EXPERIMENTS ON THE DETECTION AND MOVEMENT OF OIL SPILLED UNDER SEA ICE

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It has been suggested that over the next decade the Arctic is likely to attract substantial investment, potentially reaching $100 billion. This investment is likely to be concentrated in the shipping and hydrocarbon industries. Any increased shipping and oil exploration/exploitation in these ice-infested waters will elevate the likelihood of an accident and possible oil spill. However for the foreseeable future shipping and exploration for hydrocarbons in the Arctic is likely to occur during the summer open-water period. Consequently should an accident occur towards the end of this period, there is the possibility that oil could be distributed within a field of newly forming or formed sea ice. It is therefore important to understand the behaviour of oil under young or newly formed ice types. We present results from a controlled oil release under three new ice types, frazil ice, nilas, and pancake ice.

1. INTRODUCTION

As global temperatures continue to rise significant changes are occurring in the Arctic. The most spectacular is the retreat of summer sea ice which, if models are correct, may lead to the complete loss of the summer sea ice within a very short period of time, years to decades. However the loss of summer sea ice is not the only changes that are the ice is undergoing, for example we have seen a significant decrease in sea ice extent in other seasons (Stroeve et al., 2012), also to changes in ice type (Wilkinson et al., 2009), especially a dramatic reduction in multi-year ice (Comiso, 2012); a decline of more than 40% in sea ice mean thickness (Rothrock et al., 1999; Laxon et al., 2013); a reduction of 73% in the frequency of ridges just between 1976 and 1996 (Wadhams and Davis, 2000); and changes in ice dynamics (Rampal et al. 2009).

One of the manifestations of these changes is the alteration of the timing and length of the Arctic sea ice melt season i.e., the sea ice is melting earlier and freezing later (Rodrigues, 2008). The reduction of summer sea ice in the Arctic and extension of the Arctic navigation season has also reignited interest in the viability of the Northwest Passage (via Canadian waters) and Northern Sea Route (via Russian waters) for commercial traffic. Furthermore the increasing ease of access to the Arctic is expected to lead to intensification in the exploration and production of hydrocarbon products in ice-covered waters (AMSA, 2009). For example the United States Geological Survey (USGS) suggest that about 30% of the world’s undiscovered gas and 13% of the world’s undiscovered oil (Gautier et al., 2009); mostly in USA (Alaska), Russia, Canada, Greenland (Denmark) and Norway. If true we may see significant petroleum based activity in Arctic waters in the near future.

Arctic change gives easier marine access, which naturally leads to an increase in activities such as fisheries, shipping, tourism, oil/gas and mineral exploration and associated industrialisation, and urbanisation. A recent study by Lloyds suggests that over the next decade the Arctic is likely to attract substantial investment, potentially reaching $100 billion (Lloyds, 2012). However for the foreseeable future shipping and exploration for hydrocarbons in the Arctic is likely to occur during the summer open-water period. Should an accident occur towards to end of this period, there is the possibility that oil could be distributed within a field of newly forming or formed sea ice. It is therefore important to
understand the behaviour of oil under young ice, as well as the possibility to remotely detect the presence of oil under and within young ice types.

This paper summarises a series of experiments that were performed under three young ice types; these were a) frazil ice, b) nilas, and c) pancake ice. The experiments were performed in the Arctic Environmental Test Basin (AETB) facility at the Hamburgische Schiffbau-Versuchsanstalt GmbH (Hamburg Ship Model Basin; HSVA), Germany in December 2013.

2. EXPERIMENTAL LAYOUT

At present, it seems unlikely that governmental approval would be issued for full-scale evaluation tests involving a controlled oil release in ice-covered seas. In fact, *in situ* field studies are sometimes not ideal as they are subject to the environmental challenges, i.e. lack of control over environmental variables, and large logistical costs make it unrealistic to perform controlled experiments in the field. To avoid these limitations, controlled and repeatable experiments provide an opportunity to further our knowledge of the behaviour of oil under sea ice. These types of controlled experiments would be extremely difficult to perform under field conditions.

The aim of our experiments was to grow these ice types and characterise the behaviour of oil and evaluate potential detection approaches under these ice types. To date very little information is available on the behaviour of oil spilled within these ice types. This is because there are very few large-scale facilities that have the ability to both grow sea ice and allow the spilling of oil are few.

2.1 Experimental set up

The Arctic Environmental Test Basin (AETB) is a 30m long, 6 m wide, and 1.5m deep basin in a climate controlled chamber. In order to provide the ability to perform experiments involving frazil, pancake and nilas the AETB was sub-divided into three separate regions (see Figure 1). This same tank set up has been used successfully for frazil, nilas and pancake experiments in the past (see Wilkinson et al., 2009).

Tank 1 was the quiescent tank and as such it was our aim to grow nilas in this tank. Tanks 2 and 3 had independent wave-makers installed and we aimed to grow frazil and then pancake ice in these tanks.

Unfortunately due to the heat exchange through the far wall and view port windows of the facility, significant ice formation was not achieved in tank 1, and thus the nilas experiments were performed in tank 2. At the bottom of each tank ‘train tracks’ allowed a ‘train/trolley’ to run along these tracks equipped with various sensors to be tested. The simultaneous mounting and recording of various sensors mounted on the trolley enables each sensor to be directly compared to each other as well as ensuring that each sensor’s ability to detect oil is evaluated under the same environmental conditions. A moderately stiff plywood divider separated tanks 2 and 3.
For the spill experiments, “medium” crude was used, as this had properties similar to that of Alaskan North Slope crude (see table 1 below). These include a density of 0.856-0.890 kg/m$^3$, viscosity of 11.5 cSt (at 30 °C), and a pour point of -9 °C. The oil was deployed at temperatures of about 5 °C, so that melting of the ice by the oil was minimal. This also meant the oil was fairly viscous when spilled. A total of three oil spill experiments were carried out in tank 2 and 3.

<table>
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<th>Characteristics of Alaska North Slope and medium crude oil.</th>
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2.2 Oil injection system

The oil injection system used at HSVA can be seen in Figure 2. For each spill 10 litres (for frazil and nilas) or 5 litres (for pancake) of crude oil (at 5 °C) was poured into the funnel from pre-measured 10 litre cans. Care was taken that no air was introduced during this procedure. When the oil left the hose (diameter 5 cm) it separated into globules that rose up to the underside of the ice. The whole procedure took only a few minutes.
3. INSTRUMENTATION

The following sub-section describes the instrumentation deployed in the tanks.

3.1 Camera systems:

The camera systems in operation were a mixture of GoPros, a High-Definition underwater video camera, an IR camera, as well as a selection of hand-held digital cameras.

1) Three GoPro cameras were mounted overhead (looking down towards the tank) to image the ice and oil from above. These were placed at different locations along the whole length of the tank and took images at one minute intervals. These were generally in operation for the duration of the experiments.

2) Three GoPro cameras were mounted on the tank bottom looking upward toward the ice bottom. They also captured photographs at one minute intervals. Two of these cameras failed during the course of the experiment, but upward-looking imagery was obtained during most experiments.

3) An additional GoPro camera was mounted on the instrument trolley to provide location information and imagery of each experiment.

4) A high-definition underwater video camera was used to monitor each oil spill from below during the spill.

5) An infrared camera system was clamped to an overhead rail.

6) The participants used hand-held digital cameras to capture images of the experiments at different times and locations.

3.2 Sonar systems:

1) Two sets of AQUAscat 1000 (http://www.aquatecgroup.com) narrowband sonar transducers were deployed at different positions on the tank bottom. Transducers operated at nominal frequencies of 300 kHz, 500 kHz, 1 MHz, 2 MHz, and 5 MHz. One set of transducers was moved to the mobile instrument trolley during the spill experiments.

2) Two sets of broadband transducers at frequencies of 350-565 kHz and 700-1050 kHz.

3) A Teledyne/Odom MB1 multibeam sonar system was deployed on the mobile trolley to provide sonar imagery of the ice underside of the ice and to explore the feasibility of estimating the angular dependence of the acoustic scattering.
3.3 Optical systems:

1) Three TRIOS hyperspectral radiometers were deployed to investigate the spectral attenuation and scattering of light through the oil spills. One irradiance and one radiance sensor were deployed on a mobile trolley, and one irradiance sensor was deployed above the ice to measure the incoming radiation field.

2) The Woods Hole Oceanographic Institute (WHOI) laser fluorometer was deployed on a separate mobile trolley and profiled the underside of the ice after the oil spills.

4. YOUNG SEA ICE TYPES

For more information on sea ice the reader is referred to various academic texts dealing with the subject i.e. Wadhams (2000), Thomas and Dieckmann (2010), Weeks (2010). Below we provide a basic summary of the first stages of sea ice formation.

Once the surface of the ocean is cooled to its salinity-determined freezing point any additional heat loss produces a slight super-cooling of the water after which the formation of loose crystals known as frazil ice occurs. If both the wave and wind effects are reduced the agitation of the frazil ceases and the surface layer of frazil crystals can preferentially fuse together to form a level, thin ice cover known as nilas. This cycle is known as the frazil-nilas-ice sheet cycle. Further thickening will then occur by freezing of seawater on the underside of the ice. This downward growth process is known as congelation growth and, barring mechanical deformation of the ice sheet, the ice will form a relatively level, uniform ice sheet. Due to spatial variability of ice properties and snow cover there will invariably be some small-scale variability in ice thickness, even for very uniform ice.

However, if some kind of turbulence within the upper surface layer of a body of water persists (i.e. generated by wind, wave or current), then a different ice formation scenario occurs. This turbulence promotes a specific ice development process as the waves or swell inhibit the formation of large sheets of nilas, but do allow the frazil crystals agglomerate into small clumps. As these grow through continued freezing of frazil, they are buffeted by waves and contact with other ice clumps, so that they form small rounded pans, or “pancake ice”. As the wave energy is damped by the ice, the pancakes will begin to freeze together, eventually forming a consolidated sheet. Further thickening will occur via congelation growth on the ice bottom. This is known as the frazil-pancake-ice sheet cycle.

Once a continuous ice sheet is formed it is collectively known as first-year ice (FY). FY ice formed at the start of the winter will be between 1 and 2 m thick by the start of the following melt season, and be relatively smooth in appearance. FY ice that survives the summer melt then becomes known as multiyear ice (MY). MY ice can be many years old, is generally thick, and can be heavily deformed. It is important to remember that sea ice is in a constant state of flux, due to changing atmospheric and oceanographic conditions. Not only does the sea ice increase and decrease in thickness with the seasons (thermodynamic growth and melt processes), but mechanical redistribution of sea ice is common. Idiosyncrasies in the drift of sea ice allows the ice to be jammed together to form ridges, or is forced apart to form leads. All these changes in the morphology of the sea ice are reflected in the underside ice topography.

Within these experiments we grew only the young ice types. These were frazil, nilas and pancake ice. The section below describes three ice types.

4.1 Frazil ice

As mentioned previously frazil ice is the first stage of sea ice formation. The size of frazil crystals range from 0.05 to several millimetres in freshwater (Daly and Colbeck, 1986), and 1 to 10 millimetres in seawater (Weeks, 1998). As long as heat is being removed at a rate greater than that introduced to the system by the latent heat of fusion released during ice formation, frazil will continue to be formed through secondary nucleation. Within the laboratory, rates of frazil production have been shown to be 30 to 100 times greater in the presence of turbulence than when quiescent conditions prevail (Voropayev et al. 1995).
4.2 Nilas

If both the wave and wind effects are reduced the agitation of the frazil ceases and the surface layer of frazil can begin to consolidate. Furthermore, the upper frazil layers also have a greater propensity for heat loss because they are exposed to the cold atmosphere. This, in turn, enables them to grow, and fuse to form nilas. Nilas is observed to be extremely plastic and can easily bend to accommodate a small incoming wave field. Further thickening will continue as a unidirectional process by which seawater freezes directly to the underside as heat is conducted through the ice. This is known as columnar ice growth, and is the start of sea ice forming a continuous, thick sheet.

4.3 Pancake ice

If the wind decreases but the swell (waves) persists, frazil will continue to be agitated. Under the influence of the motion of the waves this newly formed crust of ice does not form a continuous sheet but is broken into small rounded pancake shaped pieces normally a few tens of centimetres in diameter. Around the circumference of pancake ice is a raised ridge initially 1 or 2 cm higher than the surrounding plane of the pancake. These rims are formed by the piling of frazil ice around the edges of the pancakes by the general jostling and collisions between pancakes and the cyclic pressure pulses of the wave field. Once the incoming wave energy has decayed sufficiently pancakes will freeze together, with the frazil between the pancakes acting as the adhesive, to form an extensive sheet.

5. RESULTS

5.1 Frazil ice spill

On 17 December 2013, a 10-litre controlled release of crude oil was performed under the frazil layer in tank 2. At this time the frazil layer was about a week old and the air temperature was below freezing. To produce the frazil ice we constantly ran the wave-maker at a frequency of 0.65 Hz. Before we spilled the oil the thickness of the frazil layer was measured as 8 cm (see Figure 3). The frazil layer was a loose aggregation of independent frazil crystals, with no evidence of the formation of pancakes.

Oil was spilled below the frazil layer within a wave-field present (0.65 Hz). Due to the buoyancy of the oil it floated up to the bottom of the frazil layer. Once at the bottom of the layer the oil did not spread laterally across the bottom of the ice, as with other ice types, but penetrated the frazil layer until it reached the uppermost frazil layer i.e. at the seawater surface. Once the oil was at the surface it spread horizontally across the upper surface of the frazil/seawater (Figure 4).

Once the release had been completed the wave maker was turned off in Tank 2 and the surface began to solidify to form nilas (see experiment: Nilas). Once the frazil had frozen together to form a continuous sheet three ice cores were taken (see Figure 5) (1) from near the centre of the spill, (2) from the edge of the spill, and (3) in clean ice away from the spill. These cores were placed in a deep freezer (-20°C) for 24 hours. In order to determine how the oil had penetrated the frazil layer thick sections were made from these cores. Results from these cores also suggested that the oil was only located within the upper surface of the ice (see Figure 6).
This scenario was unexpected and whilst we are still elucidating the exact mechanisms by which the oil was able to penetrate through an significant layer of frazil ice. We hypothesize that it due to the cyclic compression and relaxation mechanisms of passing waves. Field observations by Reimnitz and Kempema (1987) showed that the upper frazil layers are less agitated than the lower layers and thus it is this agitation of the frazil crystals that may allow the oil (as a buoyancy driven flow) to quickly penetrate through the frazil ice. Whether there is an upper limit on the thickness of the frazil that this process can occur is not known at this time. This very interesting result suggests that an oil spill occurring within an ocean dominated by frazil ice will most likely be confined to the surface layer of the sea ice.

5.2 Nilas ice spill

Once the wave generator in Tank 2 was turned off the sub-zero air temperature enabled the frazil to begin to freeze from the surface downwards. This produced an ice sheet of nilas. Given the thickness of the frazil layer (~8 cm) and that less than a day had elapsed only the first few centimetres of the ice were solid, with a loose aggregation of frazil crystals beneath.

On the 18th December 2013 (the day after the frazil experiment) a 10-litre release of crude oil was performed under this nilas sheet. Even though the ice conditions were very similar to the frazil ice spill, the results were very different. Once the oil was released it spread into a roughly circular patch along the underside of the ice (Figures 7 and 8). However, it was clear from the images that the bottom topography was an irregular, undulating surface and this impacted the spread of oil. There was some visual evidence of oil migrating upwards through brine channels.

The results were very different to the previous oil in frazil ice experiment as the lack of wave energy inhibited the oil migration to the surface. The oil stayed at the bottom of the ice as can be seen in the figures above. However it looked like there was some migration toward the surface at discrete points, and it was this migration that produced the spotty nature to the image below.
At with the frazil experiment, three ice cores were taken (see Figure 7) one from near the centre of the spill, another from the edge of the spill and a final core in clean ice away from the spill. These cores were placed in a deep freezer (−28°C) and thick sections were made from these cores. Results confirmed that the oil was contained at the bottom of the ice. However further sectioning of these cores provided evidence of the upward percolation of the oil through the porous ice (see Figures 9 and 10).

## 5.3 Pancake ice spill

Tank 3 was designated as the pancake ice tank. With the wave-maker continuously running for over a week the ice generated within this tank went though the process of forming frazil ice and then evolving in to pancake ice. At the time of the oil release the pancakes were between 20 cm and 50 cm in diameter, and around 10 cm thick.
In the late afternoon on 18 December 2013 a 5-litre spill of crude oil was performed amongst the pancakes. The same technique was used to introduce the oil to the underside of the ice as with the other experiments. Once the oil left the hose the globules rapidly rose to the underside of the pancake. When the oil was in contact with a pancake it immediately flowed around the underside to gather in the open water region between individual pancakes (Figures 11 and 12). Interestingly the oil did not seem to ‘stick’ to the underside of the pancakes at all.

![Figure 11. Tank 3 showing the pancake ice before the oil spill.](image1)

![Figure 12. Tank 3 showing the pancake ice after the oil spill. The blue boxes indicate where cores were taken and frozen for further analysis.](image2)

The cyclic motion of the pancakes, as the wave propagated through the pancake field, caused the open water region between pancakes to contract (at the wave trough) and then expand (at the wave peak). This concertina action had two influences on the behaviour and movement of the oil. These were:

1) The wave action accelerated the spread laterally around the pancakes.

2) The wave action enabled oil to be pumped over the rims of the pancakes. Once over the rims the oil quickly spread over the surface of the pancakes.

As with the spread of oil within the frazil ice it seems that the incoming wave field plays a critical role in the spread of oil within a pancake field.

6. SUMMARY

Initial results suggest that oil behaves very differently when spilled under various types of young ice (frazil, nilas, and/or pancake ice). This difference in behaviour suggests that some detection sensors will be more beneficial than others in detecting oil located under, within, and on top of, these ice types. Some of the more interesting discoveries regarding the behaviour of oil for each ice type were:

**Frazil**: Unlike other sea ice types the oil was able to penetrate through the frazil mixture and spread out along the ocean/ice surface. This was due to the combination of the loose nature of the frazil mixture, and importantly the presence of a wave field.

**Nilas**: Once sea ice crystals freeze together to form a continuous sheet of ice over the ocean surface our results suggest that it acts as a barrier to the surface migration of oil. No evidence of oil on the ice surface was seen during the nilas spill, although evidence of a vertical migration of oil through brine drainage channels were documented through the analysis of ice cores. In the absence of waves it was interesting to see that the loose frazil layer at the bottom of the nilas was able inhibit much of the vertical migration of oil. Under this ice type most of the oil spread out latterly along the ice bottom.

**Pancake ice**: The spread of oil in a pancake field was different again. Cameras located on the bottom of the tank revealed that the deployed oil flowed around the bottom of the pancakes and gathered in the open regions between the cakes. The oil then continued to spread in the
area between adjacent pancakes. In certain cases the wave pumping allowed the oil to breach the pancake rims and spread latterly across the upper surface of the pancake. There is still much to be analysed within this unique dataset, but these tests revealed the importance of waves in controlling the spread of oil under young ice types. Furthermore the multi-sensor approach (sonars, visible cameras, IR camera, laser fluorescence and radiometers) we conducted means that we will be better able to understand the temporal and spatial evolution of oil dispersal under different types of newly formed sea ice.

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