Chapter 11 – Arctic marine oil spill response methods: environmental challenges and technological limitations

Table of Contents

ABSTRACT

Chapter 11 – Arctic marine oil spill response methods: environmental challenges and technological limitations

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(200 words) The largest all-recognized problem in the Arctic, besides financial viability, which stops oil and gas industry from operating full scale in its seas, is environmental conditions in case of oil spill accidents are too unfavorable. Currently, nobody can conduct confident, highly efficient and fast oil recovery from the sea surface under icy, stormy, low visibility and extremely cold conditions. In 2015, Emergency Prevention, Preparedness and Response Working Group of the Arctic Council (EPPR), an international body that examines oil spill response (OSR) in the Arctic region, discussed the need of improvements in this field. In 2018, after studying the Arctic Ocean in multiple geographical marine areas, EPPR concluded that natural climate conditions of the region are too challenging for the present level of OSR preparedness. There are still many technological limitations and no optimized strategies for oil spill abatement. Thus, OSR issues are and will stay of a relevant discussion.

This chapter will focus on main available OSR methods, give an overview of challenges and limitations set by demanding Arctic environment. It will analyze each of branches – in situ burning, dispersants use, mechanical and physical response; and compare them on their efficiency, applicability, and multiple environmental, economic and technical parameters. (200 words)

Keywords: Arctic oil spill response

Abbreviations:

API – American Petroleum Institute

BOPD – Barrels of Oil per Day

EPPR – Emergency Prevention, Preparedness and Response

HFO – Heavy Fuel Oil

ISB – In Situ Burning

OSR – Oil Spill Response

PACs – Polycyclic Aromatic Compounds

SIMA – Spill Impact Mitigation Assessment

WOP – Window of Opportunity

UV – Ultraviolet

11.1 INTRODUCTION

Arctic oil spill accident can be a challenging task for responders. An example of near Arctic conditions is in the box below. For combating an oil spill, response authorities apply several methods: for example, in situ burning, mechanical recovery with oleophilic skimmers and booms, dispersants use, and sorbents use. By its nature, they can be categorized as thermal, mechanical, chemical and physical. Core mechanisms behind each are respectively combustion, adhesion, dispersion and sorption. (ITOPF 2012; Liu et al. 2016) Due to its increasing relevancy, marine oil spill response measures in the Arctic, as a study topic, has been explored in detail. The Arctic region is not anymore under one uniform umbrella with unbearable environment applicable to all its seas, it has been addressed as its sub-regions with their own prevalent ambient factors of the sea. Those factors limit oil spill response operations, with some of the sub-regions being the most problematic: e.g. the Kara Sea with its extremely low temperatures, -45 ^{o}C, long 9-month winters, gale-force winds and rapid glaciation (Vorobiev et al. 2005). Oil spill response in these marine areas due to their harsh weather patterns and extreme temperatures remain ineffective. (EPPR 2017a) In Arctic OSR toolbox, there are available solutions, which are described in a number of reports, for instance, within Arctic OSR Technology – Joint Industry Programme (JIP 2014). However, most of literature sources has a lack of well-structured information, providing concise description of each method operational conditions and its limiting metric parameters: all in one place (Wilkinson et al. 2017).

“box[Example of near Arctic oil spill event, Alaska, USA] starts”

The largest oil spill in the near Arctic latitudes so far took place in 1989 nearby Alaska, USA. The “Exxon Valdez” oil tanker has grounded on Bligh Reef within Prince’s William Sound. Eight out of eleven oil tanks were damaged to leak in the Gulf of Alaska. The spilt oil transformed into the “chocolate mousse” and reached the shoreline. It took three years to recover the contaminated beach. The abatement methods of 41,000 m^3 were delayed due to lack of prepared equipment. Only after 35 h of the accident, the tanker was surrounded by booms. While the weather was favorable, the chosen methods were ISB and to a very limited extent - use of dispersants. Thus, about 100 t were burned with 2 t residue generation, being 98% efficient. Very small part was dispersed from an aircraft. The third day started a heavy storm, which lasted for two days. After the mousse formation, the only option to remove oil from water was via the mechanical methods. In total, about 11,000 people were involved in the operations, 85 units of air fleet, and more than 1,400 of various ships. In the area, it is common to have high tides. As a result, it has had a negative influence towards polluting the closest shores. The statistics of this ecological disaster says that 370,000 birds, 200 seals and countless number of fish were deadly intoxicated. Industrial catch of fish in the area was halted. (Vorobiev et al. 2005; WWF 2011)

“box[Example of near Arctic oil spill event, Alaska, USA] ends”

This chapter provides a general overview of the oil spill response methods that can be used in the Arctic marine environment. The main contribution is to group all relevant wide-spread data into one single structured manuscript: description, key technical parameters and environmental limitations. Discussion of all included sections is based on the latest publications in the field. The presented data is provided to show a range of applicability of major oil spill response solutions **at sea** rather than recommending one or another method for certain marine conditions of the Arctic Ocean. Bioremediation along with supportive OSR tools for monitoring, remote sensing and contingency planning are not included in the discussion due to the scope of the work.

The rest of this chapter is organized as follows. The first three sections focus on primary oil spill response methods. Sect. 11.2 presents in situ burning (ISB). Sect. 11.3 examines mechanical oil spill response. Sect. 11.4 describes use of dispersants. Each section starts with a method overview. Then environmental challenges and technological limitation are demonstrated. In Sect. 11.5, secondary physical method is briefly mentioned, as a subsequent clean-up measure of primary OSR.

11.2 IN SITU BURNING OIL SPILL RESPONSE

11.2.1 Overview of in situ burning

Brief description. The main thermal method, known worldwide since 1970s, is in situ burning (ISB) (Gelderen et al. 2015; McLeod and McLeod 1972). The basic concept is that oil is burnt locally under professional control and supervision, in the place where it was accidentally spilled. Almost no further transportation of recovered oil is organized. The exception is only residue materials after the controlled burn, which are to be collected if feasible. ISB is primarily considered for situations when oil is trapped surrounded by ice. However, the method is only applicable if the oil has enough thickness to be ignited. (Michel et al. 2005; Buist et al. 2013)

Examples of equipment. In order to control the process and ensure that oil has reached the required thickness for ISB, oil slick is contained in one location. This is achieved either by means of ice sheets or fire-resistant booms: steel, ceramic, fiber-based, water-cooled or with stainless steel hemispheres. (Al-Majed et al. 2012) Oftentimes, response can be organized only with aerial means of transport, sent remotely from the shore. This is the case, when oil is naturally contained in ice. (API 2016 and 2017; ART 2012; Buist et al. 2013; Fritt-Rasmussen et al. 2012) The response is conducted with igniters (e.g. handheld type or "helitorch") and ignition systems. When oil slick requires artificial containment, fireproof booms or herding agents are applied. Sometimes, promoters, such as diesel, gelled gasoline, gelled kerosene cubes, and reactive chemical compounds are used to improve ignition of the slick and flame spreading. For installing the booms two towing vessels can be employed; for spotting the spill visually, igniting and burn monitoring, aircrafts may be also utilized. Oil removal is done by igniting it with a torch: be it from helicopter, sea vessel or other suitable way. The flame height is usually 1.5 times of the spill diameter. (API 2015; Buist et al. 2013; IPIECA 2016; Michel et al. 2005)

Efficiency of oil removal and required time. The effectiveness of ISB is a function of different parameters, such as climate, oil thickness, type, degree of emulsification, slick size, diameter, and other factors. However, the efficiency and elimination rates are usually maintained high (API 2017). About 0.5 to 4 mm of oil slick is burnt per minute. In ideal conditions, which are by EPPR 2017a with 75% of the time unlikely to happen, up to 300 tons (or 2,000 m^3) of oil can be burnt in an hour, and the removal efficiency is up to 98%. In operational conditions, these numbers are unachievable. (Allen 1988; API 2017; Buist et al. 2013; IPIECA 2016; Lampela 2011; Li et al. 2016; Shi et al. 2016; Walton and Jason 1999) Most in situ burns are completed within minutes to hours (API 2015 and 2016). The lighter the oil, the better it burns. In terms of its burning capacity, the order is: gasoline, diesel, jet fuel, heavy fuel oils, in a descending order (Table 11.1) (API 2016).

Sustainability of the method. ***Environmental aspect.*** The ISB method removes oil from water and minimizes the impact to the marine ecosystems, as all toxic petroleum-originated evaporating chemicals are eliminated during the combustion process. (API 2017; EPA 1999; IPIECA 2014 and 2016) Emitted heat is mostly - 97%, directed towards the sky. Only minor warmth is supplied back to the slick surface to create more hydrocarbon vapors and sustain the flame. The temperature of burning oil on water varies from 900 to 1,200^{o}C in the flame, whereas the slick temperature on its upper oil layers is about 350 to 500^{o}C. The oil beneath it is close to the temperature of water and the environment: water at water-oil interface is never more than 100^{o}C, heat exchange between the liquids hardly happens due to insulating properties of the oil layer. (API 2015; Walton and Jason 1999) The only substance that is left after the operations is burn residue (API 2016). The residue cannot be burnt or gasified and is transported by sea currents and tides at sea. This left-over corresponds to 2 to 15% of oil slick total volume. For lighter oils, it is 1 mm thick slick spread on surface, for heavier oils – up to 5 mm thick. For a set of 100 crude oils, only half of oils a leave residue, which would float on the surface; for the other half – the residue would sink. (API 2016) It is a very viscous, dense and biologically unavailable by-product of ISB. It is composed of semi-burned oil, without volatiles and with presence of precipitated soot (IPIECA 2016). The residue recovery is a challenging operation in the Arctic conditions. As a negative impact to marine life, it affects benthic and coastal ecosystems by its physicochemical contamination. This can cause harmful effects to coastal wildlife due to direct physical contact, resulting possibly in coating and ingestion. The residue is likely to persist in the environment for long periods of time and end up stranding on shore. However, all toxic impacts are rather localized, sparse and have small surface damage (Al-Majed et al. 2012; ART 2012; API 2016) Burn residue can be collected from water via use of vacuum suction systems, subsea pumps, skimmers, sorbents or manual means – shovels, buckets, nets. (API 2015; IPIECA 2016)

Otherwise, waste management depends on ice situation. If oil is naturally trapped in ice, less waste is generated. If oil is being contained by a fire boom, the boom gets dirty and further treatment is required. In ice free water and boom use, an OSR vessel or two are also involved in direct contact with the slick. So, further cleaning of the ship body is recommended. (IPIECA 2014) Overall, waste management aspect is less in scale of an issue in comparison with the mechanical method. In mechanical OSR, the scale of employed logistics and waste strategies can be overwhelming due to liquid oily waste to be collected, stored and transported. (ART 2012; IPIECA 2014).

Social aspect. The effects to the environment and human health are proved to be minor and local. Moreover, they are carefully monitored. In all ISB operations: weather patterns, proximity to wildlife and human population centers are obligatorily taken into account (API 2017). Health concerns are possible only, when there is a direct contact between people and the smoke plume. This can only occur, when people are unequipped with personal protective gears and the plume lies at sea level in calm weather conditions. (IPIECA 2016) Emissions level is connected with the type of oil or petroleum product, which is being ignited. The smoke produced is predominantly composed of simple molecules of carbon dioxide (73%) and water (12%). Remaining 15% are mostly particulates of soot, with minor content of carbon monoxide, sulfur dioxide, nitrogen oxides, polyaromatic hydrocarbons, and others. (API 2015; API 2017; Buist et al. 2013; IPIECA 2014)

Economic aspect. ISB may have low level of expenses as it does not require sophisticated equipment. The only constraint is a requirement for specialized booms that has a short life, and chemical herders. Personnel involvement can be low, and ISB implementation is rather fast. (ART 2012; Buist et al. 2013; Fritt-Rasmussen et al. 2012; IPIECA 2016) It is usually followed by dispersant use and mechanical recovery, as second and third places (Doshi et al. 2018). An estimated cost of organizing ISB response of 1 ton of oil offshore is about 2700 euros (Li et al. 2016).

11.2.2Environmental challenges for in situ burning

Ambient temperature. The International Association of Oil and Gas Producers states that the lower limits that ISB can be applied are 0 °C of water, and -11 °C of air. Extremely low temperatures add to work expenses, as adjustments may need to be made to the duration of work shifts, and heating systems may also be required. (IPIECA 2016)

Ice in water. Most of existing OSR methods are low efficient in ice conditions, since they were initially developed for open water (Vorobiev et al. 2005). In Arctic conditions, ice coverage over water surface varies from 0 to 100%. By type, it is from seasonal to multi-year ice, with additional types. For ISB, ice effects are demonstrated in Fig. 11.1 (ART 2012).

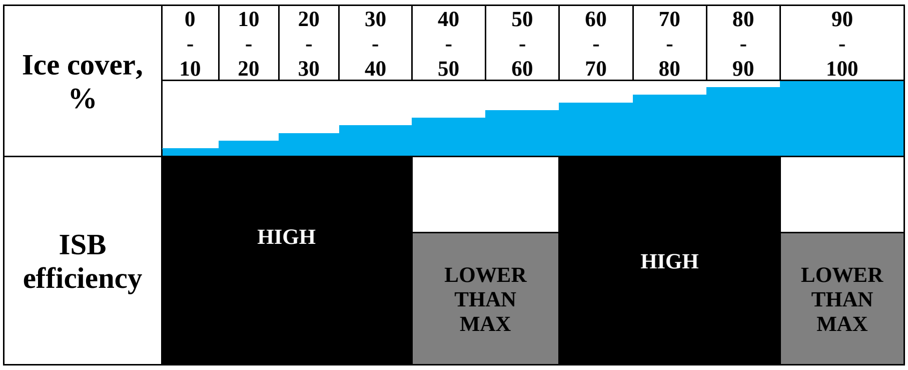


Fig. 11.1 Effects of ice cover to ISB

Scenario 1 is when the coverage is from 0 to 40%. These conditions favor OSR works, since ice can be managed by responders: e.g. fire-proof booms and herders can be used in operations. The ISB efficiency is rather high, and oil removal is full on. Scenario 2 is ice coverage of 40 to 60%, and from 90 to 100%. Responding to oil spill becomes harder and the efficiency is lower than theoretical - down to 60%. It happens due to ice physical obstacles, possible boom failures and oil weathering processes. Scenario 3 is when water surface is covered 60 to 90%, or natural containment conditions. In this case ice plays a supportive role in OSR operations by containing the oil in its trap and dampening wave influence. No booms are required. Ice contains the oil and the burning process responding with unique changes in its geometrical appearance due to mass and hear transfer (Farmahini Farahani et al. 2019). The efficiency is as high as in open water. (ART 2012; API 2015; IPIECA 2016)

As seen from above discussions, ice can both inhibit and support oil spill response. Natural containment conditions, 60 to 90% ice cover, prevent oil spreading processes at all or slow it down considerably. When the oil slick is in one place, oil thickness sustains itself in a sufficient condition much better. The oil is preserved well, while other weathering processes are also inhibited: for instance, emulsification, evaporation and biodegradation. The last two are delayed due to influence of low temperatures together with lack of solar radiation in winter (Vergeynst et al. 2018). The speed of oil breakdown processes is lowered. There are negligible effects from tidal current activities. These external conditions suit as an environment for ISB. Window of opportunity stays open much longer than in warmer latitudes. (Al-Majed et al. 2012; API 2016; Fritt-Rasmussen and Brandvik 2011) ISB is applicable in ice-infested waters - almost all conditions, where other OSR methods, such as mechanical and chemical are limited (Buist et al. 2013; Fritt-Rasmussen et al. 2012).

Mixed with snow on top of ice blocks, oil first needs to be collected in a cone pile. There is a need for a free pool of oil. Once organized this way, it may be ignited and burnt. If little oil volume is spilt on the snow, comprising up 3 to 4% of its volume, then fire starters, including diesel fuel or gelled gasoline, should be added to ignite the slick successfully and support combustion, removing up to 90% of the oil. The window of opportunity for such incidents extends to two weeks. (ART 2012; API 2017)

Wind influence. Calm water is an important condition of the environment for successful application of ISB. If the wind is stronger than 10-12 m/s, then ignition is not possible even with 10 mm oil slick thickness and absence of waves (Buist et al. 2013). This occurs due to lack of eligible inflammable vapour concentration, absence of which cannot support the combustion. The upper limit of bearable evaporation loss stays at the level of about 30%, depending however on oil types (Al-Majed et al. 2012; ART 2012; Buist et al. 2013; Michel et al. 2005; Walton and Jason 1999) When ignited, the burning process can be sustained with winds below 18 m/s (API 2016). However, winds of this strength can have negative influence on fire safety for ISB operators, taking into account the fact that the fire and the smoke spread downwind along the slick. The wind speed is also important for the smoke plume. It requires certain atmospheric turbulence conditions for its successful aerial dissolution. The speed cannot be too high or too low. Calm winds may enable formation of smoke close to the water surface, which can endanger involved personnel. Thus, wind behavior forecasts are crucial for ISB: from the start to the end, especially in the Arctic, where storms are possible. (API 2015; IPIECA 2016)

Wave turbulence. High wave activity makes the method inefficient. With currents more than 0.5 m/s as well as wave height above 90-120 cm for wind-based waves, and 300 cm for swells, ISB is not recommended, as an OSR option. All these parameters are influential on fire boom holding capacity. If it fails to contain and hold oil in one place, OSR operations will not succeed. (ART 2012; API 2015; IPIECA 2016; Michel et al. 2005)

Light effect. During the Polar Night period in the Arctic region, oil spill response using ISB can be still applicable. It can be realized safely and efficiently at night but only in cases when: vessel traffic is far from the accident site and no booms are applied. (IPIECA 2016) As for solar radiation for ISB, it affects the smoke removal from the place of operation. The solar energy enables thermal air mass movement so that warmer air rises in relation to colder one, taking with it part of the smoke. (API 2015) Considering solar radiation influence on the oil, photooxidation is a process, which is dependent on the amount of UV. It plays an important role in breaking down hydrocarbon molecules, in particular (polycyclic aromatic compounds) PACs. Another effect of photooxidation is the generation of emulsion stabilizing components that may enhance the formation of stable emulsion.

Salinity. Salinity does not decrease or enhance the burning ability of oil, but only influences its buoyancy. Water of more salty seas is denser and, hence, it makes oil more buoyant. In more sweet seas with brackish water, oil floating ability can be much less due to difference in densities of both substances. An example of brackish sea water is the southern part of the Kara Sea, a salty one – the Barents Sea. Difference between brackish and saline water is defined by the following border numbers: water, where number of salt parts per thousand (ppt) is less than 35, is considered brackish; whereas water with ppt higher than 35 – saline. Note that water with ppt below 0.5 is freshwater, but this condition is not possible at Arctic seas. (NWE 2017)

Precipitation and visibility. Frequent precipitation storms and rapid weather changes is something very common for the Arctic. All sort of precipitations is possible: snow, rain, drizzle, fog, and combinations of those. Rain in any form can decrease the efficiency of ISB. The largest effect is inhibition of hydrocarbon vapor formation during oil burning. (API 2015; IPIECA 2016) For effective oil spill response, it is crucial to observe, where the spill is to be able to contain it in a boom, and to conduct vessel operations around it for further ISB. Good visibility is not only important for people's health and safety, but also for steering vessels and aircrafts, supporting the oil abatement operations. The horizontal visibility should be at least 4 km for operational flying, and 300 m for site works. (Al-Majed et al. 2012; Potter et al. 2012; Walton and Jason 1999).

11.2.3Technological limitations of in situ burning

Oil type and its viscosity. Only hydrocarbon vapors are ignitable and burnable. Hence, oil types, which become vaporized easier, or have higher vapor pressure, are easier to ignite. They are mostly lighter petroleum products: low to medium viscose with American Petroleum Institute (API) gravity more than 32° or less than 860 kg/m^3 density. (Michel et al. 2005) Too light oils, such as gasoline with API more than 50°, are however unsafe to burn. Same applies to too heavy types, for example crude oil or HFO with API less than 20°, or density more than 930 kg/m^3, which are hard to ignite. (API 2015; API 2017; Federici and Mintz 2014; Michel et al. 2005) Below is Table 11.1 with several examples of heavy, medium and light oils and their flammability properties (API 2016; IPIECA 2016; POLARIS 2013).

Table 11.1 Flammability and ISB efficiency of different types of petroleum products and crude oils

Oil type	Oil product	API gravity, °	Flammability
Light ($\rho < 870$ kg/m^3)	Gasoline	65	very high
	Diesel fuel	40	high
	Light crude	30	high
Medium ($\rho = 870 \div 920$ kg/m^3)	Medium crude	25	moderate
	Heavy crude	20	moderate
Heavy ($\rho > 920$ kg/m^3)	Heavy fuel oil	19	moderate
	Diluted bitumen	18	moderate
	Bitumen	8	low
	Sinking oils	7	very low

The thicker, denser, and more viscose the oil, or in other words heavier, the less combustible it is. The lighter the oil – less dense, less viscose, more volatile; the more ignitable it is. Examples can be two different oil products from the table above: diesel fuel and bitumen. Diesel fuel has low density and high flammability, whereas heavy bitumen is hardly ignitable.

Thickness of the film. Thickness of oil slick, as another ISB limiting parameter, is crucial and primary for ignition and combustion maintenance. The recommended thickness is between 1 to 10 mm, depending on oil type – most importantly, its viscosity. Lighter, less viscose oils have much stronger ability to evaporate and create required inflammable hydrocarbon vapors (compared to the thicker heavier oils), and can be ignited already with 1 mm layer. Heavy types and, especially, non-fresh, emulsified slicks are to be fired at thicknesses from 4 up to 10 mm. (ART 2012; API 2015; API 2017) The most common recommended minimal ignitable thickness is from 2 to 3 mm, preferably 5 mm. Herders may be used to increase slick thickness. But it is only possible in calm conditions, with wind speeds below 1.5 m/s and negligible wave activity. (IPIECA 2016; Vorobiev et al. 2005)

Water content in oil. Due to the influence of waves, currents and winds - weathering processes, small drops of water become incorporated in oil. The percentage of one into the other may vary, forming water-in-oil emulsions. As a practical matter, oil slick water content in the form of emulsion should be lower than 20-25% (Al-Majed et al. 2012; Buist et al. 2013; IPIECA 2016). Higher water intakes make oil too foamy and stable. It can create so-called “chocolate mousse”, super emulsion. It is hard to ignite, tends to burn slowly and its fire is easy to extinguish. Another drawback is that burning these emulsions produces more burn residues. All these make ISB process inefficient with highly water saturated emulsions. The exception may take place with some crude oils: e.g. paraffinic ones. They can be treated with in situ burning with a higher percentage of water. (ART 2012; API 2015; Michel et al. 2005) Cases of 60 to 80% water intake are known, 90% are also possible. These emulsions are formed fast and stay stable. In order to ignite such substances, emulsion breaking is needed. This can be done via water removal through boiling or using specially designed chemicals. Both options work and help to create a layer of unemulsified oil covering the emulsified oil slick. Only after these measures, fire-starting becomes possible. (Walton and Jason 1999) Table 11.2 below shows the negative effects of water emulsification of the oil towards ISB operations.

Table 11.2 Effect of water content in the oil slick to ISB

Water content in oil, %	Effect on ISB efficiency
< 12.5	low
12.5÷25	medium
> 25	high

The higher the water content is in oil, the harder it is to ignite it. For example, when the water content is above 25% accelerants may be needed. Accelerants include diesel fuel or gelled gasoline (API 2015; Walton and Jason 1999) Physical transformation of oil in emulsion is also important for fire booms. Experiences from field operations have shown that, if the emulsion has a viscosity below 1,000 mPas, there is a risk for larger rate of boom leakage compared to more viscous emulsions or oils. This is important to take into account, when booming low-viscosity oils, especially in relation to towing speeds. Same applies to mechanical OSR – its boom applications. (ART 2015; Vadla and Sörheim 2013)

Specific parameter - fire safety requirements. Special country-dependent approvals are required in order to be allowed to conduct ISB operations at sea nearby population settlements. It is on state, federal and local levels. Burn plans with specific information about the site, weather forecasts, oil type, fire safety and various other organizational matters have to be presented: logistics, smoke plume behavior forecasts, air monitoring, safety distances downwind for vessels and personnel, OSR vessel orientation in relation to the smoke, communication practices, and others. Besides, ISB training for operators should be in place before actual oil spill response. (API 2015; API 2017) Factors as distance from populated areas, nature reserves and vessel traffic, movement trajectories of the smoke, and proximity of other possible combustibles are noted. As regards safe distances downwind from ISB operations, they vary depending on wind patterns and intensity. Higher winds make safe distances larger, whereas low winds decrease them. (EPA 1999; IPIECA 2016) The ISB site must be at least 1-2 km away from closest settlements (Michel et al. 2005).

Window of opportunity. Enclosure of oil between ice increases the window of opportunity (WOP). On average, WOP is 24-48 h, which applies to all OSR methods (Vorobiev et al. 2005). Due to ice-trap conditions, with at least 70% of ice, and lower evaporation in the Arctic the WOP may be extended up to 72 h and more. For heavy oils WOP is shorter, for light and medium ones – it can be longer. (EPPR 2015; Nordvik 1995; Fritt-Rasmussen and Brandvik 2011; Singsaas and Lewis 2011). The upper tested limit is documented to be more than 30 days under very calm conditions with no emulsification taking place and a high film thickness, after which the successful ignition and combustion were executed. (API 2016; Dickins 2015). Thus, the limit for successful oil spill response is broader in ice-infested waters than in open sea conditions. (U.S. Dept. of Commerce 2013).
There are several physical and chemical processes related to the spilled oil, as a result shortening the WOP: evaporation of volatile hydrocarbon fractions; dispersion of oil into droplets; oxidation of the slick edges resulting tar balls formation; emulsification; biodegradation; and evaporation. When more than 25-30% of all volatile components have evaporated, no ignition is possible (IPIECA 2016). The fresher the oil is, the more successful and efficient combustion process becomes. No fire promoters, no booms to concentrate oil are required in this case. (EPA 1999)

Distance from the shore. Distance from the mainland can be a challenge in terms of delivering equipment and responders at place. However, open water conditions and far safe distance from the shore are a must for ISB operations. (API 2015) Since this method require less arrangements than with mechanical OSR in terms of logistics and infrastructure, especially, when oil is naturally contained in ice, operations can be performed in very remote areas of the Arctic sub-regions (ART 2012). Safe distance from nearby communities and sensitive industrial objects is a crucial factor, since the amount of air pollutants in the smoke, including particulates, carbon monoxide, sulphur dioxide and polycyclic aromatic compounds can be dangerous for human health. (Al-Majed et al. 2012). Closest settlements should be no nearer than 1-2 km away from the ISB site, with common cases for distance restriction of 8 km (Michel et al. 2005). This is however a country-dependent decision.

11.3 MECHANICAL OIL SPILL RESPONSE

11.3.1 Overview of mechanical response

Brief description. The main constituent tasks in mechanical recovery are to localize and concentrate the spill via floating structures (booms) or natural containment (e.g. by ice); and to pump recovered oil from the sea surface onboard of a vessel, where the oil is temporally stored for further disposal. The first task is conducted via boom application, while the other is done via skimmers. (JIP 2014; Wilkinson et al. 2017) Mechanical OSR is a widely accepted maritime option in use for more than 50 years (Al-Majed et al. 2012; Federici and Mintz 2014). Despite the fact that oil recovery usually requires profound planning of personnel work and utilization of multiple pieces of equipment, with operations executed from a special response vessels as well as fishing ones (ART 2015); according to Rambøll Barents 2010 and ART 2012, mechanical clean-up is considered as the first OSR option among local authorities of all eight Arctic states, namely: USA, Canada, Denmark, Iceland, Norway, Sweden, Finland, and Russia. Due to fast oil spreading and breakage into separate slicks during mechanical oil spill response, the main operational strategy is to work as close as possible to the spill source. Unlike ISB, it does not require any approval on state, federal and local levels. (API 2017; DNV 2015) Most tactics of mechanical OSR are designed to feed oil to the skimmer. However, there are variations of skimming systems: e.g. two vessels with boom, single vessel with outrigger, three vessels of opportunity with boom, single vessel in ice. (EPPR 2017a).

Examples of response equipment. ***Booms***, as an OSR support tool, may be inflated by air or designed with an embedded flotation material; closely attached to the vessel, towed by it distantly or set in passive and self-sufficient drift (ART 2015; STAR 2014b). They are made from durable fabrics, which can withstand wind, waves, acids, alkalis, oil and oil products, which they do not adsorb. The symmetric configuration of every piece is usually designed so that the direction of their towing is insignificant and they can be mutually attached to each other by locks forming a long line, up to 500-600 m, creating a swath width of 100 m, with maximum 200 m. The time required for the boom installation is usually counted as 60 min for preparation works and about 30 min for actual works of loading it on the water surface (Ramazanov 2015). There are more than 150 types of boom systems, currently available on the market in application to the Arctic Ocean climate conditions. However, no matter what type it is, the main task of the boom is to: contain oil and stop its spreading at sea; prevent reaching it the coastline of islands or the mainland; or set a certain direction of oil slick movement. As it occurs under external environmental conditions, spilt oil quickly spreads over the marine surface, forms a thin layer and loses its original “fresh” oil spill thickness. Thus, booms installed around the oil slick also serve as an oil containment pool, which concentrates oil to the thickness values required for OSR. This is especially important within first 72 h after the spill incident. Usually, there are three configurations for oil collection on water: U-, V-, and J-types. Apart from common vessel organized installations, booms can be also delivered by helicopters (Al-Majed et al. 2012; ART 2012; ART 2015; Parshentsev 2006; Vorobiev et al. 2005) It is important to consider that booms may be towed by a vessel only at certain speeds: 1 knot, which is equivalent of about 1.85 km per hour (ART 2015; Singsaas and Lewis 2011). This is rather slow and comprises near twice as slow as the average pace of human walking. According to ART 2015 and Vorobiev et al. 2005 the fastest solutions allow the upper maximum speed level of 3 knots. Otherwise, with a higher speed, oil spill leakage down under out of the boom takes place. The leakage not only depends on the towing speed, but also environmental hydrodynamic conditions (wave pattern, wind speed, water currents) and boom parameters (buoyance to weight ratio, heave and roll response, and initial draft). The most common five leakage reasons in booms are related to oil entrainment, drainage, critical accumulation, boom submergence, and splash-over (Li et al. 2016)

Skimmers, the major equipment in mechanical oil recovery at sea, is a hydraulically powered mechanism equipped with rotational flat material structure, designed to adsorb viscose oil substance on its surface without addition of chemical agents. The main principle of work is the difference between physical properties of oil and water, which distinguish with density and molecular coupling with surface of various materials (Vorobiev et al. 2005). Historically, skimmers were engineered for open water surfaces (ART 2012). The latest innovation advances in the design are related to cold and icy environmental conditions, such as heating system introduction against frost formation; and better absorbing surfaces of the rotating oil collectors. Otherwise, no revolutionary advances in the basic skimming technology are expected. (Al-Majed *et al*. 2012; Federici and Mintz 2014; STAR 2014a; ART 2015) As regards technical parameters of skimmers, there are two crucial aspects to consider: pace of rotation and sorption capacity of the skimming surface. It is true for most of oil types floating on the water surface and included in the skimmer design. However, there is an upper limit, after crossing which the oil does not have enough time to stick to the brush fibers, no matter how strong its oleophilic properties are. (Al-Majed et al. 2012; Federici and Mintz 2014) The following four skimmer types are presently produced and professionally applied in operation: vacuum, weir, mechanical and oleophilic. Vacuum and weir skimmers have a drawback of intaking more water than oil but are still utilized to collect light and medium viscosity oils via vacuum sucking mechanism or gravity forces phenomenon to the recovery tank. The skimmer is applicable for very viscous heavy oil types and therefore equipped with a conveyor belt to transport it in special buckets to the storage tank. All these types - vacuum, weir and mechanical skimmers become clogged with ice particles and fail to operate well in the cold sea conditions: extremely low temperatures and freezing. The most used and efficient skimmers type in Arctic seas is oleophilic. It has either a drum, a belt, a brush, a rope mop or a disc in its structure, which rotates in contact with the upper layer of the water surface. This rotor absorbs oil on its surface and transports it for further treatment. Usually, light and medium oil types may be collected with this skimmer. (ART 2012; Li et al. 2016; Wilkinson et al. 2017) Brush and drum brush designs of this skimmer have the highest perspective in terms of application in the ice-infested waters. (Singsaas et al. 2011). They have the largest oil sorbing capacity due to the material, organized with millions of brush bristles to provide massive surface contact area; which are capable to collect oil of any viscosity. They can be self-propelled, mounted, portable and towable. Those attached to the vessel have higher capacity and resistance towards the sea ice, with examples of skimmer working surface area of 16 m along the ship stern (Lampela 2011). As regards models designed for use in the ice environment: “Polar Bear”, 60 m^3/h, with custom weir and brush drum; “Polaris”, 70 m^3/h, with brush drum; and “LRB 150”, 90 m^3/h, with oleophilic brush drum, respectively by Desmi, Framo and Lamor manufactures are skimmers particularly developed for the Arctic harsh marine conditions. Ice management and low temperature preparedness are something distinguishable, which is included in the skimmers design, and support successful mechanical oil abatement operations (ART 2015). “Polar Bear” and “Polaris” can operate in ice cover of 70%; whereas “LRB 150” can withstand 90% of ice in the working zone. (Federici and Mintz 2014; Rytkonen et al. 2015; Singsaas et al. 2008 and 2010).

Storage tanks is another component of mechanical oil recovery, used for temporary storage of recovered oil (ART 2015). Storage tanks can be of two types: independent on-water storage and onboard vessel storage. The on-water storage (barges, bladders) is only applicable in open water, without any ice present. The onboard storage is usually installed on vessel deck or below it. As a practical rule, it should be twice as large as the effective daily recovery capacity of the skimmer, should have strong pumping system, especially if handling heavy oils, and storage tank heating devices since the cold temperature may influence the oil pumping properties. (STAR 2014a)

Weir as well as vacuum skimmers, as mentioned in this section above, have a drawback of taking excessive amount of water along with collected oil – therefore the storage tank fills its capacity faster, compared to oleophilic skimmer, with declared free water content of 2% (ART 2012; LAMOR 2015). To solve the problem of abundant amount of recovered sea water, a temporary storage system with water separation process, or decanting, is often introduced (ART 2012). This measure maximizes the tank storing capacity by removing recovered water (ART 2015). Depending on the calculations and the state of oil on the water surface, the storage tanks may be of different size. If there is an example case of “chocolate mousse”, with 10% oil and 90% water in it, and the incident report says that oil spills is of 1,000 t, the size of the storage tank should be at least 10,000 t capacity. In Arctic conditions, these tanks are sometimes heated to make it flow easier. Usually, the heaters maintain 90°C in the tank. (Vorobiev et al. 2005)

Waste handling and disposal of the recovered oil is required to complete the mechanical oil spill response. It is usually done via a burning facility either onshore or sending to a refinery. Oftentimes, vessel based incineration facilities, mounted on specially equipped places, is the preferred option. Currently, there are three main types of the burners in ascending order according to their capacity: rotary cup burner – hundreds of barrels of oil per day (BOPD), augmented burner – less than 10,000 BOPD, pneumatic flare – 10,000 and more BOPD. Rotary cup burner is rather light and can be used both onboard and inland. The system's main part is the rotating fan, which blows the air in the cup and atomizes oil to be sent to the combustor. Augmented burner is a good option due to its simplicity in design. The major disadvantage is that it has only small-scale application capacity. This burner type refers to chimney-style floating incinerator, which has an aerator to support the combustion process. The last burner type, with commonly used prototypes in oil and gas industry for well testing, pneumatic flare, requires additional equipment with pressurized air to atomize the recovered oil in the system but can be also mounted onboard. This option is recommended for large-scale oil spills. (ART 2015)

Response platforms with built in equipment and capacity to transport trained personnel, as the last component, but surely not least is usually included in mechanical OSR operations. Depending on the water conditions at sea and harshness of the marine environment, the response vessels may be chosen differently: for open water – regular response ships, for thick ice seas - double hull ice-strengthened vessels of ice breaker type. In addition, there should be aerial support for monitoring and guiding the work, small multipurpose vessels and various OSR related equipment: sorbent spreaders, dispersant sprinklers, pumps, pipes, oil squeezing devices for sorbents, temporary storage tanks or sacks, incinerators, chain saws, personal protection equipment and other materials. (ART 2015; Lampela 2011; Slaughter et al. 2017; Vorobiev et al. 2005)

Efficiency of oil removal and required time. Claimed oil recovery efficiencies in ideal conditions reach as high as 80 to 95% (Li et al. 2016). In operational practice, the reported equipment efficiency ranges from 10 to 30% depending on the environmental conditions. In its turn, 30% is often an optimistic forecast; 5-15% is an actual down to earth expectation. (API 2017; EPPR 1998; Vorobiev et al. 2005). Nevertheless, mechanical OSR in icy marine environment is possible. (ART 2015; Li et al. 2016; Singsaas et al. 2011) The method is time consuming. The drawback here is the width of the skimmer and its small oil surface catch – hence, low skimmer capacity and low efficiency to collect oil. It is possible to solve this problem, by attaching the boom to it and increasing its grasp width, but at the same time slowing down the speed of work to 1 to 3 knots, or about 2 to 6 km per hour. (ART 2015; Federici 2014; JIP 2014; Slaughter et al. 2017; Vorobiev et al. 2005) Operations can be a matter of days to months to fully complete oil recovery. Oftentimes, oil spreads faster than it is recovered. (API 2015; BP 2018; Slaughter et al. 2017; Wilkinson et al. 2017)

Sustainability of the method. *Environmental aspect.* With application of this OSR, oil is mechanically and permanently removed from the surface of the marine environment. In comparison with ISB, mechanical OSR does not add visibly to air pollution on site, since incineration mostly happens onshore. Same is applicable to water contamination. (Al-Majed et al. 2012) However, minor impacts are possible due to application of the response vessels and equipment. Increased noise pollution can be one of characteristic mechanical OSR impacts. Unrecovered oil can also cause substantial marine contamination. (JIP 2014) Recovered oil, often mixed with seawater and ice, is sent further for downstream separation and further treatment. This represents a challenge in the Arctic conditions: large amount of the mixture needs to be temporarily stored and disposed afterwards. Transporting the mixture onboard, storing it in tanks supplied with heating, and disposing it then is energy intensive. It also requires onshore facilities to melt, separate and utilize oil, which are limited in these geographical latitudes. (Al-Majed et al. 2012; Lampela 2011; Slaughter et al. 2017; Wenning at al. 2018; Wilkinson et al. 2017)

Social aspect. Personnel health and safety issues is number one aspect with mechanical oil recovery, since oil spill operations are organized in the harsh Arctic ambient conditions and can last for weeks. (DNV 2015) Among possible hazards are physical – cold stress, snow blindness due to light, safety accidents due to darkness and icing; chemical – exposures to oil via inhalation or dermal contact; biological – contact with polar bears or walruses; and others. (EPPR 2017b)

Economic aspect. In general, mechanical method, as a whole technique, requires substantially large economic expenses, especially, to carry personnel and ship the equipment, when reaching far distant areas. In general, mechanical recovery of oil from the sea surface is usually an event, which requires profound planning of personnel work and utilization of multi-component set of equipment, with operations executed from a special response vessel (ART 2015). The availability of the logistics in the Arctic should be well-thought for this OSR method: food, fuel, accommodation, storage tanks and burning facilities either onboard or onshore for final utilization of recovered oil and produced waste management system. (ART 2015; Federici and Mintz 2014; STAR 2014a; Wenning at al. 2018) In addition to this, there should be response vessels with built-in equipment and capacity to transport trained personnel. Depending on the water conditions at sea and harshness of the marine environment, the vessels may be chosen differently: for open water – regular response ships, for thick ice seas - double hull ice-strengthened vessels of ice breaker type. Besides, there should be aerial support for monitoring and guiding the work, small multipurpose vessels and various OSR related equipment: sorbent spreaders, dispersant sprinklers, pumps, pipes, oil squeezing devices for sorbents, temporary storage tanks or sacks, incinerators, chain saws, personal protection equipment and other materials. (ART 2015; Lampela 2011; Vorobiev et al. 2005) An estimated cost of recovering 1 ton of oil from water is 8500 euros (Li et al. 2016).

11.3.2Environmental challenges for mechanical response

Ambient temperature. For mechanical OSR method, low temperatures are an inhibiting factor, especially, for oil skimming and pumping. As any technical mechanism, the skimmer has certain limits of its working environment, particularly in icy-cold temperatures. To avoid freezing of its moving parts due to seawater spray, provide allowed operational temperature for collecting and transporting viscous oil, and maintain its declared efficiency; circulative heating system via hot pipe water supply should be constantly in operation. (ART 2015; Singsaas and Lewis 2011) Dealing with heavy oils also become challenging. They solidify in freezing conditions because of increased viscosity. Collecting them with skimmers and transporting with pumps become difficult and, in most cases, inapplicable. Instead, nets and other suitable devices are utilized for oil recovery and appropriate solutions are found for storage and transfer. (DNV 2015; Wilkinson et al. 2017) Recommended operational temperature for mechanical oil spill response is within the range of -5 to -18^{o}C (EPPR 2017a).

Ice in water. For mechanical oil recovery, starting already at 11% ice coverage boom functionality and overall operations are jeopardized. Some of ice is captured in the boom site opposite to the vessel towing direction. Booms can be teared, strained, stretched and damaged to withhold the spilled oil. Nevertheless, booms are applicable with ice conditions up to 30%. (DNV 2015; Wilkinson et al. 2017) For mechanical recovery, ice effects are demonstrated in Fig. 11.2:

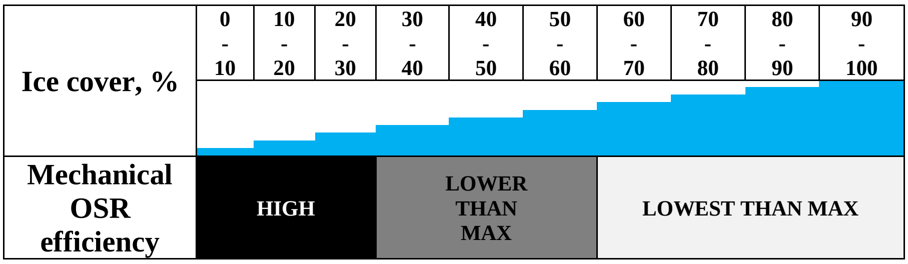


Fig. 11.2 Effects of ice cover to mechanical recovery

Ice coverage with more than 30% of total surface water area in the oil spill site is usually an obstacle for the boom installation. Independent booms lose their usability (Singsaas and Lewis 2011). In 30-60% ice-covered waters, boom systems with short attachment to the response vessel are applied. This construction has high maneuverability and strong mounting arm, which is convenient for OSR operations in icy waters. If the ice-free water surface comprises less than 40%, application of the boom is completely excluded. No artificial oil slick containment is possible. (DNV 2015; Potter et al. 2012; Økland 2000) In this case, ice naturally contains oil, decreasing turbulence influence from the waves, limits its spreading, forms walls for the oil pool and creates separate pockets of collected oil slicks. All these preserve oil for longer periods of time, making it possible to apply mechanical recovery long after oil spill happens. (ART 2012; ART 2015; JIP 2014; Wilkinson et al. 2017) For obvious reasons, the device effectiveness is lower in ice-covered waters compared to open water surface. Skimmers, as an OSR tool, in its turn also have its limitations in ice-infested waters. The most important aspect for mechanical clean-up is provision of the physical contact between the skimmer and the oil slick. Thereby, skimmer surface should be freed from interfering ice particles or blocks, otherwise the encounter rates are reduced. In this sense, several developments in the skimmer device features have been made to solve this problem. As one of the examples, an improved skimmer body may press ice blocks with a metallic screen-like structure, submerge the ice under the sea water level and, thus, reach the oil-skimmer surface contact. Another solution is built around ice processing, when some particles end up in the skimmer; where separation of oil from ice is automatically arranged (ART 2015). As one more limitation, presence of ice can significantly reduce the efficiency of mechanical OSR facilities and make it often ineffective. In comparison with ideal case open water conditions, ice-infested waters decrease applicability of the method essentially. (ART 2015) Starting already at 10% of the ice to free surface water ratio, which stand for a few drifting ice parts, skimmers lose their maximum oil recovery capacity (Dickins 2015). Up to 30% ice coverage regular open-water skimmers may be operated. In the ice range of 30-70%, specialized skimming equipment should be deployed. (DNV 2015) In addition, dealing with oil contaminated ice is a problem, which is an energy challenging task. Pumps may become clogged by ice that causes them to break down. Adapted pumps and heating systems for transport and storage are required, for example, heating coils. When separating oil from ice and melting it, only small amounts of ice are economically acceptable. (ART 2015; DNV 2015; Lampela 2011; STAR 2014a; Vorobiev et al. 2005)

Wind influence. Due to sea water droplets transferred after splashing with wind by air pumps, skimmers and booms undergo icing and accumulate frozen ice on its body. This causes booms to fail in maintaining its buoyancy. Wind can also move the boom and release it from anchor. Same applies to vessel and equipment stability. High winds provide unfavorable conditions for OSR operations. It is difficult to provide personnel safety, keep the vessels in correct position and towing speed, and rely on boom oil containing capacity and skimmers efficiency. (DNV 2015) When wind blows faster than 15 m/s in open water no mechanical recovery works are possible (BP 2018).

Wave turbulence. Mechanical OSR, as ISB, becomes inefficient in high wave activity. The more energy water have, the less efficient boom applicability becomes. Above 2-3 m wave height in open water and currents more than 0.5 m/s booms start to submerge, break and fail with oil spill containment. (API 2015; BP 2018; DNV 2015; Vorobiev et al. 2005)

Light effect. Unlike with ISB, daylight availability is usually a limitation for mechanical OSR. Light can affect working shifts of operating personnel, especially during times of the year with the lack of it – Polar nights. (BP 2018; DNV 2015; Vorobiev et al. 2005) However, in Norway, for example, the contingency plans include OSR operations in darkness with a reduction factor of 50%, provided that aerial remote sensing is available.

Salinity. Similarly to ISB, salinity affects the mechanical recovery process only by influencing oil buoyancy. Independent on spilled oil type, the oil is more buoyant in more saline sea water conditions in comparison with brackish waters. (NWE 2017)

Precipitation and visibility. Despite some advances in night vision equipment, visibility of about 1,800 m, approximately 1 nautical mile, is a limiting parameter for the operations. (BP 2018; Slaughter et al. 2017) Fog, low clouds, snow storms, darkness limit mechanical OSR operations significantly, including crew safety considerations (DNV 2015).

11.3.3Technological limitations of mechanical response

The functionality of the method, as also noticed with all other OSR methods, strictly depends on oil physical state and surrounding environmental and oceanographic conditions. It is of technical relevance in response skimmer operations to acquire data about oil slick volume, viscosity, thickness of the oil layer and its sea-conditioned temperature. (Al-Majed et al. 2012; Federici and Mintz 2014)

Oil type and its viscosity. The skimmer technology is effective with a wide variety of oil types, including strongly emulsified oils (API 2017). The only limitation is related to boom holding capacity, in similar way as in with fire-proof booms. Results from field operations with emulsions of a viscosity below 1,000 mPa·s have shown that a degree of boom leakage is higher compared to more viscous emulsions or oils. This is important to take into account: e.g. by reducing the towing speed with low-viscose oils to avoid too significant leakage. (ART 2015; Valda et al. 2013)

Thickness of the film. In mechanical oil recovery, the oil film thickness should be at least starting from the range of 1 to 2 mm and up to 10 mm, which is oftentimes reached by application of booms. If it is less than 1 mm for free drifting oils, oleophilic skimmers become inefficient. (API 2017; Vorobiev et al. 2005)

Water content in oil. With increased emulsification and weathering oil becomes significantly viscous (DNV 2015). When the state reaches characteristics of the “chocolate mousse” with viscosity more than 15,000-20,000 mPas, the only option to remove oil from water is via application of mechanical methods. As efficacy of the mechanically recovered oil in comparison to the amount of recoverable oil on the seas surface may be about 20%, it means only one fifth of the oil is to be collected. The rest four fifth is left in the marine environment to biodegrade naturally, possibly with some of the oil stranded onshore. (Vorobiev et al. 2005)

Specific parameter – storage tank capacity. Most skimmers intake more seawater than oil material: both free and emulsified sea water. Therefore, substantial capacities of storage facilities are needed. Once the storage tanks are full, they must be emptied onshore, unless burning facilities are applied (Slaughter et al. 2017). The round trip to offload the tanks and return them back to the site may be hours. In Arctic conditions, the tanks also require heating systems (API 2016 and 2017; DNV 2015). Free water separated and settled in the storage tanks can be drained off back into the booms.

Window of opportunity. Depending on ice situation, ambient conditions and oil physicochemical properties, WOP can be from 24 to more than 72 h: sometimes weeks. (EPPR 2015; Federici and Mintz 2014; Singsaas and Lewis 2011; Vorobiev et al. 2005)

Distance from the shore. One of the most crucial considerations during mechanical OSR is its pronounced logistics. The distance from the mainland should not be too large. Delivering and repairing the equipment and transport of the recovered oil is a challenge. Remote areas of the Arctic region require also availability of prepared personnel and equipment nearby an accident area. The operations are labor-intensive, thus, remoteness of the potential oil spill emergency site along the Arctic is a limiting factor. (API 2017; ART 2015; DNV 2015)

11.4 DISPERSANTS USE FOR OIL SPILL RESPONSE

11.4.1 Overview of dispersants use

Brief description. Dispersants, as the main chemical method agent, are sometimes considered as an alternative OSR option apart from in situ burning and the mechanical oil spill response options in the Arctic. Finland and Sweden avoid using them since they are forbidden due to poor environmental state of the Baltic Sea; whereas Denmark, Iceland, Norway, US and Russia allow application of dispersants after receiving special environmental permission from a local controlling authority. (Rambøll Barents 2010) The method became the most popular in the 1990s. Dispersants are stockpiled with equipment for their application by three out of five OSR centres of global coverage – Clean Caribbean Cooperative, East Asia Response Limited, and Oil Spill Response Limited. Over 70 oil spills in the last 30 years were combatted via dispersant treatment. (Vorobiev et al. 2005; Potter et al. 2012; Prince 2015)

As a chemical, dispersants are liquid substances - oily light to dark brown colour, with anionic and neutral surface-active agents and additives in a hydrocarbon solvent. Their purpose is to support oil separation into particles. The colloid system in the given case is oil, spilt as the oil slick, in water; where oil is initially the dispersed phase, and water is the dispersing medium. The surface-active agents, or surfactants, serve to lower the surface tension at the oil-water interface and dissolve the oil part of the system in 20 to 70 µm neutrally buoyant droplets. If their size is more than 100 µm, they resurface back to the water surface and form a slick again (EPPR 2015; Potter at al. 2012; Wilkinson et al. 2017). The small droplets spread through the water column, in the surface mixed layer. This is needed to break the oil film on the water surface in order to speed oil biodegradation and diffusion via turbulence action of marine currents and waves. Initial concentrations of dispersed oil droplets may be as high as 30-50 parts per million (ppm). However, after several hours, the oil concentration is lowered up to 1 ppm and less. This becomes available for dissolution and utilization, which is done by natural biological mechanisms, in particular, indigenous Arctic marine petroleum-fed bacteria (Dickins 2015). This is an effective method of natural oil spill clean-up, in action for millions of years. (Doshi et al. 2018; BP 2018; Potter et al. 2012; Prince 2015; Slaughter et al. 2017;

Vorobiev et al. 2005; Wegeberg et al. 2017) As recent studies proved, it also works in the Arctic environment (ART 2012).

Oftentimes, dispersants are applied in cases when environmentally prioritized areas are endangered. Special priority refers to the coastal areas, shorebirds and animal survival. For instance, in 1996, by responsible authorities of Wales, the decision was taken to apply dispersants promptly to avoid a 35 thousand ton oil spill reaching the shoreline. Even though in the short term, dispersants and correspondingly a large number of oil micro-droplets form a highly concentrated "cloud" of oil droplets in the water column, temporary toxic for marine species; immediate bacterial mobilization due to widely available petroleum feedstock, in the long term, functions appropriately to transform oil. Furthermore, since the interfacial area between oil and water has increased dramatically, other degrading processes, including dissolution, contribute to oil impact minimization. Usually, already after several days, first Arctic bacterial communities inhabit the droplets and start the degrading process. The time, which it would take to execute the same and relieve marine wildlife from the long-lasting negative impacts, if leaving the oil slick on the sea surface or if it reaches the shoreline, differs remarkably. As an example, oil-contaminated shore may stay affected for 10-15 years, whereas recovery of the water column at sea happens within weeks (Makhutov et al. 2016; Prince 2015). Some review articles mention half-lives of physical dispersion to be within one day, from 4 to 24 h (Li et al. 2016). The final evaluation of the environmental effect, for the Wales case, showed that this was the best possible solution, and is considered positively.

Examples of response equipment. The dispersants are usually easy to deploy and are sprayed via means of airplanes, helicopters and vessels; with rare cases of being injected subsea. The capability of different dispersant application platforms have different advantages and disadvantages depending on spill situations. For instance, airplanes have high spraying capacity, but are limited in terms of loading space, which causes long transit time between the dispersant loading stations and the place of accident. One part of dispersant volume treats up to 20-30 parts of oil. It can be easily used in a large scale, being a fast and economically feasible option, especially for remote areas. When spraying dispersants from the plane over at sea, documented consumption counts for about 50 liter per hectare (Prince 2015). Recommended dispersant viscosity for aerial application is more than 60 mPa·s (ExxonMobil 2014). One of advantages of the method is in preventing "chocolate mousse" formation – a state of oil which is hardly biodegradable and of high stability. (ART 2012; BP 2018; EPPR 2017b; Lampela 2011; Vorobiev et al. 2005) In subsea applications, dispersant-to-oil ratio (DOR) is 1 part per 100 (BP 2018; Slaughter et al. 2017).

Efficiency of oil removal and required time. The term "removal" in the case with dispersants is not applicable, since oil stays in the marine environment after the OSR approach (API 2015). The post-treatment and final oil spill elimination is directly linked to natural biodegradation processes (Potter et al. 2012). Thus, it makes sense to discuss sea surface oil elimination instead of OSR efficiency. In Doshi et al. 2018, dispersant use with aerial application was put as the fastest in comparison with ISB and mechanical treatment of oil spill. Airborne chemical treatment of oil is done 25 m above the water level and can be 40 times more efficient and several times more rapid than mechanical recovery. (API 2017; ART 2012; Vorobiev et al. 2005) There are two different perspectives on its speed: for airplanes it is 275 km/h, for vessels – 13 km/h. The response vessel speed is much slower and thus dispersant spraying is applied only for small scale spills near shore. A chemical carrier plane can arrive to the place of accident in 4-8 h. Dispersant consumption of the aircraft is 50 liters per hectare, with maximum carrying capacity of 19,000 liters. (API 2017) A laboratory documented surface efficiency of dispersants in test facilities equals 90% for fresh and weathered oils under cold conditions (Belore et al. 2009; Wilkinson et al. 2017).

Sustainability of the method. *Environmental aspect*. There are three issues to focus on: toxicity of dispersants, toxicity of dispersed oil, and biologically unavailable oil compounds. Recent studies have shown that modern dispersants are low toxic, biodegradable and rapidly diluted. Thus, they do not synergistically increase the negative impact from oil contamination. There are laboratory works conducted to develop new materials based on biological surface-active agents (Li et al. 2016). All in all, many recommendations incline towards dispersant application due to their high long-term benefit to the environment. The last statement stands by the result of comparing two scenarios: one - oil spill is naturally weathered without any OSR method being used, and two - dispersants are utilized to treat oil. In the long run, dispersants make oil biologically available much faster than it happens due to natural degrading processes. Increasing the surface area of oil in water, dispersants enable oil degradation in the time of weeks rather than without them over the period of several months or longer. Moreover, applying dispersants also eliminates a risk of contaminating coastal areas. Thus, dispersant toxicity is put second place after toxicity of oil itself. During the first two hours after oil slick dispersion, there is a peak concentration of hydrocarbons in water column. This can have the most negative effects and exposure: for example, on fish eggs and other biota in the affected water layer (DNV 2015; JIP 2014; Wilkinson et al. 2017). As for the Arctic conditions, it is believed that there is no difference between ecosystem sensitivity in the Arctic zone and any temperate climate region – biological organisms are as vulnerable. (ART 2012; Dickins 2015; Prince 2015; Wilkinson et al. 2017)

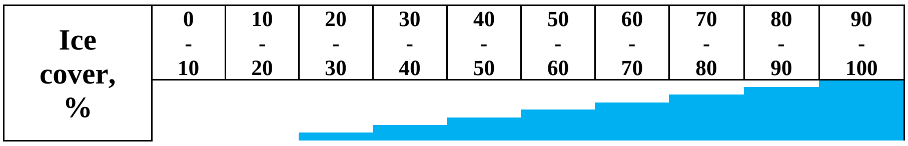
Social aspect. As the harsh Arctic environment may affect responders health and safety, it is important to prepare for potential physical, chemical, biological and other hazards. (DNV 2015; EPPR 2017b) Personal protective equipment should be applied due to possible inhalation and dermal contact (API 2017).

Economic aspect. An estimated cost of application of dispersants per 1 ton of oil in offshore conditions is 5,000 euros (Li et al. 2016). This is higher than for ISB but lower than for mechanical recovery. The cost structure eliminates two expensive and work intensive parameters: organization of clean-up operations with related involvement of people and equipment, and arranging waste management of collected oil-polluted material (Prince 2015).

11.4.2Environmental challenges for dispersants use

Ambient temperature. When lowering ambient and oil temperatures, viscosity of oil increases. The lower the temperature, the higher the viscosity, the lower the chemical efficiency is. (DNV 2015) Dispersants are possible to apply and biodegradation may occur effectively in the harsh and freezing conditions of the Arctic Ocean. (ART 2012; EPPR 2015; Vorobiev et al. 2005) In cases when dispersants are sprayed from vessels, freezing of valves and other operational OSR components is possible (DNV 2015).

Ice in water. For dispersant use, ice is an obstacle with dampening effect, which hinders the wave action needed to initiate the mixing processes needed for successful dispersion. (ART 2012; Lampela 2011) There are several scenarios about ice coverage for chemical OSR, as seen in Fig. 11.3.



Chemical OSR efficiency	**HIGH**	**LOWER THAN MAX**	**IMPOSSIBLE**

Fig. 11.3 - Effects of ice cover to dispersant use

With ice cover up to 30%, OSR operations are possible, with the fastest dispersant spraying approach applicable – airplane mounted sprayers. From 30 to 70%, ice coverage inhibits efficient airborne spraying, unless it is done by helicopters, which have higher manoeuvrability compared to planes. The method can still be organized but with slower speeds. If applied from vessels within this ice range, artificial mixing energy additional to natural levels have shown to be effective: for instance, from vessel propeller (Daling et al. 2010). Sea waves influence is lowered essentially in ice cover 30-50% (Potter et al. 2012). Ice situation with less than 30% free water surface may make chemical OSR inappropriate solution, unless manoeuvrable spray arms are available. (Daling et al. 2010, and 2012; DNV 2015; Lewis and Daling 2007)

Wind influence. Wind is a limiting factor for OSR operations, with a favorable value range of 4 to 12 m/s (ITOPF 2011b; Potter et al. 2012). Stormy weather is not a limitation for dispersants functionality, unlike it is for skimmers and booms. In contrast, sea storm is favorable for mixing oil with the chemicals. However, still there is an upper limit 12-15 m/s, above which it becomes challenging or unsafe to spray dispersants (DNV 2015; EPPR 2017a). Below 4 m/s, the ambient conditions are also limiting. It is too calm and inadequate amount of mixing energy available to support successful dispersion rates. (Vorobiev et al. 2005)

Wave turbulence. Dispersion requires sufficient mixing energy in order to break oil in droplets and to mix them into the water column. Therefore, the process is highly dependent on natural sources of such energy, being sea current or wind flows, or artificial ones – one of the most common examples of which is an underwater vessel propeller, sometimes applied along with mineral particles to enhance the mixing. (ART 2012; Dickins 2015) Thus, non-calm sea with intensive waving is a good prerequisite for chemical response: wave heights between 2 and 4 m, and sometimes 7 m, are acceptable for airborne dispersant delivery, and up to 3 m – for vessel application (EPPR 2017b; Wegeberg et al. 2017). Vessel-mounted equipment require a calmer sea state, but above 0.5 m wave height (Slaughter et al. 2017). Too high wave activity, in particular above the limit of 3-5 m wave height, may negatively affect interaction between dispersant and oil material and inhibit targeting the slick. (BP 2018; EPPR 2017a; Slaughter et al. 2017)

Light effect. For better visibility and safety during OSR operations, daylight is required. Both vessels and aircrafts require confirmation of slick location before dispersant use and when applying the chemicals. (BP 2018; DNV 2015; EPPR 2017c; Slaughter et al. 2017) Although as experience shows OSR operations are also possible in darkness with a reduction factor of 50%, provided that aerial remote sensing is available for guiding.

Salinity. The number of salt parts per million of sea water is important, since dispersants efficiencies are salinity dependent. In brackish waters, efficiency of dispersants decreases. In commercial scale, dispersants are mostly developed for seawater: for salinities 25 to 40 ppt. (ART 2012; DNV 2015; SL Ross 2010; Wegeberg et al. 2017) However, there exist also dispersants formulated for use in low-salinity and fresh water.

Precipitation and visibility. From practical point of view, no precipitations and high visibility is as required for aerial dispersant use as it is for aerial ISB (BP 2018; DNV

2015; Potter et al. 2012). Aerial visibility should be at least 2-5 km, operational in situ – 200-900 m (EPPR 2017a).

11.4.3 Technological limitations of dispersants use

Oil type and its viscosity. There is a limitation towards highly viscose gel-like oils, above 20,000 mPa·s – it results in inefficiency of dispersants (Canevari et al. 2001; Potter et al. 2012; Prince 2015). In this sense, oil type and its liquid state should be taken into account, when preparing chemical treatment of the slick. (ART 2012; Dickins 2015; Vorobiev et al. 2005) Usually any oil type with the range of viscosity between 2,000 and up to 10,000 mPa·s is suitable for the method. The efficiency lies in values from 5 to 70%. Less than 2,000 mPa·s is acceptable, and oil disperses well, with the highest efficiency - more than 70%. (Federici and Mintz 2014) Too high viscosity makes dispersion inefficient, since surfactants are washed away by the sea before they penetrate into the oil (EPPR 2017b; Prince 2015; Wedeberg et al. 2017). Table 11.3 shows how oil type affects efficiency of dispersant use. With API gravity greater than 45^{o}, density less than 800 kg/m^3, chemical OSR is not recommended, whereas with API lower than 10^{o} dispersants become inefficient. (API 2017; IPIECA 2015)

Table 11.3 Dispersibility of different types of petroleum products and crude oils

Oil type	Oil product	API gravity, ^{o}	Dispersability
Light ($\rho < 870$ kg/m^3)	Gasoline	65	high, but OSR is not recommended
	Diesel fuel /light crudes	40	high
Medium ($\rho = 870 \div 920$ kg/m^3)	Medium crude	25	high
Heavy ($\rho > 920$ kg/m^3)	Heavy fuel oil	19	moderate-to-low
	Bitumen	8	absent

Thickness of the film. Chemical dispersion occurs well with low oil slick thickness: from 0.1 to 1 mm; but work in oil thicknesses up to 10 mm. (API 2017; Vorobiev et al. 2005).

Water content in oil. After emulsification, oil becomes less available for dispersants. (Prince 2015; Øksenvåg et al. 2018) The emulsion with water content higher than 25% is too stable and difficult to disperse (Al-Majed et al. 2012; Buist et al. 2013).

Specific parameter – depth of the surface mixed layer. Since the oil droplets spread in the upper layer of water, there is a limitation to the depth of the sea in situ of the oil slick. The deeper the surface mixed layer is, the better uniform spreading will take place. (Prince 2015; Vorobiev et al. 2005) Dispersants are not approved for shallow areas (EPPR 2015). The minimum depth of the layer, at which chemical OSR might be approved is 10-20 m (IPIECA 2015). Most of the time, it is at least more than 60 m. This depth guarantees better uniform spreading in water column. (Prince 2015; Vorobiev et al. 2005)

Window of opportunity. Arctic WOP may be extended longer in comparison with lower latitudes and warmer climatic zones because of reduced weathering rates (Potter et al. 2012). However, the best use of dispersants and the highest efficiency is observed when sprayed on fresh spilt oil within 72 h after the accident. From this point of view, after recognizing an incident, the decision to apply the chemical method should be prompt (API 2017; Federici and Mintz 2014; JIP 2014; Lampela 2011; Slaughter et al. 2017).

Distance from the shore. The method is applicable remotely and does not require special arrangements for logistics and infrastructure, which is advantageous in perspective of existing infrastructure along coastlines of the Northeast and Northwest Passages. (Vorobiev et al. 2005) However, if dispersants are applied from vessels, then resupply of the chemical can become a logistical issue (DNV 2015; Slaughter et al. 2017).

11.5 PHYSICAL OIL SPILL RESPONSE

11.5.1 Overview of physical response

Brief description. The main tool of the physical OSR is sorbents. Sorbents are solid or liquid materials, which can intake liquids from the surrounding medium via two physicochemical mechanisms: absorption or adsorption. (Doshi et al. 2018; EPA 1999; ExxonMobil 2014; Federici and Mintz 2014) The liquids, or sorbate, can be both water and oil by its origin. In OSR, sorbents are commonly solid materials and are available in many geometrical forms – powders, rolls, pads, pom-poms, booms, and others. Independent on its form, water-repelling and oleophilic properties are required. Reuse of some material is possible, but rarely organized. Th reasons are time consumption and required manpower. Synthetic sorbents can be recycled several times. (EPA 1999; ExxonMobil 2014) Sorbents are frequently used to recover small amounts of oil in proximity to the shore. Operations are usually organized to do the final cleaning of oil traces; clean water surfaces of environmentally sensitive areas, or in cases, when mechanical recovery or other primary OSR methods are not applicable. (EPA 1999; ExxonMobil 2014; ITOPF 2012; Li et al. 2016; Wenning at al. 2018) Physical OSR is considered as a secondary OSR method. It is not often mentioned in major Arctic marine OSR publications. (EPPR 2017a; ITOPF 2012) Therefore, extrapolation of OSR influencing factors are made based on previously reviewed other OSR methods. It regards mainly environmental challenges.

Examples of response equipment. Sorbents are classified as synthetic and natural. Natural sorbents can be organic and inorganic. Examples of synthetic sorbents are polyurethane, polyethylene and nylon fibres; natural organic – peat moss, straw, feathers, and natural inorganic – vermiculite, wool, clay. (EPA 1999) Depending on given conditions of the spill area, response vessels, fishing nets, storage facilities, sorbent booms, sorbent pads or sorbents of other geometry may be employed. (ITOPF 2012).

Efficiency of oil removal and required time. In comparison with natural analogues, synthetic sorbents usually are more efficient and have better performance in the field: buoyancy, hydrophobicity, sorption capacity, ability to collect sorbents after use (Doshi et al. 2018; Federici and Mintz 2014; ITOPF 2012). Natural sorbents can intake up to 20 g of oil per 1 g of material, whereas synthetic ones – up to 70 g/g. (EPA 1999) With currently developed aerogels, as a subclass of sorbents, which can be both synthetic and natural in its origin – oil sorption rate can be up to 200 g/g for a variety of oils (Doshi et al. 2018). These materials have high surface area, high porosity, and good buoyancy characteristics. All this considered, it makes them ideal OSR sorbents. The only drawbacks are their high production cost, lack of durability after multiple compressions to extract oil from the material, and hydrophilicity. They intake water as well as oil. (Doshi et al. 2018; Liu et al. 2016; Mahfoudhi and Boufi 2017). The time required for operations depends on oil type and surface area of sorbents. More viscous oils react slower with the sorbent than less viscous types. Smaller size of sorbents creates better exposure opportunities for oil to be sorbed rather than when the material has larger dimensions: e.g. loose strands versus booms. (ExxonMobil 2014; ITOPF 2012) On the other hand, collecting soaked sorbents of small size may be time consuming and labour-intensive, which are both a drawback of OSR operations (Al-Majed et al. 2012).

Sustainability of the method. ***Environmental aspect*****.** One of the most vividly expressed environmental drawbacks of sorbents use is generation of excessive amount of waste (ITOPF 2012). Hence, applying this OSR method is of a waste management problem: 1 part of sorbent material can generate 70 parts of oil contaminated waste (Al-Majed et al. 2012). After collecting saturated sorbents from the water surface, temporary storage and subsequent logistical organization of sorbents and supportive tools, for instance fishing nets for lifting recovered oil, are required. Disposal can happen two ways: incineration or landfilling. Both require sanitary standards to be met: the first case – air emission (dioxin and PAHs) requirements, the second – sanitary landfill areas inland, usually far from the shoreline and the place of oil spill accident. For successful incineration, water content in the sorbent should be minimal. During sorbent collection stage and lifting the saturated material from water, leakages of incorporated oil are possible due to material sensitivity to mechanical compression. The compression can be also caused by environmental conditions: wind and sea state. (EPA 1999; ITOPF 2012) When dealing with natural sorbent materials, sinking and losing of both the material and incorporated oil is possible. Although natural sorbents are biodegradable, contamination of sea bottom and negative effects to local ecosystems makes them an inappropriate solution (Al-Majed et al. 2012; Federici and Mintz 2014). Synthetic sorbents are environmentally inert, including their unavailability for biodegradation. Some sorbents are enriched with nutrients, which enhance biodegradation rates. (EPA 1999; ExxonMobil 2014)

Social aspect. Practical health and safety considerations for personnel are as relevant as for other OSR options. With loose sorbents, powder form, protection of eyes and respiration channels is required. When dealing with booms saturated with oil, due to oil releases vessel deck floors may become slippery and cause accidents. (ITOPF 2012)

Economic aspect. In terms of economic expenses of materials, natural sorbents are usually less expensive due to their availability in large amounts. On operational level, physical OSR for large oil spills can be rather costly due to number of people, equipment and logistics needed. It is time consuming and labour-intensive process, which requires large storing capacity onboard for excessive amounts of produced hazardous waste. (Al-Majed et al. 2012; ITOPF 2012) Therefore, physical OSR is usually organized for treating small-scale oil spills and in nearshore areas. (EPA 1999; ExxonMobil 2014)

11.5.2Environmental challenges for physical response

Ambient temperature and ice in water. There is insufficient evidence and gap in the Arctic oil spill response literature regarding sorbent applicability in the Arctic conditions: ice-infested waters and low temperatures. The only mentioning is dated of 1975 by Logan et al.

Wind influence. Wind can affect operations in several ways. Some sorbents due to their light weight and small size can be blown away and carried out of the operational area. **(**ExxonMobil 2014) Some large sorbent structures, in particular booms, can be lifted above the surface, teared and squeezed so that some of oil intakes return back, resulting in secondary contamination (ITOPF 2012).

Wave turbulence. Wave action does not affect sorbents use, unless it is in the form of boom structures. With booms, holding capacity depends on the wave height in the same way, as it does for boom application in ISB and mechanical recovery. (Al-Majed et al. 2012; Federici and Mintz 2014) Sorbent booms are usually light and not durable. High wave activity can break them apart in a scale of several hours but also cause mechanical compression of booms, thus releasing some of the collected oil back to the marine environment. Towing such booms by vessels is also not desirable because the structures are too unreliable and can be easily torn due to created tension of the pull. (ITOPF 2012)

Light effect. Direct UV radiation may degrade synthetic sorbents, if they are left in outdoor temporary storage places of open type (ITOPF 2012). Although this influence may be not so pronounced in the Arctic geographical area (Øksenvåg et al. 2018).

Salinity. Both oil and sorbents are dependent on salinity levels of seawater in terms of their capacity to stay on top of the water surface – their buoyancy. If sorbents become too buoyant, their efficiency to intake oil may be reduced. External efforts are needed to force them down in direct contact with oil slick in order to recover the spill. (ExxonMobil 2014) On the other hand, once saturated with oil and some amounts of water, sorbents should stay afloat to be visible and recoverable (ITOPF 2012).

Precipitation and visibility. Synthetic sorbents are usually manufactured with white colour in order to provide better visibility in OSR operations. (ExxonMobil 2014) Snow storms, or other types of weather events are not desirable for sorbent application due to their amphipathic properties (DNV 2015).

11.5.3Technological limitations of physical response

Oil type and its viscosity. Light oils, which have low viscosity, are treated and incorporated better in the sorbent material than heavy and weathered viscous oil types. (Al-Majed et al. 2012; EPA 1999; ExxonMobil 2014; ITOPF 2012)

Thickness of the film. Sorbents are applicable for films, left after ISB or mechanical recovery, which are usually less than 1 mm. Once oil film becomes too thin, no sorption can occur any more (ExxonMobil 2014).

Water content in oil. Emulsified oils are a limiting factor for high sorbent efficiency. There can be no physical OSR organized around heavily weather oil, or oil in the state of “chocolate mousse”. (ITOPF 2012) For this parameter, the requirement is the same as with chemical OSR.

Specific parameter – incompatibility with dispersants. After being treated with dispersants, which make interface tension between the oil and water lower, oil loses its initial properties. This affects directly on sorbent application. The oil tends not to stick on the material surface, as it usually does prior the contact with dispersants. (ExxonMobil 2014) There is incompatibility with chemical OSR method. In case of mechanical OSR, sorbent application is only possible after all mechanical recovery operations are completed. With simultaneous use of both response approaches, skimmers and pumping systems may intake sorbents and become blocked by the material. (ITOPF 2012) Incompatibility is also characteristic for combining dispersant use and mechanical recovery, depending on skimming surface material. After being in contact with the chemical, oleophilic surface of skimmers, for instance, cannot recover oil from water. (ITOPF 2011b) This, however, cannot be said about disc skimmers, which maintain same degree of efficacy with chemically treated oils (Strøm-Kristiansen et al. 1996).

Window of opportunity. Fresh oil spills are preferred, while oil slicks are still not weathered and emulsified. (ExxonMobil 2014) The WOP is same as with cases of other OSR methods (API 2017).

Distance from the shore. Optimal areas of sorbents application are shoreline or nearshore areas, where distance is between the spill accident and mainland is minimal (Wenning at al. 2018). Logistics is usually a limiting factor for sorbents. Hence, it is usually applied with small scale accidents. For large spills, there is a need to collect the material with recovered oil onboard and retrieve sorbents for the next cycle of application. The collection is done with help of nets and belt skimmers. The retrieval is performed by wringing facilities. These works are labour-intensive, but also generate large amount of solid waste, especially in case sorbents are not to be recycled, but thrown away. Recycling of used sorbents is usually not preferred due to its higher cost in comparison with using fresh sorbent materials. Thus, there is excessive production of solid waste materials to be further disposed. (ExxonMobil 2014; Li et al. 2016)

11.6 SUMMARY

Based on various parameters of primary (in situ burning, dispersant use and mechanical response) Arctic OSR methods reviewed in this chapter, it is possible to make the following conclusions:

1. From an *environmental* perspective:
   There is a number of natural limitations, which can create unfavorable conditions for OSR operations, including extremely low temperatures, excessive ice cover, high wind and wave activity, daylight unavailability, brackish seawater, precipitation storms and low visibility. Traditionally, temperature, ice and darkness are put first in this list. However, all these parameters can cause critical inhibition for successful OSR. Here is an upper boundary, beyond which no OSR operations are organized: air temperature (-18^{o}C), wind (15 m/s), wave height (4 m), light availability (darkness) and visibility (air: 4 km, water: 0,3 km). A variable set of unfavorable scenarios is possible with ice cover at sea and the other parameters.

2. From a *technological* perspective:
   Oil type and its physicochemical properties define the level of difficulty for oil spill response procedures based on oil behavior in the marine environment. Such parameters as oil API gravity, oil/emulsion viscosity and solidification properties, film thickness and water content can force choosing one or another abatement method, including no oil spill response – natural attenuation. For instance, heavy fuel oil (API gravity below 10^{o}) or highly weathered and emulsified (water content of 50%) oil can only be collected by low efficient mechanical OSR. Distance from the shore is also a technological limitation: far offshore spills can be left for natural attenuation due to accident remoteness and lack of OSR resources in nearby region.

3. From a *performance* perspective:
   In ideal conditions, all three methods perform well, with cited efficiencies of more than 90% for in situ burning, mechanical and chemical OSR solutions. However, ideal conditions on both ambient and oil parameters are at least 50% unlikely for the whole Arctic maritime area (EPPR 2017a). As a practical example of mechanical recovery rate drop down in operational conditions, 95% of oil slick during an oil spill accident stays in the marine environment, leading to only 5% encounter rate (JIP 2014). Other OSR methods may experience similar tendencies, keeping however their efficiencies higher than with mechanical OSR (IPIECA 2015). None of reviewed primary methods remove oil completely from the

environment and make oil-contaminated waters crystal clear. (Vorobiev et al. 2005)

4. From an *economic* perspective:
   In descending order, from mechanical to chemical and in situ burning OSR, for organizational and logistical reasons, application of skimmers bares the highest economic costs – 8,500 euro/ton. Second place is chemical OSR with 5,000-euro cost of operations per each treated ton of oil, and third place of 2,700 euro/ton – in situ burning.

5. From a *sustainability* perspective:
   All OSR methods should be applied with caution by oil spill responders, including dealing with possible physical, chemical, biological and other hazards. By-effects to the environment consist of air emissions with in situ burning OSR, water column intoxication – chemical OSR, noise pollution and oil surface water contamination – mechanical OSR. All the effects have a temporary but excessively pronounced character. Despite their negative impacts, primary OSR methods eliminate much larger possible consequences of the oil spill, if left to be in the marine environment without any response: this may lead to long-term effects on biota and bioaccumulation on an ecosystem level (Kingston 2002).

In the Arctic marine environment, among existing OSR solutions, in situ burning OSR response is the most applicable for ice infested waters with large coverage and remote oil spill accidents (DNV 2015). Dispersants use can be applied with situations, when the weather is windy, the sea is open from ice, the hydrological state is characterized by high waves (2 m) and large turbulence. No ISB or mechanical recovery are possible in these conditions. (API 2017; Li et al. 2016; Slaughter et al. 2017) Mechanical and physical OSR works the best in proximity to the mainland with relatively calmer sea and weather conditions, including ice-infested waters. (ART 2015)

In all comparative studies of OSR methods, analyzing each method against the other – the general conclusion in relation to the Arctic marine environment is that the best operational time of the year is summer and the best OSR solution is not a singular approach but a suite of all primary abatement methods, with possible application of either of secondary methods in post-cleaning. Each combination is justified depending on the variable seasonal and geographical conditions as well as physicochemical state of the spilled oil. In practice, there exist established contingency plans already in place in advance of the spill accident. The plans are based on response analysis of the different mitigation technologies for relevant spill scenarios, including types of oil, release conditions, environmental conditions, time of the year, biological resources and other parameters. Usually decision making is conducted with help of selection tools, such as Spill Impact Mitigation Assessment – SIMA. It is used to justify choice of one or another OSR method for each particular spill case, taking into account socioeconomic and environmental conditions. (API 2017; DNV 2015; Doshi et al. 2018; IPIECA 2016; Wilkinson et al. 2017) All these is done to ensure an overall least damage to the marine environment, people health and safety.

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