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Oil Spill Behavior and Response in the Arctic

Risk Analysis of Existing Response Methods Applicable for the Arctic Conditions

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Master thesis in Technology and Safety in the High North, June 2021

Preface and Acknowledgements

This thesis is submitted as a fulfilment of the requirements for the Master's degree in Technology and Safety in the High North in the Department of Technology and Safety, UiT - the Arctic University of Norway, Tromsø. The thesis has been carried out during the period from February to June 2021.

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Abstact

Due to the demand for diversifying and modifying sources of raw materials and trade routes, the Arctic is the region of high interests. Development and carrying out the offshore activities associated with oil and gas industry and maritime transport are growing rapidly in the Arctic. However, an acute problem associated with the development of offshore activities is the ecological consequence caused by an accidental oil spill that is a complex event due to the variety of scenarios associated with the oil behavior spilled in ice-covered waters. That is why it is of high importance to develop efficient strategies for oil spill response in order to eliminate or decrease the rate of potential negative impacts for the environment, society and economics. However, unpredictable Arctic conditions and lack of appropriate and valid data regarding the effective application of the response methods lead to the demand for developing an approach that combines the challenges associated with offshore activities in cold climate conditions.

The research that has been conducted provides an overview over the spreading and behavior of oil spilled in the Arctic and main influencing factors for oil weathering as well as the existing methods for oil spill response. What is more, the risk assessment for response strategies has been carried out on the basis of hazard identification.

Abbreviations

ALARP	As Low As Reasonably Practicable
DNV	Det Norske Veritas
HAZID	Hazard Identification
HSE	Health, Safety and Environment
IMO	International Maritime Organization
IPIECA	International Petroleum Industry Environmental Conservation Association
MORICE	Mechanical Oil Recovery in Ice Infested Waters
NEBA	Net Environmental Benefit Analysis
OSR	Oil Spill Response
PPE	Personal Protective Equipment
SINTEF	Stiftelsen for industriellogtekniskforskning

Basic Definitions

Barrier:	«functional grouping of safeguards or controls selected to prevent a major accident or limit the consequences» (International Organization for Standardization, 2016, p. 2).
Consequence:	«outcome of an **event** (3.3.4.2) affecting objectives» (International Organization for Standardization, 2008, p. 7).
Emergency response:	«action taken by personnel on or off an installation to limit the consequences of a major accident or initiate and execute abandonment» (International Organization for Standardization, 2016, p. 2).
Environment:	«surroundings in which an organization operates, including air, water, land, natural resources, flora, fauna, humans and their interrelationships» (International Organization for Standardization, 2016, p. 2).
Fate:	«The outcome; the fate of an oil spill is what happens to the oil» (DNV GL, 2015, p. 8).
Harm:	«injury or damage to the health of people, or damage to property or the environment» (International Organization for Standardization, 2016, p. 2).
Hazard:	«potential source of harm» (International Organization for Standardization, 2016, p. 2).
Ice-concentration	«Defined according to the WMO nomenclature; i.e. as the percentage of the sea surface covered by ice» (DNV GL, 2015, p. 9).
Oil slick:	«A layer of oil floating on the surface of water» (DNV GL, 2015, p. 9).
Oil spill contingency plan:	«A document that describes a set of procedures and guidelines for containing and cleaning up oil spills» (DNV GL, 2015, p. 9).
Oil spill response	«Measure implemented in the acute phase of an oil spill with the aim of preventing the spreading of the oil» (DNV GL, 2015, p. 9).

Risk:	«combination of the probability of occurrence of harm and the severity of that harm» (International Organization for Standardization, 2016, p. 2).
Risk analysis:	«process to comprehend the nature of **risk** (3.1) and to determine the **level of risk** (3.3.5.10)» (International Organization for Standardization, 2008, p. 6).
Risk assessment:	«overall process of **risk identification** (3.3.4), **risk analysis** (3.3.5) and **risk evaluation** (3.3.6)» (International Organization for Standardization, 2008, p. 5).
Risk management:	«coordinated activities to direct and control an organization with regard to **risk** (3.1)» (International Organization for Standardization, 2008, p. 3).
Probability:	«measure of the chance of occurrence expressed as a number between 0 and 1, where 0 is impossibility and 1 is absolute certainty» (International Organization for Standardization, 2008, p. 7).
Vulnerability:	«The ability of an environment resource to deal with types of exposure» (DNV GL, 2015, p. 10).
Water column:	«An imaginary cylinder of water from the surface to the bottom of a water body; water conditions, temperature, and density vary throughout the water column» (DNV GL, 2015, p. 10).
Weathering:	«action of the wind, waves, and water on a substance, such as oil, that leads to distinguishing or deterioration of the substance» (DNV GL, 2015, p. 10).

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1 Introduction and Background

Due to the demand for diversifying and modifying sources of raw materials and trade routes, the Arctic is the region of high interests. That is why the international relations and cooperation between the Arctic countries are governed by various factors including economic aspects associated with energy resources of the High North. Development and carrying out the offshore activities associated with oil and gas industry and maritime transport are growing rapidly in the Arctic. However, an acute problem associated with the development of the Continental shelf and the Arctic seas is the ecological consequence caused by an accidental oil spill. Conservation of ecological balance of the marine and geological systems in the areas of oil and gas production and maritime transportation is one of the main purposes that must be fulfilled by the Arctic countries, especially taking into consideration the process of globalization and internalization of science.

Offshore operations in the Arctic associated with petroleum industry pertains to the category of socio-economic activities that is characterized by enormous degree of environmental hazards because of the toxic nature of hydrocarbons. In terms of toxicity and scale of application, oil is one of the most significant factors of environmental hazard for biota. This primarily applies to the Arctic region that is an extremely vulnerable area due to strong winds and currents, low temperatures, ice drift and a lack of daylight. Moreover, the High North regions of the continental shelf are characterized by a low level of intensity of natural recovery and biological treatment. Therefore, an accidental oil spill can cause a long-term pollution of sea water, bottom sediments, and atmosphere.

An accidental oil spill in the Arctic region is a complex event due to the variety of scenarios associated with the oil behavior in the environmental conditions that are difficult to be predicted (Wilkinson, et al., 2017, p. 424). These factors contribute to the challenges for carrying out the response activites that are governed by the physiochemical features of oil and the characteristics of the conditions for the contaminated area, including weather, climate, sea state, etc. (Singsaas et al., 2020, p. 1). That is why it is of high importance to develop effecient strategies for oil spill response in oreder to eliminate or decrease the rate of potential negative impacts for the environment, society and economics. The effeciency of response procedures can be determined as the scale of reduction of potential negative impact cause by an acidental oil spill that is evaluated in comparison with the absence of elimination activities. (Wilkinson, et al., 2017, pp. 423-424).

The risk assessment for establishing potential hazards for the Arctic ecosystem is based on the studying the behavior of oil that has been spilled in ice-infested waters. In addition, the forecasting of the drift of an oil slick demands the implementation of wind characteristics as one of the main influencing factors not only for providing more reliable results but for analyzing its impact on other Arctic features, especially ice formation (Reed & Aamo, 1994, pp. 2, 6).

Due to the fact that the Arctic region is not well-studied, it is crucial to collect appropriate data and carry out the risk assessment for existing oil spill response methods including the development of subsequent contingency management on the basis of the environmental conditions for the area that is chosen for offshore activities due to the vulnerability of the Arctic to pollution cause by any emergencies (Gudmestad & Strass, 1994, pp. 464, 471).

1.1 Research Problem

The Arctic is a unique region due to its vulnerability to any kinds of pollution and low ability for self-recovery because of severe climate conditions that slow down all the natural processes. Oil spills of any volume cause enormously negative consequences to the environment and ecosystem that have both short-term and long-term characters. The response methods that can be applied and be effective for elimination of the source of pollution plays a great role for not only preserving natural resources of the Arctic but also reducing the negative consequences for human beings. The effectiveness of oil spill response activities in the High North is reduced not only because of unpredictable weather conditions but also because of the absence of knowledge and valid data regarding the behavior of oil spilled in ice-covered waters. That is why the research problem can be defined as a critical need in the sufficient information regarding the dependence of the response methods on the harsh environmental Arctic conditions and behavior of spilled oil as well as absence of a generalized approach for the Arctic region that can use for conducting the risk assessment of response activities.

1.2 Research Aim and Objectives

Aim of the research is to study such a hazard as oil spill, its behavior in ice-covered waters and existing response methods that can be applied in the Arctic conditions. Research will also focus on the characteristics of the climate conditions of the High North and its influence on the oil spill elimination.

Main objectives that are based on the aim are:

1. Studying the spreading and behavior of spilled oil in the Arctic as well as the main influencing factors of the climate and oceanographic conditions for the oil weathering.
2. Studying the existing methods for oil spill response, including aspects for their applicability.
3. Carrying out the risk assessment of existing oil spill response methods in the Arctic conditions implementing HAZID analysis.

1.3 Research Questions

There are three research questions that contribute to the fulfilling the objectives of the thesis:

1. How the Arctic conditions influence on the behavior of oil spilled in ice-infested waters?
2. What are the existing response procedures and methods that can be applied in cold climate conditions for elimination of an accidental oil spill?
3. What are the hazards and associated effects and risks for oil spill response methods when considering the Arctic conditions as the main influencing factor?

1.4 Limitations

The limitations that have been defined and implemented into the conducting the research are:

- The thesis will present a generalized research for assessing the risk for oil spill response methods for the general environmental conditions of the Arctic region. Therefore, no certain case study will be applied for fulfilling the objectives. However, this research may be used as a basis for conducting risk assessment for a particular case.
- The research will be based on the literature review, conducted using documents of authority organizations and experimental data that are valid and reliable as well as on the experience of the researcher. The experts will not be engaged into the research process due to the absence of a particular case study. In addition, the Arctic region is not well studied yet, that is why there is no valid data associated with detailed aspects regarding the effects and subsequent consequences for oil spill response methods. That is why the results will be approximate and contribute to the presenting overview over a proactive assessment.

- The literature review is limited, considering the scale of going deeply in details for physiochemical and biological processes, in order to give a general overview over the oil spill behavior and response methods and focused on the main factors associated with the aim of the master thesis and subsequent limitations applied for conducting the research.
- The influence of ice presence will be studied as the main challenge for offshore activities in the Arctic.
- Risk scoring will be estimated qualitatively and limited due to the absence of sufficient and appropriate data associated with negative consequence for response activities.
- Due to the severe climate condition, biodegradation as a method of oil spill response will not be considered because of its ineffectiveness in the Arctic.
- Hazard identification analysis will be based on the main potential hazards derived from the literature review.

1.5 Thesis Overview

The thesis consists of six main chapter and subsequent under chapters that contribute to conducting a research and fulfilling the defined objectives. The current chapter gives an overview of the background of the research and presents established objectives and research questions as well as defines the limitations for the thesis.

- Chapter 2: presents the literature review that will be studied and analyzed for fulfilling the objectives of the thesis. The chapter is divided into four main groups that describes the Arctic environment, oil spills in this region including the behavior of spilled oil in ice-covered waters, oil spill response strategies and risk management.
- Chapter 3: discusses the methodology applied for conducting the research.
- Chapter 4: introduces the results for the third objective that is the risk assessment of the existing response methods suitable for the Arctic conditions.
- Chapter 5: discusses the finding of the research based on the research questions.
- Chapter 6: presents overall conclusion as well as recommendation for conducting future research.

2 Literature Review

The literature review is divided into four main chapters with focus on a certain topic:

- The Arctic environment (see chapter 2.1);
- Oil spill in the Arctic focusing on the process of oil weathering and behavior (see chapter 2.2);
- Existing methods of oil spill response that are applicable in this region (see chapter 2.3);
- Risk Assessment (see chapter 2.4).

The findings for each chapter contribute to the fulfilling the objectives of the research.

2.1 The Arctic Environment

The harsh environmental conditions of the Arctic that contribute to the difficulties and reduced effectiveness of offshore activities and are considered to be a cause of potential hazards are:

- Presence of ice of various types and concentrations
- Low temperatures
- Wind, waves, storms, ocean currents
- Visibility limitations
- Wind Chill effect
- Polar Lows
- Fog
- Remoteness.

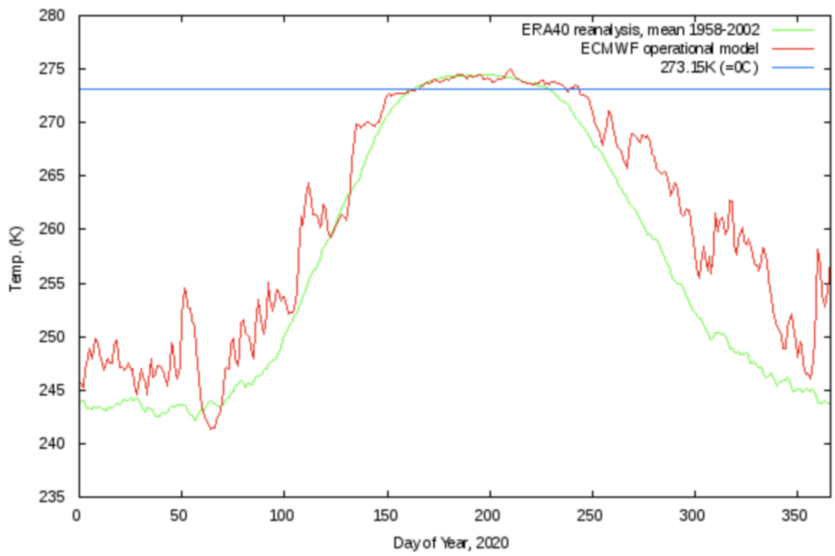
All the factors have a strong interrelation between each other. Therefore, the change of even one component of the environmental system leads to the changes in characteristics of other components.

The variability of the Arctic climatic and sea state conditions that is inherent in some areas of the High North region, especially for the Norwegian and Barents Sea, can be caused by the presence of such weather phenomenon as Polar Low Pressures that is represented as an intense cyclone with specific and unique patterns. Such a characteristic of the Arctic areas contributes to the challenges associated with the carrying out the offshore activities because it limits the possibilities for predicting climatic conditions suitable for operations (Gudmestad, 2017, pp. 1-2).

The governing characteristic of the High North is ice presence. The current state of the Arctic ice coverage is a matter of concern of stakeholders due to the observed climate change that contributes to the reduction of the ice-covered area over the past century. In addition, the Arctic region is characterized with sea ice drift that is the continuous movement of ice under the influence of low temperatures, winds and oceanographic conditions.

2.1.1 Low Temperatures

Extremely low temperatures are a well-known characteristic of the Arctic environment that affects not only other features of the High North but also contributes to reduced ability of the ecosystem of the region for self-recovery and natural biodegradation. Graph 2-1 shows the values for the temperature as a function of a day for the area of 80°N. The average temperature of the year for this region of the Arctic is approximately 13 degrees Celsius below zero.



Graph 2-1 Average temperature in the Arctic (80°N) as a function of a day (Danish Meteorological Institute, 2020)

2.1.2 Sea Ice

This under chapter describes how sea ice that is considered to be the prevailing characteristic of the Arctic can be classified.

2.1.2.1 Types and Classification

Ice properties can be distinguished on the basis of the concentration scale and the age. Figure 2-1 presents the ice edge classes grouped according to ice concentration divided into three groups. If the ice concentration is:

- o or less than 30 %, the ice can be considered as open water;
- between 30 and 70 %, then it is open ice that can exist in various modifications;
- more than 70 %, the ice is closed.

Figure 2-2 presents sea ice types derived from the age of the sea ice. Absence or low concentration of ice implies open water type. The ice that has a seasonal nature is called first-year ice while the age of higher than one year defines multiyear ice which thickness is subjected to annual changes as a result of seasonal processes of ice melting and ice growing. There is also ambiguous ice that does not have any certain characteristics.

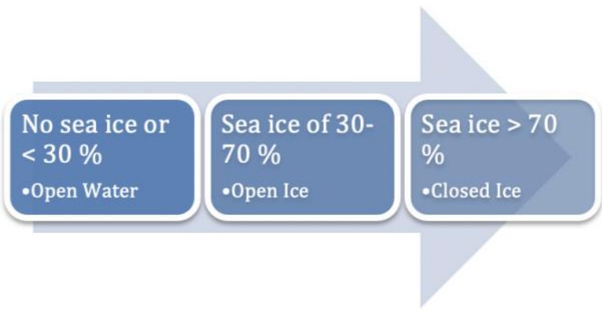


Figure 2-1 Sea ice edge classes (based on (Norwegian Meteorological Institute, n.d.))

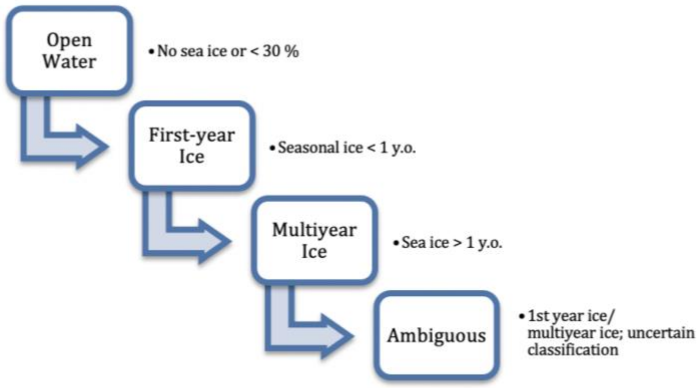


Figure 2-2 Sea ice types (based on (Norwegian Meteorological Institute, n.d.))

2.1.2.2 Sea Ice Distribution in the Northern Hemisphere

In order to carry out any activities in the Arctic, the distribution of sea ice in the Northern Hemisphere has to be studied. Figure 2-3, Figure 2-4 and Figure 2-5 show the distribution of ice concentration, edges and types in this region. The worst ice conditions pertain to the central area near the Northern Pole. The main difference between the Central Arctic and other ice-covered sea water bodies is that the ice cover there is constant. The permanent presence of multiyear ice which area can be compared with the size of the Arctic Ocean indicates that waters of the latter are affected by corresponding thermodynamic and hydrological conditions. Sea ice observed in all the other regions of the World Ocean is a seasonal phenomenon. The existence of a permanent ice coves in this area indicates a stage of glaciation in the Northern Hemisphere.

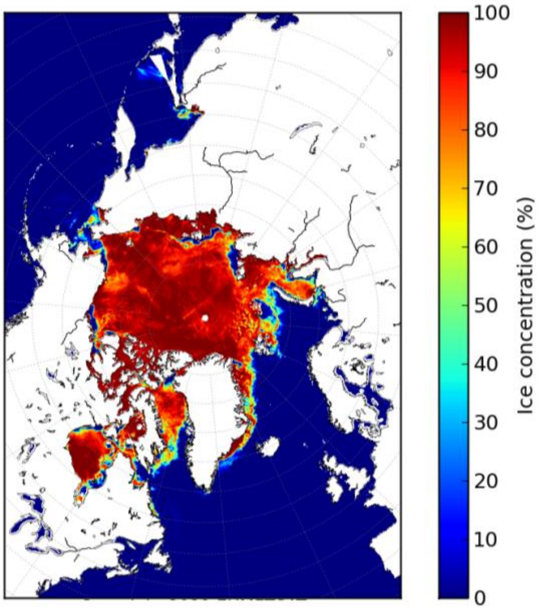


Figure 2-3 Ice concentration in the Arctic (European Organisation for the Exploitation of Meteorological Satellites, 2021b)

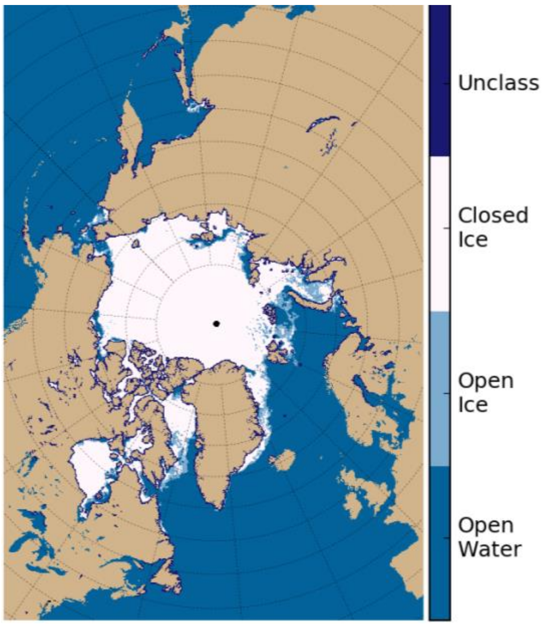


Figure 2-4 Ice edge distribution in the Arctic (European Organisation for the Exploitation of Meteorological Satellites, 2021b)

Such a phenomenon as a climate change and subsequent temperature increasing contribute to the reduction of extent of the sea ice. Graph 2-2 shown in next page presents a trend for the change of sea ice extent in the Arctic registered during the last forty years. In spite of the reduction manner, the sea ice in the Central Arctic is assumed to have same characteristics over decades or even hundreds of years due to extreme concentration and closed ice edge.

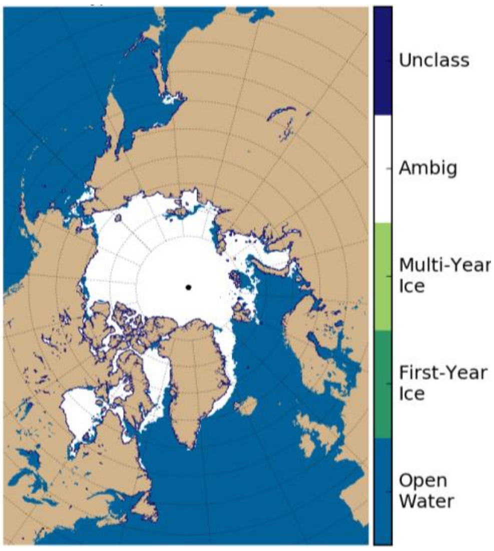
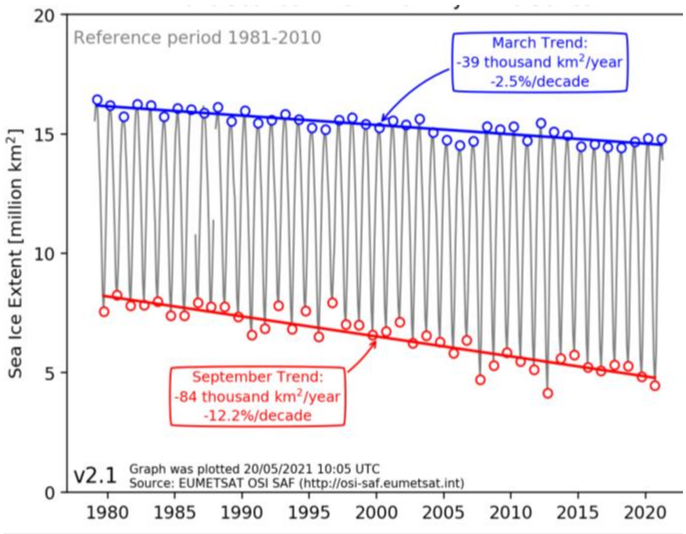


Figure 2-5 Ice type distribution in the Arctic (European Organisation for the Exploitation of Meteorological Satellites, 2021b)



Graph 2-2 Timeline of ice extent in the Arctic (European Organisation for the Exploitation of Meteorological Satellites, 2021a)

2.1.3 Oceanographic Conditions

Such characteristics of the Arctic as sea state conditions, meaning the presence of sea currents, waves and water masses, are considered to be an important influencing factor for the biological features of the ecosystem of the High North. The current systems of the Arctic seas shown in Figure 2-6 are connected through water masses that are characterized with such physical properties as temperature (that distinguish warm and cold currents), salinity and direction. Within the changing of seasons, these characteristics change throughout the Arctic seas due to the changes in water column and temperature. In addition, the changing of water temperature contributes to the variety in density characteristics of water and ice formation for some areas of the Arctic waters. Such mechanism as stratification of water masses in a vertical direction that affects the salinity gradient and contribute to convection process has impact on the ice formation, especially during the winter periods (Loeng, 1991, pp. 5, 7, 9-11).

Figure 2-6 Currents in the Arctic (Word, 2014)

2.1.4 Darkness

Darkness is an important condition to be taken into consideration when carrying out any operations in the Arctic. Table 2-1 presents an overview over the visibility conditions for the Arctic region that has been divided into three parts on the basis of latitudes: the North Pole, the Arctic Circle and the middle area. When the latitude decreases, the visibility conditions become worse. As offshore activities are mainly carried out near the Arctic Circle, rather limited visibility contributes not only to challenges but also to potential hazardous events.

Table 2-1 Characteristics of the visibility conditions for the North Pole, middle part of the Arctic region and the Arctic Circle during a year (University of Guelph)

Date	90°N (North Pole)	78.3°N (Mid-way)	66.6°N (Arctic Circle)
January 21	No Sun	No Sun	4:55 Sun
February 21	No Sun	4:41 Sun	8:52 Sun
March 20	Sun All Day	12:35 Sun	12:18 Sun
April 21	Sun All Day	Sun All Day	16:16 Sun
May 21	Sun All Day	Sun All Day	20:25 Sun
June 21	Sun All Day	Sun All Day	Sun All Day
July 21	Sun All Day	Sun All Day	20:37 Sun
August 21	Sun All Day	Sun All Day	16:23 Sun
September	Sun All Day	12:35 Sun	12:18 Sun
October 21	No Sun	4:27 Sun	8:48 Sun
November 21	No Sun	No Sun	4:53 Sun
December 22	No Sun	No Sun	2:11 Sun
	187 days of 24 hour sunlight	126 days of 24 hour sunlight	30 days of 24 hour sunlight
	163 days of 24 hour darkness	94 days of 24 hour darkness	

2.1.5 Personnel Preparedness for Working in the Arctic as an Influencing Factor for Offshore Activities

Climatic conditions of the Arctic region are defined as extreme and, in some cases, are incompatible with life. All the processes and natural phenomena pose a serious threat to the facilities and transport. Therefore, the risk of an accident is high.

Personnel that interact with external objects such as equipment and the environment form a human-machine system and takes the control functions of the system. In the extreme conditions of the Arctic region such system imposes additional requirements on the operator. In addition to the absence of chronic and somatic diseases, operator must be physically strong and mentally ready for stress, emergency situations and difficult social and psychological adaptation.

The Arctic environmental conditions significantly reduce the human capacity, productivity and present a reason for the disruption of mental processes that may lead to errors done by the operator. These may cause serious hazards and man-made disasters.

2.2 Oil Spills in the Arctic

The Arctic is a rather vulnerable region. Due to its environmental conditions and climate, the probability of oil spills is rather high. Consequences of such events are difficult to eliminate than in other regions because of severe climatic and oceanographic conditions and characteristics of slow self-recovery. In addition to long-term effects, oil spill accidents in the Arctic may lead to more severe disasters (Zhelezniak, 2020, p. 1).

2.2.1 Oil Toxicity

Oil is a complex chemical substance, and its physicochemical properties vary greatly when are affected by external factors. The composition of oil includes mixtures of many individual compounds which mass content also varies. That is why the physicochemical properties of oil are specific for each oil type. Oil as well as all inflammable substances consists of five elements, and the main ones among them are carbon and hydrogen. Oil also contains small amounts of oxygen, sulfur, and nitrogenous compounds. Such physical properties of oil as density and viscosity mainly depends on the content of various groups of hydrocarbons, heteroatomic compounds, resins and asphaltenes. Physical properties of oil are also influenced by the fractional composition that reflects the dependence of the product that is being boiled off on the increasing of the boiling point (Chandra , 2006, pp. 2-6).

Oil contains most of the elements that have negative effect on living organisms as well as flora and fauna, and this impact can not only directly affect individual parts of the body but also leads to various changes at the cellular level. In case of an accidental spill, taking into consideration the distribution of oil components in water and on land as well as their chemical and biochemical transformations, a mixture of new compounds appears instead of oil and forms a composition with new physiochemical and toxic properties. Therefore, it is of high importance to organize oil spill response and elimination of pollution as soon as possible and eliminate the threat of oil products to get into drinking water, organisms of fish, animals and therefore to humans (Transportation Research Board & National Research Council, 2003, pp. 125-128).

2.2.2 Guidelines, Standards, Policy and Management for Offshore Activities in the Arctic

The sphere of the Arctic subsoil use is a field of maximum accumulation of various legal, economic and geopolitical interests. The Arctic region and its continental shelf is a huge oil and gas area that can be considered as one of the main sources of energy in the near future. In addition to energy reserves, the Arctic region possesses a transport potential. Melting sea ice in the Arctic implies additional opportunities for the transportation of goods between Asia and Europe. The development of the Arctic region and, therefore, the implementation of the competent economic policy are becoming a priority area and one of the growth paths of the world economy. Figure 2-7 presents the hierarchy of the documents that is applied in the Arctic region for regulating offshore activities such as maritime operations and oil and gas production.

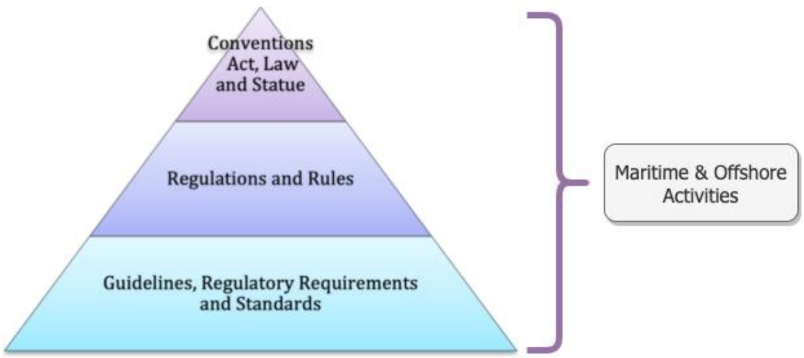


Figure 2-7 Hierarchy for offshore and maritime activities in the Arctic (adopted from (DNV GL, 2013, p. 19))

Such countries as Canada, Russia, the USA, Norway, Greenland that are located in the High North have established and developed various regulations that are implemented in the process of carrying out offshore activities. Table 2-2 shown in next page presents the regulations dominating in each country. These statues and acts are focused on the regulating and controlling the offshore activities that can cause a potential hazard for the vulnerable Arctic environment. that is why protection of the Arctic ecosystem is considered to be of a highest priority.

Table 2-2 Regulations applied in the Arctic countries (DNV GL, 2013)

Country	Statute / regulation title
Canada	– Shipping Act – Arctic Waters Pollution Prevention Act – Canada Oil and Gas Operations Act
Greenland (Denmark)	– Danish Act on Safety at Sea – Danish Safety of Ships Act – Greenland Mineral Resources Act – Danish Act on Protection of the Marine Environment
Iceland	– The Hydrocarbon Act
Norway	– The Svalbard Environment Protection Act – The Petroleum Act – The Pollution Control Act
Russia	– Law of Environmental Protection – Regulations for Navigation on the Seaways of the Northern Sea Route (1991) – Requirements for the Design, Equipment and Supplies of Vessels Navigating the Northern Sea Route (1990)
United States	– Outer Continental Shelf Lands Act (OCSLA) – Oil Pollution Act – National Environmental Policy Act

In spite of the fact that the Arctic area is divided into different sectors that belong to the Arctic countries, there is no integrated approach that can be applied by all the countries for using the Arctic reserves on the basis of focusing on the prevention of hazards that may lead to severe and even catastrophic consequences. Such an approach can be developed in a consistent manner with focusing on sustainable development of the Arctic that demands smoothing over the contradictions between economic growth, scientific and technological progress, rational use of natural resources and the preservation of the Arctic ecosystem.

2.2.3 Fate and Behavior of Oil in Ice-Infested Waters

This chapter discusses the factors that have impact on oil spreading and behavior as well as the weathering process that spilled oil is subject to. In addition, various oil-in-ice scenarios are presented, and some beneficial characteristics of the Arctic condition for oil spills are considered.

2.2.3.1 Influencing Factors

Ice is the main factor that affects the behavior of the oil in ice-covered waters. The characteristics of oil behavior mainly depends on such ice property as concentration in addition to physical features, including ice shape and porosity. It has been found out that if oil has been spilled in ice-covered water with the concentration of 30 %, its behavior will be same as in open water. If it is between 30 and 70 %, the oil behavior is difficult to be predicted due to the variety of possible scenarios. If the concentration is higher than 70 %, oil is stuck into ice and, therefore, its behavior depends on the ice movement and draft (Singsaas et al., 2020, p. 1).

In addition to ice presence, wind and sea state conditions also play a great role in oil behavior. The spreading of an oil slick is dependent on wind and surface currents that are considered to affect the behavior of oil spilled free from each other. What is more, it can be assumed that external forces as well as acceleration are not taken into account due to the equilibrium between the Coriolis force and pressure gradient (Amstutz & Samuels, 1986, pp. 305-306).

Figure 2-8 presents a scenarion of an oil spill from the vessel in open water. The spilled oil undergoes various weathering processes that are goverened by and subjected to the same direction as wind and current characterized by. The current system impacts the processes that occurs under the water surface while wind controls those ones that take place above the surface. In addition, some oil weathering activities are governed by both winds and currents. The figure also demonstates the timeline for each process in case of oil spilled in open waters. Taken into account the Arctic environment, the rate of oil weathering is reduced. In addition to hydrometeorological influencing factors including ambient temperature, the oil behavior is also affected by the characteristics of oil spill itself and oil properties.

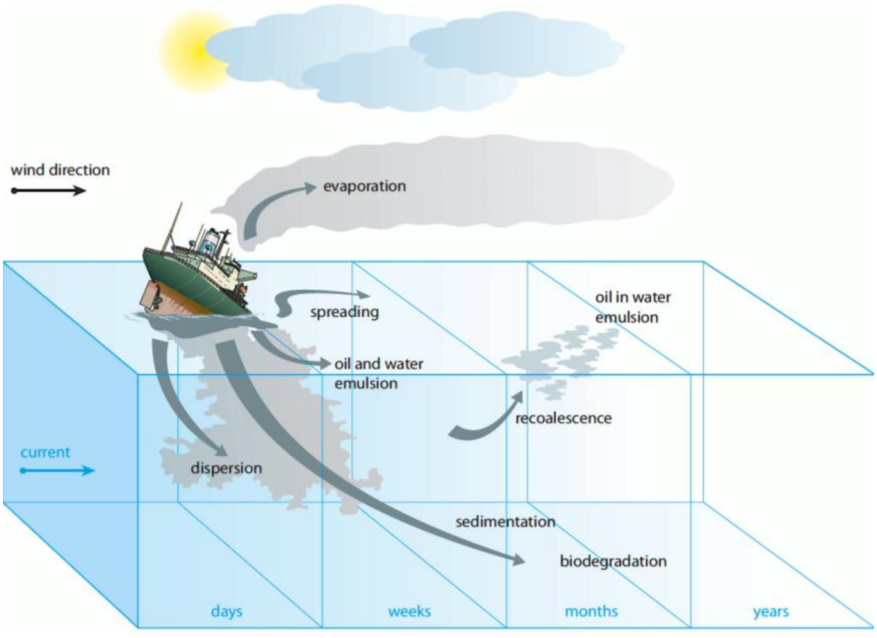


Figure 2-8 Timeline and behavior of oil spilled in open water (IPIECA, 2015)

2.2.3.2 Weathering Process

The mechanism of oil behavior in ice is dependent on such conditions as weathering rate, oil characteristics, especially viscosity and pour point, and ice features, including roughness and thickness, that affect the effectiveness of response activities. That is how the course of oil spreading events can be that ice conserves the pollutant, oil spreads into the ice or is removed from ice coverage (Singsaas et al., 2020, pp. 2, 13).

Weathering process implies a chain of physiochemical reactions which contributes to the fragmentation of spilled oil that is then disseminated in the water column in a vertical direction (US Environmental Protection Agency, 1999, pp. 5-6). Figure 2-9 gives an overview over oil weathering process that can be divided into two main groups such as early and later stage. Oil spreading, evaporation, dispersion, emulsification and dissolution take place earlier than oxidation, sedimentation and natural biodegradation (there is no capacity of the Arctic ecosystem for this natural biodegradation). Figure 2-10 shows the timeline for weathering processes for oil spilled in open water conditions where the width of each unit implies the significance of the associated weathering stage.

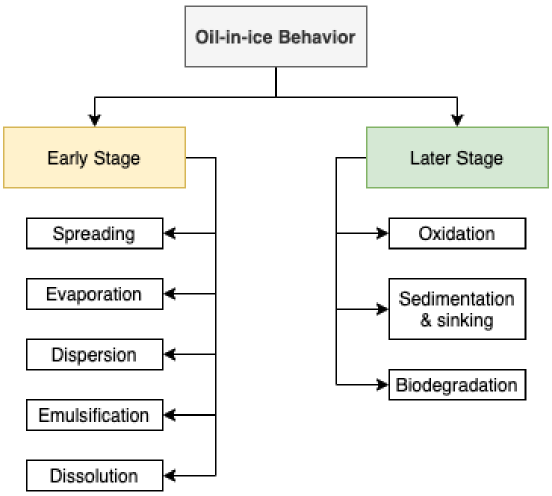


Figure 2-9 Stages of weathering process for an offshore oil spill

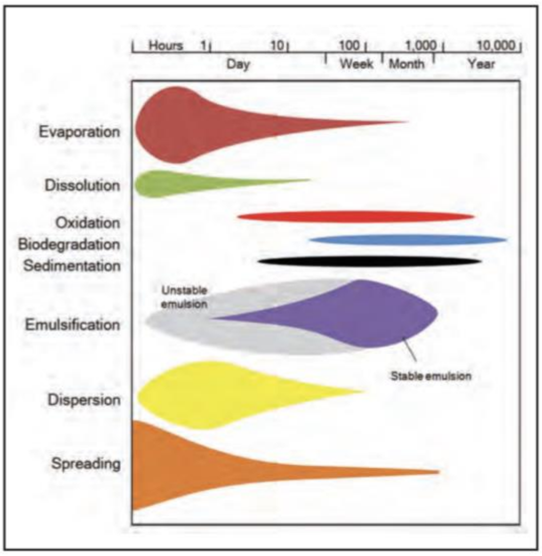


Figure 2-10 Timeline of weathering processes for oil spilled in open water (International Tanker Owners Pollution Federation, 2011)

Weathering processes typical for oil spilled in ice-covered waters are shown in Figure 2-11. However, it has to be emphasized that the weathering scenario depends on the season when oil has been spilled. When oil is spilled, the weathering starts. The ice surface is always rough and consists of various ice types with different ice concentrations. In addition to ice, there can be snow that covers the ice and melts during the summer season. Oil when spilled can be absorbed by ice and, therefore, blocked between the snow and ice. Oil spilled on the ice spreads similarly to oil spilled on land. The rate of oil spreading is mainly influenced by the oil viscosity that is increased when the ambient temperature decreases, thereby slowing done the speed of spreading. The direction of the spreading of spilled oil is affected by the wind and sea state conditions while the ice properties can be studied to determine the distance of oil drift from the source of pollution (Wilkinson, et al., 2017, p. 424).

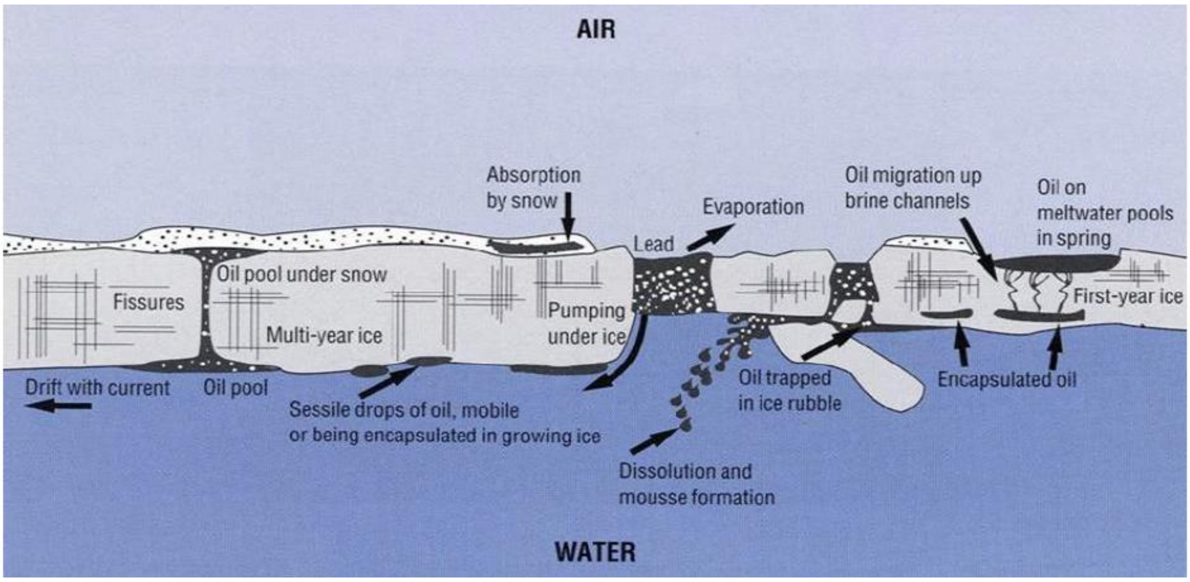
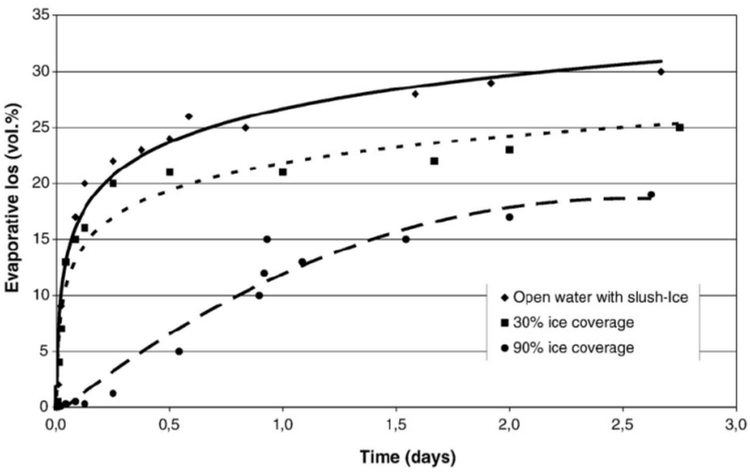


Figure 2-11 Weathering of oil spilled in ice-covered water (SINTEF, 2006)

Some volume of oil on the ice surface evaporates, but this process is slowed down in areas with the accumulation of thick layers of ice. Graph 2-3 in next page shows the curves for the evaporation process for various ice concentrations. The increasing of ice concentrations contributes to the reduction of the efficiency of evaporation. If oil freezes into the ice cover, the evaporation process stops and can be resumed under such condition as spring thawing and, therefore, oil release. The evaporation rate also depends on wind. Under the action of winds, oil is driven to the edges of thawed patches and forms a thick oil layer of several millimeters that evaporates more slowly in comparison with the case when oil is spilled in the open waters.



Graph 2-3 Evaporation effectiveness depending on various ice concentration (Brandvik & Faksness , 2009)

Some volume of oil spilled will undergo the process of dissolution and emulsification. The latter means the formation of compounds that consist of either water-in-oil or oil-in-water drops that are influenced by sea state condition and impede the oil weathering (US Environmental Protection Agency, 1999, p. 6).

Oxidation process implies the chemical reaction between oxygen and hydrocarbons that starts in case of interrelation between oil and water and that leads to the formation of a mixture characterized by the ability to be dissolved in water. An oil spot is usually being oxidated only on its borders (US Environmental Protection Agency, 1999, p. 6).

If oil is spilled under solid ice, it has more devastating effect on the marine ecosystems that accidental oil spills on open water surface. During the process of freezing, oil that has been accumulated under the ice in the depressions gets deep inside the ice where it can be located until the full ice melting. Even large crude oil spills under the solid ice cover are usually localized at a relatively short distance from the source of the spill, depending on currents under the ice layer and the properties of the ice roughness. Natural changes in the ice thickness of first-year ice, in addition to the presence of various distortive factors such as the formation of ice boulders and pressure ridges, form a reservoir where oil spilled under the ice can be localized within a relatively small area (Transportation Research Board & National Research Council, 2003, pp. 104-105).

One of the sources of the information about the behavior of oil in the marine ecosystem is the results of the studies of such a phenomenon as the natural hydrocarbon seepage to the surface that are the largest sources of oil discharging into the marine environment. Natural seepage to the surface has been going on for millions of years, and due to this fact, the environment has developed a natural recovery process (Transportation Research Board & National Research Council, 2003, p. 113).

The oil that has been frozen inside the ice and is remained in the thawed patches enters the water in the form of thin films that reach after the drifting crumbling ice when ice cover melts and breaks down. Thick oil enters the water as thicker and non-growing spots or lumps. In case of strong waves, emulsification and natural dispersion of oil begins. As thickened oil is particularly resistant to emulsification and dispersion, its slicks last much longer compared to light oil. However, under the influence of sunlight, the thickened oil heats up to the temperature that is higher than the ambient temperature. As a result, the oil can turn to a liquid aggregate state again. Oil is more extensively exposed to emulsification, evaporation, and natural dispersion after it has become liquid (Wilkinson, et al., 2017, p. 428).

Oil that has been spilled directly onto the pack ice is subjected to almost the same weathering process as in open waters in spring. Oil that has been spilled under drifting ice floes quickly comes out to the ice surface, seeping through the pores in it, and begins to evaporate. The absence of large volumes of snow ice between melting ice floes in spring conditions contributes to that oil slicks spread and evaporate much faster than in cold season. Higher spring temperatures also speed up evaporation process. As soon as oil spills are exposed to the influence of waves, the emulsification and natural dispersion processes begin (Singsaas et. al, 2020, p. 10).

Figure 2-12 in next page gives an overview over the weathering scenarios depending on where oil has been spilled as well as conditions that affects oil behavior and weathering. Oil spilled under the ice is subjected encapsulation, decapsulation, spreading and biodegradation while oil spilled on ice undergoes the evaporation process in addition.

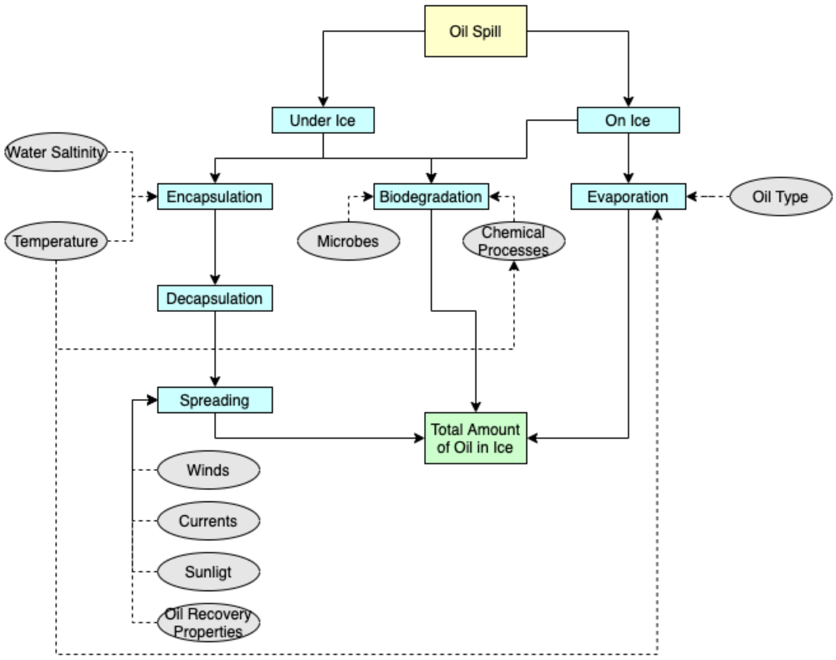


Figure 2-12 Intermediate stages of weathering of oil spilled on/under ice including influencing factors ((adopted fromSajid, Khan, & Veitch, 2020, p. 6))

2.2.3.3 Advantages of the Arctic Environment in Case of an Accidental Oil Spill

In certain cases, the Arctic conditions can be favorable for oil spill response. However, such conditions generally limit the effectiveness of methods for contamination, elimination and clin up of oil spills and operation of the corresponding equipment as well as significantly increase environmental and economic risks.

Low ambient temperature also has a positive on the rate of dissolution and penetration of heavy fractions of hydrocarbons into the water column during an emergency oil spill. Therefore, it is possible to carry out the oil spill response activities in offshore areas in harsh Arctic climate conditions without the risk of significant increase in the concentration of oil products in the water body with time.

A characteristic of the Arctic seas is the presence of solid ice that in some cases can prevent the release of spilled oil onto the shore and, therefore, reduce the damage to the environment. At the same time, sea ice impedes access to the area with spilled oil. It is important because the coastal zone is the most biologically productive area in comparison with the open sea zone (Singsaas et. al, 2020, p. 13).

2.2.4 Consequences of Oil Spill

The consequence associated with an accidental oil spill can be divided into two categories such as environmental, or ecosystem, and socio-economic as well as can have either short-term or long-term character. Figure 2-13 shows the interrelations between the defined consequences. In case of an oil spill, there are short-term impact on for ecosystem, economics and society. However, the vulnerable Arctic environment will be harmed in long-term manner. All the short-term consequences contribute to the long-term economic impact in addition to the effect from the long-term ecosystem recovery.

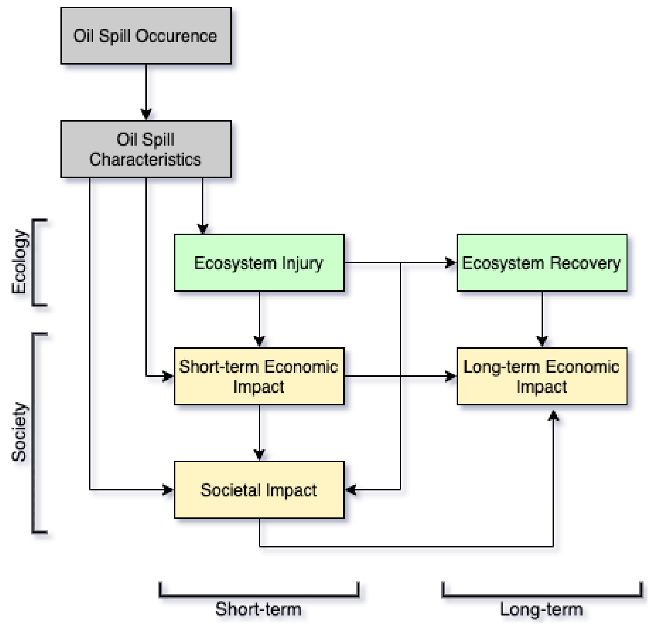


Figure 2-13 Classification of impacts caused by an oil spill (adopted from (Chang et. al, 2014, p. 3))

2.2.4.1 Environmental

Environmental consequences of oil spills are difficult to be considered as oil pollution disrupts many natural processes and interdependencies, affect habitat of all types of living organisms and accumulates in biomass. Oil is characterized with long-term decomposition and covers water surface quickly with a dense layer of oily film that impedes air and light access. Oil pollution is detrimental for the fragile Arctic ecosystems where the value of each species of flora and fauna increases because of rather low diversity in comparison with southern latitudes. The Arctic ecosystems are characterized by a low capacity for self-healing and self-cleaning that makes them even more vulnerable to oil pollution. In addition, the volume of spilled oil is not always directly proportional to the applied damage. It means that a small volume of spill may create much harm for the environment at a certain period of ecosystem development (Zhelezniak, 2020, p. 15). The environmental losses due to accidental oil spills may be hundreds and thousands of times more than the losses of the spilled oil itself.

2.2.4.2 Socio-economic

An urgent question regarding the assessment of the level of the environmental risk is the ability to determine the economic damage associated with an accidental oil spill offshore. Economic damage associated with ecological violations of the natural environment means the determination of actual and preventable material and financial losses as a result of anthropogenic impact that causes damage to both renewable and non-renewable resources such as environmental pollution, resource depletion and destruction of ecosystems (Word, 2014, p. 26).

Evaluation of the economic impact from the environmental pollution is rather urgent because any compony related to an accident will need to reserve significant capital in order to waive expenses associated with the consequences of a hazard, their rapid elimination and response, the provision of proper equipment and emergency services.

Such parameters as the costs of real losses associated with environmental pollution, expenses on its elimination and accident investigation, socio-economic impacts, losses due to unimproved opportunities and the retirement of manpower depend on variety of factors and are difficult to predict.

One of the weaknesses in evaluating the economic losses is that most methods are difficult to be adopted to a certain case. In order to calculate the real economic damage related to environmental pollution, data on the actual costs of the response, elimination and recovery of the environment needs to be applied.

2.3 Oil Spill Response in the Arctic

In case of an accidental oil spill in the Arctic conditions the oil spill response based on containment, elimination and recovery of spilled oil that may be spread along an area of up to several square kilometers is crucial. In addition, it is difficult to predict the behavior and movement of an oil spill in the Arctic conditions due to its geography that can be characterized by the presence of ocean areas with structural inconstancies (Ivichev et. al, 2012, p. 6). The stages of oil spill response can be divided into three main groups such as reactive, planning and completion shown in Figure 2-14 that is based on (Emergency Prevention, Preparedness and Response Working Group, 2015, p. 24). The efficiency and accuracy of the measures taken during each stage are a determinative factor for keeping the accident situation under control and preventing the severe hazards cause by oil spill.

Figure 2-14 Stages of Oil Spill Response

During the process of decision-making for establishing the response strategy, priority evaluation when conducting the response activities has to approached. Figure 2-15 shows the sequence of priorities where the life, health and environment must be protected from the potential acute pollution firstly, and financial interest is to be considered at the end.

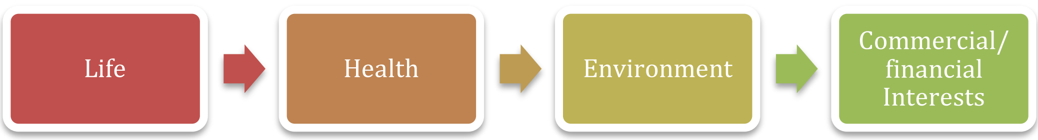


Figure 2-15 Priority chart for choosing oil spill response methods (based on (Kystverket, n.d.))

Further under chapters discusses the how oil spill response can be prepared as well as the existing response methods that can be applied for the Arctic region.

2.3.1 Preparing for Oil Spill Response

This chapter discusses the main activities when preparing for an oil spill response such as contingency planning and monitoring and detection of spilled oil.

2.3.1.1 Contingency Planning

An effective oil spill response depends on the efficiency of a contingency plan that is considered to be a kind of preparation of response activities. The purpose for establishing such a plan is to develop questions related to an accidental oil spill and, on the basis of these objections, to provide a set of measures that have to be implemented into all the stages of the response process (US Environmental Protection Agency, 1999, p. 27; Abascal et. al, 2010, p. 2099). Contingency plan for an accidental oil spill is an approach that presents an overview upon the connection betwing risk and actual response activities including the unfluencing factors such as environmental and socio-economic and capability of emergency crew and equipment to conduct to the containment procedures (WWF International Arctic Programme, 2007, p. 11). In addition, such an important contrubutor to a successful spill response as transpot facilities, that are marine vessels and aircrafts in case of offshore activities, has to be implemented into the contingency planning, especially for the challenging Arctic conditions (Gudmestad & Strass, 1994, p. 471).

Figure 2-16 in next page that has been developed from (US Environmental Protection Agency, 1999, pp. 27-28) shows the main components of a contingency plan. This framework should be based on the risk assessment (see chapter 2.4 for the description of the risk) that implies the identification of potential hazards, analysis of the natural resources and elements of ecosystem that are vulnerable to a potential unwanted event and studying the response strategies that are suitable for a chosen area including characteristics of possible oil spill scenarios.

Figure 2-16 Elements of Contingency Plan

Figure 2-16 presents stages established when developing a contingency plan for an accidental oil spill. These steps describe the order of the response activities that must be discussed and evaluated in a contingency planning framework. The success of measures implemented for on-site for pollution containment depends on the efficiency of the contingency survey.

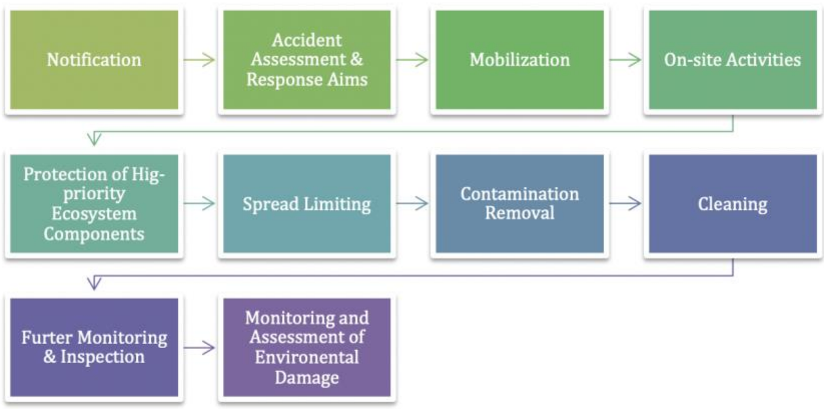


Figure 2-17 Steps for conducting oil spill response (adopted form (Kystverket, n.d., p. 7))

2.3.1.2 Monitoring and Detection

The initial information related to an oil spill can be provided by the equipment that is installed at the facilities and used for controlling oil leaking. On the basis of the received data and knowledge about the weather and oceanographic condition that were actual during the accident, it is possible to estimate the volume of spilled oil as well as the location of the pollution source (Fingas, 2014, p. 313). In order to define the position of oil slick, such techniques as monitoring and detection of the oil spilled in ice-infested waters can be applied. These are beneficial for planning oil spill response activities in the Arctic, especially taking into account their applicability in conditions of remoteness of pollution sources. However, the efficiency of monitoring and detection application depends on and may be reduced by the Arctic condition. The advantage of carrying out the detection activities when planning the response is that the oil spill can be detected for various spill scenarios regarding the oil positioning in relation to ice (Wilkinson, et al., 2017, p. 429; SINTEF, 2006, p. 37).

The methods for oil spill detection and monitoring can be divided into two groups: visual sensors and remote sensors. The method of visual sensing is based on the recognizing the signs of oil spilled in ice-covered water considering such factors as: change in color of flora, appearance of rainbow on the water surface, color change of snow or ice cover, or visible oil release. Presence of these factors can be detected when inspecting the region by aircraft or maritime vessels (DNV GL, 2015, p. 27). The oil that is spilled on the ice surface and hidden under the snow can be detected by trained dogs that are able to find the location of a potential oil spill, especially in the conditions of limited visibility (Wilkinson, et al., 2017, p. 431).

The application of the remote sensors in the northern latitudes to detect oil spills is advantageous for developing effective response planning. The remote sensing can be implemented as a combination of several techniques for providing the more accurate results (Wilkinson, et al., 2017, p. 429). The technologies that can be applied are optical sensors, radar sensors, ground-penetrating radars (GPR), acoustic systems, fluorosensors, etc. The applicability and efficiency of remote sensors depend on the environmental conditions of the pollution area and the characteristics of the oil spill (DNV GL, 2015, p. 27).

2.3.2 Existing Oil Spill Response Methods for Ice-Covered Waters

As an accidental oil spill is a hazardous event that contributes to negative potential consequences, response activities must be carried out. There are three response methods that are suitable for application in the Arctic:

- mechanical recovery with the use of booms and skimmers (see chapter 2.3.2.1);
- use of dispersants for accelerated dispersal of oil (see chapter 2.3.2.2);
- in-situ burning when spilled oil is ignited (see chapter 2.3.2.3).

In practice, the combination of named methods can be applied regarding the characteristic of the accident.

2.3.2.1 Mechanical Recovery

Mechanical recovery implies the process of containment of an oil spill with the help of special equipment such as booms and then collecting the accumulated oil using skimmers which pump the oil to be recovered to a special storage tank. The equipment can be installed from ships or fixated to a facility that has been installed beforehand (WWF International Arctic Programme, 2007, p. 9).

The activities for mechanical recovery can be divided into two main stages such as containment associated with controlling the oil spreading and recovery of spilled and collected oil that is considered to be a traditional technique (SINTEF, 2006, p. 41). It is of the highest importance to carry out containment activities for oil spilled offshore and limit oil spreading in order to reduce or eliminate the risk of further pollution if oil has been spilled in areas where ice concentration is low. Mechanical containment implies the application of booms shown in Figure 2-18 for controlling oil flow. Booms deployed must be reliable and stable because of the external forces associated with oceanographic conditions that can cause various structural failures and imbalance of facility (US Environmental Protection Agency, 1999, pp. 9-10).

Figure 2-18 Oil containment using booms (DNV GL, 2015)

The next step of carrying out the oil spill response is to conduct recovery activities using skimmers for collecting the spilled oil from the surface of the water. There are several types of skimmers depending on design, effectiveness and application case, however, the operation mechanism is the same and based on pumping the oil to be recovered into the storage tanks for further processing (US Environmental Protection Agency, 1999, pp. 10-11). The factor that influences and impedes the application of skimmers is ice presence of various concentration that limits the ability of oil to be pumped (Emergency Prevention, Preparedness and Response Working Group, 2015, p. 89). It leads to the demand for ice separation as a preparation activity for carrying out mechanical recovery in order to reduce or eliminate downtime of the response and, therefore, prevent potential hazards (SINTEF, 2006, p. 17). In addition to ice presence that is the prevailing factor for this response method, other weather conditions of the Arctic affect the efficiency of the mechanical recovery including the time needed for conducting response activities and may lead to difficulties associated with not only equipment failures but also accessibility to area of spilled oil (Word, 2014, p. 192; SINTEF, 2006, p. 45).

Due to the challenges for carrying out mechanical recovery in ice-covered waters, the need for the development of new technologies is demanded. Newly developed concept called MORICE (Mechanical Oil Recovery in Ice Infested Waters) shown in Figure 2-19 can be implemented into the response activities for ice-infested waters. The operation principle is based on «lifting the ice floes by a grated belt allowing the oil to flow to the skimmer head». That is how oil can be separated from the ice by the action of vibrating components and is available for further recovery processing. However, the MORICE units have only been designed and built, but not implemented into response activities (SINTEF, 2006, pp. 45-46).

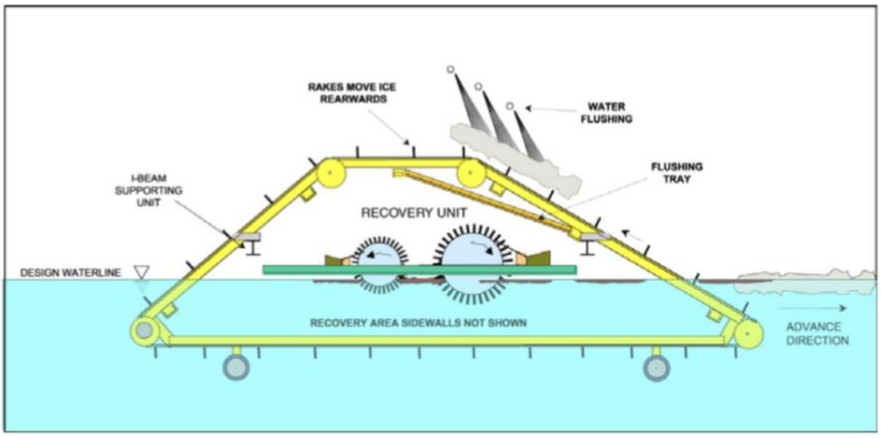


Figure 2-19 MORICE concept (SINTEF, 2006)

2.3.2.2 Use of Dispersants

Dispersants is a synthetic substance used to neutralize oil spills that are a result of an accident. Dispersants contain the same substances as used in food industry or perfumery and are non-toxic. Dispersants contribute to speeding up and improvement of the procedure related to breaking up an oil slick inro small particles that have been changed structurally as a result of processing and become soluble in water. That is why such a method is used for response to oil spill accident of a large scale (DNV GL, 2015, pp. 19-20).

Dispersants are divided into several groups such as toxic and low-toxic. In additions, dispersants can be oil-soluble, water-soluble and oil-water-soluble as well as they exist in ordinary and concentrated compositions. Despite the lower toxicity level in comparison to oil, dispersants can cause negative consequences for both the ecosystem and environment at the area of dispersant spraying. In addition, the action of dispersant affects the level of oil toxicity that grows. Therefore, the distribution of dispersants has to be carried out in accordance with safety rules and after process of decision-making and verification (REGIONAL MARINE POLLUTION EMERGENCY RESPONSE CENTRE FOR THE MEDITERRANEAN SEA, 2011, pp. 1, 4 (part III)).

The main purpose of the application of dispersants is the fragmentation of oil slick into many small droplets that are distributed being in a dispersed state by winds and currents in the water column where the oil subsequently undergoes natural biodegradation (WWF International Arctic Programme, 2007, p. 10). If properly applied, dispersants are an effective method for oil spill response and reduce or prevent the negative consequences for the vulnerable Arctic environment. The use of dispersants is considered to be irreplaceable and has to undergo the decision process if the implementation of mechanical methods or in-situ burning is impossible on the Arctic shelf due to extreme weather conditions or other contributing factors (REGIONAL MARINE POLLUTION EMERGENCY RESPONSE CENTRE FOR THE MEDITERRANEAN SEA, 2011, p. 1 (part III)).

Spraying and delivery of dispersants is carried out by air transport or water vessels. The procedure shown in Figure 2-20 in next page must involve the monitoring and controlling to ensure that the dispersing agents are applied in compliance to safety and technological requirements (DNV GL, 2015, pp. 19-20).

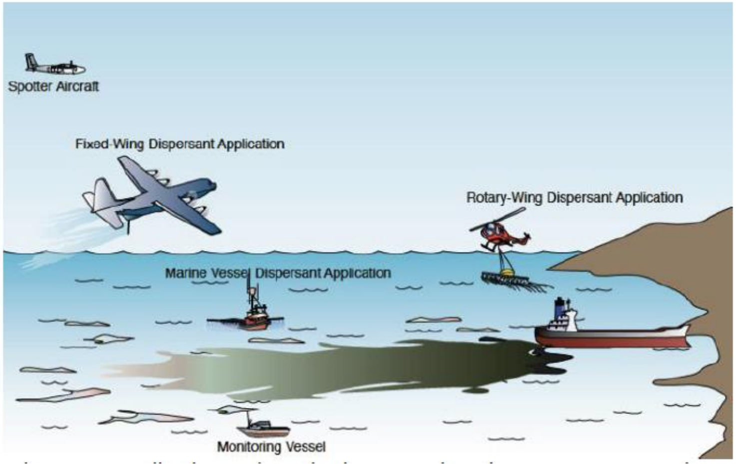
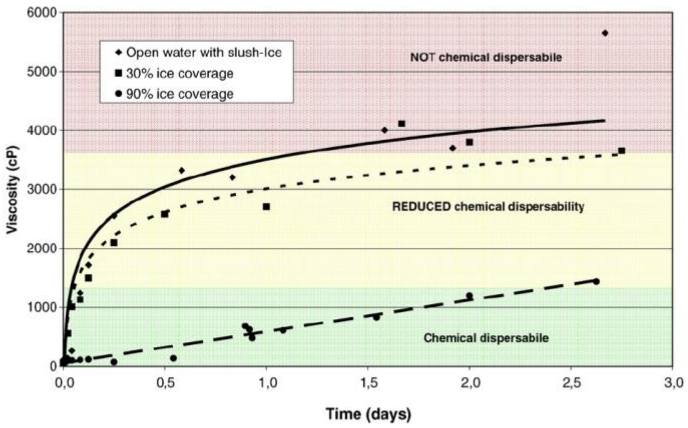


Figure 2-20 Procedure of the application of dispersants offshore (DNV GL, 2015)

The efficiency of this response method depends on such factors as application time, wave energy, water and ambient temperature, type of dispersant and oil composition that is the most influencing factor (US Environmental Protection Agency, 1999, pp. 13-14). The oil composition and properties are the main factor that determines the capability of oil to be dispersed. Oil spilled in harsh weather conditions is subjected to weathering process that causes the changes of oil properties, including temperature and viscosity (REGIONAL MARINE POLLUTION EMERGENCY RESPONSE CENTRE FOR THE MEDITERRANEAN SEA, 2011, p. 3 (part III)). Graph 2-4 represents the dependence between the ice concentration and dispersible capability of oil that is defined by the viscosity. That is why the presence of ice impedes the application of dispersants during accidental oil spills because the use of dispersants is effective when ice concentration is not higher than 20-30%. If the use of dispersants is necessary when ice has high concentration, then the ice formations are needed to be additionally processed (SINTEF, 2006, p. 41).



Graph 2-4 Dependence of oil viscosity on ice concentration that determines the possibility of applying dispersants (Brandvik & Faksness, 2009)

2.3.2.3 In-Situ Burning

In-situ burning is a method for oil spill response based on the controlled burning of the spilled oil directly at the spill site. Burning quickly removes large volumes of oil from the water. In order to ensure the process of oil burning on the water surface in ice absence conditions, the thickness of the oil film is demanded to have a certain size, and oil has to be collected and supported by fire-resistant booms suitable for application in the Arctic weather conditions (WWF International Arctic Programme, 2007, p. 9). The rapid oil removal from the water surface can protect marine ecosystem, including its inhabitants such as birds, marine mammals, etc., and the coastline from oil pollution.

Figure 2-21 shows how an in-situ burning procedure can be carried out offshore. The oil spilled must be isolated and controlled by fire-resistant booms that limits the ability of oil to spread and contribute to formation of such thickness of oil slick that are demanded for burning procedure (DNV GL, 2015, p. 22). The ability of booms to resist the heating is provided by either the presence of cooling agents or fireproof material of construction (IPIECA, 2014, p. 5). When the booms are deployed, the spilled oil undergoes the ignition process that is carried out from either from vessel or aircraft. Despite the efficiency of in-situ burning is rather high, not all the spilled oil will be burnt. As a result, the residual substances will be either accumulated on the water or ice surface or submerged (DNV GL, 2015, p. 22).

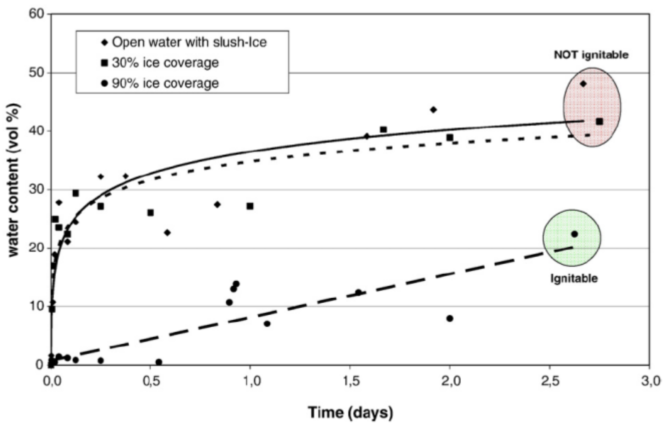
Figure 2-21 Overview over offshore in-situ burning (DNV GL, 2015)

The regulations and methods developed for in-situ burning allow to carry out this process in a safe manner. In-situ burning in open waters is limited by the necessity of using fire-resistant booms. However, in the Arctic climate conditions and ice presence can contribute to the spill preservation. The implementation of the in-situ burning technologies for oil spill elimination mainly depends on the ice concentration (SINTEF, 2006, p. 34).

In case of the ice concentration between 30 and 70%, ice slows down the spread and movement of the ice slick, but it is not able to block the oil slick in a complete manner. The use of booms under the conditions of such ice concentration is difficult. However, surfactants characterized with the ability to collect oil can be applied to get oil slicks concentrated up to a thickness that is sufficient for the combustion process (SINTEF, 2006, pp. 33-36; Wilkinson, et al., 2017, p. 435).

In-situ burning has a high efficiency in case of the ice concentration of 70 % and higher. The presence of ice prevents the oil spreading (as oil is accumulated in natural potholes and cracks) as well as the influence of the oil weathering processes is limited due to low temperatures and the limited activities of the waves within the ice field, that is how the oil burning is facilitated. As a result, the time for the implementation of in-situ burning is longer in the presence of high-concentrated ice compared to open water (SINTEF, 2006, pp. 41, 49; Wilkinson, et al., 2017, p. 435).

The effectiveness of in-situ burning activities depends on the water content of the emulsified oil that can make ignition process challenging due to the changes of physiochemical properties of oil, especially viscosity, during the weathering process. Graph 2-5 (see next page) shows the variations in the water content for different ice concentrations. The presence of ice with low concentration contributes to the increasing of water content in oil and makes the oil not ignitable while the high ice concentration enriches the ignition capacity of oil (Brandvik & Faksness, 2009, p. 163; DNV GL, 2015, pp. 76-77).



Graph 2-5 Dependence of water content on ice concentration that determines the possibility of ignition when applying in-situ burning (Brandvik & Faksness, 2009)

Despite many benefits related to the application of in-situ burning in the Arctic, there are disadvantages that are critical and may contribute to potential hazards and subsequent negative impacts (IPIECA, 2016, pp. 5, 11-12):

- Probability of secondary fires that pose a threat to human life, the environment, and facilities and implies uncontrolled burning process;
- Formation of unburned residues and a smoke plume;
- Emissions of toxic gasses into the atmosphere with subsequent hazards for public health, ecosystem, quality of water and air.

2.3.2.4 Gaps and Limitations related to Response Methods Suitable for the Arctic

The three oil spill response methods that are applicable for the Arctic conditions have been discussed in chapters 2.3.2.1, 2.3.2.2 and 2.3.2.3. These are mechanical recovery, use of dispersants and in-situ burning. This chapter gives an overview over the gaps and limitations of the conditions suitable for carrying out the response activities.

Table 2-3 shown in next page presents such conditions as ice concentration, wind speed, visibility, wave height and wind chill effect that are suitable for the application of each method. In addition, parameters shown imply either effective or possible, but impaired response. Mechanical recovery, if considering a traditional response with using only booms and skimmers, has the lowest range regarding ice concentration while use of dispersants and in-situ burning have broader parameters for application. The wind speed is critical for in-situ burning due to the possibility of uncontrolled burning. All the activities are more successful and safer when carried out in conditions of good visibility. Wave heigh also plays a significant role as response is limited in case of unfavorable wind conditions. Wind chill effect is important to be taken into account for providing the safety for the personnel. The Arctic conditions that are interrelated to each other are an influencing factor that limits the response activities for all the methods applied for ice-covered waters of the northern region.

Table 2-3 Limitations and evaluation of response effectiveness based on the environmental parameters (adopted from (DNV GL, 2015, pp. 78-79))

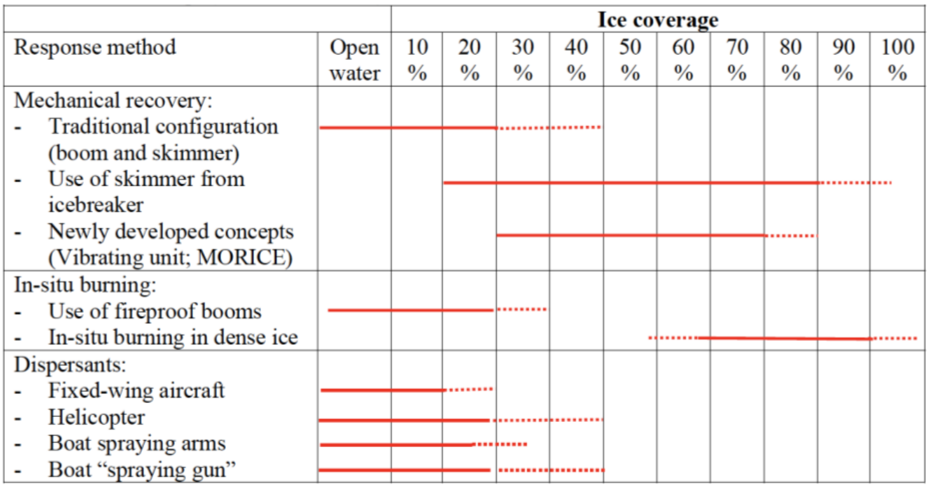
Parameter	**Mechanical Recovery**		**Use of Dispersants**				**In-situ Burning (Boom Applied)**	
			Aircraft		*Vessel*			
Ice Concentration [%]	0-10	10-40	0-10	10-40	0-40	40-70	0-40	40-70
Wind [m/s]	< 15	15-20	< 15	15-20	< 15	15-20	< 8	8-10
Light Presence	Daylight	Darkness	Daylight	Darkness	Daylight	Darkness	Daylight	Darkness
Wave Hight [m]	< 3	3-4	0,3-5	< 0,3	<=5	-	< 1	1-1,8
Wind Chill [W/m^2] – Heat Flux	< 1000	1000-1600	< 1000	1000-1600	< 1000	1000-1600	< 1000	1000-1600

- Effective response

- Possible, but impaired response

Table 2-4 in next page gives an overview of the ice concentration suitable for the application of the response methods as the ice presence is a prevailing factor for response activities. Due to the variety of possible scenarios for strategies for each method, the ice concentration varies. The development and implementation of new techniques broaden the possibilities of oil spill response in ice-covered waters. The mechanical recovery and in-situ burning have expanded availabilities for application in Arctic condition while use of dispersants is rather limited. What is more, no one method is effective for collecting oil spilled under the thick ice, even in case of using ice-class vessels.

Table 2-4 Response efficiency based on ice concentration (SINTEF, 2006)



Response method	Open water	10 %	20 %	30 %	40 %	50 %	60 %	70 %	80 %	90 %	100 %
						Ice coverage					
Mechanical recovery:											
- Traditional configuration (boom and skimmer)											
- Use of skimmer from icebreaker											
- Newly developed concepts (Vibrating unit; MORICE)											
In-situ burning:											
- Use of fireproof booms											
- In-situ burning in dense ice											
Dispersants:											
- Fixed-wing aircraft											
- Helicopter											
- Boat spraying arms											
- Boat "spraying gun"											

Despite the main knowledge gap for the Arctic such as environmental conditions that are difficult to be predicted, DNV (Det Norske Veritas) has determined average values for the applicability of oil spill response method throughout a year shown in Table 2-5. There is no doubt that response activities are more favorable when carried out during the warm months and has lower efficiency during the cold periods. In-situ burning has the lower applicability in the Arctic throughout the whole year compared to mechanical recovery and dispersants.

Table 2-5 Average applicability of response methods in ice-infested waters (adopted from (DNV GL, 2015, p. 41))

Season	**Month**	**Oil Spill Response Method**					
		Mechanical Recovery		**Use of Dispersants**		**In-situ Burning**	
		Applicability [%]					
Winter	December	38	35	43	43	11	9
	January	33		39		7	
	February	35		40		7	
Spring	March	37	45	40	48	11	21
	April	46		49		18	
	May	53		55		33	
Summer	June	68	76	69	77	44	44
	July	83		84		45	
	August	77		78		43	
Autumn	September	64	52	66	55	22	16
	October	50		53		15	
	November	43		47		10	

Whatever method has been chosen and applied, the time of the response crucial due the oil weathering that contributes to that response activities become more difficult and challenging in addition to increasing risk level of potential hazards (WWF International Arctic Programme, 2007, p. 11).

2.3.3 Economic Expenses for Oi Spill Response

The economic effects for an oil spill response, or the potential cost of the response is not easy to be estimated in advance due to the absence of knowledge related to expenses regarding the emergency crew and all the equipment needed for carrying out oil spill response. In addition, some problems are probable to be arisen in case of activities in the Arctic that is characterized by the unpredictable weather conditions. What is more, it is not possible to estimate the accurate percentage of spilled oil that will be recovered (Cohen, 1986, p. 172). Despite these facts, the primary cost for oil spill response, that is counted as the expenses related to removing of spilled oil as well as the expenses for personnel mobilization and equipment that is applied for the response activities, can be determined on the basis of summation of main characteristics for oil spill elimination such as (Liu & Wirtz, 2009, p. 472):

- Equipment cost
- Material cost
- Labor cost
- Insurance contribution to the state budget
- Depreciation
- Overhead expenses.

All these elements that contribute to the estimation of the overall response cost are based on the volume of spilled oil, its physiochemical properties and defined ratio of cleanup activities (Cohen, 1986, p. 172).

In order to give an overview of potential response cost, Table 2-6 in next page can be taken into consideration as an example. This table show the primary cost for cleanup procedures (excluding expenses for labor, some equipment, transportation and the Arctic challenges) for open waters due to the absence of sufficient data for the Arctic region (see chapter 1.4). Response cost is presented for such types of oils as light hydrocarbons, heavy hydrocarbons and crude oil as well as different response methods and determined on the basis of the volume of spilled oil. the boundaries of the expenses depend on the oil that has been recovered during the response activities. What is more, the total cost is lower if the oil spill size is higher.

Table 2-6 Primary cost for response for oil spilled in open waters (adopted from (Etkin, 2004, p. 9))

Oil Type	**Spill Size (gallons)**	**Cost of Response Method per 1 Gallon [$]**		
		Mechanical Recovery	*Use of Dispersants*	*In-situ Burning*
Light	10^4-10^5	41-87	18-26	9-18
	10^5-10^6	26-74	10-17	5-10
	> 10^6	12-31	6-11	3-7
Heavy	10^4-10^5	267-410	62-103	51-103
	10^5-10^6	103-179	54-59	41-72
	> 10^6	36-87	49-53	26-56
Crude	10^4-10^5	138-195	31-74	31-62
	10^5-10^6	92-123	29-49	16-36
	> 10^6	64-92	13-58	11-22

2.4 Risk

This chapter defines the concept of risk , that is a «combination of the probability of occurrence of harm and the severity of that harm», on the basis of risk management, gives overview over preliminary risk analysis, including discussion about HAZID (Hazard Identification analysis) and risk scoring matrix, and the risk assessment that contributes to the oil spill response planning (International Organization for Standardization, 2016, p. 2).

2.4.1 Risk Assessment

Figure 2-22 presents the process of risk management that implies the implementation all the activities and procedure that may have impact on the constitution or system and used to deal with risk (Aven , 2008, pp. 6-7). Risk management is a cyclic process that is based on risk assessment that includes risk identification, risk analysis and risk evaluation. The input for the risk assessment is the context established while the output is risk treatment.

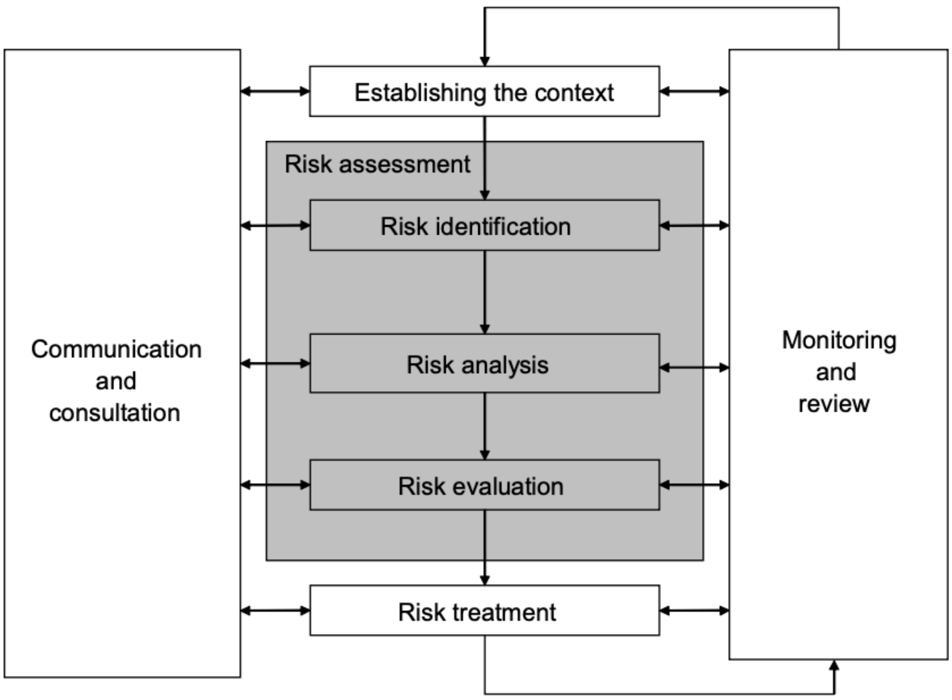


Figure 2-22 Risk management process (International Organization for Standardization, 2009)

Risk analysis that is the intermediate part of the risk assessment and a basis for further detailed analysis implies the identification of potential hazards that are characterized by probabilities and consequences as well as development of barriers for either preventing hazards or reducing and/or eliminating the severity of effects caused by these hazards. Risk analysis can be carried out on the basis of qualitative, quantitative or semi-quantitative evaluation of probabilities and consequences (International Organization for Standardization, 2016, p. 13).

All the steps of risk assessment are connected to the activities of communication and consultation that are applied for connecting the risk assessment with other management types (International Organization for Standardization, 2016, p. 9). In addition, all the parts of risk management and mechanisms are interrelated to monitoring and subsequent review that are contribute to decision-making process and verification of the elements of the risk management (International Organization for Standardization, 2016, p. 11).

2.4.2 Preliminary Risk Analysis

Risk analysis includes preliminary analysis and further detailed analysis. Preliminary risk analysis that is a basis for carrying out the detailed approach focuses on defining the risk for potential hazards. That is how the unwanted events with the high risk can be derived for further assessment. There are a wide range of techniques that can be developed and applied for carrying out the risk analysis depending on the defined objectives, data and measures available for application, compliance with established requirements. The preliminary risk analysis is developed on the basis of a qualitative framework (International Organization for Standardization, 2016, pp. 8, 15, 23).

2.4.2.1 HAZID

HAZID analysis is one of the tools used for conducting the preliminary risk analysis and based on the determining potential hazards as well their causes and consequences with (IPIECA, 2013, p. 13). However, the categories to be included can be chosen depending on a particular case study. This approach mainly focuses on establishing preventative activities and measures that have a proactive character and can be adjusted and maintained for mitigation of potential hazards (DNV GL, 2013, p. 63). HAZID is generally carried out on the basis of literature review and experience (International Organization for Standardization, 2016, p. 37).

2.4.2.2 Risk Matrix and Scoring

The evaluated risk that is a combination of probability and severity of consequence contribute to positing in the risk matrix. There are a variety of types of risk matrix that are developed for quantitative, semi-quantitative or qualitative approaches. The risk matrix shown in Table 2-7 is based on qualitative framework and suitable for carrying out the preliminary risk analysis that can be conducted for different types of consequences such as for environmental, safety, economic, etc. The risk can be scored:

- Low (green color): risk is acceptable;
- Moderate (yellow color): risk has to de reduced ALARP;
- High (red color) – risk is not acceptable and has to be reduced ALARP.

The ALARP (as low as reasonably practicable) concept means that the risk level has to be reduced by application of appropriate measures and activities regardless economic expenses (IPIECA, 2013, pp. 30-31).

Table 2-7 Risk ranking matrix for HAZID (Vista Oil & Gas SAB, 2019)

Severity	Consequences				Increasing Likelihood				
					A	B	C	D	E
	People	Assets	Environment	Reputation	Never heard of in the industry	Heard of in the industry	Has happened in the organization or more than once per year in the industry	Has happened at the location or more than once per year in the organization	Has happened more than once per year at the location
0	No injury or health effect	No damage	No effect (no or temporary impact - days)	No impact (local media, no significant concern)	L	L	L	L	L
1	Slight injury or health effect (first aid or medical treatment)	Slight damage	Slight effect (local scale, short term damage – weeks)	Slight impact (short term local concern)	L	L	L	L	L
2	Minor injury or health effect (restricted work case or LTI)	Minor damage	Minor effect (local scale, short term damage – months)	Minor impact (short term national mention)	L	L	L	M	M
3	Major injury or health effect (partial disability)	Moderate damage	Moderate effect (local scale, medium terms damage – years)	Moderate impact (medium term national concern)	L	L	M	M	H
4	< 3 fatalities, or permanent total disabilities	Major damage	Major effect (local scale, long term damage – decades)	Major impact (regional or persistent national concern)	L	M	M	H	H
5	> 3 fatalities	Massive damage / total loss	Massive effect (regional scale, permanent damage)	Massive impact (global concern and media coverage)	M	M	H	H	H

2.4.3 Risk Assessment as a Basis for Oil Spill Response

Risk assessment that can contribute to carrying out the offshore activities, including oil processing and marine procedures, in a safe and successful manner demands the implementation of the hazard identification techniques, shown in Figure 2-21, that are focused on the application into the risk approach such factors as climatic and oceanographic conditions, HSE (health, safety and environment) management established in the organization as well as historical data and experience related to the operation of both personnel and equipment for a chosen area (Gudmestad, 2017, p. 9).

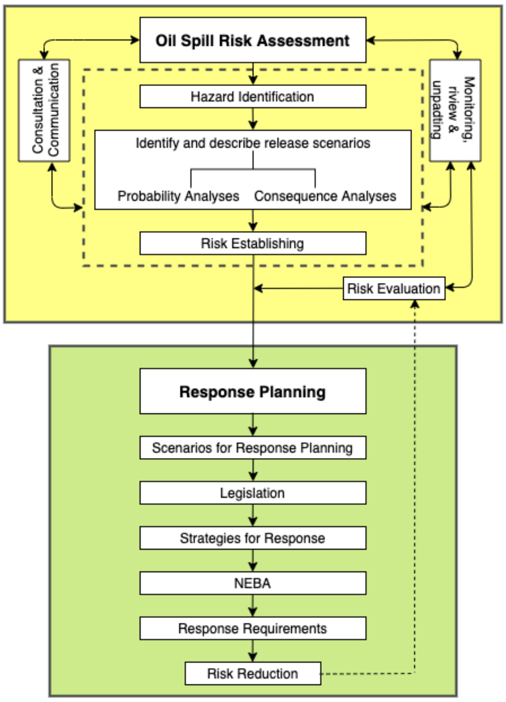


Figure 2-23 Response planning based on risk assessment of an oil spill accident (adopted from (IPIECA, 2013, p. 6))

The risk management that is applicable for carrying out the risk analysis associated with accidental oil spills contributes to the development of response planning that focuses on risk reduction as the output of the approach. The intermediate steps of the response planning framework are:

- Defining and studying potential scenarios of oil spills;
- Legislation;
- Developing response strategies and methods to be applied;
- Carrying out the NEBA (Net Environmental Benefit Analysis) focused on minimization of potential negative consequence for environment and human safety;
- Establishing the requirements to be met during the response.

3 Methodology

This chapter gives an overview of the methodology that has been used to answer to the research questions of the master thesis. The research questions are based on the objectives related to the studying of the impact of the Arctic condition on the existing response methods and measures associated with an accidental oil spill (see chapters 1.3 and 2.3.2). In order to conduct a research that fulfills the objectives of the thesis, a proper methodology that contributes to the understanding of the chosen theme has to be chosen and implemented into the research process. As a result of the research, the preliminary risk analysis that had been aimed to identify potential hazards for the applications of response activities and based on the evaluating of effects of each hazard was carried out. Such an analysis makes it possible to implement decision-making process into the contingency plan associated with the emergency response to such an unwanted event as an accidental oil spill in the cold climate conditions. The components or combination of these components was used as a basis for the studying and evaluating oil behavior in ice-infested waters and efficiency of emergency response.

3.1 Research Approach

The research approach in this thesis has been chosen to be deductive when conducting a literature review based on the collected data and studying such a field operation as oil spill response and elimination. It means that when considering the Arctic environment and its characteristics, the main influencing factors was defined in order to carry out the potential hazard identification. In addition, the description of the existing response methods that are feasible and, therefore, can be applied for the High North was focused on the relation between the effectiveness of these activities and the Arctic environment. When carrying out the hazard identification analysis, the findings associated with risk assessment were used for discussion in an inductive manner. The outcomes for each effect caused by a potential hazard made it possible to determine the relationship between all the defined hazard categories and present the overall results.

The study area of the master thesis, that is based on the reviewing and carrying out the risk assessment of oil spill response methods for the Arctic region, was subjected to give a generalized summary without focusing on a certain case study (see chapter 1.4). Due to the application of the typical parameters of the Arctic environment into the research, the results of the risk assessment can be adopted and implemented into a certain case study based on specific issues related to the chosen location and spill scenario in the North. That is why the methodology chosen is a qualitative survey, especially due to the absence of the sufficient data.

3.2 Research Strategy and Process

This master thesis is the research based on the specialization project that was aimed to study and define the consequence of an accidental oil spill for the Arctic environment and ecosystem and was written during the learning process associated with obtaining the master's degree. That is why it has been chosen to continue with the case study, that is combined of two main aspects such as oil and gas industry and the Arctic, and focus on the application of existing methods for oil spill response and elimination. The research questions (see chapter 1.3) that have been developed for conducting a research are intended to give an overview of the case study associated with this master thesis. The first and the second questions can be considered as exploratory issues including the application of the decision-making process during the working process while the third question is focused on showing possible hazards and subsequent consequences as well as present the risk evaluation and, therefore, safety measures and recommendations, for each element of the risk assessment. It should be emphasized that the discussion (see chapter 5) of the results for the risk analysis is based on the implementation the finding for the first two questions. That is how all the research questions have a strong interrelation between each other.

As the main objective of the thesis is to carry out the risk assessment for existing methods for oil spill response in the Arctic, the research process is focused on the application of risk assessment and choosing the hazard identification technique. Nevertheless, one of the main tasks when doing the research is to present a sufficient literature review that gives an opportunity to answer to the research questions. Figure 3-1 (see next page) shows activities to be done when developing the case study. As it has been already mentioned, the first two research questions have an exploratory nature and based on the literature review that can conduct to the carrying out the risk assessment and give an opportunity for the researcher to define such issues as potential hazards, its causes and subsequent effect on the chosen system as well as develop proper safety measures and recommendations.

The research process was started with conducting a sufficient literature review that focuses on the answering to the two first research questions. At the same time, when the system, or case study related to oil spill response in the Arctic, for carrying out the risk assessment had been chosen, a HAZID technique that is suitable for fulfilling the aim of the thesis based on the data availability was established. That is how the HAZID analysis was developed for defining the effects on the response process caused by the potential hazard categories and subsequent hazards associated with the extreme environmental conditions of the Arctic region. In addition, some aspects of the socio-economic factors were considered. The hazard categories are established using such potential hazardous events as the Arctic meteorological and ocean conditions, ice presence, general chemical properties of spilled oil, visibility limitations as well as HSE management and challenges associated with the remoteness and the Arctic region.

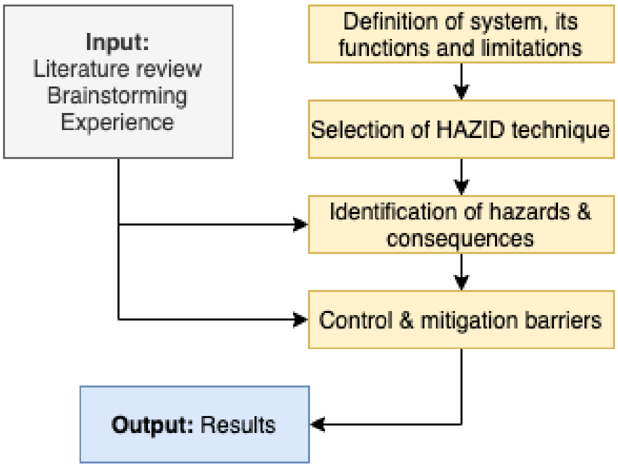


Figure 3-1 Research process chosen for conducting a risk assessment

When the process of risk assessment was being carried out, the implementation of the brainstorming sessions was necessary for evaluating the intermediate results and solving the challenges the researcher faced with. That is how it was possible to continue with developing the case study and subsequent hazard identification analysis. Such sessions were also important for establishing the correct measures to prevent, control and mitigate potential unwanted events. In addition to such instruments as literature review and brainstorming, the researcher used own experience for risk assessment procedures because of conducting a generalized research for the Arctic. In this case, it is considered to be difficult and time-taking to find experts that are able to contribute to a chosen case study. Due to the absence of the sufficient information regarding the characteristics of the offshore activities in the Arctic, safety barriers for some effects as well as the probability scoring were developed on the basis of the hazard category.

As a result of the implementation of literature review, brainstorming and experience into the preliminary risk assessment process, the HAZID analysis presents an overview over the evaluation of the existing oil spill response methods.

3.3 Data Collection and Validation

The data that was collected for conducting a research related to fulfilling the objectives of the case study for this master thesis had been beforehand divided into several groups that focus on the specific themes. Based on the chosen research purpose and strategy, the data was sorted and classified into several groups:

- The Arctic environment, focusing on it meteorological and sea state conditions;
- Oil spills in the Arctic as well as the behavior and fate of the oil spilled in ice-infested waters;
- The existing oil spill response methods that are feasible in the Arctic areas including contingency management;
- The theory related to risk assessment and hazard identification.

In addition to this information, it was necessary to include various figures, schemes, tables and graphs in order to present some data in a graphical and quantitative manner that are more sufficient to be analyzed and discussed. Using all the collected data that is consistent, arranged and performed as a literature review (see chapter 2), the research was able to be conducted on the basis of the chosen methodology and, therefore, the research questions was answered.

When carrying out any research, it is of the highest importance to ensure that the data collected is valid and reliable. That is how the results obtained can be considered as relevant. The data used for this thesis has been collected from various reliable sources and authority organizations that establish and develop standards and guidelines for offshore activities in the Arctic with the focus on the oil and gas industry. In addition, some data associated with the graphical surveys was taken from different meteorological institutes of the Arctic countries. What is more, data from the reviews of different research carried out in the High North was applied for fulfilling the objectives of the case study. Due to the absence of extensive literature sources related to certain area of the activities in the Arctic, the data collected from possible reliable sources and organizations can be considered as valid and implemented into the research process.

4 Results

This chapter presents the results for the third objective (see chapter 1.2) of the master thesis that is based on the carrying out the risk assessment and hazard identification for oil spill response in the Arctic conditions.

4.1 HAZID Flowchart

Figure 4-1 presents a flowchart for the hazard identification analysis based on the hazard identification analysis present in next under chapter.

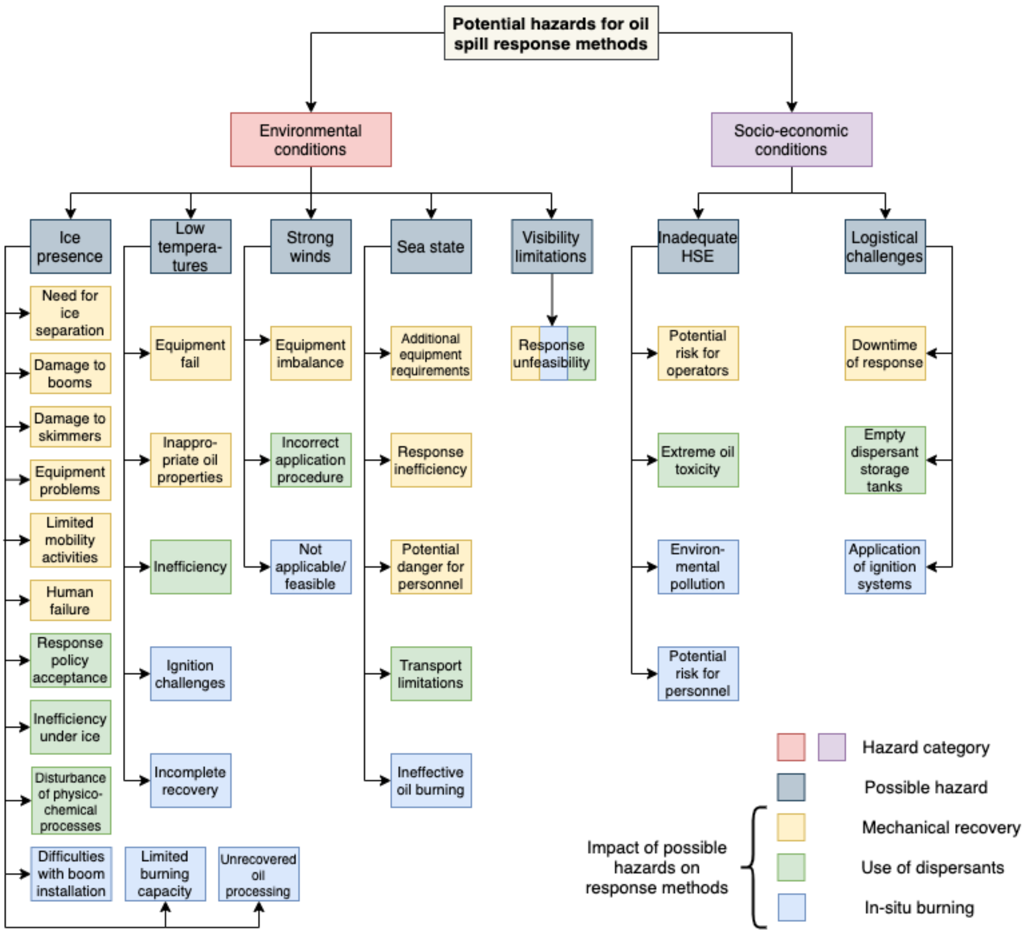


Figure 4-1 Flowchart for HAZID results of oil spill response methods

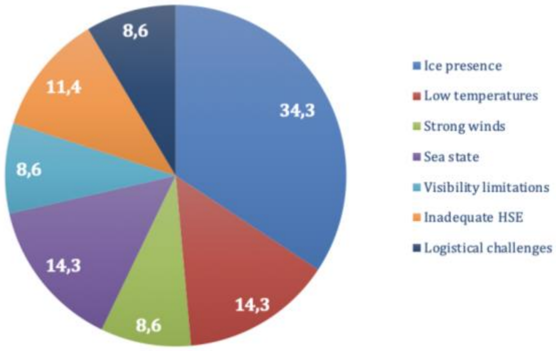
The potential hazards for oil spill response procedures are divided into two main categories such as environmental and socio-economic conditions. Each category is then split into various potential hazards derived from the literature review (see chapter 2). The environmental conditions associated with the Arctic consist of such potential hazards as ice presence, low temperatures, strong winds, sea state and visibility limitations. The socio-economic aspects lead to such potential unwanted events as inadequate HSE (health, safety and environment) management and logistical challenges. The flowchart also contains effects on the different oil spill response methods suitable for the Arctic (see chapter 2.3.2): mechanical recovery, use of dispersants and in-situ burning. The consequences associated with each method are shown in the flowchart with different colors.

Table 4-1 shows the distribution of the established effects derived from the total number of the effects, that is equal to thirty-five, in relation to both potential unwanted events and response methods. The table is based on the flowchart presented in previous page. That is how it is possible to evaluate the distribution of the hazards in a numerical manner.

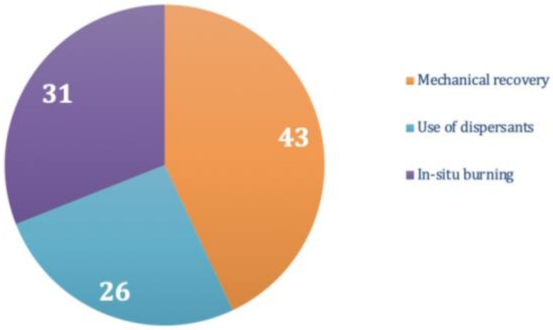
Table 4-1 Distribution of number of effects for each potential hazard and response methods in relation to total number of effects

Hazard	**Number of associated effects**	**Distribution**	**Response method**	**Number of effects**	**Distribution**
Ice presence	12	34,2 %	Mechanical recovery	15	43 %
Low temperatures	5	14,3 %			
Strong winds	3	8,6 %			
Sea state	5	14,3 %	Use of dispersants	9	26 %
Visibility limitations	3	8,6 %			
Inadequate HSE	4	11,4 %	In-situ burning	11	31 %
Logistical challenges	3	8,6 %			
Total	35	100 %	*Total*	35	100 %

Graph 4-1 and Graph 4-2 are based on the numerical values from Table 4-1 and represents the percentage of the effects on the response methods for both potential hazards and existing response methods. That is how the prevailing elements of the hazard identification analysis can be seen.



Graph 4-1 Graphical representation of the distribution of the consequences for each hazard category



Graph 4-2 Graphical representation of the distribution of the consequences for each response method

4.2 HAZID Analysis

In order to study the framework and results of the hazard identification analysis, it is important to give the description of several elements of the risk assessment. Table 4-2 consists of the possible hazards and probability estimation that is included into the main analysis. It has been mentioned in the methodology part (see chapter 3) that the position in the risk matrix for each consequence has been estimated using the evaluation of probabilities for each potential hazard. Table 4-2 describes the issues that have been taken into consideration when determining the probabilities.

Table 4-2 Probability estimation for each hazard category

Hazard Description	Probability	Comment
Ice presence	E	Based on the figures presented in chapter 0, the Arctic area is characterized by the presence of various ice classes and types that some are multiyear ice. Considering the average probability of the ice presence in this region, it can be classified as a frequent phenomenon.
Low temperatures	E	The probability of low temperatures in the Arctic region is frequent. Graph 2-1 shows that the average temperature for the region located in the Arctic Circle is lower than 0 degrees Celsius, except the period between approximately days 170 and 230.
Strong winds	C	Winds that are formed by the air pressure differences are pertain and affect the sea state conditions. Wind patterns varies for the Arctic areas and are difficult to be predicted due to the presence of the polar low pressures that generates strong winds and, therefore, impact on the oceanographic conditions. The probability is considered to be medium due to the range of variations in the size of such climatic characteristics.
Sea state	C	

Visibility limitations	E	Darkness is known as one of the main challenges for offshore activities in the Arctic region. Dividing the Arctic area into three parts, the North Pole, the middle area and the Arctic Circle, it can be estimated, using data from Table 2-1, that, in addition to approximately 1/3 part of a year of a prevailing dark hours per day, it is approximately 35% of a complete darkness (24 hours per a day) in the Arctic region. Based on such properties, the probability for the limited visibility is classified as frequent.
Inadequate HSE	B	The Arctic is a vulnerable region due to the low recovery rate of ecosystem. The Arctic countries contribute to risk reduction of any accidents and their subsequent consequences, and a lot of different policies, standards and guidelines are established and implemented (see chapter 2.2.2). However, the Arctic region is not yet well-studied, and its climatic conditions are unpredictable. Therefore, the probability for the inadequate HSE can be scored as unlikely to happen.
Logistical challenges	E	In addition to the remoteness of the Arctic region and visibility limitations, the environmental conditions of the High North make the logistics associated with oil spill response challenging, especially in case of ice presence. These factors contribute to the scoring logistical challenges as a frequent event. Even though this category is considered to be related to socio-economic conditions due to the requirements for high-quality personnel and equipment, the combination of some Arctic features contribute to presence of challenges for safety and economics.

Table 4-3 in next page shows the hazard identification analysis including preventative and corrective measures, recommendations for each element and position in the risk matrix as the result of probabilities of possible hazards and severity category for the established effects. The risk assessment is based on considering effects on each response method. The abbreviation for each of them has been used in the framework: M – mechanical recovery, D – use of dispersants, B – in-situ burning. In addition, all the effects were numbered for all the effects according to the response type. The column "Position in Risk Matrix" is colored and gives the description of the risk scoring (see chapter 2.4.2.2 for the description of the risk matrix) that is developed in a quantitative manner due to the chosen methodology (see chapter 3).

Table 4-3 Results for HAZID analysis of oil spill response methods in ice-infested areas

Hazard Category	Hazard Description	Response Method	Effects on the system (Consequen-ce)	№	Mechanism	Measures and Recommenda-tions	Position in Risk Matrix: (Probability – Severity of Consequence)
Environmental conditions	Ice presence	M	Need for ice separation	1M	Mechanical containment demands the ice to be separated from the oil that is to be removed.	Apply anti-icing systems. Ice management that is focused on detection and monitoring of ice conditions	**E - 1**
			Damage to booms	2M	In case of high ice concentration or presence of different ice combinations, the booms can change the position and be exposed to breakage as well as skimmers can loss operational efficiency.	Use high-quality equipment that is suitable for application in the cold climate condition and meets the technical requirements established by the authority organizations. The preparation of equipment for response activities is demanded, especially the winterization procedures during the winter months	**E - 1**
			Damage to skimmers	3M			**E - 1**
			Equipment problems	4M	Equipment components may be exposed to deterioration or technical or structural failures due to failures in main system that are affected by ice.		**E - 1**
			Limited mobility activities	5M	Various ice combinations and concentration may impede the response activities and mobility of equipment.	Carry out the necessary activities for preparing the site for the mechanical recovery by	**E - 1**

						applying icebreakers. Effective contingency planning, focusing on the proactive activities for oil spill response	
			Human failure	6M	Equipment used for mechanical recovery may be affected by ice behavior that is difficult to predict. Unexperienced personnel may not manage to such problem.	Implement regular trainings and exercises as well as increase the proficiency of operators. Highly qualified and experienced personnel have to carry out response procedures	**E - 2**
		D	Response policy acceptance	1D	Depending on national policy, dispersants, especially in ice presence must be approved to be implemented into response strategy.	Develop proactive management for defining dispersants that can be used for response. Adequate company/ organization management	**E - 1**
			Inefficiency under ice	2D	Application of dispersants is not possible if oil has been spilled under the ice.	Choose another response option or combine several to be able to apply dispersant considering ice concentration	**E - 2**
			Disturbance of physicochem	3D	Dispersants are effective for oil containment if the ice concentration is	Develop effective application procedure based on the	**E - 1**

			ical processes		not higher than approximately 20-40%. Ice may diminish mixing capacity and, therefore, slow down processes of dispersion.	environmental conditions and oil properties. Monitor ice conditions to choose dispersants that meets all the demands	
		B	Difficulties with fire boom installation	1B	The installation of fire booms used for in-situ burning may become a complex task due to ice presence.	Develop a technology for fire boom installation in ice conditions. Prepare the site to simplify response activities. Engage qualified and experienced operators	**E - 1**
			Limited burning capacity	2B	Specific combination of ice conditions and weather factors may influence the burning efficiency and ignition process.	Laboratory tests are demanded to develop methodology for successful and safe burning process that is feasible for various weather condition, especially in case of unpredicted changes	**E - 1**
			Unrecovered oil processing	3B	The oil that is left and not recovered demands additional monitoring and recovery activities.	Apply anti-icing systems to simplify the procedure of oil elimination if it is possible for a certain case. Improve technologies and methods for in-situ burning	**E - 2**

	Low temperatures	M	Equipment fail	7M	Cold temperature may lead to the deterioration or fail of booms/ skimmers due to spray ice formation or freezing.	Use high-quality equipment that is suitable for application in the cold climate condition and meets the technical requirements established by the authority organizations	**E - 1**
			Inappropriate oil properties	8M	Low temperature affects the flow resistance of hydrocarbons and makes them difficult to be processed.	Use equipment that has much enough capacity for oil processing. Effective contingency planning that is based on compliance with technical requirements	**E - 2**
		D	Inefficiency	4D	Spilled oil becomes more viscous under low temperatures and may not be treated by dispersants.	Improve contingency planning and implement monitoring for site conditions to predict the changing of oil properties	**E - 2**
		B	Ignition challenges	4B	Ignition procedure may be affected by low temperatures that impedes or slows down burning process. Not all the spilled oil is recovered.	Laboratory tests are demanded to develop methodology for successful and safe burning process that is feasible for various weather condition that may affect burning capacity	**E - 2**
			Incomplete recovery	5B			**E - 2**

	Strong winds	M	Equipment imbalance	9M	Wind may disbalance of transport and deploy booms.	Apply appropriate techniques to ensure that equipment installed is reliable and stable. Management focus on implementation of effective equipment and compliance with safety requirements	**C - 1**
		D	Incorrect application procedure	5D	Strong winds may impede following the required procedure related to dispersant implementation.	Engage experience and trained operators that can manage to additional challenges arisen during response activities. HSE management including regular trainings, mandatory exercises, compliance with established requirements	**C - 2**
		B	Not applicable/feasible	6B	High wind speed causes difficulties for ignition activities and transport.	Effective contingency plan focused on analyzing the applicability of response method. Choose other method that is applicable for certain weather condition. If impossible, provide the implementation	**C - 1**

						of efficient techniques tested in laboratory/field	
	Sea state (waves, currents and winds)	M	Additional equipment requirements	10M	Extreme sea conditions may require the use of specific equipment that is sufficient for a certain spill area.	Use of high-quality equipment and transport that are suitable for certain oceanographic conditions.	**C - 1**
			Response inefficiency	11M	Medium and high wind heights as well as strong waves create difficulties for equipment functioning and may lead to its loss of stability.	Ensure presence of replaceable components to prevent downtime of response	**C - 2**
			Potential danger for personnel	12M	Extreme sea conditions may create a potential danger for operators that are responsible for functioning of skimmers and/or booms.	Provide personnel with PPE (personal protection equipment). Implement regular trainings and courses to increase level of education.	**C - 3**
		D	Transport limitations	6D	If the response strategy is based on the use of marine transport, some sea conditions require certain ship types.	Effective contingency plan based on analyzing and predicting weather condition. Monitor weather conditions and ensure availability of transport that meets all the requirements for a certain area	**C - 1**

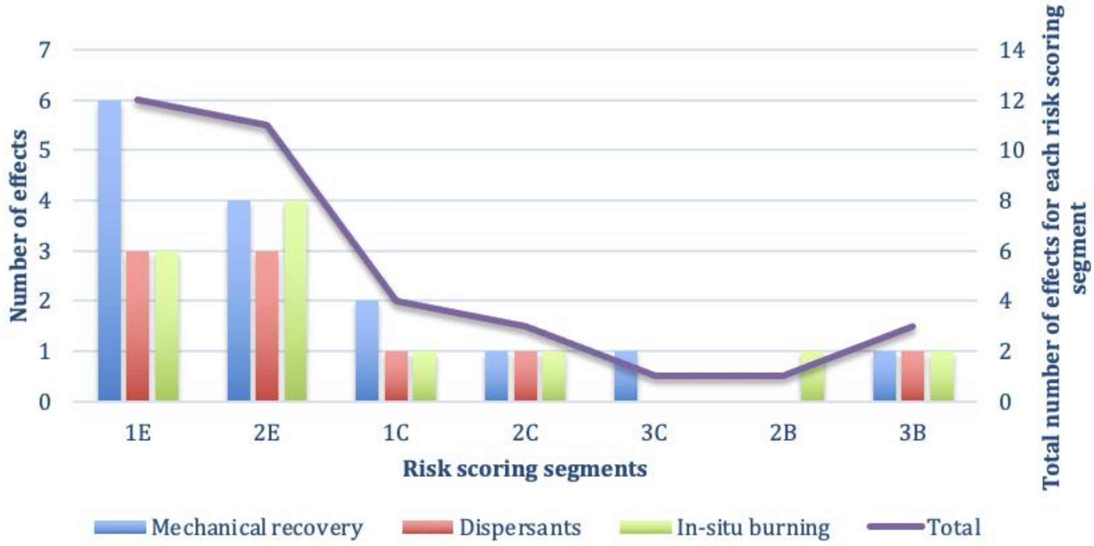
		B	Ineffective oil burning	7B	Even medium wave heights reduce the effectiveness of oil burning procedures.	Choose other method that is applicable for certain weather condition. If impossible, provide the implementation of efficient techniques tested in laboratory/field	**C - 2**
	Visibility limitations	M	Response unfeasibility	13M	Darkness impedes oil spill response due to physical inability of personnel to carry out activities that must comply with safety rules.	Contingency planning based on visibility limitations. If possible, postpone response activities. Otherwise, application of appropriate light sources from aircraft or vessel is required	**E - 2**
		D		7D			**E - 2**
		B		8B			**E - 2**
Socio-economic conditions	Inadequate HSE management	M	Potential risk for operators	14M	Arctic conditions creates difficulties for carrying out the response procedures. In case of absence of compliance with safety rules, especially during unpredictable situations, operators may get injured.	Efficient HSE management. Provide personnel with PPE (personal protection equipment). Implement regular trainings and courses to increase level of education	**B - 3**
		D	Extreme oil toxicity	8D	Improper choice of dispersants may increase oil toxicity in addition to high level due to dispersion.	Adequate HSE management. Develop and apply a proper response method that has been evaluated, tested	**B - 3**

						and satisfies safety rules	
		B	Environmental pollution	9B	Incomplete response procedure in case of in-situ burning results in the presence of unremoved residues that are a potential source of pollution, including air, water, flora and fauna.	Engage experienced and qualified personnel for burning activities. Ensure compliance with safety rules and technological requirements	**B - 2**
			Potential risk for personnel	10B	Lack of knowledge or trainings as well as absence of compliance with regulations and safety rules may lead to uncontrolled oil combustion as well as hazardous emissions.	Provide personnel with PPE (personal protection equipment). Implement regular trainings and courses to increase level of education	**B - 3**
	Logistical challenges	M	Downtime of response	15M	The Arctic conditions affect the mechanical equipment and make it vulnerable to damages and deterioration. In case of absence of proper replacement parts, response activities may undergo downtime due to remoteness of region.	Develop a response strategy that requires not only the application of appropriate equipment but also availability of additional replaceable components and elements of a system, ensuring its accessible during response process	**E - 2**

		D	Empty dispersant storage tanks	9D	Remote distances may affect response activities because storage tanks for dispersants becomes empty after dispersant application, and recharge may be demanded.	Effective contingency planning. Estimate the quantity of dispersants needed for response and ensure its availability	**E - 1**
		B	Challenges with application of ignition systems	11B	Procedure of in-situ burning requires accurate arrangement of equipment, but remoteness and logistical features of the Arctic have impact on the response activities.	Develop response plan that considers all the challenges related to transportation and installation of equipment. Ensure application of proper response strategy	**E - 1**

4.3 Overall Risk Scoring

Based on the finding for the hazard identification analysis and risk scoring, the graph that summarizes the results has been developed. Graph 4-3 shows the position in the risk matrix for the consequences of each response method as well as the total number of such effects per each risk scoring segment. It can be seen that the probability estimation includes the B, C and E scorings as well as the severity ranking for the established consequences is 1, 2 and 3 (see chapter 2.4.2.2 for the description of probabilities and consequence severity). In addition, the total number of effects per each risk segment is shown as the curve for evaluating the trend of the risk.



Graph 4-3 Distribution of effects on response methods, caused by possible hazards, on the basis of risk scoring

In spite of the fact that the preliminary risk assessment has been developed to identify potential hazards, subsequent consequences and to evaluate the risk, the hazard categories have been also evaluated on the basis of risk scoring. Table 4-4 represents the position in the risk matrix for each hazard category. The risk scoring for each element has been derived from the results for the effects (see Table 4-3) and estimated as the average value. The severity ranking for the hazard groups is evaluated as insignificant, minor or moderate while the probabilities is to be remote, occasional and frequent (see Table 4-2 for the description of probability estimation).

Table 4-4 Risk matrix for hazards categories

Severity	**Consequence**	**Probability**				
		A	B	C	D	E
		Unlikely	*Remote*	*Occasional*	*Probable*	*Frequent*
1	*Insignificant*			Strong winds		Ice presence; Logistical challenges
2	*Minor*			Sea state		Low temperatures; Visibility limitations
3	*Moderate*		Inadequate HSE			
4	*Major*					
5	*Massive*					

5 Discussion

This chapter presents the discussion for the results for the defined objectives (see chapter 1.2) of the research. The first and second objectives have been covered during conducting the literature review. The results for the third objective are shown in chapter 4.

5.1 Objective 1

The results for the first objective of the thesis that is focused on the studying the spreading and behavior of spilled oil in the Arctic as well as the main influencing factors of the weather and oceanographic conditions on the oil weathering have been developed, considered and analyzed in the literature review part (see chapter 2.2.3). In addition, socio-economic aspects have been considered on the basis of the characteristics of the Arctic environment. The findings for the first objective have been applied for conducting the risk assessment associated with the third objective.

5.2 Objective 2

The results for the second objective have been also developed and presented as a literature review. This objective is based on the studying the existing oil spill response methods that are suitable and effective for implementation in the Arctic region (see chapter 2.3.2). What is more, response procedure has been considered as a proactive approach including preparing for response and developing contingency planning (see chapters 2.3.1). As a result of the analyzed information, the limitations for applicability (see chapter 2.3.2.4) of the response strategies have been presented regarding the main influencing factors associated with cold climate conditions. The findings for the second objectives have also contributed to the conducting risk approach.

5.3 Objective 3

The third objective has been defined is conducting the risk assessment of existing oil spill response methods applicable for the Arctic on the basis of analyzing the environmental conditions of this region as the main influencing factor. It has to be emphasized that the risk assessment represents a generalized approach for the Arctic region focusing on the potential hazards and subsequent consequences. However, the framework can be applied and adjusted for a certain case study. In this case, the environmental and oceanographic conditions as well as ice concentration, that is a determining factor for establishing response strategy, for a specified location must be considered and analyzed. In addition, the characteristics of oil spill and physiochemical properties of spilled oil also must be evaluated. That is how the severity of consequences, probabilities and, therefore, the risk will be changed according to the defined input aspects.

First of all, two hazard categories, the environmental and socio-economic conditions, have been chosen in order to derive the subsequent potential hazards for carrying out the response actives. Then the hazards have been classified in relation to the mechanisms of the hazard categories that are related to each other. The flowchart for the hazard identification (see Figure 4-1) shows how potential hazards affect chosen response methods that are mechanical recovery, use of dispersants and in-situ burning. Such an unwanted event as ice presence, that is one of the main challenges for offshore activities in the Arctic and can be a outcome of the combination of other potential hazards, contributes to formation of lots of effect on the response methods. Low temperatures, strong winds and sea state conditions possess less consequences. It has to be noted that these possible hazards have strong interrelation to each other in spite of the fact that these have been split. Visibility limitations affects all the response activities. Inadequate HSE management that belongs to the socio-economic group also contributes to negative consequences and can be considered as the influencing factor in addition to the Arctic characteristics. Logistical challenges are based not only on response management but also are affected by the Arctic conditions, mainly because of the sea spray ice formation.

In order to carry out the risk assessment related to HAZID analysis, it is important to present the distribution of the number of effects for each potential hazard and response method (see Table 4-1). Taking into consideration the potential hazards, it can be seen that ice presence leads to the highest number of consequences, that is equal to 12, for response methods while the rest of unwanted events contribute to three, four or five effects. When analyzing the distribution for the response methods, mechanical recovery is more vulnerable to the potential hazards in comparison with use of dispersants and in-situ burning. The prevailing components for the hazard identification analysis are also shown graphically (see Graph 4-1 and Graph 4-2).

The hazard identification analysis presented in Table 4-3 shows the description for hazard category and subsequent potential hazards for oil spill response methods illustrated in the flowchart. All the unwanted events have been analyzed on the basis of the describing the action mechanism for each response method. As a result, barrier elements and recommendations have been implemented for each case. The measures and recommendations for all the consequences are based on the developing an adequate and effective contingency planning including proactive activities such as monitoring and detection and establishing response strategies that meet both technical and safety requirement. The challenging Arctic conditions demands the application of the high-quality and experienced personnel and reliable equipment.

Due to the limitation regarding the availability of the sufficient data associated with oil spill response in the Arctic, the probabilities for the effects have been evaluated on the basis of the potential hazards in a qualitative manner (see Table 4-2 that gives reasoning for probability estimation). The severity of each effect on response methods has been chosen focusing on the priority ranking for any response activities (see Figure 2-15) focusing on such aspects as life, health and environment while considering economic interests to be of the lowest priority. The negative consequences cause by an accidental oil spill itself have not been taken into account. After all the effects got position in the risk matrix, it can be seen that there is no category with unacceptable risk. The risks for effects are estimated as either low or moderate equally. For the moderate risk elements, the risk must be reduced ALARP with either adjusting the probability or consequence severity, including the carrying out cost benefit analysis. It has been already mentioned that the risk assessment carried out in this thesis is a generalized approach, and the risk scoring will be changed in case of determining certain characteristics for an oil spill.

The overall overview of the position in the risk matrix for each response method is presented in Graph 4-3. It can be seen that effects are distributed in the severity categories of 1, 2, and 3 (insignificant, minor and moderate respectively) while the probabilities are in B, C and E (remote, occasional and frequent respectively). Insignificant and frequent risk occupies the highest number of effects. The minor and frequent risk also belongs to the high number of associated events while the rest of effects are distributed in a same proportion.

Based on the results for the hazard identification analysis, the average risk for each hazard category has been estimated and positioned into the risk matrix (see Table 4-4). The effects on response methods associated with strong winds, ice presence and logistical challenges imply the acceptable value of risk while sea state, low temperatures, visibility limitations and inadequate HSE management contribute to the moderate risk.

Taking into consideration all the analyzed results for risk assessment presented in chapter 4, it can be concluded that all the potential hazards equally contribute to subsequent effects for oil spill response methods. What is more, all the hazards are strongly interrelated to each other and changing in one condition leads to subsequent changes in others. Mechanical recovery implies the highest number of associated effects while dispersants and in-situ burning affected by the lower number of potential hazards. However, when developing an oil spill response strategy, the efficiency and applicability of the response method must be taken into account. That is how the adequate and appropriate strategy can be developed and implemented into the contingency planning.

6 Conclusion

Based on the results and discussion related to the objectives and research question of the thesis, it is possible to derive the main conclusions:

- The oil spilled in ice-covered waters is influenced mainly by the ice conditions, including ice concentration, shape and porosity. Depending on the ice concentration, spilled oil behaves as in open waters, stuck into ice or its behavior is difficult to predict. In addition to ice presence, oceanographic conditions have a great impact on the oil spreading. The process of oil weathering is defined as a chain of physicochemical reactions which contributes to the fragmentation of spilled oil that is then disseminated in the water column in a vertical direction. The oil weathering process in the Arctic includes spreading, evaporation, dispersion, emulsification associated with the early stage while oxidation and sedimentation pertain to the later stages. The environmental conditions of the Arctic slow down the rate of oil weathering. However, sea ice presence and low temperatures may increase the effectiveness of the oil spill response operations.
- The existing oil spill response methods that can be applied in the Arctic are mechanical recovery, use of dispersants and in-situ burning. The efficiency of response procedures in cold climate conditions depends not only on the effective contingence planning but mainly governed by such environmental conditions as ice presence, wind speed, visibility and sea state conditions. However, ice concentration is the prevailing factor that contributes to the applicability of response methods. Each response technique has both advantages and disadvantages as well as may contribute to potential hazards in case of inadequate application.
- The preliminary hazard analysis that has been carried out for each response method and definition of potential hazards have proved that the ice presence causes the highest number of negative consequences but characterized by the acceptable risk scoring. taking into account the effects on the response methods, mechanical recovery is more subjected to hazards compared to use of dispersants and in-situ burning. The overall results for the risk assessment show that all the methods have approximately risk scoring as well as the climate conditions of the Arctic have impact on each other. The risk assessment has been carried out in a quantitative manner and contributes to the evaluating potential hazards for the response methods on the basis of the generalized approach that can be adopted to a particular case study.

6.1 Suggestions for Future Research

On the basis of the conducted approach, ideas for further research can be suggested:

- The Arctic conditions for the areas of the High North differ from each other and are difficult to be predicted. That is why the research that is based on the establishing possible weather scenarios for the areas that are mainly used for offshore activities can be developed in order to contribute to the creation of powerful techniques that then be implemented in the contingency planning for oil spill response strategies.
- As the data and knowledge associated with potential hazards and subsequent consequences for oil spill response activities in the Arctic are rather limited, different approaches have to be developed and data collected in order to reduce the risk of unwanted events that may occur when carrying out response activities.
- The detailed risk assessment for response methods is demanded in order to establish an effective proactive management program that focuses on the preventing severe pollution for the vulnerable Arctic region.

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