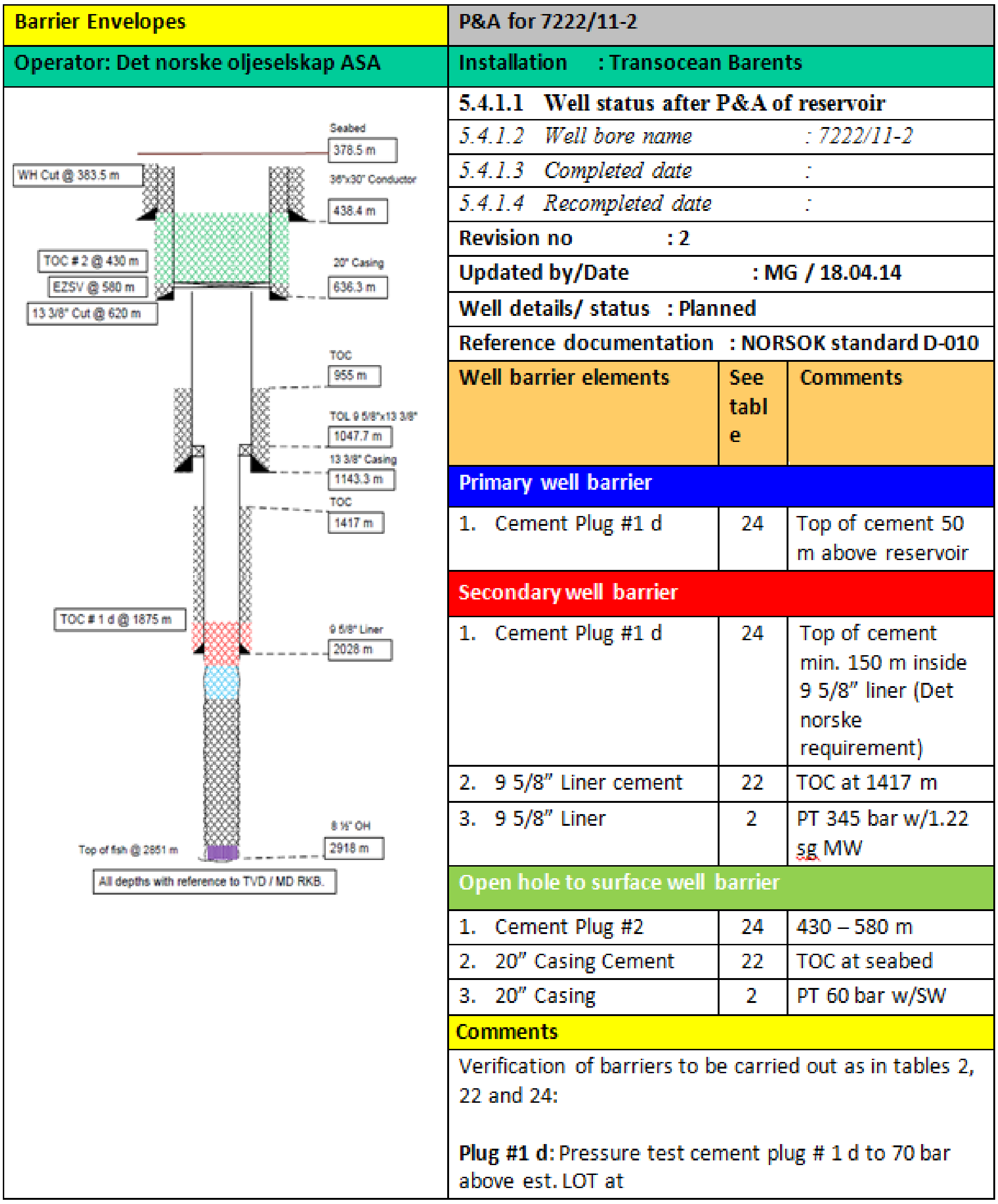


Figure 5.3: *Well schematic prior to P&A (Det Norske Oljeselskap Report, 2014)*



Barrier Envelopes

P&A for 7222/11-2

Operator: Det norske oljeselskap ASA

Installation : Transocean Barents

5.4.1.1 Well status after P&A of reservoir

5.4.1.2 Well bore name : 7222/11-2

5.4.1.3 Completed date :

5.4.1.4 Recompleted date :

Revision no : 2

Updated by/Date : MG / 18.04.14

Well details/ status : Planned

Reference documentation : NORSOK standard D-010

Well barrier elements	**See table**	**Comments**
Primary well barrier		
1. Cement Plug #1 d	24	Top of cement 50 m above reservoir
Secondary well barrier		
1. Cement Plug #1 d	24	Top of cement min. 150 m inside 9 5/8" liner (Det norske requirement)
2. 9 5/8" Liner cement	22	TOC at 1417 m
3. 9 5/8" Liner	2	PT 345 bar w/1.22 sg MW
Open hole to surface well barrier		
1. Cement Plug #2	24	430 – 580 m
2. 20" Casing Cement	22	TOC at seabed
3. 20" Casing	2	PT 60 bar w/SW

Comments

Verification of barriers to be carried out as in tables 2, 22 and 24:

Plug #1 d: Pressure test cement plug # 1 d to 70 bar above est. LOT at

Figure 5.4: *Well barrier schematic after P&A operation (Det Norske Oljeselskap Report, 2014) & (Norsok D-010, 2013)*

5.5 Properties of Permanent Well Barrier

The functions of well barrier elements are to seal permeable formation and prevent any inflow or leakage in any direction. In Norsok D-010, (2013), it is stated that a permanent well barrier element is required to extend across the full cross-section of the well, include all annuli and seal both vertically and horizontally. The barrier should be placed in adjacent to an impermeable formation. The fracture pressure of the formation must exceed the acting potential internal pressure.

Figure 5.5 shows requirement for permanent well barrier element.

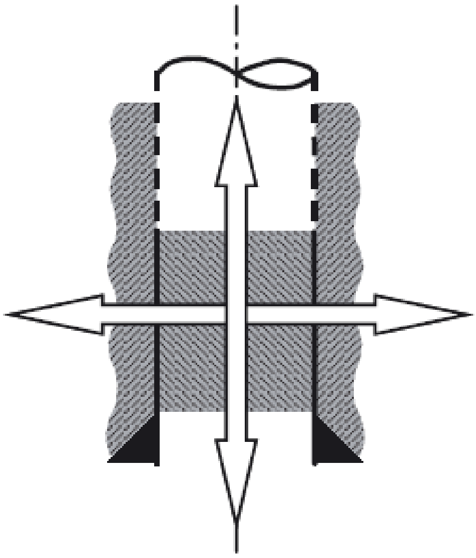


Figure 5.5: *Requirement for permanent well barrier element (Norsok D-010, 2013)*

Furthermore, Norsok D-010, (2013) states that the following features must be possessed by permanent abandonment well barrier:

1. Provide long term integrity (eternal perspective)
2. Impermeable
3. Non-shrinking
4. Able to withstand mechanical loads/impact
5. Resistant to chemicals/ substances (H2S, CO2 and hydrocarbons)
6. Ensure bonding to steel
7. Not harmful to the steel tubulars integrity

5.6 Well Barrier Requirements

When dealing with drilling and well activities, there are certain requirements that must be met and it also good to understand the barrier element functions.

According to section 4.2.3.1 of Norsok D-010, (2013), there shall be minimum one well barrier in place when there is a cross flow between two formation zones, where there is normally pressured formation with no hydrocarbon and no potential to flow to surface or abnormally pressured hydrocarbon formation with no potential to flow to surface. Whereas on formations that bear hydrocarbon and formations with abnormal pressure and has a potential to flow to surface, minimum of two barrier elements are required.

Presented below are the functional requirements of some common well barrier elements (Norsok D-010, 2013):

Creeping formation (Chapter 15.52 , Table 52 of (Norsok D-010, 2013))

The element consists of a creeping formation and is found in the annulus between the casing liner and the borehole wall. It provides continuous, permanent and impermeable seal to prevent flow of formation fluids. The requirements for verification of creeping formation include among others:

- Verification of position and length of the element shall be by bond logs.
- Application of pressure differential across the interval shall be used to verify the pressure integrity.
- Leak Off Test (LOT) at the base of the interval shall be used to verify formation integrity. The results of the test shall be in accordance with the expected formation stress from the field model.

Casing cement (Chapter 15.22, Table 22 of (Norsok D-010, 2013))

It consists of solid cement in the annulus between the casing strings or the casing/liner and the formation. It provides continuous, permanent and impermeable seal along the casing annulus or between casing strings, to prevent inflow of formation fluids and provide structural support for casing or liner strings.

The length of planned casing cement shall be:

General : minimum 100m MD above a casing shoe/window

Conductor : depends on structure integrity requirement.

Surface casing : depends on the load conditions from wellhead equipment and operations. Top of cement (TOC) should be at surface/seabed.

Production casing/liner : minimum of 200 m MD above a casing shoe. However, 200 m MD above the source of inflow shall be used if the casing penetrate the source of inflow.

Note: when unable to meet the requirements when running a production liner, the length of the casing cement can be combined with previous casing cement to satisfy the 200 m MD requirement. The requirements for verification of casing cement plug include:

- Formation integrity test shall be used to verify the cement sealing ability when the casing shoe/window is drilled out
- Verification of cement length shall be by bonding logs or 100 % displacement efficiency based on records from the cement operation.
- The actual cement length for a qualified Well Barrier Element (WBE) is required to be:
  - Above a potential source of inflow.
  - 50 m MD or 30 m MD when verified by displacement calculations or bonding logs respectively, and the formation integrity shall exceed the maximum expected pressure at the base of the interval.
  - 2 x 30 m MD verified by bonding logs when the same casing cement will be a part of the primary and secondary well barrier.

Cement plug (Chapter 15.24, Table 24 of (Norsok D-010, 2013))

It consists of a solid cement which forms a plug in the wellbore and it forms a seal to prevent migration of formation fluid from different permeable formation zones to the surface/seabed.

The minimum cement plug length shall be:

1. Open hole cement plugs
   (a) 100 m MD with minimum 50 m MD above any source of inflow/leakage point. A plug in transition from open hole to casing should extend at least 50 m MD above and below casing shoe.
2. Cased hole cement plugs
   (a) 50 m MD if set on a mechanical/cement plug as foundation, otherwise 100 m MD
3. Open hole to surface plug (installed in surface casing)
   (a) 50 m MD if set on a mechanical plug, otherwise 100 m MD.

4. The requirements for verification of cement plug include among others:
    (a) Testing of cased hole plug should be either in the flow direction or above.
    (b) Plug position shall be verified by tagging both in the case of open hole and cased hole plug type.
    (c) The strength of the cement slurry should be verified through observation of surface samples from the mixing, cured on site in representative temperature.

Material plug (Chapter 15.55 ,Table 55 of (Norsok D-010, 2013))

It consists of a solid material that forms a plug in the wellbore and it prevents undesired flow of formation fluids from the permeable formation zones and/or into surface/seabed.

The minimum material plug length shall be: Open hole material plugs

1. 100 m MD with minimum 50 m MD above any source of inflow/leakage point.
2. For a plug in transition from open hole to casing, should extend at least 50 m MD above and below casing shoe.

Cased hole plug material plugs

1. 50 m MD if set on a mechanical plug as foundation, otherwise 100 m MD

Open hole to surface plug

1. 50 m MD if set on a mechanical plug otherwise 100 m MD

The requirements for verification of material plugs are the same as the first three points under the verification requirements of cement plug.

5.7 Well Abandonment Phases

Based on Oil and Gas, UK; (2011), well abandonment operation is divided into three different phases depending on the work scope, equipment required, and/or the discrete timing of the different phases of work. These are reservoir abandonment, intermediate abandonment, and wellhead and conductor removal. The following definitions are provided in (Oil and Gas, UK; 2011)

Phase 1: Reservoir Abandonment

> Here, reservoir producing or injecting zones are sealed by placing primary and secondary permanent barriers, while tubing is left partially or fully retrieved. This phase is complete when the reservoir is fully isolated from the wellbore.

Phase 2: Intermediate Abandonment

This section includes operations as isolating liners, milling, retrieving casing and potentially installing near surface cement, in addition to isolating/sealing intermediate hydrocarbon or water bearing permeable zones by placing barriers. The tubing may be partly retrieved, if not done in Phase 1. This phase is complete when no further plugging is required.

Phase 3: Wellhead and Conductor Removal

The tasks in this phase include retrieval of wellhead, conductor, shallow cuts of casing string, and cement filling of craters. The phase is complete when no further operations are required on the well, that is, when no well equipment are left behind or protruded from the sea bed.

5.8 Operational procedure of plug and abandonment

The process of typical P&A operation is dependent on a number of factors such as the well condition, the cement status, the numbers of potential inflows, type of well and more. A typical P&A job involves the following operations:

- Logging
- Kill well
- N/D XMT and N/U BOP
- Cut and Pull Tubing
- Milling or PWC
- Cementing
- Cut and Pull Casing
- Cut and Retrieve Wellhead

5.8.1 Logging

Oil and gas wells can have several well integrity issues, and therefore prior to carrying out P&A operation, the well needs to be accessed to evaluate its conditional state. During this operational phase, cement bond logs (CBL) and variable density log (VDL) are used. CBL are run into the well to determine the quality of the annular seal of cement behind liner or casing (where the plug is going to be placed) to see if the formation is collapsed around the casing or not. This type of tool depends on proper calibration and correct interpretation of received signal and thereby the accuracy of obtained information will also be dependent on it.

Logging determines whether the plug will be set inside the casing or if a Perforate, Wash and Cement (PWC) technique or milling will be required before the plug can be set.

5.8.2 Kill Well

Before the P&A operation will proceed, the live well needs to be killed. The live well is killed by pumping heavy fluid (mud) into it to overcome the pressure of the reservoir fluids, thereby preventing any influx into the well. Two commonly used well kill operations are bullheading, and reverse circulation.

In bullheading, the kill fluid is forced down the production tubing, compressing the reservoir fluids and overcoming the reservoir pressure in the process. The pumped fluid forces the reservoir fluids back into the formation. The pumping continues until only kill fluid is left in the well and all reservoir fluids are displaced. During bullheading, losses of drilling fluid can occur and this is difficult to control. Therefore it is necessary to have contingencies on rig incase this would happen.

In reverse circulation, the kill fluid is pumped down the annulus and moves up the tubing located above the production packer, through a perforated interval. By this, the reservoir fluids are displaced by the heavier kill fluid.

5.8.3 Nipple down Xmas tree and Nipple-up Blow Out Preventer (BOP)

Well control requirements make it necessary to install a BOP after removing the xmas tree. When the well is killed, the xmas tree is said to be “nippled down” while the BOP is said to be “nippled up”.The operational sequence for when the X-mas tree shall be removed depends on the X-mas tree types.

5.8.4 Cut and Pull Tubing

The tubing and the completion above the packer can either be pulled out of the well or left in the well before the well barrier is set. It is usually required to pull out the tubing if there are control lines connected to the tubing or if there is unconfirmed cement behind the 9 5/8” casing. It is important to remove the control lines as they can be a potential leak source if cemented in place. In case of unconfirmed cement behind the casing, the tubing needs to be pulled to log the casing because logging tools cannot log through the tubing and casing at the same time.

Pulling tubing requires high loads that can be supplied by heavy intervention vessels for subsea wells. Sometimes, it is very difficult to pull the tubing. It has to be cut above the packer in such cases and left with plugging materials on the inside and outside.

5.8.5 Milling or Perforate, Wash and Cement (PWC)

Milling or PWC is required before the reservoir barrier is set if results from logging indicate poor bonding of formation/cement between the casing/liner and formation.

In milling operation, the milling tool is deployed to the depth at which the unconsolidated formation/cement is recorded and its cutting knives are activated to cut through the section. By doing this, the casing, cement, settled mud or debris present is removed from the section. The swarf from the operation is then transported to surface by pumping heavy and highly viscous fluid into the well. However, milling leads to high rig time (and high cost) because it is time consuming. The residue generated from the operation can also be harmful to personnel, and special surface equipment is required to handle the residue. Other surface equipment can also be damaged as a result of passage of the residue through them.

The PWC system eliminates most of the challenges associated with milling. The PWC tool has perforating guns which are used to perforate the desired well section. The section is then washed with a jetting tool located above the perforating guns. The washing prepares the section for plug setting. Ferg, T. E., (2011) writes extensively about this system.

5.8.6 Cut and Pull Casing

It is required that the surface plug isolates laterally. Since the 9 5/8” and 13 3/8” casings are not usually cemented all through, they have to be removed before the section outside the 20” casing can be logged and the surface plug is set for complete isolation of the well.

5.8.7 Cut and Retrieve Wellhead

In accordance with Norsok D-010, (2013), it is requirement that equipment above the seabed to be removed. No parts of the well can ever protrude the seabed and the wellhead is removed after the surface plug is installed. The cut is made 5 m below the seabed and the wellhead is retrieved to the surface.

Chapter 6

P&A Challenges in the Arctic and Possible Solutions

P&A operations in the Arctic will be exposed to challenges which will come from environmental and technical effects. Most of these challenges have to be considered in the planning phase of P&A operations in the Arctic so as to conduct safe, cost effective and environmental friendly jobs.

6.1 P&A Challenges in the Arctic

6.1.1 Extreme Weather Conditions

As discussed in chapter 2, the Arctic is well known for its extreme weather conditions which include extremely low temperatures (as low as -60 °C), precipitation in the form of snow, prolonged darkness. Others are fog which leads to poor visibility, extreme wind, polar lows etc. When combined with wind chill, freezing temperatures impose outside work limitations. This is because exposure of personnel to such temperature will affect their ability to work efficiently, and could also lead to frost bite, hypothermia and other dangerous health conditions. Such temperatures could also affect the integrity of P&A equipment. Poor visibility and darkness could make it difficult for P&A vessels to navigate through ice covered areas of Arctic waters, and could also make tracking of leakages difficult if necessary. Although usually short lived, polar lows which are usually accompanied by extreme sea waves and wind, and heavy snow pose a great challenge to P&A vessels and equipment due to the difficulty in predicting the phenomena.

It is difficult to totally avoid extreme weather conditions in the Arctic as they can be experienced both during the open water season and when the water surface is covered with sea ice. Statistics for predicting Arctic weather conditions are limited, and the influence of climate changes reduces the accuracy of predictions from the available data.

6.1.2 Sea ice and Icebergs

Presence of sea ice and/or iceberg constitutes a serious threat to drilling and production activities in the Arctic. Sea ice hinders vessel transit through Arctic waters. Since open water is required for effective operations, the length of season for drilling and other related activities in the Arctic is reduced by the presence of sea ice. Summer operation windows are usually short, which could lead to need for multiple seasons to complete tasks. This, for instance, could increase the time needed to complete the phases of a P&A operation and thereby increase cost of vessel mobilization, demobilization and well abandonment in general. It can be deduced from discussions in chapters 2 and 4 that drifting ice and icebergs will impose ice loads on P&A vessels and affect their station keeping system. Strong wind and current, such as typical in the Arctic, lead to drifting of sea ice and icebergs which could result in iceberg collision with P&A vessels and underwater P&A equipment.

Although sea ice extent and ice thickness has reduced over the past three decades, it has resulted in more severe wave actions in the Beaufort and Chukchi Seas during the open water season as it allows wind to travel over larger open water areas (Wassink, A. and v.List, R., 2013). This will affect vessel and general P&A operations performance.

Ice chart shows that the drift ice coverage varies from waters in the summer to drift ice in the winter. It is also observed that the drifting ice does not show a constant drift direction. The locally fluctuating ice drift direction is influenced by tidal currents and winds. Observation from the first dynamic positioning operations in ice in Sakhalin shows how the ice was shifting directions driven by tidal currents and wind (Keinonen, A., et al., 2000).

Figure 6.1 shows the ice motion in 24hrs. Due to this dynamic motion, it is important to take these condition in to consideration when planning to perform P&A operation.

6.1.3 Remote Location and Lack of Infrastructures

The remoteness of the Arctic and presence of little infrastructure in the region could potentially increase the cost of P&A in the region. Supply bases to Arctic fields are

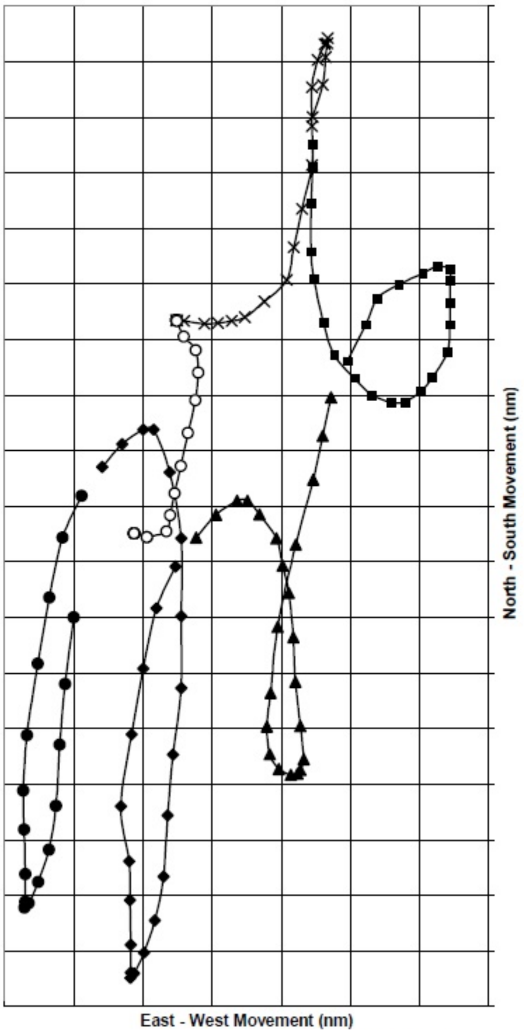


Figure 6.1: *Ice looping during the DP operation in Sakhalin (Keinonen, A., et al., 2000)*

usually very far and the supply routes are prone to disturbances from sea ice, icebergs, and extreme weather conditions. Like other tasks, this will affect the overall logistics of P&A operations in the Arctic in terms of access to field, timing of operations, materials delivery and storage. The difficulty in delivering materials needed for P&A operations means more than necessary materials might need to be planned to avoid unexpected operational delays. These contingent materials will also contribute to increasing the total P&A cost. Evacuation of personnel during emergency situations will also be challenging. Examples of Arctic developments that have been faced by logistics issues are North Star, Alaska and Chemo, Sakhalin. According to Wendler, C. and Sharma, A., (2011), North Star is cut off from supply for two periods of the year as a result of “break up” and “freeze”. The development is also faced with the problem of limited barge support for supply. In the case of Chemo, Sakhalin, supply lines for re-stocking for Chayvo operations were available just once in a year from initial start up to 2003/2004.

6.1.4 Difficulty in managing spill

Spill of whatever form is undesirable in conventional offshore fields and there are strict regulations with respect to this. However, spill is more undesirable in the Arctic as a result of the challenging and sensitive nature of the Arctic environment, and should be avoided during P&A operations. According to Wendler, C. and Sharma, A., (2011), toxic spilled oil will linger in the region due to cold weather and thick ice cover. Breakdown of spilled oil will also be hindered due to lack of sunlight in some periods of the year. From a planning perspective, spill management will be very difficult in the Arctic. Response to spill can be very expensive and time consuming as a result of the remoteness of the Arctic, thereby increasing risks of environmental damage. Furthermore, there is still much to be done in understanding the behavior of spills in cold and icy water. The typical extreme weather conditions of the Arctic will make it difficult to track spills. Special equipment will also be required in managing spill in such an environment.

6.1.5 P&A Vessel Challenges

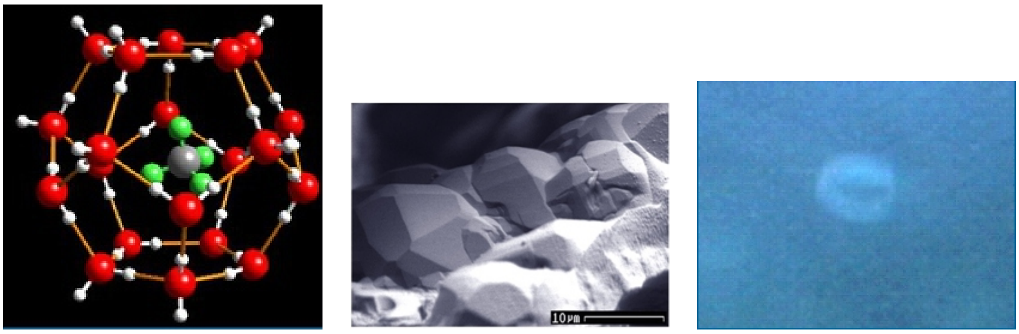
Loads from sea ice, icebergs and severe waves place restrictions on the type of vessels that can be used for P&A operations in the high Arctic and sub-Arctic. For instance, semi-submersibles are restricted to areas with more open water season and occasional sea ice cover (typically sub-Arctic areas), and harsh environments (Wassink, A. and v.List, R., 2013). This is in addition to considerations for the different water depths in the different parts of the Arctic. Vessels suitable for operations in the Arctic are costlier to build than those for other offshore areas of the world due to requirements for survival in the extreme conditions. This contributes to the high cost of P&A in the Arctic.

6.1.6 Permafrost related challenges

P&A operation in areas with Permafrost can be very challenging. Permafrost is distributed over significant span of shallow water in the High Arctic region, which implies its influence on operations cannot be overlooked. Heat can be generated when carrying out P&A operation, for example during cementing, milling and this may lead thawing of permafrost and may thereby lead to reduction in cement formation bond and leakage outside 20" casing. Temperature rise caused by P&A operation activities can make this situation worse.

Presence of gas hydrates in permafrost can also be a challenge for P&A operations. Gas hydrates are formed when gas molecules are trapped in lattice by water molecules under low temperature and high pressure. Based on the several studies taken in the East Siberian Arctic Sea and other parts, large amount of methane hydrates can be found below and also within some part of the subsea Arctic permafrost (Gustafsson, Ö. et al., 2013). Gas hydrates are composed of methane gas and water as it can be seen in the figure 6.2.

Figure 6.2a, 6.2b and 6.2c illustrate gas hydrates.



(a) Typical structure of gas hydrate *(b) Gas hydrates through Scanning electron microscope* *(c) Bubble of gas hydrate at sea floor*

Figure 6.2: *Gas Hydrates*

Gas hydrates are stable at low temperature and high pressure, and the stability of gas hydrate zone (GHSZ) is shown on the figures 6.2a & 6.2b. Cementing and milling operation when performing P&A operation can cause heat generation (transformation of mechanical energy to heat). Similar to permafrost, heating of the formation can cause problems as temperature can affect the stability of methane hydrates. Increase in temperature may lead to thawing of permafrost and this might lead to release of trapped methane gas. In worst case scenario, depending on the amount of released gas, it may cause gas leakages outside 20” casing.

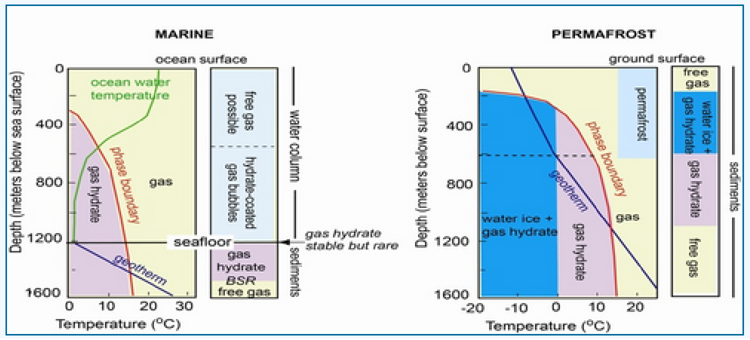


Figure 6.3: *Gas hydrate stability in marine and permafrost (USGS, 2013)*

6.1.7 Cementing Related Challenges

Cement is a common plugging material for PP&A, and cement plugs are placed at predetermined position inside the well or the annulus. This is done to provide reliable long term isolation of all flows, protect from pressure and to make sure the well does not leak. When there is no bonding (micro annulus) or poor cement bonding outside the casing, there will be a need to do section milling of the casing. During this operation, high density swarf can be generated and removing swarf in the Arctic region can be extremely costly and time consuming. The generated swarf can also pack off and this may lead to higher the equivalent circulating density (ECD) which cause losses.

Permafrost zone is also associated with low fracture zone gradient and low fracture gradient may be associated with fluid losses during P&A operation. Permafrost can slow down cement hydration reaction which can make portland cement to freeze before it develops sufficient compressive strength, and this leads to failure of cement sheath. Cement hydration is an exothermic reaction, and the heat generated by it could also lead to thawing of permafrost (DeBruijn, G., et al., 2012).

6.2 Solutions to P&A challenges in the Arctic

In order for P&A operations in high Arctic region to be possible or successful, the several challenges that have been addressed above need to be solved or taken into consideration during the early planning phase.

6.2.1 Consideration of vessel suitability to Arctic location/ Winterization/ Need for new UKOOA classification

Characteristics of the well location in terms of water depth and ice cover should be considered before deciding on which P&A vessel to deploy.

Similar to the discussion in section 4.4.4, ship-shaped P&A vessels like a Cat A vessel specially designed for operating in ice conditions can be applied in high Arctic areas such as Beaufort Sea, Chukchi Sea, Northern Greenland, Kara Sea and East Siberian Sea. Such Cat A vessels must have ice-strengthened hull with ice breaking capability. This is because these areas experience year-round sea ice cover. The vessel must also have good stability and low added resistance in waves for good seakeeping, which is essential for good transit speed through open water areas enroute the remote ice covered areas of the high Arctic, thereby reducing travel time. For good station keeping in the ice-covered waters of the high Arctic, the vessel must have a dynamic positioning system rated for P&A operations in the Arctic (Berg, T. E. and Borgen, H., 2013) & (Berg, T. E., et al., 2011). Combination of ice management procedures with the ice vaning and weather vaning capability of these ship-shaped vessels will help to improve their operability in the ice experienced in high-Arctic areas. The moonpool of the vessels will also shield P&A equipment from ice interaction in the splash zone.

Furthermore,Eikill, G.O., (2013) & Taraldsen, L., (2013) says a new rig concept known as Category I is currently under development. This is a ship-shaped vessel specially designed to operate in extreme conditions in the Arctic, capable to drill at different water depths in the Arctic with ice management, and can operate in up to 2 meters of ice. Designing this vessel also with P&A capabilities for the 3 phases of well P&A is an important consideration that can be taken up at this development phase so as to increase its versatility in the Arctic. A possible operational scenario for P&A in the high Arctic is to combine use of the Arctic LWI vessels (Cat A vessels) and Arctic drillship such as the Cat I vessel. Aspects of the job such as logging, bullheading and setting temporary plugs can be carried out by the LWI vessel while heavier operations such as cutting and pulling of tubings and completions can be done by the drillship. By doing this, the time to be spent by the drillship on P&A will be reduced, thereby making it possible to use it principally for drilling in the Arctic.

Figure 6.4 illustrates Category I vessel.

Just like what was discussed in section 4.4.4, semi-submersible P&A rigs with legs shaped like an inverted cone (for downward breaking of ice to prevent ice accumulation between the legs) will be more suitable for sub-Arctic areas such as the southern Greenland, Northern Barents Sea, Sakhalin and Sea of Okhotsk. This is because these

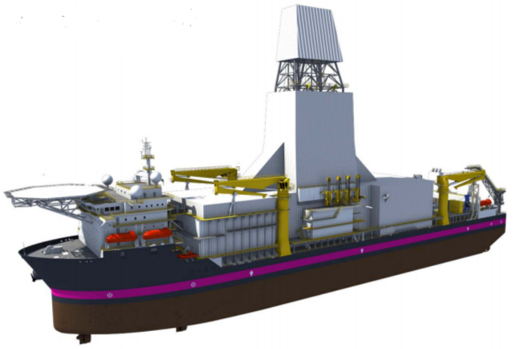


Figure 6.4: *Category I vessel (Eikill, G.O., 2013)*

areas are covered by occasional sea ice which can generate ice loads tolerable by semi submersibles when ice management procedures are applied. Furthermore, the low transit speed of semi-submersible vessels means long travel duration will be needed to reach the generally remote high Arctic areas, thereby making them unsuitable for such areas. P&A vessels in the form of jack-up rigs with circular tubular legs to reduce ice accumulation on the legs, and with inverted cone-shaped legs at the water line for downwards breaking of ice can also be applied in the shallow water areas of the sub-Arctic (Wassink, A. and v.List, R., 2013). In addition, Arctic-enabled Cat A vessels can also be combined with the Arctic-enabled semi-submersible rigs or the Arctic-enabled jack-up rigs for P&A in sub-Arctic areas.

An extension of possible ways of combining vessels for P&A phases, based on how it can be done in other areas like the Norwegian Continental Shelf (see (Birkeland, F., 2011)), can be made to reflect the possibilities in the Arctic. This is presented in table 6.1

A summary of vessel types that can be used for P&A tasks in different parts of the Arctic based on water depth and ice cover considerations is presented in Table 6.2. Note that the Jack up rigs and semi-submersible rigs here are considered to have the full capabilities of a typical Category C rig and can be combined with Cat A for some phases of the P&A, and the ship-shaped vessels refer to Cat A or Cat I or a combination of the two.

It should be noted that based on experience from the North Sea, combining different vessels for P&A tasks in the Arctic would lead to increased vessel mobilization cost. It is therefore important to evaluate the cost implications before such combinations are used in the Arctic. Another limitation to combining vessels in the Arctic is the likelihood of having limited amount of vessels suitable for Arctic conditions. Therefore, the pros and cons of vessel combination in the Arctic must be considered even before a well is drilled so as to be able to determine if it will be necessary to develop vessels

Table 6.1: *Possible ways of combining vessels for P&A operations in the Arctic*

Arctic LWI vessel	Arctic LWI vessel + Arctic Jack up rig or Arctic Semi-submersible rig or Arctic Drillship	Arctic Jack up rig or Arctic Semi-submersible rig or Arctic Drillship
LWI carries out well logging and killing of the well (present)	LWI carries out well logging and killing of the well (present)	Rig kills the well (present)
Installation of permanent barrier plugs(future)	LWI plugs the reservoir, cuts tubing and pulls Xmas tree (future)	Rig plugs the reservoir, and pulls tubing and Xmas tree (present)
Pulling of Xmas tree (present)	Rig pulls tubing, cuts and pulls casing(s) and set isolation plugs (present)	Rig cuts and pulls casings, and sets isolation plugs (present)
Cutting and pulling of Well head (present)	Rig cuts and pull wellhead (present)	Rig cuts and pulls wellhead (present)

that can be used for all phases of the P&A task.

The working areas of Arctic P&A vessels must also be winterized. Although winterization leads to increased complexity and additional vessel weight, it will help to reduce ice accumulation on the vessels, protect personnel and temperature sensitive equipment and materials from the effects of sub-zero temperature, shield the working areas on the vessel from excessive wind, and improve the flow assurance of fluids pumped into the well during the operation. Flow assurance of P&A fluids in the Arctic to prevent hydrate formation can also be achieved by using pipes with materials designed for such extreme cold temperatures and by insulating the pipes. The possibility of heating the pipes can also be considered.

The present UKOOA abandonment and vessel requirement classification presented in see section 5.1.2 does not consider the capability of different vessel types in the Arctic. Consideration of vessel Arctic and P&A capabilities in such classification will help in vessel selection during the planning phase of operations. The present UKOOA classification can be extended to include new type(s) that consider the Arctic P&A vessel suitable for a task and the possibility of ice management needs.

6.2.2 Need for Ice Management

Ice management techniques that include monitoring, forecasting and ice breaking which can provide absolute assurance that a P&A vessel can be protected from Arctic ice features such as drifting ice and icebergs are required. As discussed in section 4.5 for drilling vessels, ice management will be needed to keep ice loads within

Table 6.2: *Vessel types for P&A operations in different parts of the Arctic*

Sea	**Arctic area**	**Water depth**	**Vessel**
Beaufort and Chukchi Seas	High Arctic	88% of the seas have water depth range of 0-200m and 12% of the seas have water depth range 200-3000 m (NAMPAN, 2011)	Ship-shaped vessels with ice-strengthened hull for all water depths, but preferably for the deeper areas.
Siberian Seas (also including Kara Sea, and Laptev Sea)	High Arctic	Very shallow with average water depth of 100m (Hebert, P. D. N., 2013)	Ship-shaped vessels with ice-strengthened hull for all water depths, but preferably for the deeper areas.
Northern Barents Sea	Sub-Arctic	Average water depth range of 150-300m (Hebert, P. D. N., 2013)	• Jack up rigs with circular tubular legs and inverted cone at the water line for the shallow areas • Semi-submersible rigs with inverted cone-shaped legs at the water line for all water depths, but preferably for the deeper areas. • Ship-shaped vessels with ice-strengthened hull
Greenland Sea	High Arctic and Sub-Arctic	Average water depth of 1450 m and maximum water depth of 4800m (World Atlas, 2014)	For sub-Arctic areas: • Jack up rigs with circular tubular legs and inverted cone at the water line for the shallow areas • Semi-submersible vessels with inverted cone-shaped legs at the water line for all water depths, but preferably for the deeper areas. • Ship-shaped vessels with ice-strengthened hull For High Arctic areas: • Ship-shaped vessels with ice-strengthened hull for all water depths, but preferably for the deeper areas

tolerable limits for the P&A vessel. This procedure is also needed to be able to track any unmanageable ice feature on the path of the P&A vessel early so as to enable disconnection before a dangerous situation results. Ice breaking with a fleet of maneuverable ice breakers which work in stages will be required to manage changes in speed and direction of ice drift, and ice thickness, thereby enabling reduction in size of ice floes moving towards the P&A vessel. In addition to crushing ice, the ice breakers must also be equipped with technology for accurate forecast of ice drift speed and direction (Hamilton, J. M., 2011). Ice management can also be applied to increase the length of open water season, thereby helping to optimize time required for P&A in the Arctic. This will contribute to cost effectiveness of P&A in the region.

The possibility of towing icebergs off the path of the P&A vessel to avoid collision can also be considered.

6.2.3 Batch campaigns

Logistics challenges associated with operating in the Arctic as a result of its remoteness and lack of infrastructures can be handled by planning for batch campaigns. This could mean planning to perform P&A of a number of wells within a single campaign, especially if applying table 5.1 shows the wells that have similar abandonment needs and complexities. Rather than having to perform several trips from land to the different well locations, this would increase the possibility of performing all tasks in a single trip. This will result in cost effective P&A operations as the cost of vessel mobilization and demobilization will be reduced. This would also make it possible to perform several P&A jobs within the short open water season experienced in several areas of the Arctic.

To further combat the remoteness and lack of infrastructure challenges, P&A vessels should be designed with large storage capacity to be able to handle large amount of resources needed for batch operations without need for support from shore for a long period of time. Although this could increase the complexity of the vessel, it would greatly increase the effectiveness of Arctic P&A logistics.

6.2.4 Use of Appropriate Personal Protective Equipment (PPE)

In addition to protection from risks associated with P&A, PPE must also be certified to protect personnel against the extreme weather of the Arctic. For instance, PPE for the onshore Kharyaga field in Russia was designed with the following features to handle the extreme weather at the field (Boyer, Y. and Szakolczai, C., 2011).

- Helmets with shock resistance at low temperature

- Tinted safety glasses to withstand reflection of sun on ice/snow
- Warm overalls/gloves
- -100 °C certified safety winter boots with anti-slippery soles
- Face protection/hood for protection against wind

To satisfy these requirements, the PPE are usually heavy. Thus, risks associated with slow movement or miss-movement of P&A personnel as a result of the weight of the PPE must be considered during operations. In addition, the industry should work towards developing lighter materials for designing PPEs without losing out on the protection from Arctic weather required from the PPEs. To further optimize the weight of the PPE materials, the degree of harshness of weather on each field could be considered. For instance, PPEs for operations in the maritime climate areas of the Arctic such as the Norwegian coast can be of relatively lighter materials than those for use in continental climate areas of the Arctic such as the Siberian seas. This is because the maritime climate areas generally experience warmer temperature than the continental climate areas red (see section 2.2.1.1).

6.2.5 Spill Management

As a result of the sensitive nature of the Arctic environment, zero discharge should be considered as the baseline requirement for P&A tasks in the environment. An important way of avoiding oil spill in the Arctic is identifying the oil spill response gap which is used to account for when emergency response will be impossible or unsuccessful as a result of the extreme weather and ice conditions, and location remoteness. Identifying this at the planning phase of a P&A task will make it possible to put in place measures to avoid any form of spill (PCT, 2013). Proper risk assessment should be done to cover all P&A operation stages during the planning phase to identify all possible ways spill can be experienced, thereby making it possible to set up barriers against such. There is need to set up systems for monitoring temporarily and permanently plugged wells in the Arctic, both during and after the plugging operation so as to easily notice potential leakages in the wells and to take quick measures to stop such.

In situations when spill clean-up is possible, P&A operations should be limited to periods when spill response systems can be easily deployed to clean up spills in the Arctic. The equipment for spill clean-up should also be located in areas where they can be easily deployed.

6.2.6 Milling

When performing PP&A operation, as stated in section above, the well barrier is required to extend across all annuli both vertically and horizontally. This can be achieved by pulling out the tubing and milling the casing to get access to the formation. Study in non-Arctic areas shows that milling is the most time consuming aspect of P&A operation and it can also pose health, safety and environment (HSE) challenges. Especially in remote areas as the Arctic, milling will be of a great challenge as there will be need for swarf disposal. Therefore, it is advisable to avoid milling in such areas or to design the well in such a way that P&A can be performed without milling. For better result, the possibility of designing Arctic wells such that milling and pulling of production tubing can be avoided during P&A operations should be considered already at the well planning phase. This would go a long way in reducing Arctic P&A operational time and thereby make it possible to carry out several batch P&A operations within the short open water season in the Arctic. It would also make it possible to use simpler vessels. In general, Arctic P&A operation cost will be reduced.

6.2.7 Cementing

To avoid freezing of cement slurry in the Arctic, freeze protected slurries such as high gypsum cement, low-heat of hydration Arctic slurry (AS) and a high-solids-content, optimized-particle-size Arctic cement system (AS) could be considered (DeBruijn, G., et al., 2012). This can help the cement to flow and set as desired and thereby develop the needed compressive strength for the cement sheath to be effective at freezing temperatures.

6.2.8 Permafrost

Gas hydrates that can be encountered in thawed permafrost area during P&A operations must have been experienced first when the well was drilled. Before carrying out P&A operations in this region, it is advisable to make reference to the drilling report for an understanding of the lesson learnt while drilling the well. This will help in better planning to handle such challenges during the P&A operation. As Boyer, Y. and Szakolczai, C., (2011) stated it, it is also advisable to use high viscosity cool fluid with designed hydraulic and minimal shear to prevent thawing of permafrost. To avoid leakage behind the 20" casing which with time can lead to shallow gas migration to the surface, it can be suggested to set a plug inside the 20"casing according to the well barrier criteria mentioned in section 5.4.

Chapter 7

Conclusion and Recommendations

7.1 Overview

This thesis has shown that understanding the Arctic environment and the requirements for a P&A operation as specified in NORSOK D-010 rev-4 and UKOOA is essential to plan a successful subsea P&A operation in the Arctic. The climatic factors and offshore ice conditions of the Arctic, and the hydrocarbon potential of the Arctic geological basins were reviewed, followed by a review of drilling vessels that can operate in the High Arctic and Sub-Arctic. The characteristics and standard requirements of some common well barrier elements as given in Norsok D-010, (2013), and the well abandonment phases and work type/vessel requirement classification given in the Oil and Gas, UK; (2011) were also reviewed.

From this thesis, challenges of subsea P&A operations in the Arctic have been identified and solutions have been proposed. This chapter summarizes the solutions.

7.2 Summary

- Consideration of P&A vessel suitability to Arctic location: Use of LWI vessels (Cat A vessels) for some phases of well abandonment have proven to be cost-effective for P&A operations on the Norwegian Continental Shelf, and the possibility of using these vessels for all the phases in future is being considered. The possibility of using Arctic-enabled ship-shaped vessels like Cat A vessels should therefore be considered for all phases of P&A operations in high Arctic areas. If it is impossible to use Arctic-enabled Cat A vessels for all the phases, the possibility of combining them with Cat I vessels should be considered. For instance, the Cat A vessels can be used for phase 1 well abandonment jobs while heavier jobs can be done by the Cat I vessel.

As mentioned in chapter 6, combining vessels for P&A operations in the high Arctic could lead to increased vessel mobilization cost. There is also the chance that there will be only few amounts of vessels available for high Arctic operations. Furthermore, the length of open water season for operations is a challenge in the Arctic, and since P&A operations are time intensive, there is need for effective use of the open water season. These limitations make it important to probably develop dedicated Arctic-enabled P&A vessels that can carry out all phases of P&A operations.

It is also stated in chapter 6 that all working of Arctic P&A vessels must be winterized for protection of personnel and equipment against the harsh Arctic weather.

Also, it is recommended to have a new type(s) which consider the Arctic capability of vessels and the need for ice management included in the present Oil and Gas, UK; (2011) abandonment and vessel requirement classification presented in section 5.1.2.

- Ice management: Arctic P&A vessels should be supported by ice management procedures so as to reduce action of ice loads and to increase the length of open water season for Arctic operations which will help to extend the amount of time within which the P&A job can be done. The use of multiple stages of ice breaking in the high Arctic should be given priority.
- Batch operations: Wells with similar abandonment needs should be grouped into a single operation such that a single P&A vessel can be used for all of them. In addition to the other advantages of batch operations discussed in chapter 6, it will aid in experience transfer as several wells with similar needs will be worked with within the same period of time. To effectively carry out batch P&A operations in the Arctic, the P&A vessels should have sufficient storage capacity for stocks that can be used for several wells.
- Customized PPEs: To avoid excessively heavy Arctic PPEs, it is recommended that they should be customized to the degree of harshness of the weather at each field location.
- Spill management: Zero tolerance for discharges should be set as a baseline for operations in the Arctic. Also, it is recommended to set up systems for monitoring temporarily and permanently plugged wells in the Arctic, both during and after the plugging operation so as to easily notice potential leakages

in the wells and to take quick measures to stop such.

- Avoiding milling: Designing out the need for milling and the need to pull the production tubing must be considered during the planning phase/design phase of Arctic well. This would help in reducing P&A operation time in the Arctic and also increase the effectiveness of batch operations in the region since there is short open water season for operations. This would also make it possible to use simpler vessels, and generally reduce the cost of the P&A operations.

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