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## II. ABSTRACT

As the world energy needs rises combined with declining reserves in producing hydrocarbon field's new areas for exploration is needed. A study performed by the U.S. Geological Survey in 2008 estimated that 22% of the remaining undiscovered hydrocarbons could be located in the Arctic. This shows that Arctic Exploration and Production could provide energy for an energy-needing world. Exploration and Production (E&P) in the Arctic gives additional challenges than E&P under normal weather, temperature and latitudes. The challenges main challenges that will be faced in the Arctic are cold, ice and ice loads, rapid changing weather conditions and distance from established infrastructure. These challenges and several other needs to be adequately handled before E&P could be performed. As the Arctic is very diverse, different areas have various additional challenges that need to be handled as well.

This master thesis will be focusing on 5 areas in the Arctic in a life cycle view of a development. These 5 areas are Beaufort Sea, Baffin Bay, Greenland Sea, Barents Sea and Kara Sea. All of these areas will be presented with conditions present in the area and suggestions to make E&P possible in the specific area. For Exploration suggestions will be given to which type of drilling vessels seems to fit the areas best to get the largest drilling season and safest drilling operation. for the Production and development various development concepts will be presented for shallow water, deep water and ice inflicted areas. From these concepts suggestions for development in the 5 areas will be given.

Ice and ice loads seems to be the most challenging element in almost all areas of the Arctic. The only area that is not inflicted with pack ice and icebergs is the Central and South West Barents Sea. This gives an area that is easier and more economical to operate in, and seems to be the most interesting area for E&P. Another area with great potential is the Beaufort Sea, where E&P has a long history onshore and close to land. When moving in to great depths in the Beaufort Sea pack ice is present giving the need for ice management vessels to make E&P possible. One of the 5 Arctic areas is so heavily inflicted with pack ice and icebergs that present technology is not adequate for E&P and new technology is needed. This is the Greenland Sea, which is prone to be a constant stream of pack ice from the Transpolar Drift and icebergs from calving glaciers on Greenland.

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## VI. ABBREVIATIONS

AWSAR	All Weather Search And Rescue
BOP	Blow Out Preventer
DP	Dynamic Positioning
E&P	Exploration and Production
EEZ	Exclusive Economic Zone
EOR	Enhanced Oil Recovery
ERD	Extended-Reach Drilling
FP	Fracture Pressure
FPSO	Floating Production, Storage and Offloading
GLV	Gas Lift Valve
GBS	Gravity Based Structure
LNG	Liquefied Natural Gas
MODU	Mobile Offshore Drilling Unit
MEG	Monoethylenglycol
MPT	Multipurpose Tower
NTNU	Norwegian University of Science and Technology
RLWI	Riserless Light Well Intervention
SAR	Search And Rescue
SSV	Subsurface Safety Valve
TLP	Tension Leg Platform
TOC	Top Of Cement
TRSVSSV	Tubing Retrievable Surface Controlled Subsea Safety Valve
PP	Pore Pressure
P&A	Plug and Abandonment
USA	United States of America
WOC	Waiting On Cement
WD	Water depth
W/C	Water-to-Cement ratio

## #1 INTRODUCTION

To become less reliant on certain production areas Exploration and Production (E&P) companies are looking for new interesting acreages all around the world. Several of these areas are located in the Arctic. In 2008 the U.S. Geological Survey performed a study of the potential resource base in the Arctic, the study concluded with an estimate of 22% remaining undiscovered hydrocarbon could be located in the Arctic [1].

Arctic E&P could become a very important provider of energy for the world's rising energy needs. But operations in such a hostile environment is very challenging and require great risk awareness, to create a safe operation for both the fragile environment and personnel working there.

As an E&P prospect develops it goes through several stages, the main three stages are exploration, production and decommission. The objective of this master thesis is to provide a life cycle perspective of an arctic field development and what challenges are related to the different phases of a development.

Since the challenges are a bit different in various parts of the arctic, some classification is needed. To provide a better understanding there will be presented 5 cases in 5 different areas in the arctic. The cases are located in Beaufort Sea, Baffin Bay, Greenland Sea, Barents Sea and Kara Sea. Some parts of the Arctic Ocean is covered with ice the entire year, and other parts there is no ice present the entire year.

Ice and cold is one of the main challenges that are expected in arctic offshore Exploration and Production. Other challenges are distance from shore and logistics bases that brings additional challenges related to transport of personnel, re-supplement of goods and emergency spare parts and limited Search And Rescue capacity in the prospected areas.

To provide building bricks that the 5 cases can be developed with different exploration, development concepts and challenges will be presented in a life cycle view throughout the thesis. In the second chapter the Arctic will be defined and presented. This includes presentation of the 5 Arctic petroleum potential areas with a description of how far Exploration and Production has come so far.

Chapter three provide information about general challenges that all operation in the Arctic will encounter not only petroleum related challenges. Petroleum E&P related challenges will be presented in chapter four. In addition development and exploration concept that will provide the building bricks for the 5 cases in chapter five will be presented in chapter 4.

## #2 ARCTIC

The Arctic was previously described as the area north of the Arctic Circle at 66° 33 North. Today there is no naturally adopted southern border, since parts of the region north of the Arctic Circle doesn't show Arctic environmental conditions. On the other hand there are parts south of the Arctic Circle that show Arctic environmental conditions [2].

If a Southern border for the Arctic should be drawn the northern tree line for lowlands is a suitable border, this area fits in most parts the mean temperature for July of 10 °C. This border varies between 52° and 71° North around the world [2]. These borders can be compared to the Arctic Circle as compared in Figure 2.1.

The arctic oceans are highly diverse, from shallow continental shelf with only a couple of 100 meters depth and up to a width of 700 kilometres, to deep waters with water depths down to 4000-5000 meters. The continental shelf is made up by Beaufort sea, Barents Sea, Kara Sea, Laptev Sea, East Siberia Sea and the Chukchi Sea, they surround the Arctic Ocean. The Arctic Ocean is divided into two basins by an underwater ridge, The Lomonosov ridge. Both basins have water depths of up to 4000-5000 meters [3].

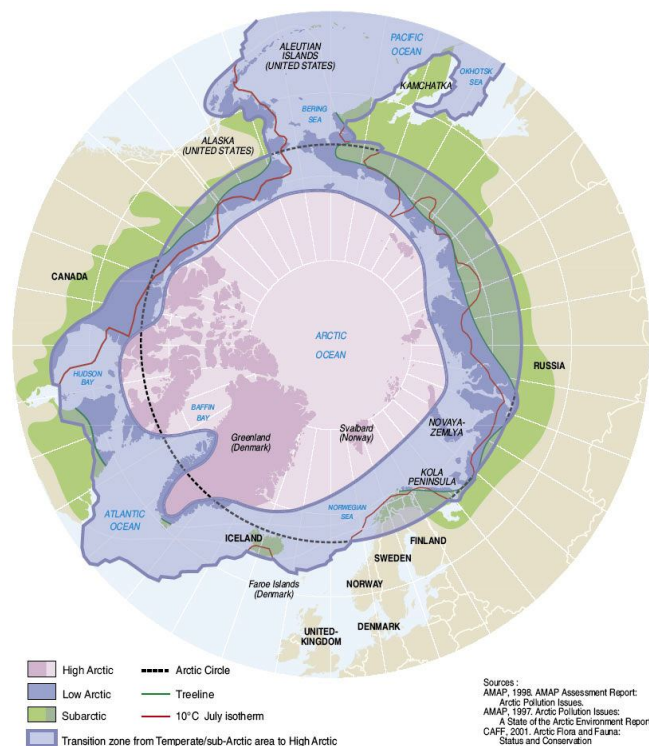


FIGURE 2.1 ARCTIC DEFINITIONS [4]

## 2.1 ARCTIC OPERATING CONDITIONS

Since the arctic is highly diverse, the definition “Arctic area” is not very precise with respect to Exploration and Production. It doesn’t tell anything about the operation conditions in the area, therefore several definitions of the different arctic areas is needed, Statoil a Norwegian E&P company has divided the Arctic Area into 3 categories: “the workable”, “the stretch” and “the extreme”. The workable is areas that are ice-free year around, the Stretch area is covered with ice parts of the year and the extreme is covered with ice all year round [5]. These categories corresponds to GustoMSC different categories for where vessels are able to operate, they have named there classification “Winterzed/Harsh Environment”, “Sub Arctic” and “High Arctic”[6]. This makes ice and weather information about the specific prospected areas vital.

### 2.1.1 ARCTIC CURRENTS

Different currents in the arctic have great effect on ice build up and ice movement, major contributing currents are Transpolar Drift and Beaufort Gyro. The circulating current in Beaufort Gyro circulate water and ice close to the North Pole over several years, allowing multi-year ice to build up before it sweeps out in to lower Beaufort Sea. The Transpolar Drift transports large volumes of ice towards northern Greenland and further southward throughout the Fram Strait towards the Atlantic Ocean. These two currents have a great impact on the thickness and distribution of Arctic Ocean ice, their flow direction can be seen in Figure 2.2 [1, 7]. Another current that affects the arctic ice conditions is the North Atlantic Current, which provide warm and high salinity water in to the Barents Sea, keeping the South-western part ice free all year round and the rest open during the summer months [8].

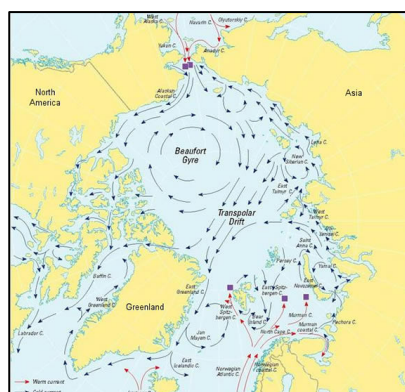


FIGURE 2.2 ARCTIC CURRENTS [9]

## 2.1.2 TEMPERATURE AND WEATHER CONDITIONS

Extreme temperature, wind chill, polar lows, ice and icing are words commonly used to characterise the weather conditions in the Arctic, and they reflect an area with extreme weather. It is normal to divide the arctic climate into two regions, the one covered with Sea ice where the average temperature per month never exceeds 0 °C, and the rest the coastal area of Siberia, Canada and Alaska often classified as the polar continental climate. This area has normally one month of the year where the mean temperature is in the range 0-10 °C [10].

During the winter months these two climate zones have quite different weather, the polar continental zone has heavy snowfall, polar lows and rapid temperature changes, which in extreme cases sink as low as -50 °C. While the ice cap covered part has little snowfall and relatively mild winters compared. During the summer months the temperature stays more the same across the arctic, with temperatures around 0°C at the ice cap to around 10°C at the coast. The coastal and open sea areas are prone to fog, drift ice and icebergs during the summer months [10].

### 2.1.2.1 POLAR LOWS

Polar Lows are small and intense low-pressure systems, which are hard to predict. They suddenly emerge when cold wind from the arctic blows over open water. The air heats up and is humidified which makes it unstable. Polar Lows are dangerous because of the sudden change, wind strength can change from breeze to Storm in just a couple of minutes, wave height can increase with 5 meters in just an hour and the humidified air can cause snow blizzards with low visibility. Creating dangerous and challenging conditions for offshore vessels [11, 12].

### 2.1.2.2 ICE

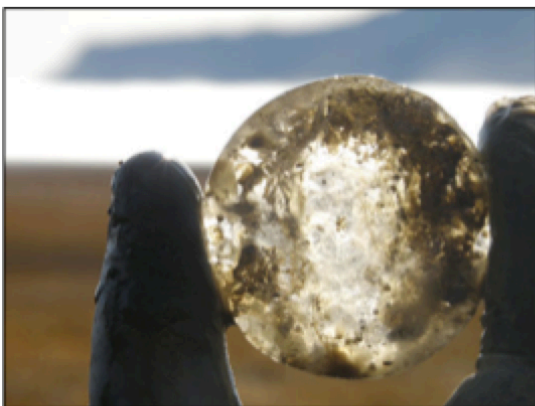
The presence of different types of ice is most likely the biggest challenge in the arctic environment. There are 4 different ice phenomena that occur in different parts of the Arctic. As Pack-ice, Icebergs, Permafrost or as Ice accretion these different types can be seen in Figure 2.3. All of these phenomena's has different challenges related with them and requires different measures to cope with them. More about the different types is given section 3.2 [4, 13].



**Pack-ice**



**Iceberg**



**Permafrost Core**



**Ice accretion**

FIGURE 2.3 DIFFERENT TYPES OF ICE [14-17]

## 2.2 ARCTIC PETROLEUM POTENTIAL AREAS

A study done by scientists from U.S. Geological Survey in May 2008, implied that 84% of undiscovered arctic petroleum resources are offshore, and the areas with the highest potential for petroleum resources are Beaufort Sea, Baffin bay, Greenland Sea, Barents Sea and Kara Sea. These areas have quite different climatic conditions and require different technologies and measures to be able to operate within [1, 18].

### 2.2.1 BEAUFORT SEA

Beaufort sea is located north of Alaska and western Canada. It Stretches from Point Barrow in the West to Prince Patrick Island in the Northeast and Southward to Canadian mainland. The Beaufort Sea has a narrow continental shelf, at its widest the shelf is 145km wide, with an average depth of 65m. Beyond the shelf the sea has an average depth of 1004m and a maximum depth of 4680m [19]. The part close to shore has an icepack that melts during the summer months. The average is 60 days with open waters, and it varies from 0 to 120 days. Further north in to the central and northern part of Beaufort Sea there are multi-year solid ice, this ice can be swept in to the southern part of the Beaufort Sea, also during the summer months. The one-year ice extent southwards varies from year to year, as for every other arctic area [1, 20].

Onshore petroleum exploration and production has a long history in Alaska and northern Canada. In 2004 Alaska produced 17% of the total oil production in the United States of America (USA). Most of the production is produced onshore in the area surrounding Prudhoe Bay. The Prudhoe Bay field has been producing since 1977 and in 2004 it produced 5% USA's total oil production. Offshore this area there are several oil discoveries in shallow water, many of them have been developed with artificial islands. [1, 20-24].

Two of them are Endicott and Northstar. Endicott is located 13 km east of Prudhoe Bay and in an area of 0.5 to 4 meter water depth, the field is developed with two artificial island located 6 km offshore connected to shore through a gravel causeway. The causeway supports the pipeline transporting the oil to shore. One of the artificial islands at the field also produces from the Liberty field. This field is located 10-12 km West of



Endicott. The production is made possible through Extended-Reach Drilling (ERD). This limits the environmental impact and economical investment needed [1, 20-24].

The Northstar field is located 10km offshore Alaska at a water depth of about 12m and the only field development in the Beaufort Sea that is not connected to shore through a causeway as can be seen in Figure 2.4. This made the need for a subsea pipeline for transporting oil to shore and gas for injection offshore. This pipeline was buried at 3 times the depth that ice is expected to be able to inflict. The new prospects in the Beaufort Sea with great potential is located in considerable deeper waters than the fields that are producing. This gives a considerably more challenging environment for E&P [1, 20-24].



FIGURE 2.4 NORTHSTAR ISLAND [25]

### 2.2.3 BAFFIN BAY

Baffin Bay lies between West Greenland and East Baffin Island. In the north it is connected to the Arctic Ocean through Nares Strait. Southwards Davis Strait leads to the Atlantic Ocean. In the center of the bay there is a pit that at its deepest is 2100m, elsewhere the bay varies in depth from 700m in the south to 200m in the north. Baffin Bay and Davis Strait has open-water over 120 days a year. During this period icebergs could be expected to sweep in to Baffin Bay and David Strait from North and from calving glaciers in the area [1, 26, 27].

Since the 1970's there has been drilled 14 wells on the West coast of Greenland. 8 of them are recently drilled i.e. 3 in 2010 and 5 in 2011. All of these wells where drilled by the Cairn Energy an international E&P company but no discovery where made. In 2012 there was done a joint industry coring campaign in Baffin Bay, a total of 11 boreholes of up to 800 meters was drilled. This is the first time a stratigraphic column of the Baffin Bay basin has been established. The study showed that the both source rocks and reservoir quality sands are present in the bay [28].

### 2.2.4 GREENLAND SEA

The Greenland Sea lies on the east side of Greenland, stretches over to Spitsbergen in the east, in the south the border to the Norwegian Sea is a line from northeast Iceland to Jan Mayen continuing to Spitsbergen, This line also mark the average edge of the Arctic ice. Average depth of the Sea is 1450m, with parts up to 4800m deep. The East Greenland Current run's through the Greenland Sea, carrying with it rivers of pack ice with potential for icebergs making an extremely challenging operation condition [1, 29, 30].

The first licenses on the shelf in the Greenland Sea were awarded in 2011. There have only been performed seismic studies by the government and no drilling has been performed on the shelf yet. Due to the severe ice conditions in this area, performing seismic studies was challenging. In addition to the seismic studies, there has been invested a great deal of money in ice related studies by a group operating companies that all have license and interests on the shelf [31].

## 2.2.5 BARENTS SEA

The Barents Sea is located north of Norway and the Eastern part of Russia as can be seen in Figure 2.5, and has a size of 1400 000 km<sup>2</sup>. It's western boarder can be considered as a line from North Cape to Bear Island and further to Spitsbergen, to the east the Sea is limited by Novaya Zemlya and to the North a line between Franz Josef Land. The North Atlantic Current flows in to the Barents Sea from southeast. This current keeps the Southern part of the Sea ice-free all year round, the northern part of the Sea is usually ice-free in the summer time. There is another stream going through the Barents Sea, "Bjørneøystrømmen", it flows southwest in the northern part of the sea with arctic cold water [32].

The water depth in the Barents Sea varies from 200 to 500 meters for the most part. Only "Spitsbergenbanken" is shallower. At its shallowest it is only 50 meters deep. In the eastern parts of the Barents Sea, one can fine some of the world's deepest sedimentary basins, parts up to 20 kilometres thick [32].



FIGURE 2.5 BARENTS SEA WITH PECHORA SEA INDICATED [33]

There have been several petroleum discoveries in the Barents Sea but to this date there is only two producing fields her. One gas field located in Norwegian waters and one oil field located in the South Eastern part also know as Pechora Sea, which is in Russian waters, More about this field is presented below in section 2.2.4.1.

The producing gas field located in Norwegian waters is called Snøhvit, located 143km from Hammerfest, and is a joint development of 3 gas discoveries in near vicinity of each other. These 3 discoveries Albatross, Askeladd and Snøhvit was discovered in the early 80's. Snøhvit and Albatross started production in 2007 and the plan is to start producing from Askeladd in 2014-2015. The field is located at a water depth between 310-340m and the first major field on the Norwegian continental shelf to be built without any offshore surface installation, and totally controlled from land. The produced natural gas is processed into Liquefied Natural Gas (LNG) and shipped to different markets in LNG tankers [34-36].

Two other interesting discoveries in the Barents sea are Goliat and Shtokman. Goliat is the first oil field development in the Norwegian part of the Barents Sea, production is estimated to start in the third quarter of 2014 [37]. Shtokman is a major gas field located in the central part of the Barents Sea in Russian waters. Gas in place is estimated to 3.9 trillion m<sup>3</sup>, making it the biggest offshore gas field in the world. Due to it's location far from any logistics hub and gas market combined with challenging environmental condition, it has been troublesome to develop. After 25 years of research, the field has yet not been developed. This provides a picture of how time consuming and costly field development in Arctic regions can be [38-40].

In 2011 a discovery was done in the Norwegian part of the Barents Sea where the Johan Castberg field was discovered. This discovery has had a major impact on the interest of the Barents Sea. This has revitalising the area as an interesting petroleum exploration area for major operators from all around the world [38-40]. All the major discoveries in Barents Sea are listed in Appendix A

### 2.2.5.1 PECHORA SEA

Pechora Sea is the name for the South Eastern part of the Barents Sea. Stretching from Novaya Zemlya in the north to Russian main land as can be seen in Figure 2.5. This part of the Barents Sea has floating ice from November until June [41]. This part of the Barents sea has an additional challenge, since the water is shallow permafrost is present over major parts of Pechora sea [42].

The only producing oil field in the Barents Sea is located in Pechora Sea shelf, called Pirazlomnoye. Production started from Pirazlomnoye in December 2013. The field is located 60 km from shore and in a water depth of 19-20meter and developed with a Steel Structured caisson that is lowered down on the sea bottom. It is designed to cope with floating multi-year drift ice that is expected in this part of the Barents Sea. The estimated field size is 72 million tons of oil, which will be produced through 40 well slots on the Prirazlomnoye platform. The field development concept can be seen in Figure 2.6. This platform has been constructed with excess production capacity that is needed for the field. It is planned that the nearby Dolginskoye field is to be tied in and produced from the same platform. In addition to those two fields there have been discovered 3 other oil fields in the Pechora Sea so far [43-45].

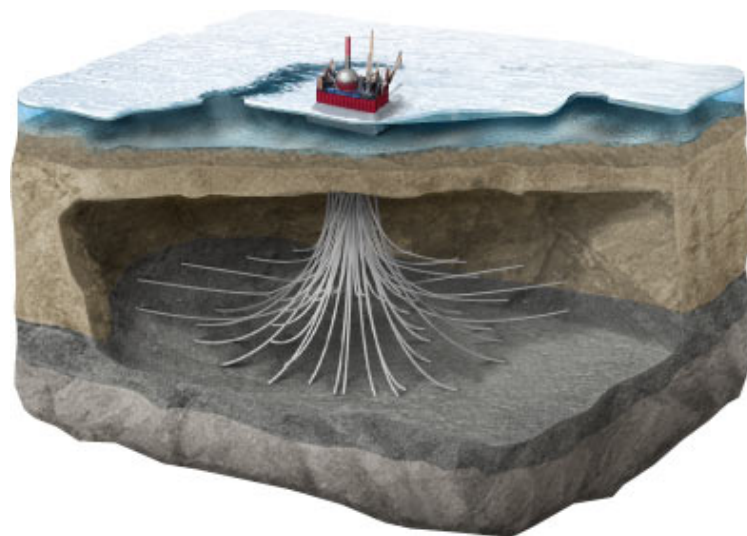


FIGURE 2.6 PRIRAZLOMNOYE FIELD DEVELOPEMENT CONCEPT [43]

## 2.2.6 KARA SEA

The Kara Sea is located north of Siberia with a size of 883 000 km<sup>2</sup>, and stretches from Severnaya Zemlya in the east to the Kara Strait and Novaya Zemlya in the West. The northern limit is a line between the most northern points on Franz Josef Land and Severnaya Zemlya, Figure 2.7 shows the location. A lot of fresh water flows from rivers Ob and Yenisej and in to Kara Sea, giving a low salinity. The Kara sea is frozen most part of the year, and is mainly a shallow sea with a mean depth of 118m [46].

In July 2014 a joint venture company between Exxon mobile a major international operator and Rosneft a major Russian operator plan to perform exploration drilling in the Kara Sea, more specific the Akademichskoye prospect in the Prinovozemelsky-1 license. This exploration well is going to be drilled with the semi-submersible drilling rig West Alpha. West Alpha has been operating on the Norwegian continental shelf the last 28 years. Before starting the operation West Alpha is going to be winterized. This is needed to make the rig suitable for the harsh environmental condition. Temperatures during the operation is expected to vary between -2°C to -23°C. Since this exploration prospect is located so far from any infrastructure no helicopter are capable of reaching the area, so crew change is planned with boat transportation from Murmansk, which is estimated to be journey of 5 days. The prospect area has about 80m of water depth and normally has open water for about 2 months [47-49].

There have been several other exploration wells drilled in Kara Sea that has resulted in discovering two gas condensate fields Leningradskoye and Rusanovskoye, and two gas fields in the near by in Ob Bay, which culminates in the Kara Sea [45].



FIGURE 2.7 KARA SEA[50]

### #3 GENERAL CHALLENGES IN ARCTIC

This chapter will give insight into challenges and problems related to the arctic environment, which is not directly related to drilling operations, but will be a problem for any operation in the arctic areas.

#### 3.1 COLD

As mentioned in Section 2.1.2 the temperature in the arctic areas is extremely low during the winter months, this will give problems for humans and machinery to work and operate within. Research has shown that working in cold conditions increases the risk for several dangerous diseases like cardiovascular diseases and strokes in addition to freeze burns. Personnel working in areas with low ambient temperature and strong winds perform poorly and take poorer decisions than personnel working under optimal conditions [13, 20, 51],[52].

Providing additional clothing to personnel affects the performance of the work force. This gives the need to minimize any exposure to the environment to keep the work force vigilance and performing. Therefore all working areas where possible should be enclosed and heated to 21° C to provide optimal working conditions. Another danger is the event of “Man Overboard”. If someone falls into the ocean hypothermia will inflict in no time. Hypothermia is also an issue related to transportation of personnel to and from operations in the Arctic, therefore there have been designed special survival suites for operations in extreme conditions, this will reduce some of the risk during transportation. The suite is shown in Figure 3.1 [13, 20, 51],[52].



FIGURE 3.1 ARCTIC SURVIVAL SUITE [52]

## 3.2 ICE

As mentioned in section 2.1.2.2 there are 4 different types of ice that exist in the arctic. Pack ice, icebergs, permafrost and ice accretion. They form in different ways and cause different complications and need to be taken into account before starting any operation in the Arctic.

### 3.2.1 PACK-ICE

Ice that forms and floats in the ocean is generally called pack-ice. There are two different types of Pack-ice, first-year ice and multi-year ice. During the summer month the normal extent of pack-ice in the arctic ocean is about 7 million km<sup>2</sup>. This ice is partly multi-year ice. From the late summer the first-year ice starts to grow and through out the winter the extent of first and multi-year ice doubles in size to about 14 million km<sup>2</sup>. The ice can reach as far south as 48 °N latitude. The only northern seas that are ice free during the winter is Norwegian Sea and Barents Sea with one exception, Pechora Sea as mentioned in section 2.2.5.1 Pack-ice is frozen seawater and therefore contains salt, making the ice softer than icebergs. Seawater's freezing point is about -1,8 °C. In some areas of the Arctic where there are large rivers that provide huge amount of freshwater sea-ice creation starts at higher temperatures. Multi-year ice contains less salt water than one-year ice and is therefore harder [4, 8, 44, 53].

### 3.2.2 ICEBERGS

Icebergs are big pieces of glaciers that break off and fall in to the ocean. They are formed from fresh water and do not contain salt. This makes them extremely hard and difficult to break. The main sources for icebergs to calve in to the arctic are fresh water glaciers. The biggest provider is the glaciers along the Greenland coast and Ellesmere Island. Greenland alone calves between 10.000-30.000 icebergs annually. Other places that calve icebergs in the arctic are Severnaya Zemlya, Novaya Zemlya, Franz Joseph land and Svalbard. When icebergs have broken off they can travel along with the arctic currents for several years before they move along the Greenland coast and in to the Atlantic Ocean and melt. When Icebergs break off glaciers, they can be up to millions of tons, but they usually break into smaller pieces as they drift with the arctic currents. These massive blocks of ice can be several hundred meters long and have deep keels. They can cause problems for offshore installations and ice management programs needs to make sure



icebergs don't collide with the installations. The deep keels can in addition be a problem for subsea equipment and pipelines and need to be taken into account in shallower waters [4, 53].

### 3.2.3 PERMAFROST

In some arctic areas the soil has temperatures below 0°C, this is called permafrost and can extend up to 1000m down in to the ground. permafrost ranging so deep in to the ground has only been seen onshore where permafrost causes a bigger problem. When looking offshore in permafrost prone area like the Pechora Sea and parts of Kara Sea the normal range is from 20-40m below sea bed extending 100m down. Permafrost has only been proven to occur in waters shallower than 40m [20, 42].

Permafrost causes problems in multiple phases during drilling and completion. When drilling through a zone that can contain permafrost it is vital to keep drilling mud temperature as low as possible. If the temperature gets to high it can cause bore hole instabilities and bore hole collapse [54]. In a cement job performed under normal conditions the cement slurry takes hours to build compressive strength. If normal Portland cement is to be used in permafrost conditions, the cement slurry could freeze before the cement build compressive strength. This will cause the cement job to fail. This gives the need for specialized slurries that can build compressive strength also bellow waters freezing point. Another issue during cement jobs is melting the permafrost, this can happens since the cement hydration is an exothermic reaction. If the permafrost is melted the cement support is lost and this will cause the cement job to fail and the casing string will have no support. With the use of cement slurries with Low-heat-of-hydration this can be prevented [55].

### 3.2.4 ICE ACCRETION

Ice accretion can be caused by two different phenomena's: Sea spray and atmospheric icing. Sea spray icing contains salt making it softer and easier to remove than atmospheric icing. The most severe of them is Sea Spray since it occurs in a much larger scale. Ice accretion is a serious problem. When the conditions for icing are meet, ice will start to grow on almost any surface, in extreme cases the build up rate can be as large as 3cm an hour. The build up of ice on platforms and ships will cause issues with weight, stability and access to critical equipment [13, 56].

### 3.3 REMOTENESS

The arctic is huge area, almost 30 million km<sup>2</sup>. With a population estimated to only 4 million people, this gives an idea of how scarcely the infrastructure is developed and how remote the area is. All activity in the arctic area requires long transportation distance in a combination with detailed logistic planning if supplies are needed. The arctic E&P prospects have the same faith, these activities require infrastructures like helicopter bases, logistics hubs and emergency health care facilities. When moving further north satellite communication will disappear. This will be a challenge for boats and drilling vessel utilising Dynamic Positioning systems to stay in place, and for communication with the rest of the world. Beyond the 74 latitude there is satellite darkness [4, 20].

### 3.4 VISIBILITY

There are several phenomena in the arctic that causes visibility issues; winter darkness, polar night and fog. During the winter months there is limited day light in the arctic region, it experiences winter darkness. Winter darkness is defined as days when the sun stays under the horizon the entire day. The time an Arctic area experience winter darkness is linked to how far north the area lies, the north pole experience 6 months of winter darkness [11].

The areas that experience winter darkness will experience midnight sun likely long as they have winter darkness, during the summer months. The reason being that the earth is tilted, it is tilted 23.4° from the vertical of the earth's orbit around the sun, this affects how much sunlight that hits northern and southern parts of the earth. Since the earth's atmosphere reflects light, the areas with winter darkness will experience some light as long as the sun stays closer to the horizon than -6°. When the sun goes under -6°, the light conditions are very limited and called polar night, artificial light is needed for outdoor activities [11].

In the summer, fog is a problem in arctic areas. Fog generates when relatively warm air travels over cold arctic water, the humidity in the air increases and fog is created. Fog drastically limits visibility and is an issue in areas where hot and cold streams meet. Like around Bear Island in the Barents Sea, this area has an average of 76 days a year when fog limits the visibility range to about 1 km [11].

### 3.5 ECONOMIC SUBSEA RIGHTS

United Nations Convention of the Law of the Sea from 1982 states that all countries with a coastline have exclusive economic zone (EEZ) up to 200 nautical miles. In areas where the continental shelf extends over 200 nautical miles the EEZ is determined with consultation with the UN. The EEZ grants economic exclusivity to any subsea resource within the area. This gives Norway, Greenland (Denmark), Iceland, Russia, Canada and USA economic rights to potential petroleum discoveries in the arctic. Most of the sea borders between the countries within the 200 nautical miles zone have been settled. After the recent agreement between the Norwegian and Russian government about where in the Barents Sea the border between the countries lie, there is only one disputed area left. This is in the Beaufort Sea between USA and Canada, but the two countries collaborate to survey the continental shelf in the disputed area [4].

## #4 CHALLENGES RELATED TO HYDROCARBON FIELD DEVELOPMENT IN THE ARCTIC

Development of an offshore petroleum field goes through several stages, from geological surveys in the first step of exploration to removal of all installation as the final step in the decommissioning. A brief development description is given in Figure 4.1. This chapter will go through the different problems associated with the different major steps in Exploration and Production of an arctic installation.

The idea is to give a Lifecycle perspective to Arctic Exploration & Production. In an arctic field development as any offshore field development management of the loads inflicted upon the installation is curtail. The largest loads on offshore installations in non-arctic environments are wave inflicted. In an arctic development the largest loads inflicted will be caused by pack-ice and icebergs. It is therefore one of the most crucial challenges to cope with throughout the development and operation of an offshore arctic petroleum production field.

In addition the cold climate and remoteness will cause problems for infrastructure, drilling, production, logistic and personnel working her.

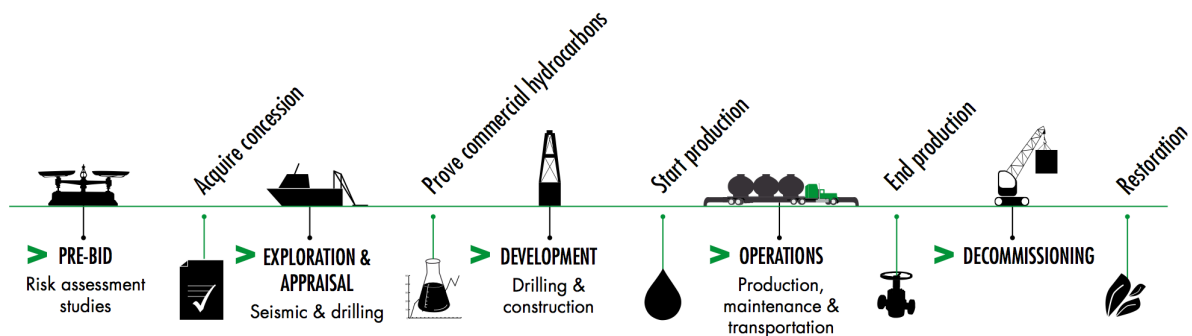


FIGURE 4.1 FIELD DEVELOPMENT STAGES [4]

## 4.1 ICE AND WEATHER CONDITIONS

As presented in chapter #3 there are several challenges related to ice and weather conditions in the arctic and sub-arctic that needs to be handled for Exploration and Production to be preformed in this harsh environment. In this section the problems related to ice and weather conditions will be presented.

### 4.1.1 ICE LOADS

Ice loads that icebergs, first-year and multi-year ice may cause on offshore installations are huge; studies of present installations in shallow waters have shown that ice loads that these installations may be subjected to could be in the range from 500 Mega Newton (MN) to 1000 MN. Which could inflict pressures between 3-8 MPa on offshore installations. Present gravity based structures like the Hibernia platform on the Greate Bangs of Newfoundland has been designed to handle maximum loads up to 1200-1500 MN. In comparison, Terra Nova FPSO located in the same area and its mooring system was designed to handle loads up to 20 MN before the FPSO needs to be detached if large icebergs threaten the installation [6, 57].

This shows that for deep-water installations in the Arctic, ice loads exceed strengths of stations-keeping systems for floating units. The pressures exerted by the ice would also be significant for the hull to cope with. To reduce the possible loads that could be inflicted, hulls should be designed with other geometric shapes to break the ice with bending and not crushing into vertical hulls. To generate bending of the ice, the hull should have a conic geometry near the water line. For fixed installations the con should break the ice upward to reduce the load inflicted on the structure by the ice. In floating installations the cone should break the ice downward to hinder the accumulation on the installation and to clear ice under the floater. Multi-leg hull and structures like Jackup, semisubmersibles and tension leg platform (TLP) can accumulate broken ice between the legs of the structure. The accumulation of ice between legs will increase the load exerted on to the mooring system and the system will need to be detached from riser or production turret. A mooring system with 24 mooring lines with the strongest available chain will have a maximum load capacity of 77 MN and ice loads exerted on a ship shaped hull could be up to 300 MN. This explains that mooring system needs to be disconnectable so that the installation can leave the site when ice loads gets to high.

To minimize the loads ice management programmes should also be put in place, more about ice management is given in the next section 4.1.2. [6, 57].

#### 4.1.2 ICE MANAGEMENT

Exploration and production operations in arctic areas has limited open water seasons, some parts has no open water season. To extend drilling seasons ice management program is needed in these areas. They are especially needed in deep arctic waters, since bottom grounded platforms and artificial islands are limited to shallower waters and floating vessels are needed for E&P. Ice management programs are needed to minimise the load pack-ice and icebergs can inflict on petroleum installations, since conventional DP and mooring systems are not capable of handling the great loads they can inflict [20, 44, 58].

The two different types of ice require different management measures, pack-ice needs to be broken into smaller pieces by icebreakers and large icebergs need to be towed away from collision course with the installation. Pack-ice management could be needed to extend drilling season in open-water areas or create drilling possibilities in areas that have year round ice. In areas with year-round multi-year ice there is a limit on how thick and tough ice icebreakers are able to break up. A typical pack-ice management program consists of multiple icebreakers working together. One larger icebreaker in front and one or more smaller icebreaker closer to the installation. The first icebreaker working in a large radius breaking large pices into medium size pices, the smaller icebreaker operates in a smaller radius breaking the medium pices into small pices that installation can handle as shown in Figure 4.2. The cooperating icebreakers works in the same pattern, this has been shown to be the most effective way for icebreaking, Figure 4.3 shows different patterns used. [20, 44, 58].

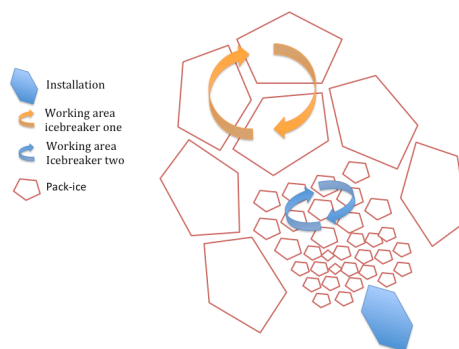


FIGURE 4.2 TWO ICEBREAKERS COOPERATING IN PACK ICE

It is important that ice and water currents are monitored 24/7 for any changing direction or pace, to keep the installation in center of the channel of broken pack-ice. It is favourable to keep this channel as wide as possible, but this will require very large working area for the icebreaker in front. So the width of the channel is limited by pack-ice pace, icebreaker capacity and ice-thickness [20, 44, 58].

Iceberg management in open-waters involve at least two tugboats cooperating. The boats uses synthetic lines between the boats to “capture” the iceberg and tow the iceberg off collision course with the installation. Some arctic areas may need both tugboats and icebreaker to manage mixed ice conditions. In the event of icebergs or multi-year ice to big or thick to be managed, the production or drilling operation needs to be postponed. Disconnection from production turret or pulling out drilling equipment is needed, before drillship or production facilities moves off location until conditions is manageable again [20, 44, 58].

During drilling of deep wells, the need to trip out of hole could be over 24 hours. This shows that ice conditions need to be monitored in a huge area around the installation. This could require helicopter reconnaissance, airborne radar, seafloor-mounted sonar and satellite imageries. Her it could be an economical advantage for different operators of fields in close vicinity of each other to collaborate, and share the costs like the fields located on the Grand Banks of Newfoundland do [20, 44, 58].

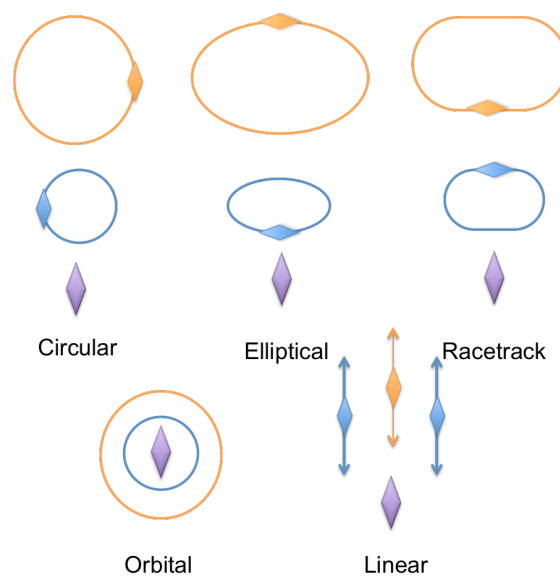


FIGURE 4.3 ICEBREAKER PATTERNS

### 4.1.3 WINTERIZATION

To make personnel and installations cope with the weather and ice conditions in the arctic, the installations need to be winterized. This is to make a comfortable working environment for the crew and to keep all systems operational at all times. Winterization usually involves shielding of all topside working areas, designing topside modules to minimize ice accretion, weather and wind protection of supply areas, increased automation to minimize manual labour, heating of hull compartments, insulation of riser, pipelines and flow lines to keep mud and other fluids flowing [6, 57, 59].

Winterization may also involve changing steel materials and coatings, since the cold environment makes different steels and alloys brittle and make them fail under much smaller loads than at non-arctic conditions. There has been developed a guideline for Arctic petroleum structures, ISO 19906. This guideline provides recommendation on how arctic design, construction, transport, installation and removal of arctic structures in petroleum developments should be conducted, this Guideline is very useful base for winterization of existing vessel and new designed vessels [6, 57, 59].



## 4.2 EXPLORATION & WELL CONSTRUCTION

Exploration and Well Construction is a costly and process with a lot of obstacles in a normal environment. When this is moved to an arctic environment several additional challenges will be added. Exploration involves seismic investigations of potential hydrocarbon prospects and if the seismic show potential, exploratory drilling is performed.

This involves drilling normally simple vertical wells in to the top of the potential formation. The pore pressure- (PP) and fracture pressure (FP) gradients that the drilling operation needs to stay within are estimated from seismic. This means there is a bigger uncertainty involved compared to production drilling, where the area has been drilled before and additional data can be extrapolated from nearby wells. Production wells can also be vastly more complex than exploration wells.

To stay within the drilling window between the PP and FP the formation is sealed off in sections with casings, as drilling proceed requiring heavier mud or if different challenging formations are met. The casings are cemented in place to seal of the annuli and to support the casing. The second casing that is set, frequently called surface casing, needs to support the weight of the wellhead, liner and tubing.

If hydrocarbons are found coring and production test are normally performed to see if the discovery is economically producible, what type of hydrocarbon is present and which properties the reservoir formation has.

Exploration and production drilling in the arctic will have to utilize drilling vessels capable of drilling in an environment where pack-ice and icebergs are presents. The vessels need to withstand potential ice loads and will require support from ice management vessels. The well construction may need other types of cements and muds to perform in the cold environment. Normal cement could not be able to build strength and support the casings in this environment. Mud rheologies are affected by temperature so they need to be designed for the cold environment expected. In addition they need to be environmentally friendly in this fragile environment. These challenges and alternative solutions are presented in the next sections.

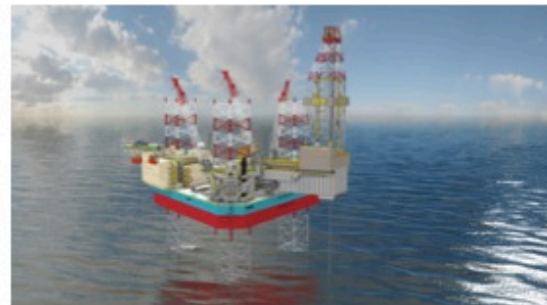
### 4.2.1 VESSELS

When choosing what type of vessel the drilling operation is going to utilize there are several factors that need to be considered. Some of the more obvious are water depth, metocean conditions and drilling capabilities. When entering arctic, sub-arctic and harsh environment other factors occur like ice conditions, operating period and self-sufficient time become very important. In addition to the drilling vessels there is the need to establish what kind of support vessels is needed, like icebreakers, tugboats, standby vessels and supply vessels [60].

There is not one mobile offshore drilling unit (MODU) that will fit every drilling prospect in the arctic. There are 3 main different types of MODU these are Jackups, Semisubmersible and Drillship. All of them have different benefits and drawbacks, therefore picking the right rig for each prospect is crucial. The three types are presented in the 3 next sections. Figure 4.4 show the three different general designee [60].



Drillship



Jackup



Semisubmersibel

FIGURE 4.4 MODU TYPES [61-63]

#### 4.2.1.1 VESSEL OPERABILITY

A major drilling vessel design company GustoMSC has in a paper from 2013 [6]. Introduced a classification of Arctic conditions that can be used for rig selection where, the Arctic is divided into 3 zones reflecting ice conditions: High Arctic, Sub Arctic and Winterized/harsh environment. This classification is basically the same as mentioned in section 2.1 as workable, stretch and extreme with different names for the environments. In the same description they have classified the different areas in the arctic. With there definitions of which conditions these rigs can handle [6]:

*“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 Beaufort Sea, Chuckci 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 environments areas with extreme low temperatures. This involves operations in areas such as Southern Barents Sea.”*

They have also provided information about which types of rigs that are suitable and preferred to use in the different areas in the arctic. This is listed in Table 4-1.

TABLE 4-1 POSSIBLE AREAS FOR DIFFERENT RIGS [6].

Area	Jack-up (limited water depth)	Semisubmerible	Shipshaped
<b>High Arctic:</b> Beaufort, Chuckci, Northern Greenland, Kara East Siberian	✓	✗	✓✓
<b>Sub Arctic:</b> Seasonal high arctic and periodic infested such as southern Greenland, Barentss	✓	✓	✓✓
<b>Winterized/Harsh Environment</b>	✓	✓✓	✓

#### 4.2.1.2 JACKUP

Jackup rigs have legs that are lowered down on the sea bottom, and the drilling equipment is jacked up from water surface. This provides a stable and relatively motion free drilling structure, which can be mobilized quickly and easily. Jackups is the most popular MODU used today. They are most often designed with 3 legs, in open-truss design similar to electrical towers. Some jackups have column legs but these are only used in shallower waters since they don't cope with stress in the same way and they are less stable than open-truss legs.

In the Gulf of Mexico, jackups have been designed to be able to operate in waters up to 165 meters, but in the arctic a practical limited has been sett to 50-80 meters water depth. This is partly because the high local loads the sea-ice can exert on the legs, excluding the use of open-truss legs. To cope with these expected high local loads use of circular protective legs has been purposed. In addition a change in design from 3 to 4 legs with greater distance between the legs will make the structure more stable and able to resist more overturning momentum. This give greater deck space and minimise the chance of ice becoming trapped between the legs [6, 60, 64, 65].

GustoMSC has designed a Jack-up series suitable for harsh and high arctic area. The most extreme in the series is capable of operating in 50m water depth and 1,5m first-ice or 30m water depth and 2.0m first year ice. In floating mode the jack up can handle waves with height up to 16.5m. It is designed with sloped hull to reduce the loads from impact with ice. The hull is an ice class hull in Polar Class 4, which means "year-round operation in thick first-year ice which may include old ice inclusions". The MODU is fully winterized giving an encourage workspace for the crew in hostile environment. The rig is capable of drilling 30.000ft and is equipped with a protective sleeve that cane be deployed to protect the drillstring in the splash zone to hinder the drillsting from being damage by pack-ice. The rig has variable deck load capacity of 7500tons and accommodation space for 150 persons. A figure of the Arctic Jack up can be seen in Figure 4.5. More specification about this arctic jackup is listed in Table 4-2[6, 65].

Another Jack up concept has been present by the University of Stavanger and Gubkin University where the hull has icebreaker shape, which makes it ideal as a standby for relief well drilling in case of a blowout. It is designed to extend the drilling season with between 4-5 weeks in ice areas like Pechora and Kara Sea. This will have a major impact of the work that can be done in one season. Today drilling season vary between 45-90 days, which in some cases is not enough to drill and test one single well [6, 65].

The concept is based on the idea that the MODU can continue to drill after the ice has started to build up since it is able to sail away even when the ice has started to get tough. The drilling is planned to be performed through one of the jack up legs to protect the drill string and tools from sea ice, since the jack up legs can be at different heights so a type of telescopic legs have been proposed to allow drilling through it. To maximise stability and center of gravity during transportation the derrick and rig floor should be placed on skidding beams, making it possible to skid it to the center of jack up [6, 65].

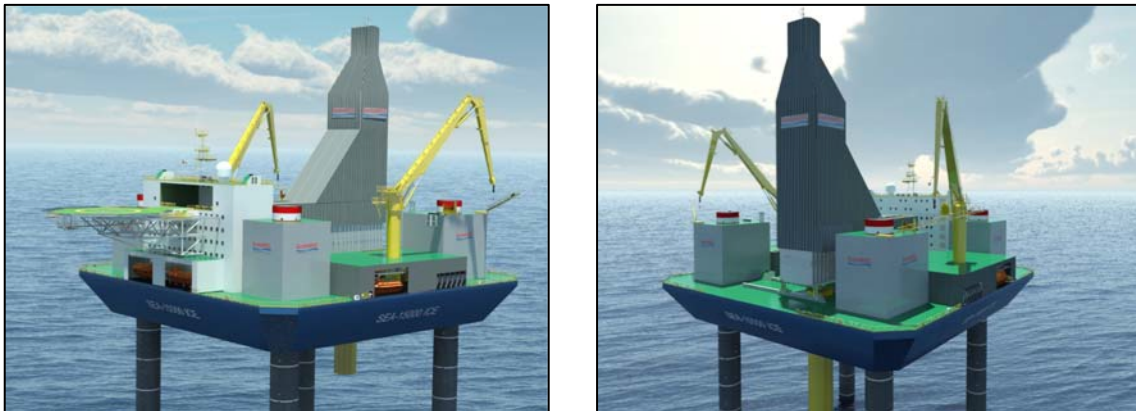


FIGURE 4.5 ARCTIC JACKUP [6]

#### 4.2.1.3 DRILLSHIP

Drillships are monohull vessels fitted with a drilling derrick or ram and moon pool to allow drilling operation to be performed. These vessels have installed mooring or dynamic positioning (DP) systems to be able to stay stable in one place during drilling operations. Drillships are easy to mobilise since they have their own propulsion system and do not require additional ships to propel them to the drill site. Combining this with their large deck space make them ideal for deep water drilling operation from 600 to 3000 meter water depths, but they can also be used in shallower water with mooring systems.

Drillships have some disadvantages they are quite expensive to rent and heavily afflicted by weather conditions, like wind, waves and currents. To cope with this movement 3 different systems are used DP, Spread mooring and Turret mooring. DP is limited to waters with greater water depth than 300-400 meters. Spread mooring is vulnerable to changing weather and ice condition due to the ships disability to change position. Turret mooring allows the ship more mobility than spread mooring but it is more complex. When moving in to the arctic the station keeping system is vital. DP system require more fuel than mooring systems and this affects the independence of the drilling operation with regards to supply. The DP system allows for quicker spudding since no hook up to mooring lines is needed, which can be beneficial in areas with short drilling seasons. Spread mooring may cause more time disconnected than turret mooring, because of the limited ship movement. Turret mooring require more time hooking up and require subsea access for anchor handling [6, 66].

GustoMSC has also designed a series of drillship suitable for arctic and harsh environment. The flagship is capable of year round operation in up to 4m multi-year ice, designed at Polar Class 2 which means “year-round operation in moderate multi-year ice conditions” This makes it able to operate in any arctic area. Drilling operation is limited to 2m first-year ice. Station keeping is kept with turret mooring with a 16-point mooring system assisted with DP. Since the ship requires subsea access to mooring system, it is fitted with two work class ROVs [6, 67].

The ship has storage capacity for 120 days without being re-supplied and carries equipment for up to two wells, with a maximum drilling length of 10,800m. Drilling derrick and rig floor is fully winterized in addition the stern is fitted with wind protection deck space for re-supplement in arctic conditions. For drilling purpose the rig is equipped with two Subsea BOPs and one surface BOP with a subsea shutoff device. A figure of the ship can be seen in Figure 4.6. More specifications about the arctic drillship are listed in Table 4-2[6, 67].



FIGURE 4.6 ARCTIC DRILLSHIP [67]

#### 4.2.1.4 SEMISUBMERSIBLE

Semisubmersible MODU are the most stable floating drilling rigs. It is normally designed with two submergible pontoons, which are submerged during drilling operation. This combined with hull mass displacement and the possibility for wave to pass through between the pontoons makes it handle harsh environment very well, minimizing roll and heave. Their stability in harsh sea conditions has made them MODU of choice in deeper water where Jackups are not able to operate. Semi submersibles are capable of carrying less equipment than drill ships making them more depending on re-supplement during drilling operation. They are capable of drilling in water depths between 30-3000m, both ends of the scale are extreme cases. When operating in extremely shallow waters the danger is that the pontoons and lower hulls may collide with the subsea BOP when marine riser is disconnected [6, 20, 68, 69].

In arctic areas the self sustainability of a MODU is very important, this makes drillships preferable over Semi submersibles, since they are capable of carrying much more drilling equipment, drilling fluids, spare parts and food supplies. Another disadvantage the Semi has is their ability to handle ice loads. They have no protection against ice in the splash zone and ice may become trapped between the pontoons, stopping the drilling operation. This makes them unfavourable for operations in high arctic areas [6, 20, 68, 69].

A new design for Semisubmersible has been developed by Huisman to make semisubmersibles more attractive for operation in high arctic regions. It will be referred to as Arctic semi throughout this thesis. The design is based on a circular rig with a conical shaped round floater and eight columns leading up to the round deck space. This design makes it suitable for deflecting ice from any direction with 16 point mooring system keeping it in place and able to operate in ice conditions up to 1,5m. During drilling the rig will be partly submerged like normal semisubmersibles. This will protect tools and drilling equipment in the splash zone from ice. In extremely shallow waters between 12-30.5m, it can be used as gravity based structure placed on the sea bottom as shown in Figure 4.7. The rig can be fitted with a normal derrick or the new concept “multipurpose tower” (MPT). This new concept multipurpose tower is developed to reduce weight, lower centre of gravity and to streamline tripping and drilling processes. The manufactures goal with the MPT is to automate tripping and eventually drilling



processes. This is beneficial for operations in arctic areas with limited drilling season. Specifications about the rig is listed in Table 4-2[70, 71].

There are several different winterized semisubmersible MODUs on the rental market at the moment, In this thesis one relatively new 6<sup>th</sup> generation semisubmersible rig designed by Aker with a good track record will be presented, shown in Figure 4.8. The rig is fully winterized with sheltered drill floor, heated fluid storage and was one of the first rigs to be fully winterised for polar conditions. Fitted with dual ramrig allowing 20% more drilling efficiency than normal one derrick or ram semisubmersibles [59], the rig is operated by the drilling contractor Transocean. More specification about the rig is listed in Table 4-2 [59] [72].

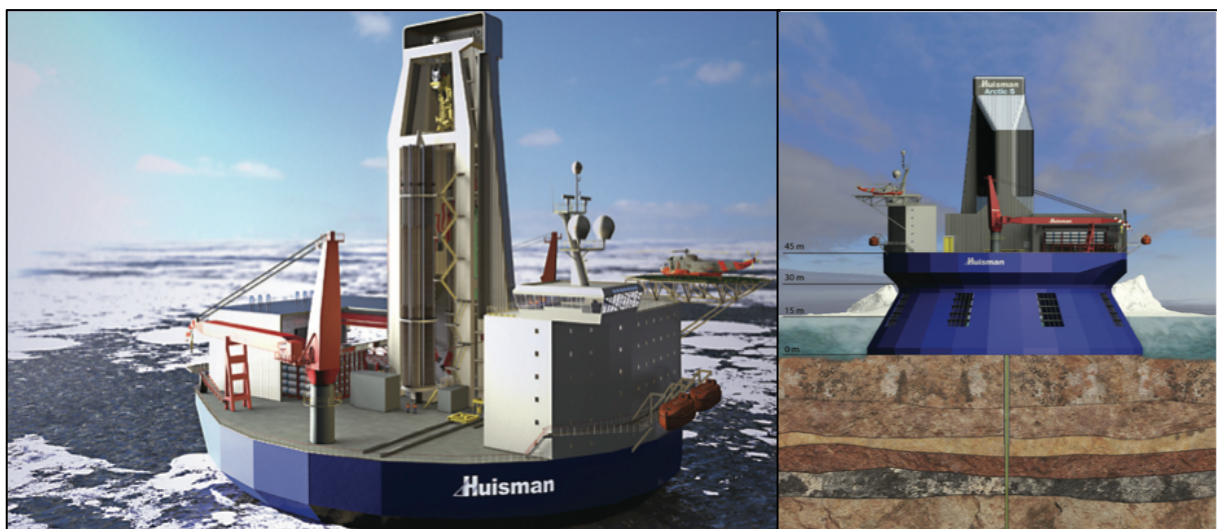


FIGURE 4.7 ARCTIC SEMISUBMERSIBEL IN FLOATING AND CAISSON MODE ON SEA BED [70].



FIGURE 4.8 WINTERIZED SEMISUBMERSIBLE [73].

TABLE 4-2 ARCTIC MODU SPECIFICATIONS [6, 67, 70, 72].

Type:	Arctic Jack up	Arctic Drillship	Arctic Submersible	Semi Winterized semisubmersible
<b>Ice conditions</b>				
Ice Class	Polar class 4	Polar class 2	Polar class 4	-
Operation	2.0m 1st-year ice (30m WD) 1,5m 1st-year ice (50m WD)	2m 1st year ice	1.5m	-
Stand-by	2.0m 1st-year ice (30m WD) 1,5m 1st-year ice (50m WD)	4m multi-year ice	1.5m	-
<b>Waterdepth</b>				
Maximum	85m	1500m	1000m	3047m
Minimum	-	80m	12m (GBS)	-
Drilling depth	9143m	10794m	12190m	9143m
Variable deck load	7500t	Two wells / 120days	16000t	-
Mud Tank	-	3600m <sup>3</sup>	2200m <sup>3</sup>	1700m <sup>3</sup>
Brine/base oil	-	1750m <sup>3</sup>	2000m <sup>3</sup>	
Bulk	-	1360m <sup>3</sup>	820m <sup>3</sup>	
Cuttings		954m <sup>3</sup>		
Mooring/DP	Jack up	16 point Turret Mooring/DP2	16 point spread mooring	DP3
Accommodation	150	200	200	140

#### 4.2.2 DRILLING SEASON

As mentioned earlier open water conditions in the arctic vary a lot. This will affect how and when drilling is possible. Before drilling in an area can start, it is important as mentioned in section 4.1 to have an ice management program capable of handling the potential pack-ice and icebergs, which could inflict the area during the drilling campaign. Drilling season is affected by how much time the specific area has open waters throughout the year, and what type of drilling vessel is possible to be used in the area [6].

In the Southern and Central Barents Sea excluding the Pechora Sea there is a history for year round open waters with the possibilities for some infrequent icebergs. This gives the potential for year round drilling operation. Drilling in the Barents Sea has been perform for several decades, but the that trend is that the operation is going further north. In may 2014 the Statoil will start to drill the most northern well in the world with the Apollo prospect located close to the 74<sup>th</sup> latitude.

Baffin Bay and Pechora Sea has normally a long open water season of over 120 days. Providing a drilling window long enough for exploration wells to be drilled in one single season, this is important for the economics of a drilling operation. Baffin Bay has a high density of icebergs, requiring ice management with the possibility of emergency disconnection of the drilling vessel. This has Cairn Energy shown to be possible during the summer of 2010 and 2011 when they drilled several wells in the area [1, 28].

The Beaufort has an open water season varying from 0 to 120 days with an average of 60 days. During the open water season the area could be inflicted with ice intrusion [1]. This intrusion is due to the currents in the Beaufort Gyro. The Gyro can sweep first year and multi year ice in to the Beaufort Sea that can be present there from a few days to several weeks. This gives the need for DP moored MODU incorporated with ice management. Deep-water exploration wells drilled in the area could possible become multi seasonal before they are completed, increasing the cost of the drilling operation. Drilling operations have been performed in the area successfully in water depths up to 67 m with the floating drilling rig Kulluk. Mostly the drilling operation took place during the open water season. Some of the wellw where drilled during the winter months with sea pack-ice present. This required assistance from icebreakers in an ice management

program. Drilling in the winter months required several periods where drilling were suspended due to the severe ice-conditions, and leading to some of the well becoming multi seasonal[1].

On the East coast of Greenland in the Greenland Sea the ice conditions is the most severe. Here there is year round presence of massive icebergs. The icebergs is transported through the Arctic with Transpolar Drift to the Fram Strait and passes potential E&P areas. This makes it an extremely challenging area to operate in. In Figure 4.8 the severity of the iceberg flow on the north east coast of Greenland from August 2000 is shown. The technology needed for drilling operations in the area is not yet available and further research is needed for E&P to take place [1].

During the open water season there is no need for a specialised arctic drilling rig capable of drilling in pack-ice. But there need to be a contingency arctic drilling rig nearby, capable of drilling a relief well during the winter months in the event of a blowout.

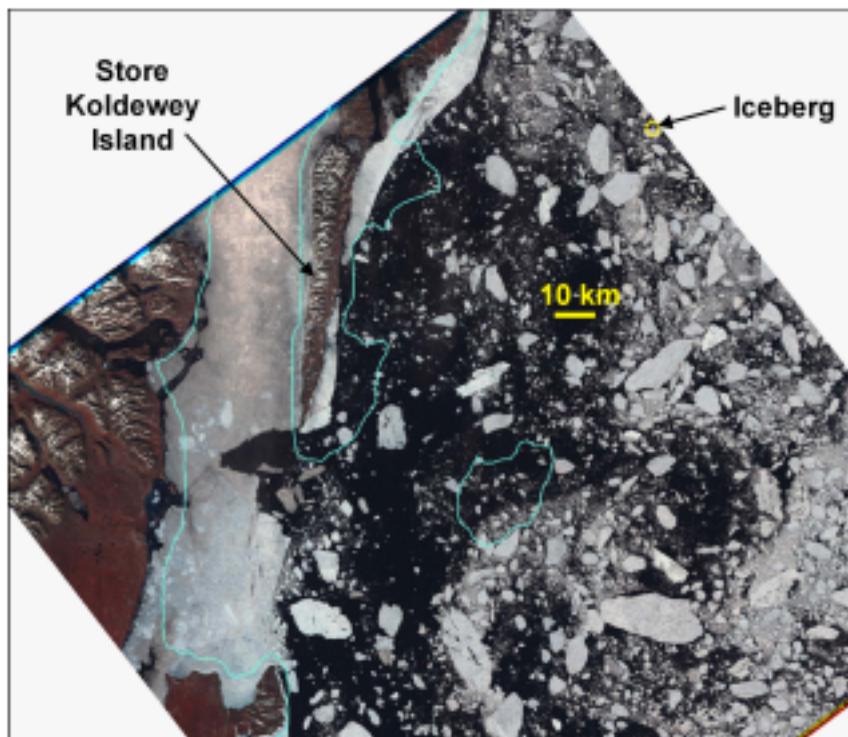


FIGURE 4.9 ICEBERG FLOW ON THE NORTH EAST COAST OF GREENLAND [1]

### 4.2.3 FLUIDS

Drilling fluids and completion fluids are a crucial part of the drilling and completion phase during well construction. First of all drilling fluid or mud is the primary barrier during drilling, other important tasks the mud have is transport and suspend cuttings, stabilize borehole, cool and lubricate the drill bit and provide buoyancy to minimize weight loadings. Drilling fluids can be water-based, oil-based or synthetic-based all of them have different advantages. Oil-based seems to have the overall best performance. But there is an issue with the environmental impact from the fluid. Water-based drilling fluids are better for the environment [54] [55, 74, 75].

When moving into the arctic the environmental considerations should be taken to limit the use of oil-based muds as much as possible, and when used dearomatized oils should be selected over low-viscosity mineral oils and diesel fuel. In the water-based mud, environmental friendly alternative biodecomposed polysaccharides should be used when viable. Drilling fluid based on this require close attention on clay inhibitors, surfactants and lubricants, to make sure the fluid performs adequately [54] [55, 74, 75].

Another issue is with areas where there is expected to be permafrost. Drilling fluids has temperatures over the freezing point. When this relative warm drilling fluid is circulated over a section where permafrost is present, the heat from the fluid will warm up the frozen rocks surrounding the borehole. This can as mention at section 3.2.3 make the borehole unstable, therefore the temperature in the mud should be kept as low as possible in these sections. Temperatures below 0° C require that fluids used are optimised for subfreezing condition to get the wanted rheological effects and to minimize washout which is big a problem in permafrost zones. Directional drilling should also be limited as much as possible in section where permafrost is present. The instability in the ground could also cause mud loss to the formation [54] [55, 74, 75].

When producing in a well with a top section placed in a layer of permafrost, the temperature difference in between the produced fluid and permafrost layer could increase wax deposit inside the production tubing. As a precaution and where possible the Subsurface Safety Valve (SSV) should be placed below the permafrost zone to hinder the build up of wax in the valve. Some wells may also require frequent scrapping of production tubing area in the permafrost layer to hinder tubing from becoming blocked by wax. Permafrost is mostly a problem for onshore drilling, but in shallow waters it has been identified offshore as well. The areas were it has been found present are Pechora Sea and parts of Kara Sea. Permafrost depth extension can vary a lot in a small area [54] [55, 74, 75].

#### 4.2.4 CEMENT

Cement is a crucial part of the well; its main task is to develop zonal isolation in the annulus. This can be between reservoir section and surface, water bearing zone and surface or between several reservoir zones in a well. This makes it one of the most important parts of establishing well integrity in a well. The cement needs to bond with the casing and fill up the entire annulus volume to prevent channelling. To achieve this all the mud in the annulus needs to be removed before the cement job is performed. Another important task the cement has is to be part of the load bearing mechanism of the well. After the surface casing is placed and cemented, the wellhead and BOP is placed on top of it. This load and the load from the additional casing to be hanged off in the wellhead, needs to be supported by the surface casing and the cement holding it in place. For the cement to be able to support this load it need to have built up enough strength. Cement builds strength during the curing process, which is a time consuming process [55].

Cement curing time is closely related to curing conditions, temperature and pressure. Temperature has the greatest impact on curing time. When cementing the top hole sections in subsea wells, the curing time needs to be as low as possible, this to minimize the MODU time waiting on cement (WOC) and limit costs. Top section or Surface casing cement needs to build adequate strength before wellhead, BOP and marine riser are place on the well. Under normal North Sea Norwegian sector conditions this is done 24 hours after cement has been placed. The cement pumping job for the surface casing is normally done with two different cement slurries, lead and tail cement slurry. This is done to minimize the hydrostatic head from the cement column, as it is pumped down in to the well and prevent the formation to fracture. First the lead cement is pumped in to the pipe and then the tail cement slurry is pumped, before both slurries are displaced out of the pipe and place down hole as seen in Figure 4.10. The lead cement usually has a higher water-to-cement ration (W/C) then tail cement, this will also affect the curing time of the slurry. When entering in to arctic and deep-water conditions the water temperature at sea bottom could be expected to be as low  $-2^{\circ}$  C in some areas. Low seawater and surrounding bedrock temperature combined with high W/C ratio will give a relatively very long curing time with normal Portland cement. It can also lead to an unknown depth of Top Of Cement (TOC), since the cement closest to the sea floor has

not had adequate time for cement to build up strength. There will be needed specialised cement slurries or incorporated additional curing time before wellhead and BOP is lowered, adding load to the well. Another option in production drilling is to perform batch drilling of top sections. This will give cement time to cure and build adequate strength while MODU is drilling top sections on nearby wells, instead of standing by and adding expensive WOC for operator. This could be extra costly in a harsh environment with a shorter drilling season, where every hour has a significantly higher value and with an even more expensive drilling campaign [76].

In shallow water with permafrost present another challenge during top section cementing as mentioned in section 3.2.3 can occur. Permafrost can hinder the cement of curing. The below 0° C temperature of the formation can in worst case scenario freeze the water in the cement slurry before it have had time to build adequate strength, and failing the cement job. Another problem in permafrost is that cement curing is an exothermic process meaning that it produces heat. This heat will affect the frozen soil surrounding, an effect being that there is no bonding between cement and borehole wall, or that a micro annulus is created. In both cases the cement job will fail. Washout in permafrost zones is also a big problem. This may increase the contingency volume of extra cement needed for a job from 100% extra to 500% extra cement at location [54].

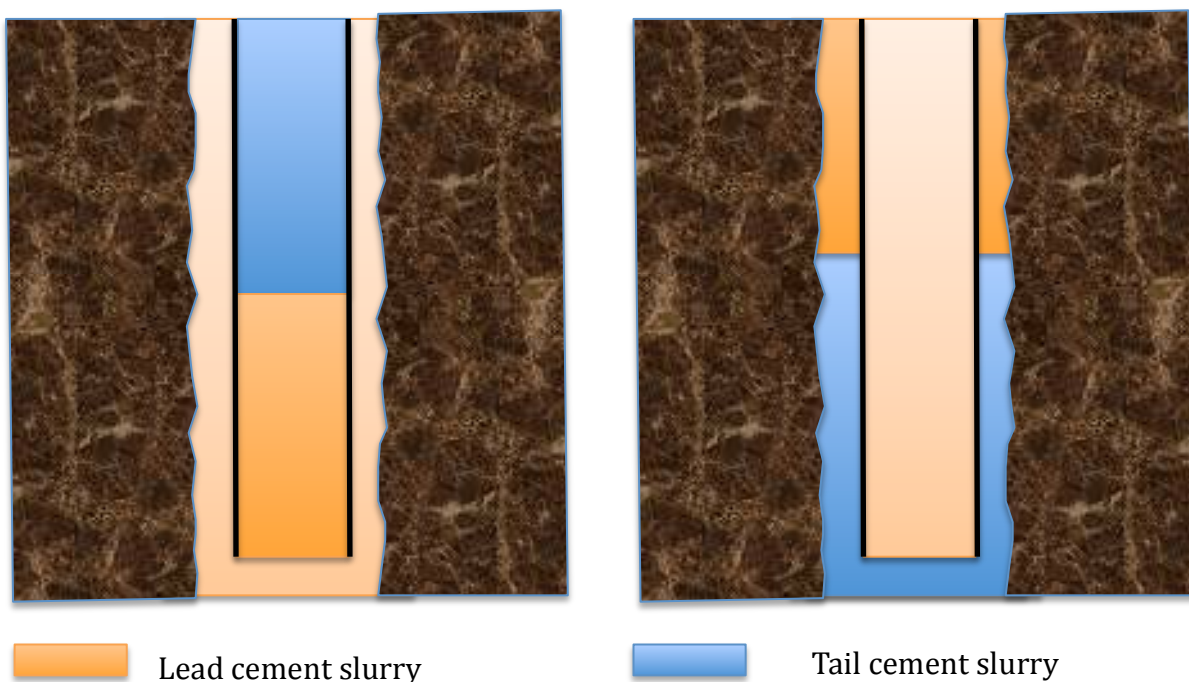


FIGURE 4.10 LEAD AND TAIL CEMENT SLURRY PLACEMENT



### 4.3 FIELD DEVELOPMENT CONCEPTS & PRODUCTION

Developing a field in the arctic area gives different challenges in deep and shallow waters. There is a history for developing shallow water fields in Beaufort Sea, Sakhalin and recently Pechora Sea. In medium depth waters there has been some developments in the iceberg-inflicted area on the Grand Banks of Newfoundland. This section will present and show some of the possibilities and limitations with different development concept for use in arctic areas. Steel Jacket platforms have been left out since they provide limited use in ice conditions [44].

Operating in shallow and deep arctic waters give different challenges, both of them have issues involving different forms of ice. In shallow waters ice limits the use of conventional Jack-ups due to the extra loading that ice could inflict. There are also problems with subsea installation in shallow waters; big icebergs stretches way below sea level and can inflict serious damage to subsea wellheads and pipelines. In shallow waters there have been used many different types of drilling and production facilities these include steel structures, gravity based structures, long reach drilling from shore and even artificial man made island. Artificial Island has a limitation of 30m-water depth, as it needs exponential increasing amounts of gravel and rocks with increasing depth [44] [1, 6, 20].

When entering deep-water there is no danger of icebergs destroying subsea equipment, since the water is too deep for any floating icebergs to hit the equipment. But icebergs can cause serious damage to top site equipment if they are not adequately designed. The development of an arctic deep water prospect would most likely involve some form of floater coupled with subsea templates. In rough areas, the floater needs the capability to disconnect from the production turret, and move to a safe area until the conditions are operable again. Different floater concepts are presented in section 4.3.4

### 4.3.1 ARTIFICIAL ISLAND

Artificial islands are man made island,s constructed with gravel, rock, steel and concrete-mates. They require large amounts of gravel. The technique used to construct the first gravel islands was to dump rock and dredged material at the site, until the island was above sea level. This proved very little strength, therefore newer islands also use steel framework to provide support and resist tidal currents. Some of the islands have concrete mats placed around the island, stretching some meters below and over the sea level to protect the islands from pack-ice and icebergs [44].

Artificial Islands have a great limitation, which is depth. 10-15m water depth seems to be the limit for artificial islands. There has been constructed islands up to 20m water depths but this require vast amount of rock and gravel. This will affect surroundings with larger gravel pits. During building of artificial island with large amounts of dredged material, the near by area could temporary become polluted with suspended particles. In the Beaufort Sea there has been a trend with the use of artificial islands as seen in section 2.2.1 but this is greatly limited with increasing water depths since parts of the Beaufort Sea is deep waters. An artificial drilling and production island is shown below in Figure 4.11 [44].



FIGURE 4.11 OOOGURUK ARTIFICIAL DRILLING AND PRODUCTION ISLAND [77].

### 4.3.2 STEEL STRUCTURES/CAISSON

Steel Structures or Caissons are installations that are placed on the sea floor. They are floated to the site where they are sunk down to the sea floor and weighted down by their own weight or with additional weight from sand or fluids. The caisson hull protects it from pack-ice and icebergs, since the hull is a massive structure it is limited to shallow waters. There have been built two facilities with this design, Molikpaq used at 30m water depth and Prirazlomnye used at 20m water depth. The Molikpaq was originally designed as a drilling rig to be used offshore Canada, but has been re-designed for drilling and production from the Sakhalin field offshore Russia. Prirazlomnoy as mentioned in 2.2.5.1 was purpose built to be the first oil-producing field in the Barents Sea and to have enough capacity to handle production from nearby discoveries, shown in Figure 4.12 [43, 44].



FIGURE 4.12 PRIRAZLOMNOYE DRILLING AND PRODUCTION CAISSON [78]

### 4.3.3 GRAVITY BASED STRUCTURES

Gravity Based Structures (GBS) are concrete structures, which were originally developed for use in the North Sea. They are constructed with reinforced concrete and are able to support heavy loads, and is therefore ideal for platforms in medium depth waters and harsh environment. These structures are suitable for developments that require drilling, production and storage in one unit. Drilling and production facilities are supported by the GBS and storage tanks can be included as part of the GBS. In iceberg-inflicted areas GBS have been used. The Hibernia field is developed with a GBS design. It was the first GBS used in extreme environment, and is fitted with a concrete caisson designed to resist an impact from a iceberg up to 1 million tons. A picture of the platform can be seen in Figure 4.13. The Hibernia platform is located in the Grand Banks of Newfoundland at 80m water depth. It is fitted with two drilling derricks and has a total of 64 well slots and the capacity to store 1,3 million barrels of oil [44, 79].



FIGURE 4.13 HIBERNIA PLATFORM [80]

#### 4.3.4 FLOATING PRODUCTION STORAGE AND OFFLOADING UNIT

Floating Production Storage and Offloading Unit (FPSO) are used in deeper waters where GBS or Steel structures would not be possible or economically viable to use. There are several different designs of FPSOs; Ship Shaped, SPAR, Buoy Shaped floater, Semisubmersible and TLP. FPSOs utilise a subsea development with a riser systems up to the floater, which include production risers, umbilical lines, chemical injection lines and often a mooring system [20, 57].

The two concepts that are most suitable for use in arctic and sub arctic regions, where ice loads are expected to cause detachment from mooring and production system are Ship Shaped and Buoy Shaped floater. They have the possibility to be self-propulsions and fitted with a system that only require a single connection between FPSO, mooring lines, umbilical cables and risers. This could make them independent of other vessels during disconnection and connection [20, 44, 57].

A ship shaped FPSO would need to be designed with a icebreaker hull or at a polar class suitable for the condition expected in the operating area, polar classes are listed in Table A-3 in the appendix. The Buoy Shaped floater need to be fitted with a conic shaped hull in the sea level zone to reduce the loads that pack-ice and icebergs could inflict [20, 44, 57].

SPAR and TLP are not suitable for areas where ice loads could become so high that disconnection from mooring and riser system is needed. SPAR cannot be fitted with a system that only has one connection for detachment they require a more intricate mooring system. Another issue is the stability of the structure during towing, this would require some de-ballasting and with a heavy topsite it could become unstable. TLP are moored down with lateral cables to the seafloor, this makes disconnection complex and may not be possible, and therefore not suitable in an area where detaching may be needed. Both TLP and SPAR installations could be suitable for areas with moderate ice loads; they can be fitted with drilling derrick and dry tree wells [20, 44, 57].

There has been installed two FPSO in iceberg inflicted areas, at the Terra Nova and White Rose fields which are located in the Grand Banks of Newfoundland. Both of them are ship shaped. Terra Nova is located in 95m water depth and White Rose in 125m. Terra Novas hull is designed to resist multi-year ice and icebergs of 100.000 tons at 0.5 m/s and 3.000 tons at 5 m/s. This required 12% more steel in the hull compared to a normal hull. A figure of the Terra nova field can be seen in Figure 4.14. An ice management programme has been established with other installations and vessels nearby and disconnection from the production turret has never been needed [44, 57, 81].



FIGURE 4.14 TERRA NOVA FIELD [81].

#### 4.3.5 SUBSEA WELLS

Subsea wells are wells where the production tree is located subsea and not on a platform. The produced fluid can be pumped to a tie in platform, FPSO or a production facility onshore. Subsea wells are developed with a subsea template where the production tree and control equipment are mounted.

For subsea wells in shallow water where icebergs are present, additional protection is needed, since icebergs have deep keels that could destroy or damage subsea templates and other subsea equipment. In these areas the templates should be placed in glory holes, as the ones at Terra Nova. Glory holes are holes in the sea bed that has been excavated down to make sure that icebergs can not possibly reach the templates. Pipes should be buried deep enough that there is no possibility that icebergs can damage them. Subsea development in harsh environment could eliminate the FPSO or platform completely, like the Snøhvit field in the Barents Sea mentioned in section 0. Where the produced fluid is transported through a 143 km pipeline to shore where it is processed at an onshore installation Melkeøya, in a much friendlier environment than offshore. When a produced fluid is transported over such a long distance a significant pressure drop will occur, in such a cold environment this could create hydrates in the pipeline that could block the pipeline completely. To hinder this from happening, the Snøhvit pipeline is injected continuously with monoethyleneglycol (MEG). The MEG is recycled at the processing plant and re-injected into the pipeline. A picture of the Snøhvit field and pipeline can be seen in Figure 4.15. The possibility of us alighting an onshore processing plant for a offshore field is limited by the distance to shore, fluid produced and ice conditions [44].

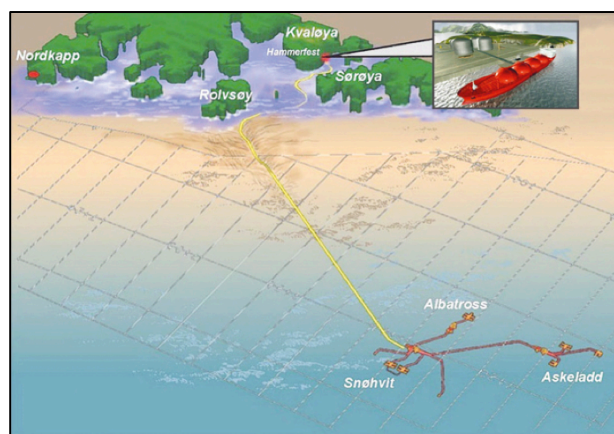


FIGURE 4.15 SNØHVIT FIELD AND PIPELINE [82].

#### 4.4 INTERVENTION AND P&A

All wells require some remedial work after they have been drilled and put on production. The required work include: Scale removal, production logging, inspections, setting or retrieving plugs and TRSCSSV, changing GLVs, zonal isolation, replacing production tubing, acid and chemical treatment. All these jobs are classified as well intervention work. To keep production rates high, well intervention is needed on all field developments. Performing well interventions on a fixed installation is much easier and cheaper than on a subsea installation. On an average it is 10 times as costly to perform well intervention on subsea well than platform wells. The growing number of subsea wells combined with operators goal of increasing total production from subsea developments, has given an increased focus on subsea intervention operations. One of the focus areas is Riserless Light Well Intervention (RLWI), which utilizes a monohull vessel to perform Wireline operations without the use of an expensive semisubmersible. A figure of the equipment involved in a RLWI operation is shown in Figure 4.16. As the name indicates RLWI is capable of performing light intervention jobs like; Production logging, perforation, zone isolation, installation and inspection of TRSCSSV, milling short sections of scale, replace gas lift valves, pumping operations, sampling, sleeve operations, well killing and repairing casing/tubing. To perform heavier intervention a semisubmersible rig or similar specialised vessel is needed [83, 84].

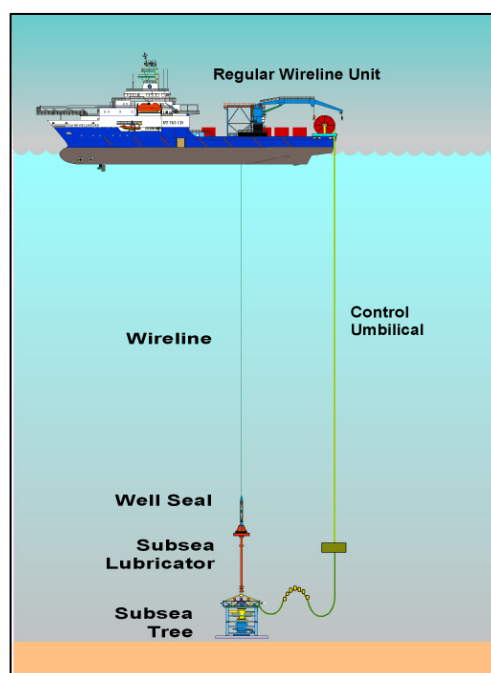


FIGURE 4.16 RLWI OPERATION [83]



#### 4.4.1 INTERVENTION ON FIXED INSTALLATIONS

Performing intervention jobs in the arctic will add challenges in the same way as for drilling and production. On fixed installations with sheltered workspace, performing wireline and coiled tubing the logistics aspect will be the most challenging. Since the operation needs to be protected from the harsh environment and performed in a sheltered and heated workspace. Coiled tubing require more space than wireline operations, and this should be thought of during the design phase of the facilities, to incorporate enough shielded and heated workspace. Offshore coiled tubing operation is shown in Figure 4.17. Some well stimulation jobs require additional vessels for mixing and pumping of stimulation fluids. For these vessels to be able to operate in ice-inflicted waters they need to be purpose built with the ability to withstand ice and wave inflicted loads. An issue with using stimulation vessels in harsh environments is the limited weather conditions. During a stimulation operation a flexible hose is connected between the vessel and the installation, these jobs usually require several hours. It may not be possible for a vessel to hold position close to a fixed installation in areas with drifting pack ice and other alternative stimulation methods may have to be used [59, 83-85].

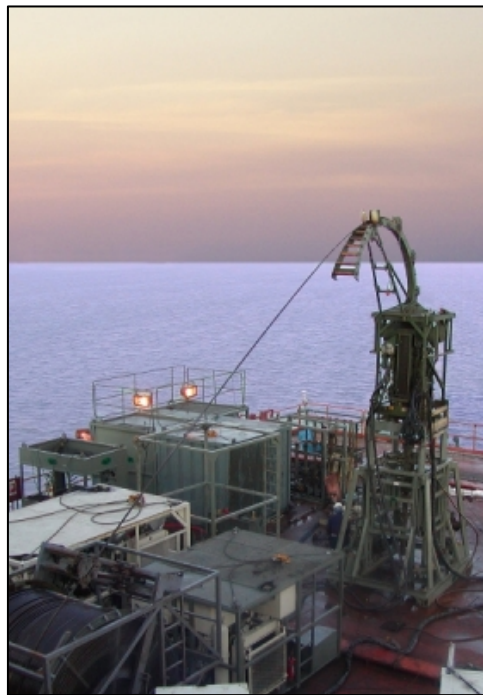


FIGURE 4.17 OFFSHORE COILED TUBING OPERATION [86]

#### 4.4.2 INTERVENTION ON SUBSEA INSTALLATIONS

For subsea developed fields in harsh and arctic environments intervention will be more challenging than on fixed installation. Intervention jobs will be dependant on new or redesigned and winterized vessels that are able to protect personnel from the environment, withstand possible ice loads and stay operational without re-supplement for long periods of time. Today's RLWI vessels are designed with unsheltered deck and workspace, the best solution is to design purpose built vessels that are suitable for year-round operation.

STX OSV has in cooperation with Marintek at NTNU and VVT Technical Reserch Center of Finland designed a Well intervention vessel suitable for year-round operation in first year ice, the vessel is shown in Figure 4.18. The vessel design incorporates a sheltered workspace fitted with a moonpool for intervention equipment to be deployed through, protecting it from drift ice. At the stern of the vessel there is an unsheltered deck space fitted with offshore subsea crane. The deck space is meant to store intervention and oil spill equipment, as the vessel is designed to be part of a first response team in the event of oil spill in addition to act as an intervention vessel. During intervention jobs in first year ice, test at Aker Arctic ice tank has show that the vessel is able to stay at location in up to 0.8m thick first year ice. The vessel is designed for conditions expected to be encountered in the Barentes Sea including the ice parts in the east and north. For operations in other parts of the Arctic additional vessels may be need for ice management purposes. For heavier intervention, drillships or circular semisubmersible rigs as mentioned in section 4.2.1 needs to be used. In ice free areas with harsh environment, ordinary semisubmersibles are possible to use for heavy intervention [6, 87].



FIGURE 4.18 ARCTIC INTERVENTION VESSEL[88]

#### 4.4.3 PLUG AND ABANDONMENT

Plug and abandonment (P&A) is the final intervention job performed on a well. It involves isolation of potential oil and water bearing permeable zones from each other and from the surface. In addition, come removing of any equipment placed on the sea bottom and some meters down into the ground, the length depends on where in the world well is located and which governmental legislation is applicable. P&A operation is a costly part of a well's life cycle and all wells should be designed to make P&A as cheap as possible and still have the required well integrity during the well's lifetime. A P&A operation consists of 3 phases. The first phase consists of isolating the reservoir section with a primary and a secondary barrier. Phase two involves the isolation of any hydrocarbon or water bearing permeable zones and placement of a surface plug to protect the hole. The third and final phase consists of removing the wellhead and parts of the top casings and restoring the sea bed back to its original form before the well was drilled, removing all visible signs from the sea bottom. This three phase has usually required the mobilization and use of MODU [89, 90].

As cement is the most used material used for plugging operations the considerations taken during casing cementation should be taken when placing P&A cement plugs. This involves using slurries designed for cold temperatures and not placing plugs in an area that is afflicted with permafrost. The best solution here is to place the plug below the permafrost zone.

To limit costs and allow limited numbers of MODU's to be used for drilling instead of P&A operations has recently encouraged the use of intervention vessels for the third and final stage of P&A. This has been very successful operationally. With the use of a specialized cutting tool that uses water nozzles to cut casings and cement in the wellhead, a cut wellhead is shown in Figure 4.19. The cost aspect of performing one single operation of third phase P&A is relatively high, because of a high mobilization fee of the vessel. When used in plugging campaigns for multiple wells the cost level reduces to level below the use of an ordinary semisubmersible. Other advantage of transferring P&A tasks to specialized intervention vessels is HSE. On a MODU removing the wellhead and casings is a non-routine operation involving several heavy lifts. When using a specialized intervention vessel the operation becomes a routine job with personnel trained for the specific task reducing the chance for a serious incident. To further reduce

cost and improve safety more Phases P&A work should be transferred from MODU's to specialised intervention vessels when technology allows it. In the United Kingdom part of the North Sea it is normal practise to place surface plugs with the use of specialised intervention vessels [89].

Minimizing the need for MODU's in P&A operation is interesting for the arctic. Since ordinary semisubmersibles are not designed for operations in ice conditions as mentioned in section 4.2.1. The number of drillship and Arctic semisubmersibles are and will be limited in numbers therefore prioritizing them for drilling operations as they were designed for should be done. Using Monohull Intervention Vessels like the one presented in section 4.4.2 should be used as much as possible to reduce the use of Arctic MODUS and to limit the cost of P&A operation. Wells should also be designed with P&A requirements from the start, since all wells will need to be plugged and to make the job as easy, safe and cost effective as possible [6, 89].



FIGURE 4.19 CUT WELLHEAD [89]

#### 4.5 ENVIRONMENTAL PROTECTION

The arctic environment is a very sensitive environment and special care should be put in place to minimise any disruption of the ecosystem, Figure 4.20 shows the endangered Arctic Fox. The arctic has a less diverse food chain, making it more vulnerable to introduction of polluting substances. All operations in the arctic should establish pollution and waste management programmes before operation start. It is vital to use environmental friendly chemicals hindering dangerous toxics getting in to the food chain. Another dangerous aspect is the event of a blowout; the distance from infrastructure makes blowouts even more dangerous. But the long history of arctic exploration onshore in Alaska and Canada has shown that the probability of a blowout is the same as for any other location in the world. But still the focus on well integrity during drilling and production should be at a higher-level than elsewhere because of the serious potential a blowout will have on the environment and wildlife [4, 6, 20].



FIGURE 4.20 ARCTIC WILDLIFE, ARCTIC FOX [91]

#### 4.5.1 SPILL PREVENTION

Accidental leakage has the most severe potential impact on the environment. Different scenarios where leakage is possible include blowout, natural disasters, explosion and fires, pipelines rupturing, tanker accidents or loading and bunkering accidents. All of these incidents could have a dramatic consequence for environment. To prevent escalation of minor operational incident evolving to dramatic catastrophes the operator must put measures and systems in place. One of the important measures to have is effective plans and spill response capabilities for all season of the year [4, 44, 92].

Most spills are small and can be handle on a local level by operators, for more dramatic spills cooperation between operators and governments emergency teams may be needed. The plans prepared by the operators should clearly describe the actions that need to be taken in the event of spills or possible spills. This including responsibilities for key emergency personnel and channels for reporting to authorities. These plans should also describe how recovered spill should be handled for temporary storage and disposable [4, 44, 92].

Periodically the plans shall be drilled and revised to identify areas where additional personal training and plan improvement is needed. In ice infested areas, oil spills can comingle beneath the ice for some time before the spill is recognised, therefore monitoring of equipment where spills are possible is crucial. The most effective way of removing spill in pack-ice area is by breaking up the ice and use conventional spill recovery methods used elsewhere, but this will create ice slush that reduces the efficiency of the skimmers and booms [4, 44, 92].

Another challenge in the arctic is the lack of daylight as mentioned in section 3.4, which provide two additional challenges. First the darkness makes spill harder to spot, secondly the lack of sunlight combined with the freezing waters increases the time oil takes to dissipate in to the air, requiring additional oil skimming capacity. Research into more efficient system of handling and retrieving oil spill from ice-infested waters is on-going. There is also the need for a standby drilling rig in the event of a blowout. The standby rig could be needed for drilling a relief well to kill the blowout. This vessels need to be able to operate in much tougher ice conditions than the vessel drilling the fist

well. If a blowout occurs late in the drilling season the standby rig need to be able to drill after the sea water has started to freeze and pack-ice is present in the area [4, 44, 92].

#### 4.5.2 WASTE MANAGEMENT

All operations during the life time of an oil filed development will produce different types of waste that need to be handled, from drilling cuttings and production chemicals, to domestic and sanitary waste. All needs to be handled in the correct way to provide a safe and environmentally friendly operation. To produce as less waste and minimize dangerous waste, pollution prevention should be used. "Pollution preventions" means eliminating, changing or reducing procedures to minimise the discharge of pollution substances to air, sea and land. Different options during pollution preventions are source reduction, reuse, recycling, treatment and responsible disposal of the waste [4].

The arctic areas give a challenging environment for cost-effective waste management. The facilities suitable for handling different types of waste are often far away from E&P site. This promotes handling of different wastes at the site with incineration and injection to disposal wells as viable options for handling suitable wastes. Dangerous and specialised wastes need to be transported very far to specialised recycling facilities. As much waste as possible should be handled on site to minimize emissions from vessels transporting waste [4].

One important aspect of handling waste and waste materials on site is that it must not expose any risk for the health of the personnel working at site and no risk for the fragile arctic environment. This will be easier to perform if facilities and processes are designed from the start to use and dispose environmentally friendly chemicals and substances throughout the life cycle of a field [4].

#### 4.5.2.1 DRILLING WASTE

A vast volume of produced waste during E&P is spent drilling mud and drilled cuttings. To reduce the volume of mud that needs to be disposed, onsite recovery should be used. Normally the used mud is sold back to the manufacturer at a lower price. The manufacturer removes all unwanted substances in the mud and refurbishes the rheological properties of the mud before the mud is sold back to drilling contractors and operations. In the arctic it will be beneficial to do this process onsite, this will have logistic and environmental benefits. Since the extra transportation leg is removed from the equation, emission from vessel transportation is reduced [4].

As mentioned in section 4.2.3 the mud used should be water based. But in some geological formation oil based mud might be used to provide the adequate well integrity and hole cleaning. When oil based mud is used additional measures must be put in place to prevent any accidental discharge. Water-based mud should also be analysed to prevent the use of toxic additives and weighting agents, which some organisms can take up [4].

For handling of drilled cuttings there are two viable options. Because of the remote location onshore disposal facilities are not an option in most cases. The two options are then reinjection or seabed disposal. As seabed disposal may cause local smothering and is not allowed in some countries legislation, the best way to handle cuttings is to re-inject it in to a suitable formation. To minimize volumes that need to be re-injected, adequate shaker capacity to handle mud and cuttings return even at high pumping rates is needed. This will limit the mud volumes sticking to the cuttings, and then again the total volume of slurry that need to be injected [4].



#### 4.5.2.2 PRODUCTION AND OPERATION WASTE

Throughout the production of an oil- or gasfield, different operations need to be performed to keep production as high as possible. Most of these operations generate different waste that needs to be handled properly. The different waste expected from production operations are listed below [4].

- Flare and vent gas
- Tank or pit bottoms
- Produced water
- Workover Wastes
- Production chemicals
- Soild waste, oil waste and wastewater, clinical waste.

Flare and vent gas is expected from all oil producing operation, during high-pressure operation. To prevent the need to flare gas and prevent black smoke emissions, facilities should be designed to handle gas from well operations. Possible usage is re-injection for pressure support or transportation to gas marked. Re-injection is most likely the most viable option. This is because of the long distance from marked makes it challenging for transportation in an economic way [4].

Tank and pit bottoms need to be emptied and cleaned regularly between different operations. The waste possibly contains different substance like oil, salt, heavy metal and radioactive minerals. The content and amount of these substances need to be quantified before proper disposal method is chosen. The possible disposal methods are re-injection in a waste formation, transportation to onshore facilities with capabilities to treat the specific substances and incineration [4].

Produced water is normally handled on site and discharged to the sea at the production facilities, after being treated through oil separators. For arctic operation the content of the produced water need to be studied before discharge is allowed. The other alternatives are re-injection for pressure support or injection into a suitable waste formation. For pressure support all the solid and oil need to be removed before the water is re-injected through specially designed and placed water injection wells, as an part of Enchaned Oil Recovery (EOR) program [4].

Well workover is a process where the well is refurbished through intervention processes, Workover involve removing the production tubing, work wastes consist mostly of brines and other completion fluids used during the completion phase and substances produced from the formation. Environmental friendly brines are suitable for discharge at the production site. Heavy brines need to be filtered out and recycled or reused. Other special workover fluids need to be identified and chemically neutralised before discharge is permitted [4, 93].

Production chemicals are needed to prevent formation or removing of scale, hydrates and other production reducing processes. Some of these chemicals require treatment like neutralization or incineration before disposal, other more dangerous chemicals need to be shipped back to the manufacture or at a treatment facility onshore [4].

#### 4.5.2.3 DOMESTIC AND SANITARY WASTE

The generated domestic waste should be properly recycled and compacted onsite, and later transported to recycling facilities onshore if reuse offshore is not possible. Waste suitable for incrementing onsite should be burned onsite-minimizing transportation to shore. Grey water and other sewage should be treated on board with compliance to local regulatory requirements before being discharged in to the sea. Normal food waste is grinded and discharged into the sea, however this may not be viable in the arctic since this could attract unwanted wildlife to the location [4].

## 4.6 LOGISTIC AND SAR

All Arctic E&P prospected areas are located far away from supply chains and hydrocarbon markets. This makes good logistics play a vital role throughout the lifetime of all fields. From restocking of facilities with food supplies, transportation of personnel to facilities, to the export of produce crude oil to the consumers, all relies on well coordinated logistics chains to the distant oil prospects throughout the Arctic. The distance from shore also makes a challenging environment for Search And Rescue (SAR) operations. These rescue and emergency operations rely very much on Helicopters. Helicopters have limited time in the air before they have to return to a helicopter base for refueling, and with long transport legs between the base and emergency locations limits air time left for crucial SAR operations. Barents Sea helicopter AWSAR in operation is shown in Figure 4.21 [13, 92].



FIGURE 4.21 BARENTS SEA AWSAR OPERATION [94]

#### 4.6.1 LOGISTIC

All logistic aspects in the arctic will become more difficult than for other regions. Harsh environment hydrocarbon developments will require specialised vessels for transportation of goods and supplies. These vessels need to be specialised for the locations where the exploration and production happens. Some areas are only reachable some periods of the year and relies on the support of icebreakers to reach the location. The involvement of additional vessels like icebreakers and other needed support vessels will make the operation more expensive and complex logistic vice, in addition to the complex engineering part needed for arctic operations. This will make developments in the arctic more costly and require more time from discovery until first oil is produced and delivered to the costumer. As seen on the Prirazlomnoye field presented in section 2.2.5.1, which was discovered in 1989, the first oil was produced early in 2014, giving a time span from discovery until production of 25 years [13, 43].

One crucial guide lesson has been presented as an important guideline to limit the cost of operation in the arctic this is “getting it right the first time”. The consequences of small delays could be fatal for a project and can mean years of delay, since operational windows could be lost. The remote areas will have added mobilisation charge on all vessels. Especially specialised installation vessels like pipe laying and lifting vessels that need to travel long distances before arriving at the job site. This will be expected for all of the prospected arctic areas since none of them are located close to existing petroleum facilities. Adding to this is the short open water season that some of these vessels need to be able to operate [44, 92].

The specialised supply vessels should be designed as double action vessels. Double acting vessels are designed with icebreaker capability at the stern. Making them more capable in pack-ice conditions where they can revers through the ice and break it. In addition to supply vessels, icebreaker class tankers will be needed to transport the hydrocarbon from production facilities to a location where it is safe for ordinary tankers. These vessels should travel as short a distance as possible, since they will be limited in number, are costly to produce and slower than ordinary supply vessels. This gives a new problem; there are very few harbours close to the arctic E&P prospects with deep-water docks. A potential solution for some of the prospected areas is the use of 5 movable GBS ship like structures, which can be placed in medium sea depth and act as a

deep-water harbour and shelter for vessels, MODU's and floating production facilities when conditions become so rough that they need to disengage their turret. The concept relies on 5 GBS with a casing of steel that can resist ice and wave loads during winter conditions. This should also have the possibility to act as supply base, shallow water drilling rig, emergency shelter location, lodging and personnel transfer location. In areas where specialised equipment is need extra equipment can be installed, like LNG storage, oil transfer equipment and sheltered storage. Image of the concepts can be seen in Figure 4.22 [44, 92, 95, 96].

In the event of problems with drilling or production facilities that require emergency supply of parts or materials, this can lead to a period of lost drilling time or production of hydrocarbon. Specialized parts needed to get facilities up and running again could take days to replace from a vendor or logistic facility. To reduce the risk of downtime in this area where utilizing time to full extent is very important, spare parts that are crucial to the operation should be kept at a logistic facility as close as possible [44].

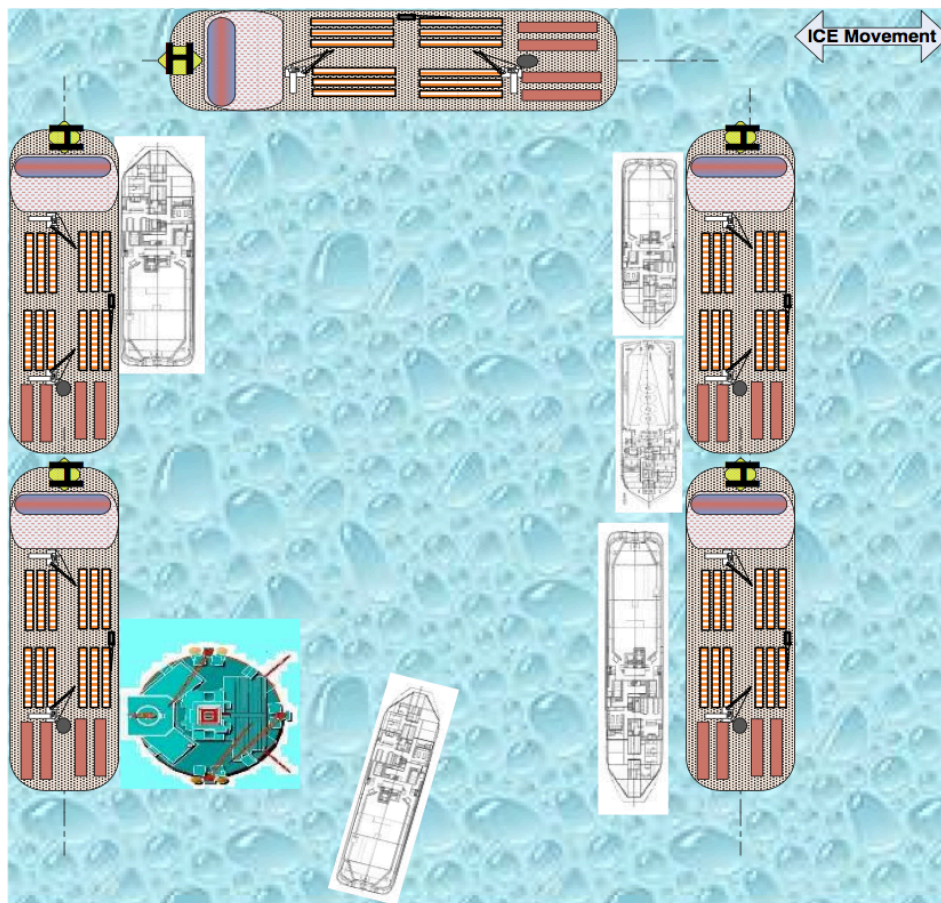


FIGURE 4.22 GBS DEEP WATER PORT AND ICE SHELTER CONCEPT [95].

Since the arctic area is a fragile environment some considerations should be taken to reduce emission and potential discharge from all vessels performing logistic task in the area. Logistic supply routes should be selected to minimize time in ice-waters to reduce fuel consumption and risk of damaging the vessels. Specialised supply vessels should be designed with parameters from the specific operation area to reduce potential drag from waves and ice, this vessels should be build with impact-proof materials and design that is able to absorb energy from impacts in arctic sub zero temperatures. To support the supply vessels observation of supply routes should be performed to reduce the risk of icebergs and small ice chunks from damaging the vessels. To reduce the impact of a discharge to the environment there should be a limit on how much heavy fuel a vessel is permitted to carry in arctic waters. Other fuels should be considered like biofuels and LNG [96].

#### 4.6.2 RESCUE AND EVACUATION

The arctic environment makes a challenging environment for Search rescue and evacuation. Different weather phenomena's like cold, polar lows, fog, polar night, ice and rapid changing weather conditons combined with the remote locations affect these emergency operations. Emergency response could be needed in all of these weather conditions, requiring systems capable of handling them. Helicopter used need to be All Weather Search and Rescue (AWSAR) capable of operation under harsh weather conditions. A normal lifeboat is not suited to operate in ice-inflicted areas. A specialised amphibious vessels have been designed for these conditions the Arktos, but they require support by icebreakers during the winter since survival time in the cold weather is limited. Arktos the amphibious vessel can be seen in Figure 4.23 [44, 96].

Another challenge is the limited capacity of SAR helicopters and vessels in the arctic. The operators need to establish enough capacity to handle emergency response and evacuations. This could also benefit local communities and other industries, this has all ready been seen in the Norwegian part of the Barents Sea. Here Statoil and ENI have established SAR base in Hammerfest to provide offshore SAR capacity for Snøhvit, Goliat and Exploration in the area. The AWSAR helicopter located at the site operated by Bristow Norway has on several occasions provided SAR assistance for fishermen and

other activities in the region. This is a positive effect that other Arctic areas could benefit in the same way from. Recently the countries surrounding the arctic have signed the Arctic SAR agreement. This agreement describes how international collaboration in Arctic SAR operations should respond and use available national emergency equipment within the different countries across the borders [44, 96, 97].



FIGURE 4.23 ARKTOS AMPHIBIOUS LIFEBOAT [98]

## #5 ARCTIC PROSPECTS

This chapter will provide 5 different prospects in different arctic environments, to give an understanding of the diversity in operations in arctic environment. First the characteristics of the area will be presented then an exploration and operational concept for E&P will be presented for each area based on the information provided in the previous chapters. The different prospected locations are shown in Figure 5.1.

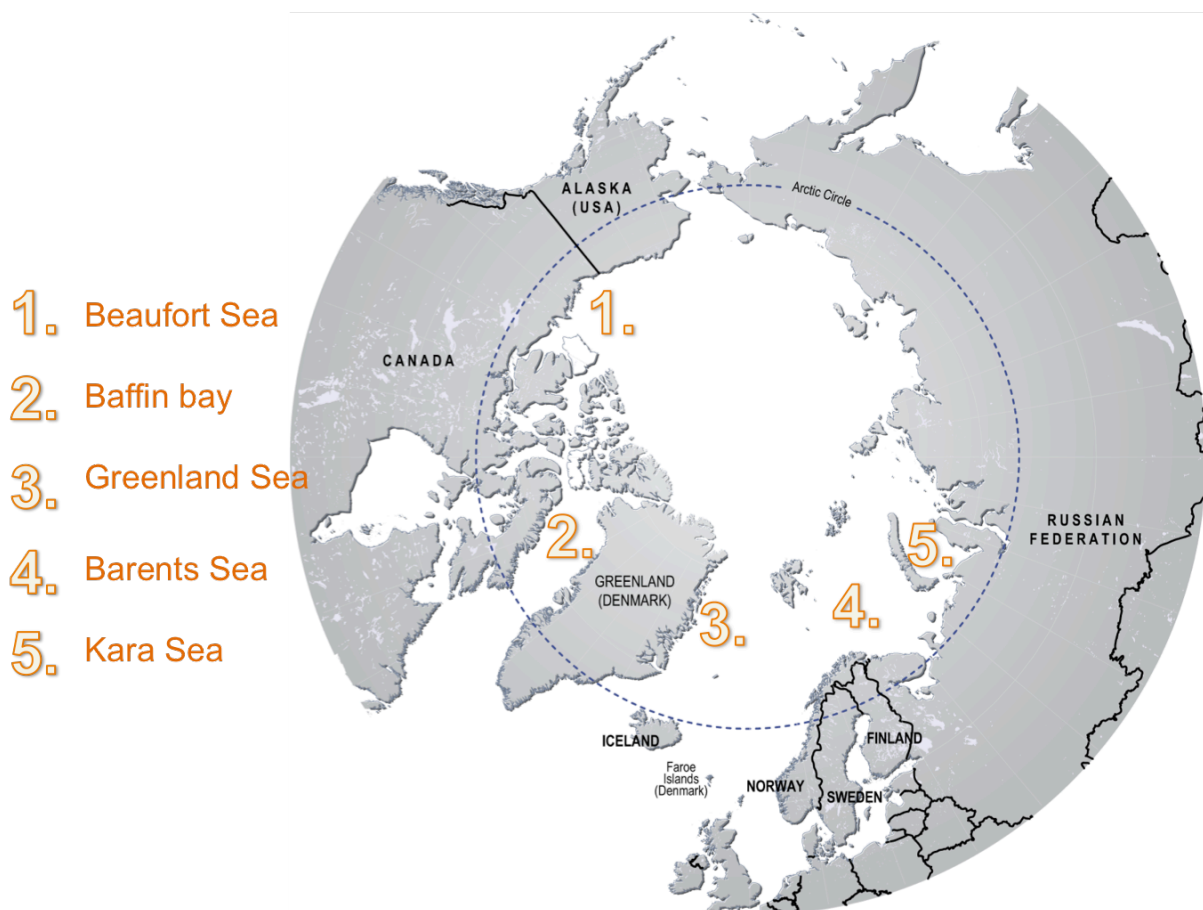


FIGURE 5.1 ARCTIC E&P CASE LOCATIONS[99]



## 5.1 CASE I: BEAUFORT SEA

Beaufort Sea is an interesting prospect for offshore Arctic Exploration. The area surrounding Prudhoe Bay has shown to be rich in petroleum onshore and offshore. Going further offshore in this area could hold vast petroleum reservoirs, this means entering a high arctic environment with deep water. Since the average depth in the Beaufort Sea is 1004 m this will be used as the water depth of the prospect and multi year pack-ice sweeps is expected in the area, as presented in section 2.2.1 and 4.2 [1, 20].

Exploration drilling in this area will be best suited with the Arctic drillship design from GustoMSC with the support of an ice management operation consisting of at least two icebreakers working together to minimize the ice loads exerted on the Drillship by multi year pack-ice. Most of the exploration drilling will be performed during the open water season but with ice sweeps. The Arctic Semisubmersible is also capable of drilling in this area, but the lower variable deck load is a great disadvantage in this area. The drillship has the capacity of drilling two wells and stay offshore without being resupplied for 120 days. This is not possible for the Semisubmersible [6, 20].

If a discovery should be found viable for development, the best development solution seems to be a ship shaped FPSO with subsea templates. The ship shaped FPSO need to have a Polar Class capable for year round production and emergency disconnection from the production turret. Since the prospect is in deep water the subsea templates don't need to be placed in glory holes for protection from icebergs. For transportation of produced fluids icebreaker tankers seems to be the best solution both technical and economically. Since the nearest deep water harbour is in Dutch Harbour on the south side of Alaska, a closer alternative should be established. An option is to use the GBS port concept presented in 4.6.1, a possible location would be north of Prudhoe Bay where it can act as a logistic centre, tanker terminal, ice shelter and SAR base for the entire region. This option is most likely dependant on more the just one field or one huge to be economically viable [1, 20, 95].

For intervention purposes a vessel like the one present in 4.4.2 should be designed with metaocean and ice conditions present in the Beaufort Sea, to be able to perform as best as possible all season of the year [96].

## 5.2 CASE II: BAFFIN BAY

Baffin Bay has shown potential for exploration and production, as mentioned in section 2.2.2. During the coring in 2012 both source rocks and potential reservoir sands were found in the bay. This has given extra interest in the area by several E&P companies. The prospect in this area is placed at 500m water depth, since the shelf varies from 700-200m. The area has a long open water season with possible sweeps of icebergs during this period.

The 11 exploration wells drilled in the area by Cairn Energy, were drilled with conventional drillship and Semisubmersible. They were supported by several ice management vessel, to assist if icebergs swept into the area during the open water season. So for additional exploration in the area during the open water season conventional drillships or semisubmersibles will be an alternative, this will also be more economical than use of specialised arctic vessels which are more expensive to hire. For production drilling at a later stage, it will be advisable of using an Arctic Vessel for year round drilling [1].

This area would also benefit from being develop with Ship shaped FPSO with subsea templates as in the previous section about the Beaufort Sea Case. Here there are a much greater threat of icebergs than pack-ice, so the ice management need to have the capability to redirect very large icebergs away from a possible producing FPSO. When icebergs get to large the FPSO will have to disconnect from the production turret and move to a safe location. Ship shaped FPSOs ability of being self-propellant is a benefit, since no extra supply vessels are need when moving the FPSO, which some other concepts need as presented in section 4.3.4 [1].

### 5.3 CASE III: GREENLAND SEA SHELF

On the north east coast of Greenland it is very difficult to operate due to the Extreme Arctic Environment. The technology present today is not advanced enough to perform drilling or production here. But several companies have shown interest in the area and licenses been provided. The challenging environment have made it necessary for the license period to be much longer, to provide adequate time for the operators perform studies inn to the ice conditions in the area and develop adequate. Seismic studies have been performed in the area. But even this have been difficult to perform and had to be aborted several times during the acquisition. So until new technologies are present drilling will not be performed her. Figure 5.2 show the heavily iceberg inflicted northeast cost of Greenland [31].

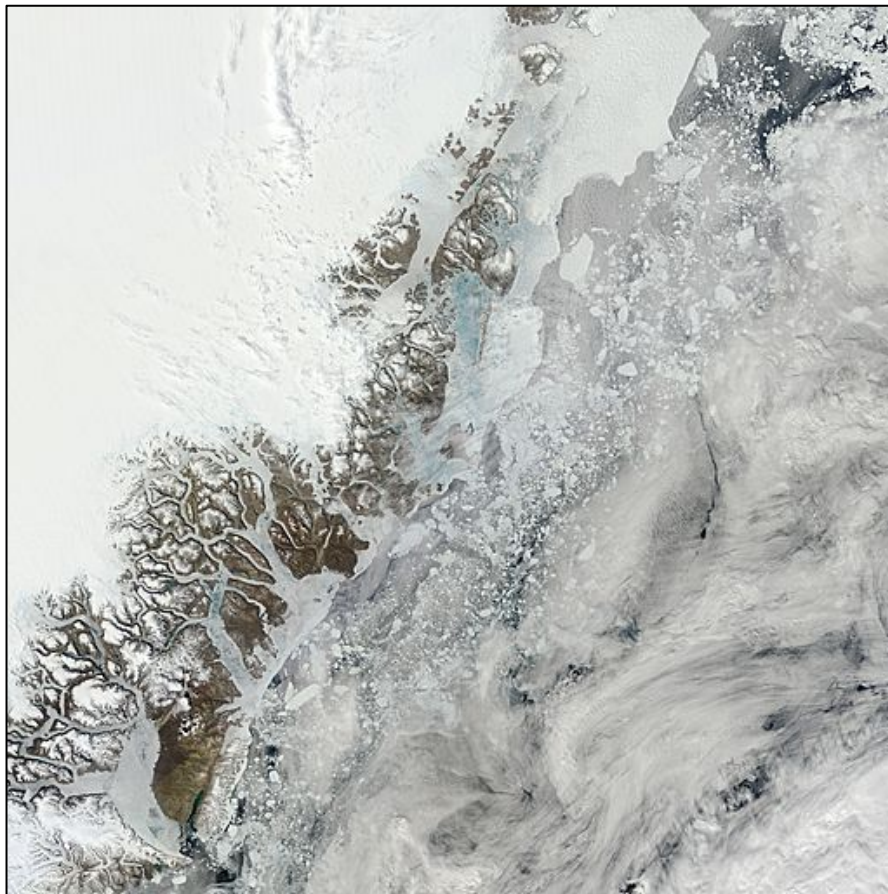


FIGURE 5.2 SATELLITE PICTURE OF THE NORTHEAST COST OF GREENLAND [100].

## 5.4 CASE IV: BARENTS SEA

The Barents Sea has already been identified as an area of great interest for the petroleum industry. As presented in section 2.2.5 there are two producing fields in the area and several additional discoveries in the area. Most of the Barents Sea is classified as Harsh Environment and some of it as Sub-Arctic environment. The Northern and south eastern part is covered with pack-ice part of the year, leaving the rest with year round open waters. Her two different cases will be presented, the first Case IV A will have year round open water in the central part of the Barents Sea with about 300m water depth and harsh environment. The other one Case IV B will be in the southeastern corner in the Pechora Sea, where pack-ice is present part of the year and with a water depth of around 20m and permafrost might be present. The area could be classified as sub-arctic.

There have been drilled over 90 exploration wells in the Barents Sea so far; most of them have used conventional semisubmersible rigs. The trend now is to use winterised semisubmersible for year round drilling in the ice-free waters of the Barents Sea, like Aker built and Transocean operated winterized drilling rig presented earlier in section 4.2.1.4. Statoil is using this rig for the Apollo well, the world's most northern offshore exploration well. This rig will be suitable for case IV A. For the areas with ice part of the year Huisman's Arctic Semisubmersible drilling rig could be an option for year round drilling. This rig could also be used in the shallow waters in Case IV B as a caisson-drilling rig placed on the Sea bottom. The special thing with drilling here is that there might be permafrost present, this will need drilling fluids and cement to be designed with this in mind as presented in section 4.2.3 and 4.2.4. Most of the Barents Sea will not require ice management during operations, but the area involved in Case IV B will require it if year round drilling is planned.

The two cases will have two quite different development solutions, Case IV A will have a development concept similar to ENI's Goliat and Case IV B will have a similar to Gazprom's Prirazlomnoy. Goliat is being developed with a large circular FPSO and subsea templates. The FPSO is winterised with sheltered working area. The Goliat utilises electrical power produced onshore, led offshore with a subsea cable. This will reduce emissions, which should be limited as much as possible in the arctic. A figure of the Goliat field development is shown in Figure 5.3. Hammerfest is developing to

become a logistic base for the Norwegian part of the Barents Sea, but as the industry moves east other closer areas may become needed [101].

Case IV B will need some form of sea bottom founded structure capable of handling pack-ice loads, similar to the steel caisson on the Prirazlomnoy field. All production drilling could be done from the caisson, as it seems as the best solution to use an integrated drilling production, storage and offloading facility. To handle the possible permafrost in ground, SSV need to be placed below the permafrost area to prevent it becoming blocked from scaling or wax, frequent intervention jobs involving removing scaling and wax should be expected. For transportation of the produced oil there would be the need for icebreaker class tankers in corporation with ice management vessels. The closest harbour and logistic centre is Murmansk [43].



FIGURE 5.3 GOLIAT FPSO [102]

## 5.5 CASE V: KARA SEA

The discoveries in the Kara Sea have shown that the petroleum system is present in the area. The Kara Sea is classified as High Arctic with multi year ice present and shallow water area with a short open water season. Figure 5.4 show the Ice infested Sea June 10<sup>th</sup> 2001.

As mention in section 2.2.6 the exploration drilling activity planned this summer, is going to utilize a winterized semisubmersible to drill the prospect at 80m sea depth. The Semisubmersible used relies on open waters. This only give a very short drilling window, and other alternative MODU's seems to be a better match for the area. The arctic semisubmersible design from Huisman could provide a much longer drilling season. Other areas in Kara Sea with less than 50 m water depth seems ideal for GustoMSC Arctic Jackup. Ice management will be need to support the different MODUs in the Kara Sea [6].

The shallow waters in the Kara Sea makes development with bottom founded Caisson a good alternative, alternative being Steel structures or GBS. The different waterdepths will determine which of the two are applicable to use. Since the area is quite a distance from the nearest harbour, 5 days, logistics and planning will be a crucial part of operation and development of a field in the Kara Sea [49].

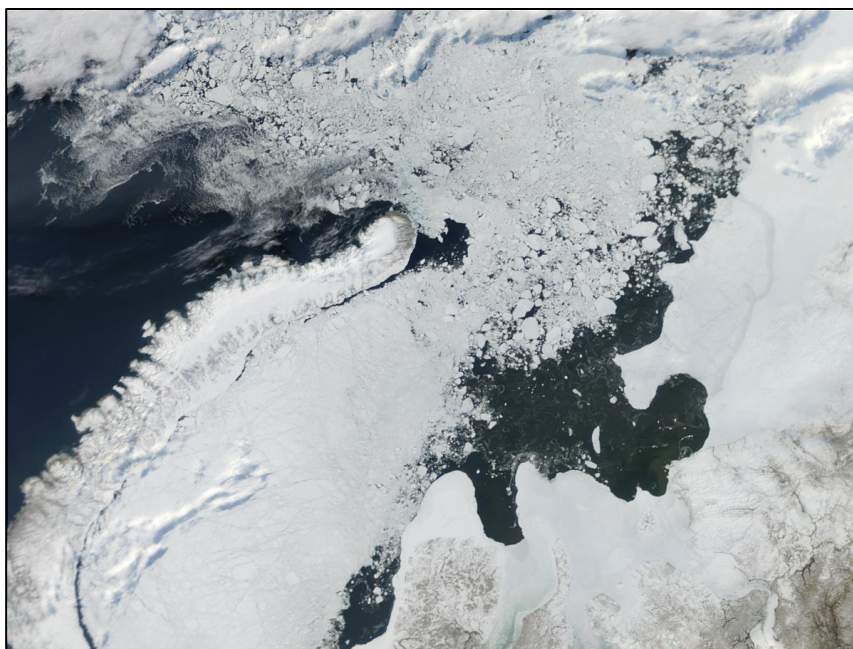


FIGURE 5.4 KARA SEA JUNE 2001 [103]

## #6 DISCUSSION AND CONCLUSION

As the world's energy demand rises, new exploration areas are needed. The Arctic seems to be one of the most interesting areas for exploration. The Arctic has become more available for exploration as the multi-year pack-ice has retracted, giving a longer open water season in a greater area. However, there is still a large amount of different challenges that need to be overcome before E&P can be performed successfully.

It seems like Arctic Exploration and Production is feasible from a technological view in almost all the areas with an open water season. The only area where it is at the moment not feasible is the Greenland Sea on the West coast of Greenland. Here the year-round presence of large amounts of huge icebergs makes a hostile and dangerous area for all kinds of shipping or drilling activity.

Through this thesis, challenges throughout the different phases of E&P have been presented. Most of the challenges have been of a technical nature. One of the most challenging aspects has been left out so far, and that is the profitability of E&P in the Arctic. To make an Arctic discovery economically viable, the potential produced oil needs to be huge, gas discoveries will most likely not be profitable due to the additional process and transportation costs and the high supply to the market from unconventional shale gas.

Almost all aspects of Arctic exploration and production are drastically more expensive than elsewhere. Specialised drilling vessels will be limited in number and expensive to hire, in addition, expensive ice management vessels and operations are needed in most of the areas. Only the largest E&P companies have the economic backbone and technical operational skills to support these complex operations. The challenges in the Arctic condense down to 4 points:

- Environmentally safe operation
- Political/society acceptable Arctic operation
- Overcome technical challenges related to ice and cold
- Profitable investments

here the environmentally safe operations consist of the ability to operate in this fragile environment without causing damage to the environment and wildlife. Political/society acceptable operation is closely related to the point above. If arctic E&P is to be developed the industry needs to have political willingness, and this again require the society to have confidence in that the E&P industry is capable of operating in the arctic in an environmental friendly way.

The technical challenges related to ice and cold has been the main focus of this thesis and involves ice management, winterization, design of fluids and cements, transportation, logistics and making a suitable environment for personnel to work in. The Profitable investments relate to all the 3 other points. If an Arctic prospect is to be developed, the three first points will need to be feasible in a way that will give economically value to the companies or countries investing.

The arctic area that seems the easiest to support these 4 points offshore is the Barents Sea. Where development of prospect in areas with year round open water, could make development of costly icy areas more economically viable due to the nearby presence of the industry. This again could also make the Kara Sea more interesting for the same reason. Another area of interest would be the Beaufort Sea with it's petroleum history on land and close to shore, but this area seems to be more challenging economically due to the possible presence of multi year ice throughout the year.



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## Appendix A.

TABLE A-1 FIELD DISCOVERIES BARENTES SEA

Field discoveries Barentes sea				
Field name	Petroleum type	Location in Barents Sea	Waters	Discovered
<a href="#">Murmanskoye</a>	Gas	Southern	Russian	1983
<a href="#">Severo-Klidinskoye</a>	Gas	South-western*	Russian	1985
<a href="#">Pomorskoye</a>	Gas condensate	Pechora Sea	Russian	1985
<a href="#">Severo-Gulyaevskoye</a>	Oil and Gas condensate	Pechora Sea	Russian	1986
<a href="#">Shtokman</a>	Gas condensate	Central	Russian	1988
<a href="#">Prirazlomnoye</a>	Oil	Pechora Sea	Russian	1989
<a href="#">Ludlovskoye</a>	Gas	Central	Russian	1990
<a href="#">Ledovoye</a>	Gas condensate	North Eastern	Russian	1992
<a href="#">Varandey</a>	Oil	Pechora Sea	Russian	1995
<a href="#">Medynskoye</a>	Oil	Pechora Sea	Russian	
<a href="#">Dolginskoye</a>	Oil	Pechora Sea	Russian	1999
<a href="#">Goliat</a>	Oil and gas	South-western	Norwegian	2000
<a href="#">Snøhvit</a>	Gas	South-western	Norwegian	1984
<a href="#">Johan Castberg</a>	Oil	Western	Norwegian	2011
<a href="#">Gohta</a>	Oil	South-western	Norwegian	2013
<a href="#">Wisting Central</a>	Oil	North central	Norwegian	2013

TABLE A-2 FIELD DISCOVERIES KARA SEA

Field discoveries Kara Sea			
Field name	Petroleum type	Location in Kara Sea	Discovered
<a href="#">Rusanovskoye</a>	Gas condensate	South-western	1989
<a href="#">Leningradskoye</a>	Gas condensate	South-western	1990
<a href="#">Severo-kamennomyszkoye</a>	Gas	Ob Bay*	2000
<a href="#">Kamennomyszkoye</a>	Gas	Ob Bay*	2000

TABLE A-3 POLAR CLASSES, INTERNATIONAL ASSOCIATION CLASSIFICATION SOCIETIES [104].

<b>Polar Class</b>	<b>Ice Description (base don WMO Sea Ice Nomenclature)</b>
<b>PC 1</b>	Year-round operation in all Polar waters
<b>PC 2</b>	Year-round operation in moderate multi-year ice conditions
<b>PC 3</b>	Year-round Operation in second-year ice which may include multi-year ic inclusions
<b>PC 4</b>	Year-round operation in thick first-year ice which may include old ice inclusions
<b>PC 5</b>	Year-round operation in medium first-year ice which may include old ice inclusions
<b>PC 6</b>	Summer/autumn operation in medium first-year ice which may include old ice inclusions
<b>PC 7</b>	Summer/autumn operation in thin first-year ice which may include old ice inclusions