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Oil Spill Preparedness and Response in the Arctic

The effect of low temperature on oil spill response operations in the Arctic with respect to overall equipment effectiveness

Markus Helfjord Rolandsen

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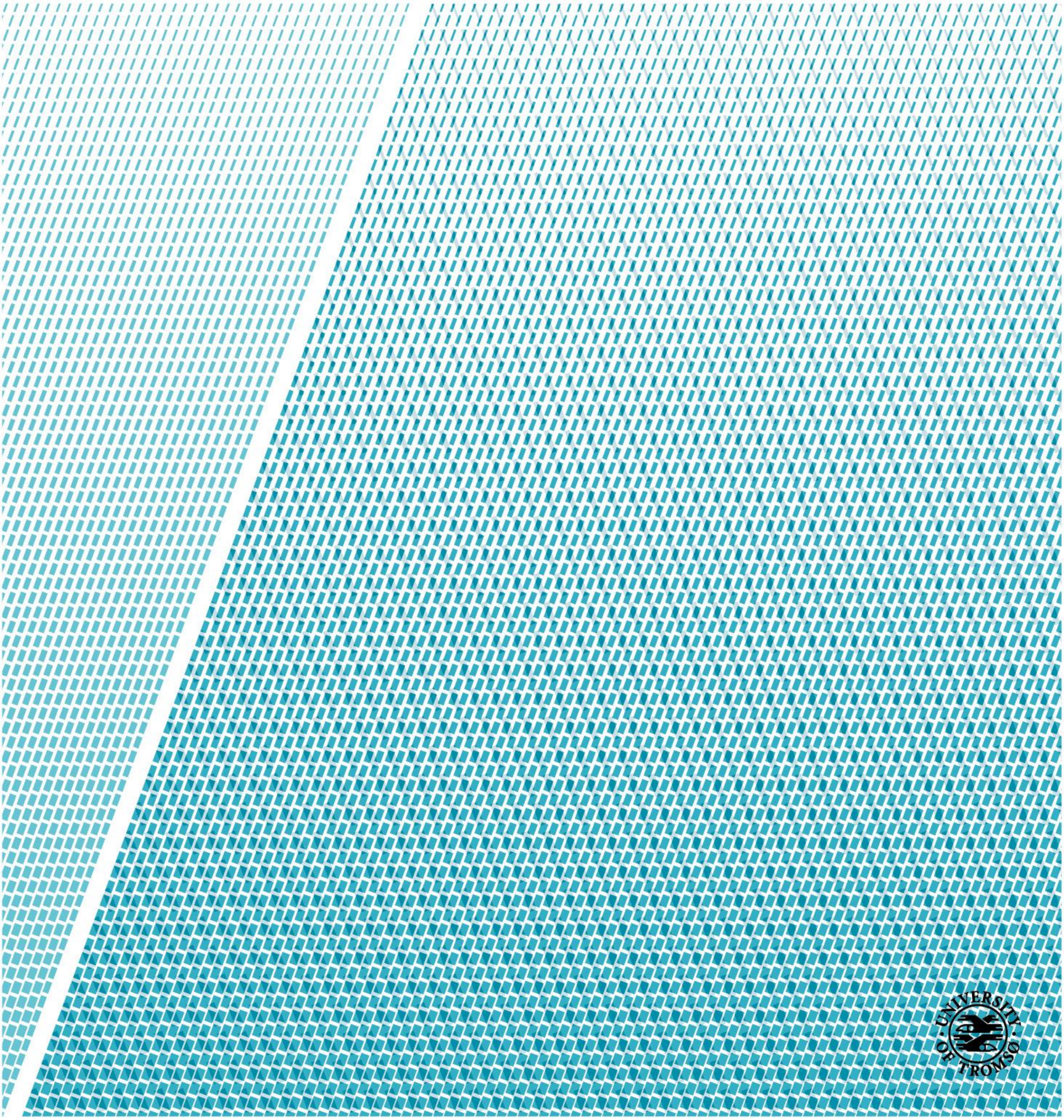

Abstract

Effectiveness is an important term in oil spill response operations. Literature often relate to the level of effectiveness connected to either mechanical containment and recovery, in-situ burning or chemical dispersant application. The term effectiveness in oil spill response operations can be related to existing theory and the perspective of Overall Equipment Effectiveness (OEE). The perspective of OEE can further be related to the perspective of Reliability, Availability, and Maintainability (RAM).

This research study will review the effect of low temperature on oil spill response operations in the Arctic through a literature study. The literature study will cover research related to oil spill response operation in the Arctic and evaluate the effectiveness in general terms.

Further in the literature study, the approach to effectiveness in oil spill response operations is discussed. Based on this discussion and on existing theory of OEE and RAM, it is found clear relevance in evaluating the effect of low temperature on RAM performance in oil spill response operations.

To evaluate the effect of low temperature on RAM performance in oil spill response operations, existing literature and research covering RAM performance of oil and gas production facilities in the Arctic was reviewed, along with research covering oil spill response operations and Arctic operations in general.

This literature review, with its focus on low temperature as influencing factor, has led to some suggested aspects for improving RAM performance of oil spill response operations in the Arctic. These aspects for improvement are alleged to substantiate the OEE of oil spill response operations.

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Notation and abbreviation

CM	Corrective Maintenance
PM	Preventive Maintenance
MTBF	Mean Time Between Failures
MTTR	Mean Time to Repair
NCA	Norwegian Coastal Administration
NOFO	Norwegian Clean Seas Association
OEE	Overall Equipment Effectiveness
RAM	Reliability, Availability, Maintainability
TBF	Time Between Failure
TTR	Time to Repair
MDT	Mean Down Time
RCM	Reliability Centered Maintenance
TPM	Total Productive (Preventive) Maintenance

Basic definitions

Availability (OEE)

Represents the percentage of scheduled time that the operation is available to operate. The availability metric is a pure measurement of uptime that is designed to exclude the effects of quality, performance, and scheduled downtime events (Stamatis, 2010).

Performance (OEE)

Represents the speed at which the machine runs as percentage of its designed speed. The performance metric is a pure measurement of speed that is designed to exclude the effects of quality and availability (Stamatis, 2010).

Quality (OEE)

represents the good units produced as a percentage of the total units started. The quality metric is a pure measurement of process yield that is designed to exclude the effects of performance and availability (Stamatis, 2010).

Availability

The ability of an item (under combined aspects of its reliability, maintainability and maintenance support) to perform its required function at a stated instant of time or over a stated period (Rausand & Høyland, 2004).

Reliability

The ability of an item to perform a required function, under given environmental and operational conditions and for a stated period (Rausand & Høyland, 2004).

Maintainability

The ability of an item, under stated conditions of use, to be retained in, or restored to, a state in which it can perform its required functions, when maintenance is performed under stated conditions and using prescribed procedures and resources (Rausand & Høyland, 2004).

Maintenance

The combination of all technical and corresponding administrative actions, including supervision actions, intended to retain an entity in, or restore it to, a state in which it can perform its required function (Rausand & Høyland, 2004).

The Arctic

The regions around the North Pole.

High North

From the High North strategy of the Norwegian Government: Land- and ocean area from Sør-Helgeland in the south to the Greenland Sea in the west and the Pechora Sea in the east.

Boom

temporary floating barrier used to contain an oil spill. Conventional/passive boom systems are usually towed in U- or J-formation by two vessels. Active boom systems can be towed at higher operational speeds by one vessel.

Viscosity

Having a resistance to flow; substances that are extremely viscous do not flow easily.

Oil spill response

Measure implemented in the acute phase of an oil spill with the aim of preventing the spreading of the oil.

Skimmer

Device used to remove oil from water surface.

Oil slick

layer of oil floating on the surface of water.

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1 Introduction

1.1 Oil Spill in Cold Climate

Multiple sources of oil spills in ice-affected areas include marine activities connected with oil and gas exploration and production, cargo vessels, research vessels, cruise ships, drilling operations and pipelines. Compared with other world trade routes (Suez, Panama, Straits of Malacca etc.) the absolute numbers are still small, but the gradual increase in vessel traffic along the Northern Sea Route (NSR) and other areas, gives rise to an associated increase in spill risk (EPPR, 2015).

While ice is a characteristic year-round physical feature in central parts of the Arctic Basin, many parts of the Arctic with Oil and Gas activities today have no ice present at any time. This applies for areas such as the southern Barents Sea on the Norwegian Continental Shelf (Joint Industry Programme, 2017). The ice conditions in the Arctic in late summer is illustrated through Figure 1.1. This shows the great variability of the ice environment across the Arctic area, where the severity and duration strongly depends on time of the year and location. Such environment conditions, consequently affect the consideration and choice of optimal oil spill response options in terms of location and timing.

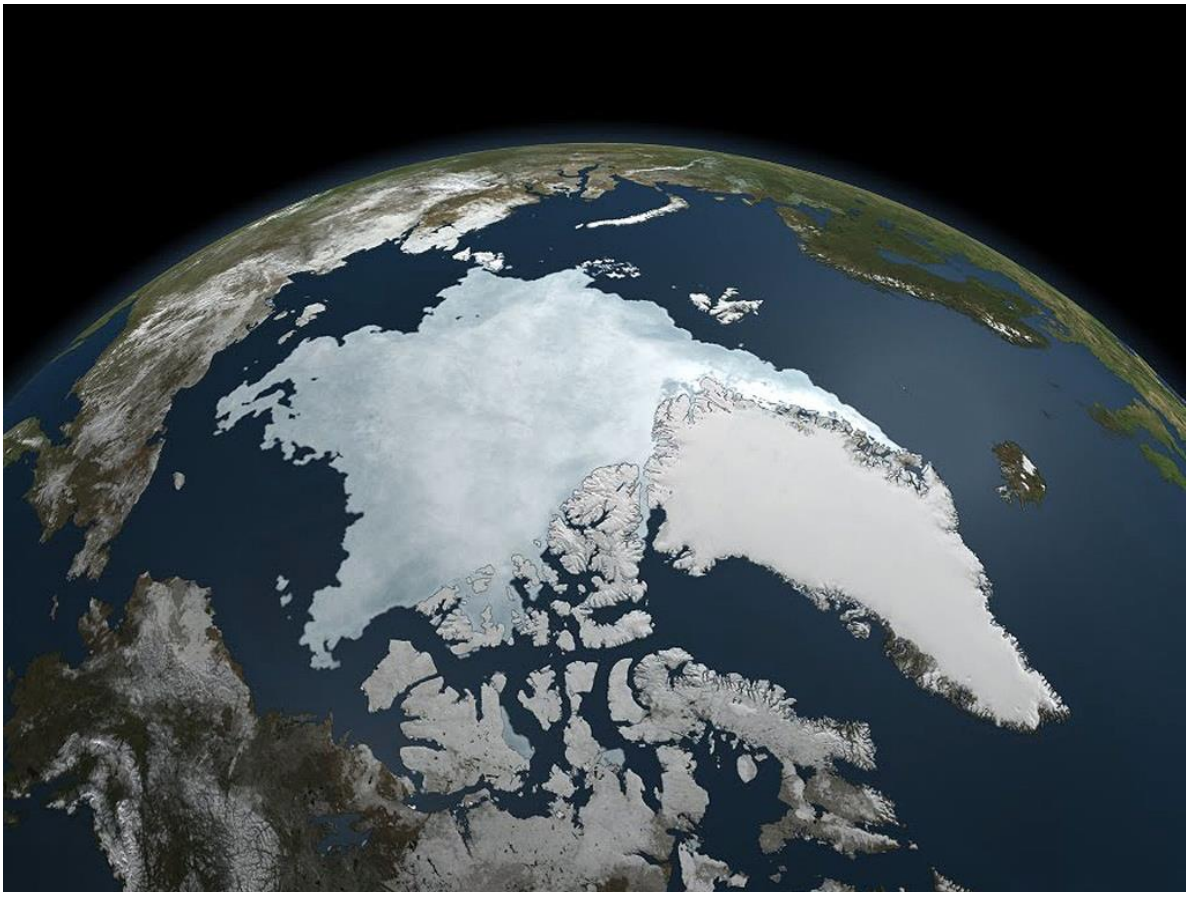


Figure 1.1 Arctic ice pack close to the time of minimum coverage, sept 9, 2011, Source: NASA

When choosing a response strategy, key factors such as local conditions need to be considered. Although, there are several strategic tools to apply in a response operation, using these effectively in a real incident could be extremely challenging. The challenges can be related to factors such as: coping with the dynamic nature and unpredictability of ice; the remoteness and great distances that are often involved in responding in Arctic areas; the impacts of cold temperatures, ice and harsh operating environment on response personnel and equipment; and the frequent lack of onshore infrastructure and communications to support and sustain a major response effort (EPPR, 2015).

The dynamic ice conditions introduce some challenges in developing effective Arctic oil spill response plans, however, the presence of ice may also provide a significant advantage over open water response. Ice cover (60 % or more) can greatly slow the oil spreading and weathering rates, contain oil in relatively small areas, rapidly isolate the oil from direct contact with many marine species, and delay shoreline oiling (Joint Industry Programme, 2017). Such circumstances will give the responders the benefit of planning time, which cannot be overstated in Arctic areas. In addition, any significant ice concentration can severely limit the effectiveness of mechanical containment and recovery, and at the same time, increase the window of opportunity for successful burning and/or dispersant applications (EPPR, 2015).

The Arctic region is currently the major focus of the media, government, and many other organizations worldwide, reflecting the rapid pace of Arctic climate change and concerns about the environmental risks associated with projected new developments, such as shipping, oil and gas, mining, etc. (EPPR, 2015). Hereby, the spill risks are divided into two groups, vessel traffic and oil and gas activity.

1.1.1 Spill risks from vessel traffic

The Norwegian Coastal Administration (NCA) has provided estimates for the coastal traffic in Norwegian waters from 2013 to 2040. The region of Svalbard is estimated with a total increase of 41% in designated distance. Fishing vessels stands for the main part of the designated distance of this region. The expected increase mainly concerns fishing vessels, passenger- and expedition ships, and transpolar traffic in a longer time perspective (Funnemark, Dahlsett, & Johnsrud, SARINOR2, 2017).

A wide range of petroleum hydrocarbon fluids are transported across Arctic ice-covered waters. Such voyages are associated with risk of spill to the environment. In addition, the presence of large volumes of on-board bunker oil on all ice-going vessels (e.g. tankers. ferries, cruise ships, container ships, bulkers) poses a significant additional pollution risk. Many vessels still rely on IFO 380 fuel, mainly due to economic reasons. Ongoing discussions have considered the feasibility of restricting the use of such heavy fuel oil in the Arctic (EPPR, 2015).

Although crude oil and petroleum products may represent the largest cumulative volume transported by sea, future spills are most likely to be dominated by release of bunker fuels from general cargo vessels. The spill size from a tanker will potentially be much larger in quantity, but the probability of such spill is extremely low. The potential for a large spill event (>700 tons) during the 2000s was seven times less than in the 1970s. This is a result of improved vessel engineering and operating/management procedures (EPPR, 2015). The occurrence of large oil spills from oil tankers since the 1970s is shown in Figure 1.2.

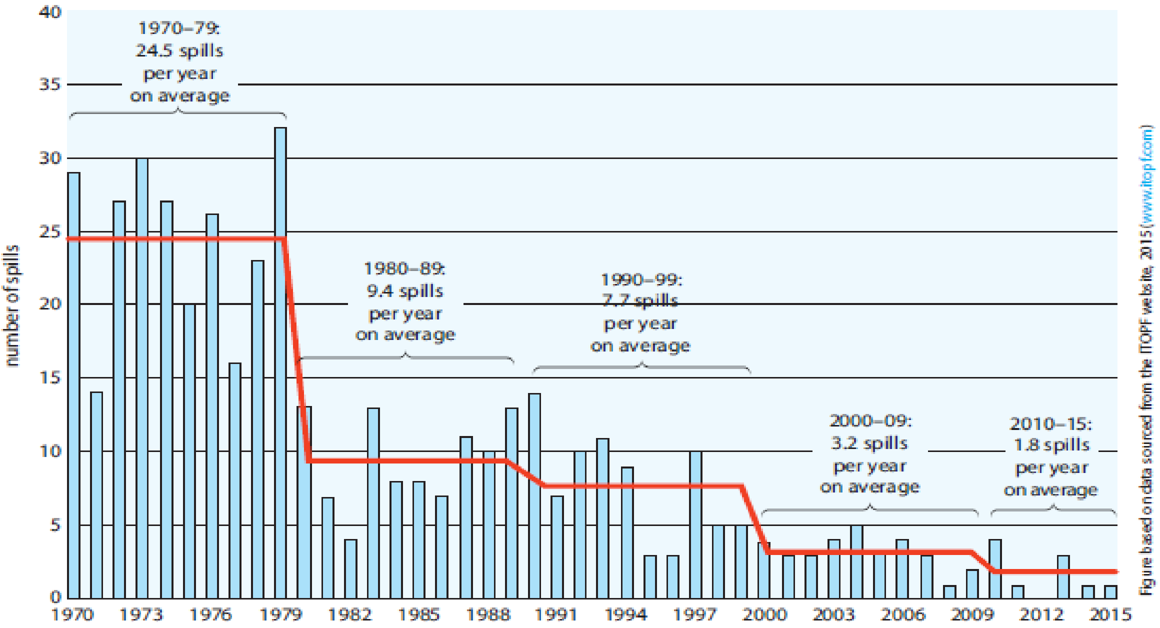


Figure based on data sourced from the ITOPF website, 2015 (www.itopf.com)

Figure 1.2 The number of large spills (> 700 tonnes) from oil tankers, 1970 to 2015

1.1.2 Spill risks from oil and gas activity

Oil and gas exploration and production activities in ice-covered waters are highly unpredictable and vary depending on individual company strategic plans, seismic prospects, political challenges, permit approvals, legal injunctions and, most importantly, overall economics (EPPR, 2015). While Arctic fisheries and tourism have increased, the recent downturn in world oil prices combined with the need to reduce our carbon footprint in line with the legally binding Paris Climate Agreement has potentially reduced the attractiveness of investment in the Arctic. For instance, several major oil companies have announced the abandonment or suspension of their drilling operations in the Arctic ocean. However, operations do continue (Wilkinson, et al., 2017).

According to the Norwegian Petroleum Directorate, there are a great number of undiscovered resources on the Norwegian Continental Shelf, and a large part lies in the Barents Sea. In the 23rd and

24th licensing round several new areas were announced. Exploration wells have been, and are being drilled, one area is already operational (Goliat), and several areas are in planned development. To this point, the ongoing exploration of oil and gas in the Barents Sea lies south from the ice edge (EPPR, 2015). If the expected future development of oil and gas activities in the Barents Sea becomes reality, there will be a substantial increase of permanent maritime response resources by 2030 (Funnemark, Dahlsett, & Johnsrud, SARINOR2, 2017).

Currently, six of the eight countries bordering the polar region are pursuing or considering further exploration for oil and gas resources in the Arctic: Canada, Greenland (Denmark), Iceland, Norway, Russia, and the United States. Russia is likely to be the most active area for new exploratory drilling in marine areas affected by ice cover the next decade, considering the fact that the majority of undiscovered oil in the Arctic lies on the Russian Continental Shelf (EPPR, 2015).

Norway is a leading country when it comes to oil spill preparedness and response. An important reason for this is the country's work on documenting and testing response technologies through exercises such as Oil on Water led by Norwegian Clean Seas Association and Norwegian Coastal Administration (Joint Industry Programme, 2017). In the early work on this thesis, a phone conversation with operational adviser in NOFO, Ivar Schanche, implied the need for more knowledge about how low temperature impacts effectiveness of response operations, both in terms of equipment and human performance. This led to a deeper investigation of low temperature's effect on oil spill response operations in the Arctic, which is further explained in the problem statement.

1.2 Problem statement

The overall goal of oil spill response is to control the source as quickly as possible, minimize the potential damage caused by the accidental release, and employ the most effective response tools for a given incident. Giving the responders the flexibility to apply the most effective tools to suit the prevailing conditions is the key to mounting a successful response and minimizing impacts to the marine environment (Joint Industry Programme, 2017). Although, an oil spill response operation intends to spare the environment, it is of great importance to use strategies that are effective, but also environmentally beneficial. A Net Environmental Benefit Analysis (NEBA) is a strategic tool used by decision makers that formalizes the evaluation and comparison of expected response effectiveness against the potential environmental impact of the oil and response activities (EPPR, 2015). NEBA is an important part of choosing the correct response countermeasure, but this thesis will mainly focus on the effectiveness of the countermeasures.

When responding to an oil spill, either from a vessel accident or from a deep-sea blowout, the behavior and fate of spilled oil is an important consideration in evaluating the potential oil spill response options in the Arctic (EPPR, 2015). Low temperatures may impact the rate and extent of oil weathering and spreading in ice-covered waters and will, for instance, affect the window of opportunity for oil spill countermeasures, such as dispersant application and in-situ burning (Sørstrøm, et al., 2010). In a mechanical recovery operation, it is of great importance to apply the right type of equipment in relation to the behavior of oil (e.g. oil viscosity) to achieve effective recovery. The knowledge of oil behavior will therefore be important in choosing the most effective countermeasure, as it will affect the performance of equipment used.

In all response operations in the Arctic, independent of the applied countermeasure, equipment will be exposed to environment conditions. The conditions in the Arctic are often quite different from those in more temperate regions, and may impact the equipment performance. For instance, very low temperature may change the properties of seals and filters and therefore increase the failure rate and decrease the equipment or system reliability, or icing on equipment may change the shape and accessibility of equipment (Barabadi, 2011). Such impact will affect overall equipment effectiveness. To evaluate the effect of low temperature on oil spill response equipment, the research done on oil and gas exploration and operation in the Arctic is considered to be relevant as complement to the subject.

In every Arctic operation where humans are involved, the human-equipment interaction play a crucial role in determining the equipment performance. It is shown that operational and maintenance personnel may be significantly affected by the Arctic conditions (Balindres, Kumar, & Markeset, 2016). In an oil spill response operation, it is a consistent interaction between humans and mechanical equipment, which must be considered. In this thesis, the effect of low temperature on human performance is discussed in relation to several types of Arctic operations, such as petroleum production and escape, evacuation, and rescue (EER), in addition to oil spill response operations.

In general, this thesis seeks to evaluate the effect of low temperature on Overall Equipment Effectiveness (OEE) in oil spill response operations. The temperature is an important environment factor which can be considered an influence factor by itself (air temperature or sea temperature), but also in combination with other factors such as wind and humidity, which further can create new influence factors such as wind chill effect (Naseri & Barabady, 2016) or superstructure icing (EPPR, 2017). This makes temperature an environment factor that can influence the OEE in different ways.

OEE is a broad topic which has its origin from the automotive industry (Stamatis, 2010), and has been further developed towards other areas, such as the oil and gas industry. Research by Naseri and Barabady (2016) and Barabadi (2011) has mainly focused on the perspective of reliability, availability, and maintainability (RAM). These terms are highly reliant of each other and reflects important aspects of OEE. The vast majority of the successful designs have given considerable consideration to both reliability and maintainability. The degree to which these attributes are incorporated in a product determine the system effectiveness (Niebel, 1994). This leads to a relevance in evaluating the low temperature effect on equipment reliability and maintainability.

The perspective of OEE in the context of oil spill preparedness and response is uncommonly introduced, although, literature such as EPPR (Guide to Oil Spill Response in Snow and Ice Conditions in The Arctic, 2015) and Sørstrøm et al. (Joint industry program on oil spill contingency for Arctic and ice-covered waters, 2010), refers to the terms effectiveness, efficiency, and performance in great scale when evaluating different oil spill countermeasures. Another example is the paper of Naseri and Barabady (Performance of skimmers in the Arctic offshore oil spills, 2015), where they seek to discuss the performance of skimmers in the Arctic offshore from the viewpoint of effectiveness and availability. These viewpoints can be associated to the theory of OEE and RAM, respectively

The preliminary literature study of this thesis has led to the development of a figure which intends to illustrate the effect of low temperature on OEE in oil spill response operations. OEE is fundamentally based on the availability, performance, and quality of the equipment (Stamatis, 2010). These three measures are considered to be affected through the equipment itself and humans interacting with the equipment. The illustration is shown in Figure 1.3 and is used as an outline for discussing low temperature as a key influencing factor on OEE and RAM performance in oil spill response operations in the Arctic.

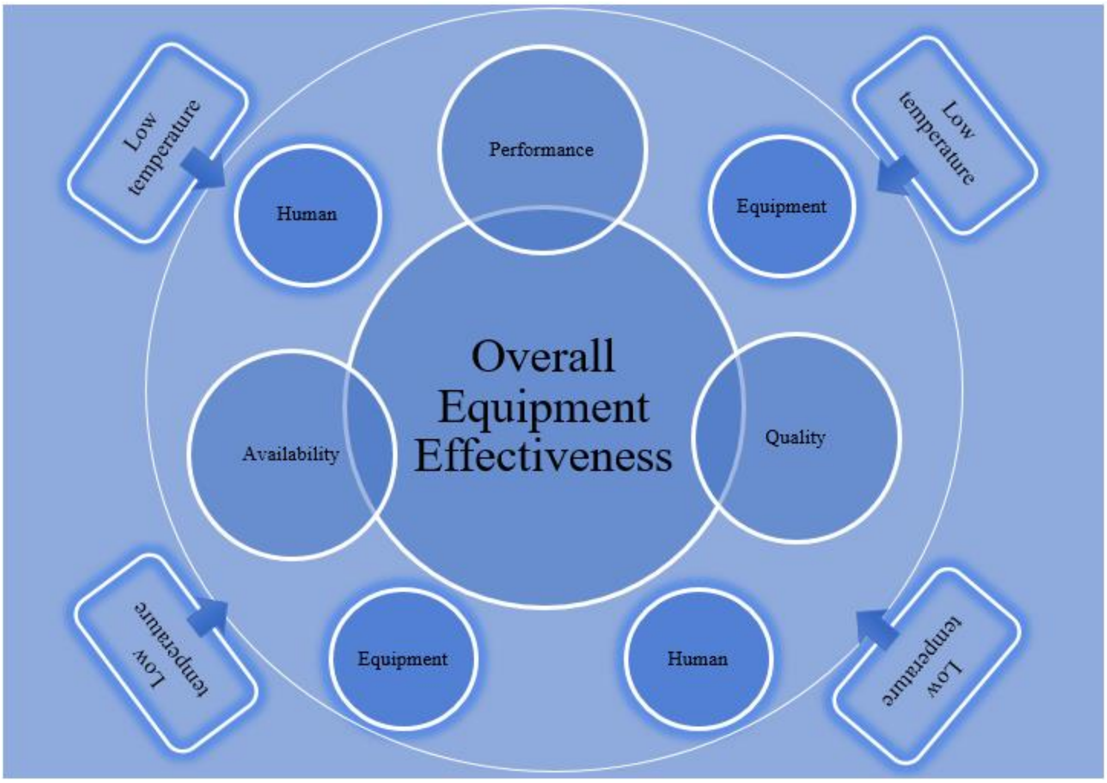


Figure 1.3 Illustrative explanation of the effect of low temperature on Overall Equipment Effectiveness (OEE).

1.3 Research questions

Based on the above discussion, the main problem of the research study is to take into consideration the effect of low temperature on Overall Equipment Effectiveness (OEE) in oil spill response operations in the Arctic. The following research questions are established based on the research problem:

1. What are the challenges related to oil spill response operations in the Arctic and how will low temperature affect the Overall Equipment Effectiveness (OEE)?
2. How can Reliability, Availability, and Maintainability (RAM) be incorporated as attributes to determine the effect of low temperature on OEE?
3. How can improvement of RAM performance, considering the effect of low temperature, substantiate improvement of OEE?

1.4 Research purpose and objectives

The purpose of this research is to study the effect of low temperature on oil spill response operations, considering the perspectives of Overall Equipment Effectiveness (OEE) and Reliability, Availability, and Maintainability (RAM). The main objective of the study is to implement OEE and RAM perspectives in oil spill preparedness and response in the Arctic to make improvements on the area. The temperature is evaluated as environment factor because of the need for improvement both as a qualitative and quantitative influence factor. More specifically the sub-objectives of the research are:

- To review and discuss the challenges related to low temperature in oil spill response operations in the Arctic and the approach to effectiveness in current literature covering oil spill response operations.
- To review and discuss the applicability of incorporating RAM as attributes to determine the OEE of oil spill response operations in the Arctic.
- To study the effect of low temperature on RAM performance in oil spill response operations in the Arctic, and present aspects for improving RAM performance.

1.5 Limitations of the research

During this study the effect of low temperature on oil spill response operations is based on reviewing literature from different areas such as the oil and gas industry and escape, evacuation and rescue (EER), in addition to literature in oil spill response operations. The experience from Arctic operations in general is considered to be relevant when evaluating the effect of low temperature, although some aspects may be restricted to specific operations.

Low temperature is one of many environment factors in the Arctic. This makes it unavoidable to not evaluate other environment factors through the literature review. The low temperature often affects oil spill response operations in combination with factors, and create new factors such as ice. Although, factors such as presence of ice or icing is not considered as influence factors on OEE and RAM performance in this study. Low temperature has the potential for wide discussions regarding in what ways it affects OEE or RAM performance. It may be considered an important influence factor in different ways, which are not covered in the conclusions of this study. An example may be the presence of ice or superstructure icing.

The study does not make use of any methods for analysis or calculations but has the intention to reflect and evaluate from established perspectives such as OEE and RAM. These perspectives are uncommonly introduced for evaluating and improving oil spill response operations. Therefore, the assumptions and conclusions presented in this study must be carefully evaluated as they intend to establish a viewpoint for future research in oil spill response operations.

2 Research methodology

2.1 Introduction

This chapter provides a brief description of the research approach, methodology, and the techniques for collecting relevant information which are used in this study in order to achieve the research objectives.

The reason for this study is discussed in section 1.1 and 1.2. In the next step, some research questions were defined in accordance with the main project problem, as given in section 1.3. To find solutions to the research questions, the main goal of the research was defined and further broken down into several research objectives, which are presented in section 1.4.

The term research is widely used and very general, but can be defined as any activity to systematically find out things you did not know. It should contribute to advancing the field in focus. The research methods are the techniques used to carry out the research itself (Walliman, 2011). It can be said that research is the activity of questioning and answering systematically (Dane, 1990).

It is important to choose the right research method. This is crucial to the results and the validity of the research done. Therefore, it is necessary to have a good methodology to achieve a systematic research with results that are valid (Walliman, 2011).

This study seeks to evaluate the effect of low temperature on oil spill response operations based on the two perspectives, OEE and RAM. These perspectives are believed to have similarities which result in the fact that one perspective will substantiate the other one. These commonalities are proven by presenting theory from Stamatis (2010), Rausand and Høyland (2004), Barabadi (2011), and Naseri and Barabady (2016), to mention some.

2.2 Research purpose

The research purpose for any researcher is related to what kind of result the research work should produce. A researcher can try to explore, describe, explain, understand, predict, change, evaluate and assess impacts (Blaikie, 2010). This research should describe established theories and explain the correlation. In addition, these theories are applied to the area of oil spill response operations in the Arctic.

The purpose of proving the correlation of these perspectives is the fact that research on oil spill response operations such as EPPR (2015), EPPR (2017), Join Industry Program (2017), and Sørstøm et al. (2010) continuously discuss and evaluate how operational conditions in oil spill response operations impact the effectiveness. Although, these impacts, from the perspective of OEE and RAM performance, is uncommonly evaluated. RAM is a well-established perspective in the oil and gas industry with the purpose of improving production performance, quality, and availability, according to research by Markeset (2010), Barabadi (2011), Naseri and Barabady (2016). Considering this, the aim has been to evaluate and discuss the methods and findings from Arctic operations that consider the perspective of RAM, to reflect on the transferability to oil spill response operations in the Arctic.

2.3 Research method

In the first chapter of this study, existing theory of OEE and RAM will be presented and applied as a baseline for the research objectives. The research method of this study can be considered a literature review which first evaluates the challenges related to oil spill operations in the Arctic and how the low temperature is considered to impact the effectiveness. In this part, literature discussing oil spill response operations, specifically, is reviewed, and aims to cover the first research objective. In the next part of the literature review, RAM performance in Arctic conditions is evaluated through literature covering different Arctic operations where low temperature is considered as influence factor. Backed up by presented theory of OEE and RAM, this part of the literature review aims to cover the second research objective. Further, it is attempted to evaluate and discuss the findings from the literature review, and existing theory of OEE and RAM, to reflect on the effect of low temperature and discuss aspects for improvements from a RAM perspective. This part aims to cover the third research objective.

2.4 Reliability and validity of research results

According to (Yin, 2003), by the term high reliability of research, means that another researcher will be able to achieve the same results as in the study. The methodology used should have a good overview and structure to it, so that the same procedures are done every time. This research study has based most of the conclusions on existing theory of OEE and RAM together with evaluating well established research covering oil spill response operations in the Arctic, oil and gas production facilities, and other Arctic operation studies.

Research validity can be thought of as how well the study results compare with the real-life scenario (Yin, 2003). The research results are based on logical relationships between OEE and RAM as theoretical perspectives, and logical relationships between low temperature as influence factor on RAM performance throughout oil spill response operations in the Arctic, oil and gas production in the Arctic, and other Arctic operations.

3 Overall Equipment Effectiveness (OEE)

The OEE is used as an indicator of how well machines, production lines, and processes are performing in terms of availability, performance efficiency, and quality. These indicators also relate to Reliability and Maintainability (R&M). The three items of OEE depend on accurate and timely data and, above all, on an understanding of when and how to do the R&M. The essence of OEE and R&M is to establish system effectiveness, which means that a machine individually or as a part of a subsystem or as a system must be operating as designed (Stamatis, 2010).

With its origin from the manufacturing industry, OEE breaks the performance of a manufacturing unit into the three components: Availability, Performance, and Quality. Each component points to an aspect of the process that can be targeted for improvement. The calculation formula for the OEE is given in percent (Stamatis, 2010):

$$OEE = Availability \times Performance \times Quality$$

3.1 Availability

Availability, from a manufacturing point of view, represents the percentage of scheduled time that the operation is available to operate. The availability metric is a pure measurement of uptime that is designed to exclude the effects of quality, performance, and scheduled downtime events. The formula is given as (Stamatis, 2010):

$$Availability = \frac{Available\ Time}{Scheduled\ Time}$$

3.2 Performance

The performance part of OEE represents the speed at which the machine runs as percentage of its designed speed. The performance metric is a pure measurement of speed that is designed to exclude the effects of quality and availability, and is given by the following formula (Stamatis, 2010):

$$Performance = \frac{Actual\ Rate}{Standard\ Rate}$$

3.3 Quality

The quality metric represents the good units produced as a percentage of the total units started. The quality metric is a pure measurement of process yield that is designed to exclude the effects of performance and availability. The formula for quality is given as follows (Stamatis, 2010):

$$Quality = \frac{Good\ Units}{Units\ Started}$$

3.4 Reliability, availability, and maintainability (RAM)

Stamatis (2010) refers to reliability and maintainability (R&M) as a discipline which is founded on several techniques that are meant to direct both machine suppliers and users beyond the question of "Will it work?" to a quantifiable analysis of "How long it will work without failure?" In this study R&M is referred to as RAM, which includes the same discipline.

To further explain the context between OEE and RAM, some basic concepts from the perspective of RAM is important to determine. The purpose is to avoid a sloppy use of terms and to highlight the relevance of using the theory in conjunction with oil spill response operations.

3.4.1 Availability

The availability has been defined from an OEE point of view in section 3.1. In terms of RAM, availability depends on reliability and maintainability, and it combines R&M into one measure (Stamatis, 2010). Availability can then be defined as:

The ability of an item (under combined aspects of its reliability, maintainability and maintenance support) to perform its required function at a stated instant of time or over a stated period of time (Rausand & Høyland, 2004).

Some authors and standards use the term dependability. The availability is a function of *i)* the (inherent) reliability of the item, *ii)* the maintainability of the item, and *iii)* the maintenance support. This is illustrated in Figure 3.1.

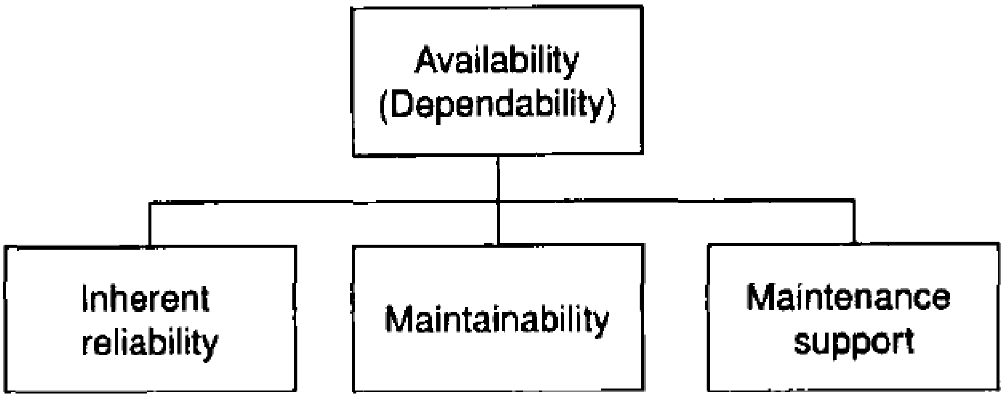


Figure 3.1 Availability (dependability) concept. Source: Rausand and Høyland (2004)

If we consider a repairable item that is put into operation at time t = 0. When the item fails, a repair action is initiated to restore the function of the item. The state of the item at time t is given by the state variable:

$$X(t) = \begin{cases} 1 & if\ the\ item\ is\ functioning\ at\ time\ t \\ 0 & otherwise \end{cases}$$

The mean time to repair the item is denoted as MTTR. The total mean downtime, MDT, is the mean time the item is in a nonfunctioning state. The MDT is usually significantly longer than the MTTR, as it includes time to detect and diagnose the failure, logistic time, and time to test and startup of item. The mean uptime, MUT, is defined to be the time when the item is in operable state and equals the mean time to failure, MTTF. Both concepts can be used, where MUT is more commonly used in maintenance applications. The mean time between failures, MTBF, is the time between the consecutive occurrences of failures. The whole concept is shown in Figure 3.2, where reliability and maintainability relate to the uptime and downtime, respectively.

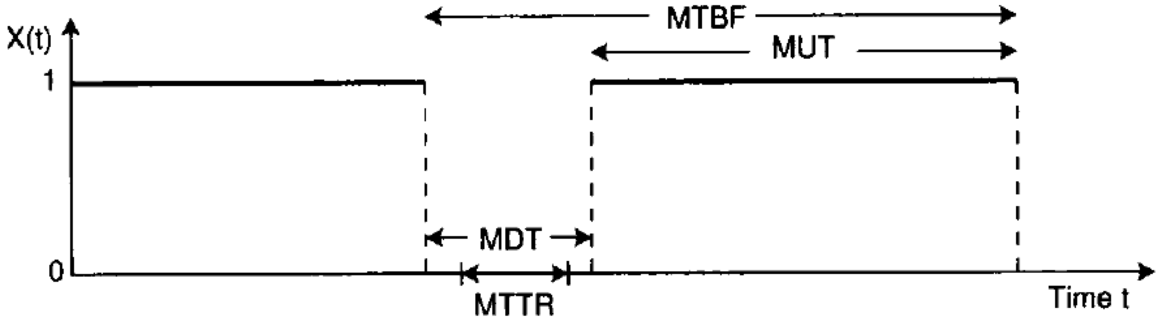


Figure 3.2 Concept of availability. Source: Rausand and Høyland (2004)

3.4.2 Reliability

Reliability is strongly connected to maintainability and availability, and is defined as:

The ability of an item to perform a required function, under given environmental and operational conditions and for a stated period of time (Rausand & Høyland, 2004).

During the design phase, the aim is to achieve the highest possible system reliability. In the operational phase, the aim is to improve reliability performance through modification of the system or/and through modification of the operation and maintenance strategy (Barabadi, 2011).

Mathematically, the item's reliability, R(t), which is the probability that the item survives the time interval (0,*t*] and is still functioning at time *t*, is given by (Rausand & Høyland, 2004):

$$R(t) = \Pr(T > t) = 1 - \int_0^t f(u)du$$

Where T is a random variable denoting time-to-failure of the item and *f(u)* is the probability density function of the item's times-to-failure.

The functions of system components and their corresponding failure modes must be clearly specified in accordance with reliability definitions. Some components may have various functions and operating modes. In this regard, each operation mode or component's function may be associated with its own reliability performance (Barabadi, 2011). Furthermore, the conditions under which a component operates should be known. In this regard, we refer to the environmental and operational conditions (e.g. temperature, wind, icing, etc.) (Naseri & Barabady, 2016).

As one can understand, increased reliability implies less failure of machinery and, consequently, less downtime and loss of production. In other words, it is a statistical measure of equipment or component performance.

3.4.2.1 Reliability as a quality measure

The concepts of quality and reliability is closely connected. Reliability may in some respects be considered to be a quality characteristic. Complementary systems are therefore being developed and implemented for reliability management and assurance as part of a total quality management (TQM). According to common usage, quality denotes the conformity of the product to its specification as manufactured, while reliability denotes its ability to continue to comply with its specification over its useful life. Reliability is therefore an extension of quality into the time domain (Rausand & Høyland, 2004).

3.4.3 Maintainability

The ability of an item, under stated conditions of use, to be retained in, or restored to, a state in which it can perform its required functions, when maintenance is performed under stated conditions and using prescribed procedures and resources (Rausand & Høyland, 2004).

According to the definition of maintainability, maintenance crew should have adequate skills to fulfill required maintenance tasks. The conditions, in which a maintenance task is operated may impact the maintenance time. Such conditions may be the location of the failed component, accessibility, organizational factors, inventory level, and weather conditions. In general, the aim of maintainability is to minimize maintenance time and labor hours.

The maintainability of an item depends on design factors like ease of access to the item, ease of dismantling, ease of reinstallation, and so on. The maintenance support depends on the maintenance personnel, their availability, skills, and tools, and on the availability and quality of spare parts. Maintenance is defined as (Rausand & Høyland, 2004):

The combination of all technical and corresponding administrative actions, including supervision actions, intended to retain an entity in, or restore it to, a state in which it can perform its required function.

Reliability and maintainability has a great influence on maintenance support requirements and performance. Other influencing factors on the need and delivery of support are: location, infrastructure (communication, transportation, etc.), the operating environment, type of system, training of operation and maintenance personnel, and spare parts (Barabadi & Markeset, 2011).

Mathematically, maintainability M(d) of an item is measured as the probability that the maintenance is accomplished within the time interval (0,d] (Naseri & Barabady, 2016):

$$M(d) = \Pr(D \leq d) = \int_0^d h(u)du$$

Where D is a random variable denoting downtime and *h(u)* is the probability density function of item’s downtimes. Maintainability analysis requires detailed historical maintenance data, such as times spent on each corrective maintenance or preventive maintenance task performed previously (Naseri & Barabady, 2016)

3.4.3.1 Maintenance tasks

Maintenance concepts are divided into two groups, namely preventive maintenance (PM) and corrective maintenance (CM). PM is planned maintenance performed when an item is functioning properly to prevent future failures. It aims to decrease the probability of failure of an item, and may involve inspection, adjustments, lubrication, parts replacement, calibration, and repair of items that are beginning to wear out. CM is a type of maintenance usually called “repair” and is carried out after an item has failed. The purpose of corrective maintenance is to bring the item back to a functioning state as soon as possible.

3.4.3.2 Optimization of maintenance

In the optimization of a maintenance strategy, it is often referred to reliability centered maintenance (RCM) and total productive maintenance (TPM). Many industries (e.g. the nuclear power, aviation, defense, and offshore and shipping industry) have fully realized the important connection between maintenance and reliability and have implemented the RCM. The RCM approach is a main tool to improve the cost-effectiveness and control maintenance in all types of industries, and hence to improve availability and safety (Rausand & Høyland, 2004).

TPM is an approach to maintenance management that was developed in Japan to support the implementation of just-in-time manufacturing and associated efforts to improve product quality. TPM activities focus on eliminating the *six major losses*, in which they are represented by the terms availability, performance, and quality. (Rausand & Høyland, 2004). In this regard, one can understand that optimization of the maintenance tasks has a direct connection to availability, performance, and quality.

3.5 RAM and OEE

The objective of designing for maintainability is to provide equipment and facilities that can be serviced efficiently and effectively and repaired efficiently and effectively if they should fail (Niebel, 1994). The statement of Niebel (1994) is clarifying and expresses resemblance between RAM and OEE. He further states that equipment should be designed with sufficient reliability so that it will be operable for an anticipated life cycle at optimum availability. Thus, reliability is a function of design, which means that once the design has been completed and released for manufacturing, the reliability of the product or system has been determined. Functional designs, where the technology of maintainability has been given considerable consideration, will inevitably result in simplified maintenance that can be performed both effectively and inexpensively.

Considering the theory of OEE and RAM, a clear resemblance can be seen. Reliability and maintainability, together with maintenance support are important factors to express availability, whereas availability is an important factor in calculating OEE. RAM is often used as an acronym for reliability, availability, and maintainability, where maintenance support can be considered as included in maintainability. With the perspective of RAM, one can consider all three factors of the term as performance measures of an item. By evaluating how low temperature will affect the RAM performance of oil spill response equipment it may be reasonable to draw comparison with performance as a part of OEE. Reliability has been discussed as a quality measure, and the optimization of maintenance tasks, from a TPM perspective, reflects upon the key losses through availability, performance, and quality (Rausand & Høyland, 2004). By these means, the comparison of RAM and OEE shows many similarities. Both perspectives reflect upon the measures availability, performance and quality, which are considered important when evaluating oil spill response operations.

Although OEE is a calculation measure, with its origin from the manufacturing industry, it is considered suitable to discuss and map how low temperature affects the three key factors, availability, performance, and quality in oil spill response. To make it a calculation measure for oil spill countermeasures, a more comprehensive research needs to be done. The above discussion implies that the level of reliability and maintainability on equipment determines system effectiveness (Niebel, 1994). Backed up by the above discussion, this study will evaluate and discuss how low temperature will affect RAM performance of oil spill response operations.

First, a literature review has been conducted with the aim of mapping challenges related to low temperature in oil spill response operations and the impact of effectiveness. Further in the literature study, research covering RAM performance in Arctic regions has been discussed and evaluated.

4 Literature Review

This chapter seeks to evaluate the challenges related to low temperature in oil spill response operations in the Arctic and how this is considered to impact the effectiveness of the different oil spill countermeasures. Further, research on RAM performance in Arctic operations is discussed and evaluated.

4.1 Oil spill response in the Arctic

In this section mechanical containment and recovery, in-situ burning, and dispersant application is described as the three main oil spill countermeasures. Remote sensing is also described but is considered a support for oil spill countermeasures and not a complete countermeasure by itself. The chapter intends to give a brief understanding of oil spill response operations in the Arctic and the related challenges. In addition, a review of current literature covering oil spill response effectiveness is discussed.

4.1.1 Mechanical containment and recovery

Mechanical Containment and Recovery was regarded as a primary response strategy for responding to marine oil spills in Arctic open water in the JIP (Joint Industry Programme, 2017). This is also considered as the primary response strategy in the Norwegian oil spill preparedness and response (Alsos, et al., 2015). However, there is recognized operational and practical limitations to relying only on mechanical containment and recovery systems for spill in ice. The Southern Barents Sea on the Norwegian Continental Shelf is ice free year around, but sea ice, sea spray icing and icing on equipment must be highly considered in these areas. Therefore, additional oil spill response strategies are often included in the dimensioning of oil spill preparedness in the High North.

Containment and recovery can be defined as actions taken to remove oil from the water surface by containing the oil in a boom and/or recovering the oil with a skimming or direct suction device or sorbent material. Another important process involves pumping recovered fluids to a storage system (Joint Industry Programme, 2017).

Figure 4.1 Open-ocean mechanical recovery systems (source: NOFO)

The complete system to support the skimmers usually involves deployment of containment booms in a configuration that directs oil toward the skimming system, thereby maximizing the amount of oil meeting the skimmer (the oil encounter rate). The system may also involve onboard treatment of recovered fluids and decanting of water to maximize the recovered oil storage capacity. A mechanical recovery system is completed by disposing or recycling the recovered liquids and oil contaminated materials (Joint Industry Programme, 2017).

An important and limiting factor in effective containment and recovery operations is the availability of recovered oil storage on the skimming vessel. The size of storage, in comparison to the recovery capability of some of the recovery systems, is a critical factor. Weir skimmers are prone to high levels of water pick-up which rapidly fills storage barges or tanks to capacity with large quantities of water (Potter, Buist, & Trudel, 2012). This requires effective decanting processes, which is the process of separating water from recovered oil, to avoid inefficient use of storage tanks.

Specialized Arctic skimmers include improved ability to handle larger volumes of cold viscous oil and oil/ice mixtures with low water uptake and heating of critical components to prevent freezing. Various viscous oil pumping systems and techniques have also been developed to facilitate efficient transfer of cold and viscous oil-water mixtures and small ice pieces. Basin and field tests in the U.S and Norway have documented the capabilities of specially designed Arctic skimmer systems in a range of ice conditions (Joint Industry Programme, 2017).

In any incident of oil spill in open water or very open drift ice conditions, the oil rapidly spreads to form a thin layer (thickness of one millimeter) on the water surface. This usually happens before oil booms can be deployed. To deal with a large oil spill, several kilometers of such booms must be managed by several vessels to concentrate the thin layer of oil for recovery by skimmers. A skimming system can usually operate in 0,5 m/s forward speed. This is the key limiting factor controlling the total volume of oil that can be practically recovered as a percentage of the oil spilled. High capacity skimmers often recover significant quantities of water along with the oil (Joint Industry Programme, 2017).

A problem in terms of mechanical recovery is that there is no practical and effective way to recover significant volumes of oil spread on the surface of drifting, melting ice with existing skimming systems. Small volumes could be potentially recovered by using an over-the side brush bucket skimmer, but this type of operation could not deal with large volumes of oil spread over large area of ice such as would result from a blowout flowing for any extended time period with pack ice moving past the discharge site. A potentially much more effective strategy for dealing with this scenario is to ignite the oil from air when it surfaces in the spring (EPPR, 2015)

Small amounts of drift ice, as little as 10 %, or slush/brash between the larger floes can interfere with the flow of oil to the skimmers and result in decreased performance from the skimmer's theoretical performance. Although, presence of ice with sufficient concentrations (generally 30 % coverage) dampens wave action. With even higher ice coverage, the ice acts as a barrier for preventing the oil in spreading, and thereby greatly reducing the contaminated area. With an ice coverage increasing over 60 %, the oil is close to completely contained by the ice without the need for booms. In these situations, skimmers can operate effectively in trapped oil pools between floes, if the water surface is not clogged with slush or brash ice that reduces the oil flow to the skimmer (Joint Industry Programme, 2017).

A considerable amount of equipment and logistical support as well as local or designated options for oily waste disposal are required for mechanical recovery operations in large oil spill events. Operational constraints and lack of infrastructure in most Arctic areas, leads to a need for considering a range of available response tools together with the mechanical recovery as a primary countermeasure.

The 2011 Godafoss incident is described as the most recent example of lessons learned when responding to a vessel spill under freezing conditions. This experience is valuable as it reveals the challenges faced by the responders even with the benefits of considerable infrastructure in the region, which is far more extensive than would be available if a similar accident occurred in most areas of the Arctic. A considerable portion of the spilled oil was recovered in this case, demonstrating that in spite of the known drawbacks of mechanical recovery in dealing with very large spills, this strategy can work effectively in recovering oil from small to medium sized spills, even with freezing conditions A short reflection from this operation is given by EPPR (2015):

> *Different recovery methods were employed which varied in their effectiveness in the ice conditions. Booms needed to be sufficiently durable to withstand the extra force created by the contained ice, which could cause them to tear or become temporarily submerged. Most skimmers operated at a significantly reduced efficiency, due to both the high viscosity of the oil and the presence of drifting sea ice within the slick. The incident highlighted a number of areas that would benefit from improved technical solutions, such as minimizing the quantity of ice recovered with the oil and increasing the effectiveness of pumping highly viscous oil at low temperatures.*

4.1.2 In-situ Burning

In-situ burning is an oil spill response countermeasure particularly suited to remote, ice-covered waters. The key to effective in-situ burning is thick oil slicks. If ice concentrations are high, the ice can limit oil spreading and keep slicks thick enough to burn. In drift ice conditions and open water, oil spills can rapidly spread to become too thin to ignite. Fire-resistant booms can collect and keep slicks thick in open water. Although, light ice conditions are challenging for oil booms to be effective (Buist, Potter, Nedwed, & Mullin, 2011).

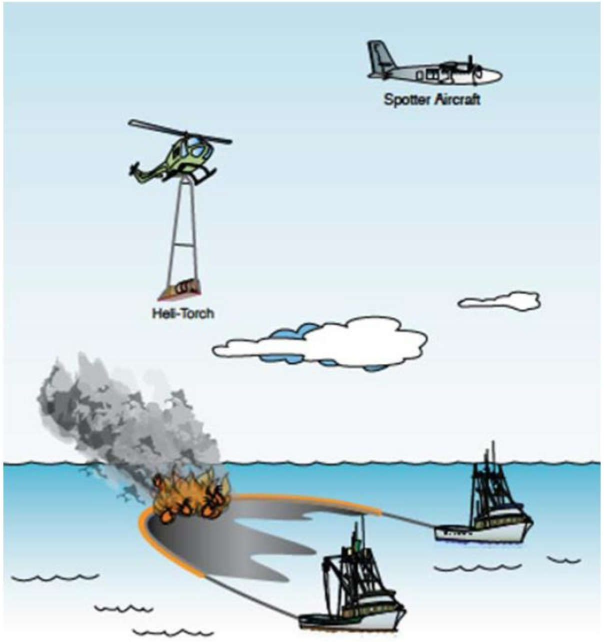


Figure 4.2 Typical offshore in-situ burning operations (Source: NUKA 2010)

In-situ burning in ice and Arctic environments is regarded as safe, environmentally acceptable and a proven technique backed up by over five decades of research and operational experience. In 1993, a U.S./Canada joint experiment (Newfoundland Offshore Burn Experiment) successfully burned crude oil in fire-resistant booms in the open ocean and monitored a large suite of environmental parameters including smoke composition, residue toxicity, and upper water column impacts. Results demonstrated no significant risk to human populations, wildlife or responders (Joint Industry Programme, 2017).

Experience with burning fresh, weathered, and emulsified oils and petroleum products in a range of ice conditions in test tanks has led to some basic rules. To achieve 60-80 % removal efficiency in most situations, the starting thickness of crude oil needs to be between 3-5 mm. Such thickness can arise naturally with sufficient ice concentration, if not, fire-resistant booms are applied (Joint Industry Programme, 2017).

In an experimental spill under solid ice in Norway in 2006, 3.400 liters of crude oil were allowed to surface naturally through the ice and then burned with an overall removal efficiency of 96 %. A portion of this oil was exposed to weathering on the ice surface for over one month before being successfully ignited. Similar high efficiencies were documented for in-situ burning of oil mixed with ice contained within fire-resistant booms during the 2009 SINTEF Oil in ice Field Experiments (Joint Industry Programme, 2017).

The consensus of the research to date on spill response in broken ice conditions is that in-situ burning is a suitable response technique, but the effectiveness will vary greatly with the initial spill conditions, and specifically the slick thickness. For spills that occur in static ice fields of relatively dense ice, the oil will be contained to a great extent and the slick thicknesses required for effective burning will be maintained. On the other hand, oil spilled in lesser concentrations of ice will tend to spread and thin over time, making burning ineffective unless some form of containment can be employed (Potter, Buist, & Trudel, 2012)

4.1.3 Chemical Dispersant Application

There is a growing acceptance worldwide that use of dispersants to counter the effects of an oil spill offers many advantages and can often result in a net environmental benefit when considered in relation to other response options. A major reason for this growing support and increased reliance on dispersant is the advent of improved dispersant products that are low in toxicity to marine life and more effective at dispersing heavy and weathered oils, that earlier were believed to be undispersible. This capability has been demonstrated through extensive laboratory testing, field trials, and dispersant application on actual spills (Lessard & DeMarco, 2000).

Dispersant application enhances biological dispersion by reducing the surface tension at the oil- and water interface, making it easier for waves to create small oil droplets that remain in suspension for long periods and are rapidly diluted in the water column to below toxicity thresholds of concern. An effective dispersant application is largely dependent on currents and wind dynamics. These parameters affect the dilution process of dispersed oil (Joint Industry Programme, 2017).

The SINTEF Oil in Ice Joint Industry Program demonstrated the effectiveness of dispersants in a range of ice conditions in meso-scale basin tests and field trials. As a part of that project, a new controllable applicator arm was developed to deliver dispersant more effectively to isolated oil pockets in the ice (Joint Industry Programme, 2017). The figure below shows a scheme of the applicator arms before they were constructed and tested. At this point it was recommended to focus on the further work in improvement of dispersant application technology on vessels as application platform for operations under cold and ice-covered areas (Lewis & Daling, 2007).

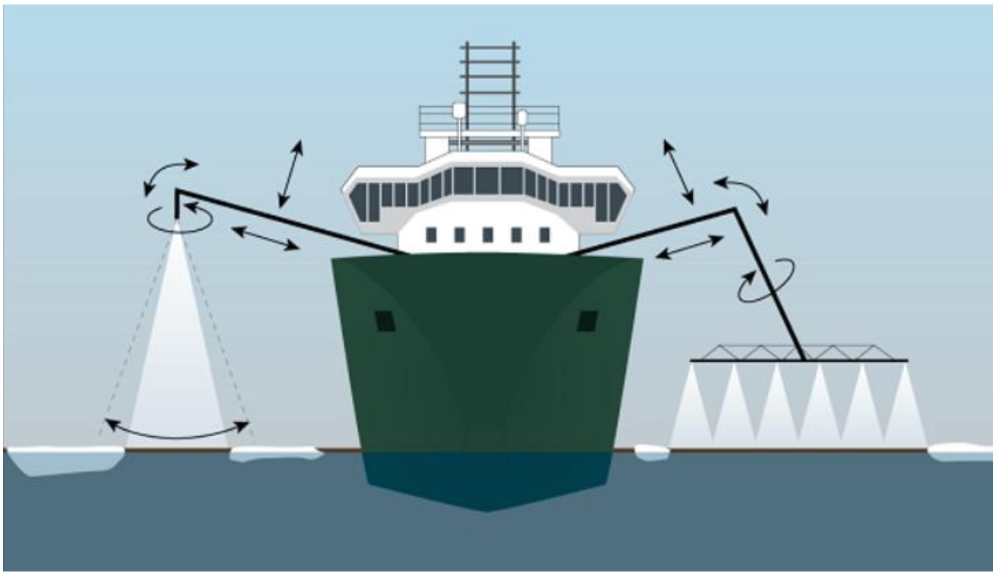


Figure 4.3 Chemical dispersant application developed by SINTEF (Source: Oil in Ice JIP)

Research and test programs over the past 20 years have looked at addressing important concerns regarding potential dispersant use in Arctic conditions, specifically their likely effectiveness in cold air and water temperatures, in the presence of ice, and in brackish water due to melting ice and river outflows. This research has shown that the critical parameters for effective dispersant use in a response include the performance of the dispersant, the oils dispersibility, the application of the dispersant, and the availability of sufficient energy for the dispersion process (Potter, Buist, & Trudel, 2012). When comparing weathering of oil vs. dispersibility, a lower oil viscosity will lead to more effective dispersion process. The main concern for critics of dispersant application in Arctic areas, is that when temperature decreases, chemical processes slow down and oil viscosity increases, and making it more difficult to disperse (EPPR, 2015). Sørstrøm et al. (2010) showed that the viscosity range for different oils are generally lower when weathered in high ice concentrations (90%) compared to no ice, and that results in a higher dispersant effectiveness for some of the oils.

There is a general misconception that cold temperatures inhibit dispersant effectiveness. However, a substantial amount of testing and research exists to prove the effectiveness of dispersants in cold water (Potter, Buist, & Trudel, 2012).

4.1.4 Remote Sensing

Remote sensing plays a major part in oil spill recovery as it gives crucial information about the location and spreading of the oil. It will normally act as an information source in order to support effective combat of the oil, and not a sole response method in itself (DNV GL AS Oil & Gas, 2015).

Remote sensing of oil spills includes detection, monitoring, and tracking of oil. The use of sensors makes it possible to detect oil on the water surface, under the ice, within the ice sheet, or on top of the ice. These sensors can be applied to platforms such as satellites, aircraft, helicopters, autonomous underwater vehicles etc.

Information about the oil's location and spreading provides key input for choosing appropriate response tactics, both for combating and protective measures. In addition, it leads to the ability of forecasting oil movement, further plan ahead, and adapt response objectives and tactics to the expected conditions ahead in time (DNV GL AS Oil & Gas, 2015).

To perform remote sensing in remote areas becomes more important due to limited direct access and restricted visibility due to fog, precipitation, snowdrift, and seasonal lack of daylight. The presence of ice may both facilitate and complicate the tasks of monitoring, detecting, and tracking oil. In general, broken ice slows down the spreading of oil on the sea surface, which makes the location and movements of oil more predictable compared to open water. This may reduce the need for frequent observations. If oil is located under ice or snow, it will be more challenging for remote sensing. Although, there is limited experience with remote sensing in ice (DNV GL AS Oil & Gas, 2015).

The main types of remote sensing platforms are:

- Satellite platforms
- Airborne platforms
- Surface platforms
- Subsea platforms

From this subsection and the previous subsections, 4.1.1, 4.1.2, and 4.1.3, it is obvious that the fate and behavior of spilled oil is one of the key challenges related to oil spill response operations in low temperature, and Arctic conditions, in general. The next subsection intends to evaluate the behavior of spilled oil in Arctic conditions through current literature covering this subject.

4.1.5 Behavior of spilled oil in Arctic conditions

The knowledge in behavior of oil spills in Arctic regions is rather limited compared to more temperate regions. The Oil in Ice JIP led by SINTEF (Sørstrøm, et al., 2010) aimed to close these knowledge gaps and use the increased knowledge to improve the capability to predict fate of oil spills in ice, as well as predicting the window of opportunity for the use of various countermeasures and techniques in ice. The key findings and conclusions of the Oil in Ice JIP are based on their own studies and previous national and international projects.

Some of the conclusions and key findings from this project is that the oil weathering process is significantly reduced in ice-covered waters, depending on ice type, ice-coverage, and energy conditions, which can be an advantage and contribute to the enhancement of response effectiveness for some oil spill scenarios. As well as improving knowledge on this area, the results and experience gained during this project has formed an important basis for further development of technology, and improvement of response strategies in ice-covered waters. When considering oil spill response operations in ice-covered waters it is important to mention that low temperature is an important factor which also affects the fate of oil and further the effectiveness of countermeasures, equipment and tools. The occurrence of ice is highly connected to low temperatures, and vice versa, which makes it natural to reflect on both and additional important factors, although the main purpose is to consider the effect of low temperature. The presence of ice and the cold temperatures can greatly reduce the spreading and weathering of spilled oil (Potter, Buist, & Trudel, 2012), which will be further evaluated in the next subsections.

4.1.5.1 Spreading of oil in cold water

Viscosity of oil refers to its resistance to flow. High viscosity oils do not flow as easily as those with lower viscosity. All oils become more viscous (i.e. flow less readily) as their temperature falls, some more than others depending on their composition. This factor is very important in governing the rate of spreading and the equilibrium slick thickness in cold water commonly experienced in ice-covered areas (EPPR, 2015).

Equations for warm water oil spreading has been proven to give unreasonable predictions for spreading of cold viscous oils. Through such findings, researchers proposed a “viscosity correction factor” or substituting oil viscosity for water viscosity in spreading models (Potter, Buist, & Trudel, 2012). It is also noted through this research that the oil spreading will cease when the ambient water temperature approaches the pour point of the oil. The pour point is defined as the temperature at which oil will cease to flow. Because of the increased viscosity, an oil slick on cold water is usually thicker and occupies a smaller area than it would do in temperate regions.

Viscosity-dependent clean-up operations such as skimming and pumping generally become more difficult as the spilled oil cools. This may reduce the effectiveness of mechanical recovery, whereas the condition exacerbates with the presence of slush or ice pieces, where ice may limit the flow of oil to skimmers as the water surface may be clogged with slush or brash ice. On the other hand, in-situ burning becomes more effective for thicker oil films (EPPR, 2015).

4.1.5.2 Spreading of oil in ice and snow

The most dramatic difference between oil spills in open water and with the presence of ice is found by comparing the spreading rate (EPPR, 2015). The spreading of oil is mainly determined by the oil viscosity. In this case, the temperature is an important factor, as cold temperatures will increase the viscosity and tend to slow the spreading rate. Any oil spilled on the surface of rough ice may be completely contained in a thick pool bounded by ridge sails and ice blocks. Therefore, slicks on ice tend to be much thicker and smaller than equivalent slicks on water (Potter, Buist, & Trudel, 2012).

Even large spills of crude oil underneath solid or continuous ice cover will usually be contained within relatively short distances from the spill source. This will be dependent on currents and ice roughness, combined with deformation features such as rubble and ridging which provide large natural reservoirs that effectively contain oil spilled underneath the ice within a relatively small area.

In pack ice of sufficient ice concentrations, oil spills tend to spread far less and remain concentrated in greater thickness than in ice-free waters. In ice concentrations greater than 60 to 70 %, the ice floes touch each other at some point and create a natural barrier for oil spreading. As the concentrations of ice floes diminishes, the potential for oil spreading increases until open water sea state is reached (30% or less). (Potter, Buist, & Trudel, 2012).

Spills on and under ice will generally not move independently of the ice but will remain in the vicinity of the initial contact area. In this case, the movement of spilled oil is determined by the movement of the ice. Through studies, it is shown that the currents required to move oil along the undersurface of the ice will range from 15 to 30 cm/s under typical sea ice and 5 cm/s under smooth freshwater ice. Currents in most Arctic areas are not in sufficient speed to make this happen (Potter, Buist, & Trudel, 2012). Considering this, one can understand that in ice-covered areas the predicted movement of oil can in most cases be predicted through the movement of ice, and additionally advance the window of opportunity for response countermeasures.

It is obvious that the spreading of oil is greatly reduced by the presence of ice and the resulting slicks are thicker than on open water. The reduction of spreading leads to a number of advantages such as extended response times, limiting the oiled area, and extends the window of opportunity to implement a given strategy (EPPR, 2015). For instance, in sufficient concentrations of pack ice the ice itself may operate as a barrier and contain the spilled oil. In such situations, the application of oil containment booms may not be necessary as the ice thickness is sufficiently high to ignite or collect with skimmers. The Arctic conditions, such as presence of ice and low temperature, will also affect the chemical properties differently than more temperate regions. This is studied through the next subsection.

4.1.5.3 Oil Weathering

When crude oil is spilled into the sea, several natural processes take place and changes the chemical properties of the oil. All these processes have the collective term “weathering”, which includes (Potter, Buist, & Trudel, 2012):

4. Evaporation
5. Emulsification
6. Dissolution
7. Dispersion
8. Biodegradation
9. Oxidation
10. Sedimentation

The weathering processes starts instantly after the oil is released from its container, which may be a pipeline, tank, or vessel. The relative importance of each process varies with time. Spreading, evaporation, dispersion, emulsification and dissolution are most important during the early stages of a spill, and oxidation, sedimentation and biodegradation show their results in longer-term processes. The rate of weathering is affected by physical factors such as temperature, winds, waves, and the presence of ice. The different weathering processes of oil in water and ice are illustrated in Figure 1.1.

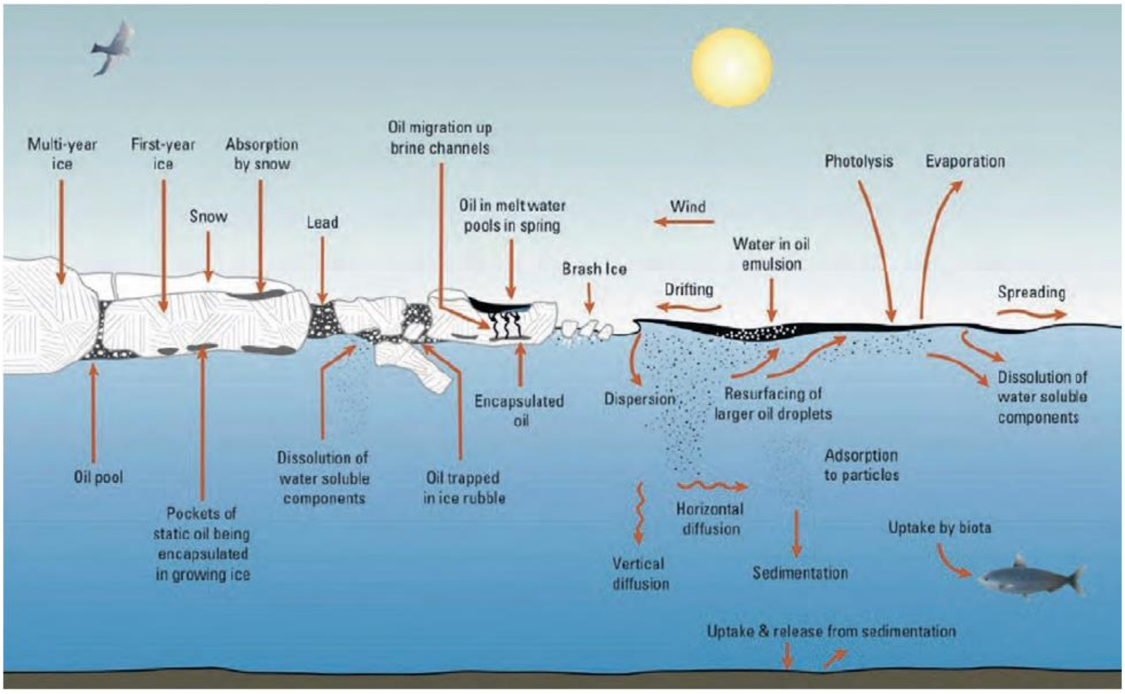


Figure 4.4 Weathering processes in ice and at the ice edge. Source: (EPPR, 2015)

Evaporation is the preferential transfer of light- and medium-weight components of the oil from the liquid phase to the vapor phase (Potter, Buist, & Trudel, 2012). Most crude oils and light products (e.g. diesel and gasoline) evaporates significantly faster than heavier and more viscous oils (e.g. bunker fuel oil and emulsified oil). Although, low temperature and the presence of ice and snow tend to speed down the rate of evaporation. Oil encapsulated in an ice sheet will undergo virtually no evaporation during winter months. When the ice melts during spring months the oil appears on the ice surface in melt pools. Oil on melt pools tends to be herded by the wind against the edge of the pools to a thickness of several millimeters. The thick oil layer will evaporate more slowly relative to slicks on open water (Potter, Buist, & Trudel, 2012).

The formation of water-in-oil emulsions are referred to as emulsification, which is the creation of mixtures that have reduced weathering capabilities and are usually more difficult to burn, disperse and mechanically recover. Natural dispersion is the process of oil droplets forced into the water column. These two processes are driven by wave action mixing the oil slick. With the presence of ice, wave actions are dampened, and the result is a slower emulsification and natural dispersion process (EPPR, 2015).

Dissolution is the process where water-soluble compounds in a surface oil slick dissolve into the water column (Potter, Buist, & Trudel, 2012). Components that undergo dissolution in sea water are the light aromatic hydrocarbon compounds which are also those to be lost through evaporation. The evaporation process is 10 – 100 times faster than dissolution, which makes dissolution most relevant for fresh oil finely dispersed in the water column and, in general, a minor weathering process. Low sea temperature and presence of ice tends to slow down the dissolution process.

Changes in oil properties will also result in the need for changes in the use of oil spill countermeasures, such as mechanical containment and recovery, chemical dispersion, and in-situ burning. For instance, after a certain time, the oil will no longer be ignitable or difficult to disperse or mechanically recover, due to emulsification. Therefore, oil weathering processes plays a key role in determining the window of opportunity for different countermeasures. In Arctic areas, low temperature and the presence of ice often goes hand in hand and has a significant effect on oil weathering processes, in terms of slowing them down. This may affect the use of countermeasures positively by increasing the window of opportunity for both dispersant use and in-situ burning.

The next section will evaluate and review existing literature covering effectiveness in oil spill response operations.

4.2 Oil spill response effectiveness in the Arctic

In this section, literature considering effectiveness of the three different response countermeasures, mechanical containment and recovery, dispersant application, and in-situ burning will be reviewed. The focus will be on evaluating how low temperature impacts the effectiveness of these countermeasures. Effectiveness and efficiency are broad terms which tend to be expressed in great extent by different studies, mainly without referring to the theory of OEE.

4.2.1 SINTEF Oil in Ice JIP and other research

In the early stages of the Oil in Ice JIP led by SINTEF, a state-of-the-art report was conducted to map the three different countermeasures, mechanical containment and recovery, dispersant application, and in situ-burning (Brandvik, Sørheim, Singsaas, & Reed, 2006). The report presents important factors that impacts the effectiveness of each countermeasure.

Mechanical recovery operations in ice-infested waters will meet totally different problems than in open water. The opportunity to test and adapt techniques under real field conditions were considered as lacking during development of recovery equipment. The following list presents the challenges associated with mechanical recovery in the presence of ice, according to Brandvik et al. (2006).

- Limited/difficult access to the oil
- Limited flow of oil to the skimmer
- Separation of oil from ice and water
- Icing /freezing of equipment
- Detection of oil in various ice conditions

Recommendations for further improvement of mechanical recovery were, among others, related to winterization of existing concepts, improvement of ice processing, and separation of ice and water, whereas all these areas may be related to the impact of low temperature.

To evaluate the effectiveness of dispersant application the following parameters were considered as most important by Brandvik et al (2006):

- Access (contact) of the dispersant to the oil.
- Sufficient mixing energy for the dispersion process
- Oil properties at low temperature (weathering degree), with special focus on viscosity and pour point.
- Dispersant performance and properties under the relevant conditions (salinity, temperature, oil type)

Recommendations for further improvement of dispersant application were, among others, improved documentation of effectiveness, improvement of application technology, and extended time window for use of dispersants. When it comes to improvement of technology, this can be related to winterization of vessel- and helicopter-based equipment.

In-situ burning was, at this point of the JIP project, considered with a potential to be an effective oil spill response technique in Arctic and remote oil spill scenarios. Although, there was a large need for operational field testing of in-situ burning to verify knowledge established through laboratory and basin studies. The fundamentals of in-situ burning were presented in the following points by Brandvik et al. (2006).

- Oil properties or oil type
- Oil weathering ("window of opportunity")
- Environmental condition (especially wind and waves)
- Safety hazards (human and the environment)
- Oil availability for ignition/burning
- Igniters
- Fire-proof boom systems

One of many recommendations for further improvement was to establish a laboratory methodology based on oil properties, weathering behavior, measured ignitability/burning effectiveness, to measure the window of opportunity for in-situ burning.

During the later stages of the Oil in Ice JIP, a large number of small- and medium-scale tests were performed under controlled conditions in the laboratory facilities at SINTEF's Sealab. Tests were run with a number of combinations of oil types, ice concentrations, temperatures and other important parameters which affect the behavior of oil as well as the possibilities for efficient oil spill countermeasures with the various available techniques. Some important parts of the test program were carried out at the outdoor test facilities at Svea Research Station (Svalbard), and lastly, two large-scale field experiments were conducted in the marginal ice zone in the Barents Sea (Sørstrøm, et al., 2010).

The laboratory and field experiments of the Oil in Ice JIP led to a number of findings and conclusions to be drawn in terms of effectiveness. Some of the findings are presented in the following points in accordance with Sørstrøm et al. (2010).

- Verification of in-situ burning and chemical dispersion as highly effective response methods. Both techniques have been tested and proven to be effective for elimination of oil in ice. In some cases, the energy input in the oil-ice system will be reduced with increasing ice coverage. Adding extra mixing energy extends the operational possibilities for use of dispersants.
- The presence of cold water and ice can enhance response effectiveness by 1) limiting the spread of oil and 2) slowing the weathering process, which may contribute to the enhancement of response effectiveness for certain oil spill scenarios. Still, the window of opportunity is limited, and rapid

decision-making and action are required to make use of the available window of opportunity for all three response methods.

- In ice-covered waters the time-dependent weathering process is significantly reduced depending on ice type, ice coverage and energy conditions. This can be an advantage and contribute to the enhancement of response effectiveness for some oil spill scenarios.
- Each response countermeasure evaluated during the program demonstrated some merit in responding to an oil spill in Arctic environment, and the availability of all the response options is considered as being the key to a successful oil spill response operation in the Arctic.
- A systematic way to predict the operational time window for various response options has been identified, thereby demonstrating that efficient spill response may be accomplished whether the techniques are used individually or in combination.

The report from EPPR (2015) also touches the subject of effectiveness in oil spill response operations, and occasionally make use of the term overall effectiveness. It is stated that for the different response countermeasures, the overall effectiveness depends on the speed of advance (e.g., vessels towing boom at less than 1 knot, aircraft speed), the swath or sweep width (e.g., boom opening, aircraft or vessel spray arm width), burn removal rate, and skimmer recovery rate, among other factors, such as the possible need for lightering and decanting.

As one can understand, calculating the expected recovery or removal rate for a particular response effort is a complex process, with no simple method to estimate spill response effectiveness. Potter et al. (2012) states that the knowledge gained from laboratory, tank, and field experiments under Arctic conditions can be used to determine operating limits for different countermeasures. However, EPPR (2015) states that operating limits by themselves are not good indicators of response effectiveness. Actual removal rates depend on many interrelated factors, such as oil thickness, degree of emulsification, sea state, wind speed, weather, darkness, and the availability of experienced aerial spotters to guide marine crews to the thickest parts of a slick, etc. These factors may all be influenced by low temperature to different extent. From this perspective, EPPR (2015) presents several important points on how extreme cold air temperature, as an influence factor, impacts oil spill response operations:

- Impact safety on deck due to dangerous wind chill effects;
- Impact responder safety because of potential for severe frostbite;
- Decrease worker efficiency from fatigue, leading to a need for frequent rest and warm-up breaks;
- Require all equipment (pumps, hoses etc.) to be suitable for use in freezing temperatures. All equipment needs to be fully winterized;
- Contribute to equipment breakdowns due to changes in oil viscosity, hydraulic leaks or brittle failures, and;

- Limit helicopter operations – lowest acceptable temperatures are set by the operators and manufacturers.

In the literature review by Federici and Mintz (Oil Properties and Their Impact on Spill Response Options, 2014), it is stated important factors for measuring effectiveness of the three response options, in-situ burning, dispersants, and skimmers, individually.

For in-situ burning three factors emerged as the most important in determining the effectiveness: 1) oil slick thickness, 2) oil properties (flash point, volatility, and API gravity, and 3) oil emulsification. Many oil properties, such as vapor pressure, volatiles content, flash point, API gravity, and degree of emulsification are correlated to how well oil will vaporize and ignite (Federici & Mintz, 2014). Applying in-situ burning in an Arctic location one can understand that these three factors will be affected by low temperature, among other environment conditions related to the Arctic.

To measure dispersant effectiveness, the definition of chemical effectiveness is applied. Chemical effectiveness is the amount of oil that the dispersant displaces into the water column compared with the amount of oil remaining on the surface slick. The formula is simply given as:

$$Effectiveness\ (percent) = \frac{Amount\ of\ Oil\ in\ Water\ Column}{Initial\ Amount\ of\ Oil\ Slick} \times 100$$

Federici and Mintz (2014) consider oil composition, oil properties, and the spill environment (temperature, wave turbulence, sea salinity etc.) to be the most important factors to affect the dispersant effectiveness.

For skimmers, the term performance is used instead of effectiveness by Federici and Mintz (2014). They consider the most commonly reported metrics of skimmer performance, which is defined below:

- Oil recovery rate (ORR). The volume of oil recovered by the device per unit time (m^3/h).
- Recovery efficiency (RE). The ratio expressed as a percentage of the volume of oil recovered to the volume of total fluids recovered (percent).
- Throughput efficiency (TE). The ratio expressed as a percentage of the volume of oil recovered to the volume of oil encountered (percent).

The paper of Naseri and Barabady (2015), discusses the overall performance of a skimming operation from two perspectives: availability and effectiveness. From an availability point of view, a system must be able to function as per designed, and if it fails one must ensure that the system can be restored to the working state within a minimum period of time. From the perspective of effectiveness, the system, while in working state, must be able to deliver, produce, or recover as per design. For instance, pumps must have the ability to pump the recovered mixture into the separation facilities with a rate determined by the manufacturer, and skimmers must be able to skim the oil from the water surface as per designed rate (Naseri & Barabady, 2015).

Further in the report, they discuss parameters that affect the availability performance and effectiveness of a skimming operation. From the viewpoint of effectiveness, they divide the influencing parameters (operational conditions) into the following points (Naseri & Barabady, 2015):

- Oil slick thickness
- Oil viscosity
- Operator performance
- Sea ice concentration
- Climatic conditions

From the perspective of availability, they illustrate the key operational conditions that affect the availability performance of skimmers in the following figure…

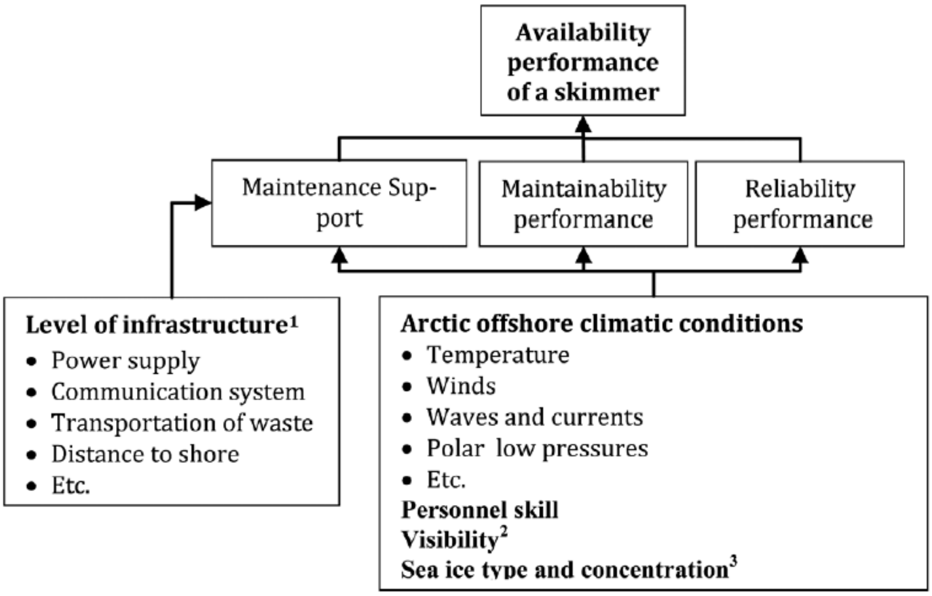


Figure 4.5 Key operational conditions that influence the availability performance of a skimmer in the Arctic offshore. Source: (Naseri & Barabady, 2015)

An important consideration about the two perspectives of effectiveness and availability, is that these perspectives can be seen in relation to OEE and RAM, respectively.

4.2.2 Summary

Through Figure 4.5 presented by (Naseri & Barabady, 2015) one can see that influencing parameters such as climatic conditions, sea ice concentration, and operator performance (personnel skill) are presented from the viewpoints of effectiveness and availability. Oil slick thickness and oil viscosity are only mentioned when considering the effectiveness. These two factors are both related to the behavior of spilled oil. When evaluating the overall performance from the two perspectives (availability and effectiveness) there will be commonalities that can raise the discussion of availability as a measure for effectiveness and vice versa. For instance, it may be legitimate to discuss oil slick thickness and oil viscosity as influencing factors on the availability performance. Reliability performance as a part of availability performance, relates to the working state of equipment and must, according to Rausand and Høyland (2004), take all influencing parameters which may contribute to failure modes or equipment downtime, into account. This will make it reasonable to include oil slick thickness and oil viscosity as parameters to affect reliability of skimmers, and thereby the availability.

The above studied literature in section 4.1 to 4.2 reflects upon many important factors that may impact the effectiveness of an oil spill response operation. Arctic environment conditions, such as presence of ice, waves, winds, temperature, etc. are all important in the work on mapping the effectiveness.

Low temperature as an influencing factor does great impact by itself, but also in combination with factors such as presence of ice and wind. It may both improve and dis-improve the effectiveness with its influence on oil slick thickness, oil viscosity, oil spreading, oil weathering, and in general, the behavior of spilled oil (Sørstrøm, et al., 2010). It may impact the performance of personnel as humans are highly sensitive to cold temperature exposure. Wind chill effects, potential for severe frostbite, and reduced fatigue are some of the aspects that need to be carefully mapped in this relation. Cold temperature will also impact the equipment as it contributes to breakdowns due to changes in oil viscosity, hydraulic leaks, and brittle failures (EPPR, 2017).

Each oil spill countermeasure is impacted by low temperature, but in very different ways. When the conditions restrict the use of, for instance mechanical recovery, it may be more efficient to apply in-situ burning or chemical dispersion, or a combination of these. The availability of each countermeasure is therefore considered important, because of the opportunity to choose the most effective option (Sørstrøm, et al., 2010). To possess the necessary resources for each countermeasure at the oil spill location is one part of the availability. Another part is to have the knowledge about the level of availability for each option in relation to the oil spill scenario. This requires comprehensive research, testing, experience from similar conditions, and use of efficient methodologies to collect data.

Level of availability can be expressed as availability performance, which is considered an important perspective by Naseri and Barabady (2015), besides effectiveness, when estimating overall skimmer performance. With this consideration, availability relates to a system's ability to function as designed, and if it fails one must ensure that the system can be restored to the working state within a minimum timeframe. Effectiveness relates to the system’s ability, while in working state, to deliver, produce, or recover as designed.

While the perspectives of availability and effectiveness are used for skimmer operations, only, by Naseri and Barabady (2015), this study attempts to apply the perspectives for all oil spill countermeasures. Availability performance is considered as a baseline for discussing low temperature’s effect on OEE in oil spill response operations rather than separating into two perspectives. This is backed up by existing theory of OEE and RAM and the relation between them.

The next part of the literature review covers research on RAM performance in Arctic operations with low temperature as main influence factor. Literature from oil spill response operations are also evaluated in certain parts to reflect on the relevance of RAM perspective in oil spill response operations.

4.3 RAM performance under Arctic conditions

The research on RAM performance under Arctic conditions has mainly been related to the exploration and production of oil and gas. Less research has been conducted on the oil spill preparedness and response operations. Response operations does not include production equipment, but largely relies on mechanical equipment which are to perform under arctic conditions, like oil and gas production facilities. In these circumstances, a successful oil spill response operation will depend on the RAM performance of the equipment used, such as oil containment booms, oil skimmers, support vessels and aircraft, and different equipment used during in-situ burning and dispersant application. The principles of RAM performance of oil and gas production facilities in the Arctic may be transferable to the oil spill preparedness and response operations in the Arctic, considering that mechanical equipment and personnel are affected by the Arctic climate in both areas. With these considerations, a literature review is conducted on research covering RAM performance in Arctic operations, to evaluate how equipment and human performance may be impacted by low temperature from this perspective.

4.3.1 RAM concept

Operational environment may have a considerable influence on the reliability performance and maintainability performance of an item. In the Arctic region with harsh climate condition, sensitive environment and remote location, these influences are more critical. To achieve effective reliability and maintainability analysis and management, all technical challenges and influence factors must be identified. Then, based on the way that these factors influence the failure mechanisms, maintenance processes and other support activities, appropriate statistical approaches must be selected to quantify their effects (Barabadi & Markeset, 2011)

For instance, the low temperature may change the properties of materials, increase the failure rate and decrease the system reliability. Wind, icing, snowfall and darkness in combination with low temperatures can also reduce the maintainability and operational effectiveness drastically (Barabadi, 2011).

Production performance is a term used to describe the capacity of a system to meet demand for deliveries or performance. In the oil and gas industry, the production performance concept plays an important role in supporting the decision-making process for the managers and the engineers dealing with challenges to meet the varying demands of customers as well as production control and the optimization of operation and maintenance strategy (Barabadi & Markeset, 2011).

Considering the production performance term by Markeset (2010), which consists of the Dependability (RAM) concept and the functional performance, it is attempted to understand how this can be seen from an oil spill response operation perspective. Hereby, we will consider the dependability part of Figure 4.6. The objectives of dependability management relate to obtaining the optimum overall economy of the production system during its life cycle phases; reducing health, safety, environmental and other risks; improving quality; as well as considerations related to human factors and customer satisfaction. The International Electrotechnical Commission (IEC), defines dependability as a collective term which describes availability performance and its influencing factors, namely reliability performance, maintainability performance, and maintenance support performance (Barabadi & Markeset, 2011). This concept is considered the same as RAM performance (Naseri & Barabady, 2016) where maintenance support is included in the maintainability part.

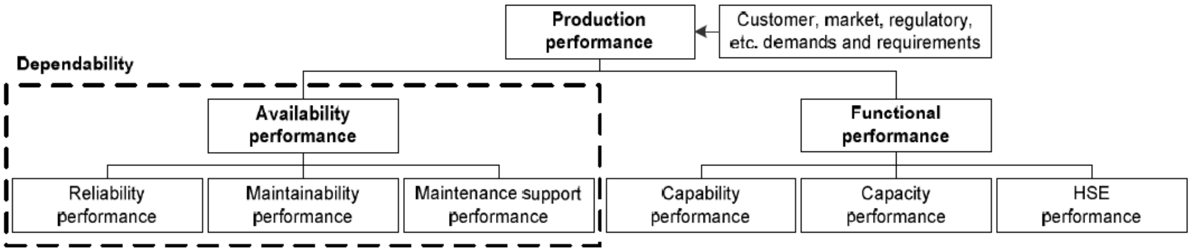


Figure 4.6 Concept of dependability (availability) in relation to production performance. Source: (Markeset, 2010)

Dependability (RAM performance) can be an important viewpoint in discussing the overall performance of an oil spill response operation, such as mechanical containment and recovery, which consists of the processes of containment by booms, storage and separation, and transportation. Naseri and Barabady (2015) states that while the equipment/system is in working state, it must be able to deliver, produce, or recover as per design. For instance, pumps must have the ability to pump the recovered mixture into separation facilities with a rate determined by the manufacturer, or skimmers must be able to skim the oil from the water surface as per designed. This statement reflects important aspects to evaluate from a RAM perspective.

Through all the stages of a mechanical recovery operation, or other operations in the Arctic, the environment conditions play an important role for the outcome of RAM performance. The next section will have a closer look at the "given conditions".

4.3.2 "Given conditions"

Through the definitions of the RAM concept, one can understand that the "given conditions" play a key role. Given conditions can be the surrounding environment (e.g. temperature, humidity and dust), condition indicating parameters (e.g. vibration and pressure), the operating history of machine/equipment (e.g. type and number of failures and repairs), the skill of the operator or maintenance crew, etc. (Barabadi & Markeset, 2011).

One of the important issues that may affect the RAM performance is the environment conditions (Barabadi & Markeset, 2011). Therefore, it is necessary to consider the effect of the local environment, first when we design, modify and improve the equipment to meet the performance criteria and goals, but also in the operational phase, when we observe and measure the performance of equipment, perform preventive and corrective maintenance, as well as collect data to improve the performance. This requires a careful mapping of the environment conditions over a sufficiently long period of time to get reliable data about their effect on the RAM concept.

Parts of the Arctic are covered by sea ice, glacial ice or snow. Fog is also a common atmospheric phenomenon during summer time. From a reliability and maintainability point of view, the technological challenges for an oil and gas production facility may be categorized in three main groups according to Barabadi and Markeset (2011): *i)* harsh climatic conditions; *ii)* lack of suitable and sufficient infrastructure; *iii)* long distance to the market. The report from Funnemark et al. (SARINOR2, 2017), has considered the following aspects to cover the main challenges related to oil spill response operations in the High North: *i)* Logistics, communication and infrastructure, *ii)* Nature environment and climate, and *iii)* Organization, management and competence. The categorizations are relatable, and most importantly for this thesis, low temperature is considered as an important environment factor to affect operational conditions, such as working environment, maintenance- and response tasks, material properties, human performance, and equipment effectiveness.

The next subsection will evaluate low temperature as an environment factor, but also as an influencing factor on RAM performance.

4.3.3 Low temperature – A key environment factor

A ‘cold region’ is often defined in accordance with a low temperature. The temperature of 0°C has been cited as the key element in this definition because materials such as metals, plastic and lubricants begin to show the effect of cold temperature on their properties below 0°C (Larsen & Markeset, 2015). High-strength steels, many plastics and polymers become brittle at low temperatures and are susceptible to fracturing and cracking by thermal stresses. Furthermore, in very low temperatures, fluids will freeze, and the equipment characteristics of hydraulic oils can change (Barabadi & Markeset, 2011).

The temperature varies according to location and season. In the Arctic, the coldest months are often January or February, and the warmest month is July. Winter temperatures can drop below -50°C over large parts of the Arctic region, and average July temperatures can range from about -10 to +10°C (Barabadi & Markeset, 2011).

The southern parts of the region may also experience the Arctic cold. The lowest mean temperature measured for a week-long period in the Norwegian sector is -15°C at Bjørnøya (74° northern latitude between Norway and Spitsbergen), and -5°C at ‘Tromsøflaket’ (Larsen & Markeset, 2015). Equipment and facilities in such Sub-Arctic areas must be resistant to low temperatures, but also the large variations in temperature during a short period of time, because large temperature variations may also cause strain on equipment (Barabadi & Markeset, 2011).

Both air and sea surface temperatures vary considerably over the Barents Sea during winter and summer periods. This is mainly due to flow of various water masses with different temperatures, diverse wind speeds and directions, latitudinal changes in solar radiation rates, and presence of sea ice in northern areas and usually open waters in western and southwestern regions (Naseri & Barabady, 2016). Sea surface temperatures are considered important for both oil and gas plants and oil spill response operations as it impacts temperature-dependent processes taking place at the sea floor (e.g. subsea wellheads and manifolds) and behavior of spilled oil at sea (Potter, Buist, & Trudel, 2012).

In the Norwegian Standard N-003, sea and air temperature on the Norwegian Continental Shelf is illustrated with an annual exceedance probability of 10^{-2} (NORSOK, 2007). The variations in highest and lowest air temperatures are shown in Figure 4.7, and the highest and lowest sea surface temperatures are shown in Figure 4.8.

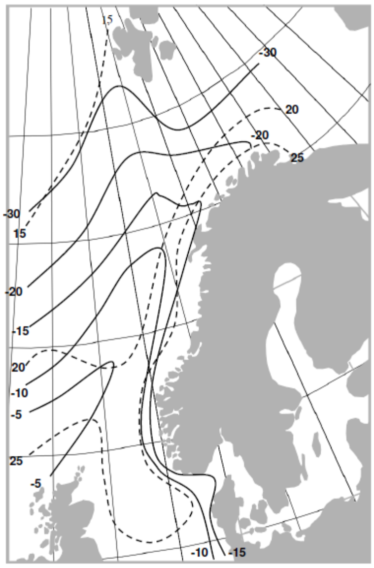


Figure 4.7 Highest and lowest air temperature with an annual probability of exceedance of 10^{-2} (temperatures are given in °C). Source: (NORSOK, 2007)

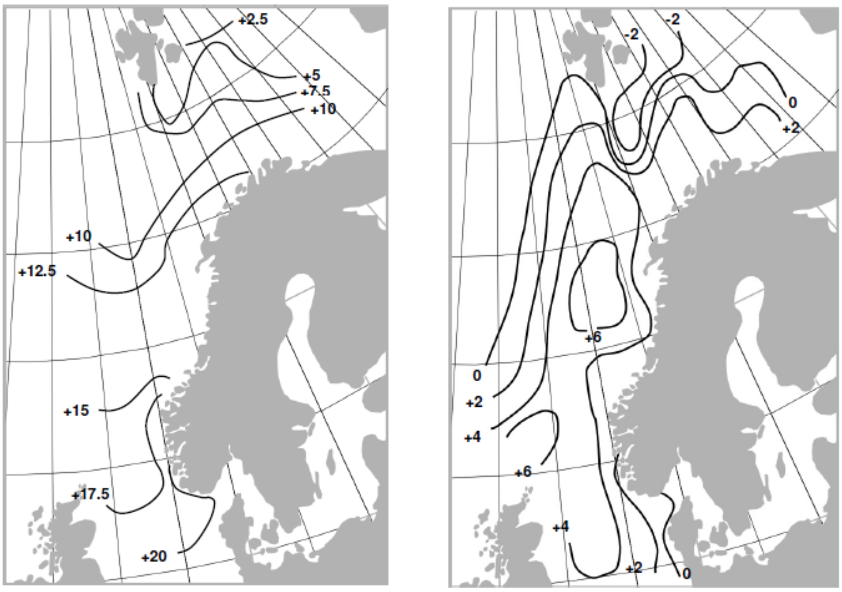


Figure 4.8 Left: Highest surface temperature in the sea with an annual probability of exceedance of 10^{-2}. Right: Lowest surface temperature in the sea with annual probability of exceedance of 10^{-2} (temperatures are given in °C). Source: (NORSOK, 2007)

The temperatures presented in above Figure 4.7 and Figure 4.8 are used for design purposes but are considered as relevant information and important data sources for oil spill response operations in the process of developing and designing equipment, operation and maintenance strategies. For instance, the effect of low sea and air temperatures has great effect on oil spill behavior. This may further impact reliability and maintainability of response equipment.

Low temperature in combination with wind is important to consider in Arctic areas. This combination creates the wind chill effect, which is defined as "the air temperature with no appreciable wind (i.e., still air) that would affect the same heat loss rate from exposed skin, as that due to the actual dry bulb temperature with wind" (Naseri & Barabady, 2016).

In general, wind speeds over the Barents Sea is lower than those over the North Sea and Norwegian Sea. Although, the combination of wind speeds and air temperature results in more severe wind chill effects in the Barents Sea. To compare the combined effects of air temperature and wind speeds, the probability density function of wind chill temperatures in the North Sea (Ekofisk Platform), The Norwegian Sea (Draugen), and Barents Sea (Hopen and Bjørnøya) is compared in figure…This shows that Hopen and Bjørnøya is associated with comparatively lower wind chill temperatures than those in the North and Norwegian Seas (Naseri & Barabady, 2016).

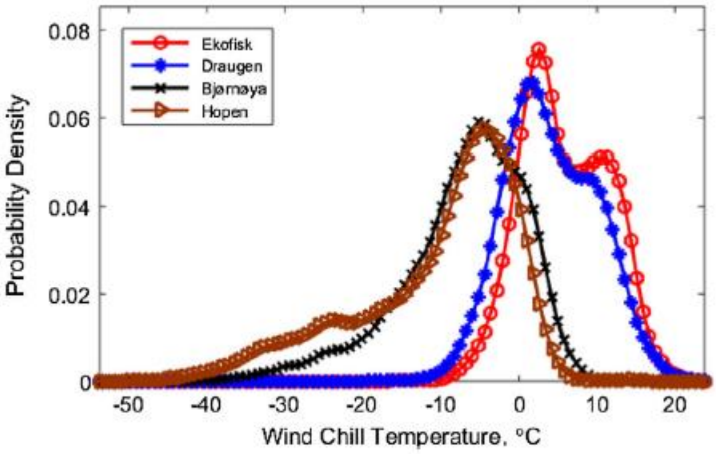
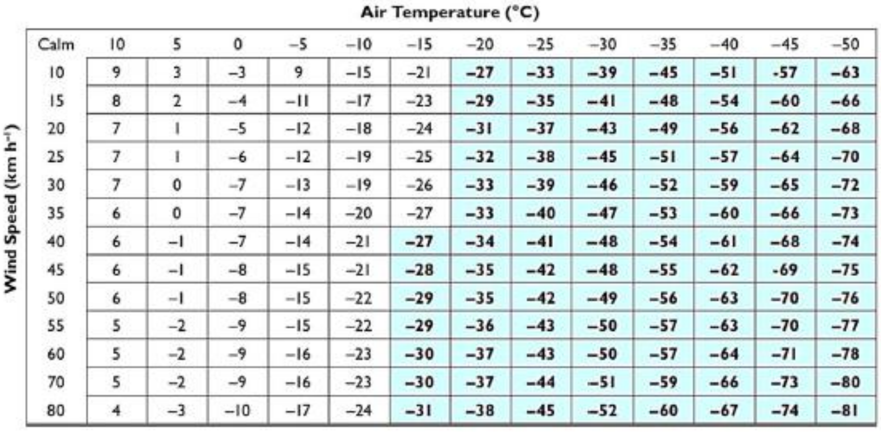


Figure 4.9 Probability density function of wind chill temperatures in °C over four locations in the Norwegian Continental Shelf. Source: (Naseri & Barabady, 2016)

4.3.3.1 Effect on RAM performance

The effect of low temperature on maintainability can be discussed from the viewpoint of decreased performance of maintenance crew. Maintenance or repair time can be increased due to the effects of cold environment on the human's cognitive performance (Mäkinen, et al., 2005). Human exposure to cold temperatures may result in reduced manual skills, coordination and accuracy with impact on productivity and safety, reduced decision-making ability, and increased risk of accidents from reduced alertness, manual dexterity and coordination, to mention some examples (Balindres, Kumar, & Markeset, 2016). Low temperature in combination with wind introduces the wind chill effect, which reflects upon the felt temperature by the human body (Naseri & Barabady, 2016). This is considered an important parameter in studies where the feasibility of different oil spill countermeasures is estimated, whereas increased wind chill can severely reduce the working periods of personnel (EPPR, 2017).

One of the most widely used wind chill models is developed by Osczevski and Bluestein (2005) which is presented in Figure 4.10.



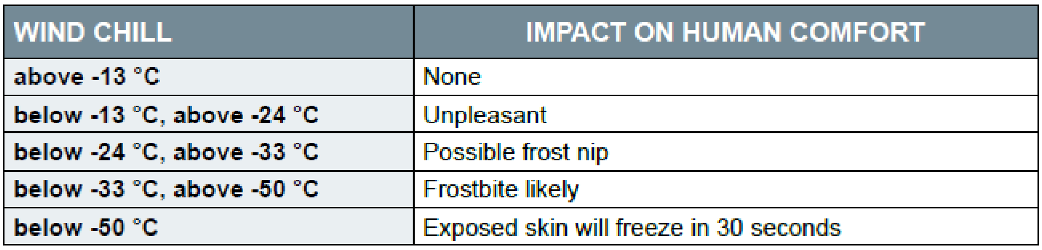
Air Temperature (°C)

Wind Speed (km h^{-1})

Calm	10	5	0	–5	–10	–15	–20	–25	–30	–35	–40	–45	–50
10	9	3	–3	9	–15	–21	**–27**	**–33**	**–39**	**–45**	**–51**	**-57**	**–63**
15	8	2	–4	–11	–17	–23	**–29**	**–35**	**–41**	**–48**	**–54**	**–60**	**–66**
20	7	1	–5	–12	–18	–24	**–31**	**–37**	**–43**	**–49**	**–56**	**–62**	**–68**
25	7	1	–6	–12	–19	–25	**–32**	**–38**	**–45**	**–51**	**–57**	**–64**	**–70**
30	7	0	–7	–13	–19	–26	**–33**	**–39**	**–46**	**–52**	**–59**	**–65**	**–72**
35	6	0	–7	–14	–20	–27	**–33**	**–40**	**–47**	**–53**	**–60**	**–66**	**–73**
40	6	–1	–7	–14	–21	**–27**	**–34**	**–41**	**–48**	**–54**	**–61**	**–68**	**–74**
45	6	–1	–8	–15	–21	**–28**	**–35**	**–42**	**–48**	**–55**	**–62**	**-69**	**–75**
50	6	–1	–8	–15	–22	**–29**	**–35**	**–42**	**–49**	**–56**	**–63**	**–70**	**–76**
55	5	–2	–9	–15	–22	**–29**	**–36**	**–43**	**–50**	**–57**	**–63**	**–70**	**–77**
60	5	–2	–9	–16	–23	**–30**	**–37**	**–43**	**–50**	**–57**	**–64**	**–71**	**–78**
70	5	–2	–9	–16	–23	**–30**	**–37**	**–44**	**–51**	**–59**	**–66**	**–73**	**–80**
80	4	–3	–10	–17	–24	**–31**	**–38**	**–45**	**–52**	**–60**	**–67**	**–74**	**–81**

Figure 4.10 Wind chill equivalent temperature (°C) chart, with air temperature in °C and wind speed in km/h. Shaded area indicates when frostbite can occur in less than 30 min. Source: (Osczevski & Bluestein, 2005)

Outdoor work may require specialized work clothing, which can reduce dexterity and prolong the time it takes to accomplish tasks. Planning for work in this environment requires attention to vessel conditions, crew training and gear, and the number of personnel required (which may be higher due to the need for rotating personnel on short shifts) (EPPR, 2017). In these circumstances, one must be aware of the effect of wind chill on maintainability performance. Figure 4.11 presents the impact from wind chill on human comfort.



WIND CHILL	IMPACT ON HUMAN COMFORT
above -13 °C	None
below -13 °C, above -24 °C	Unpleasant
below -24 °C, above -33 °C	Possible frost nip
below -33 °C, above -50 °C	Frostbite likely
below -50 °C	Exposed skin will freeze in 30 seconds

Figure 4.11 Impact of wind chill factor. Source: (EPPR, 2017)

Low temperature can have adverse impacts on equipment reliability due to negative effect on their constituting materials and elements. Mechanical properties, such as ductility and brittleness for polymers and metals may increase, and thereby lead to brittle failures (Naseri & Barabady, 2016). Pumps and hoses in a mechanical recovery operation may freeze and lead to downtime of the equipment. Low temperature may also affect the ability to pump fluids during dispersant application, due to increased viscosity or freezing (EPPR, 2017).

One can understand that low temperature will affect both reliability and maintainability, and thereby RAM performance of equipment in many ways. Through the literature studied, low temperature can be considered as an influence factor on equipment itself and the human performance. How low temperature will impact these two categories is reviewed more thoroughly in the next two subsections.

4.4 Equipment performance

Low temperature is considered to affect the equipment performance by its impact on materials and fluids. This is further reviewed in the following subsections.

4.4.1 Behavior of materials and fluids in low temperature

Cold regions engineering has a general need for the evaluation of materials at low temperatures. Performance of many structures, equipment, and components is seriously affected when the weather becomes very cold. At low temperatures, materials tend to become hard and brittle. As a result, legitimate concerns are raised about their reliability and safety in such cold weather (Dutta, 1988).

Cold regions material problems are many. Brittle-fractures initiated by low temperature or high strain rate (or both) have at times caused large-scale damage. In cold weather (0°C to 5°C) merchant vessels have broken in two while in harbor, bridges have collapsed, and pipelines and gas storage tanks have ripped open (Dutta, 1988). This may also raise the concern for vessels, systems, and equipment used during oil spill response operations as they will operate in the same environment as a potential oil spill in the Arctic.

Most manufactured materials exposed to low temperatures show substantial loss of useful structural properties. This includes the functionality of electrical and electronic devices such as cables, wires, switches, pushbuttons, lighting elements, gauges, etc., which may be impaired at low temperatures due to the changes in material properties of metals, plastics, rubbers, and changes in rheological properties of fluids used in such devices (Naseri & Barabady, 2016). Generally speaking, decreased temperature results in increased hardness, yield strength, and modulus of elasticity, but decreased fracture toughness/impact strength, fatigue strength, Poisson’s ratio, thermal expansion, and specific heat (Dutta, 1988).

The material types can be divided into metals, plastics/polymers, and fluids, which all are considered relevant for equipment used in oil spill response operations.

4.4.1.1 Metals

The most significant property change in metals at low temperatures is the increase in brittleness. When metallic objects are subjected to stresses in low temperatures, instance by an impact, the object or structure will shatter or fracture more easily than in more temperate conditions. This is exemplified in Figure 4.12

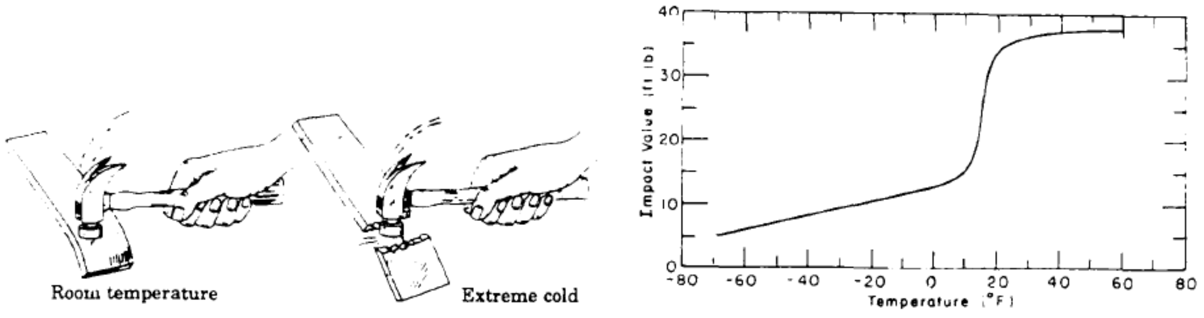


Figure 4.12 Impact test results for a steel pipe material. Source: (Dutta, 1988)

Metals with face-centered-cubic (FCC) lattice structure (e.g. nickel, copper, aluminum, lead, silver) show some ductility at low temperatures. A larger group of body-centered-cubic (BCC) metals (e.g. iron, chromium, molybdenum, tungsten) show a marked decrease in ductility. By examining the stress-strain relationship for BCC-metals at different temperatures in figure…, one can observe the loss of ductility. As the temperature is lowered, both the yield point (where the ductility begins) and the ultimate strength point (where failure occurs) may increase to a higher stress value, but fracture may begin at much lower strain value. The fracture mode transition from relatively ductile to relatively brittle is believed to occur because of the very rapid rise in viscosity with decreasing temperature (Dutta, 1988).

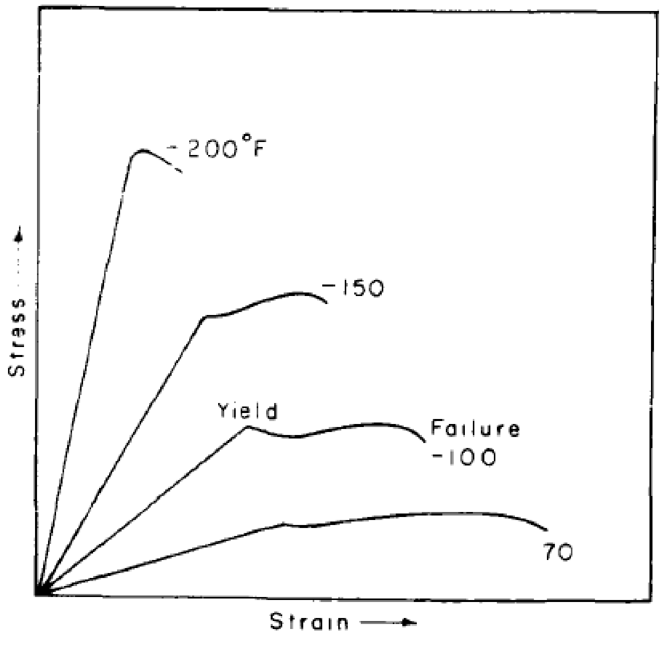


Figure 4.13 Typical stress, strain curve of a body-centered cubic class metal at decreasing temperatures. Source: Dutta (1988)

Because of the onset of brittle fracture, one cannot depend on most standard constructional carbon steels in cold region temperatures. The low temperature properties of metals presented in Dutta

(1988), indicate that stainless steel is probably the best-suited ferrous metal for cold use. Unlike other steels, stainless steel has no transition from tough to brittle in cold environment. The properties of aluminum do not degrade at low temperature, and it is a preferred material for many cold weather applications. The ductility of cold-worked copper actually increases at low temperature, which makes it an applicable metal for use in cold regions.

4.4.1.2 Plastics/Polymers

Plastic materials also become more brittle at low temperatures, but they are not as consistent as metals. Some plastics, such as polyethylene, a thermoplastic polymer, remain tough at temperatures as low as -73°C. On the other hand, serviceability of rubber components (e.g. tires, inner tubes, cable, hose, bushings, seals) are seriously affected by low temperature. Rubber develops brittleness and loses flexibility. Its loss of resilience is associated with changes in hardness, volume, and coefficient of thermal expansion.

Both time and temperature influence the behavior of polymers. With increased temperature they become less brittle, and with low enough temperature it behaves as glass. The upper limit of the glassy region is called the glass transition temperature, T_g. Commonly observed temperatures of T_g are in the range of -53°C to -97°C (Dutta, 1988). Figure… presents the typical thermomechanical behavior of a simple polymer.

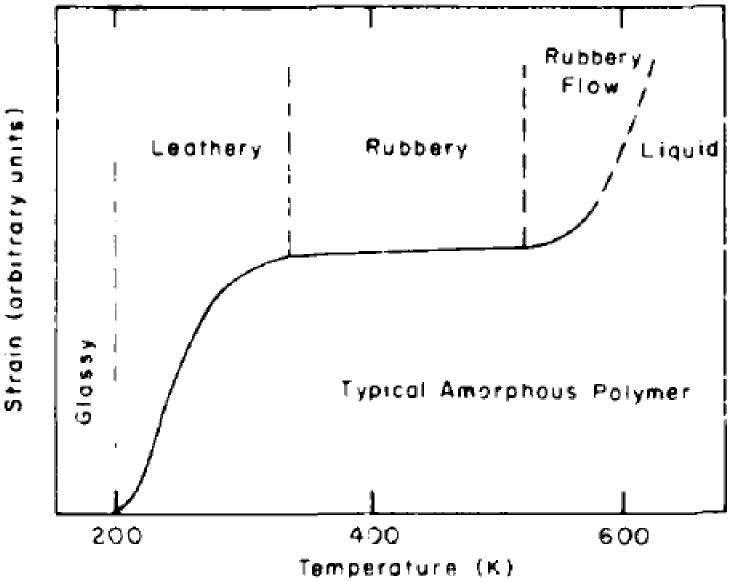


Figure 4.14 Thermomechanical curve of a simple polymer. Source: Dutta (1988)

The molecular structures that influence the behavior of polymers are *i)* branching, *ii)* chain length (molecular weight), and *iii)* crystallinity. How low temperature affects these parameters are therefore considered important when evaluating reliability of equipment or components consisting of polymers.

4.4.1.3 Fluid properties

Low temperatures can change the properties of fluids such as lubricating oils and crude oils. In this manner, low temperatures can contribute to failure of certain equipment units such as bearings, turbines, pumps, valves, etc. The viscosity of lubricants and crude oils increases with decreased temperature and is of significant importance as it determines the friction losses (Naseri & Barabady, 2016). With increased viscosity of lubricants more energy is required to operate equipment, and it can finally wear out the lubricated contacts. It may also affect the ability to pump fluids during dispersant application, which may be a result of increased oil viscosity or nozzle icing (EPPR, 2017).

In the next section, the effect of low temperature on human performance is reviewed.

4.5 Human performance

The environment consists of different environmental stressors such as heat, cold, noise, and illumination, which affect the physiological responses of humans. Mainly, cold temperature will be considered as a stressor in this section. A number of researches have been conducted to study the human performance in cold environments, e.g. Mäkinen et al. (2005), Balindres et al. (2016), Kumar et al. (2012). Bercha et al. (2003), defines human performance as the way in which a human being carries out or attempts to carry out a given task. For the purpose of reliability analysis, human performance has two primary components; namely, reliability or lack of mistakes with which the task is carried out, and the time over which the task is carried out.

Bercha et al. (2003) further states that stress is one of the most influential factors, where the relationship between human performance and stress can be described non-linearly. Too little stress and too much stress both leads to less than optimum or deficient performance. An in-between level is considered to be necessary to perform reliably. Through this, stress is related to both psychological and physiological stress. In figure… a hypothetical relationship between performance, stress, and task load illustrates that somewhat level of both stress and task load is necessary to achieve high human performance.

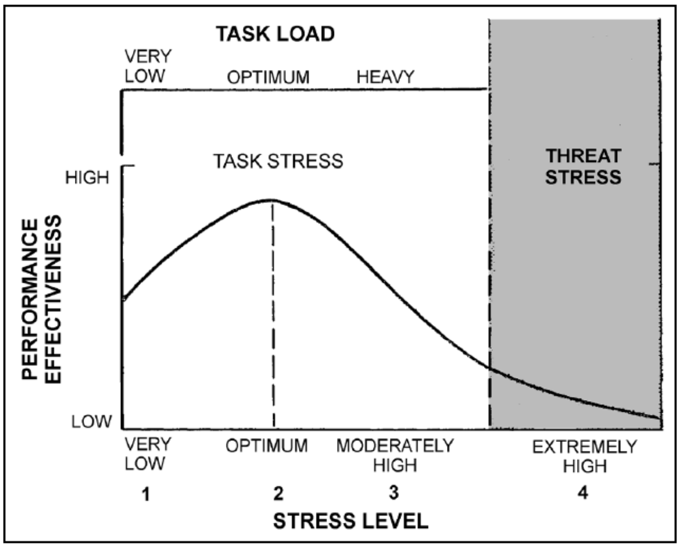


Figure 4.15 Hypothetical relationship between performance and stress with task stress and threat division. Source: Bercha et al. (2003)

The problems associated with human exposure to cold are often considered through the effect on manual performance and the risk of frost bites. The effect on human mental performance has been less emphasized or not considered at all. The knowledge of today suggests more attention towards this area (Norsk Olje og Gass).

4.5.1 Human factors

There has been a strong association between decreased manual performance and cold environment. Generally, there are two kinds of effects from cold on human performance, *i)* the peripheral effects, and *ii)* the central effects. The peripheral effects relate to the influence on strength and manual dexterity and the central effects relate to the influence on cognitive performance (Kumar, Barabady, Markeset, & Kumar, 2012).

Cognitive performance can be defined as the ability of maintenance personnel to perceive and process information mentally from maintenance environment, and to decide on actions to be taken. Manual dexterity can be defined as the motor skill that is determined by a range of motions by arm, hands, and fingers. Of all parts of the body, the hands/fingers are among the most probable locations for cold stress related to thermal discomfort (Kumar, Barabady, Markeset, & Kumar, 2012). By increased cold, the viscosity of the synovial fluid in human bodies increases, which causes slower movement. The phenomenon is called joint stiffness and when it increases, more muscle power is needed to make movements. This might eventually lead to musculoskeletal injuries.

When cold induced effects are observed, they are often connected to complex cognitive tasks which relies on the short-term memory. Under more extreme low temperatures, the long-term memory and consciousness will also be affected. Although, the cognitive performance may sometimes be difficult to register because the effects may be camouflaged through increased effort from personnel (Funnemark, Dahlsett, & Johnsrud, 2017).

Besides the immediate effects on cognitive performance, dark and cold environments may also affect the mental state of humans and thereby reduce the cognitive and physical performance. Through the above discussion one can understand the importance of evaluating low temperature as an influencing factor on both manual and mental performance, as they may equally contribute to risk actions.

The amount of risk actions for an operator with normal clothing for indoor work is at its lowest in surrounding temperature of +20°C (Norsk Olje og Gass), and will increase by either increased or decreased temperature if the clothing is unchanged. This is shown through Figure 4.16, where the curves represent heavy workload ("tungt arbeid"), moderate workload ("moderat arbeid"), and light workload ("lett arbeid") in relation to temperature and occurrence of risk actions.

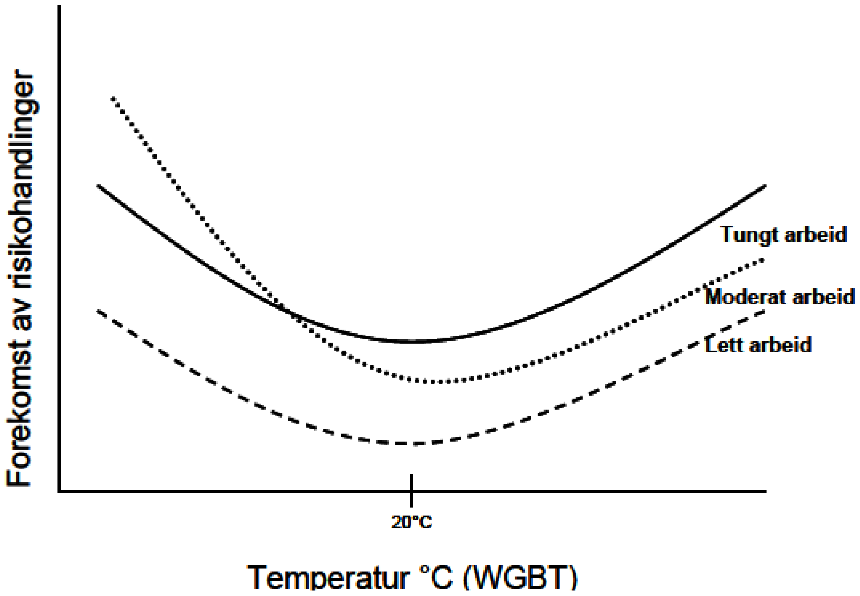


Figure 4.16 Relationship between occurrence of risk actions and surrounding temperature for indoor work environment with normal clothing costumed for work in 20 °C. Source: (Norsk Olje og Gass)

The same relationship between occurrence of risk actions and temperature may be transferred to outdoor work in cold environments. Although, the clothing will be customized for lower temperatures and the lowest amount of risk actions (bottom of the curves) will move towards a lower temperature. Being aware of the relationships in the diagram (Figure 4.16) may be a reminder of the human sensitivity to temperature and the importance of correct clothing in relation to temperature and workload to avoid, for instance maintenance related failures.

Kumar et al. (2012) intends to evaluate ergonomic issues in maintainability. To reduce maintenance related failures, they consider four human factors to be important. The same factors are considered by

Balindres et al. (2016) as influence on human-equipment interaction and human performance in general:

1. ***Anthropometric factor:*** Deals with the measurements of the human body such as stature, sitting height, shoulder height, eye height, hand length, forward reach, wrist circumference, force, and weight. Anthropometric data are used in ergonomics to specify the physical dimensions of equipment, clothing, furniture, or workspaces to ensure matching dimensions between the equipment or clothing and the user. Especially in the design process of a product, this parameter is important to enhance maintainability. For instance, the dimensions of clothes to protect from low temperatures need to be correctly sized to keep body parts isolated and at the same time avoid restrictions of movement.
2. ***Human sensory factors:*** Human sight, hearing, smell, and touch. When considering low temperature as a parameter in the design phase for maintainable systems, parts that needs to be handled with human touch must be easy accessible to keep the exposure of hands to cold equipment at a minimum.
3. ***Physiological factor:*** Stress produced due to environmental factors and conditions, such as cold climate, which will reduce the sensory capacities. When developing maintenance plans, the low temperature needs to be considered as a stressor, in which it will affect the physiology of personnel. By these means, working periods may need to be shortened to avoid cold injuries.
4. ***Psychological factor:*** Concerns the capacity of the mind to think and respond. Working in cold temperatures for long periods may affect the human mind in terms of motivation or focus. Maintenance policies and procedures must therefore take both the physiological and psychological aspects into account when humans are exposed to cold temperatures.

4.5.2 Heat loss

The greatest danger related to cold environment exposure is the cooling of the human body as a result of imbalance between heat production and heat loss. The heat production in the human body can be released in different ways. The greatest part of the heat loss from human bodies occurs through convection (heat flow from the surface of the body to the surrounding air), which is reinforced by increased wind. The influencing factors are the temperature of the body surface, air temperature and wind speed (Norsk Olje og Gass). About 50-80 % of the total heat loss may be due to convection, and therefore an important consideration for human performance.

The most important factors determining the heat loss is given in Table 1 below:

Table 1 Heat loss factors. Source: (Norsk Olje og Gass)

Heat loss	***Description***
Convection	The surface of the body heats up the surrounding air. (50-80 % of the total heat loss from human body).
Conduction	The surface of the body heats up the surface of items or equipment. For instance, when handling cold tools, the heat flows from hand to the surface of the tool.
Evaporation	Effective way to lose heat when the body is overheated but may result in humidity inside the protection clothes and defect the isolation capacity.
Respiration	Relates to the heat loss through breathing. This can be reduced by the use of masks.
Radiation	Heat radiates from the body surface to colder surfaces. With the use of protection clothes, the temperature gradient between the surface of the clothes and the environment is decreased. Although, solar radiation may lead to heat transfer in the opposite direction, through clothes towards the human body.

Clothing is the most important factor to decrease heat loss when operating in cold environments. Although, hard work may also create the need for cooling down. The blood flow to the head is not reduced when exposed to cold, which makes it an important body part to regulate the temperature. In -10°C a person in rest without sufficient clothing may lose more than 50 % of all the heat from an unprotected head (Norsk Olje og Gass). This may be favorable during hard work when there is a need for releasing excess heat. In other situations, it will be necessary to control and reduce the heat loss. The factors of heat loss are therefore highly important to consider when developing and designing protection clothes and developing maintenance procedures to facilitate high human performance.

4.5.3 Effects of cold exposure

Working in cold environment may lead to several potential consequences for the human performance. Balindres et al. (2016) and Kumar et. al (2012) list some important points, whereby some are suggestions through the above discussion.

- Reduced manual skills, dexterity, coordination and accuracy with an impact on productivity and safety.
- Increased risk of musculoskeletal injuries from stiffness of muscles and joints and reduced peripheral circulation.
- Increased risk of accidents from reduced alertness, manual dexterity and coordination.
- Discomfort from cold stiff hands and feet, runny nose and shivering.
- Impaired ability to perceive cold, cuts, pain, and heat.
- Reduced decision-making ability.
- Potential for aggravating existing injuries/illnesses or lead to development of injuries/illnesses

The above points will all contribute to risk actions, not only of importance for the safety of the operator, but also for the quality of completed work. Working outside the optimal temperature range of the personal protection clothes will reduce the concentration towards the tasks, and the incorrect actions may lead to failures or lower quality of completed work.

The next chapter will comprehend the literature reviewed in chapter 4 to evaluate how the effect of low temperature on oil spill response operations can be seen from a RAM perspective. Further, aspects for improving RAM performance will be discussed.

5 Findings

This chapter aims to apply the findings of the literature review. First, reliability and maintainability issues related to the effect of low temperature in oil spill response operation are considered. Further, based on the studied effect of low temperature, aspects for improving RAM performance are discussed

5.1 Reliability issues in cold environment

All factors that affect the reliability of equipment should be considered in the design phase. In this section the factors affected by low temperature in oil spill response operations are evaluated. By these means, evaluating reliability issues of equipment includes evaluating effectiveness issues.

Oil slick thickness is considered to be the most important factor to determine the effectiveness of a skimming operation (Naseri & Barabady, 2015). A thinner oil slick results in lower encounter rate (Schulze, 1998). In the means of low oil encounter rate the flow of oil towards a skimmer will be low. The skimmer may perform with expected recovery rate, but the recovery efficiency may be considerable low due to the amount of water recovered with the oil. From a RAM perspective, the oil slick thickness will then affect the reliability of a skimming operation.

In an Arctic environment with relative low temperatures the oil slick thickness tends to increase in relation to more temperate regions due to slower weathering processes, increased oil viscosity and thereby decreased spreading rate (Potter, Buist, & Trudel, 2012). Low temperature may therefore lead to higher oil encounter rate for a skimming operation. In-situ burning is reliant on 3-5 mm oil slick thickness to ignite the oil and achieve 60-80 % removal efficiency (Joint Industry Programme, 2017). The low temperature's effect on oil slick thickness may therefore lead to increased reliability of both skimming operations and in-situ burning.

Various types of hydrocarbon oils have different viscosities. In addition, the weathering processes can contribute to the changes in viscosity of oil. In a low temperature environment, the viscosity tends to increase. For instance, the viscosity of spilt oil can rise from a few centipoise (cp) to more than 160.000 cp. Based on the various factors such as working principle of skimmers, their size and shape, an increase of oil viscosity may lead to either increased or decreased oil recovery rate (Naseri & Barabady, 2015). It is therefore important to evaluate the low temperature's effect on oil viscosity, and design features of skimmers must be specified with reliability as a function of oil viscosity. Available reliability data for skimmers with respect to oil viscosity may in this case improve the effectiveness of a skimming operation by being able to choose correct skimmer type for the given scenario.

The change of oil viscosity in low temperature is also considered important for the effectiveness of dispersant application. With slower weathering rates the oil viscosity tends to increase and reduce the effectiveness of dispersant application (EPPR, 2015). Although, Sørstrøm (2010) has proven that high ice concentrations (90%) may reduce the viscosity range for different oils and result in higher dispersant effectiveness. The discussion of chemical dispersant effectiveness may continue, but one may conclude that low temperature and oil viscosity are important factors to consider in the reliability of a chemical dispersant application.

Oil slick thickness, oil viscosity, and oil weathering are considerably affected by low temperature and considered as important influence factors to the reliability of equipment in oil spill response operations. How they may affect the reliability of response operations is therefore important to measure.

The behavior of materials and fluids in equipment or systems are all affected by low temperature. The increased possibility for brittle-fracture in metals and plastics is considered to have a great effect on equipment reliability (Dutta, 1988). In addition, the change in fluid properties may cause failure and downtime on equipment.

Human performance must also be considered from a reliability perspective. Low temperature may reduce manual skills, dexterity, coordination, accuracy, etc. (Balindres, Kumar, & Markeset, 2016) and may lead to equipment downtime. The equipment design is therefore considered important to avoid human failures during operation and maintenance.

The factors affecting reliability of equipment in a low temperature environment is summarized through table…, either by contributing to reliability or unreliability.

Table 2 Low temperature influence factors on equipment reliability in oil spill response operations.

Reliability factors in low temperature	***Contribution to reliability***	***Contribution to unreliability***
Metal behavior		• Increased possibility for brittle-fractures may lead to equipment downtime. • Loss of ductility may lead to equipment downtime.
Plastics/polymers behavior		• Increased possibility for brittle fractures may lead to equipment downtime.

		• Loss of ductility. May lead to failure of for instance boom components and downtime of equipment.
Fluid behavior		• Failure of certain equipment units such as bearings, turbines, pumps, hoses, valves, etc. may lead to equipment downtime • Increased viscosity of lubricants may wear out the lubricated contacts and affect the ability to pump fluids during dispersant application and lead to equipment downtime. • Pumping may also be affected due to nozzle icing or freezing in general and lead to equipment downtime.
Oil slick thickness	• Increased thickness improves burning rate for in-situ burning. • Increased thickness leads to reduced spreading and higher oil encounter rate.	
Oil viscosity	• Change in viscosity of spilled oil may lead to increased recovery rate in skimming operation.	• Change in viscosity of spilled oil may lead to decreased recovery rate in skimming operation and need for change of equipment. • Increased viscosity may lead to decreased dispersion effectiveness and thereby lower reliability.
Oil weathering	• Slower weathering rates increases the window of opportunity for in-situ burning and dispersant application, which may lead to increased	• Slower weathering rates may increase the oil viscosity and affect the reliability of dispersant application. • Emulsified oil is usually more difficult to burn, disperse and

	operational time for the countermeasures.	mechanically recover. (Presence of ice may reduce the emulsification process)
Human performance		• Reduced manual skills, dexterity, coordination, accuracy, cognitive performance, etc. may lead to risk actions and equipment downtime.

The reliability factors from Table 2 are considered important to evaluate when designing equipment for operations in low temperature to achieve high reliability.

In the next section, maintainability issues in cold environment are evaluated.

5.2 Maintainability issues in cold environment

The human-equipment interaction in cold environments may lead to increased downtime in many ways. A major problem with working on equipment with bare hands is the increased risk of cold injuries. On the other hand, the use of protection clothes may lead to reduced accessibility to equipment parts due to reduced mobility. The exposure to cold may also lead to reduced cognitive performance, which may affect the ability to solve a problem in a given time frame. Kumar et al. (2012) evaluates important maintainability issues. Some of these issues are summarized in table… together with issues from the above literature review on human performance. All probable reasons for the maintainability issues are assumed relevant for each maintainability issue.

Table 3 Maintainability issues in low temperature environment.

Maintainability issues	***Probable reasons due to human factors***	***Probable reasons due to heat loss factors***
Increased inspection time or fault detection time *Increased access time to reach failed component*	• Improper anthropometric consideration: Cold protective clothing increases the measurement of body dimensions and reduces mobility. • Improper human sensory consideration: handling cold equipment with bare hands or	• Convection: Lack of protection clothes with proper isolation. Head is not protected from cold. • Conduction: Exposing bare hands to cold equipment or walking on cold surfaces in shoes with poor isolation.

Increased removal time for failed unit *Higher repair time* *Increased replacement time for failed unit* *Increased testing time to verify repair*	inefficient gloves, protection clothes affects the sensory skills by reduced vision, hearing and touch. • Improper physiological consideration: Workload is too heavy, too long working period, improper clothing. Leads to frost bite, muscular stiffness, breathing difficulty, coordination etc. • Improper psychological consideration: Work load is too heavy, too long working period, improper clothing. Leads to reduced cognitive performance, decision-making ability, alertness, motivation, concentration, etc.	• Evaporation: Excess heat creates evaporation in protection clothes and reduces isolation capability. • Respiration: Lack of using mask to avoid breathing cold air. • Radiation: The average radiation temperature is increased by solar radiation and heats up the protection clothes. May lead to excess heat.

Based on the evaluation of low temperature effect on equipment and human performance, the next section discusses important aspects for improving RAM performance in oil spill response operations.

5.3 Reliability Management

An effective reliability program and management requires identifying influence factors on system reliability, and the way these influence factors affect reliability. Barabadi and Markeset (2011) determines an item to be a function of *i)* the actual design, *ii)* how well the equipment is maintained, and *iii)* the operating conditions that include the environment and operational issue. To design equipment or systems with high reliability, considering the temperature as an environment condition and parameter, the multidisciplinary approach from Barabadi and Markeset (2011) may be used:

- Collecting and using all relevant information related to the effect from low temperature.
- Selecting the appropriate statistical approach for reliability analysis.
- Continuous improvement in reliability in the operation and development phase.
- The integration of technical and commercial issues.

In the Arctic offshore, the experience, knowledge and access to data is rather restricted compared to southern parts of the world. This applies both for oil and gas activity (Naseri, 2016) and oil spill preparedness and response (Funnemark, Dahlslett, & Johnsrud, 2017), and other areas. This implies the need for further research, testing and studying methods for treating available data relevant for oil spill response operations. In reliability analysis, different types of data can be used, such as historical data, accelerated life test data, expert opinions (Naseri, 2016), etc. The lack of data can be related to *i)* the operational environment (e.g. temperature, wind speed, etc.) and *ii)* the historical data of equipment's performance, such as time to failure (TTF), time between failures (TBF) or time to repair (TTR).

The lack of data about the operational environment can be related to the lack of a robust weather modeling and forecasting techniques (Barabadi, 2011). EPPR (2017) used different metocean datasets to estimate viability of different oil spill response options in the Arctic. It is also important to evaluate the uncertainty when using such data. Barabadi et al. (2011a) used Monte Carlo simulation to quantify the uncertainty related to the operational environment on reliability performance under Arctic conditions. The uncertainty of low temperature effect on equipment reliability in oil spill response operations must therefore be considered. Good estimates of expected performance of, for instance oil skimmers, will result in correct choice of skimmer type in relation to the oil viscosity for certain oil spill scenarios.

When there is no local historical data of equipment performance to predict equipment reliability one should look for historical data from reference areas. In order to ensure precise prediction, it is of importance to consider that each region has its own influence factors. Therefore, the difference between the effect of low temperature between the collected area (reference area) and the desirable area (target area) must be considered. If this information is not available, historical data must be used with caution to avoid any bias in the result (Barabadi & Markeset, 2011). This may be a realistic challenge for oil spill response operations considering the lack of experience and testing of response equipment in Arctic areas (Funnemark, Dahlsett, & Johnsrud, 2017).

Barabadi and Markeset (2011) proposes a procedure that must be implemented to use the available historical data in conjunction with covariates for predicting reliability in the design phase. The temperature may in this case be considered a covariate. First, the covariates and their effect magnitudes on reliability in the reference area are formulated. Further, these results are extrapolated based on the covariate's effect magnitude in the target area. This was further developed by Barabadi et al. (2014) to cover RAM data collection.

Selecting the appropriate statistical approach is an important stage in investigating whether the existing systems meets the reliability goals or if the system needs to be modified or redesigned. The model from Barabadi and Markeset (2011) must be able to quantify covariate's effect on reliability and to be built on correct assumptions that reflect the low temperature condition in the target and reference area. Through the evaluation in section 5.1, quantifiable effects from low temperature on materials, fluids, oil spill thickness, oil viscosity, and oil weathering will be important to determine. Oil spill thickness, oil viscosity, and oil weathering may operate as individual covariates affecting oil spill equipment reliability, with low temperature as an in-direct covariate. This may also apply for, for instance superstructure icing, where temperature operates as an important in-direct covariate (EPPR, 2017).

5.3.1 Modelling low temperature effect on reliability

Available methods for the covariate analysis on reliability can be broadly classified in two main groups: parametric model and non- (or semi-) parametric model. With no statistical or experimental evidence about the appropriate distribution shapes for reliability, which may be the occasion for operation of production facilities in Arctic environments, Barabadi and Markeset (2011) suggests non-parametric methods to be more appropriate. They further evaluate the application of Cox regression analysis (non-parametric method) and accelerated failure time model (parametric method). These assumptions may be totally wrong for Arctic regions (Barabadi & Markeset, 2011). Naseri (2016) gave special attention to the use of expert judgements to develop expert-based models for reliability analysis of oil and gas production facilities. The application of such statistical methods should also be evaluated for low temperature and other environment factors affecting reliability in oil spill response operations in the Arctic.

5.3.2 Winterization

Winterization of equipment has been stated as an important part of maintaining effectiveness in oil spill countermeasures (EPPR, 2015). Winterization of exposed areas on vessels, systems and equipment in oil spill response operations is important to consider where anti-freezing or anti-icing measures are required (DNV, 2013). Before winterizing equipment or exposed areas, it is important to identify any operational temperature limitations and restraints imposed on the work area in response operations. At this stage, the modelling of low temperature effect on reliability and maintainability becomes important. Some examples of winterization measures are heating of spaces for sensitive equipment, hard removable covers, use of electric heating blankets or heat tracing can be a solution for protection of equipment on open decks or unheated spaces. The use of anti-freeze additives or use of low temperature fluids in liquid systems alone or in combination with supplementary heating may also apply to winterization (DNV, 2013). In general, winterization may lead to increased uptime on equipment and systems, but also less time used on maintenance tasks. Proper winterization may therefore result in both improved reliability and maintainability in oil spill response operations.

5.4 Maintainability management

Maintainability is influenced by factors called maintainability attributes. These attributes can be divided into *i)* personnel (maintenance crew), *ii)* design, and *iii)* logistic support, according to Barabadi and Markeset (2011). How these attributes can be applied to oil spill response operations are discussed in the following subsections.

5.4.1 Personnel

Considering the personnel attribute, the human performance is significantly reduced in cold environments due to human sensitivity with low temperature (Mäkinen, et al., 2005). Ergonomics play an important role in eliminating or reducing human error and increasing maintainability (Kumar, Barabady, Markeset, & Kumar, 2012). In addition, the maintenance crew must be trained to repair equipment under Arctic conditions, where low temperature is an important influence factor (Larsen & Markeset, 2015). The personnel attribute can also be seen in relation to the human-equipment interaction, which also may reflect on the design attribute.

5.4.1.1 Human-equipment interaction

In oil spill response operations, vessels, aircraft, mechanical recovery equipment, and equipment for in-situ burning and dispersant application are all reliant of the human-equipment interaction. Several aspects of human-equipment interaction in maintenance work must be considered while trying to find solution to problems caused by improper design characteristics of any equipment (Kumar, Barabady, Markeset, & Kumar, 2012). The following factors reflects on human limitations in low temperature in relation to handling equipment:

i. ***Visual access:*** the ability of maintenance personnel to see what is being done, to see immediate surroundings in order to identify the possible dangers in working environment.
ii. ***Physical access:*** the ability of maintenance personnel to position or reposition the body or other parts of the body within the work environment in a better ergonomically viable posture in order to perform the given task. The ability to manipulate tools etc. within the environment.
iii. ***Physical mobility:*** The ability of maintenance personnel to maneuver the body or part of the body, often with tools, within the work environment in order to perform maintenance task
iv. ***Strength:*** The ability of maintenance personnel to generate the right amount of muscular force via hand-tools and other equipment, for manual tasks.
v. ***Muscular and physiological endurance:*** The ability of the operator to maintain a certain level of performance for a certain period of time, while using tools and other equipment.
vi. ***Cognitive performance:*** The ability of maintenance personnel to perceive and process information mentally from the maintenance environment, and to decide on actions to be taken.

The instruction manual, arrangement and design of equipment may in this case determine the speed and accuracy of the personnel.

vii. ***Education and training:*** The ability of maintenance personnel to perform tasks successfully. This requires the ability to comprehend written and other instructions from maintenance manuals and apply them to tasks, being able to meet the low temperature conditions, and being aware of the associated risks. Education and training leads to reduction of mistakes by maintenance personnel.

5.4.1.2 Cold-protective clothing

When operating in cold environments, cold protective clothing must be designed in relation to the ways of heat loss from the human body, such as convection, conduction, evaporation, respiration and radiation (Norsk Olje og Gass). In addition, anthropometric factors, human sensory factors, physiological factors, and psychological factors must be considered (Kumar, Barabady, Markeset, & Kumar, 2012). The protection clothes for cold environment often requires garments consisting of several layers of heavy thermal insulating materials which affect physical performance, which in turn, is measured in terms of energy cost. Murphy et al. (2001) reported that the use of heavy clothing of 9,3 kg resulted in increased energy cost and increased physiological and psychological demand when performing tasks for a longer period. The use of protective clothing is necessary while working in cold environment, however, by designing equipment that require less maintenance or facilitates ease of maintenance leads to reduced repair time and maintenance activities and thus the exposure of a worker to cold can be reduced significantly (Kumar, Barabady, Markeset, & Kumar, 2012).

5.4.2 Design

In the design phase it is important to consider design characteristics such as accessibility (adequate access to for visual and manipulative tasks), disassembly/assembly (easy opening/fastening of parts and components of various assemblies or subsystems), standardization (use of standard components), interchangeability (those parts in equipment that will need to be replaced should be designed with the minimum number of sizes, types, assemblies, and subassemblies), simplicity (minimizing number of components/assemblies), identification (e.g. labeling the components/assemblies, test points, arrow marking for connectors), modularization (functional packaging of units) etc. (Niebel, 1994).

5.4.2.1 Equipment Maintainability

To create an effective design with respect to maintainability, it is important to identify maintenance problems caused by the environment conditions, such as low temperature. Such condition may affect for instance the accessibility. A study by Seminara and Parsons (1982), reports that the most common complaint made by a group of maintenance personnel working at a nuclear power plant was the lack of accessibility to equipment requiring maintenance action. After several interviews, the proper access to the equipment by maintenance personnel was rated as a major obstacle and key issue for effective maintenance, and it was also found that 30% of savings in overall maintenance time could be achieved if proper access to equipment is available (Seminara & Parsons, 1982). During oil spill response operations time may be crucial as the window of opportunity determines the applicability of oil spill countermeasure. Time spent on maintenance may therefore result in failed operations. Considering this, designing equipment and systems for oil spill response operations must give high priority to both reliability and maintainability.

A large number of failures during operations of a system may be as a result of the fact that equipment may not have been properly maintained or designed. Poor maintenance could be identified from the cost of maintenance. Poor design can affect the human-equipment interaction in many ways and increase the maintenance time. High rates of accidents and injuries may indicate that the human factors have not been considered in the design process. The cold conditions will double the impact on maintenance personnel by restricting their ability to reach the equipment and parts of components compared to normal environment (Kumar, Barabady, Markeset, & Kumar, 2012). It is therefore important to consider ergonomic design in cold region oil spill operations in order to reduce maintenance downtime.

The equipment should be designed in such a way that it provides easy access for disassembly or assembly while working with cold-protective clothing such as gloves. In addition, proper illumination must be considered to avoid personnel to bend over some obstacle to get close enough view of defect components. This will reduce the exposure to cold and energy cost as a result of heavy protective clothing. For example, covers and maintenance hatches should be properly lighted, easy and quick to open and close, and fasteners should be designed for operating with gloves. This will decrease maintenance time and also enhance the safety and job satisfaction. Therefore, to improve equipment maintainability in the design phase one must involve considering ergonomic factors (Kumar, Barabady, Markeset, & Kumar, 2012).

5.4.2.2 Workspace design for maintenance

In the design for maintainability, work space is very important. In order to design suitable workspaces, the physical environment such as noise, vibration, wind, temperature, icing, snow, sea-spray, etc. must be mapped and described accurately. Thereafter, their effects on the work space must be identified (Barabadi & Markeset, 2011). For instance, the wind chill effect may dictate some terms for maintenance work space. Then, based on these effects, considering anthropometric data and ergonomic factors, the working environment must be designed. After evaluating the effect of wind chill in the design phase, some modification or redesign may be necessary to achieve desirable maintainability performance. For instance, this may include building shelters to avoid exposure to wind. This may increase the ability for personnel to work over longer periods.

For example, when considering oil spill response operations in a cold region, the workplace design on board vessels must take ergonomic factors into account in the initial stages, including the workers' anthropometric measurements when wearing cold-protective clothing, their physiological performance in the cold, their visual access, their cognitive performance, and the placement of equipment. In the past, designers have usually ignored or underestimated the consequences imposed by protective clothing and the limiting impact of clothing on manual dexterity, field of vision, and other human sensory skills (Seminara & Parsons, 1982). By improving workspace design, one may increase visibility, accessibility of equipment, and reduce improper working posture. This may cut maintenance downtime and increase the safety on a vessel used in oil spill response.

5.4.3 Logistic support

An oil spill response operation is associated with a great amount of logistical support. For instance, in mechanical recovery the recovered oil must be transported from vessels to disposal facilities on land. The storage tanks on vessels have limited capacities which implies the need for logistical support (Joint Industry Programme, 2017). Taking into consideration the high cost of logistic support and maintenance, an accurate prediction of logistic support resources can play a key role for cost-effective operation and maintenance. Barabadi and Markeset (2011) state that the main logistic support resources which have strong impact on operational availability and maintainability are *i)* spares, *ii)* repair facilities, and *iii)* personnel.

The number of required spare parts are often based on the equipment reliability. If the environment factors, such as low temperature, has not been considered in the reliability of equipment, the estimation of required spare parts may be wrong. Ghodrati and Kumar (2005) modified and improved existing methods to obtain the optimum spare parts' requirement considering operational environment. Such methods may be applicable for planning spare parts provision in oil spill response operations.

The transportation of maintenance crew and spare parts to vessels on the oil spill location may be difficult due to weather conditions. Barabadi and Markeset (2011) state that the main strategy under these conditions, for oil and gas production facilities, must be based on the maintenance crew on the platform performing maintenance activities as far as possible. This may also apply for oil spill response operations located offshore and leads to the need for designing equipment in such a way that it can be repaired as easy as possible.

5.4.4 Modelling low temperature effect on maintainability

In order to consider the effect of the operational environment on the maintenance strategy, the first stage is to estimate the magnitude of its effect on maintainability (Barabadi & Markeset, 2011). This estimation can assist the management in deciding which operational environment factors are more important from a maintainability point of view. For instance, the low temperature must be described and quantified based on the way that it can affect maintainability of oil spill response equipment. It is important to realize that low temperature as a covariate can be combined with other covariates and make new covariates. The wind chill factor, which is a combination of wind and temperature, is an example of this. Another example may be superstructure icing, which may combine waves, winds, humidity, and sea-and air temperature.

There are few models available for predicting the influence of various factors on maintainability. The statistical methods used in the field of reliability can also be used in maintainability analysis. In general, parametric methods have been used more frequently. One important consideration when modeling low temperature (or other environment factors') effect on maintainability, is the time-dependency (Barabadi, Barabady, & Markeset, 2011 b).

Barabadi et al. (2011 b) discussed the effect of time-dependent covariates on maintainability and on the failure rate. They showed that the effect of ambient temperature as a time-dependent covariate has a great effect on maintainability of crushing plant. In many methods that are used to optimize the replacement intervals, the main assumption is that replacement can take place at any moment and the replacement cost is constant. This may lead to wrong predictions in Arctic areas, where environment conditions vary greatly between seasons.

To map the effect of low temperature on maintainability in oil spill response operations in the Arctic, future research may investigate the application of different statistical methods applied in the oil and gas industry. This may contribute to improvement of maintainability and maintenance procedures.

6 Discussion

This chapter discusses and presents the results of the study. The topics for discussion are based on the stated research objectives.

6.1 Oil spill response effectiveness in the Arctic and the related challenges

The first part of the first research objective of this study is to review and discuss the challenges related to low temperature in oil spill response operations in the Arctic. The first section of the literature review covers this objective. The environment conditions affect operations in many different ways. Especially, low temperature and the presence of ice have great effect on the behavior of spilled oil, which affects the oil spill countermeasures both positively and negatively. The important parameters of oil spill behavior are considered to be oil slick thickness, oil viscosity and weathering of oil. The weathering process, emulsification, is considered important as it may result in reduced weathering capabilities for spilled oil. Emulsified oil is usually more difficult to burn, disperse and mechanically recover. Low temperature affects the parameters of oil spill behavior by increasing oil slick thickness and oil viscosity, and slowing down the weathering rates. This impact also results in reduced spreading rates. These effects are usually reinforced by the presence of ice, but this factor is not thoroughly discussed in this study. Although, the effects of low temperature may for instance increase the oil encounter rate for containment and recovery operations, increase the burning efficiency for in-situ burning, and affect dispersant application. A main concern of dispersant application is that when oil viscosity increases due to the impact from low temperature, the oil will be more difficult to disperse. Although, Sørstrøm et al. (2010) showed that the viscosity range for different oils are generally lower when weathered in high ice concentrations (90%). By this, it may be a reasonable allegation that oil will be much more difficult to disperse in cold open water than in water with high ice concentrations. However, in open water the possibility for waves and currents are much higher and will contribute to more effective dispersion process. As can be understood, the impact from low temperature and other environment factors on oil spill behavior involves complex processes and is a central part of the oil spill response challenges in the Arctic region.

The second part of the first research objective is to review and discuss the approach to effectiveness in current literature covering oil spill response operations. The effectiveness of the different oil spill countermeasures is often related to the behavior of oil, but aspects such as low temperature effect on equipment and human performance are mentioned as important to consider. The research by Naseri and Barabady (2015) evaluates skimmer performance from the two perspectives, effectiveness and availability, where each perspective relates to the theory of OEE and RAM, respectively. With these two perspectives, the effect of low temperature is covered through the behavior of spilled oil, and the equipment and human performance in a structured manner. Considering the theory of these two perspectives and their relation, the effect of low temperature on oil spill countermeasures may be evaluated through the perspective of RAM and thereby substantiate the effect on OEE.

6.2 RAM as attributes to determine the OEE of oil spill response operations in the Arctic

The second research objective of this study was to review and discuss the applicability of incorporating RAM as attributes to determine OEE of oil spill response operations in the Arctic, with low temperature as influencing factor. This was reviewed through research covering RAM performance in Arctic operations such as oil and gas production. This part of the literature review evaluates the perspective of RAM in Arctic conditions and the effect of low temperature on equipment and human performance, and considers the relation to oil spill response operations. The experience from oil and gas production includes many relatable challenges, although, the main difference is that oil spill response operations must consider the complex processes of oil spill behavior. This factor is highly affected by low temperature and Arctic conditions. To consider this factor from a RAM point of view it must be considered as either contributing to reliability or unreliability for an oil spill response operation. How this can be applied to methods of RAM was attempted to discuss in the findings of the study.

6.3 Aspects for improvement of RAM considering the effect of low temperature

The third research objective of this study was to study the effect of low temperature on RAM performance in oil spill response operations in the Arctic, and present aspects for improving RAM performance. This was partly conducted in the literature review and mostly in chapter 5 Findings. The reliability and maintainability issues in section 5.1 and 5.2 intends to reflect on important factors in oil spill response operations impacted by low temperature. In section 5.3 and 5.4, different aspects for improvement through reliability management and maintainability management is discussed. These aspects are used in the oil and gas industry, but are considered relevant for improvement of RAM performance in oil spill response operations.

One important aspect for improvement is modeling the low temperature effect on both reliability and maintainability. This involves taking into account all the factors where low temperature affects the reliability and maintainability of oil spill response operations. Based on the literature review, low temperature is considered to affect the equipment and human performance. These two factors must be further broken down to evaluate how the low temperature affects human and equipment performance. This may include the effect on, for instance, oil slick thickness, oil viscosity, human psychological performance, equipment materials, etc. By modeling the effect of low temperature on reliability and maintainability of equipment and systems in oil spill response operations, it is through theory of RAM and OEE considered to also model the factors of OEE, namely, availability, performance, and quality.

Although, modeling of environment effect on reliability and maintainability in oil and gas production located in the Arctic is considered challenging due to lack of data, according to Barabadi and Markeset (2011) and Barabadi et al. (2014). It is therefore assumed to be just as challenging for oil spill response operations in the Arctic. This may lead to the need for future research on statistical methods that can be applied to available data from other areas than the Arctic. Further it should look for alternative data sources, such as expert opinions.

From the viewpoint of this study, to evaluate the effect of low temperature on OEE in oil spill response operations in the Arcitc, it should be considered to evaluate the effect from a RAM perspective in greater scale. This allegation may be substantiated by the quote from Niebel (1994):

The vast majority of the successful designs have given considerable consideration to both reliability and maintainability. The degree to which these attributes are incorporated in a product determine the system effectiveness.

Considering the quote, the key to improved OEE seems to be through improvement of RAM performance.

7 Conclusion

With estimates pointing towards increased industrial activities and shipping traffic in the Arctic region the next decades, the need for effective and reliant oil spill response operations will increase. The probability of large spill accidents has decreased considerably the last decades due to improved technology. Although, the gradual increase in vessel traffic, along the Northern Sea Route, gives rise to an associated increase in spill risk.

Considering the harsh climate of the Arctic, oil spill response operations will, potentially, meet great operational challenges. The main challenges can be related to *i)* Logistics, communication and infrastructure, *ii)* Nature environment and climate, and *iii)* Organization, management and competence. This study covers parts of the three categories given by Funnemark et al. (2017). With the aim of reviewing the challenges related to low temperature in oil spill response operations it may be concluded that low temperature has its main effect on i) the behavior of spilled oil, ii) human performance, and iii) equipment performance. The effect of low temperature on oil spill behavior may lead to positive effects for oil spill response operations, such as reduced spreading and increased window of opportunity for certain countermeasures. It may also lead to negative effects through increased oil viscosity, which may reduce chemical dispersant processes.

The overall goal of oil spill response is to control the source as quickly as possible, minimize the potential damage caused by the accidental release, and employ the most effective response tools for a given incident. How to employ the most effective response tools for a given incident has been extensively studied for oil spill response operations in the Arctic. This has resulted in increased knowledge on how the Arctic environment conditions impact the effectiveness of the different countermeasures.

Effectiveness can be related to Overall Equipment Effectiveness (OEE), which further has been proven relatable to Reliability, Availability, and Maintainability (RAM). By implementing RAM perspectives to evaluate the effect of low temperature on oil spill response operations, it may give rise to improving the fundamentals of OEE (availability, performance, and quality). This is shown by reviewing existing research on RAM performance in Arctic operations and existing theory of RAM and OEE.

With the implementation of reliability management and maintainability management, and considering low temperature as influence factor on oil spill response operations, it may be suggested aspects for improvement. The most important factors in low temperature is considered to be behavior of materials and fluids in equipment, oil slick thickness, oil viscosity, oil weathering, and human performance. These factors must be considered in the design for reliability. It must be evaluated how these factors contribute to failure modes of equipment to create design solutions for new equipment or modifications of existing equipment or maintenance strategies. Further, in terms of maintainability, it must be evaluated how low temperature will affect the maintenance crew, the maintainability design of equipment and work environment, and the logistic support of an oil spill response operation. This will imply the need for operation and maintenance strategies. In general terms, sufficient reliability and maintainability management must be based on historical data and applicable statistical methods to process the low temperature as parameter. As oil spill response operations in the Arctic region, and Arctic operations in general, are associated with limited experience and lack of data, alternative methods for gathering data may be considered, such as expert judgement.

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