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Challenges and Solutions for COSL's Operation in the Arctic

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AND


COSL
铸就国际一流
Code of Conduct 员工操守
Integrity, Dedication,
Teamwork and Self-discipline
诚信、敬业、协作、自律

Content

Abstract

The enormous oil and gas fields located in the Arctic region, has given this area the name "Middle East No. 2". Due to limited experience and availability of technology/facilities which can withstand severe environmental conditions, the oil and gas exploration and production in this region are, however, not carried out quickly.
Recently, the rapid increase in oil price and decrease in the recoverable oil volumes worldwide have driven the focus of the oil companies to the Arctic. In addition, the advancement of technology and equipment has made the oil and gas production in this region more feasible and cost-effective than in the earlier time. The combination of extreme low temperature, icing, permafrost and icebergs, extreme weather caused by the Polar Lows, vulnerable biological environment, strict environmental regulation, unreliable logistics support and insufficient infrastructure has resulted in huge challenge for the safety and efficiency of the oil and gas operation in the Arctic.

China Oilfield Services Limited (COSL) owns a most complete oil service chains such as a large number of drilling units; jack-up rigs and semi-submersible platforms, seismic service vessels, supply boat service and multiple kinds of oil field technology services. Aiming to be a leading energy services company, COSL has decided to extend their oil service market into the Arctic region. However, the coldest operational region for COSL is currently located in Bohai Bay and they have adopted the solution of moving away from the ice. COSL has also been experiencing extreme weather, such as hurricanes, which occurs frequently in the South China Sea. Due to their geographical location, i.e. far away from the Arctic region, and the limited company strategy in deep water service, COSL has not yet started research activities in the Arctic region. In order to obtain greater knowledge about the Arctic region, the author of this thesis had been given the opportunities by COSL to complete his Master Degree in Offshore Technology, specialized in Industrial Asset Management, at University of Stavanger (UIS) for one year. It is well known that Norway, which is located just south of the Arctic region, has accumulated abundant experience of operations in the Arctic area.

As Professor Ove T. Gudmestad is an expert in research related to the Arctic region, the author decided to take this opportunity to work on the topic for his thesis with his guidance and supervision. With reference to the company's existing operation mode, experience in the Arctic and COSL's operation capability, this thesis presents a gap analysis and a risk assessment related to work in the Arctic by taking the human performance and emergency response to oil spill in the Arctic as examples for discussion. In order to help COSL in starting the preparation for working in the Arctic, this thesis proposes some suggestions regarding drilling rigs construction, personnel training, and oil field technology improvement.

摘要（Abstract in Chinese）

北冰洋海底蕴藏有巨大的油气资源，号称“第二个中东”，但是由于自然环境恶劣，受技术和装备的限制，一直没有大规模开发。近年来，随着一直高涨的油价和传统产油区可采储量下降的影响，各个油公司纷纷把目光投向北冰洋，技术和装备的进步也使此区域的油气开采活动成为可能。低温、结冰、浮冰、冰山、冻土、极地低压带的恶劣天气、脆弱的环境、严格的排放法规、不可靠的后勤支持、不足的基础设施等等，都为北冰洋地区的油气作业提出巨大的挑战

中海油田服务股份有限公司（COSL）是亚洲范围内石油服务链条最完备的石油服务公司，拥有亚洲最大的钻井船队，提供物探船服务、三用工作船和多样的油田技术服务，并且一直矢志于建设成为世界一流的能源服务公司，所以不能错失进军北冰洋的机会。但是目前中海油服最低温的作业区域在渤海湾，应对浮冰的措施还是躲避；极端天气的作业经历主要集中在南中国海，飓风多发地带；受地域（远离北冰洋）及公司战略（深水技术发展当先）影响，COSL 对北冰洋地区的研究探索还是个空白。

笔者受 COSL 资助去挪威斯塔万格大学（UIS）进行了为期一年的留学，挪威与北冰洋接壤，在该地区的石油作业经验丰富，而且斯塔万格大学海洋技术专业的古墓斯塔教授是北冰洋方面的专家，所以笔者利用这个难得的机会，在古墓斯塔教授的指导下，完成了这篇论文，文章借鉴已有的作业模式和经验，对照 COSL 现有的作业能力，进行风险识别（选取北冰洋地区人的表现和溢油应急作为例子），提出应对措施，为 COSL 在今后的船队建设、人员培训以及油田技术（低温水泥浆，无污染泥浆体系，超低温条件下钻机，以及高防冰等级工作船的建造）发展方面提出建议，从而为 COSL 进军北冰洋市场做好储备。

Acknowledgements

I would like to express my deepest gratitude to my university supervisor, Professor Ove T. Gudmestad, for guiding me patiently in completing this master thesis and for his valuable advice and supervision. Without his unprecedented support, I would not be able to complete this thesis within the given time frame. His lectures on 'ARCTIC TECHNOLOGY' have triggered my idea to write my thesis about a gap analysis between the requirements of working in the Arctic and the capability of my company, i.e. COSL. Through presenting this idea to Professor Ove, he concurred that it is a valuable topic and encouraged me to work on this area for my thesis. He has given me valuable resources and helped correcting the thesis word by word, which deems to be a burden for him as supervisor for many master and doctorate students. In October last year, professor Ove visited Beijing for one week with the purpose of providing us advice and guidance in writing the thesis. Most of this thesis is written based on his lectures in 'Marine Technology' and 'Arctic Technology'.

I would also like to gratefully thank Professor Tore Markeset for providing lectures in 'Condition Monitoring' which gave me some ideas for developing my solutions regarding the modification of equipment in the Arctic. In addition, I would like to thank Professor Janyansa P. Liyanage, who is the lecturer of the courses 'Performance Indication & Decision Engineering' and 'Human-Technology-Organization', for inspiring me in seeking improvement of management in the Arctic. My gratitude also goes to the other professors who have been passing me their valuable knowledge and guidance during my study in University of Stavanger.

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My company - COSL Equipment Department, who has supplied me the updated statistic data of COSL;

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Last but not least, I am indebted to my family; especially my dear wife and lovely son, for their continuous and unconditional support so that I could have energy and endeavor to finish this thesis. Be engaged heavily in my work and thesis, I have not spent much time with them, which is also my pity.

2013-4-10
Jakarta, Indonesia

1. Introduction

1.1 ARCTIC

Arctic is the shallowest, smallest and coldest ocean of all the four oceans in the world. Generally speaking, Arctic is the area around the North Pole. The Arctic researchers also argued three main definitions for the precise definition of Arctic in the website of NSIDC (http://nsidc.org/arcticmet/basics/arctic_definition.html), which are defined respectively: first, locations in high latitudes where the average daily summer temperature does not rise above 10 degrees Celsius; second, the area north of the treeline (the northern limit of upright tree growth); third, the area in the north of latitude above which the sun does not set on the day of the summer solstice (usually 21 June) and does not rise on the day of the winter solstice (usually 21 December), the Polar Circle, figure 1.1.

Figure 1.1 Map for three definitations of Arctic
This map of the Arctic is from the The Perry-Castañeda Library Map Collection. The treeline was added at NSIDC based on information from National Geographic 1983, Armstrong et al. 1978, and Young 1989

In the oil and gas business, the term 'Arctic' is used to describe the huge region around the

North Pole which encompasses notably the northern parts of Europe (Scandinavia, Iceland and Greenland), Asia (Siberia and far east of Russia), North America (Canada and Alaska) (Pilisi, N. et al., 2011). This region is attracting the attention from the world, especially from the oil companies because of its considerable oil and gas reservoirs. One report from U.S.G.S shows that: geology-based probabilistic analyses have found that significant oil and natural gas reserves, about 25% of the world's remaining non-detected oil and gas resources maybe found in the deep Arctic (Bird, 2008; Houseknecht et al, 2010). The latest research proposed that the oil and gas reservoir in Arctic is double of that was estimated by humans: 160 billion barrels of oil, which can be consumed for 5 years as per the current yearly petroleum consumption; and one third of global unproven natural gas is expected to be stored in the Arctic. Some petroleum researchers call Arctic 'second Middle East'. Majority of the oil and gas resources are locates in the regions where water depth is less than 500 meters; natural gas is mainly in 4 regions: the south of Kara Sea, the north of Barents Basin, the south of Barents Basin and Alaska Slope.

Due to plenty of challenges such as floating ice, icebergs, extreme low temperature, vulnerable environment, limited infrastructure and difficult logistics and therefore high costs, oil fields in this area have not been developed like in other oil areas.

Oil and gas development in the northern coastal areas off Alaska and Canada can be traced to the late 1960's. Popular solutions for all year operations in these heavy ice conditions are gravel islands, gravity base structures (GBS) and floating units. Besides these areas, exploration and production activities are performed in other waters where the sea is not covered by ice for the whole year. The main locations for these types of development are offshore Sakhalim (Keinonen, A. and Truskov, P., 2001), Grand Banks (Lever, G. V. et al, 2001), Bohai Bay and Cook Inlet (Figure 1.2). The oil companies trend to make the use of floating production units, bottom subsea installations or a combination where satellite fields are developed by subsea equipment. (Gudmestad, O. T. et al., 2007).

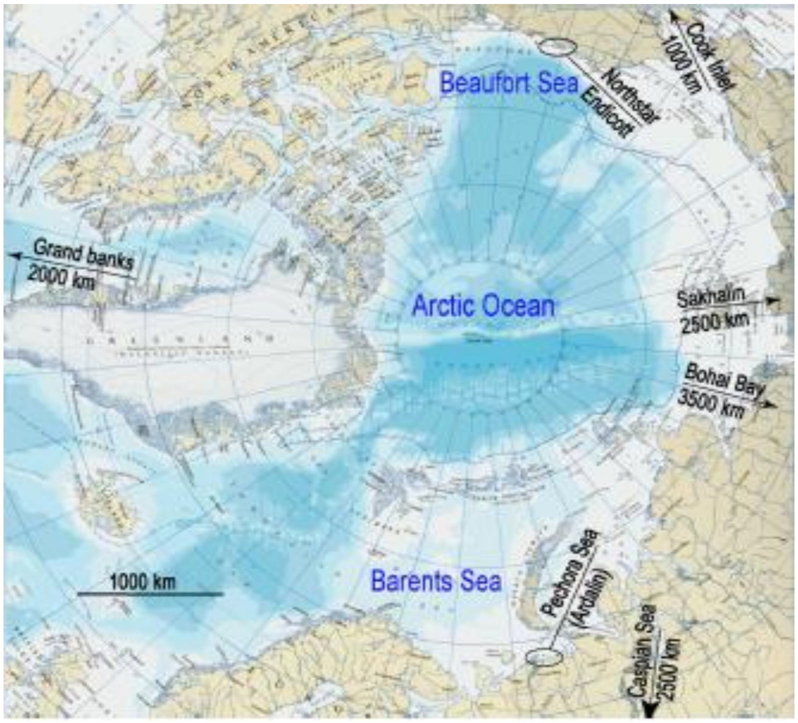


Figure 1.2 Overview of the Arctic Regions and areas with ongoing oil activities (Gudmestad, O. T. et al, 2007)

Some key drivers make the oil and gas development in Arctic attractive and feasible:

1. Remaining recoverable reserves in traditional oil and gas abundant areas (Middle East, Gulf of Mexico, North Sea, West Africa, etc.) are decreasing sharply, it is possible that their production cannot meet the global demand, which will sharpen the balance of energy supply and demand;
2. The oil price has been kept in high position for long time, which could be expected to be higher if the energy supply doesn't improve properly;
3. Global climate is changing to warmer and warmer, which has caused the ice-free season longer, longer operation windows make oil development in Arctic more economical;
4. The latest breakthrough of technology and equipment has made the exploration and development in this region cost-effective and reliable, which mitigates risk as well.

All the oil companies now consider oil development in some areas where are difficult before, e.g. deep water and Arctic, as we know, there are some deep water areas in Arctic as well. Arctic deep water oil operation will be more difficult because of combination of challenges both in deep water and Arctic. Some oil field service companies have started their research and practice in Arctic, the company who grasps advanced technology or equipment for Arctic operation, will be competitive in the development of Arctic.

Figure 1.3 shows the majority of current oil and gas exploration and production facilities located in the North Sea, Barents Sea, Beaufort Sea, Alaska and Kara Sea. Almost all of them are onshore or close to the shore, because of heavy ice condition, poor logistic support and lack of infrastructures in the remote areas. One report from American National Ice and Snow Data Center says that: ice cover area of Arctic in September 2012 is 3,410,000 km^2, which is the second smallest ice cover since human has record about it, only a little bigger than that of September, 2007.

Figure 1.3 Oil & Gas exploration & Production in the Arctic
Courtesy to http://www.grida.no/graphicslib/detail/fossil-fuel-resources-and-oil-and-gas-production-in-the-arctic_a9ca

Such challenges as sea ice (drift ice and icebergs), icing, extreme weather, weak logistics, permafrost, etc. must be overcome for oil operations in the Arctic, but different regions of the Arctic have different characteristics, so it is necessary to discuss challenges of all the regions respectively and relevant solutions for the operation there.

Norwegian Sea:

Because its latitude is not very high, so very few freezing situations can be met, this is easy for oil operations;

The wave condition is very tough, so the operators should pay more attention to stability of floating units.

From Norwegian Sea to Barents Sea west/south of Bjørnøya:

The wave condition here is similar with Norwegian Sea;

The weather tends to be more unpredictable because of Polar Low pressures；

Potential icing is expected due to cold weather;

Floating ice should be taken into consideration even only small probability. Some strategies and guidelines may be helpful:

For temporary operations:

- Normally stay away from the floating ice;
- The columns or legs of drilling rigs could be ice-strengthened;
- The support vessels can be selected with ice class.

For permanent facilities:

- When the structures are designed, 100 years situation should be looked into, which means this situation could be found with 10-2 annual probability;
- When the situation is worst and exceed the capability of the rig, it should be able to move out of that location, to ensure safety and environment security.

From Barents Sea west to Barents Sea east:

- Shtokman project is a case to be referred.
- The temperature is much colder and some regions are seasonally frozen;
- Considerable icing is expected;
- The risk for floating ice is quite high;
- Icebergs are not uncommon to be met.
- For temporary operations:
- Ice free period should be selected as operation window;
- Floating ice solution should be considered in the emergency response plan;
- Ice strengthening should be required for the structure.

For permanent installations:

- Ice management is the best choice;
- at Shtokman we expect ice every three years on return and icebergs every thirty years on return;
- The operation units can be towed away in worst case.

Grey zone, Figure 1.4:

This area is claimed by Norway and Russia as their territory, but they had an agreement for the new border line accepted by the two countries in 2011, and oil companies from both countries will work together to develop this rich-oil area. This zone is supposed to store huge prospects of several billion barrels of oil.

The condition is quite similar to West Barents Sea, but sometimes the operators will face challenges of more icing and more probability for ice.

Figure 1.4 New border line in the Barents Sea between Norway and Russia (Grey Zone) Courtesy to http://foreignpolicyblogs.com/2010/04/28/russia-and-norway-agree-on-border-in-barents-sea/

Overall conditions for the Barents Sea

Quite a few oil & gas fields already have existed in Barents Sea for decades, and rich experience about how to deal with conditions in this area has been gained. Current development projects are displayed in Figure 1.5.

Generally no hindrance from ice is found in this region, even if some small pieces of ice floating in south part is possible. Sea ice takes place every three years which lasts from 3 weeks to three months normally. Seasonal conditions in Barents Sea go as follows:

In summer：

- Atmosphere temperature：5℃ to 25℃;
- Sea water temperature: 6 to 8℃;
- Fog and sleet in the air;
- Perpetual day, so sun can be seen in 24 hours;
- Logistic support is from the closest base

In fall (September to November):

Weather is unstable and unpredictable (weather forecast is uncertain) which is influenced by polar low pressures.

Spray ice takes place in this season which can make the critical vessels lose stability Winterization is necessary to ensure efficiency and reliability of the equipment in the following aspects:

- To protect the personnel exposed to low temperature, wind chill effect must be taken into consideration;
- To ensure operation flow such as drilling fluid;
- To protect the equipment to be frozen;
- To ensure reliability of some emergency response equipment, e.g. fire water, lifeboat, liferaft, survival suits

Figure 1.5 Current Oil & Gas Development in Barents Sea
(From FUGRO website, 2005)

In winter (November to February):

The weather is getting even colder;

Perpetual night brings more darkness to Barents Sea, which challenges safe operation due to poor visibility;

More sea spray is expected, which can be forecasted except in polar low pressure conditions. A Polar Low Pressure System is a special meteorological phenomenon found only in South Pole or North Pole regions. Noer, G. (2009) defined **a polar low** as a small, but fairly intense atmospheric low pressure system found in maritime regions, well north of the polar front, whose typical diameter is 100–500km and average life span is 18 hours. The polar low pressure system is so powerful that it is able to give strong and rapidly changing winds and dense showers of snow or hail, which leads to more unpredictable characteristics comparing with the larger and more common synoptic lows. One good example illustrating how unpredictable is: during the passage of a polar low the wind speed typically can increase to storm force in such a short time as 1/2 – 2 hours while changing wind direction, which is accompanied with heavy snowfall and poor visibility in most of the cases. Sometimes high waves take place together with the polar low, and they may occur simultaneously with the onset of the strong wind. It can be imagined how challenges it will be when strong wind, high wave, poor visibility, heavy snow showers and drift ice or ice bergs take place at the same time. Polar Lows is a rare special case of strong troughs.

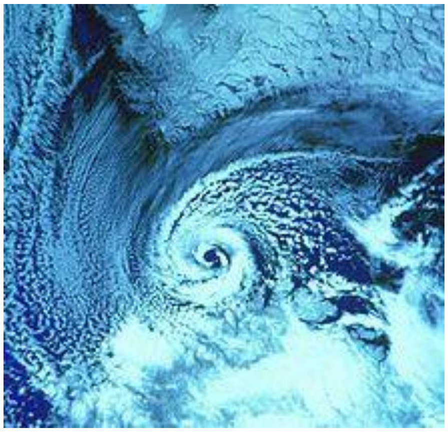


Figure 1.6 Polar low over the Barents Sea on February 27, 1987
(http://en.wikipedia.org/wiki/Polar_low)

Except Arctic regions mentioned above, there are some other main Cold Climate areas which attract oil companies' interests:

Newfoundland

Main challenge is the threat from ice bergs, so proper ice management methods, say, monitoring, forecasting, iceberg towing and platform moving away ability are necessary.

Bohai Bay

It is an internal bay, the north side of which will be frozen in the winter with normal thickness of 50cm ice, main concern of operators in this area is IIV （Ice Induced Vibrations）. There was a production platform collapsed because of damage from IIV to its legs. Small waves and little drift ice are expected, so some measures should be taken to protect risers from damage.

Caspian Sea of Kazakhstan:

Ice is the main challenge: heavy ice ridges and ice cover less than 1 meter are factors of design basis; because water depth is not deep (3-5 meters), sometimes the ice can be down to sea floor, subsea pipelines and other equipment should be well protected. Production gravel islands can prevent ice from reaching the production system and even the ice is piling up.

Global warming imposes both positive and negative effects on oil and gas operations in Arctic: it is true that the global climate is becoming warmer and warmer, which both reduces thickness and areal coverage of the sea ice in summer months, and the operation time windows are getting longer comparing with past years. All the factors mentioned above have made the oil and gas development more efficient and attractive in Arctic. The warming might, however, cause ice floes to break away from the ice pack or icebergs or from glaciers to drift into areas where oil and gas activities are being planned, threatening the safety of offshore structures, floating units and personnel.

1.2 The oil field services company, COSL

China Oilfield Services Limited（COSL）was founded through merging of 7 different oil & gas service companies on Sep-26th , 2002. Since the date of birth, COSL has developed fast to be the leading integrated oilfield services provider in the offshore Chinese market. Its services cover each phase of offshore oil and gas exploration, development and production, the four core business segments of which are geophysical services, drilling services, well services, marine support and transportation services. Since 26th March 2004, COSL's stocks can be traded by means of Level I unlisted American Depositary Receipts at OTC over-the-counter market in the United States. The ticker symbol is CHOLY. COSL has listed its 'A' shares on Shanghai Stock Exchange "SSE" under the ticker 601808 since 28th September 2007.

Figure 1.7 Newly launched seismic vessel of COSL, HYSY720
COSL official website: http://cosl.com.cn

COSL has the largest fleet of offshore oilfield services facilities in China. To date, COSL is operating 34 drilling rigs, among them 27 are jack-up drilling rigs and 7 are semi-submersible drilling rigs, 2 accommodation rigs, 4 module rigs and 8 land drilling rigs. In addition, COSL also owns and operates the largest and most diverse fleets in offshore China, including 75 working vessels and 3 oil tankers, 5 chemical carriers, 8 seismic vessels (figure 1.7), 5 surveying vessels, and a vast array of modern facilities and equipment for logging, drilling fluids, directional drilling, cementing and well work-over services, including FCT （Formation Characteristic Tool）, FET（Formation Evaluation Tool）, LWD （Logging-While-Drilling） and ERSC （ELIS Rotary Sidewall Coring Tool）, etc.

As the largest listed offshore oilfield services company in China, COSL not only provides services of single operations for the customers, but also offers integrated package (IPM) and turnkey services. In fact, since its birth, COSL has committed itself to be a competitive oil & gas services supplier in the international oil and gas market. COSL’s business activities are conducted not only in offshore China, but are also extended to different regions of the world including North and South America, the Middle East, Africa, Europe, South East Asia and Australia. COSL and its employees are dedicated to provide premier quality services, while adhering to the highest health, safety and environmental standards.

In 2011, COSL’s DOC Document of Compliance was approved by the Maritime Safety Administration of the People’s Republic of China for renewal of certificate. COSL maintained the certificates issued by DNV (Det Norske Veritas) through the annual review in compliance with ISO9001, ISO14001 and OHSAS18001 standards.

With the drive of “ALWAYS DO BETTER”, COSL will endeavor to provide domestic and international clients with safe, quality, productive and environmental protection services. COSL commits itself to realize win-win situation for shareholders, clients, employees and partners. It is steadily making headway toward being one of the world’s top class oilfield services companies. COSL is devoted to develop into an outstanding international service company.

COSL has established its corporate image, cultural spirit, performance guidelines, core values and staff code of conduct following years of engagement in production, business and operation management.

Backing its development strategies and mission is the corporate spirit “Always Do Better”, under which COSL hosts its corporate cultural activities that cover a wide-ranging number of activities. These activities help enrich the depth of the corporate culture, creating a harmonious ambience that is conducive to gather, nurture and incentivize talents. This blend of corporate culture, an outcome of years of refinement and sublimation, has been gradually evolving into a momentum featuring unrelenting urges to influence, gather, sympathize, propel and compete, driving the Company’s ongoing development.

Corporate Spirit: Always Do Better, Figure 1.8

COSL corporate spirit “Always Do Better” embodies COSL staff’s self-initiated unrelenting pursuit of improvements and innovations. It means firstly recognition of their results and improvements achieved; secondly their openness to face its own shortcomings and inadequacies; thirdly the limitless room for improvement for today versus yesterday, for tomorrow versus today; fourthly their choice to improve facing stiff competition, or be otherwise eliminated

Figure 1.8 Corporate Spirit of COSL

COSL official website: http://cosl.com.cn

Performance Guideline: Do Everything Diligently

COSL performance guideline "Do Everything Diligently", figure 1.9, embodies the diligent and attention-to-details attitude promulgated by COSL staff, encouraging each of the staff members to start from their own experience, from now and from every single task and review if they had not been adequately diligent yesterday, how to be more diligent today and the most diligent tomorrow as part of their ongoing pursuit of their "Always Do Better" corporate spirit.

Figure 1.9 Performance guideline of COSL
COSL official website: http://cosl.com.cn

Core Value: "Win-Win" with Shareholders, Customers, Employees and Partners

COSL corporate core value "Win-Win" with Shareholders, Customers, Employees and Partners, figure 1.10, highlights COSL's recognition and understanding of the importance of balancing interests of shareholders, customers, employees and partners in its pursuit of "Win-Win" results in every count. That is a framework in establishing adequate values to continue to exist. It illustrates high standards of sense of responsibility and missions.

Figure 1.10 Corporate Core Value of COSL

COSL official website: http://cosl.com.cn

Code of Conduct: Integrity, Dedication, Teamwork and Self-discipline, Figure 1.11

Assigning integrity, dedication, teamwork and self-discipline as essential elements of COSL's staff code of conduct highlights their expectation of the quality of staff we employ. Integrity is the basic moral requirement COSL demands from its staff. Dedication is the basic attitude our staff in doing their work. Teamwork is the basic protocol they adopt in managing our tasks. It is particularly crucial within a matrix-style framework of management. Self-discipline is an attitude to impose self-restraint to regulate a staff member's own actions.

Figure 1.11 Code of Conduct, COSL

COSL official website: http://cosl.com.cn

As mentioned before, COSL never gives up its ambition to make an excellent performance in Arctic. In fact, COSL already has a subsidiary - COSL Drilling Europe AS, the head office of which is located in Stavanger, Norway.

COSL Drilling Europe AS (CDE) is operating two accommodation rigs, COSL Rig Mar and COSL Rival, both of which own long term contracts with ConocoPhillips.

The first semi-submersible unit of CDE - COSL Pioneer, has been delivered in November 2010, which has been awarded an up to 5 year contract with Statoil with start-up in May 2011. The rig arrived Norway in April 2011 and is now working at Brugdan II, Faroe Island. Due to the excellent performance of the rig and crew, COSL Pioneer already got high positive evaluation from the clients.

The second semi-submersible drilling rig COSL Innovator, has already commenced operation on 8th November 2012 under an eight-year service contract with Statoil. The third one, COSL Promoter, has recently received an Acknowledgement of Compliance certificate ("AOC Certificate") issued by The Petroleum Safety Authority of Norway, which indicates it already got the competence to start operations in Norway. AOC Certificates are mandatory credentials which companies and drilling platforms need to obtain before they can operate in Norwegian waters. To get them, both the companies and equipment need to meet very stringent requirements to prove that they are qualified to work in Norway. This is the fifth time for a drilling platform of the Group platforms received an AOC Certificate, after COSL Rival, COSL Rig Mar, COSL Pioneer and COSL Innovator, which demonstrates the Group's operational management capabilities. COSL Promoter is supposed to perform drilling service under an eight-year service contract with Statoil in the first quarter of 2013.

The development target of CDE is to be the preferred supplier of accommodation and drilling services, which will play an essential role in COSL's Arctic strategy due to its location virtue. As mentioned before, so far COSL had little research about oil and gas operations in Arctic, which is not in accordance with its ambition to be an international services supplier. So this thesis will perform a gap analysis between COSL current capabilities and requirements for service suppliers in Arctic, then some key development directions and strategies will be recommended as per the gap analysis.

2. Main challenges

In this chapter, the main challenges will be discussed for COSL's service activities in Arctic, e.g. vessel icing, sea ice, extreme weather conditions, weak logistic support, etc. Some negative effect of them might be critical. Solutions to these challenges will be analyzed and recommended.

2.1 Vessel icing

Vessel icing is caused by the combination of sea spray and cold temperature, the former will be frozen when it contacts with cold surfaces of vessels. Sometimes strong waves and wind could lead to more serious icing conditions. Gudmestad, O. T. (2012) has listed 4 key factors for icing: Wind, Waves, Low Air Temperature and Open Water, all these factors are not uncommon in Arctic, besides them, another unfavorable factor, Polar Low pressure systems, which is difficult to be forecasted, could make the situation worse and usually change vessel icing to disasters; capsized vessels.
Main negative influences of vessel icing are:

2.1.1 Stability of vessels

To illustrate this phenomenon, some basic knowledge of vessel stability needs to be introduced.

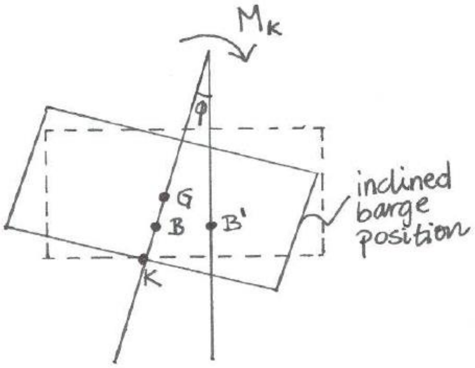


Figure 2.1 Inclined Barge Position
Gudmestad, O. T. (2012)

In this drawing:

- B is the original position of the center of buoyancy
- G is the center of gravity

- φ is the angle of inclination
- B is the center of buoyancy in inclination mode
- K is the keel
- M_k is the moment causing the inclination

From geometry,

$$\overline{GM} = \overline{KB} + \overline{BM} - \overline{KG}$$

The distance between ‘G’ and ‘M’ has close relationship with initial stability of vessels, which means the ability of the vessel to recover back to its initial position after the inclining moment (for example wind load) is taken away. The wider it is, the better is the stability for the vessel.

When the vessel gets more spray icing, its gravity center becomes higher, which leads to shorter distance between ‘G’ and ‘M’, which will result in poorer stability. The loss of stability might lead to extreme rolling and/or pitching and topside flooding, if this condition gets worse, the catastrophic loss of stability, capsizing, might occur (Guest, P. 2001; US Navy, 2001). Figure 3.2 was supplied by the icing group, department of Earth and Atmosphere Sciences, the University of Alberta, which shows a Dutch tanker Anna Broere’s crew being rescued by a helicopter, the tanker was losing its initial stability due to heavy icing. Finally M/S Anna Broere was abandoned in the Baltic New Year’s Eve 1978.

Figure 2.2 M/S Anna Broere was abandoned in the Baltic New Year’s Eve 1978 due to heavy icing

Courtesy of The Icing Group, Department of Earth and Atmospheric Sciences, The University of Alberta

Overland (1990), Fett and Kozo (1992) and Fett et al. (1993) have reported a tragic example related to sea spray icing. In January, 1989, there was heavy icing in the Bering Sea region and in Gulf of Alaska, which had been forecasted correctly. Most of the crab fishing vessels selected the Pribilof Islands as shelter and remained safe. But one crab vessel, the 31-meter F/V Vestfjord, attempted to cross the Gulf of Alaska from the east during the heavy icing period just because it had missed the start of the crabbing season and would try to make up for lost time. Whether she intended to ignore the severe icing forecast, or couldn't seek shelter, or some reason else, only the litigants themselves know. What we know is from the last report from this crab fishing vessel: at 1010 UT, January 29th, the location of the vessel is approximately 60-70 miles south of Kodiak Island and heavy icing condition was reported by the captain. By the moment of the report, it was probably too late to take evasive actions and the ship was never heard from again, a loss of six lives.

2.1.2 Equipment onboard function lost

Quite a few of equipment of the vessels are located on the main deck, such as communication systems, firefighting equipment, cranes, ventilation pipes, weapon systems of a fleet, and so on. This equipment is exposed to the sea spray and is easy to get sea icing, which will discount their function and capability, in the worst case, the function maybe totally disabled. Figure 3.3 illustrates a vessel in severe icing condition, without effective de-icing method, it was rendered useless by sea spray icing: e.g. the navigating officers were blinded by the thick ice outside the navigating office windows.

Figure 2.3 Extreme icing

Photo from lecture slide of Gudmestad, O. T. (2012), difficult to find the origin and courtesy to the original photographer

2.1.3 Operations on deck are restricted and risky

Figure 2.4 vessel icing in Arctic

Photo from lecture slide of Gudmestad, O. T. (2012), difficult to find the origin and courtesy to the original photographer

As shown in the Figure 2.4, the deck could be very slippery after icing. Combined with severe movements caused by strong winds and high waves, all the operations on the deck will suffer high risk, and accidents such as collisions between items and falling will be not uncommon.

2.1.4 Fuel consumption increased

The vessels with sea spray ice are like soldiers with heavy armors, the similarity of which is the additional weight of them, it is obvious that extra fuel consumption is unavoidable.

Regarding serious icing condition in Arctic and associated negative effects, different modes of icing, stability calculations for vessels, see also:
http://www.tc.gc.ca/eng/marinesafety/tp-tp10038-78-wi-icing-61.htm

2.2 Sea ice

It is undoubted that the image of the Arctic in most people's imagine is related to snow and ice, so one of the characteristics of Arctic is the sea ice aspect including ice cover, drift ice floes, the ice edge and icebergs. For better understanding of the challenges of sea ice to offshore oil and gas operations in Arctic, it is necessary to explain some relevant terms as per DNV, WMO and some other international or national standards or specifications.

Sea ice: is the ice features frozen from sea water, meaning all the ice in the sea, such as brine ice, ice floes, fasten sea ice, ice ridges, etc.

Fasten ice: ice that remains attached to the seashore of the main land or islands; in most cases it is immobile, also with the name of fast ice or landfast ice.

Drifting ice: ice cover or ice floes which can be moved with the force of wind, wave or current.

Both ice types (Fasten ice and Drifting ice) mentioned above will impose threats to offshore oil and gas operations.

Sea ice can be classified to first-year ice, multi-year ice (including second-year ice) as per whether it has survived through at least one melting season.

First-year ice: sea ice which has been formed during the current or prior winter without surviving one summer melt season.

Multi-year ice: sea ice that has survived at least one summer melt season,

Second-year ice, which is regarded as one type of multi-year ice by some researchers, is ice that has survived only one summer melt season. So when these two terms appear at the same time, **multi-year ice** should be interpreted as ice that has survived at least two summer melt seasons.

Level ice: plate of ice with relatively uniform thickness, also called sheet ice.

Pack ice: sea ice consisting of discrete floes which is not fasten ice.

Rafted ice: ice feature formed from the superposition of two or more ice sheet layers.

Ridge keel: portion of an ice ridge that extends below the water line; a ridge keel can consist of a consolidated layer and an unconsolidated layer.

Broken ice: loose ice consisting of small floes, broken up as a result of natural processes, could be formed by active or passive intervention

Consolidation: this is the process of freezing of pore water in voids within ice rubble, between floes, or between soil particles, Consolidation of soils, involves drainage of pore fluid as a result of overburden pressures.

Consolidated layer: portion of an ice ridge in the water formed by the ice consolidation process.

Unconsolidated layer: part of an ice ridge keel or ice rubble found below the consolidated layer that consists of unconsolidated or only slightly bonded ice blocks, also named unconsolidated rubble layer

Floe: relatively flat piece of sea ice greater than 20 m across, There are typical sub-categories: small (20 to 100m across, medium (100 to 500 m across), big (500 to 2 000 m across), vast (2 to 10 km across) and giant (greater than 10 km across).

Iceberg: glacial or shelf ice (greater than 5 m freeboard) that has broken (calved) away from its source. Icebergs can be freely floating or grounded, and are sometimes defined as tabular, dome, pinnacle, and wedge or blocky shaped.

Ice island: large tabular shaped ice feature that has calved from an ice shelf or glacier.

Ice ridge: linear feature formed of ice blocks created by the relative motion between ice sheets. A compression ridge is formed when ice sheets are pushed together and a shear ridge is formed when ice sheets slide along a common boundary.

Ice scenario: combination of circumstances involving the presence of ice, resulting in actions or action combinations on a structure.

Stamukha: grounded ice feature composed of broken ice pieces or rubble.

Rubble field: region of broken ice blocks which can float together as a continuous body.

S**cour**: soil erosion caused by wave, ice or current action.

2.2.1 Sea ice cover and drift ice

One of the main tough challenges resulting from sea surface being covered by sea ice (Figure 2.5), will lead to restricted passages or even no passage for vessels and severe ice load to the oil and gas facilities. When the ice is driven to interact with platforms by waves, current or wind, the supporting legs of the facilities may be destroyed by fatigue caused by repeated loading. To prevent ice floes to climb to platforms, some facilities are designed with breaking cones to break the ice floes. Another threat to the platforms is ice induced vibration (IIV) which turns out to be a new challenge to operational safety.

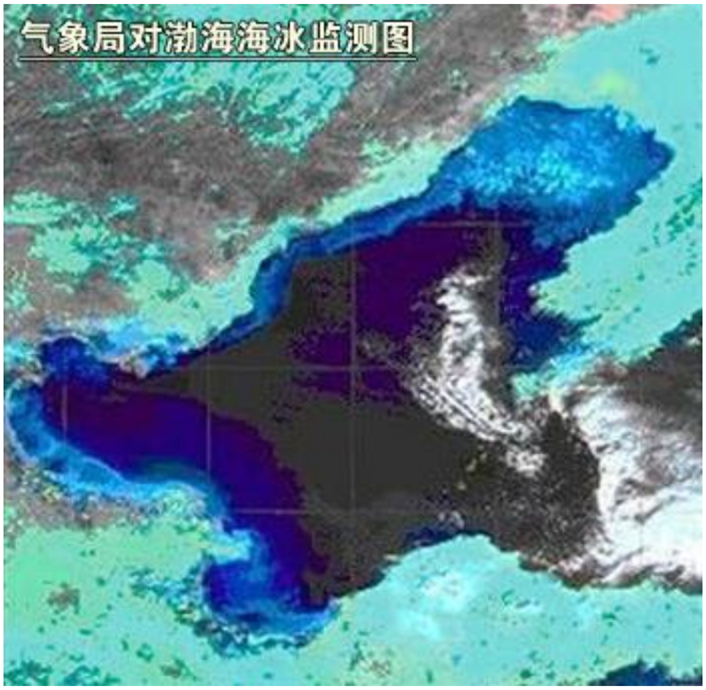


Figure 2.5 Sea ice condition of Bohai Bay on 2013-01-13, where the ice is marked in grey color.（satellite photo）
Courtesy to http://www.guancha.cn/society/2013_01_21_122049.shtml

To understand the detailed negative influence of the sea ice cover in the Arctic, it is necessary to introduce the ice cover characteristics in this area. The Barents Sea， Beaufort Sea and Grand Banks are three different typical regions with Arctic ice cover characteristics, which can be taken as examples to introduce ice cover conditions of Arctic. Before discussing the characteristics of the ice cover, it is necessary to introduce some special features of sea ice which are different from fresh water ice. Due to the brine in the sea water, the freezing point of sea water is lower than for fresh water; when sea water is getting frozen; brine pockets are formed at the same moment which causes the density of sea ice to be lighter than fresh water ice.

Høyland (2010) has proposed three methods of how ice grows, from below, from above and from inside. For thin ice cover, main ice formation takes place in the water & ice interphase because latent heat is transported from the warm water, then through the ice to the cold air. For thick ice cover, rafting effect is the main denoting factor for ice development. When ice cover is flooded, superimposed ice will appear above the original ice cover. Besides the conditions mentioned above, there is another case for growth of superimposed ice: Precipitated snow can depress the ice so that seawater comes up in cracks or seeps up through interconnected brine pockets. For land fast ice cover the ice layer is created when water coming from snow melting encounters with a cold zone, which is fresh ice or almost fresh ice because it is made of snow melting water. New ice can be produced from inside the ice cover as the temperature sinks inside, which is an important process to desaline the ice. Figure 2.6 illustrates the composition of the ice cover and how it grows.

The melting process proceeds from above, inside and below the ice cover as well. Current and turbulence (underlying velocity) below the ice cover reduce the ice growth or melt the ice, because both of them have the same frictional tendency. Essentially, this effect is similar to the rocks along the sea shore being eroded. Some brine might be melting to keep the brine at the freezing point and then water will drizzle down into the nearby brine pockets, which results into more brine pockets inside the ice cover, just an opposite physical process to ice growth inside. The melting from above is quite different: unstable weather condition, water and wet snow on the ice cover surface will assist melting locally; as a result, radiation and high air temperatures cause melt from above the surface.

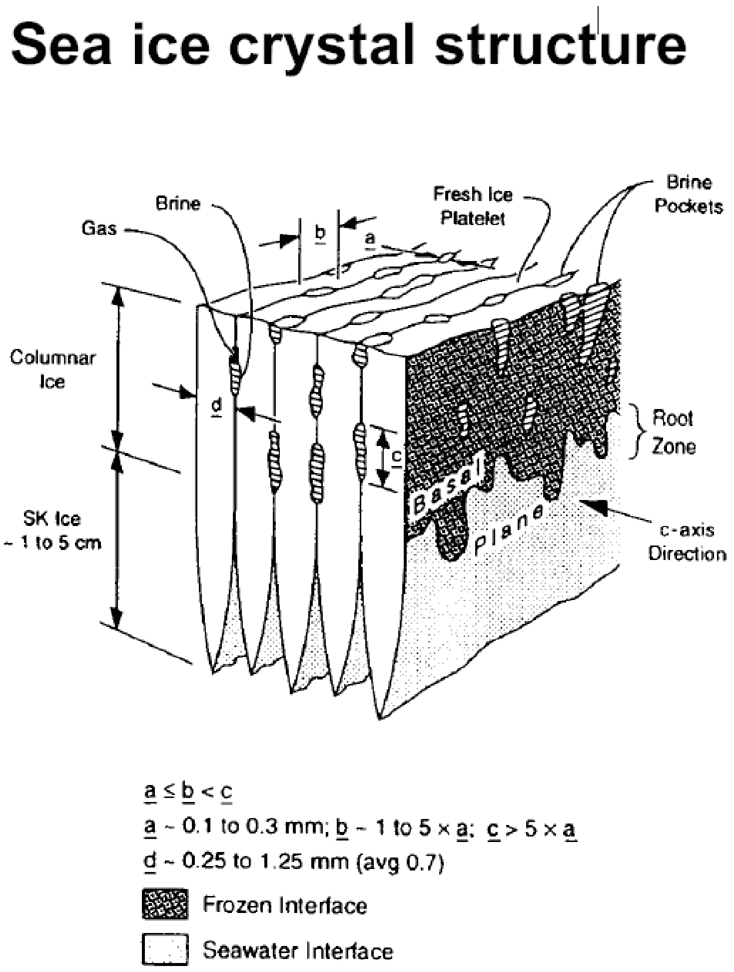


Figure 2. 6 Sea Ice Crystal Structure
Courtesy to Høyland (2012), UNIS/NTNU

Figure 2.7 illustrates the most common sea ice related features in the Arctic region. As defined above, fast ice is fasten to the land and sea bed; with the water depth increasing, there is a transitional zone between fast ice and drift (pack) ice, which will develop into fast ice if the air temperature gets lower, and change to drift ice if air temperature gets warmer. The drift ice zone lies on the other side of the transitional zone, which can move under the force of wind, wave and current.

When ice floes move relatively to each other, they are pushed together, and a compression ridge is formed; if ice sheets slide relatively along a common boundary, a shear ridge is formed. When the weather starts getting cold, some pressure ridges are generated, the keels of which can be so deep as to touch the sea bed which will decrease their mobility. In the northern parts of the Arctic, some ice ridges already have existed for multiple years, when ice floes are pushed by the force of wind, current or wave, new pressure ridges are produced step by step. To the side of the ice cover which is close to the open water, the thickness of ice floes is getting smaller so that strength is poorer which results fracture when powerful current occurs. So the general trend from sea shore to open sea is: fast ice to drift ice floes, strong strength to weak, thick to thin, multiyear floes to one year floes, shear effect to compression effect and then to tension force, 10/10 ice cover to ice free or open water.

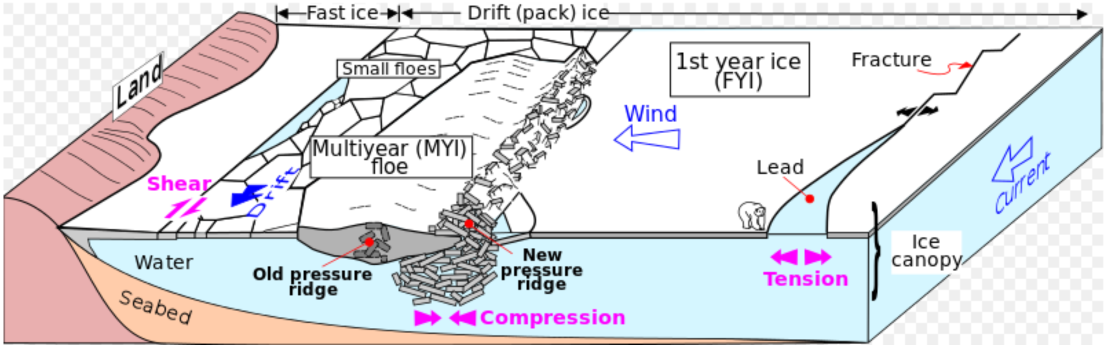


Figure 2.7 Schematic representation of a hypothetical scenario showing some of the most common sea-ice related features

Courtesy to Lusilier(2012)

(http://en.wikipedia.org/wiki/File:Sea_ice_Drawing_General_features.svg)

Wind, wave and current could drive the drift ice floes or icebergs to move, the force of which might be considerable, posing vital threats to offshore oil and gas facilities. Size and drift velocity of the ice floes determine how much the force will be. So when the force is discussed, size and velocity of the drift ice are two common characteristics to be considered. In the winter of 1971, Chinese scientists calculated data from 'Hai Two' well: for one ice floe with size 6km * 6km, and height of 1.5 meter, even with very slow velocity, the pushing force could be 4000 tons, which is able to cause almost all the offshore engineering constructions such as petroleum platform to fall down. Ref also Fig 2.8.

Figure 2.8 Ice condition in Bohai Bay

Except pushing force, the expanding force of sea ice could destroy harbors and offshore vessels as well. E.g., when the sea ice temperature decreases 1.5℃, 0.45 meter extra length can be produced for 1000 meters long sea ice being expanded, which is powerful enough to destroy vessels in sea ice. For the effect of ice related damage, see Figure 2.9.

Figure 2.9 A view of ice related damage to a vessel
Courtesy to Dunderdale, P. and Wright, B. (2005)

The horizontal load caused by the ice cover is easily understood by most people, but there is another kind of load in another direction, the vertical load, which is easily neglected. Due to the limited thickness of the ice cover, expanding forces in the vertical direction is so small that they can be out of consideration. But there is one other huge vertical load which mainly comes from two reasons, first of which is because of tide rising and tide ebbing, which could lead to vertical forces to offshore facilities frozen in the sea ice, the base of which could be destroyed fatally. To cite an example, in 1969, Bohai bay, the Sea-2 platform, which had been fabricated with 15 piles with 2.2 cm wall thickness, OD 0.85 meter, 41 meters length, and driven 28 meters deep in the sea bed, had been destroyed by a considerable upward vertical load. On another platform, Sea-1 platform, with a weight of 500 tons, all the support ribs had been broken by the vertical load of sea ice.

The second main reason effect of vertical load of sea ice is the interaction of sea ice breaking which depends on offshore structure slope. Figure 2.10 could illustrate this load effect obviously.

In the left illustration, it is obvious that the interaction force of the ice cover can be decomposed to horizontal pushing force and vertical pressing force, which has the same effect as gravity, just like the structure's weight. Oppositely, the force of the ice cover in the right illustration can be decomposed into a horizontal pushing force and an upward vertical force, which is similar to buoyancy, attempting to draw the piles of the base out of sea bed.

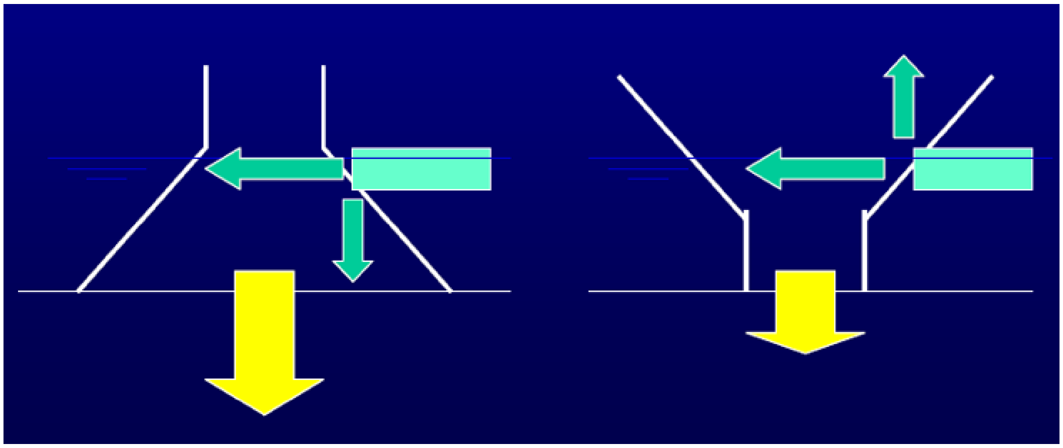


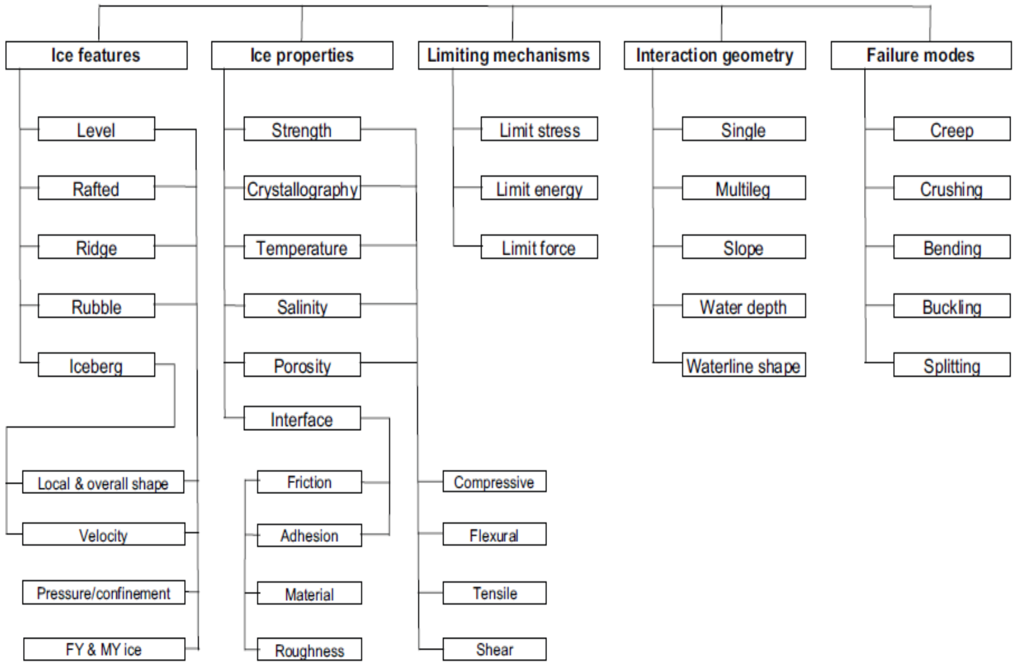
Figure 2.10 Downward and Upward vertical load demonstration.

Just as mentioned above, the slope of the structure must be considered and designed as per the practical ice condition of the operation region. A well designed structure slope can take the advantage of the vertical ice load to optimize the stability of the offshore facilities, while a poorly designed support structure slope will destroy the stability of the structure and pose a fatal threat to the safety of them. Especially in the Arctic area, if the designers have failed to take the interaction of ice and slope into consideration, any disaster is possible, such as capsize or excessive overturning moment. Figure 2.11 is one windmill foundation for offshore use in Denmark.

Figure 2.11 Windmill foundation, Denmark.
Courtesy to Gudmestad, O. T. (2011)

Obviously, this foundation will suffer from the upward vertical force, but this force can be eliminated by its own weight, especially the huge base, which will help to withstand the overturning moment caused by the ice cover's horizontal force as well.
For ice interaction scenarios, Løset et al. (2006) have concluded regarding some influencing factors, as shown in Table 2.1:

Table 2.1 Factors influencing interaction scenarios



Courtesy to Løset et al. (2006).

From this table, it is not difficult to identify the main factors influencing ice interaction scenarios, such as sea ice types/features, ice properties, ice inherent characteristics, limiting mechanism, interaction geometry/ slope of structures, and failure modes as well. In most of the research articles, when ice cover features are discussed, sea ice cover types, ice sheet thickness, ice floes size, velocities of drift ice floes and strength of sea ice are the items spoken of by most people, some other items like roughness, friction, adhesion and failure modes and limiting mechanisms are researched by the specialists, because they have involved a lot of professional knowledge. Nevertheless it is favorable for better understanding sea ice characteristics to know some influencing factors better.

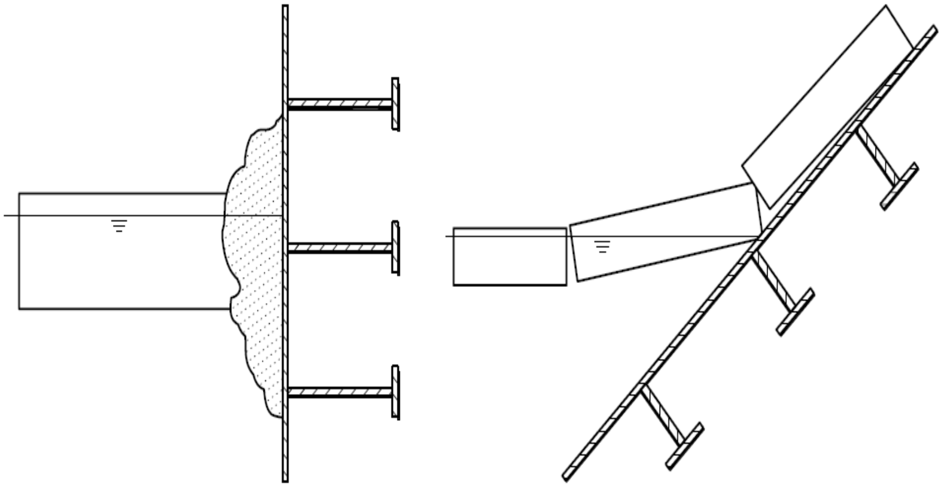
L øset et al. (2006) have listed 3 limiting mechanism for sea ice breaking, which need some basic knowledge of Mechanics of Materials. These mechanisms can help the designers and researchers to understand the negative influence of ice breaking on the offshore structures:

The limit stress mechanism: this mechanism works when ice failure processes adjacent to the structure, compressive, shear, tensile, flexure, buckling, splitting are the main factors controlling the ice action, A typical characteristic of which is that the ice feature has sufficient driving force to fail the ice.

The limit energy mechanism (limit momentum mechanism): this mechanism occurs when the kinetic energy (or momentum) of the ice feature is the main factor to limit the ice action, large isolated floe (e.g. multi-year ice in summer), ice island or iceberg impacts work in this mechanism.

The limit force mechanism: occurs when actions from winds, currents and the surrounding pack ice on an ice feature in contact with the structure are insufficient to fail the ice against the structure.

L øset et al. (2006) have recommended sloping structure for offshore facilities suffering ice cover load for the following reasons: structures with vertical walls in the waterline region generally experience much more severe ice actions than sloping ones under the same ice conditions. This principle is not difficult to understand: just as Figure 2.12 shows, for vertical structures, the failure mode of the ice covers is crushing failure, while bending failure is the main failure mode for sloping structures. As we known, the crushing failure will cause bigger energy impact than ice failure in bending mode.



a) Crushing failure (vertical structure)

b) Bending failure (sloping structure)

Figure 2.12 Different ice failure modes on structures
Courtesy to Løset et al. (2006)

The advantages of slope changes lie in the following aspects:

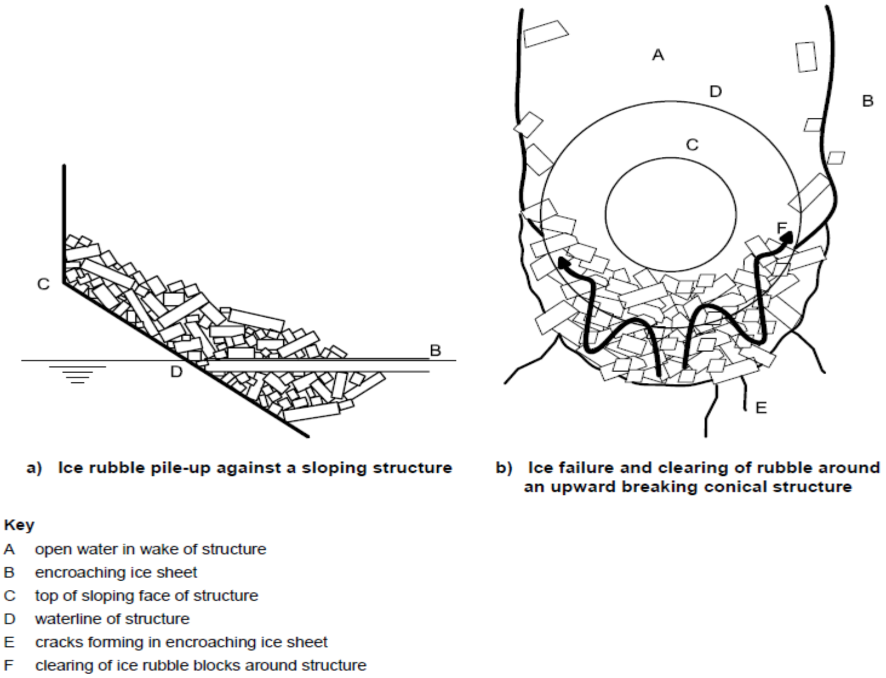
- Failure loads of sloping structures is less than ice load on vertical ones;
- The slope affects the characteristic of ice covers breaking frequencies and thus reduces potential resonance problems, which may cause structures fatigue damage.

So if it is possible, the designers should select sloping shapes for the facilities in ice infested region.

Sloping structures are not the best choices in all cases. The advantage of sloping structures may be reduced by:

- rubble accumulation at the structure
- high velocity of the advancing ice sheet

If large amounts of ice rubble accumulate on the sloping surface, flexural failure can be impeded besides bending failure, and the mixed modes of failure can occur with potentially larger actions.



a) Ice rubble pile-up against a sloping structure
b) Ice failure and clearing of rubble around an upward breaking conical structure

Figure 2.12 Different ice failure modes on structures
Courtesy to Løset et al. (2006)

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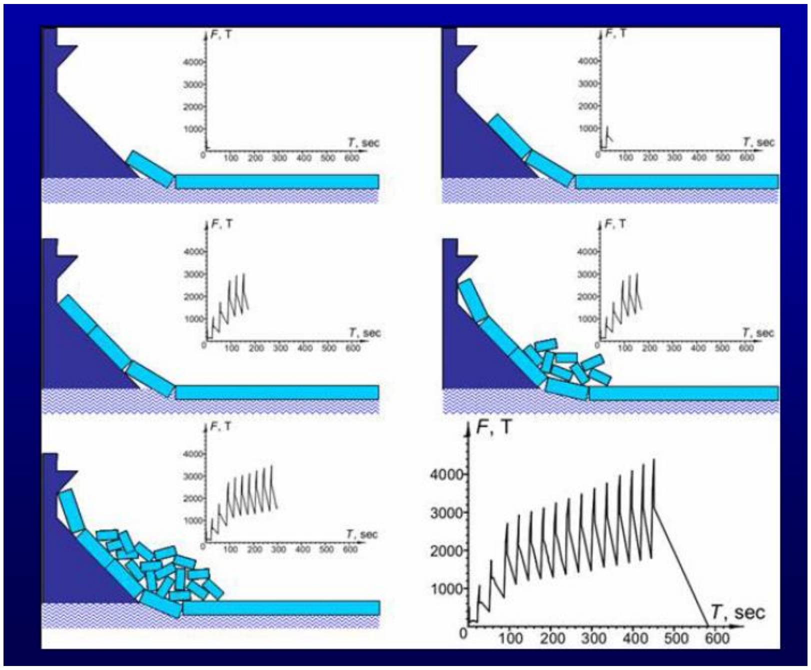


Figure 2.13 Different stages of ice interactions

Courtesy to Løset et al. (2006)

When the ice sheets move against an offshore structure such as an offshore platform, severe vibrations can be induced. If the ice failure frequencies mentioned above are close to the natural inherent frequencies of the structures, resonance will occur, which will enlarge the scope of vibration and pose another fatal threat to the structures. The vibration caused by ice breaking on the platform is called Ice Induced Vibration (IIV). Figure 2.14.A demonstrates the principle of IIV, which has connections with ice characteristics such as ice thickness, ice compressive strength, ice velocity, and structures' vibration frequencies, relating to ice breaking period, structures' projected area and other factors. So when the designers are designing the dimensions of the platforms, they must prevent resonance to occur to avoid fatigue damage and to improve the efficiency and sleep quality of people working on the platform.

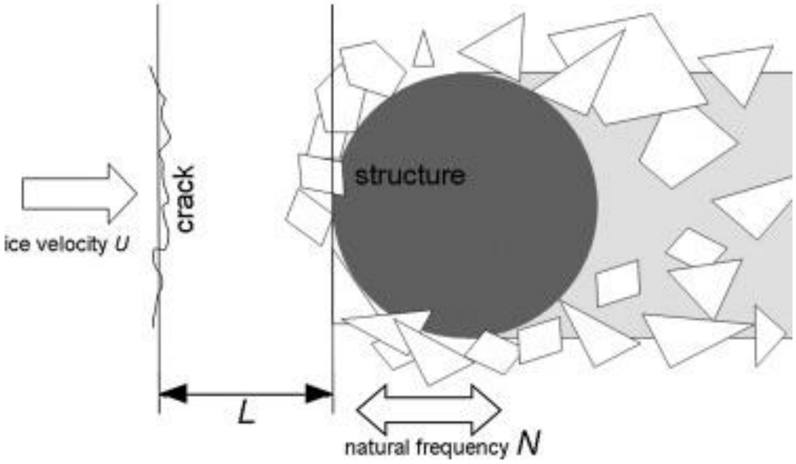


Figure 2.14.A Illustration of Ice Induced Vibration
Courtesy to Scientdirect.com

Research results show that a vibration of larger amplitudes of a column structure is produced by moving ice sheets at the lower speed, while the values of ice force applying on rectangular structure are not sensitive to the variation of the ice velocity, and triangle structures suffer far smaller ice forces than rectangle ones. (Liu, Y.P. et al., 2011).

There is another important variable for the platform design in the Arctic, especially for ice action calculations: freezing degree days (FDD), defined as days of departures of air temperature from 0 ℃. When the temperature falls below 0 ℃, it gives a positive value, whereas it becomes negative when the temperature rises above ℃. This index is a measure of both duration and magnitude of below-freezing temperatures during a specified period. Therefore, the cumulative value of FDD for a given winter season or a given winter tells how cold it has been for how long. As such, FDD has been used to describe weather patterns and climate warming or cooling over time, as well as a proxy for the state of melting or freezing of arctic sea ice (Polar Science Center, 2010). After many years' record and investigations, the researchers have listed reference values for the following regions:

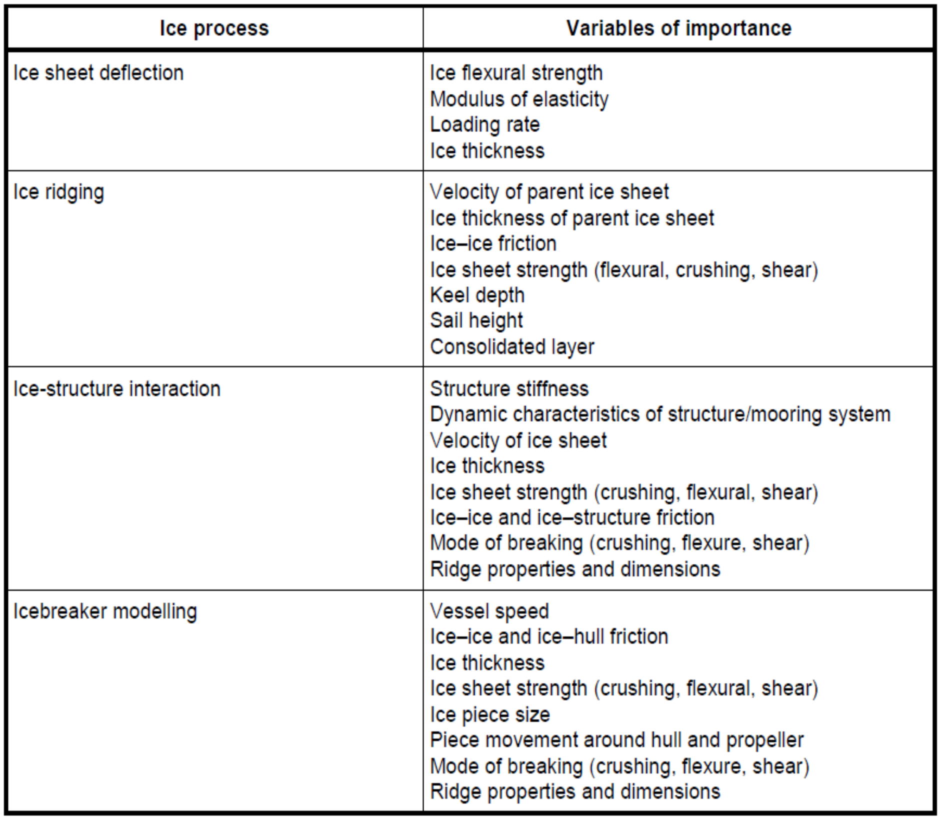
Central Arctic, about 4 000 freezing degree days per winter season (e.g. Beaufort Sea);

Sub-arctic, around 2 000 freezing degree days per winter season (e.g. Okhotsk Sea – off northeast Sakhalin Island);

Other Arctic regions, about 1 000 freezing degree days per winter season (e.g. Okhotsk Sea – Aniva Bay, North Caspian Sea, Cook Inlet, Baltic Sea, Bohai Bay).

Løset et al. (2006) has concluded some important variables and processes which are listed in Table 2.2, for oil companies that want to start operations in Arctic regions, they should first collet all the data for these variables precise and clear enough, otherwise accidents or trouble beyond expectation will disturb their operations, and downtime or even disasters is unavoidable.

Table 2.2 Important ice variables and ice processes



Ice process	Variables of importance
Ice sheet deflection	Ice flexural strength Modulus of elasticity Loading rate Ice thickness
Ice ridging	Velocity of parent ice sheet Ice thickness of parent ice sheet Ice–ice friction Ice sheet strength (flexural, crushing, shear) Keel depth Sail height Consolidated layer
Ice-structure interaction	Structure stiffness Dynamic characteristics of structure/mooring system Velocity of ice sheet Ice thickness Ice sheet strength (crushing, flexural, shear) Ice–ice and ice–structure friction Mode of breaking (crushing, flexure, shear) Ridge properties and dimensions
Icebreaker modelling	Vessel speed Ice–ice and ice–hull friction Ice thickness Ice sheet strength (crushing, flexural, shear) Ice piece size Piece movement around hull and propeller Mode of breaking (crushing, flexure, shear) Ridge properties and dimensions

Courtesy to Løset et al. (2006)

Barents Sea and Grand Banks are two typical Arctic regions and due to long period of offshore oil and gas operation, rich experience can be referred, so they can be taken as examples in order to introduce sea ice cover and iceberg characteristics.

Figure 2.14 shows the sea ice extent in December, 2012, as per report from National Snow & Ice Data Center; total ice cover area at that moment was 12.20 million square kilometers (4.71 million square miles). The magenta line shows the 1979 to 2000 median extent for that month. The black cross indicates the geographic North Pole. Even if the winter of 2012 was almost the coldest one during that last 2 decades, it is obvious that the ice cover shrank during the last 2 decades of 20th century, which results from global climate warming and Green House Effects.

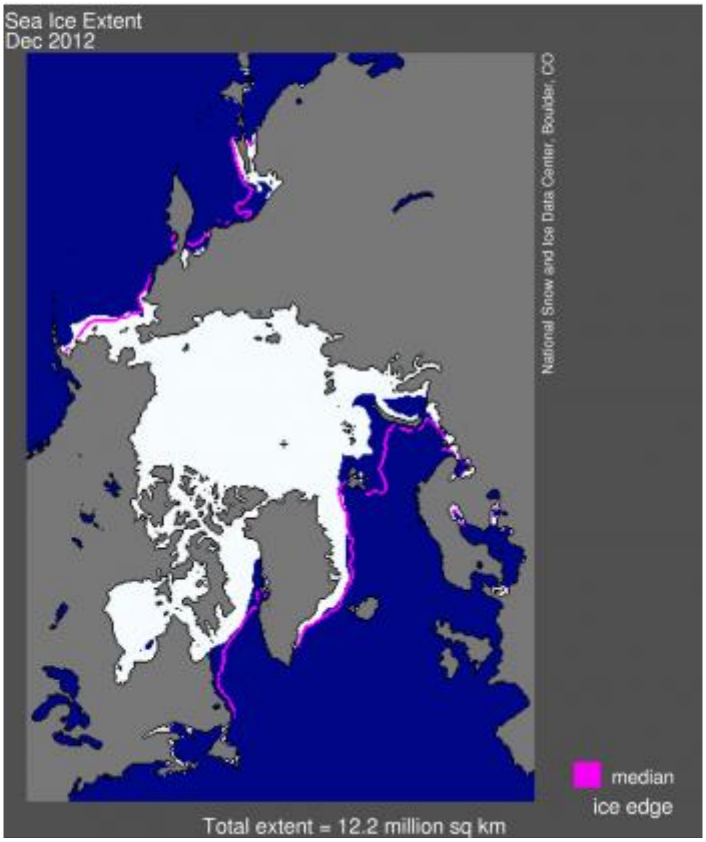


Figure 2.14.B: Arctic sea ice extent for December 2012
Courtesy to National Snow & Ice Data Center

Figure 2.15 is the latest photo taken from North Pole by satellite, which shows ice cover conditions of different Arctic regions: Barents Sea is the moderate ice cover region, so it is fitful for offshore oil and gas operations for its rich oil and gas reservoirs, in fact, the main challenge in the Barents Sea is drift ice sheets, sometimes ice cover and iceberg are possible in the northern and eastern part; East Siberian Sea suffers similar condition with Barents Sea, so it is another charming region for oil companies. Ice conditions in the Greenland region is more challenging, because this place has been covered by sea ice longer time, so both ice cover and drift ice should be taken into consideration, and iceberg threat is severe as well. But some successful offshore oil and gas operations there can supply favorable experience, especially in ice management and station keeping. The specific sea ice characteristics will be discussed in detail separately.

Figure 2.15 Latest Arctic ice cover condition
Courtesy to http://assets.knowledge.allianz.com/.

Barents Sea

Figure 2.16 shows a map of the Barents Sea location, which lies between Norwegian Sea and Kara Sea, both of them are rich in oil and gas reservoirs. Barents Sea has abundant oil and gas resources as well; however, due to vital challenge of operation in this area, not so many oil fields have been developed as in the Norwegian Sea, but several of them already have proved to be successful.

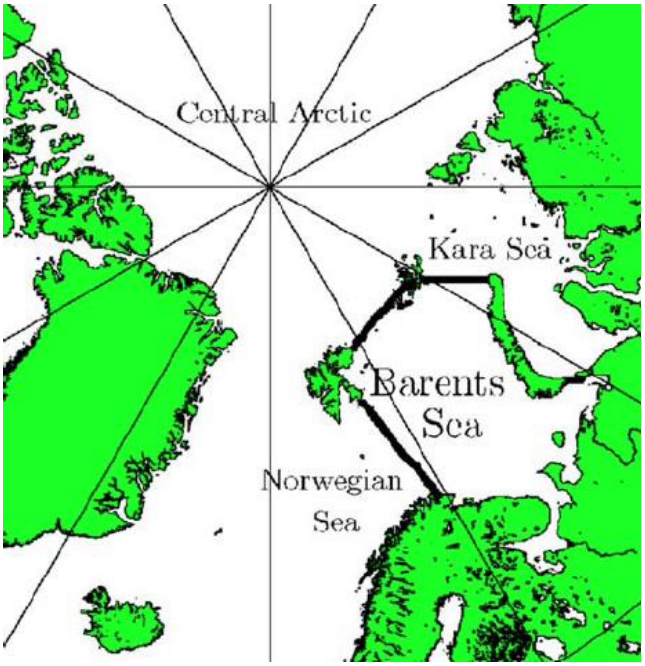


Figure 2.16 Map of Barents Sea and surroundings

Courtesy to Koenigk, T. et al. (2009)

Kvitrud and Hønsi, (1990) has proposed that the most extreme known expansion of sea ice occurred in June 1881. At that moment, the sea ice extended so far as to reach 20 km north of Berlevåg on the east coast of Finnmark during a short time. Generally the sea ice edge of sea ice is at 71° 30'N to 72° N.

DNV (2008) has described the different ice regimes in the Barents Sea from shore to open sea as shown in figure 2.17 Multiyear ice is generally thicker than first year ice because it survived at least one melting season while the latter is frozen the same winter. Rubble, hummocks and ridges are produced through collision of ice floes. Ice close to the shoreline may freeze to shore or shallow sea bottom and become immobile to some extent or absolutely. That is why it is called fast ice. Pack ice is ice on the open ocean drifting with wind and current. Ice concentration, wind and current determine the rate of motion. The Shear zone is the transition zone between the two regimes where the ice from the two regimes meet, grind against and pile upon each other, where one may find large piles of ice that is grounded, often called shtamukhas.

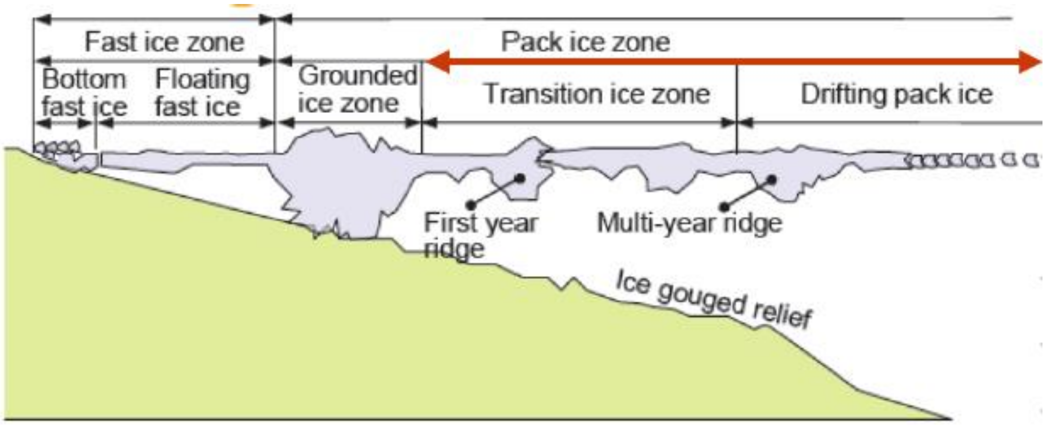


Figure 2.17 The different ice regimes going from shore to open sea

Courtesy to DNV (2008)

Geir Kjærnli at DNMI (2011) has record the ice boundaries in the Barents Sea weekly with the help of satellite. If we extrapolate to the level of 10^{-4}, we will find that in most parts of the Barents Sea ice must be taken into account in the design of offshore structures.

Mobil (1988) has listed some key parameters related to sea ice damage: thickness of the ice, the relative velocity between ice and platform, the physical ice properties, and the size of the ice-fields. All the parameters mentioned above are agreed by most of the researchers. All the oil companies having interest in Arctic oil and gas should carry out research to investigate these factors. Even if the data about sea ice of Arctic already increased much more than before, it is not enough yet to ensure safe operations in the Arctic, so more data collection jobs need to be done in future research to secure a safe way of managing sea ice.

Because of the severe sea ice condition in most parts of the Barents Sea, it has to be taken into account in design. The damage potential on the platforms is mainly on local elements in the splash zone. Station keeping for floating structures in Barents Sea still have to confront big challenge in northern and eastern parts of the Barents Sea.

Grand Banks

The Grand Banks region is regarded as one of the toughest operational environments in the world. All the following factors such as strong waves, strong winds, structural icing, poor visibility, icebergs and sea ice, will influence routine operations and the design philosophies for the development systems which will work in this region. Sea pack ice is recognized as the critical environmental constraint. In fact, some scientists have taken floating ice as the most representative feature to differentiate the Grand Banks from other regions with oil activities in the world.

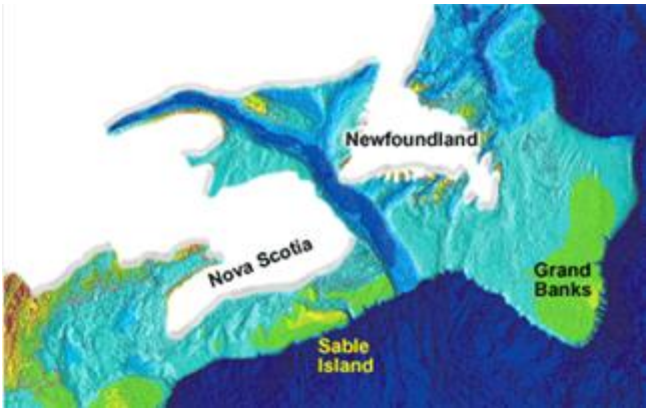


Figure 2.18 Grand Banks location in Arctic

Courtesy to National Source Canada

As shown in Figure 2.18, the Grand Banks is an important region in Arctic for oil and gas development. Dunderdale, P. and Wright, B. (2005) have concluded for this region that pack ice occurrence is not on a yearly basis. Even so it is still necessary to determine sea ice features in this region because they vary much in different regions, some of them might cause trouble to the oil and gas operations. Figure 2.19 shows representative regions of oil and gas development on the Grand Banks (B. Wright & Associates Ltd, 1998).

The Grand Banks are close to the extreme southern line of the pack ice cover which is produced off the East Coast of Canada in winters. Pack ice is the main challenge in this region. Although it is not an annual occurrence, it can move into the region from northern waters, such as Baffin Bay, Davis Strait, the Labrador Sea, and the waters off northeast Newfoundland (B. Wright & Associates Ltd, 1998).

When the pack ice moves southwards from these areas towards the Grand Banks, both the temperatures of the water and air get higher, in combination with influence of more open ocean conditions, the pack ice tends to be dissipated. A typical example is that as the ice moves southwards, the southward flowing Labrador Current at the north end of the Grand Banks also tends to keep any encroaching pack ice to the east and west of its central crest. Even though pack ice intrusions are not expected to occur every year, some parts on the Grand Banks do experience this condition every several years, which will last from a week to a month or more. On the northern and eastern part, these pack ice occurrences can be more frequent.

The thickness of sea ice comprising the East Coast pack is normally not quite thick, (0.3 to 0.7m), and is usually not continuous in terms of its coverage. Floe sizes varying from tens of meters to hundreds of meters in extent are common (B. Wright & Associates Ltd). More extreme sea ice conditions can also occur, such as slightly thicker first year ice, pressure ridges and rafted ice areas, and small multi-year ice floe fragments.

The drifting pack ice will also influence other marine operations, such as tanker loading from either fixed or floating production platforms, regional ship transits and platform resupply.

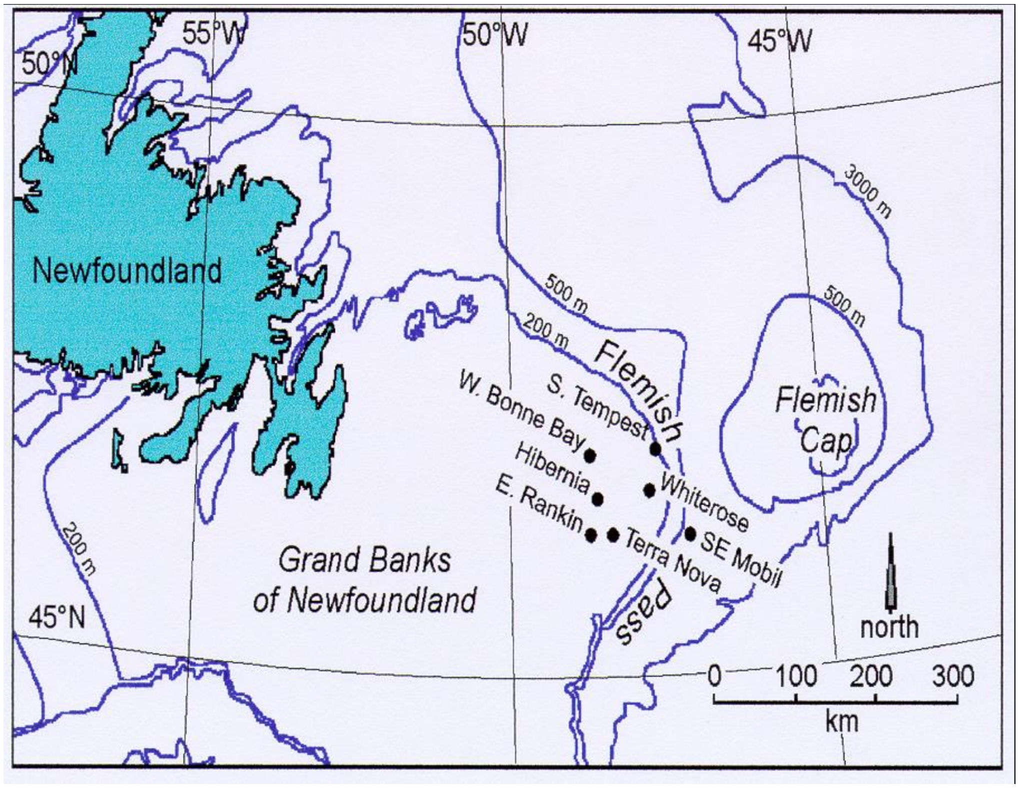


Figure 2.19 Representative Grand Banks locations for oil development

Courtesy to B. Wright & Associates Ltd, 1998.

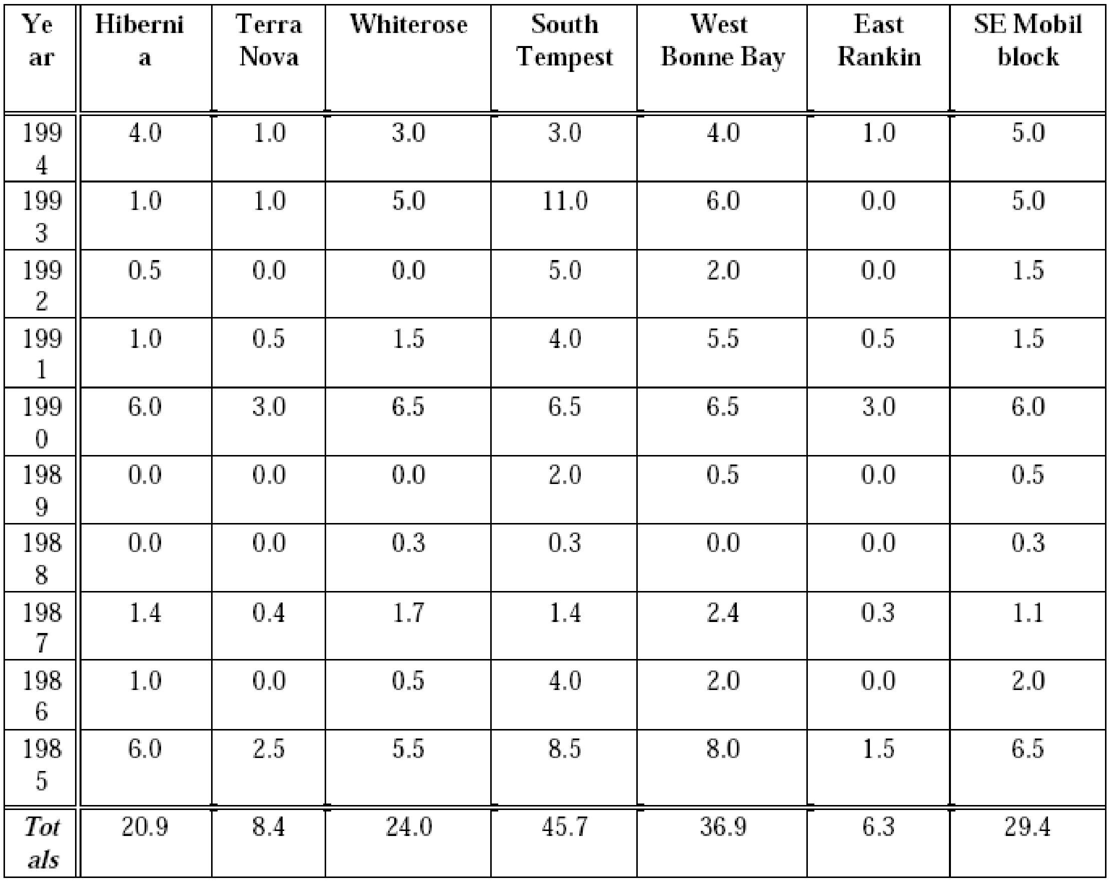
B. Wright & Associates Ltd (1998) has concluded that the statistics are showing that pack ice occurrences in the region are not particularly frequent; neither are the characteristics of the pack ice severe. Even so, precaution about ice threats on the Grand Banks cannot be given up because certain locations on the Grand Banks do experience pack ice invasion: an average of 20 to 30 days of pack ice coverage annually, some more exposed sites in extreme years are suffering 50 to 70 days of pack ice coverage. The potential damage of sea ice in the regions where it is occurred frequently is much more terrible than that in the regions it is a normal issue, because people will take it as a case with small probability so the measures to prevent its damage are easy to be neglected.

One of the main challenges in this region is the station keeping trouble for the vessels in the sea with pack ice coverage. The pack ice, especially the moving ice, could cause heavy load to the mooring systems being beyond their rated working limits, or to their dynamically positioning systems. Far from this, it is also important to acknowledge that the complicated environmental conditions on the Grand Banks are unique. For example, the combination of pack ice, waves, growlers, and small icebergs within the Grand Banks pack ice cover, will bring new challenges for station keeping operations in the area.

Table 2.3 shows the pack ice coverage period for different regions on the Grand Banks.

Comparing with the ice free time window, the period with ice coverage can almost be neglected, which will not cause considerable downtime related to pack ice package. However, it is necessary to make a precise estimation for the downtime caused by pack ice, because total daily cost for an oil company in the Arctic could be around millions of US dollars, it is one of the key variables for an economical evaluation. The historical ice charts show that the central and southwestern sections of the Grand Banks tend to lie in a pocket of bergy water, while the northern and eastern parts of the region often lie inside the southern boundary of the advancing pack and the southward drifting ice tongue that is seen off the Flemish Cap.

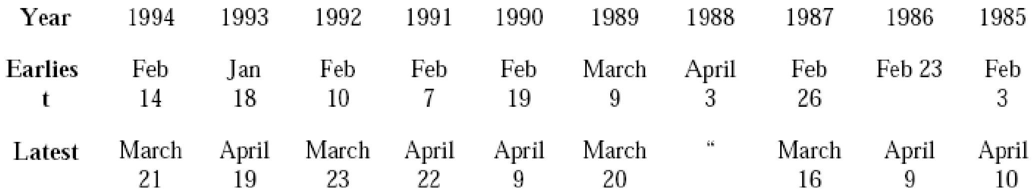
Table 2.3 Number of weeks of pack ice occurrence (in any concentration) by year. Courtesy to B. Wright & Associates Ltd (1998)



Year	Hibernia	Terra Nova	Whiterose	South Tempest	West Bonne Bay	East Rankin	SE Mobil block
1994	4.0	1.0	3.0	3.0	4.0	1.0	5.0
1993	1.0	1.0	5.0	11.0	6.0	0.0	5.0
1992	0.5	0.0	0.0	5.0	2.0	0.0	1.5
1991	1.0	0.5	1.5	4.0	5.5	0.5	1.5
1990	6.0	3.0	6.5	6.5	6.5	3.0	6.0
1989	0.0	0.0	0.0	2.0	0.5	0.0	0.5
1988	0.0	0.0	0.3	0.3	0.0	0.0	0.3
1987	1.4	0.4	1.7	1.4	2.4	0.3	1.1
1986	1.0	0.0	0.5	4.0	2.0	0.0	2.0
1985	6.0	2.5	5.5	8.5	8.0	1.5	6.5
Totals	20.9	8.4	24.0	45.7	36.9	6.3	29.4

If oil companies want to draw up their drilling schedule, another important data for them is the exact time window distribution (when the operations can be started and when they have to suspend the operation for the next time window), so table 2.4, which was proposed by B. Wright & Associates Ltd (1998), is favourable to the oil operators.

Table 2.4 Earliest and latest pack ice occurrences at any one of the seven reference locations.



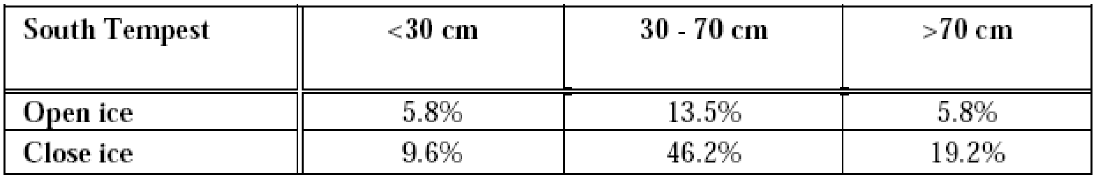
Year	1994	1993	1992	1991	1990	1989	1988	1987	1986	1985
Earliest	Feb 14	Jan 18	Feb 10	Feb 7	Feb 19	March 9	April 3	Feb 26	Feb 23	Feb 3
Latest	March 21	April 19	March 23	April 22	April 9	March 20	“	March 16	April 9	April 10

Courtesy to B. Wright & Associates Ltd (1998)

Table 2.5 is more valuable for reference, which shows ice occurrence frequencies combined with ice thickness and ice concentration. Ice thickness levels have been reduced to three ranges that are considered most relevant for moored vessel station keeping operations. Concentrations have been combined to represent “open ice” (1-6/10ths concentration) and “close ice” (7-9/10ths concentration). From this table, it is not difficult to find that ice types with thickness of 30-70 cm range predominate throughout the Grand Banks region, either in close or open concentrations. Except at the Terra Nova and East Rankin locations, close ice concentrations are usually more frequent, which experience the least pack ice presence. The four locations most often covered by pack ice are divided from the remaining three, with respect to the occurrence of thicker ice (exceeding 70 cm) in close concentrations. Between 13 % and 20 % of the close pack ice incursions that occur at these four locations are made up of at least one-tenth coverage first year ice (70-120 cm) or greater. An additional distinction between the upper four and lower three locations (in terms of severity) lies in the frequency of close and open pack.

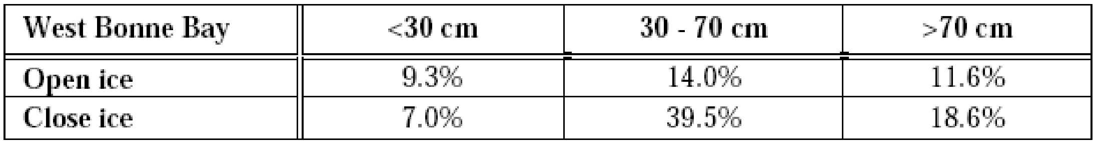
Table 2.5 Occurrence frequencies for combined ice thickness and ice concentration categories

Courtesy to B. Wright & Associates Ltd (1998)



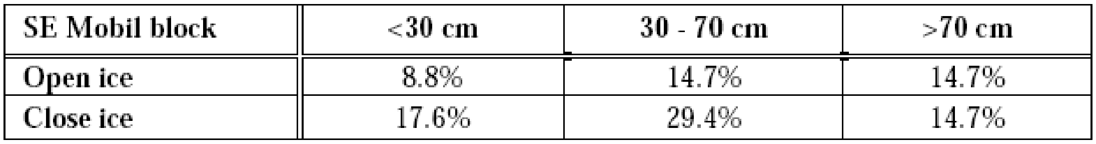
South Tempest	<30 cm	30 - 70 cm	>70 cm
Open ice	5.8%	13.5%	5.8%
Close ice	9.6%	46.2%	19.2%

52 occurrences, 1985-1994.



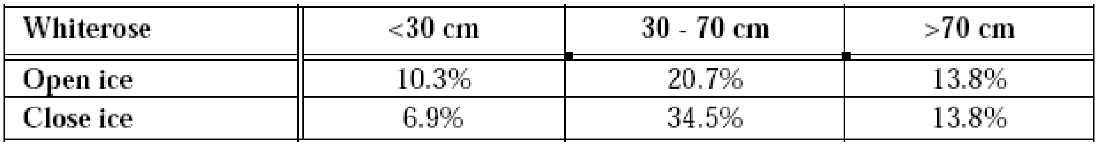
West Bonne Bay	<30 cm	30 - 70 cm	>70 cm
Open ice	9.3%	14.0%	11.6%
Close ice	7.0%	39.5%	18.6%

43 occurrences, 1985-1994.



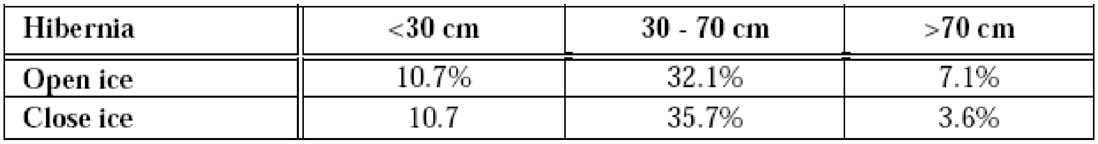
SE Mobil block	<30 cm	30 - 70 cm	>70 cm
Open ice	8.8%	14.7%	14.7%
Close ice	17.6%	29.4%	14.7%

34 occurrences, 1985-1994.



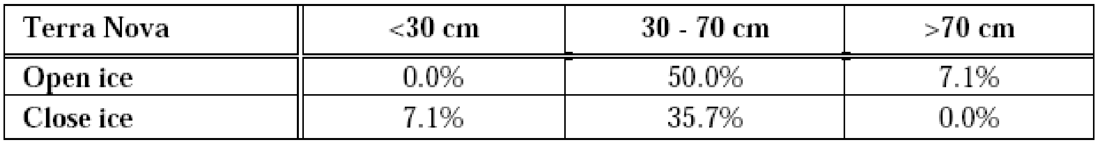
Whiterose	<30 cm	30 - 70 cm	>70 cm
Open ice	10.3%	20.7%	13.8%
Close ice	6.9%	34.5%	13.8%

29 occurrences, 1985-1994.



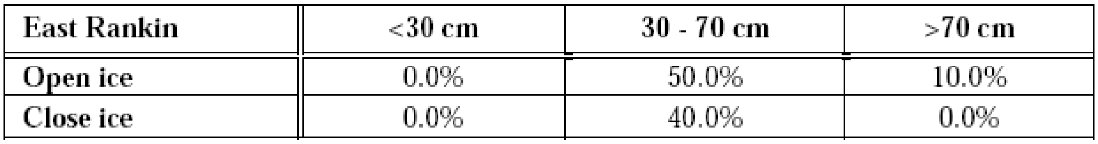
Hibernia	<30 cm	30 - 70 cm	>70 cm
Open ice	10.7%	32.1%	7.1%
Close ice	10.7	35.7%	3.6%

28 occurrences, 1985-1994.



Terra Nova	<30 cm	30 - 70 cm	>70 cm
Open ice	0.0%	50.0%	7.1%
Close ice	7.1%	35.7%	0.0%

14 occurrences, 1985-1994.



East Rankin	<30 cm	30 - 70 cm	>70 cm
Open ice	0.0%	50.0%	10.0%
Close ice	0.0%	40.0%	0.0%

10 occurrences, 1985-1994.

Another risk caused by ice cover is about oil spill, the potencial disaster of which comes from 2 aspects: firstly, oil spill will be more difficult to be detected in the sea sueface covered by the sea ice sheet, especially for the sea covered with large sea ice sheet, sometimes when the oil was found in the ice free water, the oil spill already in severe codition or catastrophe; secondly, the operation for clearing spilled oil is tougher in the sea water surface with ice cover, in some cases it is impossible. So enough attention should be laid on the oil spill prevention in the Arctic region, which will be discussed further in the chapter 4.

2.2.2 Icebergs

An iceberg is a large piece of ice that has broken off a glacier or an ice shelf and is floating freely in open water (Wikipedia, 2013). The possible results for icebergs could be: frozen into pack ice (one form of sea ice); as it drifts into shallower waters, it may come into contact with the seabed, a process referred to as seabed gouging by ice, which is a disaster for any subsea pipeline located on the sea bed.

Figure 2.20 An iceberg in Greenland off Cape York
Courtesy to http://en.wikipedia.org/wiki/Iceberg

Features of icebergs on the Grand Banks

Noble Denton Canada Ltd. & B. Wright & Associates Ltd (2005) have reviewed features of icebergs on the Grand Banks region, which is a representative area for iceberg activities and current Arctic oil and gas operations. Icebergs and small glacial ice masses can be contained within the East Coast's moving pack ice cover of the Grand Banks, besides in the open sea water, which have a dominant influence on the design of Grand Banks development systems. Potential risks from icebergs result from: large icebergs are of most importance in terms of the global forces that they may exert on structures, and the potential for deep iceberg keels to damage subsea facilities. Bottom founded structures must be designed to withstand iceberg impact forces, because they cannot move off the locations to avoid collision with the icebergs, while most floating structures can reduce the risks through this way. Smaller glacial ice masses should not be neglected for both fixed and floating systems, due to the high local impact loads that they can impose. The icebergs and small ice masses could pose threats to the vessels navigating or station keeping in the area, since interactions with them may result in structural damage.

DNV has done a lot of research about icebergs in the Arctic and rich outputs have been gained. Icebergs are frozen fresh water, which are the results of glaciers that calve, i.e. when smaller or larger pieces of glacial ice breaks off from their “mother” glacier. Due to the combination of heat, wind force and current force and the influence of other icebergs, they could come in many shapes and sizes. Fig. 2.21 shows examples of different shapes and size definitions (DNV, 2008).

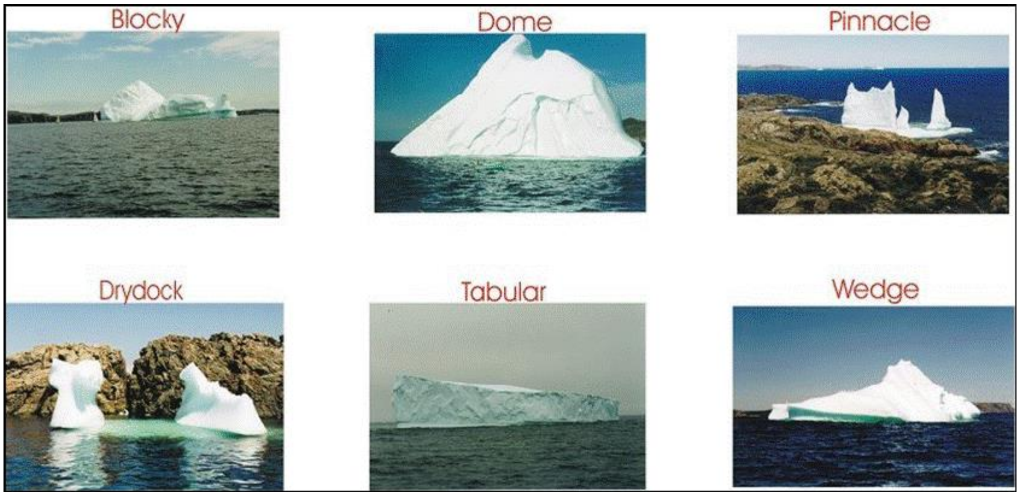


Figure 2.21 different shapes of icebergs
Courtesy to DNV, 2008

The icebergs might pose much the same threats as sea ice, as mentioned before, including: extreme local and global loads on offshore facilities; scratching of the sea bed; complication and hampering of operations and, although less so than sea ice, making the rescue, evacuation and oil spill response more difficult, proved by the research results that the response actions for the oil spill in the regions with sea ice or icebergs are tougher, because the vessels performing the response tasks are taking the risks of collision with the icebergs.

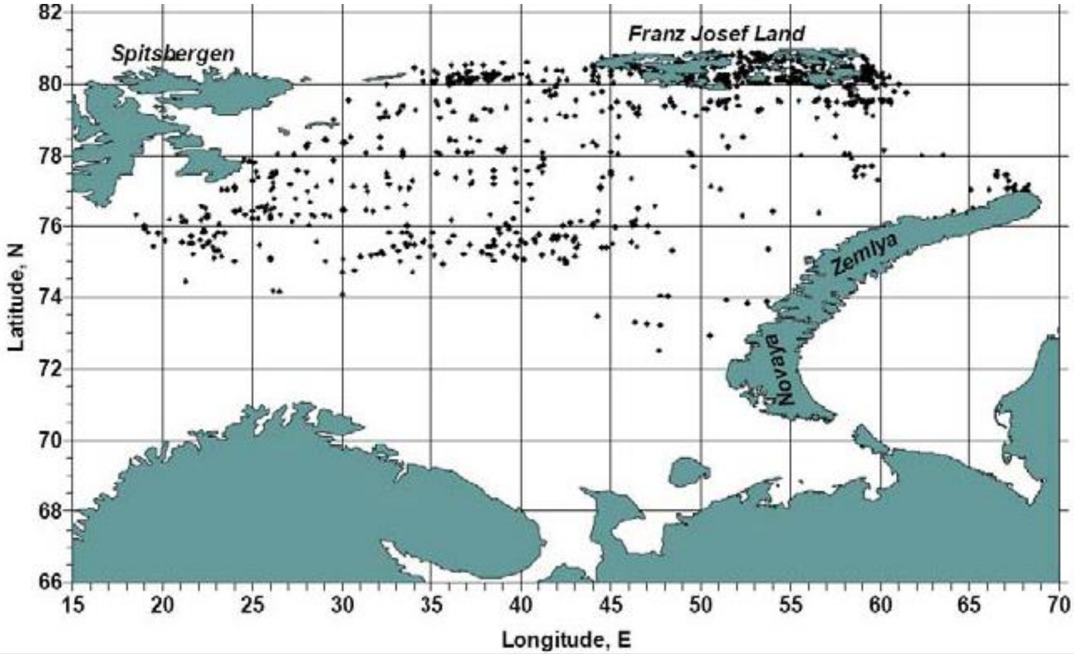


Figure 2.22 Location of icebergs observed in April 1928-2005 in Barents Sea
Courtesy to Arctic and Antarctic Research Institute, St. Petersburg, Russia

Despite that many icebergs have been observed in the Barents Sea, it is necessary to collect more data about icebergs, because quite different results are obtained as per different resources, indicating that the data are insufficiently specified (Internal DNV study). Many uncertainties lie in the Russian data, in particular the uncertainty about icebergs that were not observed. Only too few reliable observations of iceberg masses (roughly 400) are available to give a good probability distribution and the Norwegian data archives are biased towards medium and large icebergs, so smaller iceberg data needs to be supplemented. Far from that, longer records of ice drift speeds are necessary to make a precise estimation.

Eik (2009) has reported that the projects on the Grand Banks, named Hibernia, Terra, Nova, White Rose and others, have suffered iceberg threats in open sea water for 3 years in every 4 years, and have suffered icebergs in pack ice for 1year in every 6 years. He also reported some successful cases for iceberg towing: icebergs more than 5 million tons have been successfully towed; the iceberg shapes only influence the towing to low extent.
In Northern Barents Sea, the result is different: an iceberg of 200,000 tons surrounded by 10/10 slightly deformed 0.5m thick ice has been attempted towed; single line tow approach has been attempted; one towing failed - the towing vessel became unsteerable during tow and headed into sea ice rather than the nearby open sea as planned; another failure case - towing line broken because of uneven load in the towline and damage caused by the sharp parts of the iceberg.

Iceberg data collection

One of the main challenges for operations in the Arctic is the insufficient iceberg data (DNV, 2008). Even if iceberg data has been collected by the researchers and oil operators in the last 3 decades, it is still not enough for establishment of an efficient iceberg database. The global weather changes were speeded up in the recent years, which decreases the reference meaning of the current iceberg data base. The global warming does supply longer iceberg-free seasons for oil operations, at the same time, Extreme weather occurrences are more frequent than 50 years before. It can be imagined if the platforms encounter with a severe iceberg condition much larger than they are designed to withstand, the damage could be fatal, and if oil spill or oil blowout happens, this will be a catastrophe to the vulnerable Arctic biological system. Because of the iceberg cover, the recovery job will not be as efficient as in the other regions without iceberg cover. So a precise and reliable iceberg database will be of the key precondition for iceberg management.

2.3 Extreme weather conditions (low polar pressure, wind and wave)

Polar lows

Besides the photos about the white view due to covered by the ice and snow, another condition in most people’s mind about the Arctic is related to the heavy snowfall, strong winds, high waves and poor visibility, all these factors might hamper offshore operations such as navigation of vessel, loading and offloading of material, flight of helicopter and some other routine operations. In fact, all the physical conditions mentioned above are mostly caused by the Polar Lows, or in other words, the Polar Lows could make the conditions severe and more challengeable. The Polar Lows has been discussed in the chapter of introduction, but it would be discussed further due to its disaster results when combined with other extreme weather conditions, and it is one of the most distinctive features of the Arctic differentiating with other regions.

Gudmestad, O. T. and Karunakaran, D. (2008) have stated that Polar Lows are small, rather intense low pressure systems in the Arctic. Essentially they are rare special cases of strong troughs, which could limit offshore operation to some extent. DNV (2008) proposed that Polar Lows are examples of small scale features because common low pressure systems with the diameter are of thousand kilometers or more, much bigger than the Polar Lows with the diameter of only a few hundreds kilometers. When an air stream northward flows over the warm sea surface, Polar Lows might be induced. That is why the Polar Lows occurs more frequently in the north Barents Sea than in the south. Figure 2.23 shows one typical photo taken by a satellite over the north of Scandinavia.

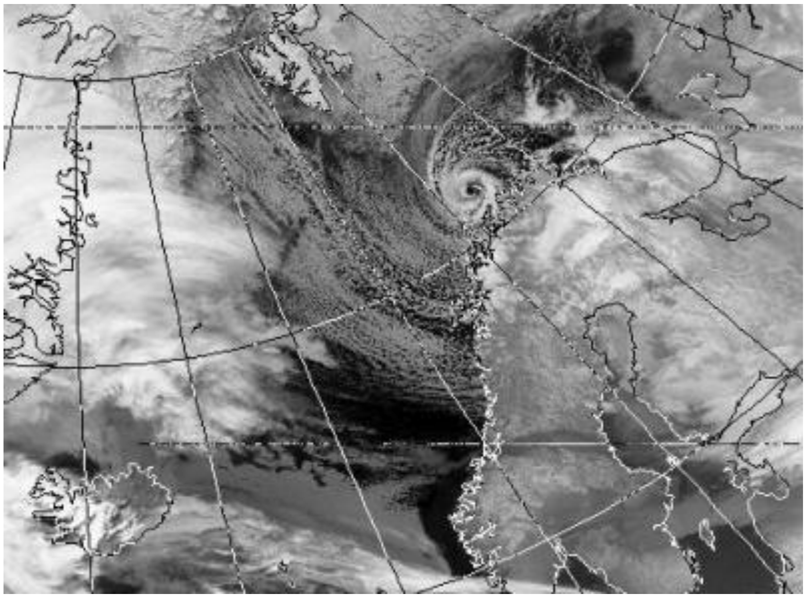


Figure 2.23 Satellite picture of a polar low over the north of Scandinavia (Copyright: University of Dundee).

Ref. Helmholtz-

Zentrum Geesthacht, Centre for Materials and Coastal Research

For oil and gas operations in the Arctic, Polar Lows during the period from September to the early summer of the second year have been concerned because they would influence normal offshore operations to high degree, which is risky and negative in economics for a rig with the day rate of several millions US dollars.

The best solution for the Polar Lows and other extreme weather is to predict them precisely, which is another challenge, because not enough data are available in the far north part of the Arctic, this condition is same for the reliable models. Figure 2.24 shows the example of stations that report into the global observing system for weather forecasts in the North Sea and the Barents Sea. So lots of work about data collection in the Barents Sea are still necessary, including establishment of more weather observation stations.

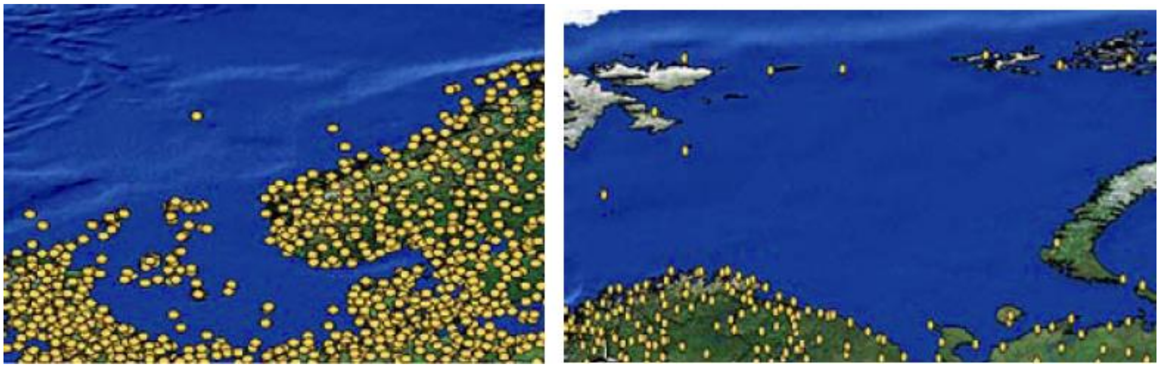


Figure 2.24 Example of stations that report into the global observing system for weather forecasts. Left: North Sea; right: Barents Sea.
Courtesy to US National Climatic Data Center

Hamilton, 2004 and Kristiansen et al., (2011) have concluded the main characteristics of the Polar Lows:

- It is usually formed in cold air outbreaks winter time;
- normally developed rapidly;
- in most cases in the forms of gale or storm force winds, seldom hurricane;
- heavy snow showers, icing, changing wind direction from time to time;
- they might last for 6 hours to 1-2 days
- their diameters are in the scopes from 100 km to 500 km
- Might be more frequent due to global change

The main challenge for the offshore operation in the Arctic is the combination of the Polar Lows with other tough physical environmental factors such as high waves and strong winds, because the former could make the latter factors worse. Due to its small scales, the Polar Lows can be generated without any indicators and change frequently, but the destroy results they would make to the local area could be destructive. Besides, they are not easy to be forecasted. To avoid this effect, Polar Lows' power must be considered when the offshore facilities are to be designed for operation in the Arctic, and sufficient safety factors need to be put in the design principles. When the decision makers trade off on the design principles, over design is preferred to risk from accidents due to offshore facilities' insufficient capability to withstand the complicated destroy from the Polar Lows.

Precise forecasting has been researched by lots of oil companies and institutes, two main jobs have been concentrated by them: data collection and prediction model optimization. The first job requires sound cooperation of different countries around the Arctic, only after they share their data selflessly with other partners, could the data base be enriched and more reliable. For the second job, there is no other choices except the prediction models would be optimized through repeated contrasts between the forecasting and actual condition, and then improve the models.

DNV (2008) has reported some successful cases for forecasting of the Polar Lows by the use of prediction model from the Norwegian Meteorological Institute. Figure 2.25 illustrates the forecasting of a Polar Low in the Barents Sea.

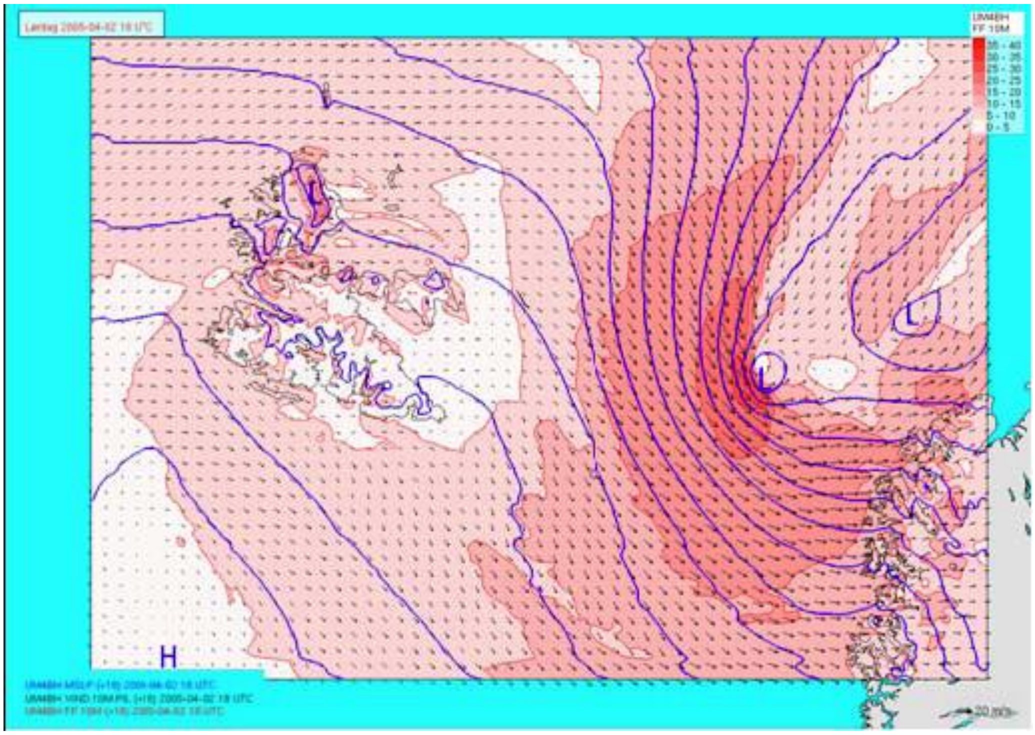


Fig 2.25 Forecast of a polar low in the Barents Sea with the Norwegian Meteorological Institute's mesoscale weather prediction model (horizontal resolution 4 km). Courtesy to the Norwegian Meteorological Institute

Wind and Waves

Sea state and tidal currents are representative features of physical environment in the Arctic for determining design criterion. In NORSOK N-003, DNV (2008) has compared 100 years' data of sea state and tidal currents in the North Sea. Figure 2.26 demonstrates that even in the same sea, there are significant varieties in both of the conditions. The north part of the Arctic is similar to the Barents Sea.

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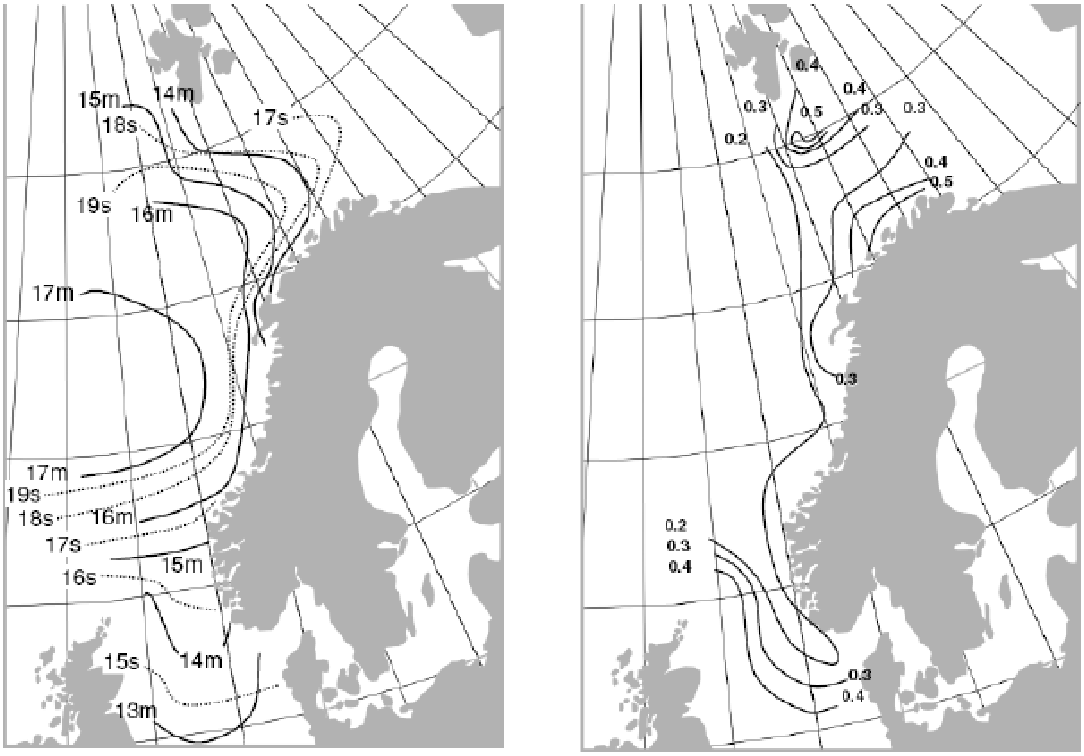


Fig. 2.26 100 years sea state (left) and tidal current (right) on the Norwegian shelf (NORSOK N-003)
Courtesy to DNV (2008)

There are quite a few shortcomings of Meteorological data in the Barents Sea, which has been concluded by DNV (2008)

- Only short records are available, rare cases for 5 years or more;
- No sound spatial coverage;
- Most of the measured temperature data from open sea are not reliable;
- Among the poor records, most records for the open ocean (buoy) are data for the late 1980'ies or early 1990'ies, poor coverage the last15 years, which we are interested in.

Based on the records available, DNV (2008) has depicted one location distribution for the rough positions of wind and waves records on the Norwegian shelf that are 5 years and longer, and regular Meteorological stations, as shown in Figure 2.27.

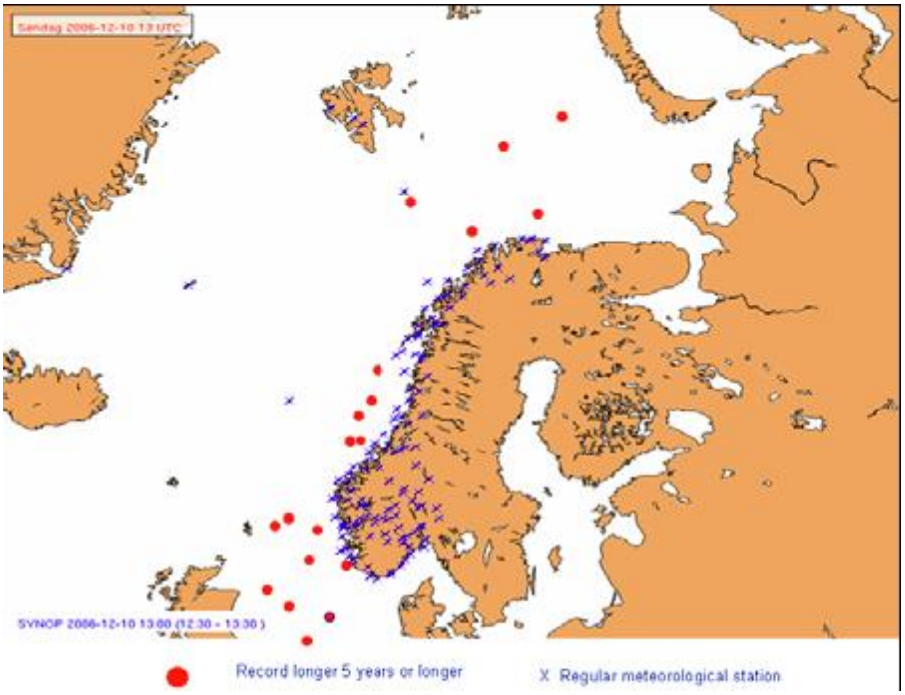


Fig. 2.27 Rough positions of wind and waves records on the Norwegian shelf that are 5 years and longer.
Courtesy to DNV (2008)

Wilcken (2012) has cited a typical example about offshore operation influenced by the Polar Lows in the Barents Sea. One pipeline was planned to be laid in Snøhvit oilfield from October to November of 2004 by the reel lay vessel CSO Apache. This job was designed to two trips: the estimated offshore work time are 12 days for the first trip and 18 days for the second trip respectively. As per the capability of CSO Apache, the acceptable operational wave height was 2.5m to 3.0m and at least 2-3 days of acceptable weather was required for the start of installation work. Final result is: the first trip took 12 days and then take 30 days for waiting for the acceptable weather, but after 30 days of waiting, the work had to be abandoned and could not be completed due to the bad weather; the remaining work has to be postponed to the next year, which is caused by the Polar lows in November 2004.

2.4 Low temperatures

Besides icing, sea ice and snow, the other factor relevant with them and which is also a distinctive factor is the extreme low temperature. Normally the temperature in the winter in the Arctic could be as low as -40℃, and the lowest temperature in the Arctic is -68℃ human has recorded in that region (Wikipedia). The potential hazards caused by extreme low temperatures could impose threats on many aspects such as personnel safety, equipment condition, operational reliability and so on, and some of main influence have been listed:

- Low temperature could hurt the personnel physically;
- Under low temperature, human reaction and judgment might be slow, unreasonable and rigid;
- It is difficult to keep operations flow; such as mud to secure the safe and continual operation;
- Due to the physical expansions when fluid is frozen, destruction is possible for pipelines and equipment;
- Because of the discounted capability of the personnel and the equipment, the operational efficiency cannot reach its best extent;
- The low efficiency will induce higher costs for the oil company, which could be significant for a rig with daily rate of millions of USD;
- Escape and first-aid equipment, like escape routes, might lose their functions due to freezing;
- Slippery working area would hamper normal operations of the crew, decrease the working efficiency and increase the accident possibility;
- When exposed to the low temperature for quite a long time, people tend to make more mistakes and induce more accidents, one of the main causes is that they are prone to take a short cut by disobeying working procedures to fleet from the cold as soon as possible;
- Icing caused by low temperature would increase both dimensions and weights of the offshore facilities, resulting in load increase and stability decreasing, particularly for floating structures;
- Another hazard comes from increased probability of falling objects (accumulated snow block, ice lumps etc.), threatening personnel and equipment;
- The functions of other key equipment, e.g., detecting equipment and communication systems, such as radars and satellite signal receivers might be discounted due to icing and extreme low temperature.

Regarding the life rafts shown in Figure 2.28, the readers can imagine whether they can be released as expected and even if it is managed to release them into the sea, whether they would act normally?

Figure 2.28 Icing condition of life rafts in the Arctic
Courtesy to DNV (2008)

Another example of a severe icing condition of key equipment, an anchor winch, is illustrated in Figure 2.29. How can the anchor be dropped as desired in case anchor action is necessary for ensuring the security of the vessel? All these factors must be taken into consideration before the operations in the Arctic are carried out. The properties of some material on the offshore facilities might be affected by the cold and then result in loss of functions.

Figure 2.29 Severe icing of anchor winch in the Arctic
Courtesy to DNV (2008)

Besides the negative effects caused by the low temperature to the equipment, the influence to the personnel seems more dangerous, because the human beings are more fragile to withstand the extreme low temperature than the equipment. Gudmestad, (2012), Dahl-Hansen and O’Connor (2008) have concluded concerns about personnel safety when working in the cold.

The term ‘cold’ is relevant to 4 aspects in fact:

- Low temperature; it is the most essential feature;
- Humidity; the moist condition would bring more chill feeling than the dry cases;
- Wind; wind can cause a much colder feeling, which is called the wind chill effect;
- Exposure/duration time; the longer one is exposed to the low temperature, the colder feeling he will get.

The direct hurts from the cold are different types of frostbites, which occur for skin exposed to the cold air or organs without proper clothing for protection, Figure 2.30 shows some typical frostbite in the Arctic region.

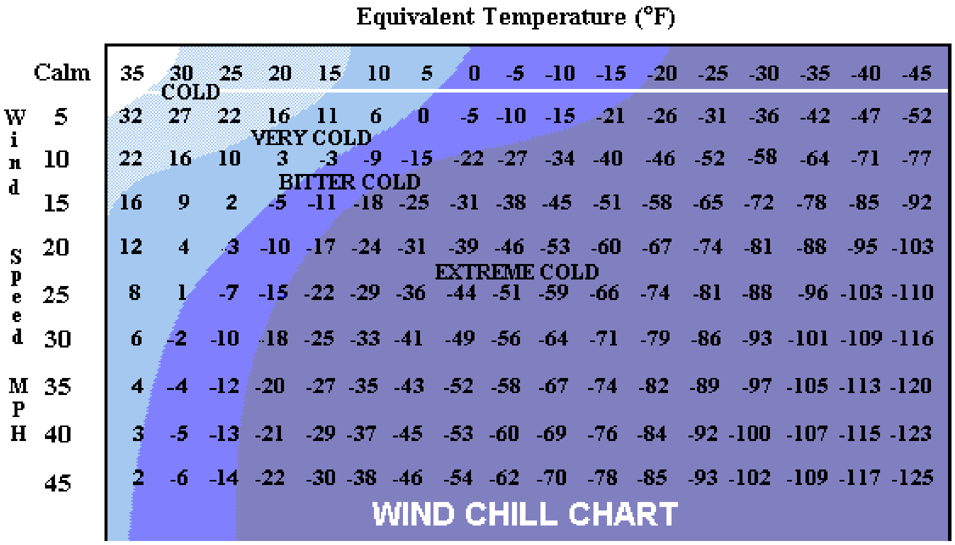
Figure 2.30 Typical frostbites in the Arctic
Courtesy to Lloyd, E, L, (1994)

Except direct hurt such as frostbite, there are quite a few indirect injury cases related to the cold condition: in the Arctic region, considerable accidents related to collisions and falling down caused by slippery operation floors have been reported, most of which are caused by the freezing surface due to cold atmosphere. Figure 2.31 illustrates one bone broken accident related to these reasons.

Figure 2.31 X-ray photo of bone broken accident
Courtesy to Dahl-Hansen and O'Connor (2008)

In the Arctic, one factor which makes the original cold environment much colder is the existence of wind, which is called the wind chill effect. National Weather Service Weather Forecast Office (2001) has defined this effect as 'the rate of heat loss on the human body resulting from the combined effect of low temperature and wind. As winds increase, heat is carried away from the body at a faster rate, driving down both the skin temperature and eventually the internal body temperature'. Fatal threat can be caused if exposed to low wind chill for a long time for human beings and other animate objects; while for the inanimate objects, such as vehicles, wind chill could cool their temperature to the actual air temperature in shorter time than in the condition without wind chill effect, but National Weather Service Weather Forecast Office (2001) believes that this effect would not cool the temperature of animated objects lower than the actual temperature.

Before the Second World War, Siple and Passel created the first wind chill formula and tables based on their working experience in the Antarctic, which were published by the National Weather Service until the 1970s. The philosophy of this theory was drawn from the cooling rate of a small plastic bottle as its contents froze while suspended in the wind on the expedition hut roof, at the same level with the anemometer. This Wind chill Index (Table 2.6) did supply a pretty good indication of the severity of the weather, and this table was considered as the old wind chill chart (National Weather Service Weather Forecast Office, 2011).

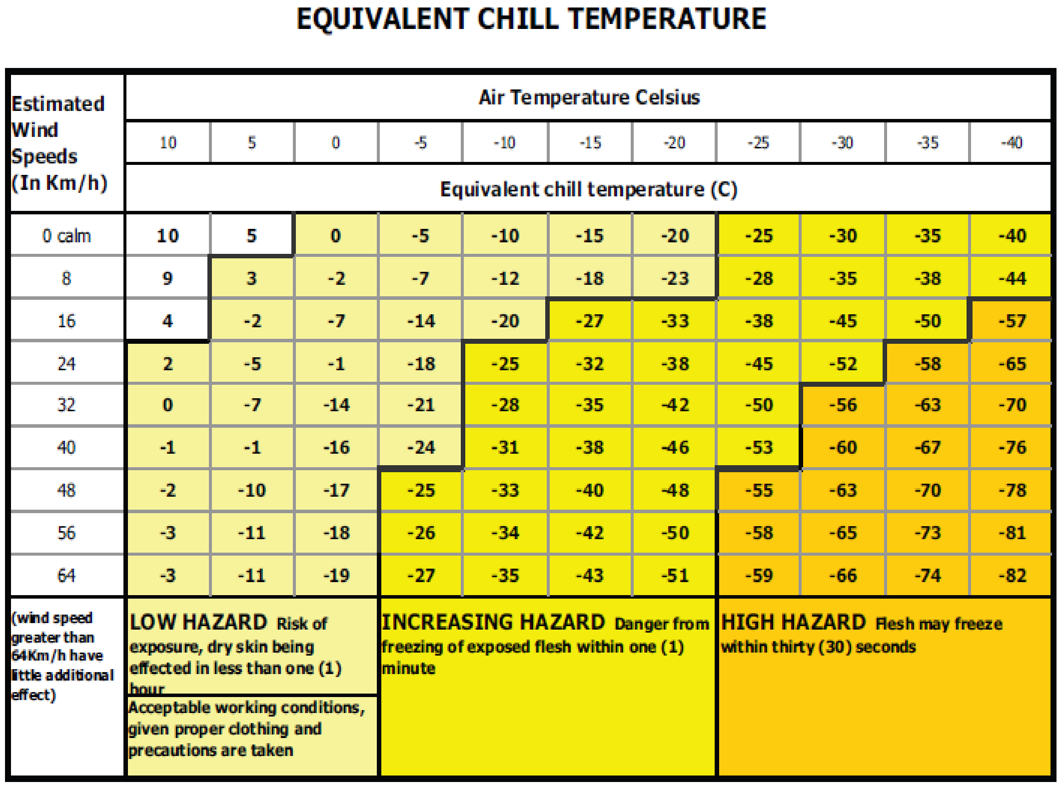


Equivalent Temperature (°F)

Calm	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
5	32	27	22	16	11	6	0	-5	-10	-15	-21	-26	-31	-36	-42	-47	-52
10	22	16	10	3	-3	-9	-15	-22	-27	-34	-40	-46	-52	-58	-64	-71	-77
15	16	9	2	-5	-11	-18	-25	-31	-38	-45	-51	-58	-65	-72	-78	-85	-92
20	12	4	-3	-10	-17	-24	-31	-39	-46	-53	-60	-67	-74	-81	-88	-95	-103
25	8	1	-7	-15	-22	-29	-36	-44	-51	-59	-66	-74	-81	-88	-96	-103	-110
30	6	-2	-10	-18	-25	-33	-41	-49	-56	-64	-71	-79	-86	-93	-101	-109	-116
35	4	-4	-12	-20	-27	-35	-43	-52	-58	-67	-74	-82	-89	-97	-105	-113	-120
40	3	-5	-13	-21	-29	-37	-45	-53	-60	-69	-76	-84	-92	-100	-107	-115	-123
45	2	-6	-14	-22	-30	-38	-46	-54	-62	-70	-78	-85	-93	-102	-109	-117	-125

Table 2.6 Old wind chill chart
Courtesy to NOAA (2001)

NOAA (2001) has proposed that in the 1960s, another term ‘wind chill equivalent temperature (WCET)’ has been reported, which is believed to be another name of wind chill, but the people who had made this change are still unknown. WCET was defined as the temperature at which the windchill index would be the same without wind (NOAA, 2001). Even this change shows the severity of the weather with the influence of the wind, it is still not accurate enough. Eagan found that people are rarely still and that even when it is calm, air movements exist, so he redefined that the absence of wind condition is when the air speed is lower than 1.8 meters per second (4.0 mph), which was about the lowest limit of the wind speed which a cup anemometer could measure. This optimization of the wind chart led to more realistic (warmer-sounding) values of equivalent temperature (NOAA, 2001). Table 2.7 shows the relationship between WCET and actual atmosphere temperature/wind speed.



EQUIVALENT CHILL TEMPERATURE

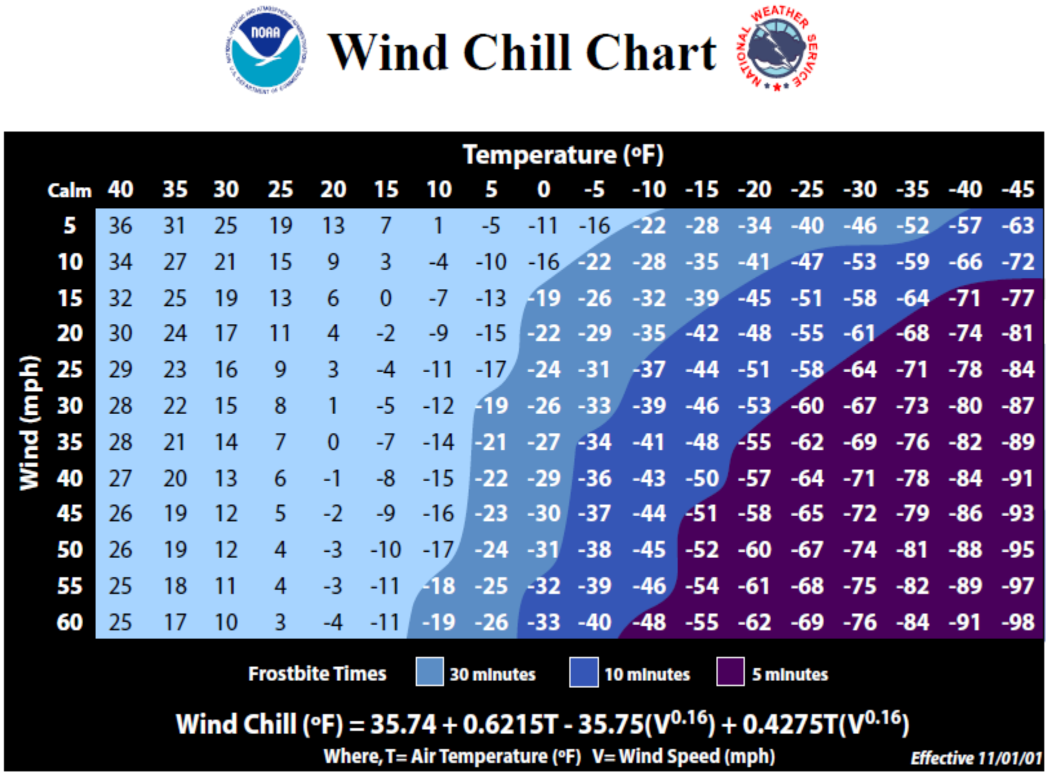
Estimated Wind Speeds (In Km/h)	Air Temperature Celsius										
	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40
	Equivalent chill temperature (C)										
0 calm	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40
8	9	3	-2	-7	-12	-18	-23	-28	-35	-38	-44
16	4	-2	-7	-14	-20	-27	-33	-38	-45	-50	-57
24	2	-5	-1	-18	-25	-32	-38	-45	-52	-58	-65
32	0	-7	-14	-21	-28	-35	-42	-50	-56	-63	-70
40	-1	-1	-16	-24	-31	-38	-46	-53	-60	-67	-76
48	-2	-10	-17	-25	-33	-40	-48	-55	-63	-70	-78
56	-3	-11	-18	-26	-34	-42	-50	-58	-65	-73	-81
64	-3	-11	-19	-27	-35	-43	-51	-59	-66	-74	-82
(wind speed greater than 64Km/h have little additional effect)	**LOW HAZARD** Risk of exposure, dry skin being effected in less than one (1) hour Acceptable working conditions, given proper clothing and precautions are taken			**INCREASING HAZARD** Danger from freezing of exposed flesh within one (1) minute				**HIGH HAZARD** Flesh may freeze within thirty (30) seconds			

Table 2.7 Equivalent Chill Temperature
Courtesy to www.docstoc.com

National Weather Centre has published the updated Wind chill Temperature (WCT) index test conditions (Table 2.8):

- Wind speed was calculated at five feet height (typical height of an adult human face) based on readings from the national standard height of 33 feet (typical height of an anemometer);
- All the calculations are based on human face models;
- Modern heat transfer theory was employed (heat loss from the body to its surroundings, during cold and breezy/windy days)
- The calm wind threshold has been reduced to 3 mph comparing with the old wind chill chart;
- Consistent standard has been referred for skin tissue resistance calculation；
- No influence from the sun has been considered (i.e., clear night sky is the big test back grounding). (National Weather Centre, 2001)

Diagram 2.1 illustrates the wind chill temperature comparison of new wind chill chart and the old one.



Wind Chill Chart

Wind (mph)	Temperature (°F)																	
Calm	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
5	36	31	25	19	13	7	1	-5	-11	-16	-22	-28	-34	-40	-46	-52	-57	-63
10	34	27	21	15	9	3	-4	-10	-16	-22	-28	-35	-41	-47	-53	-59	-66	-72
15	32	25	19	13	6	0	-7	-13	-19	-26	-32	-39	-45	-51	-58	-64	-71	-77
20	30	24	17	11	4	-2	-9	-15	-22	-29	-35	-42	-48	-55	-61	-68	-74	-81
25	29	23	16	9	3	-4	-11	-17	-24	-31	-37	-44	-51	-58	-64	-71	-78	-84
30	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87
35	28	21	14	7	0	-7	-14	-21	-27	-34	-41	-48	-55	-62	-69	-76	-82	-89
40	27	20	13	6	-1	-8	-15	-22	-29	-36	-43	-50	-57	-64	-71	-78	-84	-91
45	26	19	12	5	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79	-86	-93
50	26	19	12	4	-3	-10	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81	-88	-95
55	25	18	11	4	-3	-11	-18	-25	-32	-39	-46	-54	-61	-68	-75	-82	-89	-97
60	25	17	10	3	-4	-11	-19	-26	-33	-40	-48	-55	-62	-69	-76	-84	-91	-98

Frostbite Times ▨ 30 minutes ▨ 10 minutes ▨ 5 minutes

$$\text{Wind Chill } (^\circ F) = 35.74 + 0.6215T - 35.75(V^{0.16}) + 0.4275T(V^{0.16})$$

Where, T= Air Temperature (°F) V= Wind Speed (mph)

Effective 11/01/01

Table 2.8 New wind chill chart
Courtesy to NOAA (2001)

Diagram 2.1 illustrates the wind chill temperature comparison of new wind chill chart and the old one.

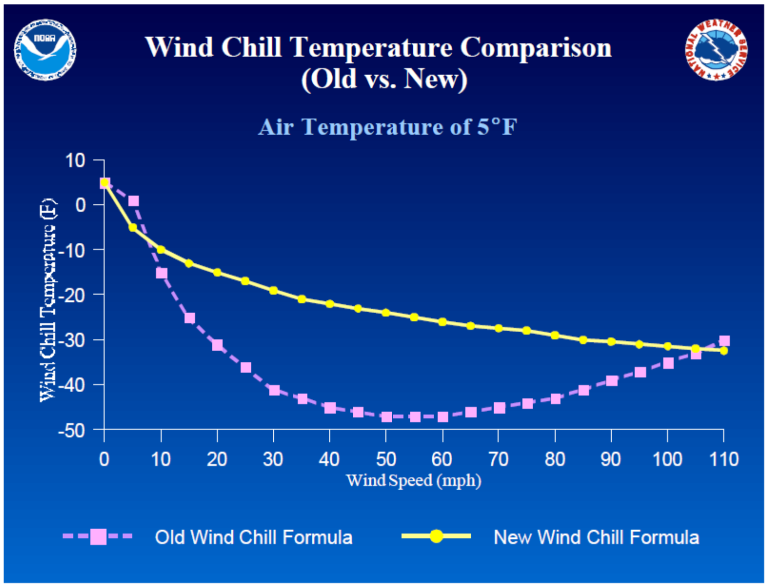


Diagram 2.1 New vs. Old wind chill temperature
Courtesy to NOAA (2001)

From this diagram, it is obvious that when the wind speed is between 10 to 105 mph, the wind chill temperature or equivalent temperature in the new chart is higher than that in the old chart, which is more close to the reality, so it is more meaningful for the Arctic operation.

The main challenge of the wind chill to personnel is that the heat loss of operators would limit the working time in exposed areas and the outdoor time, which reduces operational efficiency to some degree. Furthermore, personnel might be more prone to catch physical hurt such as frost bite and other related injuries, to lose concentration on the safety/operation procedure they are supposed to follow, and to commit more errors of low levels.

DNV (2008) has reported low temperature related (cold allergy) diseases：

- Cold temperature would make the blood thick and reluctantly to move, resulting in peripheral vascular disease;
- The paralysis caused by the cold could induce damage to the peripheral nervous system, or in other words, peripheral neuropathy, which could be more offensive to the diabetics;
- Human being tends to employ more tobacco, alcohol or even drug in the cold condition;
- Except physical problems, the crew also suffer the psychological negative obsession if work in the cold, other factors in the Arctic such as working in prolonged periods of light (polar summer) or darkness (polar winter), in remote or isolated conditions, which are the typical features of the Arctic, could make the psychological problems worse;

Dahl-Hansen and O’Connor (2008) have stated some features related to hypothermia, one of the most common threats to personnel in the Arctic. Hypothesis is defined as the chilling of the body’s core temperature below 35 ℃ (95 ℉),

- Fatigue and mental confusion are normally the first feeling of the victims;
- The further development symptoms are uncontrollable shivering, slurred speech, poor coordination and poor judgement;
- When the body temperature keeps falling, shivering gradually disappears and the victim may behave irrational;
- The worst consequence of hypothermia could be fatal if the condition is totally out of control;

- Hypothermia is harmful because the victim could not realise that he already is in the dangerous edge;
- The best first-aid solution is to warm up the victims immediately by an external source.

Romsey Australia (2010) has classified different levels of hypothermia as follows:

- ‘Normal human temperature’ means 37.6°C rectal temperature or 37.0°C oral temperature
- At 35.0 ℃ one would get the maximum shivering
- Consciousness will become ambitious if hypothermia cannot be released;
- Clumsy actions

If the condition keeps changing worse, the more dangerous hypothermia could be as follows if temperature is lower than the specific levels:

- 33.0 ℃ Heat is kept losing unless effective protection;
- 30.0 ℃ Heart may stop working if irritated;
- 26.0 ℃ Victims seldom recover to their conscious;
- Pupil will not react to light and Breathing and heartbeat might stop
- 20.0 ℃ Heart standstill
- 16.0 ℃ is the lowest temperature of accidental hypothermia when a victim has the possibility to recover.

2.5 Weak logistic support due to remoteness of area

Logistics is one of the critical factors for continual and safe operation of oil and gas operations. But this support in the Arctic is currently much weaker than in the other regions. Figure 2.32 shows the main oil and gas development activities in the Arctic US and Canada; figure 2.33 shows the potential oil and gas resource in this region determined by BP (2012). Through the comparison of both of the figures, it is obvious that current oil and gas developments are only locate in the areas not far from the land. One of the driving reasons for most oil and gas resource staying undeveloped is no reliable logistics support there.

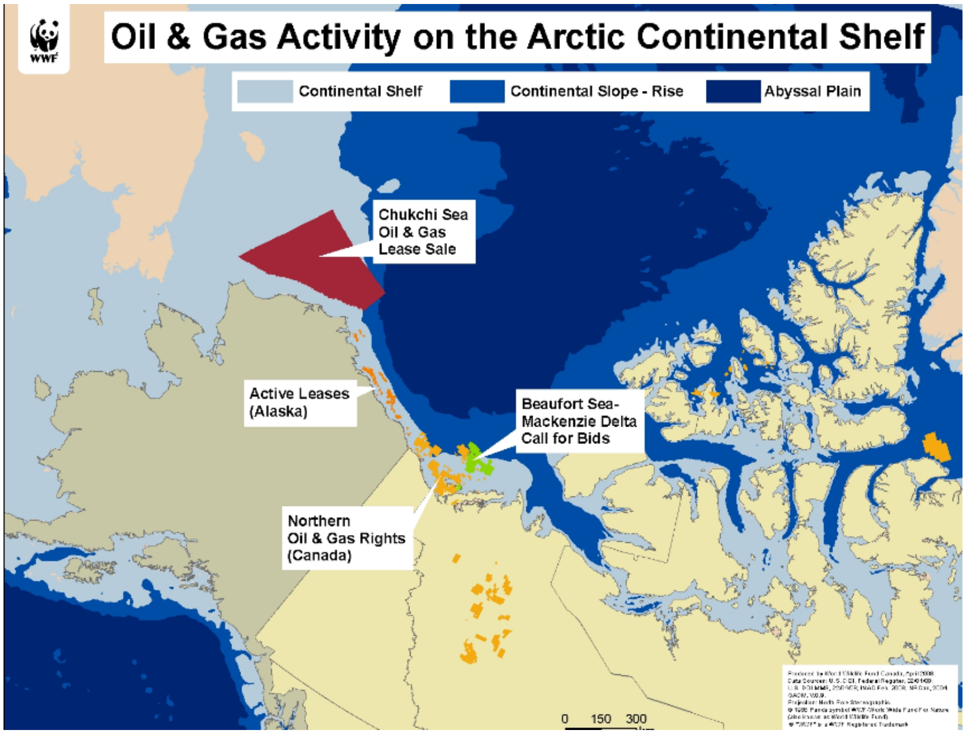


Figure 2.32 Current oil and gas activity in the Arctic
Courtesy to WWF (2012)

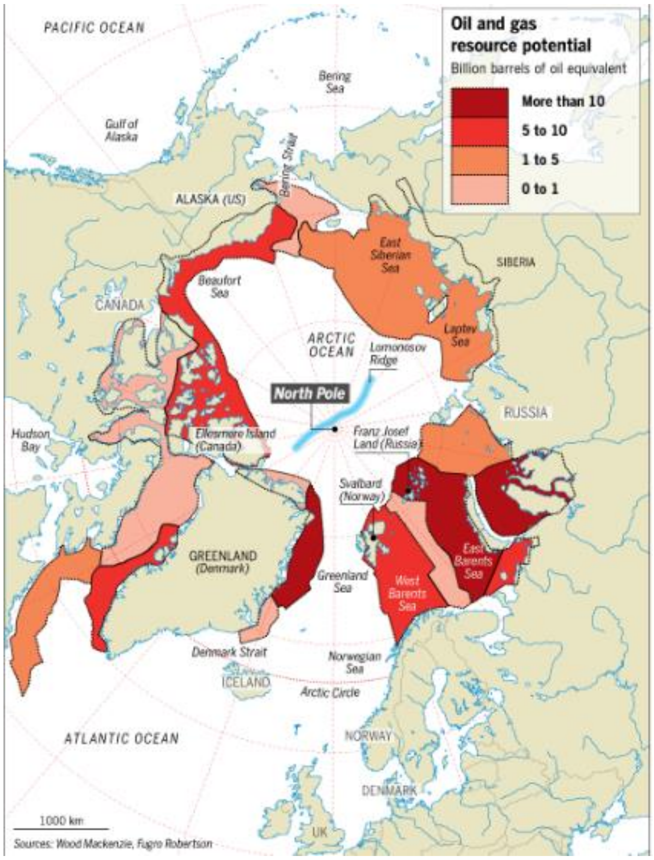


Figure 2.33 Potential oil and gas resource in the Arctic

Courtesy to BP (2012)

DNV (2008) has concluded that these are the reasons for this condition:

- Remoteness
- Most of those oil and gas resources are located far from the support bases, it is tough to fulfil the mission of supply;
- The construction of infrastructure lag behind development of oil and gas, which would delay response to accidents and emergency;
- Some potential oil and gas reservoirs are in the far north of the Arctic, poor communication hampers efficient communication and logistics

- Darkness: a long perpetual night in the winter imposes negative effects on the human psyche, resulting in low efficiency and reliability of the crew in logistics;
- Extreme weather: Polar Lows, strong winds, waves and currents threaten the main transportation for offshore oil operations-marine vessels and helicopter for emergency rescue;
- Ice cover and icebergs also restrict routes and availability of the vessels;
- Seismic activity and sand waves may destroy sea bed and disturb installation foundations, even if this phenomenon generally appears lower in the Barents Sea than in the North Sea, but exception may be the area around Spitsbergen. (DNV, 2008)

2.6 Permafrost

Figure 2.34 illustrates the permafrost distribution condition in the world, it is clear that almost all these special geological phenomenon are located in the Arctic region. During the ice age, glaciers covered large areas that now are marine environment. Permafrost, therefore, exists in pockets in the sea.

Main threat from the permafrost is that: it stays hard when the temperature is low, which could supply sound foundations for the subsea facilities and pipelines; but when the weather changes to warmer, it starts melting, so the foundation is not reliable anymore. Far from that, during oil and gas development, the permafrost formation has to be drilled through, and the surface casing has been bonded with the formation through cement, on the other hand, the permafrost could melt and freeze plenty of times due to the heat from the drilling fluid and other heat producing processes of drilling operations.

Barnes, R. J. (2011) has listed problems from permafrost on the land due to drilling: in summer, permafrost will thaw and the surface becomes soft and boggy without drainage, and the water accumulated will attract mosquitos and flies which would transport diseases, then the crew has to suffer a tough life.

Figure 2.34 Worldwide permafrost distribution
Courtesy to www.ribendili.baike.com. 2013

2.7 Vulnerable ecology environment

Actually the biggest challenge in the Arctic for the oil companies is the risk for the environment, because this region has had low temperature for a long time and there are rarely external visitors which would bring bacteria. The specific biological system in the Arctic is brittle and has almost no immunity to external staff, especially the bacteria-free zone below the ice cover. As shown in figure 2.35, it is not easy to establish this biological system and it would be more difficult to recovery if it has been destroyed, and it may even be impossible to recover forever.

Figure 2.35 Multiple Specifies of biological Arctic
Courtesy to DNV, 2008.

Except the vulnerable biological systems, the presence of ice brings new troubles: such as difficult to find and position an oil spill; some recovery measures for the oil spill are more difficult than in the other regions. Firstly, the ice cover could be a good shield for the spilled oil, i.e. when the oil is detected in the edge of ice cover, the original spill point could be far away from the detecting point. Secondly, the low temperature and the complex movements of the ice cause spilled oil to sink. Figure 2.36 illustrates how complicated the movement of the oil could be with the influence of a combination of wind, ice, current and low temperature.

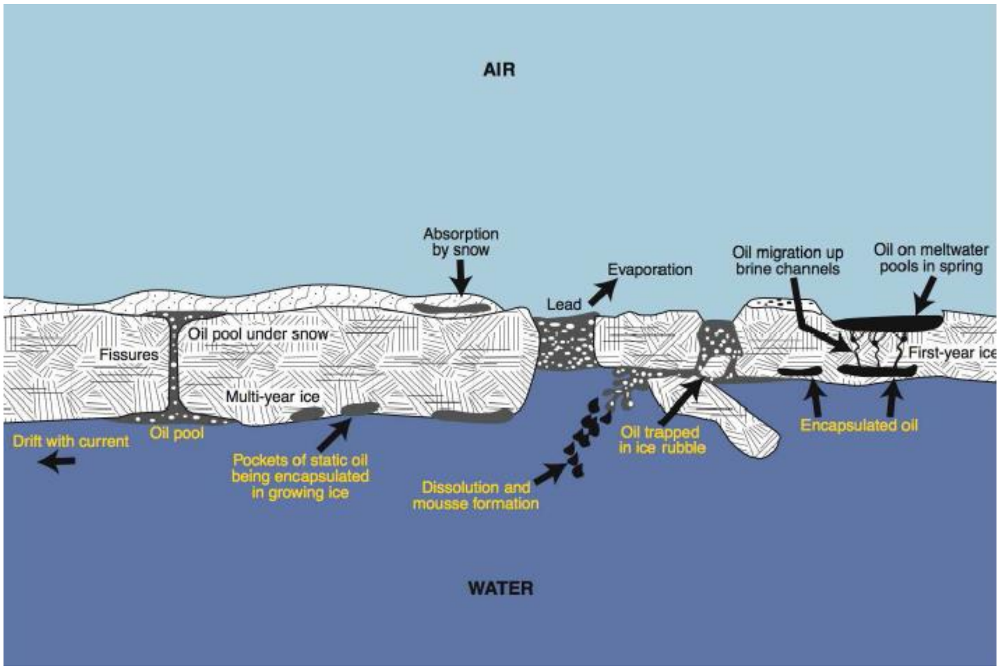


Figure 2.36 Typical oil drops movement in the Arctic
Derived from original sketch by A. Allen.

Because the Arctic biological system is so weak to withstand external pressure, the current regulations about environment from international standards and laws are awfully strict, chemical additives allowed to be used here are quite limited, or in other words, most of the chemical materials proven to be successful in other regions are prohibited to be utilized in the Arctic, so if one wants to take a market in this potential huge oil and gas area, one has to find substitutes for these forbidden materials, or one needs to make some innovations, to invent new systems, which can achieve the desired function target and be environmental friendly at the same time. This is a challengeable mission and the interested companies should start their research as soon as possible, to help them to catch the best opportunity.

3. Solutions

3.1 Vessel icing management (icing predictor, icing model, icing coating)

The basic solutions for vessel icing are: icing predictor, vessel geometry design promotion, icing coating and effective de-icing method.

3.1.1 Icing predictor

Since the negative influence of vessel icing is so severe, the best way to avoid is to predict it beforehand. Some vessel icing principles need to be introduced first.

Guest, P. (2001) described that Sea spray icing occurs when cold, wave-generated spray comes in contact with exposed surfaces and the air temperature is below freezing, which listed 2 main factors for vessel icing: environmental factor and vessel characteristics. Environmental factors means natural objective environmental elements, such as wind speed, atmosphere temperature, water temperature, wave and swell characteristics. Because some factors have potential relationship among them, so Guest, P. (2001) concluded there are 3 main environmental factors and minimum values of them for vessel icing:

- High Wind Speed - Usually above 18 knots or 9 m/s, but sometimes lower
- Low Air Temperature - Below freezing of sea water (-1.7℃)
- Low Water Temperature - Usually below 7 ℃

Overland (1990) has developed one algorithm which is accepted by most marine technicians to predict sea spray vessel icing nowadays. This algorithm was based primarily on reports from vessels that were 20 to 75 meters in length. The algorithm presented by Overland (1990) is:

$$\mathbf{PPR} = \frac{\mathbf{V_a(T_f - T_a)}}{\mathbf{1 + 0.3(T_w - T_f)}}$$

Meaning of the symbols in the formula:

PPR = Icing Predictor (m℃s-1)
Va = Wind Speed (m s-1)
Tf = Freezing point of seawater (usually -1.7 ℃ or -1.8 ℃)

Ta = Air Temperature (℃)
Tw = Sea Temperature (℃)

Table 3.1 shows the expected icing class and rates for 20 - 75 meter vessels that are steaming into the wind, which is widely used by the marine operators in high latitude:

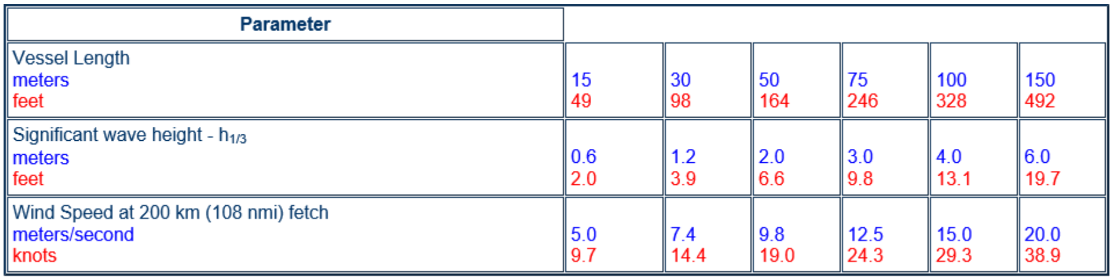
Table 3.1 Icing Class and Ice Accumulation Rate

PPR	<0	0-22.4	22.4-53.3	53.3-83.0	>83.0
Icing Class	None	Light	Moderate	Heavy	Extreme
Icing Rates (cm/hour) (inches/hour)	0	<0.7 <0.3	0.7-2.0 0.3-0.8	2.0-4.0 0.8-1.6	>4.0 >1.6

3.1.2 Vessel geometry design optimization

It is not uncommon that in the same environmental condition, the severity of icing of different vessels could vary. That is what Guest, P. (2001) has pointed out another important factor for vessel icing: vessel characteristics, which include: ship speed, ship heading, ship length, ship freeboard, ship handling and ship cold soaking. Generally speaking, the favorable factors for vessel icing are: less freeboard, travelling fast, heading against the wind and wave direction, more superstructures on the deck. Overland (1990) has calculated a threshold wave height, $h_{1/3}$, and associated wind speed, for a 200 km fetch at which enough sea spray reaches the decks and superstructures to cause severe icing, assuming air and water temperatures reach the threshold for vessel icing in as per environmental factors requirement, Table 3.2.

Table 3.2 Threshold Wind Speeds for Icing to Occur on Various Length Ships, Overland (1990)



Parameter						
Vessel Length meters feet	15 49	30 98	50 164	75 246	100 328	150 492
Significant wave height - $h_{1/3}$ meters feet	0.6 2.0	1.2 3.9	2.0 6.6	3.0 9.8	4.0 13.1	6.0 19.7
Wind Speed at 200 km (108 nmi) fetch meters/second knots	5.0 9.7	7.4 14.4	9.8 19.0	12.5 24.3	15.0 29.3	20.0 38.9

Note: data in this table can be used as a rough reference and calculation basis, the vessel icing condition could be more severe than it.

One drawing, figure 3.1, stated by Ryerson illustrates the development trend of the vessel icing as per its geometry and substructure deployment, which can be used to optimize the vessel design.

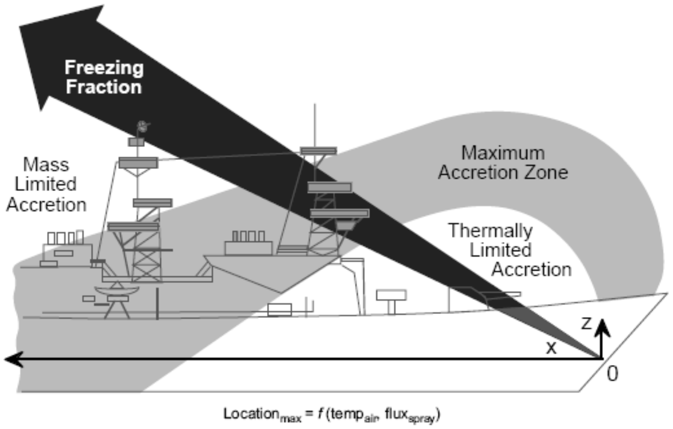


Figure 3.1 Vessel icing trend
Courtesy to Ryerson

US Navy (1989) has proposed another critical ship factor to consider - cold soaking, which means that when a ship has stayed in cold temperatures for a long time (e.g. 2-3 weeks for most US Navy Vessels) the body of the ship will remain cold even if the air temperature is warmer. In this situation, icing may be more severe than expected given the current environmental conditions. This example tells us that the interaction among ship characteristics and environmental factors could be very complicated, so the captains or marine experts in Arctic should consider all the factors together, the vessel icing conditions should never be underestimated.

In case of a computer or calculator is not available, Overland (1990) has developed the following nomograms (figure 4.2) for quick reference. They display sea spray icing potential class as a function of wind speed and air temperature for a given sea temperature, which are based on the work by Overland (1990). The effect of cold sea water is taking more weight here. Generally, icing is not a problem when sea temperatures are higher than 7 ℃, and no cases with higher temperatures were considered when the algorithm was derived. But it could be possible for icing to occur at these higher sea temperatures, so they have been included below.

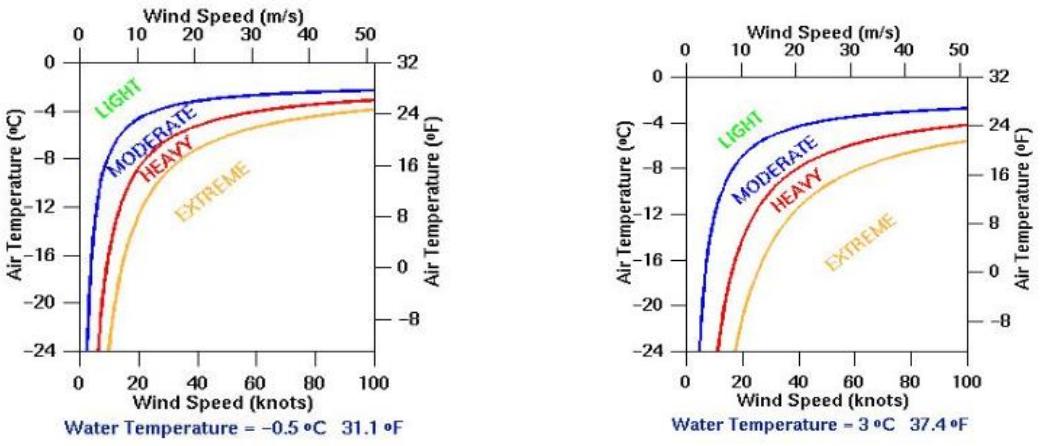


Figure 3.2 Nomograms of Icing for Various Water Temperatures

Courtesy to Overland (1990)

These nomograms could be used for icing in fresh water such as rivers or lakes, but some changes need to be made because freezing temperature of fresh water is different from that of sea water. Overland (1990) worked out how to adjust icing predictor for sea water to be used for fresh water: to minus 1.7 ℃ from the water temperature and add 1.7 ℃ to the air temperature before using the icing predictor, or just use the algorithm mentioned above directly and just assign $T_f = 0$.

There are 2 other solutions for vessel icing: preventive measures such as ship coating to treat the surface of the vessel to prevent it from icing and deicing, which means removing ice to mitigate its negative effect.

3.1.3 Preventive measures

The best solution for vessel icing is to find a safe shelter for the vessels; if a vessel fails to find shelter, the captain should adjust the heading direction of the vessel to suffer minimum sea spray on it, at the same time try the best to remove the ice. It could be a disaster if the crew waits until the vessel accumulate with large amounts of ice.

One effective measure is ‘hydrophobic coating’, or ice fearing coating, which means the treated surfaces is hostile to water, then minimize the ice amount built up on them. This method is easy to understand, without plenty of water residue on the surface, the icing condition could not be severe. US Navy (1988) has recommended two hydro-phobic coatings for prevention of sea spray icing on vessels:

- Flourocarbon penetrating coating (FPC) is normally used to reduce hull drag and has been found to be a good ice-phobic coating as well.
- Vellox 140

Some issues need to be considered when these chemicals are used for icing preventive coating. Firstly, when water or wind brush the surfaces coated with these chemicals, they are easy to be taken away, so the function of them is temporary, to ensure a long term function, they need to be reengaged from time to time. Otherwise large amounts of ice will be built up unexpectedly. Secondly, these chemicals are slippery so they cannot be used on the surface of main deck or stairs where the crew often works.

3.1.4 Ice removal

If all the preventive measures mentioned above fail, the last choice is to remove the ice to prevent negative effects caused by large amounts of ice. Guest, P. (2005) stated that physical removal is the most effective method in this condition. Just make sure the right occasion to take this action is the first time when the condition is safe for the crew operation. Besides, the tools for this operation should be properly selected: no sharp blade or outstanding edges, which might damage the metal surface of equipment or vessel. So tools made of wood or plastics are recommended.

US Navy (2005) have suggested some useful tools for ice removal based on their experience:

1. Baseball bats
2. Large wooden mallets
3. Steel-bladed ice scrapers
4. Straight bottom shovels
5. Spades
6. Hoes
7. Picks
8. Brooms
9. Snow shovels

The importance of these tools for vessels in the Arctic is not lighter than the other evacuation equipment such as life boat, so enough amounts of these tools should be stocked onboard which might save the vessel and whole crew. Figure 3.3 shows how the crew works to remove ice with an ice mallet. Without effective tools, the disaster caused by severe icing is not unexpected.

Besides physical removal method, Guest, P. (2005) has recommended some chemicals which will be helpful and their virtues as well:

1. Rock Salt (Sodium Chloride) Most economical
2. Calcium Chloride Faster acting than rock salt
3. Urea Less corrosive than above
4. Ethylene Glycol
5. Methanol
6. Other light de-icers including alcohols

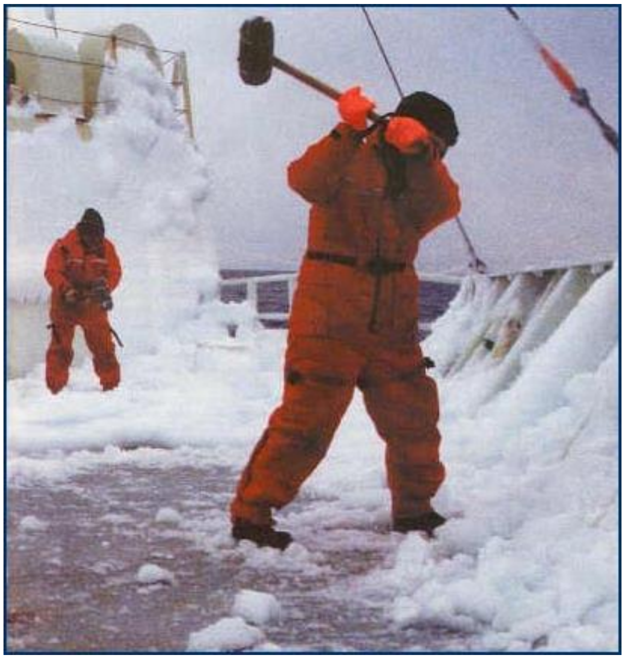


Figure 3.3 Research Vessel 'Knorr' Captain A.D. Colburn, pounding on the foredeck with an ice mallet

Courtesy of Pickart (1997) in Oceanus Magazine

Considering extreme icing condition in Figure 3.3, it is necessary to install automatic de-icing instruments for the navigation cabins, which can prevent ‘blinding the captain’ during navigation. Effective winterization for the vessel is another useful method to avoid vessel icing. How to improve reliability of critical evacuation equipment such as life boat should gain the attention of marine experts.

3.2 Ice management

There are several definitions of Ice Management (IM): Eik (2009) proposed that ice management is the sum of all activities where the objective is to reduce or avoid actions from any kind of ice features; while Noble Denton Canada Ltd. & B. Wright & Associates Ltd (2005) think ice management is a general term that is often used to describe the support activities a stationary vessel or platform may require to allow it to maintain position and continue operations in moving ice. In my minds, ice management is all methods used to reduce the negative influence of sea ice or icebergs on the vessels or facilities operating in cold ocean regions, especially to improve the safety and efficiency of offshore operations, which makes the operation reliable and economical, it is acknowledged by human that sea ice or iceberg could induce accidents or disasters to the vessels or facilities.

Noble Denton Canada Ltd. & B. Wright & Associates Ltd (2005) have recommended that ice management should include:

- ice monitoring and forecasting
- ice hazard detection and tracking
- ice alert system
- icebreaking and/or clearing (including iceberg towing), as required, as a means of physically reducing the threat of potentially hazardous or operationally restrictive ice interactions with the vessels or platforms

3.2.1 Ice cover management

Some other important items in ice management not mentioned above are weather forecasting and other marine parameters such as wave, current, etc. which are critical variables influencing the ice movement to high degree.

So ice management is a systematic procedure, involving science of Physics, Mechanics, Dynamics, Meteorologists, Risk Analysis and so on. In simple words, ice management can be understood as ice breaking and ice clearance plus ice detection and ice monitoring. The previous successful experience could be referred to in the operation of Arctic.

Pilisi, N. et al. (2011) have concluded a typical ice management solution for Beaufort Sea. Figure 3.4 shows the overall ice management systems in Arctic oil and gas operation campaign.

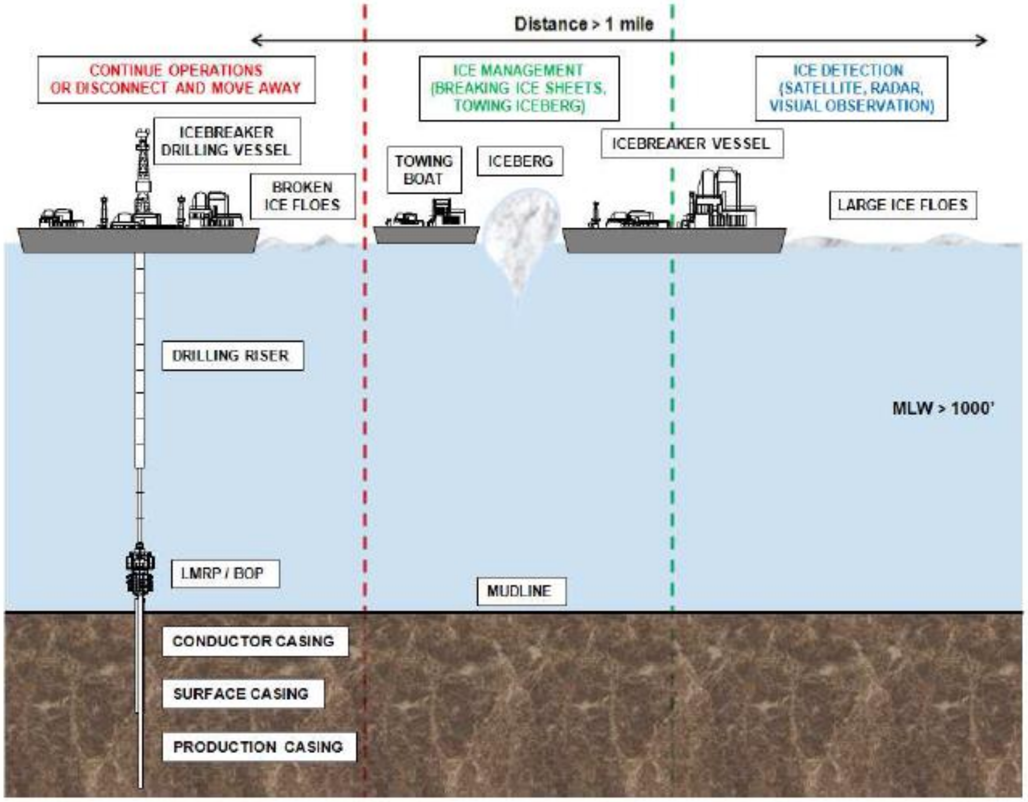


Figure 3.4 Ice management solution for the Beaufort Sea
Courtesy to Pilisi, N. (2011)

Firstly, one or two ice breakers navigate in the upstream of the drilling site, keeping 0.5 km to 2 km distance from it, the number of ice breakers depends on the condition of sea ice cover, the larger and the thicker of the ice floes are, the more ice breakers are needed; the velocity of ice floes is another important factor for determining ice breakers' quantity, more ice breakers can ensure better ice breaking efficiency. The deployment of the ice breakers should be as follows: the bigger ice breaker should fulfil its responsibility in the more distant location and the smaller ones work in the closer position. Figure 3.5 shows one good example from southern Grand Banks.

There is a tradeoff for the distance between the ice breakers and the platform: short distance can bring well controlled ice breaking result, at the same moment it is risky for the platform to collide with ice breakers. It has been well known by the researchers that both station keeping and movement of boats are more difficult in severe ice conditions.

All the ice breakers should be arranged based on the regional and local weather condition and ice movement, so without ice monitoring and weather forecasting the ice management cannot be successful, the latest technologies could make the ice monitoring and weather forecast more reliable and more precise. Backman (2009) has recommended such technologies as airborne radar, satellite imageries, helicopter reconnaissance and notably visual observations.

Figure 3.5 Ice management for a drill ship in pack ice

Courtesy to Dunderdale, P. and Wright, B. (2005)

Once an ice hazard is detected, an ice breaking mission can be carried out: the bigger ice breaker break the ice sheet into smaller pieces, then the smaller ice breakers will break the small ice pieces into much smaller ones, which will not threaten the safety of the platform, and in most cases the smaller ice breakers could produce one almost ice free passage for the offshore oil facilities. Crocker (1998) proposed that several small supply boats should be stand-by to tow ice bergs or ice ridges if their drift direction would influence the safety of the platforms.

If all the measures mentioned above still cannot eliminate the threat of the ice floe or ice bergs, the drilling boat should be able to suspend operations and disconnect risers to move away from the drilling location, then come back to resume the operation when the working condition is safe. So the risers should be designed easily to connect and disconnect to decrease high cost for downtime.

Dunderdale, P. and Wright, B. (2005) have recommended some virtues which can help winterized drilling ships working in the Arctic: having at least four thrusters (two in the bow and two in the stern) for good station keeping in pack ice region; azimuth propulsion is recommended as well to ensure that the drill ships can keep their position in very difficult ice and weather conditions.

In the ice management systems shown in figure 3.4, decision making plays a key role for the safety of the oilfield facilities and operation efficiency. After ice or ice bergs hazards are detected, ice breakers start to break the ice floes or an ice berg towing mission is launched; if this fails to obtain satisfactory result, the offshore facilities will suspend their operations and be moved away, but the time window between identification of the necessity of suspending operation and moving the drilling ships to the safe area is usually long enough. To solve this problem, an experienced ice management crew is necessary, which has already proven that they can make a good balance between safe operation of the facilities and unnecessary down time. In addition, if nobody can ensure the sea ice threat elimination, releasing the facility is the best choice, because oil facilities' accidents will be disasters in the Arctic, especially to the vulnerable biological environment. If the ice management quality can be improved to a high level to be able to deal with most ice threats encountered, both operation efficiency and safe operation level will benefit from it.

In fact, besides the ice management level the capabilities of the drilling ships should be well designed targeting at extreme sea ice conditions in the interesting operation regions, if either of them has been optimized, the oil exploration and development activities can be performed safely and economically. Most current drilling ships in the main stream of the world are not designed to work in severe ice conditions, or in other words, they are not ice-class vessels.

Multiyear ice is thicker and harder than the first year ice, which is tougher to be broken and requires more powerful ice breakers, but the volatile drift direction of the sea ice floes troubles ice management as well, which will destroy the safe passage for the operation facilities made by the ice breakers' sheet. Figure 3.6 illustrates this effect, safe passage is not reliable any more by the disturbance of ice flowing direction change.

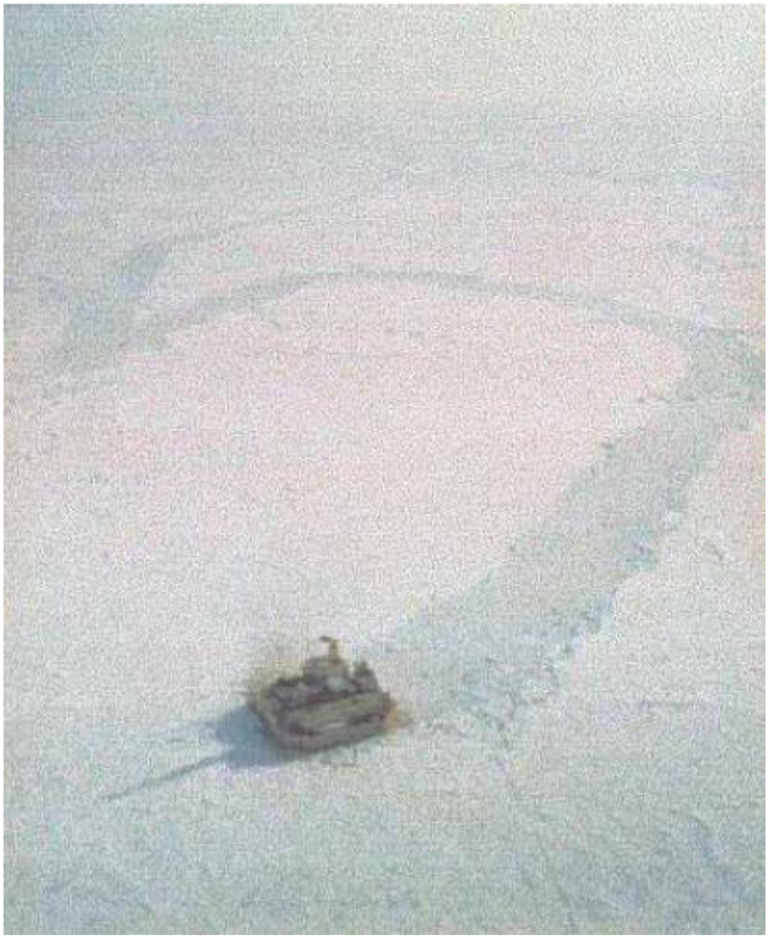


Figure 3.6 Typical wake conditions behind the Molikpaq structure in continuous moving pack ice with variable drift directions.
Courtesy to B. Wright & Associates Ltd (1998)

The first step of ice management is Ice Forecast, if the future sea ice condition has been forecasted precisely, oil operators can make the decision based on the forecast, which can make a good balance between potential accident and high cost caused by unnecessary operation suspending or evacuation. In the exploration drilling north of the 73rd parallel, the operators established systems for monitoring ice that could represent a danger during drilling, including both icebergs and sea ice.

Mobil (Armstrong, 1988) and Norsk Hydro (Engseth, 1989) have recommended some elements in monitoring, which can be referred by other oil companies:

a) Satellite observations of the ice borders, (DNMI）

b) Plane and helicopter missions to look for sea ice and icebergs,

c) Supply ship that can go to the ice border and patrolled the area

d) Satellite buoy on the ice to see how the ice moves

e) Ice forecasting from DNMI and others

f) Use of reports from the other parties, such as coast guard

Engseth (1989) has proposed that sea ice forecasting cannot be always trusted or reliable. According to some old sayings: nobody can forecast the future absolutely right. So some safety factor should be applied together with sea ice forecast. The weather in Arctic could change suddenly without any sign, which cause the transformation from a weak sea ice to severe sea ice condition and potential disaster to oil platforms.

Forecasting of icebergs is impossible unless each iceberg is equipped with modern instruments, such as Global Position System (GPS) signal senders, so that one may know where they are at any given time. In this case, good radar systems can be relied on to give warnings of the icebergs when they are at a certain distance from the platforms. Of course helicopters can be sent to monitor the movement of icebergs which are close to the warning distance of the platform; corresponding emergency response procedures should be employed to deal with the iceberg at different distances posing different threats on the platforms.

The forecasting service in the Barents Sea is not as good as that found further south, partly because more oil development activities and more sea ice data are available further south in the Barents Sea. This gives a lower safety level than what one is used to for operations sensitive to weather.

B. Wright & Associates Ltd (1998) have recommend some design principles for offshore facilities on the Grand Banks:

Any fixed platform must be able to withstand the forces that are associated with these sea ice conditions, both globally and locally. Essentially, these load levels are typically low compared to the design loads that are associated with iceberg impacts.

Conventional floating platforms that are not ice strengthened shall avoid pack ice incursions by moving off location. For the floating platforms designed to work on the Grand Banks, an adequate level of ice strengthening, a capable mooring system, and the use of ice management support vessels should ensure station keeping in sea ice, with a high level of reliability. Obviously, ice strengthened floating systems would also require effective and reliable protection against any glacial ice masses embedded within the pack ice cover to remain on location with confidence.

Ice management in high speed

If the ice breakers work with high speed, the effectiveness of the ice breaking would be in desired condition as well, but some potential risks have to be acknowledged, Figure 3.7 (Noble Denton Canada Ltd. & B. Wright & Associates Ltd, 2005):

- Hull damage is the first factor to be considered when determining maximum icebreaking speeds. High speed will cause significant ice load to the hull of the boat and it must be limited to that which is safe for the vessel's ice class specification.
- The amount of ice/propeller milling would suffer more wears when the vessels experience high speed.
- Sharp high speed turns carried out in heavy ice will increase ice interaction (and potential damage) on the steering equipment.
- In well managed ice, care should be taken to monitor engine room cooling water temperatures, because slush and small pieces of ice drawn into the engine cooling intakes can cause rapid overheating, resulting in sudden propulsion shut down and machinery damage, which is risky in ice environment: should propulsion shut-down on a support vessel, it might not be under control and serious collision with platforms is not impossible

Figure 3.7 Ice management for drill ship in the Beaufort Sea
Courtesy of Noble Denton Canada Ltd. & B. Wright & Associates Ltd (2005)

Specific Ice Management Methods

There are five basic pack ice management techniques used to reduce ice load levels and defend floating platforms that are station-keeping on a mooring or by dynamic positioning, which have been proved effective in certain ice situations. When an ice breaking fleet (more than one ice breaker) is operating up-drift of a platform, each of which can use a different technique that is most suitable for its operating capability (Noble Denton Canada Ltd. & B. Wright & Associates Ltd. 2005). The combination of different ice management methods usually gives a better performance than that of one method only. Three of the five basic techniques involve particular icebreaking patterns, including the linear, sector and circular techniques. The other two are ice clearing procedures, or ice dispersal, including pushing heavy ice floes and the use of high power propeller wash to break thin ice and clear brash ice and small floes from around the station-keeping unit.

Linear

The linear technique means the ice breaker in the up-drift of a floating platform is navigating in straight lines, parallel to the direction of the ice drift. This method performs well when the ice drift speed is fast and the ice drift direction remains reasonably constant, Figure 3.8.

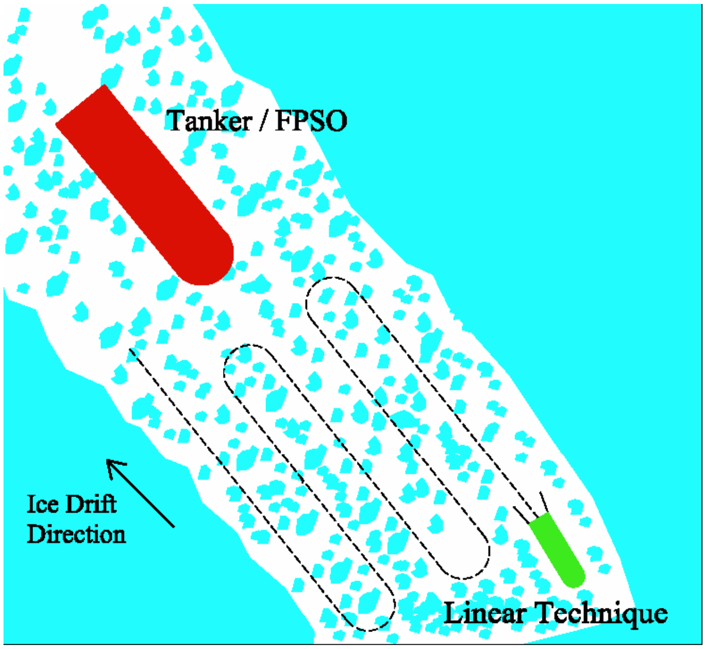


Figure 3.8 Illustration of Liner Pattern
By Noble Denton Canada Ltd. & B. Wright & Associates Ltd (2005)

Sector

This technique could provide wide managed pack ice coverage around the approaching ice drift direction, which requires the support vessel to steam back and forth across the drift-line between 2 designated bearings which make up of the sector. This pattern is useful when ice drift speed is slow and/or when the drift direction is changing rapidly, Figure 3.9.

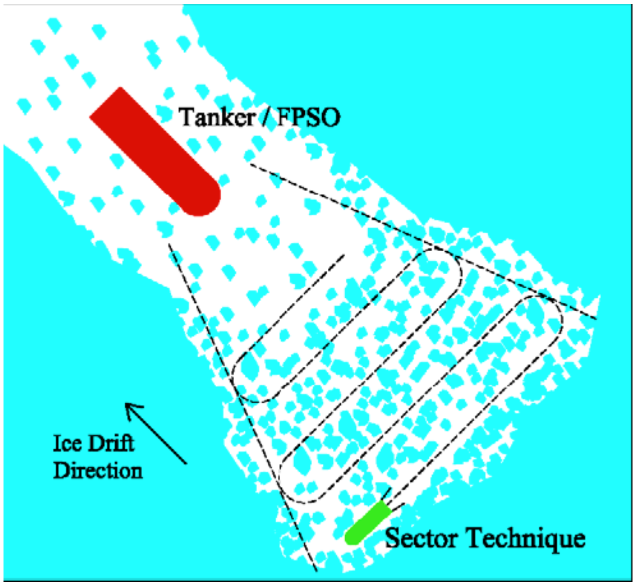


Figure 3.9 Illustration of Sector Pattern
By Noble Denton Canada Ltd. & B. Wright & Associates Ltd (2005)

Circular

This technique requires the support vessel to steam in a circular pattern on the up steam of the platform location. The diameter of the circles is determined by the speed of the ice drift, and the maneuverability and speed of the support vessel. This pattern is useful in high concentrations of thin ice or small diameter thick ice floes and when the ice drift direction is variable, Figure 3.10.A This pattern could also make a circle completely around a platform as an effective method to relieve ice pressure.

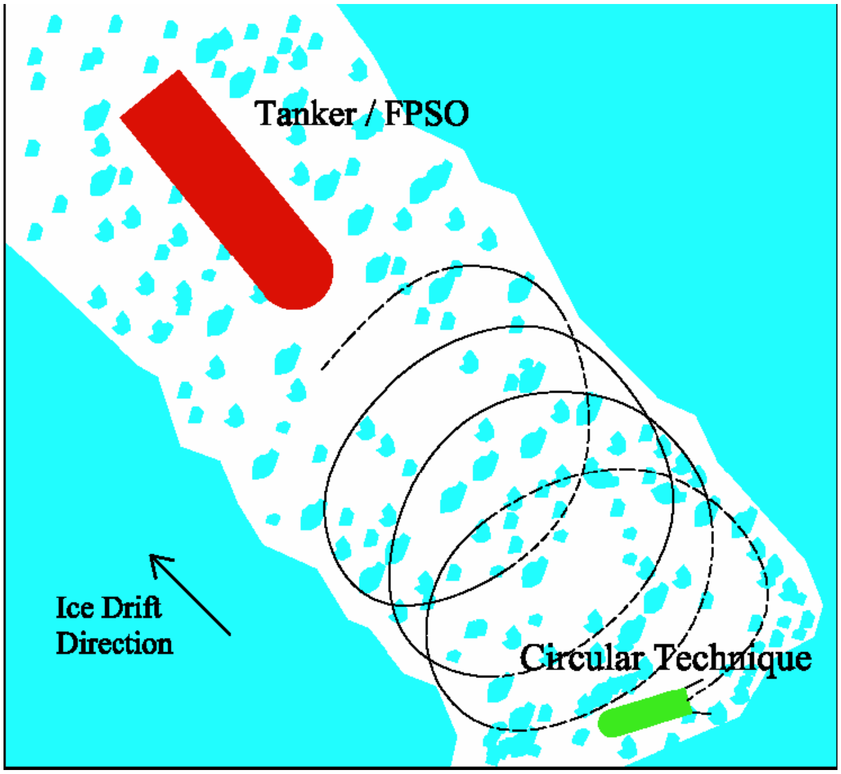


Figure 3.10.A Illustration of Circular Pattern
By Noble Denton Canada Ltd. & B. Wright & Associates Ltd (2005)

Pushing ice

This is an effective way of removing medium and large ice floes from the drift line, Figure 3.10.BThe pushing direction is perpendicular to the approaching ice. Comparing with ice breaking method, this technique is preferred because the threat to the platform is removed from the drift-line whereas the broken ice pieces after being broken may still pose a threat to the platforms. Possible negative effect of this technique is that later change of ice moving direction could become a threat as well. To allow full power pushing, the bow strength of the vessel(s) used must be appropriate. It is recommended that at least two vessels to be used to prevent floe rotations.

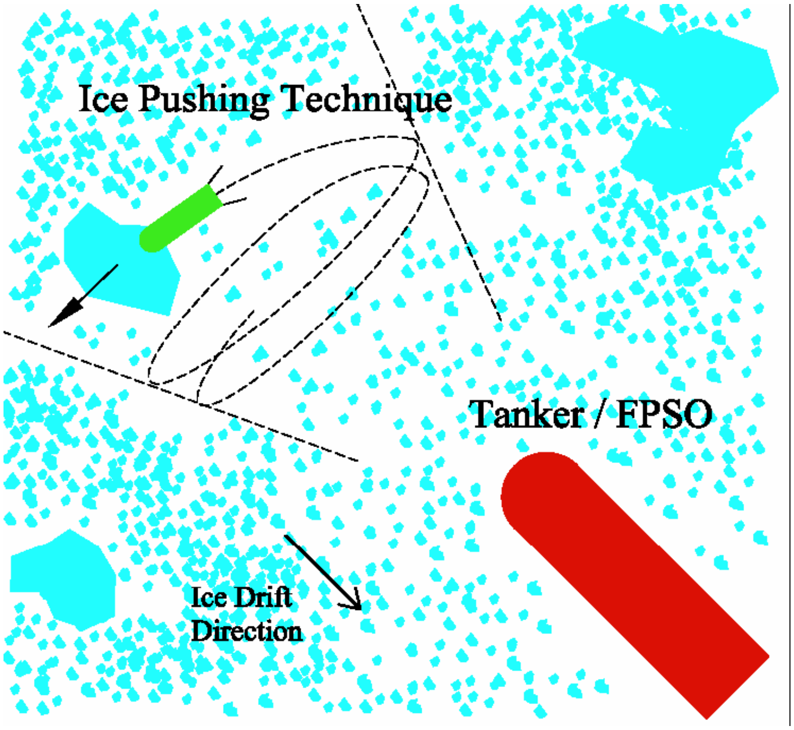


Figure 3.10.B Illustration of pushing ice
By Noble Denton Canada Ltd. & B. Wright & Associates Ltd (2005)

Potential risks of pushing large sea ice floes

It is obviously that pushing ice out of the direction is one good choice for controlling the large ice floes with high degree of reliability. Some aspects should be taken into consideration when this operation is carried out (Noble Denton Canada Ltd. & B. Wright & Associates Ltd, 2005): The ice load on the bow of the vessel pushing a large sea ice floe can be significant, which is depended upon the ice characteristics such as the size and thickness of the floe, the age of the ice (in terms of compressive strength), and some other factors including wind force, current and wave effect on the ice floe and the power used by the ship to achieve the desired deflection away from the platform being protected. The pushing force applied to a large ice mass must not be higher than the level of ice strengthening (stiffening) in the bow region of the support vessels. Amount of “in-built” stiffening to resist ice damage varies with the construction (ice classification) of the vessels. Same philosophies go with icebreaking, the less the amount of ice strengthening a vessel has in its bow area, the less power that it can safely apply. Clearly, the restricted power used for the supply vessels to avoid ice damage on the hull would reduce the effectiveness of ice management in the pushing method. So it is recommended for the vessels engaged in ice management, to have the ability to monitor ice loads on their hulls, by installing mounted strain gauges in the sensitive areas.

Propeller Wash

Propeller washing is a good option to deal with small pieces of thick ice, even if present in high concentrations, which can be very effective to reduce or prevent ice accumulation against the platform. This technique is particularly effective when used by vessels installed with azimuthing main propulsion, which allows the support vessel to remain almost stationary up-drift of the platform on the drift direction, with the propellers angled outwards and using high power to wash ice to both sides of the platform. Even though there are some restrictions to the use of this approach, for example, if there is only one vessel and poor visibility which prevents knowing what ice may be coming from further up drift, or if the ice drift direction changes sharply, there might be not enough reaction time for the vessels on duty. Refer to Figure 3.11.

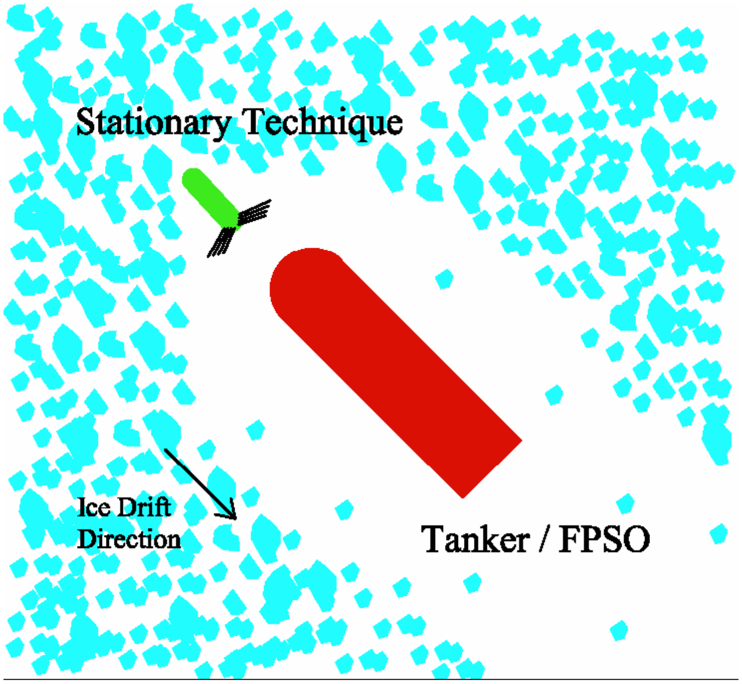


Figure 3.11 Illustration of propeller watch
By Noble Denton Canada Ltd. & B. Wright & Associates Ltd (2005)

To reduce sea ice data uncertainty

The uncertainties behind the sea ice data will bring potential risk for ice management, because they could cause trouble for decision makers. So how to reduce the uncertainties is one of the key questions for the researchers. The following activities are proposed by DNV (2008) to reduce the uncertainty with respect to data availability:
It is necessary to collect more data on characteristics of sea ice – frequencies, drift speeds, thickness, consolidated layer, mechanical properties etc. To achieve the targets mentioned

above, the following work should be focused on:

- Increasing the spatial as well as temporal database for predictions of extreme conditions;
- Deployment of automatic data collection;
- Satellite and other remote sensing data;
- Modeling of drift and creation of different types of sea ice such as pressure zones, ridging.

3.2.2 Iceberg management

The management of icebergs can be divided into the following steps (Eik, 2009):

- Iceberg detection;
- Iceberg forecasting, monitoring and tracking;
- Threat evaluation of the iceberg;
- Physical iceberg management such as iceberg towing or suspend the operation and move the platforms away to avoid collision.

Among all the iceberg management steps, to suspend the operation and release the platforms is the passive measure, but it is the last choice for the offshore facilities to prevent disastrous accidents.

Eik (2009) has concluded regarding the physical iceberg management methods:

- Line or net towing;
- Propeller washing;
- Water canon deflection

Actually the methods mentioned above require that the vessels performing the iceberg management missions are powerful enough comparing with the mass of the icebergs. Otherwise the missions are impossible. For example, if one small vessel is used to tow a big iceberg, the vessel might lose control by the force of the iceberg combined with current, wave and wind, furthermore, the worst results could be the capsizing of the vessel. Figure 3.12 shows how one iceberg was towed in the Arctic.

Figure 3.12 Illustration of iceberg towing
Courtesy to McClintock et al, 2002, PERD report

Some successful cases in the Arctic

There are quite a few successful cases for offshore oil operation with the favor of ice management (Eik, 2009):

Kulluk in Beaufort Sea

- 44.7 down days in 585 operating days (92% operability);
- 8 times move off the location;
- Only 1 incident reported when Kulluk was pushed off location due to impact from a heavily ridged multiyear ice floe (5km x 8km area, 0.6 m/s drift speed).

Effect of ice management:

Low ice concentration – thin ice (0.5m): 65% reduction in mooring loads;
High concentration – thin ice (0.5m): nearly no reduction in loads;
Low concentration – thick ice (2m):75% reduction in loads;
High concentration – thick ice (2m):40% reduction in loads.

Sakhalin in Caspian Sea:

- Seasonal oil production in Sakhalin 2 from the year 1999;
- Ice management systems applied to the production system from June to December when the ice freezes up and break up;

- There are lot of similarities of ice management in this region and in the Beaufort Sea;
- It takes long T-time to lower the SALM safely to the sea floor (1 1/2 to 2 days);
- A few weeks of operation time was extended with the use of Azimuth icebreakers.

Data collection for icebergs – frequencies, sizes and drift

The base of excellent iceberg management is the complete and clear understanding of spatial and temporal variation of iceberg occurrence, motion, size and mass, which can be realized by the following activities (DNV, 2008):

- Re-evaluate the reliability and precise degree of the existing databases;
- Field programs such as tracking buoys, stereo photography, remote sensing techniques and on-site observations should be carried out;
- Optimized models for iceberg drift, including deterioration. Statoil already has started research in this direction; however, this job needs to be done with cooperation of all countries around the Arctic.
- Experience of iceberg management in pack ice is still little for reference;
- Ice and iceberg forecasting, which has strong links to ocean forecasting, needs improvement.

Russia has carried out systematic investigation of ridges and thickness and accumulated rich information in the northeast Barents Sea, and has a long record of systematic iceberg observations although with large uncertainties regarding annual occurrences and size/mass distributions (DNV, 2010).

Some suggestions about future missions for improving ice management performance

More metocean data in the Arctic region covering more areas need to be collected with sufficient duration, particularly for currents, wind, waves and open ocean temperature. It will be more favorable that the data is combined with an extended meteorological observational network for weather forecasts. Essential data for hindcast studies, such as wind and temperature at severe heights, waves and currents also requires being more extensively verified (DNV, 2008).

Even exploration and production drilling have been performed successfully in waters prone to icebergs; Eik (2009) has proposed some activities in the future to raise iceberg management level:

- How to incorporate different iceberg management methods together is considered to be a key factor for the success;
- Technology for iceberg handling is proven in open water – **not** in ice covered waters (more than 4/10 ice cover), so research about this kind of operation needs to be endeavoured;
- Technology for detection and tracking of iceberg features will consist of a wide range

of instruments, and invention of new technology and instruments is necessary;

- How to include the effect of ice and iceberg management systems in the design will help to prevent over-design and improve reliability.

3.3 Solution to the Meteorological environment in the Arctic

The best solution for reduce the uncertainties in the Arctic is to predict the destructive weather precisely and timely. As discussed above, currently both the data collection and the prediction models are not satisfactory, then another technique, hindcast, has turned out to be a good solution.

Metocean conditions vary widely from region to region in the Arctic, so site specific information is necessary for the researchers. Unfavorably, data collected for pure scientific reasons are seldom sufficient, especially for use in design and operations of offshore structures and ships in the Arctic. Now it already turned out to be a big challenge to collect the needed data. DNV (2008) has concluded that measured data is seldom available for more than 30 years (Gulf of Mexico, North Sea, Indonesia). Fortunately hindcast data in some areas, can be used to improve extreme weather prediction, which can cover up to 50 years and longer.

Contrast to forecast, which is based on considerable data or observations, hindcast is an efficient and useful technique to reproduce nature when there are not enough observations (DNV, 2008). Wikipedia (2013) defines the hindcast as a way of testing an existing model, which is performed through inputting known or closely estimated data into the model to see how well the output matches the known results. Another name of hindcasting, backtesting, might be a better explanation of its true meaning. One sound example cited by DNV (2008) is to utilize knowledge of the physical processes which causes wind from differences in air pressure and waves from the winds. Essentially most of the weather forecasts were performed based on air pressure which has been proved with acceptable accuracy and reliability for decades. That is why it is possible to produce weather maps that could date back to the early 1950's or even longer. Though this way huge number of points over large areas can be located, and data record with span of 40 – 50 years could be found. This philosophy goes well when it is used for calculating currents.

DNV (2008) has proposed that hindcast is recommendable to be developed as a technology because it creates significant data both in time and space, but there still some points need to be paid attention such as:

- All hindcast models need to be validated and verified before they are used for prediction;
- Verified models should have no incorrect model code or programming errors etc.
- Validated models are expected to supply a satisfactory description of nature;

- Comparison between computed and observed conditions should be taken to verify the validation of the models;
- Shorter observational records are preferred to be used for validation check rather than required for calculation, Figure 3.13 illustrates how the shorter records have been used for the validation of hindcast data in the Barents Sea.

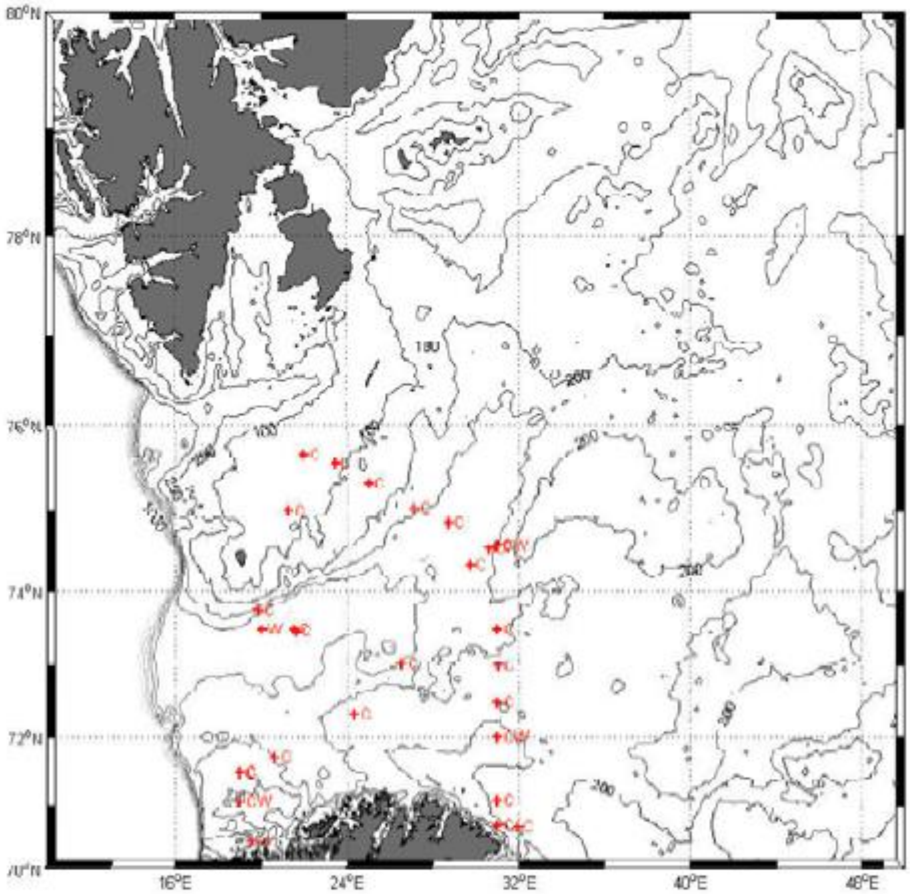


Fig. 3.13 Shorter records of waves and currents in the Barents Sea that can be used for hindcast validation.
DNV, (2008)

Two distinctive features can be found when comparing hindcast in the North Sea and in the Barents Sea:

- Historic weather maps for the North Sea are more accurate than the Barents Sea;
- Verification of data are more extensive in North Sea than in the Barents Sea.

Due to the above facts, it is reasonable to say that hindcast data in the North Sea can be employed with more confidence than that for the Barents Sea.

The hindcast condition of the Arctic region can be discussed with the example of hindcast for the Barents Sea as of spring 2008:

- A hindcast database giving wind and waves every 75 km for the time window between year1955 to year 2007 is available so far;
- This data archive shows that the Barents Sea has a “milder” wind and wave condition than that in the North Sea, which might be different with most people’s expectation;
- A new Norwegian hindcast database with more records covering wind and waves for every 10 km for the Barents and North Seas for the years 1955 – 2002 will be available soon, which can benefit offshore operation to high extent. The hindcast database which both covers longer time windows and intensive observations are expected. Figure 3.14 shows an example of winds from this archive for the North, Norwegian and Barents Seas by the Norwegian Meteorological Institute. The archive could list wind, temperature and water content at 40 different heights above the sea surface in addition to waves;
- Some other sources such as European Centre for Medium-Range Weather Forecasts, Fugro Ocean or US Navy can be referred to.

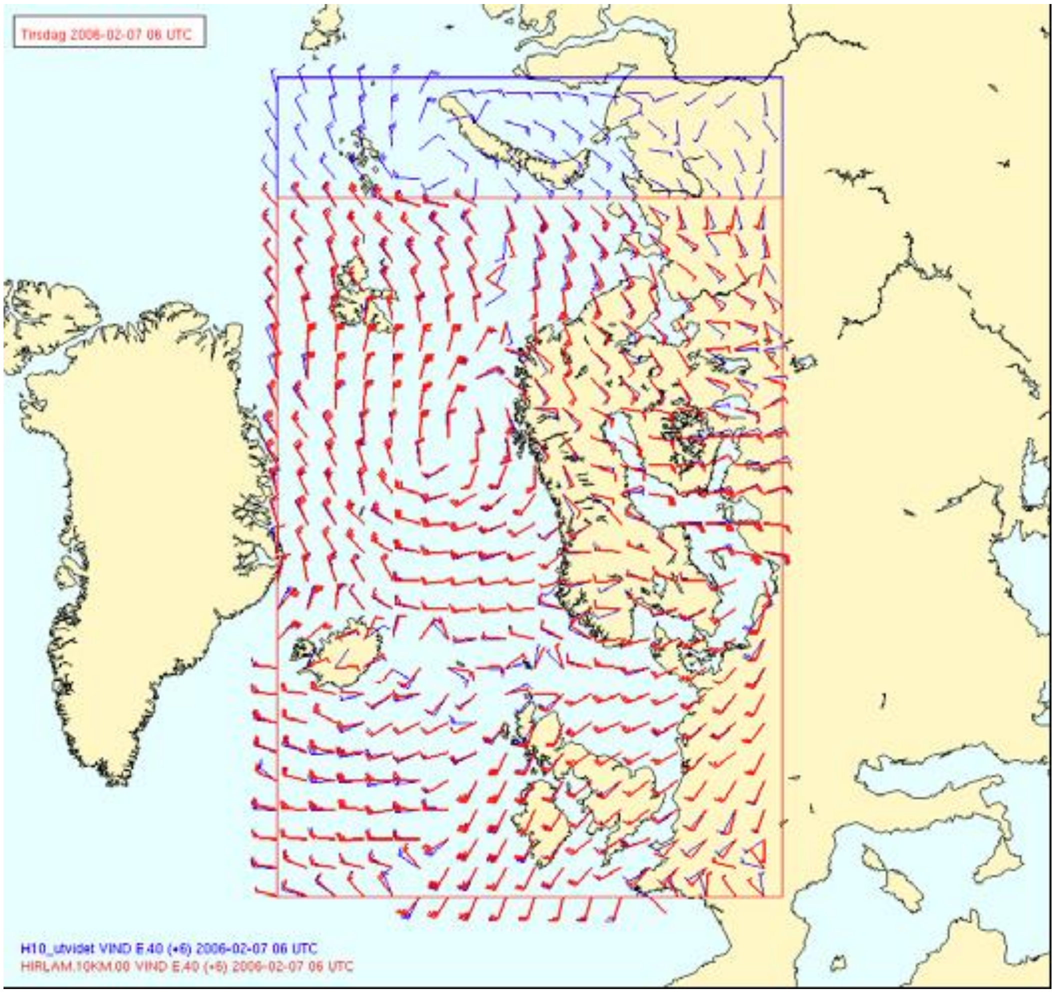


Figure 3.14 Example of coverage of the New Norwegian hindcast archive for wind and wave.

Courtesy to Norwegian Meteorological Institute (met.no)

To avoid or mitigate the negative influence caused by the extreme weather in the Arctic, one of the best solutions is to make accurate predictions, which can both enhance efficiency and safety level of operation. As mentioned above, this mission needs support of considerable data and optimized models. Currently, the records in the Barents Sea are neither enough in the quantity, nor with the good quality, or in other words, with larger uncertainties comparing with the data in the North Sea. So when the data in the Barents Sea are to be employed, this factor must be taken into consideration.

So the conclusion can be drawn up that weather forecasts are less reliable in the Barents Sea than in the further south region such as the North Sea, because of two main reasons: fewer meteorological stations at sea and the occurrence of small scale atmospheric phenomena which are difficult to forecast. Then it is fair that the probability of failing or disrupted operations in the Barents Sea is higher than its south neighbors.

Based on lots of experience both successful and failed, DNV (2008) believes that it is a challenge to predict extreme ice and metocean conditions that will occur only once every 100 years or more, because it is truly small probability case. Only few valuable record can be referred, because just from the last century, human started systematic research for the Arctic, which compares with the period of 100 years, it is not long enough for supply rich data. Statistical data and approaches can be taken as design basis, while for operations the weather forecasts is the only access to be trusted. Reliable prediction of ice and metocean extreme values requires statistically reliable data and proper statistical models and methods.

The statistical data base can be established and enriched in this way: after a data base has been established which covers all the needed information, the data will be subjected to statistical analysis to estimate values as per desired safety levels; for the practical employment, even 30 – 50 years may be insufficient for rigorous statistical determination and uncertainty, both from data and from statistical approaches, will adhere to the estimates at the 10^{-2} and 10^{-4} levels (DNV, 2008). The standards mentioned above do not give little guidance on how to perform the statistical analysis and deal with the uncertainties. In some international standard it is only stated that interpretation by specialists is usually needed.

DNV (2008) has proposed some points for collection and application of the data base. To compensate the regional climate varieties and to secure the same level of reliability in different regional climates it is critical to evaluate the needs and requirements that are placed on the data bases. These considerations should include but not limit to:

- The records are long enough to catch seasonal and inter-annual variability;

- Ensure the relevant and right type of data are collected;
- The observational uncertainty connected to the different measurement techniques has not been neglected and kept as low as possible;
- That weather forecasting is secured with the right spatial and temporal coverage of weather observations;
- That processing and analysis approaches and tools are transparent, verified, documented well and have widespread acceptability.

So next mission for the researchers is to pay more efforts on collection of more data covering more regions and lasting for longer period, through international cooperation this mission can be performed with higher efficiency and reliability.

3.4 Solutions to low temperatures

To solve the challenges of extreme low temperature, there are some solutions which already have been proven effective, such as to use winterized offshore facilities, which can protect the equipment and the crew; to furnish the personnel with proper personnel protection equipment (PPE); to improve the working environment physically (e.g. heating the cabins); to use equipment with special material for the low temperature; besides the measures mentioned above for hardware. Some measures about ‘software’: to set up special crew change schedule; to select fitful personnel to work in the Arctic; to reinforce relative training; to optimize the emergency response and first-aid steps as per the Arctic environment. Some key solutions will be discussed in the following parts.

Winterization

It has been recognized by all researchers that a well winterized rig is the best solution for operation in the Arctic. The term “winterization” is defined as the procedure to modify a common rig to be fitful for running in the cold winter, most of the modification procedure will be physical, such as constructing wind walls, heating personnel operation platforms, insulating exposed fluid pipelines and using special material for the equipment to withstand extreme low temperatures, etc. This solution is believed to be effective because it works for both equipment and crew. Figure 3.15 illustrates a typical winterized drill ship from Transocean which is capable of working in the Arctic, the wind wall already covers all directions of the rig and no exposed pipelines exist.

Figure 3.15 Preliminary artistic rendering of the Transocean Arctic Drill-ship
Courtesy to Scott Brittin, et al. (2011)

Gudmestad and Karunakaran (2012) have stated their points about the winterization of the rigs: because the aspects of subzero temperature might threaten the work in the cold regions, it is necessary to 'winterize' the vessels to avoid negative effects. They recommended that this winterization procedure could follow the ISO 19906 [2010], which includes but is not limited to the following aspects:

- To avoid destruction from freezing of fluid in the pipelines, the pockets or dead ended pipes should be eliminated or the pipelines should be designed to be able to self-drain;
- To maintain a flow in lines (such as fire water and cooling water branch lines) to prevent freezing due to flow suspending;
- To insulate all the exposed pipelines and other parts which need to be keep warm;
- Protective heating, usually combined with insulation: the heating may be internal (e.g. when heating components within a tank or vessel) or external (e.g. when heat tracing tapes on instrumentation and piping);
- Enclosure can be used together with the method of heating from an internal heating element or by a heating/ventilation system;
- To use chemical or mechanical seals on instrumentation;
- To use wind walls to reduce rate of heat loss, can help to save energy;
- Some chemical additives (for example methanol) can be used to reduce the freezing point of fluids;

The methods mentioned above already have been taken use of in the Arctic oil and gas operation and proven to be successful.

There is a big challenge for the winterization in the oil and gas operation. Because the gas or fluids from the well might be highly toxic such as containing H_2S, or explosives which cannot be accumulated in high concentrations, so good ventilation is required, which will take away the warm air, and plenty of energy has been wasted. Even though, it is no other better options to solve this contradiction. Ventilation and winterization are just like enemy lovers, they have conflictions, but they still have to stay together.

Scott Brittin, et al. (2011) has proposed one god solution for this problem: one design team has devised an approach which passed air from one space to another space when it is possible, in order to reduce the heat load while keep sufficient air movement to meet the requirement of safety.

The sensitivity and function of detectors for the toxic or explosive gas must be ensured, because in the fully enclosed area, if there is anything wrong with the ventilation, the detectors will be the last chance for the rig. So it is recommended to use the most reliable products and the inspection or certification frequency should be much higher than other no winterization rigs.

Figure 3.16 shows the comparison for the same rig before and after it is modified with wind walls.

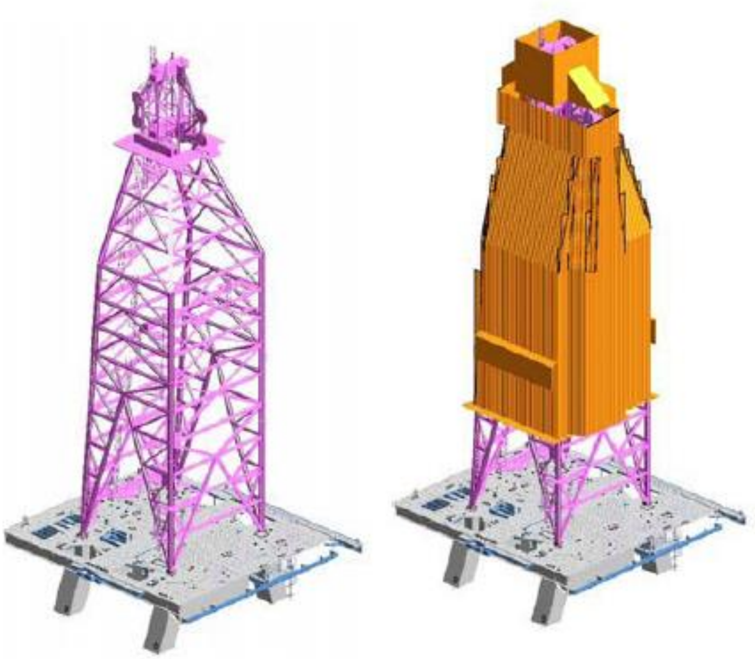


Figure 3.16 Derrick and rig floor with wind wall and without
Courtesy to Koo, Choi and Ha (2010)

DNV has a specific standard for vessels supposed to work in the Arctic, which is divided into 3 levels: Winterized basic, Winterized cold (t_1, t_2) and Winterized Arctic (t_1, t_2). Except Winterized basic, the other 2 levels are required to be followed by vessels in the

Arctic. Winterized Arctic (t_1, t_2) has the highest requirements. The following parts of the vessels should be well designed as per the DNV standard:

- Anti-icing and de-icing equipment should be equipped for different areas. Heating capabilities shall be specified;
- A diagram showing how compressed air has been supplied to main consumers outside machinery space;
- Electrical single line distribution diagrams for anti-icing and de-icing equipment with information about:
  - Full load
  - Cable type and cross section
  - Make, type and rating of fuse and switch gear;
  - Make, type and rating of heating cable
- Heat balance calculation;
- Manual for anti-icing and de-icing procedures;
- Test program for anti-icing and de-icing systems;
- Storage facilities and specification of hand tools for manual ice removal, protective clothing, lines etc. to be carried onboard;
- Mechanical de-icing arrangement, methods and location;
- Fastening arrangement and spacing of electrical cables and fluid pipes for heating purposes;
- Electrical schematic diagram, for all control and instrumentation circuits, with information on make, type and rating of all equipment;
- Calculation of fuel bunker capacity;
- Documentation of stern tube/CP propeller oils, if applicable;
- Calculation for Oil Outflow Index;
- Documentation as specified for the class notation OPP-F;
- Arrangement for anti-freezing of ballast tanks and fresh water tanks

This DNV Winterization notation was considered to be the most instructive means of determining vulnerabilities regarding the influence of extreme cold weather and for making early decisions on critical steps in the design and planning phase of the vessels.

Another negative challenge caused by fully enclosed working area is pressure difference, which can be dangerous in some cases: e.g. if someone pulls to open the door with higher pressure on the other side, the door might hit him with the combined force of the pressure difference and his own force to overcome the self-latch effect of the door.

There is another concern which has the same philosophy in the work shop of explosive products, such as fireworks. As per the regulation, the doors for this kind of factories must be designed to push to for opening (suppose the people stand in the room), if the door is to pull for opening, in case when there is an explosion, the door is difficult to open because people have to overcome the pressure difference first. So the designer of the winterization must take this into consideration.

One useful method for solving pressure swings is recommended by Scott, Brittin et al. (2011): to apply 2 sets of dampers into the boundary enclosing areas. Two-way type and mechanically actuated dampers were selected to be installed in the required places, considering the predominant anticipated sea state, a selected number of which would be fitted with heater grids. The other dampers without heater grids would be used only for the extreme sea states, or in other words, the worst conditions, which could compensate the functions of the other types of dampers (Brittin et al, 2011).
Fletcher, H. (2011) has referred to one successful winterized land rig, Nabors 536 in Kharyaga of Russia, Figure 3.17 shows the location of the oil field and the well site.

Figure 3.17 Kharyaga oil field location and Nabors 536 rig
Courtesy to Fletcher, H. (2011)

Nabors 536 is just a semi-winterized rig, because only rig floor and the monkey board have been enclosed, the catwalk is still exposed. This rig can get through the winter, but there are some modifications which can improve the efficiency and allow it to work in the much colder conditions, e.g. a fully enclosed derrick and catwalk (Fletcher, H. 2011).

Figure 3.18 indicates how severe the operation condition could be. That is why Fletcher, H. (2011) strongly recommended that rig equipment must be certified to -40℃. Some key equipment, such as elevator or well control equipment, if they lose function due to the extreme low temperature, the result could be a catastrophe. So a chart ‘equipment capacity vs. temperature’ must be available on site. During drilling, if the drill pipe is stuck, can the driller use full lifting capability of the rig to release the stuck? If in the normal temperature, yes; but in the Arctic, most of the equipment capability has been discounted due to the negative effect of the low temperature to the material. So most the rigs cannot fulfil their supposed responsibility in the Arctic area.

Figure 3.18 Frozen TDS and hydraulic Elevator
Courtesy to Fletcher, H. (2011)

Besides the factors mentioned above, there is another measure proven to be useful; suitcases and containers, which can protect pipelines to a high extent. Pipelines are one kind of components easy to be damaged by the cold. A corridor can be used to protect the connections between rig and mud package, which makes the visual inspection and maintenance easier. Figure 3.19 shows how the rig, mud package and suitcase are connected together. One more virtue of this design is it can make the rig move between different slots faster and more convenient. One key issue should be kept in mind that all the equipment for the suitcase and mud package should be explosive proof.

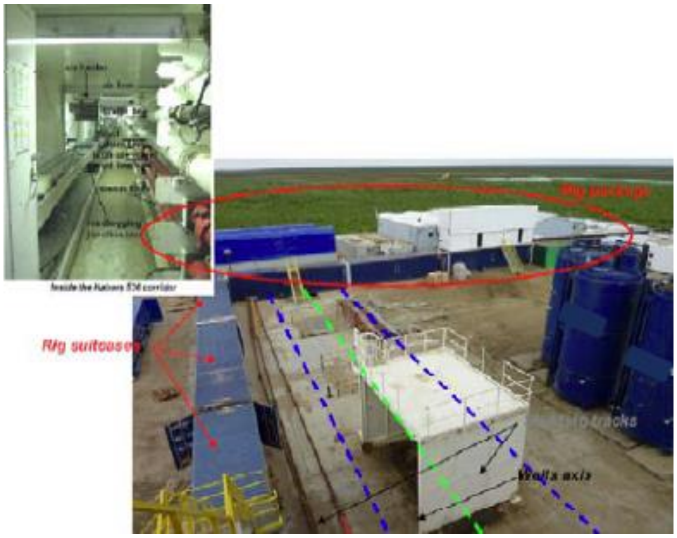


Figure 3.19 Rig lay-out suitcase and mud package
Courtesy to Fletcher, H. (2011)

Personnel

Even with the best winterization rigs, the personnel still need to work in the exposed areas where no protection from wind wall or other physical protection exist, so how to make the crew work safely and efficiently is another challenge to the designers and decision makers. One of the absolute rules in the Arctic is that if the temperature is lower than -40℃， all the operations must be stopped until the environment changes warmer.

To protect the personnel from attack of the cold, the principle about heat loss and heat gaining should be acknowledged, which is recommended by Dahl-Hansen and O’Connor (2008), as shown in figure 3.20.

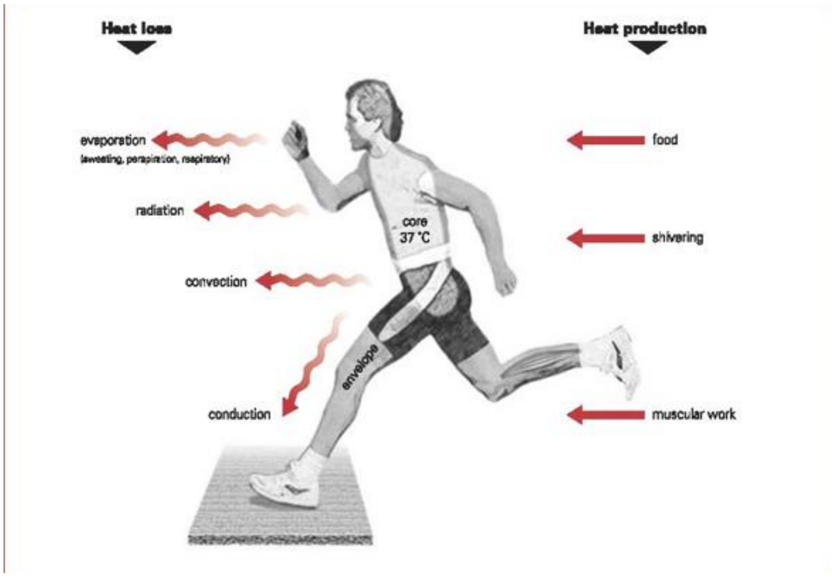


Figure 3.20 Heat loss and Heat production, a diagrammatic representation of man’s thermal exchange with his environment
Courtesy to Dahl-Hansen and O’Connor (2008)

The diagram shown above illustrates two methods to conserve heat: to reduce heat loss and increase heat production. As shown in the diagram, there are 4 kinds of heat loss:

- **Convection –** This happens when the heat is transferred by movements of the air close to the skin, wind chill effect belongs to this type;
- **Radiation -** The heat is transferred from the warmer objects to the cooler objects in the surrounding environment.
- **Conduction –** The heat is transferred between objects which are contacted together;
- **Evaporation -** The physical process that the fluid state into the air state.

So the design of personnel working space should be as per these 4 types heat transferring types to prevent heat loss, and the same rule goes well for the selection of personnel protection equipment (PPE). When the human body's temperature is lower than normal, some instinct reactions indicate how the humans protect themselves: the blood vessels in the skin, muscles, fat and bones would constrict to reduce heat loss and reduce sweating, which is a typical way for heat loss.

Another solution is to produce more heat to compensate the heat loss as per the diagram:

- ✓ To take more food of high energy;
- ✓ Muscles starts work automatically (Involuntary shivering, up to 3-5 times than resting level)
- ✓ Normally the fitful and strong personnel have better capacity to shiver
- ✓ To engage more physical activity, e.g. up to ten times resting level, which prove to be an efficient way.

Dahl-Hansen and O'Connor (2008) have recommended some combinations of clothes which suit the Arctic operation environment:

- Internal Layer (underwear): function of moisture absorption and transportation, which will take away the sweat immediately and make the personnel feel comfortable;
- Middle Layer (shirt, sweater): function of insulation and moisture transport, which could help to prevent attacking of the cold and remove the sweat produced during work;
- External Layer (wind breaker, protection against the external arctic clothing, rain gear), function of windproof, waterproof and breathe, which would help the workers to withstand the strong wind, rain, snow and dry the sweat produced inside quickly.
- This combination of clothes is called 'smart' clothes combination, and already proved to be functional in the North Sea, hundreds of thousands of workers in the oil and gas industry have benefited from this method.

FMJ & FJM

To improve the reliability and safety level of operations in the Arctic, two principles - FMJ and FJM - need to be introduced, which are instructive to the work in the extreme conditions.

FMJ, with the full calling 'fit the man to the job', is the philosophy that proper workers should be selected for particular jobs, e.g. physical strong and psychological healthy people can be selected to work as fire fighters; people with innovation should be selected to work in the creative jobs.

This rule goes well in the personnel selection of the Arctic. Dahl-Hansen and O’Connor (2008) have listed some personnel who are not recommended to work in the cold regions:

- ✓ Personnel with cardio-vascular diseases
- ✓ Raynauds syndrome infectors, usually with white finger indicating constriction of blood vessels
- ✓ Asthma caused by cold air;
- ✓ Urticaria infected person;
- ✓ People having caught previous cold injury;
- ✓ People who tends to abuse alcohol and drug, or heavy smokers who may have respiratory problems,
- ✓ Severe obesity people (Body Mass Index (BMI) > 35)
- ✓ Other disease infectors who could be worse affected by the cold.

FJM, with the full name of ‘Fit the job to the man’, is the opposite theory to FMJ, which is the guiding philosophy of ergonomics, based on the argument that in most of the human engineering and workspace design, the job tasks should be designed to suit the characteristics of the worker, because the supporters of this approach have assumed that a suitable set of worker characteristics can be specified; around which the job can be designed, and this can be done for any job. All the physical modification of the rig to improve the safety and comfort can be considered as one kind of FJM.

To date, some offshore facilities have utilized one kind of advanced technology, condition monitoring, to monitor the condition of their critical equipment, which can be employed in the Arctic region as per the FJM philosophy. Modern sensors could be installed on the equipment placed in the area where it is inconvenient for people monitoring by routine inspection, then the condition of the equipment can be monitored by the personnel in the office, or even onshore through remote signal transmission. This method could eliminate outside working time of crew, without sacrifice the reliability of the equipment.

xcept above mentioned hardware, there are some soft management ways to improve personnel safety in the Arctic, e.g. to optimize crew change schedule, which will reduce people’s work in the exposed cold environment; to avoid sending single people to work in the cold, try to stay in pairs, then each person could look after the well-being of the other; to arrange the work systems in Buddy system, to allow people to assist each other; work in the exposed cold area is just like the work in the sealed container / tank, the risk level of these two operations is similar to some degree; to keep good communication, then if anyone in danger might be detected immediately.

There are some other methods that might be favorable: to store additional supplies of food, water, clothing and gasoline all the time; to set up an emergency or evacuation plan; to have a communications system for backup; to prepare the best and reliable medical support; to establish appropriate medical surveillance routines and health alarming system; to improve work/rest regimes, and other operational routines to help workers prevent fatigue and manage stress, which could cause severe psychological disease and high accident rate (DNV, 2008).

3.5 Solutions for weak logistic support

Some constructive and feasible solutions targeting at the weak logistic support have been proposed by the Arctic researchers and oil companies.

- To improve the poor logistics service, capable vessels are necessary. Serck-Hansen and Gudmestad (2011) have stated that for the vessels' design requirements in the Arctic, generally speaking, all the vessels supposed to work in this area should be designed as per "ice class". Even ice conditions might vary in different parts of the Arctic, to ensure the complete operability of the vessels in the winter, the 'ice class' level is recommended to be the vessels construction standard;
- For the vessels designed to allow for flexibility in contracting outside the main area for the design and the time foreseen, Gudmestad and Karunakanran (2012) have advised to implement some ice strengthening, because specialist vessels might be very competitive in the winter season to carry out offshore support jobs;
- If the ice condition is worse than the vessels' withstanding capability, it might be helpful to make up a fleet with ice breakers, which could help to establish safe access for the other vessels;
- A well panned schedule is required, especially in the Arctic where the logistics activities are strictly restricted, good preparation and quick response are preferred;
- Investment in construction more bases close to the oil and gas fields is worthwhile, which should be of the function of support stations;
- Big size helicopters with modern communication and rescue equipment are recommended, because they can fly for long distances and could withstand tougher weather conditions such as waves or wind/current;
- When the logistics is not reliable, the rig should be able to store enough food, fuel and water, etc., so the 6th generation rigs is recommended, because its huge deck could store more material, which will reduce the frequency of the logistics supply, then decrease the risk caused by unreliable logistics (Pilisi et al., 2011), Figure 3.21 shows the currently widely utilized drilling structures in the Beaufort sea, one of the distinctive feature between the 5th and 6th generation rigs is that the latter owe larger deck area, which is competitive in the Arctic;
- Enough spare parts should be places offshore, especially for the critical equipment such as well control components;

- Reliable modern communication and experienced professional operation and maintenance crew is a must, in case it is impossible to send specialists offshore to fix the equipment, the crew onboard should be able to fix the problems with the instructions of experts onshore via video or audio, based on the condition description from the people offshore sent information with the photos or videos, this method could improve the reliability of the rigs and reduce the non-production time.

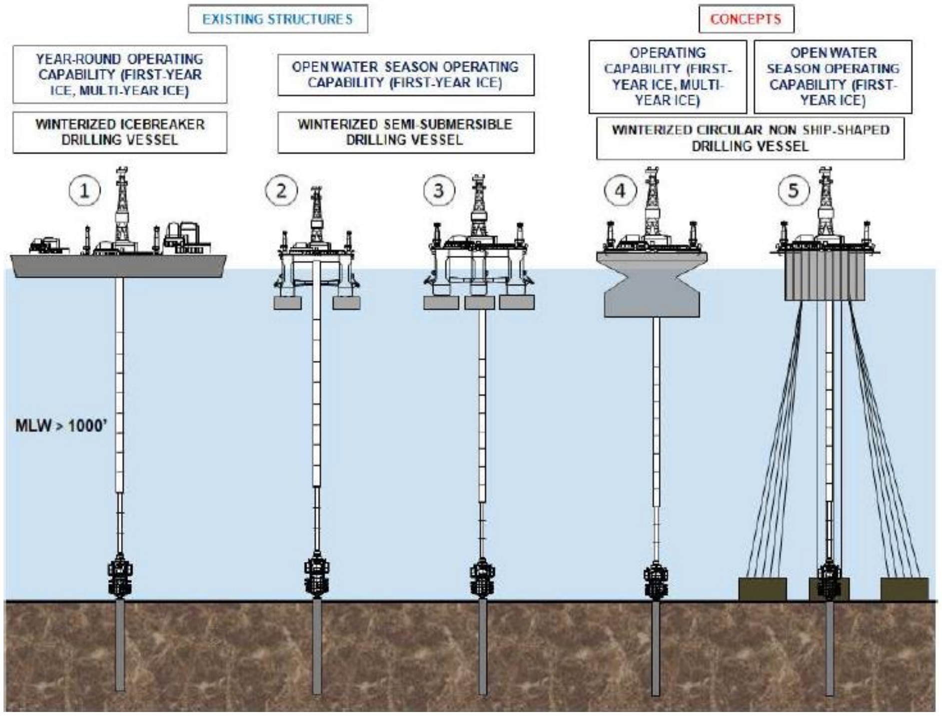


Figure 3.21 Drilling Structures (generation 1~5) in the U.S. Beaufort Sea
Courtesy to N.Pilisi et al (2011)

3.6 Solutions to soil with permafrost

For the permafrost on the land, Barnes (2011) has proposed solutions: well pads，which could minimize damage to the permafrost. Generally a gravel pad with the height of 1m is built up on top of the permafrost, which would insulate and protect the vulnerable environment; besides the advantages mentioned above, well pads will allow for convenient skidding of the rigs and equipment between wells.

For the offshore permafrost, the solution is quite different.

ISO (2003) has special regulations about cement slurry lab tests and operations on-site, aiming at simulating actual permafrost conditions, to eliminate the trouble caused by it:

Temperature: all the material and equipment used in the test should be preconditioned as per actual temperature in the Arctic, and the precision should be controlled to no more than +/- 1℃ (+/- 2℉); The mixing water and chemicals should be pre-chilled as per requirement; all the temperature should be recorded and reported clearly.

Thickening time: it should be carried out in a consisometer at 4℃ (40℉) and atmospheric pressure；

Compressive strength: to simulate multi times freezing and melting during drilling operations, ISO (2003) has established one test procedure for compressive strength test in the Arctic permafrost regions, say, this test started Monday, the procedure about curing temperature and lasting period is:

1) 48h at 4℃ (40℉) Monday to Wednesday;
2) 24h at -7℃ (20℉) Wednesday to Thursday;
3) 24h at 4℃ (40℉) Thursday to Friday;
4) 72h at 38℃ (100℉) Friday to the second Monday;
5) 72h at 77℃ (170℉) the second Monday to the second Thursday;
6) 24h at 38℃ (100℉) the second Thursday to the second Friday;
7) 72h at -7℃ (20℉) the Second Friday to the second Sunday;
8) Raise to 4℃ (40℉) and repeat cycle on Monday.

This procedure is recommended by API as well, because the permafrost is really a particular case in the oil development. Some cement slurries are efficient in the low temperature, and some are functional in the middle or high temperatures, but it seems they cannot supply satisfactory bonding in the permafrost, because after several times their bonding interfaces have been frozen and melted, it could not supply efficient isolation anymore. So the test procedures mentioned above would screen if a cement slurry is satisfactory.

3.7 Solutions to protect the vulnerable environment

There are more than one reason for the slow and late oil and gas development in the Arctic: remoteness, tough weather, weak logistics, etc. The strict regulations should be one of the reasons mentioned before. And to find the right balance point between the oil activities and the environment will be a mission needing time and efforts from all the parties: the international organizations, the governments, the scientists, the oil services companies and the oil companies.

Based on their long period research in the Canadian Beaufort Sea, Pyc and Fortier (2011) have proposed recommendation for minimizing the impact on the environment by the oil and gas development activities. Data collection is the first and upmost job for evaluating the marine operations, which should include: data collection before the operation, which can be taken as the decision making base (e.g. the sea bed condition could determine whether anchor operations could be performed, as shown in the Figure 3.22); data collection during the operation which could help to monitor the impact of the operation to the environment; and data collection after the operation, which could be taken as the final evaluation of the influence on the environment caused by the operation. So the data collection job lasts much longer than the operation itself. Far from that, the monitoring mission has the function of alarming, if anything abnormally has been detected, the operation might be suspended until the reasons have been found and corrective measures have been taken.

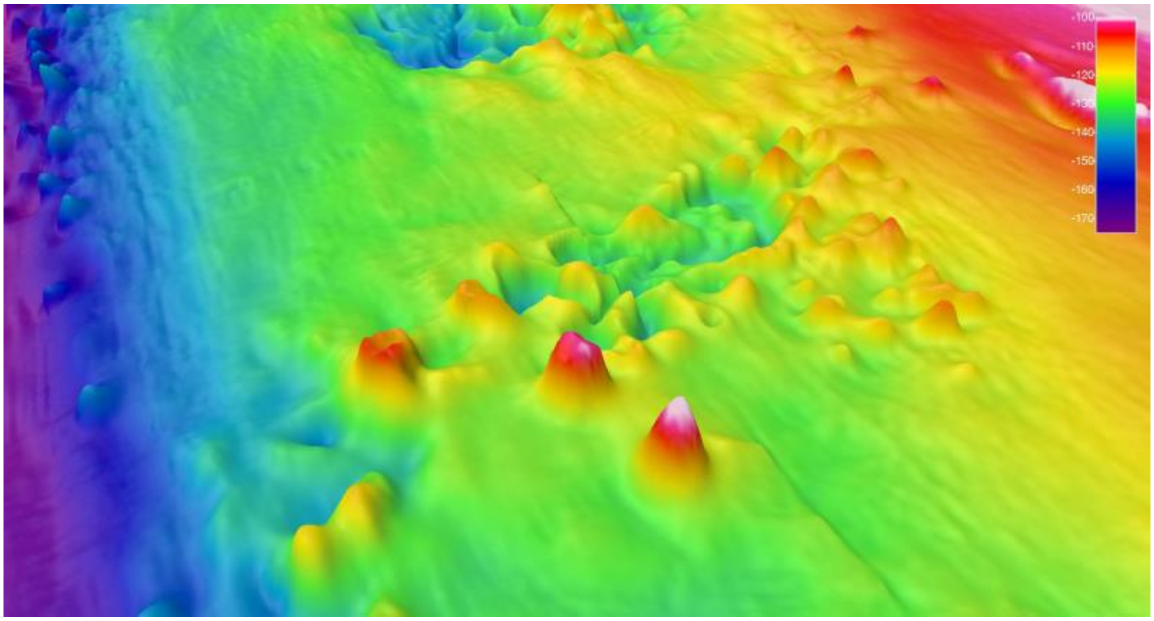


Figure 3.22 EM 302 multibeam 3D oblique image of a rouge seabed, representing equipment anchoring challenges
Courtesy to Pyc and Fortier (2011)

Oil development activity is a newly born business for the Arctic, so there is not more experience or data which can be referred such as how serious the impact to the environment would be, then it is necessary to invest in constructing more sampling stations to collect data for analyzing. Figure 3.23 illustrates one biophysical sampling station invested by BP.

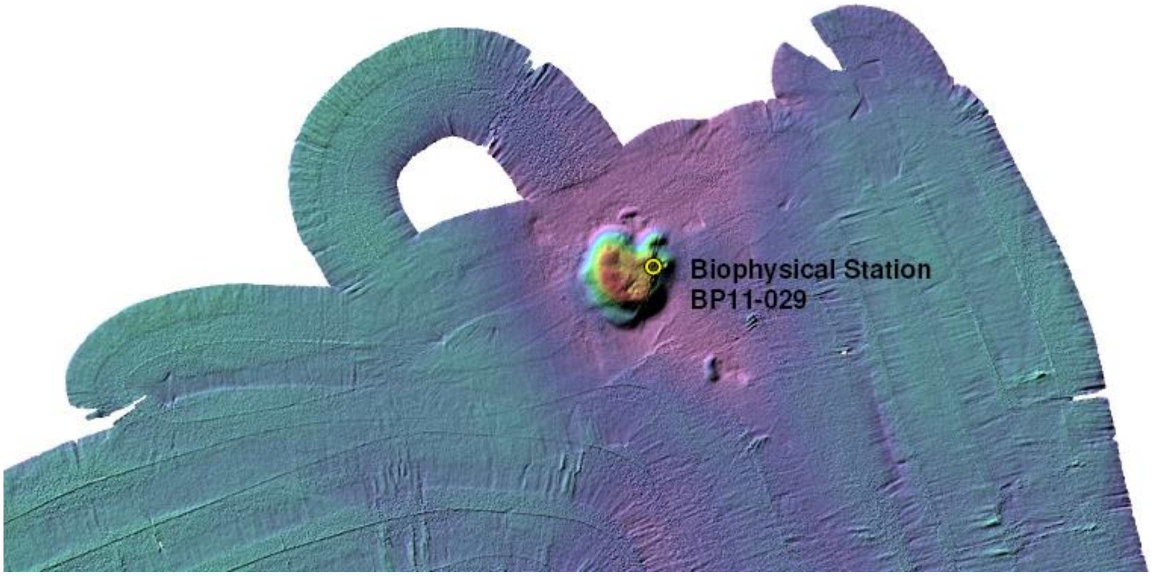


Figure 3.23 2011 biophysical sampling station located on a venting feature identified during the 2010 program
Courtesy to Pyc and Fortier (2011)

The types of the data could be multiple-purpose, such as the following:

- Oil spill dynamical modeling;
- Sea bed stability for modeling situation for anchoring;
- Assessment of sea bed hazards and regions of instability;
- Drilling waste disposal modeling;
- Environmental impact evaluation;
- Environmental protection schedules such as monitoring;
- Drilling design and execution. (Pyc and Fortier, 2011).

The most efficient and cost effective method for data collection in the Arctic is through collaboration of all the interested parties. One typical example cited by Pyc and Fortier (2011) is that the oil company BP has taken use of ArcticNet to extend its team to involve researchers from government and academies and then this collaboration turned out to give better quality deliverables from the research. To share what you already have means you can gain what others already have. Through selfless cooperation, the accumulated significant amount of information could be a sound base for the decision makers, and a favorable contribution to the scientific research for the remote but abundant Arctic.

National governments in the Arctic would play a crucial role in the environment protection of this area. When there is no feasible information to be referred for the potential impact posed by the oil development activities to the environment, the most important role of the governments is to set strict regulations to tightly restrict the activities threatening the environment, until there is clear proof showing that this activity is harmless to the Arctic biological system, otherwise the regulation cannot be loosen. Some non-government organizations should help the governments to monitor and detect the environment destroy actions.

It is well known that regulations and standards in the North Sea about environment protection is nearly the strictest in the world currently, but the biological systems in the Arctic is more vulnerable than that in the North Sea, so higher level standards are required in this area. Furthermore no single country owns the Arctic, so these standards should be accepted by all the counties having interest there. Figure 3.24 shows the standards level recommended by DNV (2008).

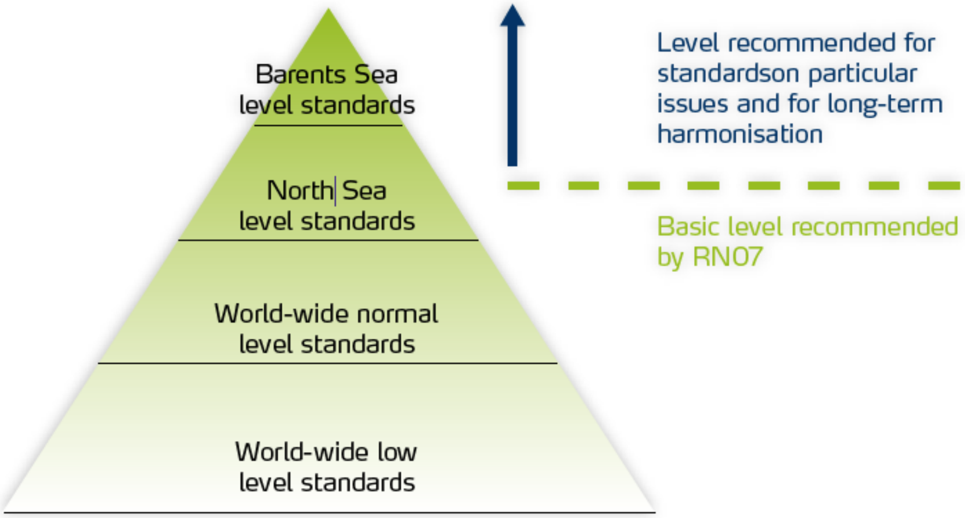


Figure 3.24 Illustration of recommended standard level
Courtesy to DNV (2008)

Statoil has set a good example of how the oil company is fulfilling their responsibility to protect the environment: Use of “Total Fluid Management” (TFM), aiming at planning and operating towards cost and resource efficiency while minimizing the associated environmental impact (Svensen and Taugbøl, 2011). This method requires a well-designed incorporation of planning and executing drilling fluid programs and the relevant drilling waste treatment, and the drilling fluid contractors will get economic incentives when re-use of mud is optimized. In the traditional type of drilling fluid contract, the oil companies are charged by the unit price of the material, which means the more material is used; the more is the income for the contractor. While Statoil has signed another type of the contract with the mud service suppliers: the fluids are bought on a technical specification rather than individual components and the suppliers are obliged to buy the used fluid back. In this case, only when the re-use of fluid is optimized the contractors can make the maximum profit. This type of contracts would drive the drilling fluid contractors to increase the re-use percentage of the fluids by themselves. Figure 3.25 shows how the percentage of re-use fluids is accounting for the total fluids volume.

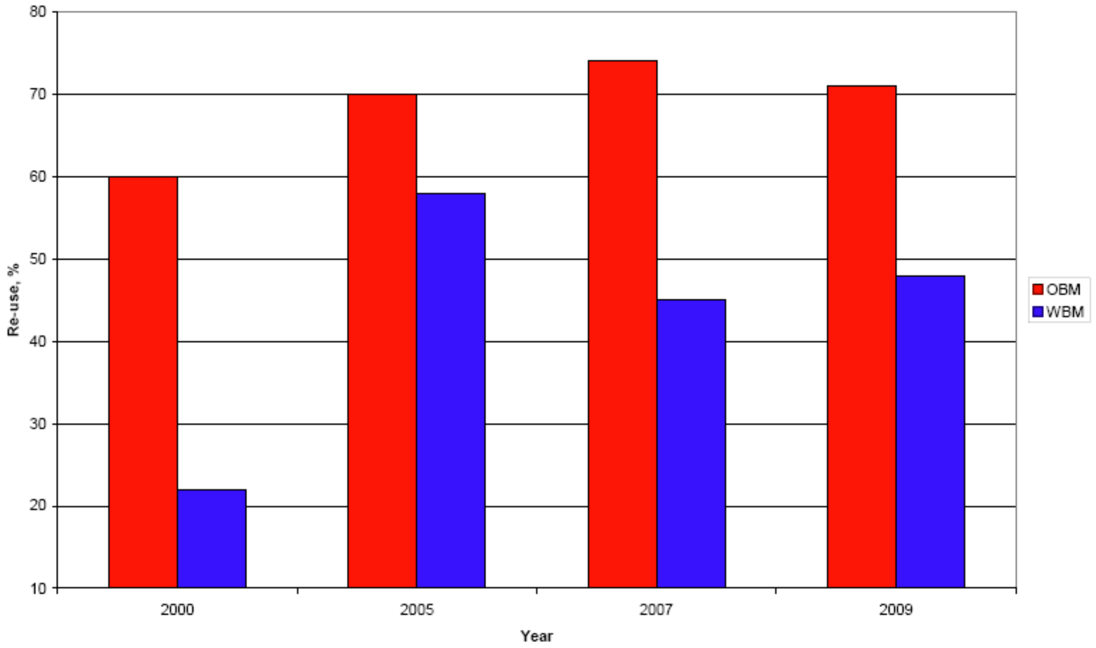


Figure 3.25 The percentage of Re-use of drilling fluid volume as percentage of total volume utilized in Statoil drilling operations offshore Norway, Courtesy to Svensen and Taugbøl, 2011.

Another virtue of TFM is: not only has the cost for the mud material been reduced, but the cost for disposing the drilling waste because the volume of drilling waste from the drilling fluid has been minimized, which is a significant cost especially in the Arctic, where strict environment law and high cost of treating the waste because of the remoteness and needs for expensive ice-class vessels. After introducing this methodology, Statoil has reported that 17% cost of drilling fluid and drilling waste handling has been cut (Svensen and Taugbøl, 2011). Oil based mud (OBM) has been preferred because it has virtues such as excellent pay zones protection, better function for directional drilling, but it carries a higher risk for the environment and higher cost for drilling waste disposal. So far, some new types of water based mud (WBM) have the similar properties with OBM but are more environmental friendly. WBM is recommended to be used in the Arctic. The re-use factor of OBM has been raised from 60% in the year 2000 to recently 70%; while that of WBM has been raised from 20% in the year 2000 to 45% currently.

3.8 Other methods to improve operation efficiency

All the oil companies with interested in the Arctic have to face the challenge of cost and operation efficiency, as mentioned before, considering ice management fleet, ice-class offshore facilities for oil development, the daily rate of the total cost could be millions of US dollars or more, in this case, even half an hour operation time reduction means considerable cost being saved for the operators. Some innovative attempts already have been proven to be both technically feasible and cost effective, such as use of Aluminum Drill Pipe (ADP) and fast-setting cement in the low temperature.

Due to many challenges for drilling with offshore facilities in the Arctic, such as restrictions by ice, icebergs or extreme marine conditions, it is recommended to drill to the target from the land or from artificial islands, which is called extended reach drilling (ERD) or extended reach well (ERW) technology. But this technology requires heavy rig capability because of the considerable drag force and rotation friction, especially in the horizontal section; traditional steel drill pipes tend to be brittle in the extreme cold temperature in the Arctic. So all the factors mentioned above make the ERD technology not feasible. This problem has been solved by the application of Aluminum Drill Pipe (ADP), which keeps the operators satisfied (Alexey et al., 2011).

SPE publications 1~3 have concluded about the favorable features of ADP:

- Nonmagnetic;
- Resistance to Hydrogen Sulfide (H_2S) and Carbon Dioxide (CO_2) ;
- When the pipe is bended, less stress produced inside;
- When the pipes are in uneven rotation, less dynamic stress inside;
- When dipped into drilling fluid, better buoyancy due to low density;
- High strength-weight ratio, as shown in Figure 3.26;
- Low weight. (Alexey et al., 2011)

Under the extreme low temperature, ADP has additional advantages comparing with steel drill pipe in the following aspects:

- Fatigue resistance is getting better with the lower temperature;
- Aluminum alloy has no cold-shortness threshold like steel material;
- Plasticity and ductility increase with the lower temperature, as shown in Figure 3.27. (Alexey et al., 2011)

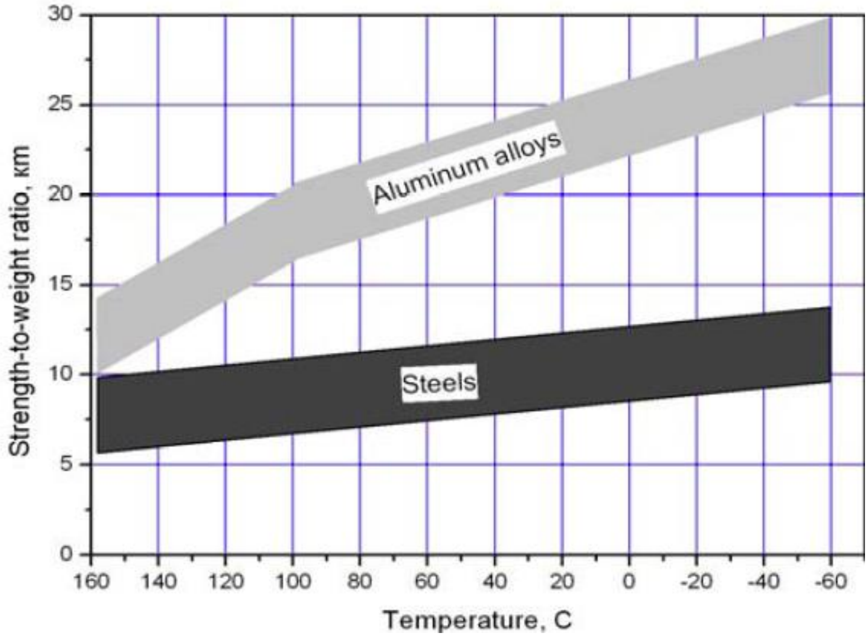


Figure 3.26 Aluminum alloys and steel's specific strength dependence on temperature
Courtesy to Alexey et al. (2011)

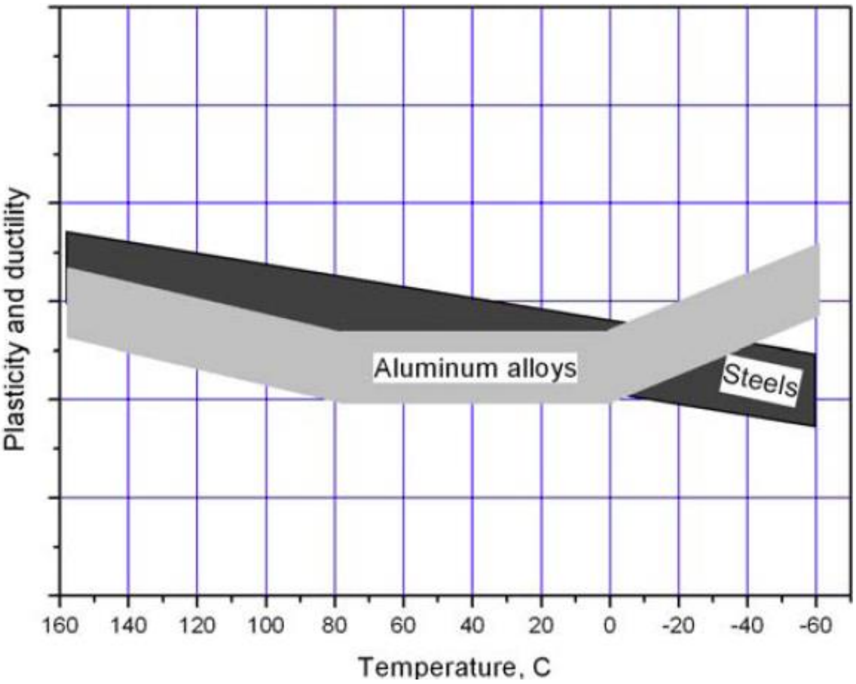


Figure 3.27 Aluminum alloys and steel's plasticity and ductility dependence on temperature
Courtesy to Alexey et al. (2011)

ADP is a very promising tool for oil and gas development activities in the Arctic due to the benefits it can supply as mentioned above. One special type of ADP, LAIDP, with the full name of "light-alloy improved dependability pipe" has been introduced for ultra-deep wells, due to its incomparable advantages, which is believed to be the catalyst for the industry growth, because it improves both technical and cost-effective feasibility. Because of the favorable buoyancy due to its low density, to drill well with the same bit size and same depth, the lifting capacity for the rig drilling with LAIDP is much lower than for the rig with traditional steel drill pipes, the data shows that for the same well, if the required rig lifting capacity with LAIDP should be at least 125 tons, while at least 200 tons lifting capacity is required with the steel drill pipe (Alexey et al., 2011), so the benefit is obvious, because the rig selection range is much broader with the LAISP, or in other words, the same rig utilizing LAIDP can drill deeper wells than that using steel pipes, which could save the oil companies plenty of money. This virtue is really attractive at this moment, because of the high oil price, all the oil companies are eager to drill more wells for increased production, but this desire is limited by the availability of competent rigs, if they could use lower class to achieve their targets, it is certain they are pleasant to start their operation when the other preparations are ready.

Figure 3.28 shows a comparison of the weight on the bit (WOB) of using LAIDP and SDP in a specific well, when building up inclination in a sliding drilling mode. At the depth of 1786m, WOB of SDP is much bigger than that of LAIDP, but with the depth increasing, attenuation of the WOB of SDP is much faster (due to the accelerated drag) than that of LAIDP; an SDP drill string completely losses WOB at 2688m, which means buckling, and completely stuck pipe, while a LAIDP string still keeps 34.5kN WOB at 3126m, which is the target depth, and it is possible to drill deeper (Alexey et al., 2011).

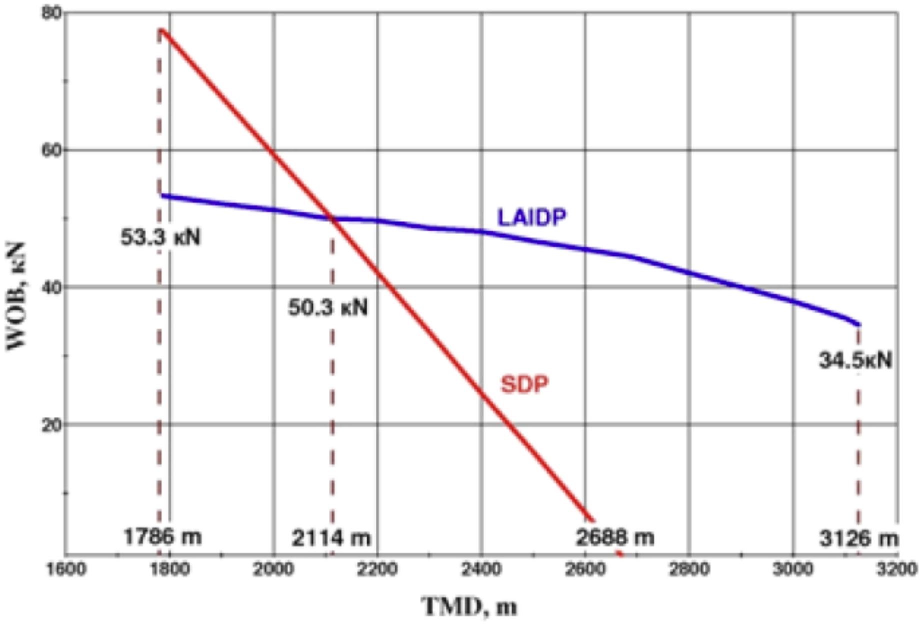


Figure 3.28 Possibility of transmitting WOB by Horizontal Section of Steel and ADP in one typical well in the Arctic
Courtesy to Alexey et al., 2011

The virtues of drilling with ADP are not limited by what is above mentioned, because of less drag for sliding drilling, it can drill an ERD (equivalent circulation density) well without using a steerable-rotation system (Baker Hughes) or Power Drive (Schlumberger), with daily rate of hundreds of thousands of US dollars, so the cost-effective feature is attractive to the operators as well. This economic return to the project could change a project economically from infeasible to be appealing after utilizing ADP. Figure 3.29 illustrates how the yield stress of the ADP increasing with the decreasing temperature, which is promising in the Arctic conditions (Alexey et al., 2011).

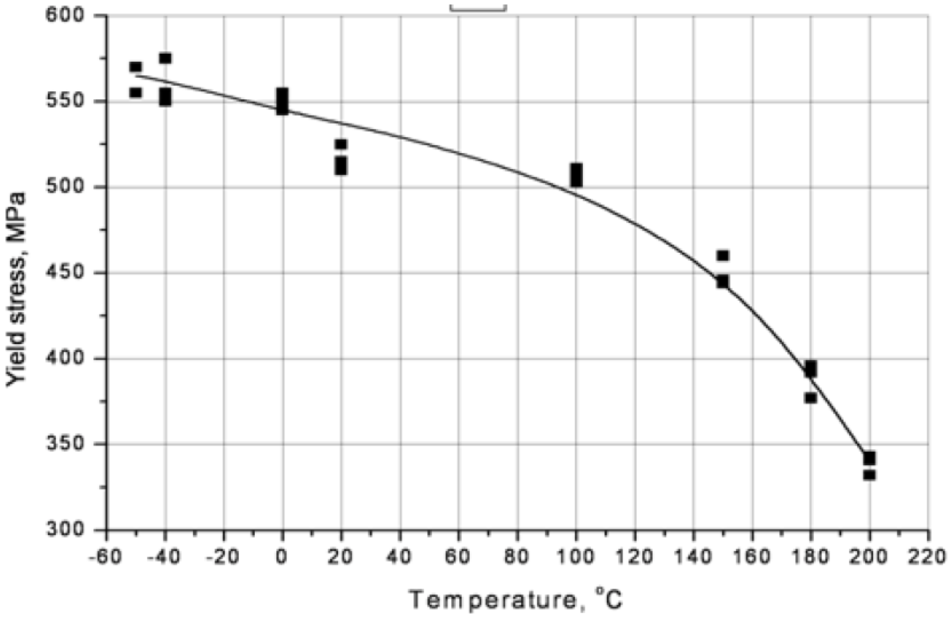
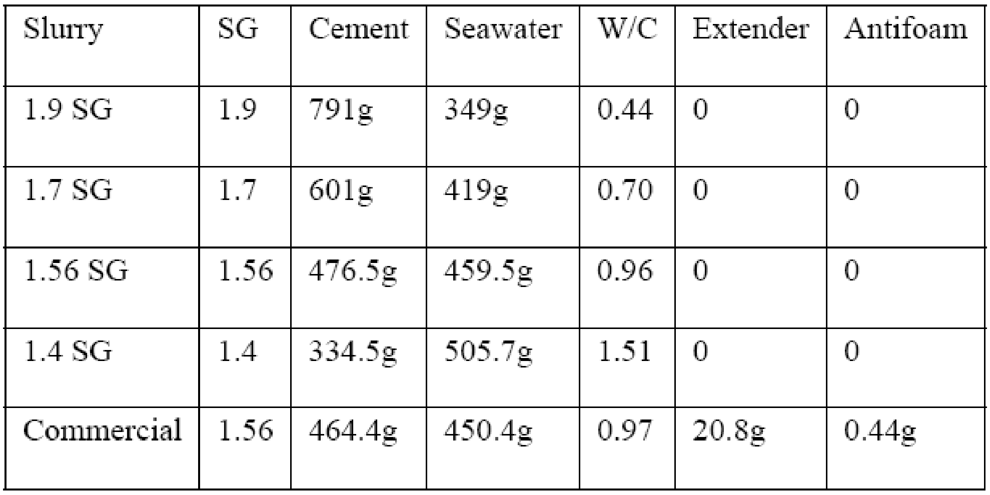


Figure 3.29 1953T1 Aluminum Alloy Yield stress dependence on temperature
Courtesy to Alexey et al., 2011

One good example of utilizing ADP as a torque-reduction tool has been presented in the SPE articles, describing one ERD program in the South China Sea by CACT (CNOOC-AGIP-CHEVRON-TEXACO Operators Group), after replacing 2000 meters steel drill pipes with ADP, the significant torque-and-drag reduction effect allowed the well to be drilled in the required time frame. Data shows the ADP string can achieve the reduction of weight in the mud with 1.7 times than the original steel drill pipe strings. (Alexey et al., 2011).

Low temperature cement slurry

The importance of top casing or conductor to the oil operations is well known, which is to supply passage for the drilling fluid of the following drilling procedures and to support the next casing string and the riser or wellhead connection. If the sea bed is in good condition, they can be driven directly into the soil, eliminating the necessity of cementing; if the sea bed condition is not that ideal, the conductor or top casing will have to be bonded with the soil through cement. In the early research, most attention has been laid on the formation integrity of the casing shoe, which is crucial for the next drilling job, because if it is not sound enough, the high hydraulic pressure caused by ECD (equivalent circulation density) would break through the formation and serious mud loss is possible, which is troublesome and costly to deal with. The formation of surface casing is usually too weak to hold the high hydraulic column pressure right after the cementing job, to avoid this problem without losing quality of formation integrity of the casing shoe, the composition of low density lead cement slurry with high W/C (water cement) ratio and high density tail slurry with low W/C ratio have been widely used in the surface casing cementing design, because the tail slurry would produce very good bonding quality around the casing shoe. AS shown in Figure 3.27, tail slurry is spotted around the casing shoe and the lead slurry is placed above the tail to the surface. Because of the low density of the lead slurry, total hydraulic column pressure of the fluid in the annulus is lower than for the only tail slurry column.



Slurry	SG	Cement	Seawater	W/C	Extender	Antifoam
1.9 SG	1.9	791g	349g	0.44	0	0
1.7 SG	1.7	601g	419g	0.70	0	0
1.56 SG	1.56	476.5g	459.5g	0.96	0	0
1.4 SG	1.4	334.5g	505.7g	1.51	0	0
Commercial	1.56	464.4g	450.4g	0.97	20.8g	0.44g

Table 3.1 Slurry Composition (given in gram per 600 ml)
Courtesy to Lorents et al 2011

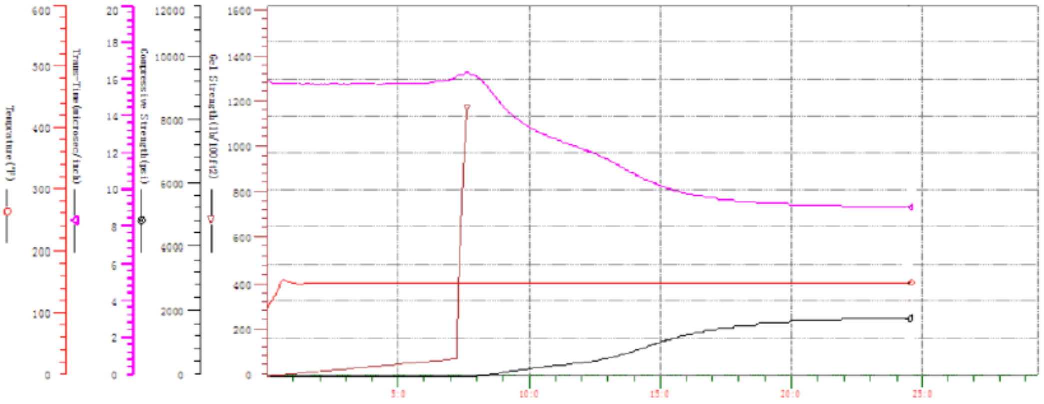
Even though the combination of lead and tail slurry can help to solve the risk of formation loss, when this technology is used in the Arctic, another big challenge has troubled the operators: slow compressive strength development in the low temperature of the lead slurry. At the beginning, only the development of tail slurry compressive strength has been paid attention, because at that moment it is well accepted the idea that the function of the lead slurry is just to fill up the annular. Recently this idea has been considered as a misconception due to at least the following 3 reasons:

1) Surface casing would bear extreme high load if it cannot take the support from the formation through cement bonding, and this load could destroy the surface casing if next layer of casing string is long enough, which is fatal to a casing holding high pressure; to wait on cement to set hard enough, the next drilling operation such as connecting the well head to the riser, must be suspending until it is believed so, the cost for WOC (wait on cement) is considerable to the operators;
2) The lead cement slurry for surface casing might go through a shallow gas zone, if the slurry doesn't get the desired strength in a short time, the gas would cut through into the slurry column and form a channel to generate a gas passage to the surface, which is troublesome as well;
3) Some development projects might take batch drilling mode, which means to drill and run all the surface casings in one batch and then drill and run next casing string one well by another, so if the neighbor surface casing lead cement has not enough strength, mud of the well being drilled would displace the lead slurry out and generate channel for the new passage, this condition is awfully tough, the author of this thesis had very bad experience with this condition in the PL19-3 A development project in 2002, which has taken big amount of cost to solve the problem.

As mentioned before, the density of lead slurry is low due to its high W/C ratio, which is very slow in strength development in low temperature. In other regions, it can be optimized to be set hard faster via adding some accelerators, but the same solution is infeasible in the Artic because most of the chemicals are prohibited to be used in here, both the types and quantities. Generally the cement slurry with high W/C ratio tends to have more free water, if it is accumulated in the annular for some volume, it will be frozen in the low temperature and destroy the casing due to expanding.

One solution is available for solving shallow gas problem, which is the optimized slurry recipe with good property for gas blocking. The simulation indicates that after the cement slurry has been displaced to right position, at the early stage it is still in fluid state, so the hydraulic column pressure above the shallow gas zone would keep the gas in the formation and not be able to cut through into the slurry column; at the late stage, when the cement slurry is already very hard, enough to be cement stone, the gas cannot go into the stone either. In fact the gas cut always occurs when the cement slurry is just a lose hydraulic column pressure but still not hard enough to be cement stone, which can be indicated by the static gel strength, and one special instrument, UCA (ultrasonic compressive analyzer) can be used to test the value of static gel strength without destroying the compressive strength development of the cement slurry.

The time window for possible gas cut can be indicated by the static compressive strength value, which is the period between the static compressive strength values 100psi to 500psi, which means that when the static compressive strength is lower than 100psi, the hydraulic column pressure is enough to prevent gas cut; when the static compressive strength is higher than 500psi, the cement stone is hard enough to prevent gas cut as well. So if this time window of the existence of one type of slurry is short enough, it is the preferred slurry. Some oil companies require this time window from static compressive strength 100psi to 500psi to be less than 30 min or 45 min normally. The slurry in Figure 3.30 has the required time window of 5 minutes, so it has excellent gas block function and would have fantastic performance in a shallow gas wells.



Temprature 1: 150.00	Gel GV1 (75) : 424 Minutes	Comp-Strength CV1 (594) : 250.23 psi	Comp-Strength Start:7: 28
Temprature 2:	Gel GV2 (100) : 425 Minutes	Comp-Strength CV2 (720) : 457.54 psi	Final Comp-Strength:1,848.46 psi
Pressure1: 1450.00	Gel GV3 (300) : 427 Minutes	Comp-Strength CV3 (740) : 501.73 psi	Tester:Admin
Pressure 2:	Gel GV4 (500) : 430 Minutes	Comp-Strength CV4 (760) : 553.66 psi	
Remark:			

Figure 3.30 UCA curve for typical gas block cement slurry aiming at shallow gas
Courtesy to Sun 2013

So the cementing engineers need to pay attention to find the cement slurry recipe meeting the requirements of low density, fast strength development, less free water and good gas block properties. The challenge is low density cement slurry with high W/C ratio, so the compressive strength development is awfully slow, and due to the low temperature condition in the deep water sea bed and in the Arctic, it will be much slower; but the oil companies require the slurry to have early compressive strength to be cost effective. Cement slurry named low density and early desired strength, blended with microsphere might be competitive comparing with traditional cement, but the challenge of chemical additives for the environment still need to be investigated and reported, and substitutes need to be found for the components forbidden to be used in the Arctic.

4 Some risk assessment in the Arctic

Due to the tough natural conditions and crew without rich experience in the Arctic, there are many risks for companies working in the Arctic- These cannot all be discussed in this article, so just some representative risks will be assessed here, such as human factors and oil spill response.

4.1 Human factor

In modern organizations having operations in the Arctic, human is the operator for most equipment, executors for the plans and procedures, and the final decision makers, on the other hand, the limitations of human have made them the party who are easy to commit faults, especially in the organizations with advanced automatic equipment and software, furthermore, people tend to make more faults when they are over stressed or in extreme conditions, such as when there is low temperature. So the uncertainty of the human reaction is one of the key challenges for safety and efficiency. No matter how advanced the equipment is, if the people in charge of operating it don't operate it in correct way, the harm it could cause would be considerable. In fact, the more advanced or more powerful the equipment is, the more destructive the negative effect could be. The reason for human making wrong decisions or committing fault might be his/her own mental limitation or external stress, or a combination of these two factors.

But it does not mean that stress is always negative. Figure 4.1 illustrates the relationship between human performance and stress level, which is recommended by Bercha et al. (2003). From the curve, it is easy to find out: reasonable high "task stress" could help to improve human performance effectiveness, which is best at the optimum stress level; with the increasing of task load, human performance tend to be worse; if the stress keeps going heavier, the performance is too poor to be accepted, which is considered a threat stress, when human performance could be dangerous. So how to find the optimum task stress and keep the crew under this stress level is one of the missions of the decision makers in the Arctic. The FJM (fit the job to the man) theory could help to solve this challenge with the adjustment of crew change schedule, in the PPE (Personnel protection equipment) requirement or in ergonomics. Figure 4.2 shows how the Ergonomics can improve people's working condition and working efficiency as well.

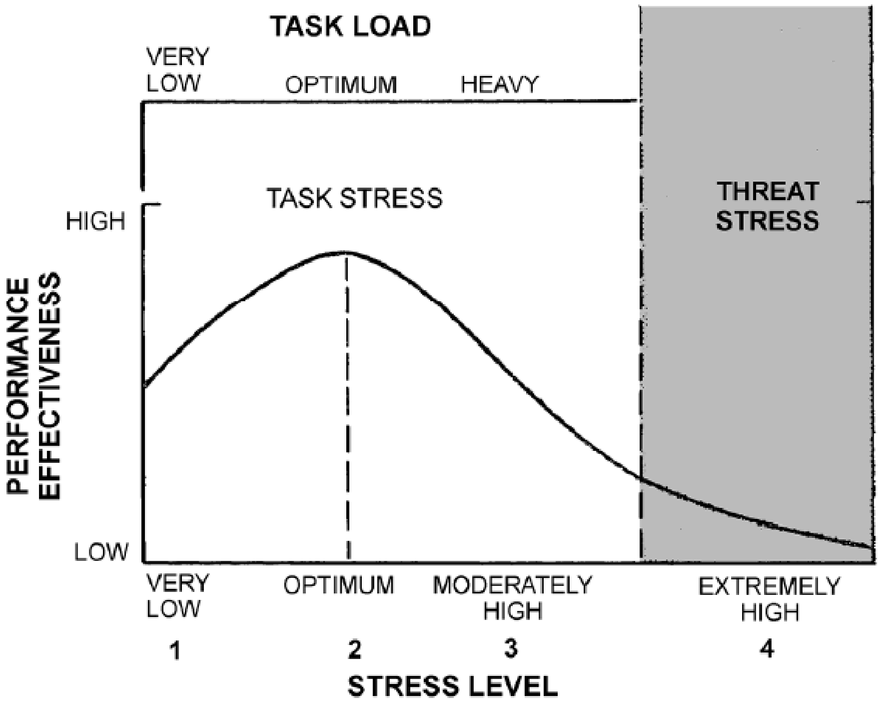


Figure 4.1 Hypothetical Relationship between Performance and Stress level
Courtesy to Bercha et al (2003)

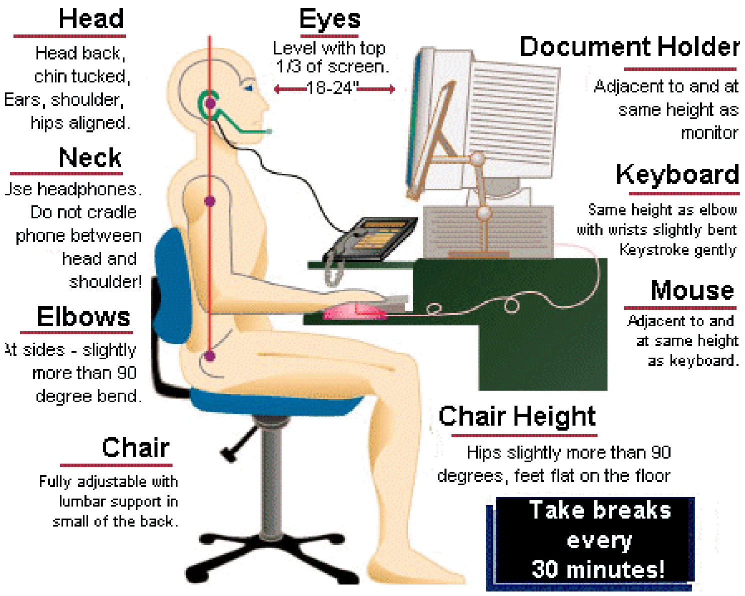


Figure 4.2 One typical illustration of Ergonomics in office
Original photo from UCAR website

Due to the distinctive weather and natural conditions in the Arctic, the operating crew suffers more stress than in other places and the personnel can easily be fatigued. DNV (2008) has analyzed the relationship between work stress and fatigue in the Arctic.

Typical stressors in the Arctic are: remoteness, work and safety responsibility, extreme cold, strong wind, Polar Lows, high waves and currents, long period darkness/light, concern about accidents and evacuation, etc. When the stressors are combined together, the comprehensive effects on human performance are more complicated, the introduction of one new factor to the existing system, might magnify the harm from the other existing factors, e.g. DNV (2008) has concluded that the harmful results on human health of vibration and noise would be stronger in cold and other Arctic environmental factors. So a better understanding of the interaction of combined stressors is one of the key factors for establishing appropriate methods to optimize performance and safety (DNV 2008).

About the stress management, the experts from Russian and Norway, have drawn their conclusion about how to deal with different kinds of stressors in the Arctic, based on their research and investigation in the Barents Sea (DNV, 2010). Figure 4.3 shows the relationship between exposure situation and stress management. As mentioned before, any neglecting of surveillance or insufficient support might cause destructive accident. Strict operation standards should be set up and some effective measures should be taken to ensure all human behavior follow the procedure.

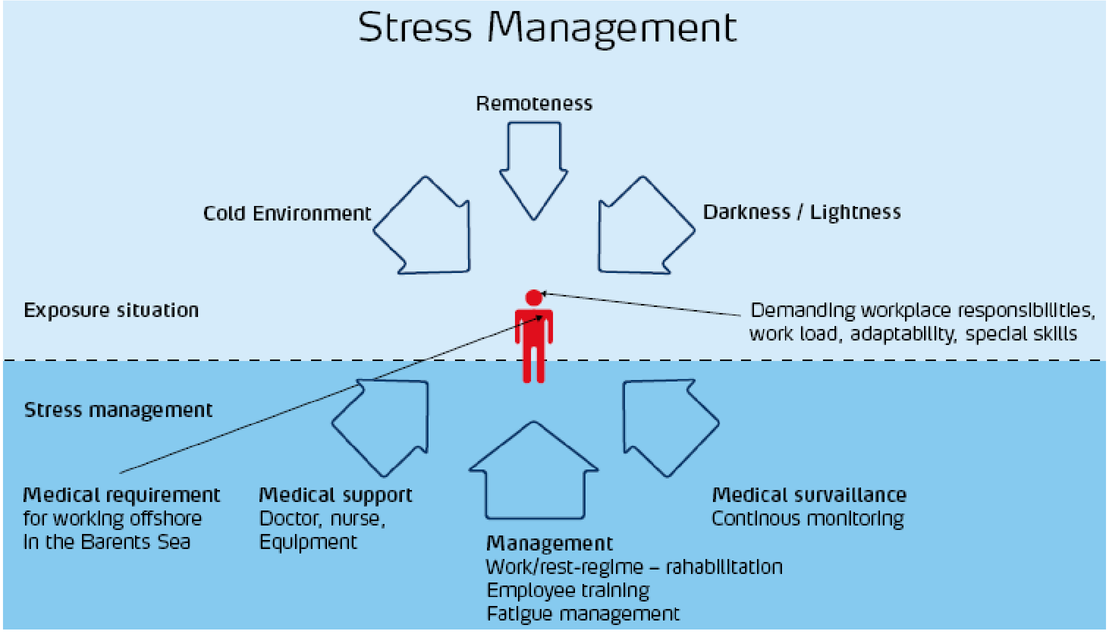


Figure 4.3 Exposure situation and stress management
Courtesy to DNV (2010)

Training plays a key role in optimizing human performance and minimizing risk in the Arctic. DNV (2010) has given their recommendations about special aspects of working in the Arctic, which involve basic medical knowledge (basics of body temperature, heat exchange theory, how to identify hypothermia / temperature-related symptoms, effective measures to deal with hypothermia, cold injury or concern of adverse effects of the cold, hazard caused by carbon monoxide poisoning and alcohol in the extreme cold), warm keeping theory (about how to supply sufficient nutrition for different working positions and conditions, clothing requirements), competence requirement for the crew (acclimatization to the Arctic, some kind of illness infectors to influence on tolerance to extreme cold) and phycology knowledge such as relationship between fatigue and stress.

Except all the aspects mentioned above, decision makers should keep attention on the psychology condition of the operation crew. If they find that someone is overstressed, they should find some way to help them to release the stress; if the condition does not change to the better, they must move this kind of people from the working position, because he/she tends to commit more faults, which might be very dangerous for the safety of crew and operations. As shown in Figure 4.4, this guy would not follow all the operation and safety procedures as expected, which could be a significant potential risk. So in the Arctic, psychological health is also important, because human is easy to catch mental diseases. If human are not defeated by the panic and desperation when there is emergency, they will make correct judgment and decision, then take proper actions. So this kind of practice and training should be taken objectively.

Figure 4.4 How if people over stressed

Courtesy to meimeidu website

Team work is one necessary feature for the people working in the Arctic, surveillance, good communication, emergency response and first aid, etc. almost all activities require sound cooperation of the crew.

Because humans have not carried out plenty of operation in the Arctic, not enough cases could be referred to, so experienced working team with sound safe operation records is preferred at this moment, which could help to reduce the risk and improve the performance in every aspects. The researchers should speed up their work on how physical and mental health conditions influenced by the special Arctic natural environment, e.g. the needed frequency for personnel's physical examination for detecting abnormal human health. It is worthwhile to invest in establishing simulation environment of the Arctic for training. Some distinctive features of the Arctic must be identified, such as non-reliability of common communication equipment because of the magnetic influence by the Magnetic Pole.

4.2 Oil spill response

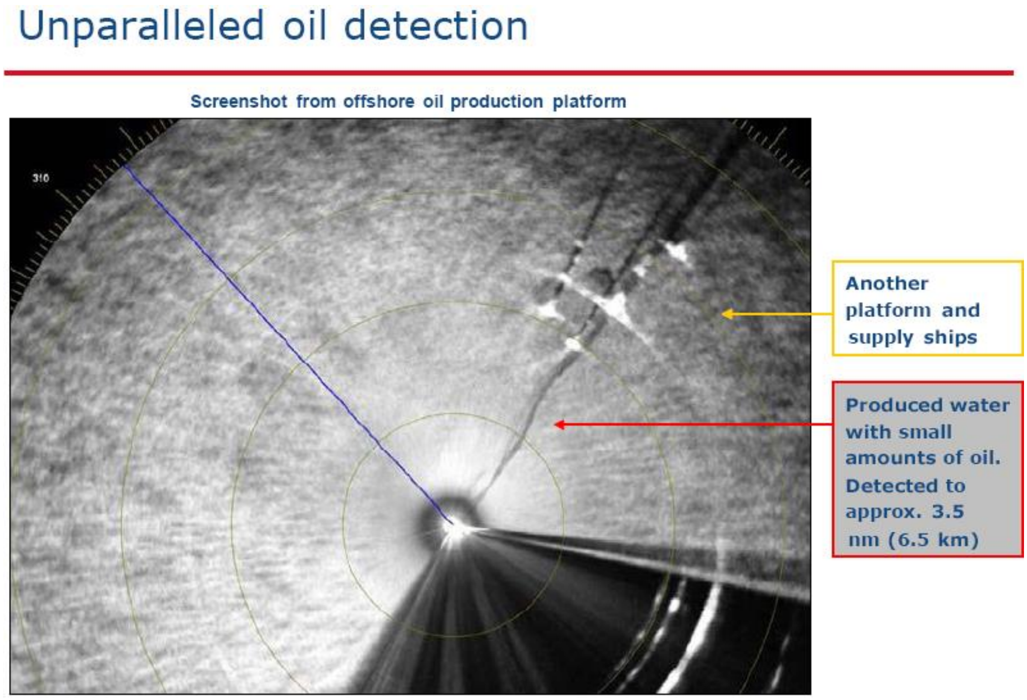
The vulnerable environment in the Arctic has nearly no tolerance to external invasion such as spilled oil, so the measures for prevention oil spill, for oil spill detection and clean-up are critical for environment protection, which is discussed as a typical example. Oil spill has been discussed exclusively because the shock resulted from the severe accident in the Gulf of Mexico by BP in 2010, April.

Offshore oil spill occurs in the following conditions: blow out, rupture of subsea pipelines, loading or offloading of the oil and equipment problem for machine or hydraulic oil invasion into cooling water. So the first step in the management chain is to prevent oil spill:

- reinforce inspection frequency of the subsea pipelines, monitoring oil transportation pressure;
- ensure the reliability of critical well control equipment such as BOP, spool and accumulator, etc.;
- attention to the running conditions of hydraulic pumps and diesel engines, keep monitoring machine oil or hydraulic oil level, sampling of the discharged cooling water;
- to ensure subsea pipeline quality; a enough investments should be put on the construction and laying of them;
- When weather or equipment is not in an accepted condition, all oil loading and offloading operations should be suspended.

Even all the preventive steps have been taken, oil spill still cannot be avoided absolutely. It is well known that the earlier oil spill is detected and effective measures are taken, the smaller the pollution and the cost for clean-up would be. So the oil spill detecting equipment and technology play essential roles in this respect. Except measures mentioned above of monitoring transportation pressure and human surveillance, some new and advanced technology could be induced to optimize the operations. Isaksen and Harvo (2011) have proposed advanced radar technology combined with new sensor and Polarized technology to perform 7/24 surveillance in all-weather to help monitoring oil spill or rescuing people-over-board, this kind of equipment and technology from Sea-Hawk already has been proven successful by the field experience.

Figure 4.5 shows one typical spill oil which is detected by the radar from one oil production platform, the concentration of the oil is only 6ppm and the distance between the spilled oil band and the radar is 6.5km, both the long distance and the low concentration can illustrate how accurate the new technology is.



Unparalleled oil detection

Screenshot from offshore oil production platform

Another platform and supply ships

Produced water with small amounts of oil. Detected to approx. 3.5 nm (6.5 km)

Figure 4.5 Unparalleled oil detection: Produced water with 6ppm oil component Courtesy to Isaksen and Harvo (2011)

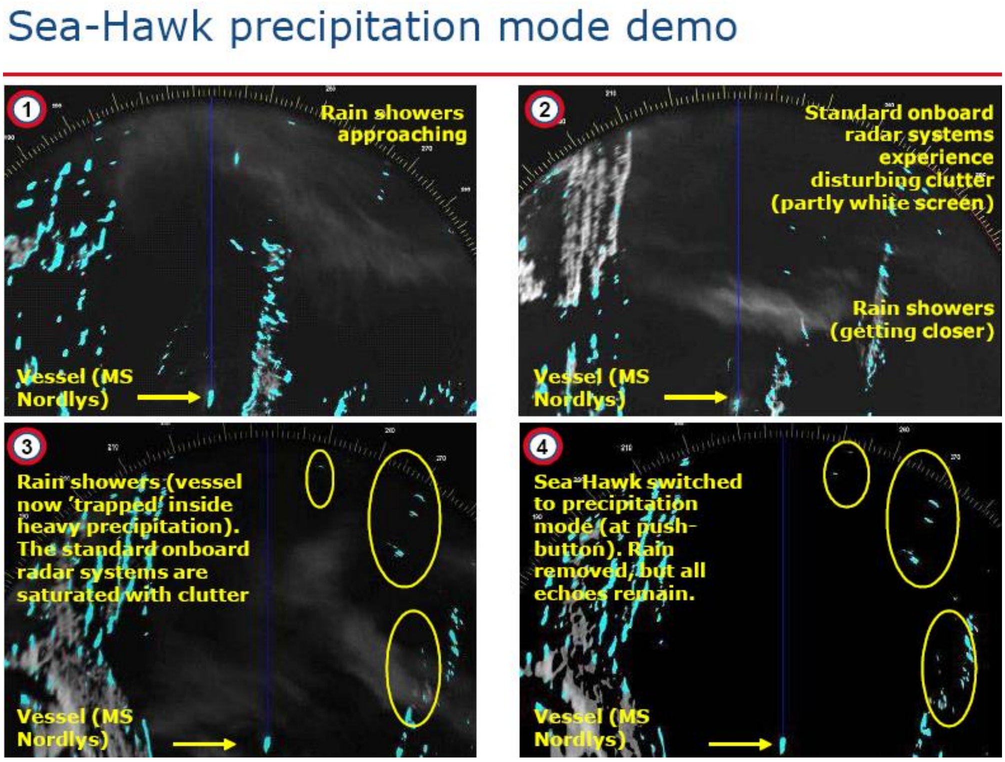


Figure 4.6 Sea-Hawk precipitation mode demo
Courtesy to Isaksen and Harvo (2011)

Figure 4.6 illustrates how the "precipitation mode" of the Sea-Hawk radar can eliminate the influence of the weather, which is more required in the Arctic where weather influence always exists. This optimization is very valuable for application in the Arctic. In fact many military advanced technologies and equipment could be taken for civil use in the Arctic for improving the environment protection or the human safety level, just as in the example mentioned above.

Due to the low temperature and the presence of ice cover, the migration mechanism of the spilled oil is quite different from the other regions. So the emergency response measures should be set up as per the special features of the Arctic to make sure they are effective and economical. Figure 4.7 shows the spilled oil condition in ice floes with 4-6/10 concentration pack ice.

Figure 4.7 Oil in slush between ice floes in 4-6/10 pack ice
Courtesy to Dickins (2011)

The particular natural conditions of the Arctic play complicated roles in the migration of spilled oil, some are favorable (ice cover and low temperature could slow down the oil spreading and provide a longer time window for response) and some are troublesome (the ice cover might cause the oil spill below it difficult to be detected). Dickins (2011) has concluded about the special features of spilled oil and some effective methods for clean-up as follows:

- in high ice concentration (higher than 7/10), the spilled oil is easily to be immobilized and encapsulated in the ice, which helps to control the pollution to spread to bigger area;
- oil encapsulated in the ice is separated from all physical processes such as evaporation, emulsification and dispersion, which improves the possibility for effective combustion (burning) in the later phases when this task is easy to be carried out;
- fast ice could be used as natural barrier to prevent spilled oil to spread or contaminate the vulnerable coastal regions, where most animals' activities are performed;
- low temperature would make the spilled oil thicker and more viscous, resulting in slow spreading rate and smaller contaminated area;
- evaporating rate has been reduced due to the low temperate and presence of ice, so lighter and more volatile components could remain in the water for longer time which is easy to be burned for clean-up;
- The ice could hamper the traditional mechanical oil clean-up while it could help to form a thicker oil film which is easier for burning.

The negative influence of the cold and the ice for oil clean-up are:

- The ice cover could be a shield for the oil under it, which is difficult to monitor, and monitoring is not feasible by vessels navigating in the ice pack;
- Oil spreading in the slush and brush-filled leads and opening in the pack ice, is resulting in extreme low efficiency of skimming, Figure 4.8 shows one oil burning job for oil mixed with ice cakes.
- Sensitivity of oil spreading in the ice causes that a change of the ice cover and ice floes might stimulate the spreading of the oil film, e.g. when the vessels approach the spilled oil, the fluctuation may push the oil film to be more thinner and less unrecoverable;
- Gelling is possible because of the gelling point of crude oil. (Dickins, 2011).

Figure 4.8 Burning oil mixed with ice cakes and pieces collected within a fire resistant boom

Courtesy to SINTEF Oil in ICE JIP

Anyway, the best solution is to prevent oil spill, because the environment is so brittle. Even if burning has been proven to be successful and efficient way for clean-up, the smoke after burning is still polluting the atmosphere. In fact it is just a method to use one less harmful way to deal with another more harmful way. In the future, the research about oil particles migration, and evaluation about the current method for clean-up, such as burning and emulsification, requires introduction about more advanced technology and equipment for surveillance of the oil spill.

5 Conclusions

It should be noted that collecting long term ice and metocean data could not be completed without significant resources and efforts. It is a task requiring international cooperation. Long records of ice and metocean data will allow better planning of operations and may contribute to reducing emissions to air from ship traffic and bring more environment-friendly maritime and offshore activities in the high north

6 COSL capabilities (gap analysis)

Even if COSL is the largest offshore oil services company in the Asia currently, it still has a long way to go for supplying competitive oil and gas services in the Arctic. We will discuss the gap between its capability and the Arctic requirement.

Seismic

The majority of China's offshore seismic market has been occupied by COSL, besides; they also have also supplied services in South East Asia, Europe, America, Africa and Middle East, which involves offshore seismic data collection and data processing / explanation. But the seismic vessels of COSL are not certified to work in the Arctic region, both the equipment and the crew need to be upgraded or trained for the competence of working in this area.

Drilling

27 jack up rigs, 9 semi-submersible platforms, 2 accommodation platforms, 4 sets of module rigs and 6 sets of land rigs make up of COSL drilling fleet; 3 more semi-submersible platforms are being constructed now. All COSL's rigs have been installed with advanced top drive systems, modern solid control units, and diesel engines with big horse power and mud pumps. 2 platforms after modification could drill HPHT wells. As shown in Figure 6.1, HYSY 981 is the newly built platform for deep water drilling, which is capable of operations in maximum 3000 meters deep water and drilling 12000 meters deep wells.

The coldest region in China for COSL drilling operation is Bohai Bay, the lowest temperature is -20℃. In fact, when severe ice cover came, COSL's rigs were moved off the location for evacuation. The ice management methods mentioned above were seldom used due to low ice class of the rigs and lack of ice breakers. The ice breakers were utilized only when the passages were needed for the material-supply vessels. But the branch of COSL- COSL Drilling Europe, AS is working in the North Sea, so they will help COSL to accumulate more data and experience. Anyway, COSL's equipment and crew are not competitive in the Arctic for the time being now, so there is still a long way to go.

Figure 6.1 HYSY981-COSL's deepest water platform
Courtesy to COSL (2012)

Oil field technology service

Wireline logging, directional drilling, cementing, drilling fluid, production optimization are the main services of technology services of COSL. They need to be improved in the following aspects:

- low temperature cement slurry with enough early compressive strength;
- drilling fluid with all composition which can be used in the Arctic region (following the strict standards and regulations);
- drilling waste disposal (following the strict standards and regulations);
- material for stimulation fluid composition;
- workover has the similar challenge as drilling.

Shipping

COSL owns the biggest offshore transportation vessels fleet with the fullest functions. Besides 90 vessels for supply of material and guarding, COSL have 3 oil tankers and 5 vessels just for chemical transportation.

Most of these vessels are not ice-class and only several vessels are ice breakers. So if COSL has ambitions to work in the Arctic, it is worthwhile to invest for purchasing or constructing more ice-class and ice breakers to be competitive in the extreme and ice covering Arctic.

7 Recommendations for COSL’s strategy about Arctic market

- COSL should collect more information about the Arctic including ice data, working conditions and operation experience, through cooperation with companies already performing operations, with the countries around the Arctic and with the research institutes working on the relevant research, because COSL is still a newcomer to the Arctic, the information mentioned above will be favorable to COSL’s services’ development in the Arctic;
- Try to incorporate the effect of ice management into the design of offshore structures, because ice management can reduce the load of ice to some degree, this incorporation could avoid over-design;
- COSL needs to recruit some experts and operation crews who are experienced in Arctic offshore oil and gas operation;
- COSL should adjust its strategies about its equipment upgrading plan, some special facilities with the capability for ice breaking, and ice class platforms need to be considered for fabrication;
- Some oilfield services technology which can improve safety, reliability and efficiency, such as cementing at extra low temperature, should be developed, which will make COSL’s services’ ability more competitive;
- The chemical services should follow the strict environmental regulations in the Arctic, so COSL needs to find the substitutes for the chemicals which are not environmental friendly, to be compatible with the fragile biological system of the Arctic;
- COSL needs to start contacting with capable and experienced companies such as Sea-Hawk, to talk about possibility to install the advanced equipment on his rigs supposed to work in the Arctic

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