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Literature review report of oil in ice

D4.1

WP4: Combat of oil spill in coastal arctic water - effectiveness and environmental effects

Experimental *in situ* burning of oil in ice. Photo: A. Dragsted

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1 Executive Summary

The aim of this report is to review relevant literature in the preparation for further research about *in situ* burning of oil in ice within WP 4 (Task 4.1.1). Thus, this review report gathers and compiles the relevant literature on oil in ice with focus on the behaviour of oil in ice and burning of oil in ice (*in situ* burning).

In situ burning of oil has been shown to be of high efficiency in controlled field experiments with high ice concentration. Initial field studies from the 1970s and 1980s proved that ignition of crude oil released during melting from land fast ice can be highly effective.

Other studies also investigated oil behaviour in ice. These studies demonstrated among others that oil can be ignited during a limited window of opportunity after it starts to emerge at the surface. While they clearly established the feasibility of the method, some operationally important questions were left open, e.g. relation between burn rate and rate of oil release.

From the review, it is evident that the research completed in relation to burning oil in ice primarily focused on small-scale and mid-scale tests in the laboratory or field trial test facilities. Very few large scale experiments are completed. The most studied ice conditions are static pack ice, however also research including burning of oil on the ice, in snow and in melt pools, released after being encapsulated in the ice until the spring melt have been conducted. Very few tests have been done in dynamic ice, however these studies indicated that burning is very sensitive to movements, the coverage of the ice, the thickness of the oil and where or not frazil/brash ice is present.

The major focus on the experimental work has been to establish knowledge about the feasibility of the method, including knowledge about the burning efficiency, mass loss rate and more operational parameters such as ignitability, igniters, required oil slick thickness, weathering state /window of opportunity etc. Hence, very little have been done to understand the heat transfer mechanisms between the burning oil and the ice. It was discussed that the interface between oil and ice were more efficient at transferring heat from the oil to the underlying ice compared to the transfer of heat to underlying water. Hence, also much higher initial oil slick thicknesses were required to burn oil on ice. Therefore increased knowledge about the link between ice and the heat feedback mechanisms from the burning oil is needed to fully understand the potential of burning oil released from the ice during spring melt. Also the link between oil release rate and the burn rate is not known. All such input is also important to be able to model the development of the ice during burning.

2 Introduction

In situ burning is one of the countermeasures available for responding to oil spills, in marine but also in other environments e.g. ice/snow, freshwater, marshes. During an in situ burning operation the oil is ignited on the sea surface and through this burning, the oil volume is substantially reduced. The method has been hardly ever used, until 2010 during the Deepwater Horizon incident in the Gulf of Mexico, where between 220,000 and 310,000 barrels of oil where burned during more than 400 burns (Mabile 2012). In situ burning has also been found to be an effective measure for oil spills in Arctic ice filled conditions (e.g. Sørstrøm et al. 2010).

This review report gathers and compiles the latest available literature on oil in ice with focus on the behaviour of oil in ice and burning of oil in ice (in situ burning). To understand the main principles of in situ burning a short overall description of the method is included.

3 Oil in ice

There is a wide spectrum of oil-in-ice interactions (Figure 1). While each scenario comes with its own characteristics of oil weathering, and constraints and feedbacks of *in situ* burning, there are recurring questions related to the feasibility of *in situ* burns: constraints on oil ignition posed by initial conditions, and feedbacks on oil pool and oil supply by melting snow and ice.

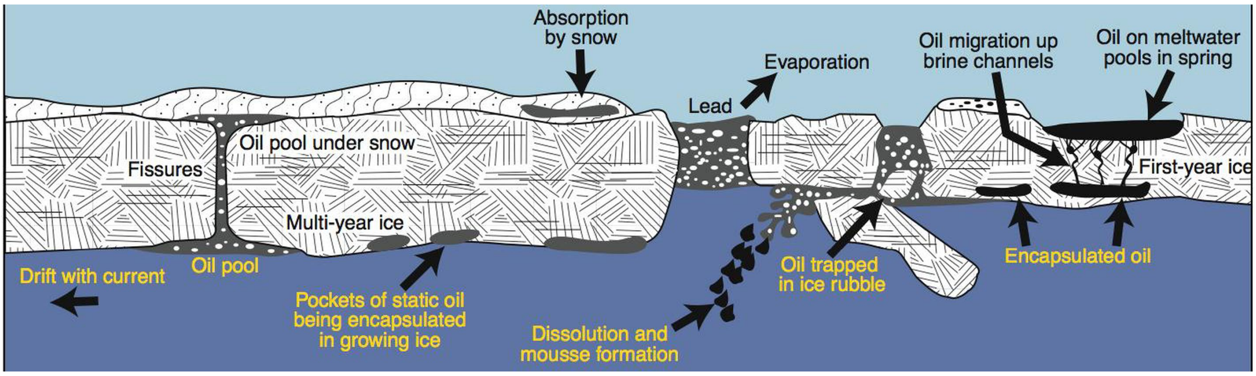


Figure 1: Sketch of oil-in-ice configurations after Al Allen (Dickins 2011).

The most surprising oil–ice interaction may possibly be the migration of oil through solid sea ice (Figure 1, right hand side). Although sea ice is strong enough to pose a hazard to operations in ice-covered waters, it is not completely solid. A matrix of ice hosts a network of pores (µm and bigger) and drainage channels (sub-mm to cm-size in diameter) that contain fluid brine even at the height of winter (Petrich and Eicken 2010). Size and interconnectivity of pores increase with temperature and result in a region of several cm thickness at the bottom of the ice that can be infiltrated by oil spilled beneath ice in winter (Figure 2; Petrich et al. 2013). As ice growth continues, oil entrained and encapsulated inside ice gets almost entirely separated from the environment and does not weather (e.g., NORCOR 1975; Dickins 2011). Once the ice warms in late spring, the connectivity of the pore network increases to the point that oil is able to migrate to the surface (being less dense than brine), first through larger channels and later including large fractions of the interconnected pore space (e.g. NORCOR 1975). While this process has been studied exhaustively (NORCOR 1975) and is understood qualitatively, quantitative descriptions however of the mechanisms do not exist beyond ad-hoc estimates (e.g., Dickins 1992; Fingas and Hollebone 2003; Buist et al. 2008). Oil entrainment and migration affect spill detection and remediation strategies, with the window of opportunity for potential oil ignition being limited to a few days to weeks after surfacing, and redistribution with ice drift and release to the environment, potentially into coastal regions (NORCOR 1975; Dickins et al. 2008; Pegau et al. 2016).

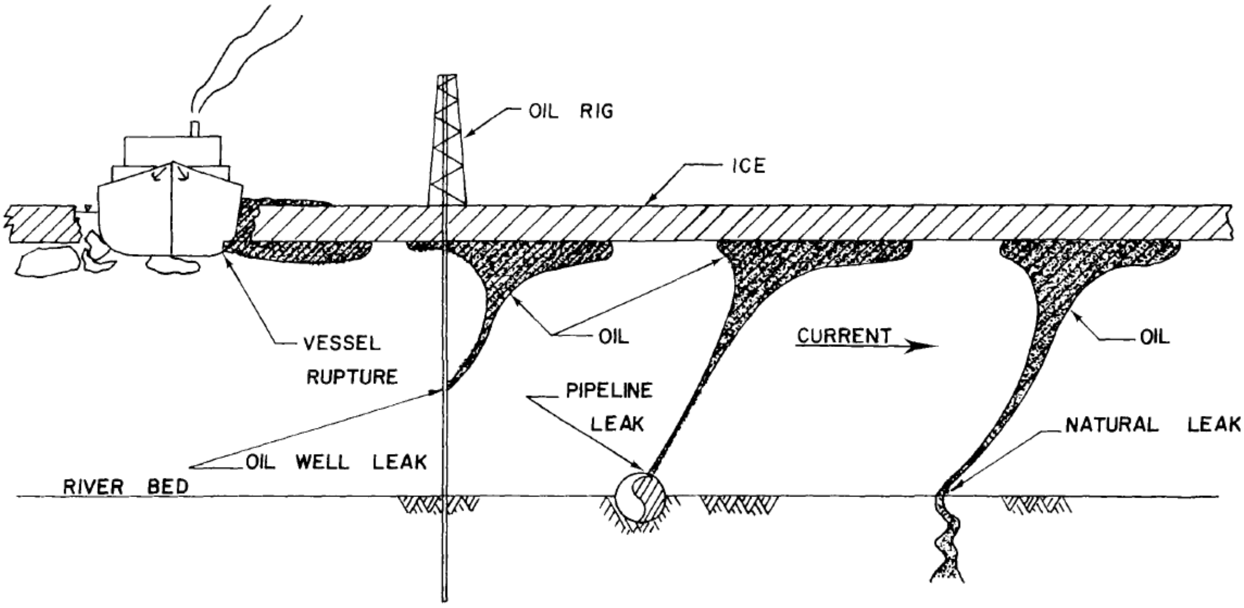


Figure 2: Schematic representation of events which could result in oil spilled beneath sea ice. From Uzuner et al. (1979).

3.1 Meltpond Evolution during Melt

Over the course of a few weeks in spring, sea ice changes from a snow-covered solid to a porous structure throughout with surface meltwater pooling above weak ice and porous ice (Figure 3). The process of meltpond development undergoes several stages (Petrich et al. 2012; Polashenski et al. 2012). During winter, a snow cover with snow drifts will have developed on the ice. In spring, the snow begins to melt and meltwater accumulates on the surface, wetting the snow above and infiltrating the sea ice pore space below. Water entering the pore space may freeze to form an impermeable layer. The thinner areas of wet snow decrease in albedo, causing that snow to melt faster and expose the ice below to further ablation. As melt continues, ponds grow in areal extent and depth, forming a surface pattern on smooth, undeformed ice that is highly correlated with the initial snow cover (Petrich et al. 2012). At this stage, the meltpond surface is above the ocean surface level (i.e. freeboard) as the ice below is not very permeable. This stage as been termed the pre-melt phase (Polashenski et al. 2012). The initial oil surfacing and spreading described by NORCOR (1975) took place during the pre-melt phase. Following the pre-melt phase, discrete flaws in the ice open for surface water (still above freeboard level) to drain into the ocean (Figure 4). Polashenski et al. (2012) showed that these flaws may be brine channels that widened in a positive feedback mechanism due to fast downward flow of warm meltwater. During this stage, meltwater flows toward the drainage holes (not unlike rivers) and meltpond coverage decreases considerably (Figure 5). Eventually the impermeable surface layer ablates (melts) and ice becomes porous, allowing vertical fluid exchange over wide swaths of the ice (Polashenski et al. 2012). At this point hydrostatic equilibrium is reached between the surface of the meltponds and the ocean level, and meltponds continue to grow through ablation.

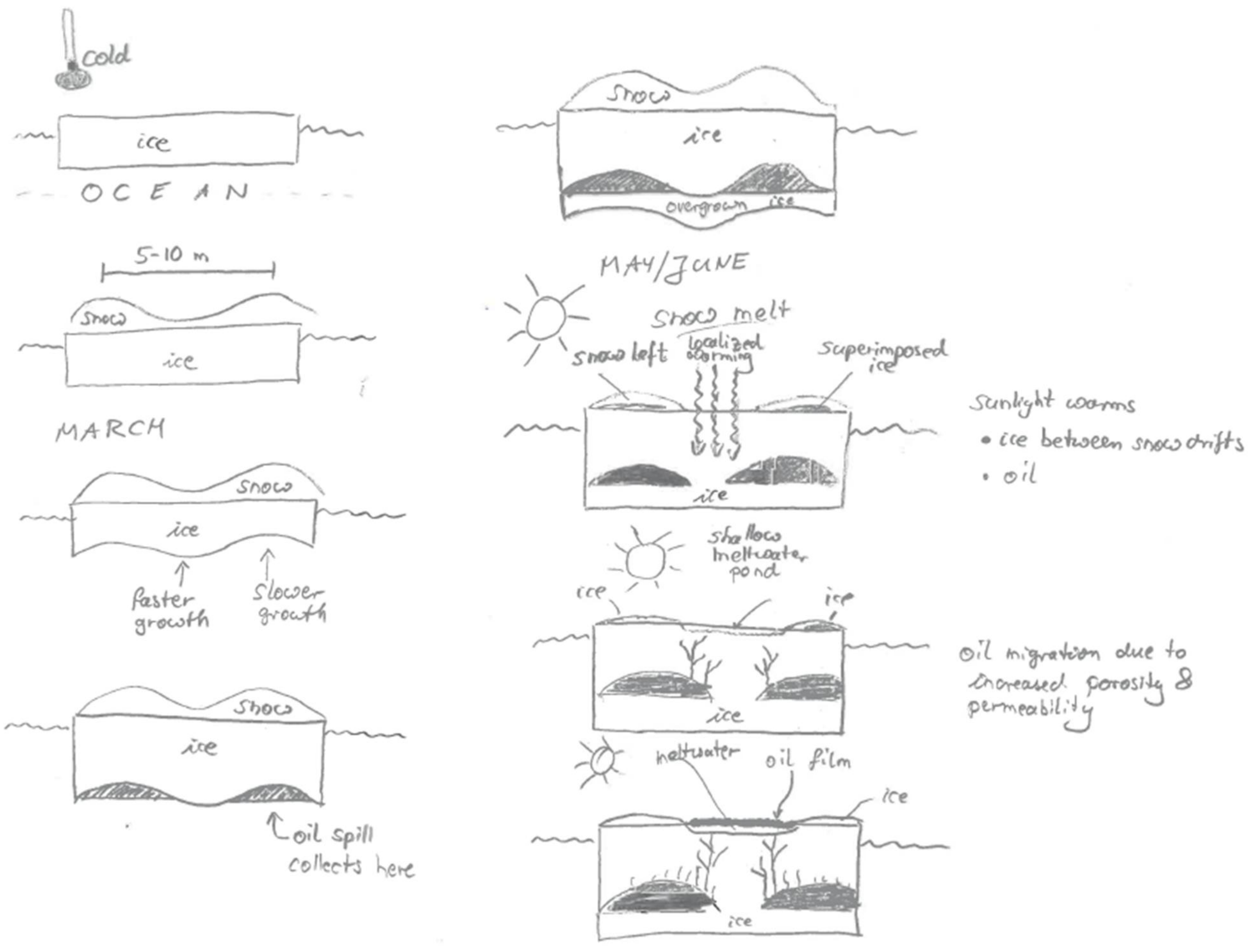


Figure 3: Schematic of the melt process from the perspective of oil.

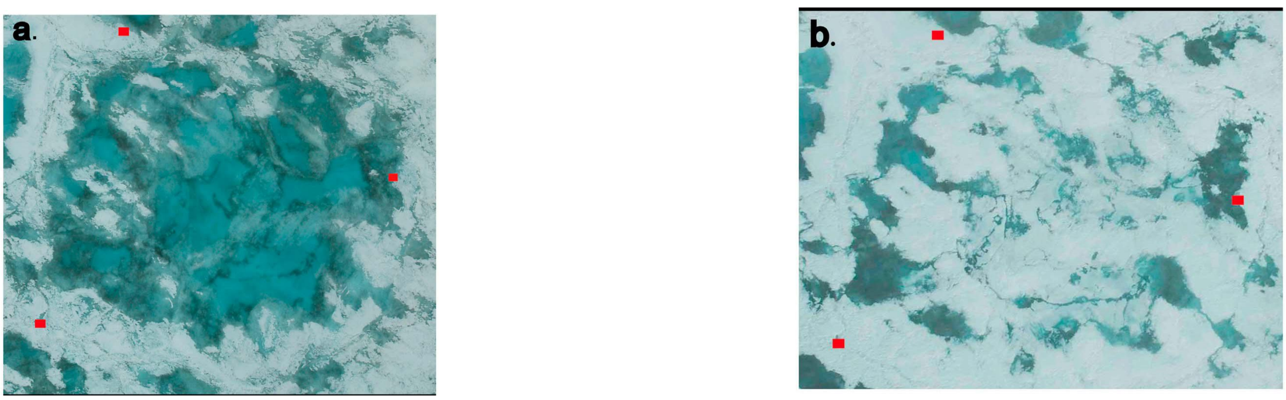


Figure 4: Arial view of a meltpond basin (a) at the end of the pre-melt stage and (b) after onset of drainage. The photos represent a change that occurred within 18 hours. Diameter of meltwater basin in (a) is approx. 10 m. Control points are marked red. From Polashenski et al. (2012).

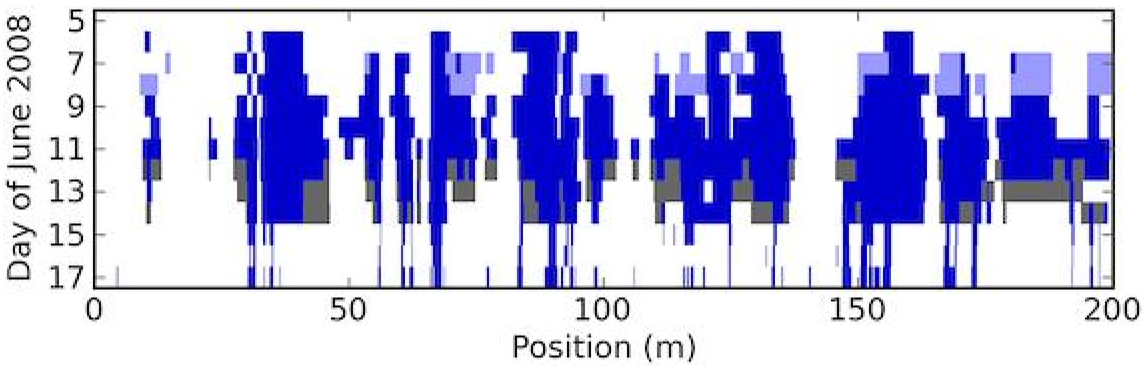


Figure 5: Development of surface characteristics along a linear transect between 5 and 17 June 2008: snow, bare ice or white, decaying ice (white); slushy ice (light blue); melt pond (dark blue); suspended ice (gray). Note the increase in meltpond coverage until 11 June (pre-melt stage), followed a decrease due to surface drainage. From Petrich et al. (2012).

3.2 Oil Release during Melt

Petrich et al. (2013) estimated that between 2 and 10 L of oil per m^2 of ice can entrain the sea ice pore space after a spill. This is in addition to the holding capacity for oil of ice due to natural undulations (Wilkinson et al. 2007). During the NORCOR (1975) test in the Canadian Arctic (a vast experimental set-up including eleven discharges of a total of 56 m^3 of crude oil in a small bay, Cape Parry in Canada (Norcor, 1975)), oil penetrated the thin layer of ice and the lower 4 to 6 cm of brine channels in cold ice following a spill. Oil started to reach the surface through brine channels before surface meltponds developed and while the surface was still snow-covered. Oil lenses of 1.5 m diameter developed within 24 hours and snow started to darken due to the oil. No differences in surfacing had been found between oil lenses at different depths in the ice, and it has been presumed that this is due to mutually compensating effects: while ice closer the ice–water interface is warmer and hence more porous, it is reached by less solar radiation (NORCOR 1975). However, in separate experiments reported by Buist et al. (1981), it was found that the earlier in the season oil had been spilled, the earlier it appeared on the surface during melt.

No difference in oil behaviour had been found in NORCOR (1975) experiments between two different crude oils with different viscosities (factor 2.5) but whose common characteristics were a low pour point (Norman Wells and Swan Hills). During the warm phase (ice temperature -4 °C), oil spilled newly beneath the warm ice surfaced within one hour. Once it reached the surface, the ice penetration by oil appeared indistinguishable from oil that reached the surface after encapsulation during the winter (cf. Figure 6). Due to absorbed solar radiation, the channels containing oil widened during the melt phase. Also, the interstitial pore space filled with oil, reaching concentrations of up to 7% in the ice. Although oil continued to flow through the ice during the entire melt phase, all oil was not released until the ice had melted to the level of the original oil lens (NORCOR 1975).

Buist et al. (1981) further noted that oil first appeared on the surface slowly, followed by the exposure of “most” of the oil within a matter of days. Approximately 80% of the oil had surfaced prior to break-up of the ice cover.


Figure 6: Oil surfacing though sea ice during the pre-melt stage during experiments of NORCOR (1975). Photo from Dickins (2011). Circles are estimated at 10-20 m diameter.

3.3 Weathering in the Sea Ice Pore Space

It has been found repeatedly that crude oil does not weather while entrained inside the sea ice pore space. Hence, oil that could be ignited before an under-ice spill can be ignited once the oil surfaces. A limited number of field experiments have been performed that involving oil spilled beneath ice and *in situ* burning: Glaeser and Vance (1971) performed weathering experiments of oil on water, ice, and under ice, and burn experiments of oil on ice. They found that Prudhoe Bay crude oil could be ignited on ice to burn and released enough heat into the ice beneath to open channels that drained water. Weathering of oil took place mostly within the first 5 days of being exposed to the air. Weathering beneath sea ice was not the focus of the study but had been tested for only one day. Weathering was found to be not significant.

NORCOR (1975) found that crude oil sitting on top of the ice or meltponds absorbed light and reached temperatures of 5 to 10 °C. Oil encapsulated in the ice lost only insignificant fractions to ocean or atmosphere over the winter and could be ignited after it reached the surface. Fresh crude oil slicks could be ignited for up to 3 weeks. Details regarding the burning process are described in Section 5.1.

Buist et al. (1981) spilled oil and gas mixtures under ice. They observed that small oil droplets (under thin ice) were mostly exposed to the surface due to surface ablation while oil concentrated in lenses (under thick ice) moved through the pore structure in spring. As a result, oil contained in pools under the ice was burnt more efficiently once it surfaced than oil in droplets. Droplet formation was greatly enhanced with the amount of gas discharged with the oil.
None of the oil rising to the surface came in emulsified form. Since air was used as gas, some of the light ends of the crude had been lost beneath the ice. Little or no weathering of the oil took place while the oil was encapsulated in the ice. However, significant losses of light ends occurred once the oil reached the surface in spring.

Buist et al. (1981) found that spills appearing earlier in the season released more oil to the surface by the time of break-up than spills appearing later in the season. In general, burn efficiencies were more determined by slick thickness than by pool area, volume, or oil age. It was also noted that water started to boil beneath the burn.

Buist et al. (1983) tested the behaviour of stable water-in-oil emulsion. Emulsions appeared at the surface only after the ice had rotten to the level of the emulsion lens. At the time of break-up, 15% and 50% of the emulsion and crude oil, respectively, had surfaced. Solar radiation aided ice melt above the emulsion. The burn of emulsion was possible with difficulties (proper choice of starter and herding were critical) while crude oil was no problem.

4 Basics of *in situ* burning of oil on a water surface

The principle behind *in situ* burning is that the spilled oil is ignited directly on the spill site. To do so, it requires oxygen, a thick (> 1 cm) and relatively fresh oil slick and an igniter that is able to heat the oil to its fire point. The fire point is the temperature where the oil is warm enough to release sufficient vapours to maintain continuous burning (as burning is related to the vapour phase) and typically a few degrees above the flash point (Buist et al. 2013). The oil is thickened by either fire-resistant booms or in ice conditions the ice can act as the containment. Chemical herding agents have also been shown to be able to contract the oil to ignitable thicknesses.

The key heat feedback mechanisms are shown in Figure 7, where the radiative heat transfer from the flames and back to the oil slick surface is the driving mechanism for the continous burning of larger pools (the flames having a turbulent flow regime). For smaller pools (<0.6 m) convective and radiative heat contributions to the oil slick are equal (Buist et al. 2013). When the thermal wave going through the oil slick reaches the water interface, the water will act as a heat sink, due to the much larger thermal diffusivity of water compared to that of crude oils (Torero et al. 2003). Flame out will occur when the oil slick is so thin that the heat sink to the underlaying water is too high to sustain burning.

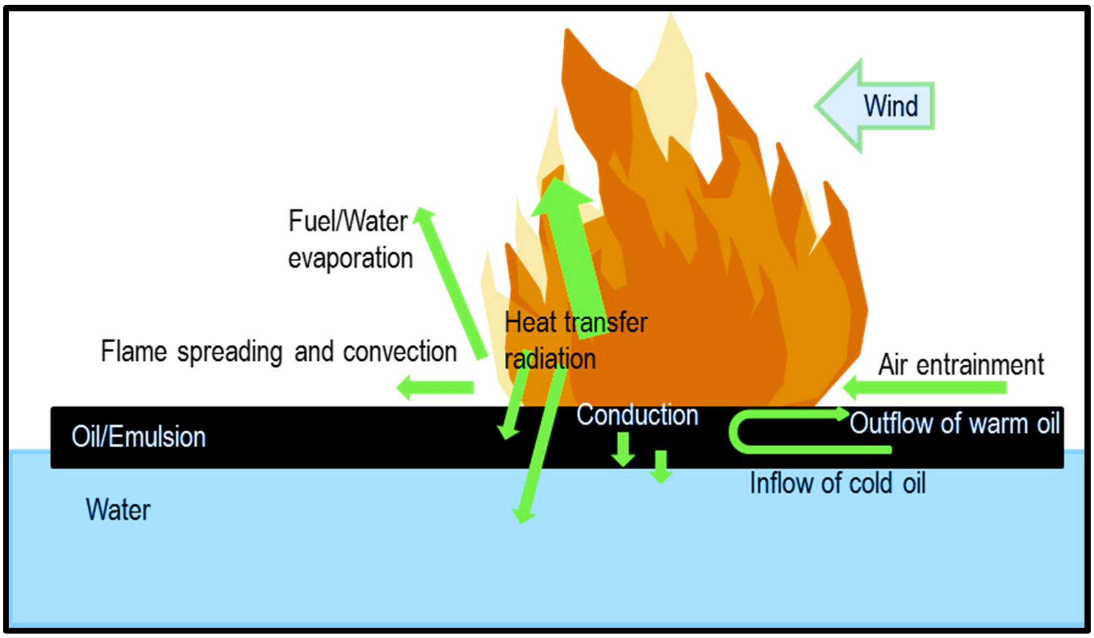


Figure 7: Key heat transfer processes during *in situ* burning operation on water. From Fritt-Rasmussen (2010)

The heat feedback to the slick is a small fraction compared to the total heat release (Mudan and Croce 1995 in Torero et al. 2003). Twardus and Brzustowski (1981 in Buist et al. 2013) has estimated the heat feedback to be 2-3 % of the heat combustion and Torero et al. (2003) suggest that 0.18 and 0.39 % of the heat released by the flame is fed back to the fuel surface. Further Mudan and Croce 1995 in Torero et al. 2003 assume that the net heat feedback per unit area is independent of the pool diameter and therefore they express the "*heat flux per unit area reaching the surface*" as:

$$\dot{q}_s'' = X\frac{4\rho_\infty C_p\left(T_\infty g\left(T_f - T_\infty\right)\right)^{\frac{1}{2}} d^{\frac{1}{2}}}{\pi} \quad (Eq.1)$$

X the fraction of the total heat release fed back to fuel surface,
C_p [J/kgK] is the specific heat at constant pressure and ambient temperature for air,
T_∞ is the ambient temperature,
T_f is the average flame temperature,
g is the acceleration of gravity (g = 9:81 m/s^2),
d (diameter of the fuel pool) is the characteristic length scale,
ρ [kg/m^3] is the density of the air at ambient temperature
∞ stands for ambient conditions.

For crude oils it has been found that most of the radiative heat flux is absorbed close to the surface and thus radiation through the oil could be neglected (Garo et al. 1996 in Torero et al. 2003). The impact of natural convection within the fuel and water is considered to decrease with increasing viscosity of the oil, thus for highly viscous oils conduction can be assumed to be the dominating heat transfer mechanisms (Torero et al. 2003).

According to Torero et al. (2003) the heat release from pool fires has been well investigated and the following expression correlates well with experimental measurements:

$$\dot{Q} = \rho_\infty C_p\left(T_\infty g\left(T_f - T_\infty\right)\right)^{\frac{1}{2}} d^{\frac{5}{2}} \quad (Eq.2)$$

$\dot{Q}$ [W] total heat release from the combustion process
C_p [J/kgK] is the specific heat at constant pressure and ambient temperature for air,
T_∞ is the ambient temperature,
T_f is the average flame temperature,
g is the acceleration of gravity (g = 9:81 m/s^2),
d (diameter of the fuel pool) is the characteristic length scale,
ρ [kg/m^3] is the density of the air at ambient temperature
∞ stands for ambient conditions.

Flames from *in situ* burning are characterised as diffusive flames, as oxygen must diffuse to the combustion zone (Buist et al. 2013). The combustion is starved (inadequate oxygen amount), as can be seen from the colour of the flames (yellow/orange) and from the smoke production might also be an indicator of this. Also different flame regimes could be expected as a function of the diameter of the burn, where pools with a diameter > 1 m are considered as turbulent flow regime (see Figure 8). According to Buist et al. (2013) based on different researchers the flame temperatures is of 900-1200 °C for burning of crude oils on calm water. For larger oil pools (>1 m) the turbulent flames, oscillation of the flame height and smoke production makes the assessment of the flame height difficult (Buist et al. (2013). Heskestad (1995) in Babrauskas (?) recommends the following equation for estimating pool fire heights:

$\boldsymbol{H = 0.235\dot{Q}^{0.4} - 1.02D}$ **(Eq. 3)**

H flame height [m]
D diameter of burning slick [m]
$\boldsymbol{\dot{Q}}$ Heat release rate of fire (kW), where:

Note that during vigourous burning the flame height increases.

An expression of the heat radiated from flame and smoke to external vertical surfaces at ground level have been established by Shokri and Beyler (1989) in Buist et al. (2013). According to Buist et al. (2013) it is not perfect, but acceptable for estimates, particular for larger diameter (17 m) a reduction in heat relase is found

$$\boldsymbol{\dot{q}^{n} = 15.4\left(\frac{L}{D}\right)^{-1.59}},$$

$\boldsymbol{\dot{q}^{n}}$ incident heat flux [kW/m^2]
L distance from pool center to target [m]
D diameter of burning slick [m]

Burning rate / regression rate (e.g. g/s, mm/min – equivalent to the volumetric loss of liquid pr. unit surface area of the pool in unit time (Drysdale 1998)) is the mass difference of oil (before/after burn) divided by burning duration. According to Buist et al. (2013) typically burning rates have been measured to be around 3 mm/min for thick (>1 cm), fresh slicks in relatively large pools (>3 m diameter). However, variations can be found depending on oil type, weathering degree of the crude and ambient conditions (wind, temperature). The regression rate will go through three stages, the initial stage where the regression rate will increase, the quasi-steady regime where the regression rate is almost constant and the final stage where the regression rate will decrease due to the effect from the below water (heat sink) (Torero et al. 2003).

Another way of indicating the success of the burn is by the burning efficiency calculated as the amount of oil eliminated from the water surface relative to the original amount.

The size (diameter) of the burning area seems to affect the result for burning rates and burning efficiency, where a diameter of 1-2 m is suggested to be the limit for having the highest burning efficiencies as well as burning rates (van Gelderen et al. 2015). For such large slicks burning layers of oil about 100 mm can result in burning efficiencies of 90-99 % as flame out typically occur when the slick thickness reaches about 1-10 mm (Buist et al. 2013), where the heat loss to the water below the oil is too high to continue burning. The relation between pool size and burning efficiency is related to the heat loss to the water beneath the slick and the heat feedback mechanisms. For larger pools the heat feedback to the oil is relatively higher compared to smaller pools, as typically investigated in laboratory scale.

The relation between regression rate and pool diameter is shown in Figure 8.

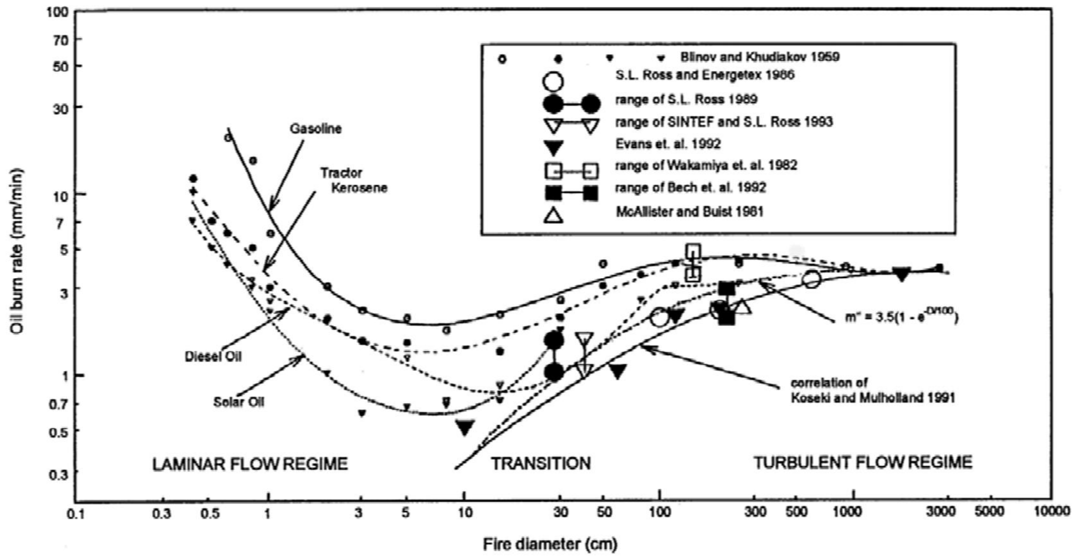


Figure 8: The regression rate of liquid pool fires (different oil types) as a function of the diameter of the pool. From Buist et al. 2013/Marine Spill Response Corporation.

Boil over is a phenomenon where the water just below the oil is superheated, because the oil isolates the water from the air whereby the water cannot vaporize. At a temperature of 120 °C violent boiling of the water will occur resulting in water vapours as well as oil droplets being ejected through the oil and in the flames. This is seen as boil over or vigorous burning. Burning rate, heat release and flame height increases during such an event. Boil over/vigorous burning is frequently seen in the laboratory, where the exchange of water below the oil is not sufficient. Boil over has rarely been reported during open water operations. This is considered to be due to flow/exchange of water below the oil. However, boil over has been reported in operations in melt pools. (Buist et al. 2013)

5 Overview of experimental ISB of oil in ice/snow studies

Since the first burning of oil spill *in situ* took place in 1958 on the Mackenzie River in Canada, several operations, both experimental as well as incidents, involving burning of oil in ice/snow has been carried out. A graphical outline can be found in the Figure 9 below (Buist et al. 2013). To overview the various experimental studies that have been completed in relation to burning oil in ice, often different types of ice/snow are used to categorize the work. This categorization is also followed in the below review:

- *Burning oil on solid ice*
- *Burning oil in broken ice/pack ice*
- *Burning oil in snow*
- *Burning oil in ice cavities*

A. USCG experiments near Barrow, AK 1971-1972
B. Experiments by McMinn near Barrow, AK, 1971-1972
C. Experimental spill in Balaena Bay, Canada, 1974-75
D. Experiments in yellowknife, Canada, 1976
E. Experiments by Energetex in Waterloo, Canada, 1977
F. Experiments at McKinley Bay, Canada, 1979-80
G. Experiments by Energetex at McKinley Bay, Canada, 1979-80
H. Experiments at McKinley Bay, Canada, 1981
I. Experiments at Prudhoe Bay, AK, 1982
J. Experiments at McKinley Bay, Canada, 1982
K. Tier II burn tests at Prudhoe Bay, AK, 1983
L. Experiments at OHMSETT, NJ, 1984-86
M. Experiments at Cape Bretton, Canada, 1986
N. Experiments in Calgary, Canada, 1986
O. Experiments at Svalbard, Norway, 1990-94
P. Experiments in Barents Sea, 1993
Q. Experiments at Prudhoe Bay, AK, 2002-03
R. Experiments at Svalbard, Norway, 2006-08
S. Experiments in Barents Sea, 2008-2009

1. Pipeline spill, Near Normal Wells, Mackenzie River, Canada, 1958
2. Tanker *Raphael* spill, Finland, 1969
3. Tank farm accient in Deception Bay, Canada, 1970
4. Tanker *Arrow* spill, Chedabucto Bay, Canada, 1970
5. Collision of *Othello* and *Katelysia*, in Tralhavet Bay, Sweden, 1970
6. Diesel spill in ice choked river, Sweden, 1972
7. *Imperial St. Claire* spill in Lake Huron/Georgian Bay, Canada, 1976
8. Barge *Bouchard* #65 accident in Buzzards Bay, MA, 1977
9. Cargo vessel *Edgar Jourdain* spill, Hall Beach, Canada, 1980
10. Storage tank leak, Warwick Lake, Canada, 1983
11. Tank farm release, ME, 1993

Figure 9: Map showing experimental spills (left column) and actual incidents involving burns in ice (right column). From Buist et al. (2013)

The literature search showed that most of the research related to *in situ* burning was experimental work conducted in Canada, USA and Norway and often published as grey literature i.e. non-peer-reviewed technical reports or often conference proceedings. Due to the lack of peer review it is important to be critical in the quality of the work. Still, grey literature was included in this review report since it is considered to be a unique and highly relevant and important source of information within this field of research. However, much of the grey literature was not always available, thus it was not possible to consult the primary reference, and therefore often Buist et al. (2013) is used instead. Buist et al. (2013) "*In situ burning in ice-affected waters: state of knowledge report*", compiles the current knowledge state of *in situ* burning in ice-affected waters based on a literature review, as well as knowledge from practical experience (experiments, field tests and response experience) of the authors.

5.1 Burning oil on solid ice

One of the experimental programmes initiating the research containing burning of oil in ice filled waters was the Norcor (1975) experiments taking place in the beginning of the 1970s. The focus of this vast experimental set-up was to study the interaction of oil with Arctic sea ice. The experiments included eleven discharges of a total of 56 m^3 of crude oil in a small bay, Cape Parry in Canada (Norcor, 1975). During spring melt oil was released from the ice, thus burning of oils from melt pools was also included to the study. For the ignition of the oil, paper towels soaked with gasoline or naptha was used. The oil was ignited in test area NW 4 (see Figure 10), and the flames spread to NW3 and NW7 rapidly. Secondary fires were started in SH2, NW6 and SH1. The burning lasted approximately 30 minutes and the burning efficiency from these experiments was found to be 90% (Norcor 1975). Other important findings from the study related to burning of oil in ice/snow was that oil that was found entrained in the snow, flowed into the burning pools due to the heat from the burning. The heat also resulted in a slightly enlargement of the melt pools, the snow melt however was lower than expected (Norcor 1975).

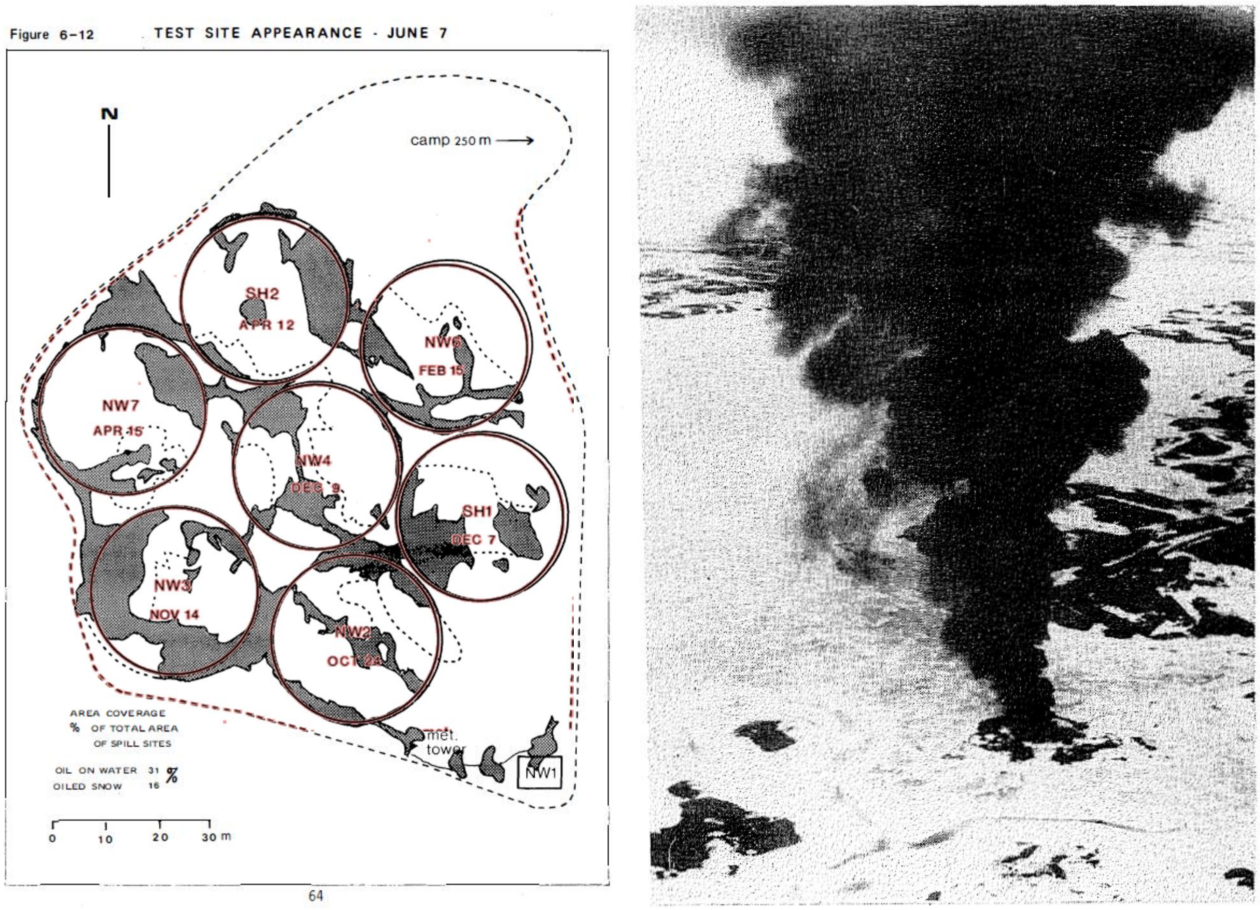


Figure 10: NORCOR test sites and oil appearance prior to burning (left) and smoke plume during burning (500 m rise) (right). Adapted from Norcor, 1975.

Several other experiments including burning of oil in melt pools were conducted in the late 1970s/80s. The reports are hard/impossible to find, thus information about the experiments and major findings from these experiments are based on the reference Buist et al. (2013).

A series of oil weathering and burn test were completed in metals pans designed to mimic melt pools at a test site near Yellowknife, NWT. The experiments showed good burning efficiencies (Belicek and Overall 1976 in Buist et al. 2013).

Another large study (Energetex 1977 in Buist et al. 2013) also including burning oil in melt pools found that wind (up to 7 m/s) as well as herding agents was able to herd the oil into ignitable slicks thicknesses. The oil was ignited and burned with burning efficiencies up to 85 %.

From an oil spill during the winter 1979/80 simulating a subsea blow-out taking place offshore Mckinley Bay, Beaufort Sea under landfast first-year sea ice the oil appeared during spring break-up (Buist et al. 1981 in Buist et al. 2013; Dickins and Buist et al. 1981 in Buist et al. 2013). Approximately 50% of the oil on the surface was ignited by use of igniters deployed by helicopters and burned. Individual melt pools were found to have a burning efficiency of 90%. The average burning rate was found to be 1 mm/min. This is somewhat lower than the rule-of-thumb for unemulsified crude oil on water of 3.5 mm/min (>3 m diameter) according to Buist (2000). As for the Energetex studies the oil was also found to be herded by the wind against the ice edges.
A few other studies also found similar burning efficiencies even in low air temperatures (-32°C), and for emulsions appearing during spring melt (63%). Further details can be found in Buist et al. 2013.
An experimental work took place on Svalbard in March-May 2006, where 3400 L of crude oil were released under first year sea ice (45 cm). After 23 days the oil was naturally appearing on the ice surface. The oil was ignited and approximately 2500 L were successfully burned. The average burning rate was found to be 3.1 mm/min and the burning efficiency was 96 % (Dickins et al. 2008).

5.2 Burning oil in broken ice/pack ice

The first documented test of *in situ* burning in broken ice took place in 1983 (Tier II large scale tests) showing that oil could be ignited and burned in broken ice (Buist and Dickins, 2003).

During 1984, 1985 and 1986 at The National Oil Spill Response Research & Renewable Energy Test Facility (OHMSETT) test burns (both laboratory scale and larger scale) were completed in broken ice, with different covers ranging from 30-90 % and different crude oils, both fresh and weathered (Smith and Diaz 1985a, b, 1987). The overall findings from the different tests were that it is possible to burn oil in broken ice, but highly emulsified oils with an increased flashpoint will inhibit the burning (Smith and Diaz 1985a, b, 1987). Lowering the water temperature was also found to reduce the burning efficiency and burn rates and minimum slick thickness was found to be 2.5 mm on cold water (2- 6.5 °C) (Smith and Diaz 1985b). The laboratory burning efficiencies ranged from 30-50 % whereas the test tank burning efficiencies were found to be between 85-95 %. This difference is considered to be due to the differences in the heat transfer regimes, that is depending on the poll diameter. A pool diameter above approximately 1 m should be considered as turbulent burning rate (Smith and Diaz 1985b).

In situ burning of crude oil (evaporated 10-40 L) in ice leads (1x 10 m, 5x 5 m, etc.) were completed in the test basins at Esso Research Ice Basin (30 m x 56 m) in Calgary, Canada (Brown and Goodman 1986; Brown and Goodman 1987). Important findings from these studies were that: oil herded by moderate wind into long narrow leads could achieve high burning efficiencies up to 90 %; flame spreading; burning rate and to some extent burning efficiency are reduced by the presence of brash ice (Buist and Dickins, 2003). Boil-over was also found in these experiments (Brown and Goodman 1986). Temperature measurements during the burning, showed a slightly increase of 5 °C found 3-8 cm below the water level. The wind was found to influence on the regression rates, where more wind resulted in a higher regression rate. This is considered to be due to the wind herding of the oil resulting in a more efficient heat transfer from the flames to the oil. However, brash ice was found to decrease the burn rate by impeding the heat transfer. The effect of the geometry of the lead was not as apparent (Brown and Goodman 1986).

Several small field tests were performed in the fjord ice at Svea, Svalbard, Norway (end of 1980s - beginning of 1990s). These tests included fresh water and weathered crude oils (Statfjord/Gullfaks). The primary focus of this research programme was to look into the burning of emulsions, the influence of wind and waves on the burning efficiency and finally to develop efficient igniters (Bech et al., 1992; Bech et al., 1993; Guenette and Wighus, 1996). Important findings from these studies were that emulsions can be ignited and burned having the right igniter. During some of the burns also heat flux densities and temperature inside the fire plume was measured (Guenette and Wighus 1996). Fluctuations in the flame temperature were found. This was explained by turbulent eddies in the fire plume and fluctuations in the fire intensity. Flame/smoke temperatures varied from 400-1300 °C. The maximum heat flux density was 400 kW/m^2, measured in a 15 m pool diameter and 6.8 meter above sea surface. Secondary burns was also seen in basins 1.5 and 3.5 meters away due to the relatively high wind (8-11 m/s) resulting in the flames being deflected directly over the neighbouring basins (Guenette and Wighus 1996). The paper Guenette (1997) compiles most of the information in relation to the tests done in Norway in the 1990s within *in situ* burning.

For burning in brash ice and high ice concentration high burning efficiencies have been obtained (Buist and Dickins, 1987). In 2002/2003 further tests (small scale and mid-scale) were completed to study the minimum ignitable thickness, combustion rate, residue amount and effects of waves on thin oil slicks burned in frazil or brackish ice (Buist et al 2003). The small pieces of brash, frazil or slush ice will accumulate with the oil against the larger ice floes and thereby control the thickness and spreading of the oil (Buist et al., 2003). Therefore, it is important to know the content of slush ice in between ice floes, and not only the solid ice forms, as often reported, since the slush ice concentration can significantly slow and limit the oil spreading even in low to moderate solid ice concentrations (Buist and Dickins, 2003). From Buist et al. 2013 a set of “rules-of-thumbs” are found based on these experiments; these are cited below:

- *The minimum ignitable thickness for fresh crude in frazil ice or small brash ice pieces is up to double that on open water, or about 1 to 2-mm.*
- *The minimum ignitable thickness for evaporated crude oil in frazil ice or small brash ice pieces can be higher than on open water, but is still within the range quoted for weathered crude on water, about 3-mm with gelled gasoline igniters.*
- *For a given spill diameter, the burn rate in calm conditions is about halved on relatively smooth frazil/slush ice and halved again on rougher, brash ice. Wave action slightly reduces the burn rate on open water, but the halving rule seems to apply in waves as well.*
- *The residue remaining on broken ice in calm conditions is about 50% greater than that on open water or 1.5-mm. The residue remaining in brash or frazil ice in waves is slightly greater than in calm conditions, at about 2-mm.*

The authors suggest that the differences between open water burns and burn in ice are due to the mass and heat transfer processes that are changed as a result of the presence of ice. The higher minimum ignitable thicknesses for burning oil on ice compared to water (no clear difference of ice type) might be a result of stronger heat loss to the ice stemming from an oil–ice interface pinned to temperatures close to 0 °C due to latent heat requirements for melt. It is speculated by the authors that the solid nature of the ice would restrict the convective flows within the oil (Buist and Dickins 2003).

The lower burn rate is explained as follows (citations):

“*When a thick slick on water is ignited, almost immediately some of the back-radiated heat begins to warm the underlying water. If the same slick is on ice, the substrate cannot begin to warm until it melts the ice. The colder slick would produce fuel to feed the combustion at a comparable slower rate, which would result in a smaller combustion zone (lower flames) and less heat radiated back to the slick to volatilize liquid oil. The physical differences in the interface created with oil on frazil and brash ice would explain the different burn rates measured for the two substrates. The surface of a frazil ice substrate is relatively smooth and involves smaller ice crystals; the surface of a brash*

ice substrate is much rougher and involves larger ice forms that would enhance heat transfer into the brash ice, compared with the frazil ice." (Buist and Dickins 2003).
The burning efficiencies were also lower for burning oil in brash ice as well as frazil ice compared to burning on water; again this is explained by the increased heat transfer processes from the oil slick to the ice below. Note that brash ice burns extinguished sooner than burnings in frazil ice (Buist and Dickins 2003).

A series of experiments (from laboratory scale to field-scale) were completed at Svalbard, Norway from 2006-2008 and in the Barents Sea (2008-2009) (large-scale experiments in the marginal ice zone east of Hopen Island). These experiments included studying the ignitability of different crude oils at different weathering degrees (Fritt-Rasmussen and Brandvik 2011) as well as testing chemical herding agents with oil in ice (Buist 2010). The result added knowledge to understand the window of opportunity for *in situ* burning in pack ice and the usefulness of chemical herders in relation to *in situ* burning (Sørstrøm et al. 2010).

Only two field experiments in large scale for *in situ* burning in broken ice are reported:

1. First (according to Buist and Dickins 2003) in 1986 at the coast of Nova Scotia, where two 1 m^3 crude oil (Alberta Sweet Mixed Blend) were released in close pack ice (90 % ice cover) with brash ice and burned with burning efficiencies of 93 % and 80 %.
2. Second in 2009 in the Barents Sea (see above) where 2 m^3 of crude oil (Troll Blend) were released in 70-90 % ice cover and burned after a couple of hours of weathering with success (95%) (Fritt-Rasmussen and Brandvik 2011). A picture of this field experiments is included in Figure 12.

Figure 11: Photograph of the large scale *in situ* burning of oil in broken ice (70-90 %) in the Barents Sea (Photo: J. Fritt-Rasmussen).

From the many studies the overall findings about the ice cover in relation to *in situ* burning can be concluded: The ice coverage is of high importance for burning oil in broken ice. 60-70 % – 90 % ice cover the ice will act as natural containment. Up to 30 % the oil will spread as in open water. In between those ranges the conditions are difficult as the oil can spread to some extent that will make additional containment necessary but not possible.

5.3 Burning oil in snow

According to Buist (2000) oil in snow can be burned with great success (up to 70 % snow). Other studies also show that it was necessary to pile the oiled snow into a volcano shaped pile and ignite it from the inside (Buist et al. 2013). An example found in Buist et al. (2013) can be seen in Figure 12. One of these studies was field experiments conducted by Sveum et al. (1991) on Svalbard. The overall findings were that 90-99 % burning efficiency were measured and that very low oil concentrations could be ignited by supply of additional fuel (promoter).

Figure 12: Burning oiled snow, that are piled into a volcano-shaped pile. From Buist et al. (2013), source Alaska Clean Seas.

5.4 Burning oil in ice cavities

More recently (2013-2015) a range of laboratory studies were completed at the facilities at Worcester Polytechnic Institute, US and funded by the bureau of Safety and Environmental Enforcement (BSEE), US to study the fundamental problem of burning oil in an ice-cavity from a fire science point of view. These studies focused on the burning of oil in freshwater ice cavities and included a range of different laboratory tests. According to the authors no research has been done before on burning of oil in ice cavities (Rangwala et al. 2013). In the following the most important are highlighted from these studies.

Bellino et al. 2013. Bellino, P.W., Rangwala, A.S., Flynn, M.R. 2013. A study of in situ burning of crude oil in an ice channel. Proceedings of the Combustion Institute, 34, 2539-2346.

The purpose of this laboratory experimental work was to calculate the mass loss rate of burning oil mixtures oil in ice channels with varying widths to determine the efficiency of the burning.

In the beginning of the burn, the oil was at a depth in the ice, where the burning was starved and burned inefficiently due to lack of air. The ice melt resulted in reduced ullage height and increased surface of burning fuel, both processes leading to increased mass loss rate. At a certain height the ice melts formed a lip in the ice. Two zones were identified in the mass loss burn rates: the first increasing from self-sustained burning to peak mass loss rate and the second phase seen by a rapid decrease in the mass loss rate, due to a thin oil slick and hence an increase in conduction losses.

The average mass loss rate was calculated to be 0.06 g/s. The main explanation for this low mass loss rate was considered to be the melting of the ice walls during burning, whereby the critical oil film thickness (for extinguishing) would be reached sooner. The melting of ice results in a dynamic environment that differs from that on open water.

Rangwala et al. 2013. Rangwala, A. S., Simeoni, A., Xiaochuan S. 2013. Burning behaviour of oil in ice cavities. BSEE report.

Three ranges of set-ups were studied; small-scale (5-15 cm) intermediate (15-30 cm) and large scale (~1 m). Burning of crude oil as well as octane was included in the studies. As part of the experimental work among other things convection, radiation and conduction (laterally and in-depth) were analysed during burning.

From the smalls-scale experiments:

According to the authors, burning of oil in ice cavities is dominated by the ice walls that act as a significant heat sink and particular for small cavities these losses can be considered as a considerable lateral heat loss. A simple conceptual drawing is made to illustrate the processes (Figure 13).

The study showed that the cavities must have a diameter larger than 4.5 cm; otherwise the heat losses to the surrounds are too high to sustain continuous burning.

Several small-scale initial trials were completed to determine the depth of oil and the fuel layer thickness to avoid spillage of fuel out of the cavities during burning. To avoid spillage, the fuel layer thickness (L) / the depth (H) (L/H) should be less than 0.5 to avoid spillage for ANS crude oil.

Lowering the surrounding temperature from 20 °C to -10 °C was found to lower the mass burn rate. To decouple the impact from the flames, the authors looked into the situation "*if a fuel in an ice cavity were exposed to a constant heat flux without the consequent burning*" by exposing only the oil in ice to external radiant heat flux from a conical heater. The results showed that the external heat flux applied (30 or 50 kW/m^2) resulted in the same final increased size of the cavity (going from 5 to 14 cm, which is in the same range as for the burning experiments). Based on this the authors suggest that the characteristics of the fuel, e.g. temperature, vaporisation, heat of gasification and viscosity, are more important for the ice melting rather than the heat feedback on the flame.

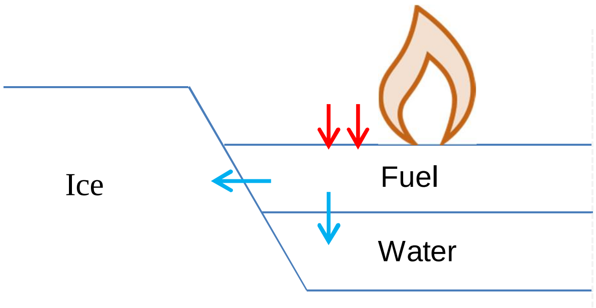
From the intermediate scale experiments:

Important focus was to ensure that the burning did not result in a breach of the ice (enough ice) or overflow of the oil. The breaching of the ice is related to the burning time, which again is related to the fuel thickness. Boil-over occurred in all the tests with ANS. The radiative heat flux was found to be increased by the oil slick initial thickness.

From the large-scale experiments:

The set-up consisted of a 1 m^2 ice cavity in a 3 m^2 ice block. Burning efficiency of 85 % and regression rate of 2.5 mm/min was measured. Boil-over was also observed and it appeared earlier than the smaller scale experiments. This is explained by the authors to be a result of less flow of cold melt water into the cavity.

The heat flux was measured at different stations around the cavity. A relatively low heat flux was measured close to the fire compared to the station more far away. This is explained by the strong convective air current that is being cooled by the ice, thereby also lowering the heat flux from the flames to the top of the ice. A lateral cavity was also formed; approximately 10 cm thick. The authors calculated that this lateral cavity could corresponds to 12 % of the fuel is potentially being trapped in that space.



Heat loss: conduction through the sides and bottom →
Heat input: heat from flames by convection and radiation →

Figure 13: simple outline of the heat release transfer mechanisms of burning fuel (based on input from Farahani et al. 2015).

Farahani et al. 2015. Farahani, h.F., Shi, X., Simeoni, A., Rangwala, A.S. 2015. A study on burning of crude oil in ice cavities. Proceeding of the Combustion Institute, 35, 2699-2706.

This study focused on burning of crude oil in small ice cavities, in laboratory scale experiments. The icy walls make out for a significant heat sink, resulting in lateral heat losses, particular for 5-10 cm cavities. This again leads to melting and increasing of the diameter of the cavity, resulting in a reduction of the fuel thickness, however also reduction of the ullage, due to rise of the oil. In other words the heat flux from the flames melts the ice, increases the cavity diameter, hence more burning surface of oil leading to increased mass loss rate. The impact of the wall is however found to decrease with increasing diameter of the hole. A strong coupling between mass loss rate and geometrical changes are hence found. During burning the ice is melted leading to a penetration of the fuel into the ice that creates a small ice lip.

Shi et al. 2016. Shi, X., Bellino, P.W., Simeoni, A., Rangwala, A.S. 2016. Experimental study of burning behaviour of large-scale crude oil fires in ice cavities. Fire Safety Journal, 79, 91-99.

This project studied burning behaviour of ANS (Alaska North Slope crude oil) in the presence of ice, in ice cavities having a diameter of 28 cm and 110 cm. The major findings were that the average burning rate is greater but the burning efficiency is much lower compared to burning without ice. The authors suggest that this lower burning efficiency is due to oil being trapped in pockets (lateral cavities that appear during burning) in the ice. The burning efficiency is also impacted by the initial oil film thickness and the size of the cavity.

Ice melt of the cavity walls during burning is due to the heat transfer from the hot oil to the ice and heat transfer from the flames to the ice surface. Due to ice melt, the oil was found to raise 3 cm during the burning, results from a study with a smaller cavity showed 7 cm rise. Therefore it is concluded that for larger fires the flame radiation have a relatively minor contribution to the expansion of ice cavities. The authors also suggest that the relatively high ullage (20 cm) and thereby low air entrainment are the reasons for this.

Boil-over was seen for initial diameters of the cavity larger than 25 cm. The measured heat fluxes for both sizes of experiments showed that boil-over significantly increases the heat flux. An increasing oil slick thickness was also found to increase the heat flux as well as the time to the boil-over phase and the intensity of the boil-over. The 1 m^2 burning experiment showed that the heat flux right at the ice edge was about 1/3 compared to the heat flux measured 30 cm further away. The authors conclude thereby that most of the heat flux from the flames goes outwards rather than to the ice.

For the oil tested, the top of the oil slick had a temperature of 150 °C during burning. In the vapour phase just above the oil the temperature was found to be 350 °C and the highest temperature measured in the flames were around 600 °C.

6 Knowledge gaps and concluding remarks

The aim of this project was to review relevant literature in the preparation for further research about *in situ* burning of oil in ice within WP 4 (Task 4.1.1). Thus, this review report gathers and compiles the relevant literature on oil in ice with focus on the behaviour of oil in ice and burning of oil in ice (*in situ* burning).

From the above review, it is evident that the research completed in relation to burning oil in ice primarily focused on small-scale and mid-scale tests in the laboratory or field trial test facilities. Very few large scale experiments are completed. The most studied ice conditions are static pack ice, however also research including burning of oil on the ice, in snow and in melt pools, released after being encapsulated in the ice until the spring melt have been conducted. Very few tests have been done in dynamic ice, however these studies indicated that burning is very sensitive to movements, the coverage of the ice, the thickness of the oil and where or not frazil/brash ice is present (Buist et al. 2003). The major focus on the experimental work has been to establish knowledge about the feasibility of the method, including knowledge about the burning efficiency, mass loss rate and more operational parameters such as ignitability, igniters, required oil slick thickness, weathering state /window of opportunity etc. Hence, very little have been done to understand the heat transfer mechanisms between the burning oil and the ice. It was discussed that the interface between oil and ice were more efficient at transferring heat from the oil to the underlying ice compared to the transfer of heat to underlying water (Buist and Dickins 2003). Hence also much higher initial oil slick thicknesses were required to burn oil on ice. Therefore increased knowledge about the link between ice and the heat feedback mechanisms from the burning oil is needed to fully understand the potential of burning oil released from the ice during spring melt. Also the link between oil release rate and the burn rate is not known. All such input is also important to be able to model the development of the ice during burning.

For specific burning of oil in ice cavities a range of studies were initiated in recent years.
These studies showed that a lateral ice cavity/lip forms during burning. A somewhat similar phenomenon was seen during burning of crude oil on the fjord ice on Svalbard in 2008. The oil was poured on the fjord ice and covered with snow before it was ignited after several hours. It was seen that the oil could burn in these lateral ice cavities for some time until they were starved (Figure 14). Thus, in relation to burning oil in ice more knowledge is needed to understand the driving mechanisms for this generation of lateral ice cavities.

Figure 14: Burning oil on top of the fjord ice on Svalbard. Note that the burning is actually taking place under the snow/ice cover in the lateral ice cavity that was made as a result of the burning of oil. Photograph: J. Fritt-Rasmussen.

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