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Svalbard 2006 Experimental Oil Spill Under Ice: Remote Sensing, Oil Weathering Under Arctic Conditions and Assessment of Oil Removal by In-situ Burning

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ABSTRACT

This paper describes the findings from an experimental spill of 3,400 liters of Statfjord crude under first-year sea ice in Svalbard, Norway in March 2006. The objectives were to:

1. Test commercially available radar and acoustics systems in detecting oil spilled under ice.
2. Document the weathering processes governing crude oil behaviour in ice.
3. Evaluate the effectiveness of in-situ burning as an oil removal strategy.

The results of this project will be used in planning new Arctic oil exploration and development programs. With the growing awareness of the Arctic basin as a potentially important province for new oil and gas discoveries, there is a critical need to: (1) develop new technologies to detect and map spills under ice; (2) increase the understanding of oil behaviour in ice and: (3) continue to demonstrate the capabilities of in-situ burning as an important and safe Arctic response tool.

Tank tests conducted in 2004 (Dickins et al., 2005) showed that radar systems could detect and map oil pools as thin as 2 to 3 cm under controlled conditions under model sea ice up to 40 cm thick. This field experiment created a much larger-scale spill under thicker 65 cm natural sea ice to further evaluate potential remote sensing systems as practical operational spill response tools.

The findings of the 2006 experiment: (1) demonstrated for the first time the ability of ground penetrating radar to detect and map oil under natural sea ice from the surface; (2) documented oil weathering with a relatively warm ice sheet under spring conditions; and (3) proved the effectiveness of in situ burning as a primary oil removal strategy under Arctic conditions.

Oil weathering results are discussed and compared with small-scale field experiments performed on Svalbard during the period 2003 – 2006. Low temperatures and lack of waves in ice act to reduce oil spreading, evaporation, emulsification and dispersion. As a result, the operational time window for several spill response strategies such as dispersants and in-situ burning may be significantly extended compared to oil spills in open water.

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Reports from this project are available for download through the MMS website http://www.mms.gov/tarprojects/569.htm

BACKGROUND

Detection and Mapping Oil Under Ice

A concentrated research effort in the 1980's analyzed and tested a variety of technologies such as radar, electromagnetic and acoustics to detect oil in or under solid ice. Dickins (2000) summarized the state of the knowledge, based on these historical results. Unfortunately, none of the older research led to a practical operational system that could provide a reliable means of detection in an actual spill situation. This deficiency is recognized as a priority research area in terms of advancing future Arctic spill response (Dickins, 2004). With the rapidly increasing interest in Arctic oil exploration and development expected over the next decade, solutions to the problems of oil in ice detection are likely to remain a high priority.

In response to this ongoing requirement, the Minerals Management Service (MMS) sponsored the continued evaluation of several potential oil and ice detection systems through a series of tests at the US Army Cold Regions Research Environmental Laboratory in Hanover NH (Dickins et al. 2005) and over natural sea ice off Prudhoe Bay, Alaska (Dickins and Bradford, 2005). This work provided a basis for the 2006 field evaluations reported here.

Oil in Ice fate and Behavior

An extensive body of research over the past 20 years includes laboratory studies and field experiments aimed at understanding the fate, behavior and weathering processes for oil spilled under arctic conditions. Much of this research was performed in the US, Canada and Norway. Smaller experimental oil releases including fresh and emulsified crude under solid ice (up to 6 tonnes per spill) were performed in 1974, 1979, 1981 and 1983 (e.g. NORCOR, 1975, Dickins et al., 1981, Comfort *et al.*, 1983). The first experimental spill in broken ice was carried out in 1986 on the Canadian East Coast (SL Ross and DF Dickins, 1987). This project was followed in April 1993 by the first large-scale experimental oil spill (26 m^3) under Arctic pack ice conditions performed in the Barents Sea marginal ice zone (Vefsnmo and Johannessen, 1994; Brandvik *et al.*, 2004). No further experimental spills have taken place in broken ice since that time.

These earlier field experiments proved invaluable in understanding weathering processes of oil in a variety of spill scenarios (including a simulated subsea blowout) and environmental conditions (including wind, waves, ice conditions, drift and spreading in the marginal ice zone). These studies showed clearly that different oils have different weathering properties under Arctic conditions at sea compared with spills under more moderate temperatures as summarized in Payne et al. (1991). Field observations regarding weathering at low temperatures and in broken ice were also studied in small and meso-scale lab facilities (Singsaas *et al*, 1994).

Several reports give a good overview of the state of knowledge regarding oil fate and behavior in ice (e.g., Løset *et al*., 1994 and Vefsnmo *et al*., 1996). Work to date has led to a good general understanding of the key processes controlling the behavior of fresh and emulsified crude oil in a variety of ice conditions including landfast and broken pack ice. However there is still much to be learned, for example about the detailed processes of oil encapsulation and migration under different climatic conditions, and the behavior of different oil types in a range of possible ice regimes.

In-situ Burning as an Arctic Spill Countermeasure

The consensus of research on spill response in broken ice conditions is that in situ burning is often a highly effective response technique in both solid and broken ice conditions, with removal rates exceeding 85 percent in many situations. Experience includes burning oil on melting solid ice and in pack ice and slush during relatively large field experiments (e.g., Norcor 1975, Dickins and Buist 1981, Shell et al. 1983, SL Ross and DF Dickins 1987, Singsaas et al. 1994). Research has also demonstrated the potential for in situ burning in broken ice through several smaller-scale field and tank tests (SL Ross et al. 2003, Shell et al. 1983, Brown and Goodman 1986, Buist and Dickins 1987, Smith and Diaz 1987, Bech et al. 1993, Guénette and Wighus 1996), and one large field test (Singsaas et al. 1994).

SCOPE AND OBJECTIVES

This study incorporated the following objectives focused on the technical areas of remote sensing and oil weathering behavior.

Remote Sensing

The 2004 CRREL tank tests showed that GPR systems could detect and map oil pools as thin as one inch (2 to 3 cm) under controlled conditions under model sea ice up to 40 cm thick (Dickins et al., 2005; Bradford et al. 2005). The Svalbard field experiment created a larger-scale spill under thicker natural sea ice to further evaluate potential remote sensing systems as practical operational tools by expanding the operating boundaries (spill size, ice thickness, airborne measurements). Primary objectives of the remote sensing study components on Svalbard were to:

- Test a second-generation radar system incorporating improvements in reliability and software with crude oil spilled under thicker sea ice (up to 1 m) and over a large enough area to allow airborne (helicopter-mounted) measurements at low altitude in addition to surface 2-D and 3-D surveys.
- Test currently available acoustic technology, building on earlier success in Canadian trials from the 1980's and utilizing the latest processing hardware and software with a new approach to coupling the transducers to the ice surface through a water film.

Oil Fate and Behavior in Ice and Clean-up Effectiveness

Scientific and engineering objectives in the areas of oil behavior in ice and the implementation of effective clean-up strategies included:

- Documenting the vertical migration rate of oil as a function of air and ice. temperatures and ice crystal structure, salinity and brine volume.
- Mapping and documenting oil distribution and spreading under the ice.
- Documenting the rate and extent of oil encapsulation following the spill
- Documenting migration of water-soluble components through the ice, and evaporation and possible emulsification on surface melt pools.
- Evaluating the effectiveness of in-situ burning when the oil surfaces in spring.

TEST LOCATION AND LAYOUT

SINTEF applied for approval to carry out the experiment through the Governor of Svalbard's environmental section. A permit was granted on February 16, 2006 based on positive experiences with previous oil spill experiments carried out on Svalbard by SINTEF and UNIS. The 2006 spill took place in a fjord on the island of Spitsbergen part of the Svalbard group administered by Norway and centered on 78° North Latitude in the Norwegian Barents Sea (Fig. 1).

SINTEF's field station at Sveagruva, "Polartun", was used as a base for the fieldwork. Svea is the main coalmining site on Svalbard. Figure 2 below shows the relation of the experimental site on the ice to the field station (10 min by snow machine).

Figure 1: Map of Svalbard showing the main island of Spitsbergen, the principal population center Longyearbyen, and the research location at Sveagruva.

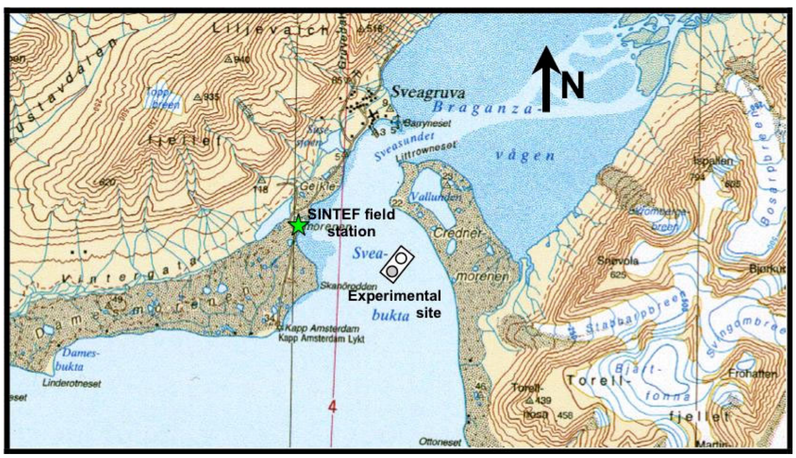

Figure 2: Location map showing the field station and the experimental site near the coal mine at Sveagruva.

The experiment was designed around the concept of a controlled oil release under ice with sufficient surface area, volume and film thickness to permit measurements at a realistic field scale. In this experiment the oil was held in place under the ice by a circular plastic skirt inserted through the ice. Two weighted spill containment skirts were installed as 11.2m diameter circles (area 100 m^2) through 45 cm ice, in late February 2006. Total skirt material length was 40 m to allow sufficient overlap and prevent leakage. The skirt depth of 150 cm allowed for ample material hanging beneath the ice to reliably contain the oil. The two test areas (one intended for the spill and one as a control) were installed in line with the prevailing wind direction approximately 30 m apart (Figure 3).

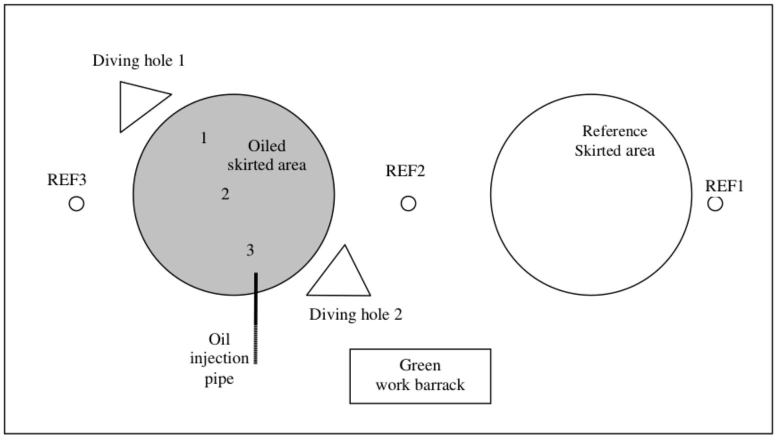

Figure 3: The relative position of the two skirted areas and the sampling positions. The shaded area held the oil; the other was used as a reference and back up.

SUMMARY OF KEY RESULTS

The full volume of 3,400 liters of Statfjord crude oil was successfully released on schedule, and fully contained within a skirt inserted through the ice. Divers measured the oil film thickness distribution under the ice using a specially developed probe (Figures 4 & 5 below). Monitoring of the oil under the ice also used through-the-ice video cameras inserted through holes around the skirt perimeter.

The average theoretical film thickness based on the size of the skirted area (100 m^2) and the amount of oil released (3,400 l) was calculated as 3.5 cm. However, natural variability in the ice thickness (±5+ cm on average) created deeper pockets of oil in some areas. The field data measured on-site by the divers are given as blue numbers in Figure 4 and the interpolated thicknesses in black numbers. The average difference between interpolated and measured data is < 5%. The "bi-modal distribution" of the oil film in two areas with significantly higher thickness than the rest of the area (14 to 18 cm measured), might be explained by the position of the release pipe and maybe changing tidal currents during the oil release.

The volume of the interpolated oil layer thickness (inside the circle) shown in Figure 4 is approximately 4,030 liters. This corresponds to an average film thickness of 4.1 cm, or approximately 20% higher that the theoretical thickness based on area and spill volume. This is probably due to an overestimation of the thick areas based on a limited number of field measurements in the thick areas (blue numbers in Figure 4).

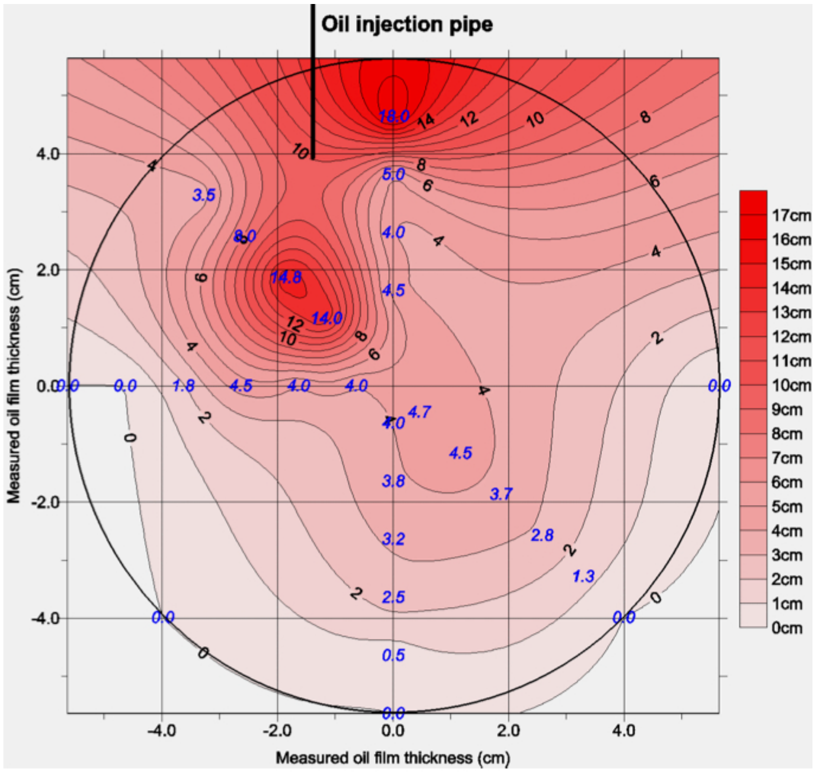

Figure 4: *Under-ice oil film thickness. Field data acquired by divers are given in blue italics, interpolated curves (Krieging algorithm) and estimated thicknesses in black numbers (cm). The circle represents the skirted area. No significant amount of oil was spilt outside this circle.*

Figure 5: *Diving operations to monitor the oil layer thickness under the ice.*

The following section highlight key results within each of the three research areas.

Remote Sensing

Ground Penetrating Radar: Surface-based ground-penetrating radar (GPR) operating at 500 MHz clearly delineated changes at the ice water interface caused by emplacement of oil. Further, this experiment demonstrated that GPR operated from the ice surface is capable of differentiating oiled regions of the ice under surface from the background response. Based on a qualitative comparison of the measured oil thickness distribution and radar results, it appears that the lower detection limit at a frequency 500 MHz is on the order of 1 to 3 cm oil film thickness. Results are consistent with the analysis of 500 MHz data from the controlled test at CRREL completed in 2004 (Dickins et al., 2005). Further details are provided below.

Three-dimensional surface-based (3D) GPR surveys were conducted before and after oil emplacement (Figs. 6 & 7). The data were acquired along 42 profiles in an orthogonal grid with 21 profiles in each direction. The orthogonal grid was important to test for azimuthal anisotropy in the GPR response related to preferred orientation of ice crystal formation. The total grid size was 20 x 20 m with GPR profiles on 1 m centers, with an inline trace spacing of 5 cm. Data were acquired continuously by reversing the direction of acquisition for every other profile.

Data processing included a time zero correction to account for system padding and drift, a high pass filter (sliding median subtraction with window width equal to twice the period at the characteristic antenna frequency), and relative amplitude gaining (data scaled to t^2). Additional processing steps included subtracting the background data from the data acquired after oil emplacement. This step highlights reflection amplitude changes due purely to the presence of oil. The differencing step was done by taking the absolute value of the Hilbert transform of the data. The Hilbert transform is a complex representation of a time series, and its computation allows computation of the total energy contained in a signal, the phase or shape of the signal, and details of the signal spectrum. This operation is a better measure of the total reflected energy and eliminates effects due to phase rotation of the recorded waveform that may be induced by the introduction of a layer that is thinner than the wavelength of the signal.

After oil emplacement, the radar reflection from the base of the ice within the containment skirt undergoes a 180° phase rotation. This obvious change in the reflectivity occurs because crude oil has a much lower dielectric permittivity (K~2) than either sea ice (K~5) or seawater (K~87) so that displacement of sea water with oil significantly alters the dielectric permittivity structure of the system. The reflection coefficient changes from positive to negative at the base of the ice since oil has a higher velocity (lower permittivity) than ice or water. The reflection from the base of the oil pool was evident as a low amplitude reflection with the same polarity as the ice/water interface reflection outside the containment area.

As the oil thins toward larger x and y values, the oil film is no longer clearly resolved, but the team recorded a reflectivity anomaly that is a tuning response due to the presence of the oil film. Figure 8 shows the amplitude difference from background along the profile at x= 12 m which clearly highlights the oil induced reflectivity anomaly. This tuning response occurs in areas where the oil film is thinner than about ½ a wavelength of the signal (~13 cm) and is a maximum at ¼ wavelength (~7 cm).

Figure 6: *Team conducting GPR data acquisition along established gridlines with the 500 MHz system (see also Fig. 7)*

Figure 7: *Close-up of GPR 500 MHz antenna. Note grid lines.*

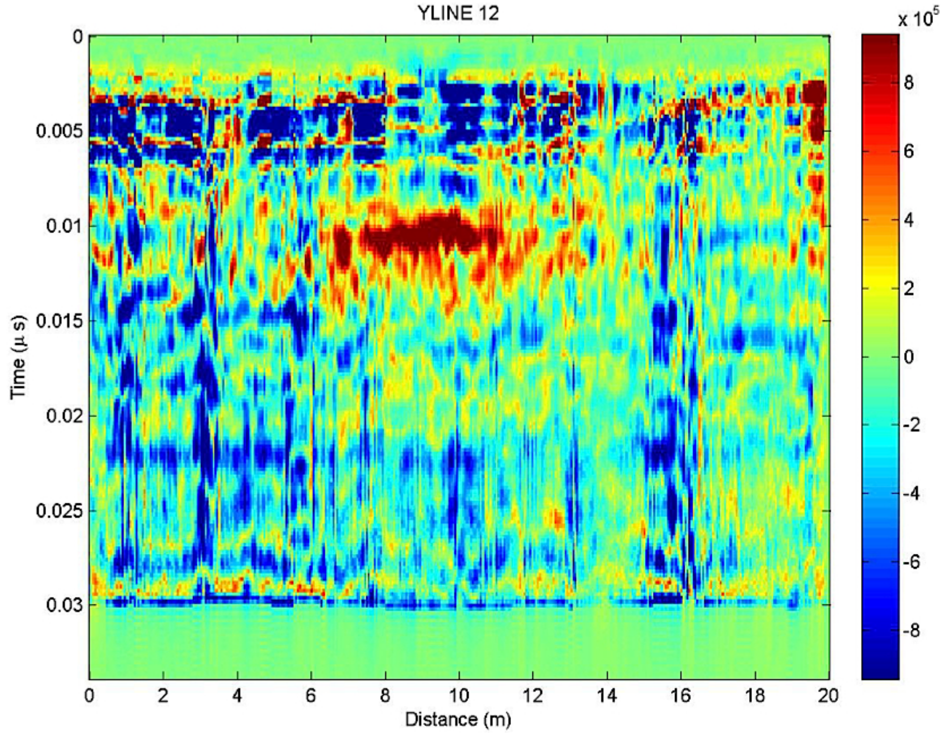

Figure 8: Difference image at x=12 m. The oil-induced change is obvious as a large high amplitude anomaly near the center of the profile at 0.01 microseconds.

Different radar imaging attributes are sensitive to varying thickness of oil films. A phase change (or change in the reflected wave shape) was observed over most of the containment area after oil was emplaced and may prove to be the most robust indicator of the presence of oil. The phase change was most prevalent in the area of thick oil where reversed polarity was observed. A high amplitude response was observed in areas where the oil film thinned and reflections from the top and base of the ice interfere.

Optimal radar detection of trapped oil in an uncontrolled setting will require simultaneous computation and analysis of each of these waveform attributes. Software developed under an earlier phase of this project is designed with this capability (Bradford, 2005).

In addition to lateral heterogeneity at the surface and within the ice matrix, complexity at the ice/water interface has a significant impact on the GPR attributes. Deterministic measurement of these variations is exceedingly difficult but would be required to compute oil film thicknesses from the measured GPR response. Therefore, while it is possible to determine whether oil is present or not, it is considered unlikely that meaningful measurements of film thickness can be made under typical field conditions.

The airborne radar tests were not as definitive, however it does appear that the 500 MHz system is capable of penetrating at least 0.65 m of relatively warm sea ice and the potential to detect oil from an airborne platform with higher-power radar systems in the future looks promising. At a frequency of 1000 MHz, it is possible to image the snow pack and snow ice interface in detail from a low altitude airborne platform (5 to 10 m), suggesting a strong potential to detect oil at the ice/snow interface with existing off-the-shelf systems (see Figs. 9 & 10). There is a broad application for GPR in this role, as evidenced by a recent decision by Alaska Clean Seas to purchase a dedicated GPR system for detection of future accidental spills under snow originating from above-ground pipelines on Alaska's North Slope.

Figure 9: The airborne system configured with the 500 MHz antennas, which are visible between the skids. The antennas are connected via coaxial cables to the recording system within the cabin.

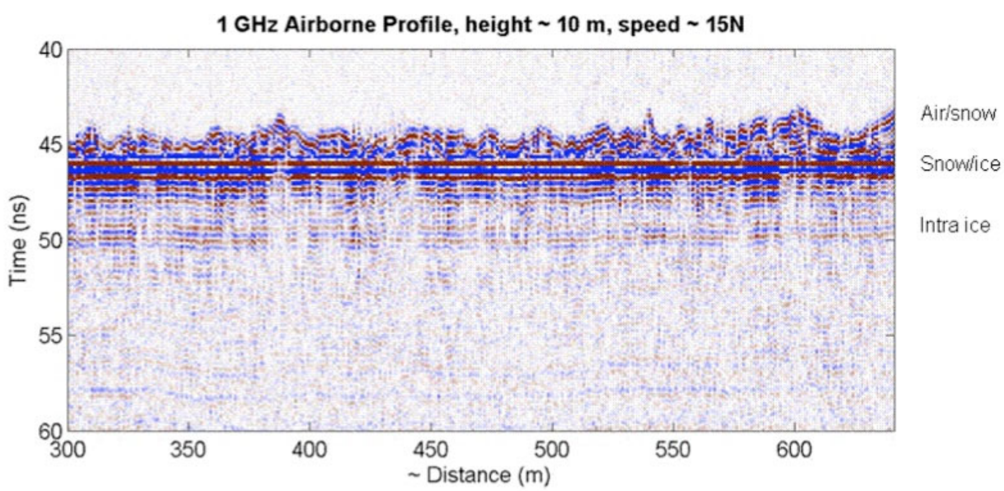

Figure 10: Airborne Data acquired over the test cells using the 500 MHz airborne configuration. The phase rotation from the base of ice reflection is evident in the oiled cell on the left. The interpretation is somewhat ambiguous due to the presence of reverberation with comparable amplitude to that of the event interpreted as the base of ice. This may be multiples from within the ice column. The data were flattened to the snow/ice reflection.

<u>Conclusions</u>: Ground Penetrating Radar was successfully deployed from the ice surface to detect and map the presence of oil under 65 cm of ice. In summary the radar results demonstrated that a well-defined, measurable anomaly is induced by the presence of oil films as thin as 1-3 cm under the ice. The surface radar imaging attributes provide a strong indicator where oil is present and can be clearly differentiated from the background response.

Airborne radar shows strong potential to detect oil at the snow/ice interface with existing systems, and to measure ice thickness and detect oil at the ice/water interface with higher-powered systems in the near future.

Since it is expensive and logistically difficult to conduct more than a handful of large-scale field experiments, future development of radar detection systems will depend largely on an intensive computer modeling effort to understand the radar response to a variety of sea ice conditions and oil types and distributions, and to fully define the limitations of the radar method.

All of the experiments to date have been performed on first-year ice with relatively even top and bottom surfaces. Detection of oil under ice through multi-year ice or rafted/ridged first-year ice might be difficult or impossible. While snow cover does not substantially affect radar penetration, the presence of voids and upturned blocks within rough ice is expected to present a major challenge. Limited experience with operating the GPR over simulated ice rubble (Dickins et al., 2005) gave cause for some optimism that GPR may be able to detect the oil under an uneven ice surface. However, results were not definitive in the tank experiment, in part because of interference introduced by the oil containment skirt.

Acoustics: Acoustic imaging through sea ice is possible under ideal surface ice conditions, as proven through past trials in Canada. The ice surface must be free of trapped air (e.g. snow) and a solid coupling with the ice surface is required. Acoustic coupling was achieved in this project by removing the snow and applying a small amount of seawater directly to the ice surface immediately before soundings were acquired. Once coupled to the ice surface, the acoustics transducer acquired data along the surface in profile at similar speeds to GPR acquisition. Modeled and field acoustic results suggest that adequate impedance contrasts exist to provide a measurable reflection at ice/water, ice/oil, and oil/water interfaces. Acoustic methods may be preferred over GPR where active brine channels are present (excessive radar attenuation) and where the ice surface is free of snow accumulations, for example relatively young sheets early in the winter.

<u>Conclusions:</u> Acoustic imaging shows promise in identifying crude oil beneath sea ice under certain conditions. However, GPR appears to be a more robust tool to image through sea ice under a wider range of circumstances where substantial snow accumulations are common on the ice surface. Acoustic methods may have their place in specialized applications, for example: smooth ice roads and/or thin ice accumulations where high salinities would reduce the probability of detection with radar. Preliminary findings from this phase of the project are contained in Liberty et al. (2006 and 2007).

Oil Behavior

The weathering of the oil under the ice with respect to vertical migration, evaporative loss and water content was monitored through oil and ice sampling at regular intervals throughout the field period. The oil was first observed on the ice surface under the snow inside the skirted area on April 20 after 24 days under the ice (March 27 to April 20). The rate of bulk oil migration through the ice was monitored by visual inspection of the ice and by analyzing the oil content in ice cores (Fig. 11).

The rate of oil surfacing observed in this experiment on Svalbard (Figure 11 below) makes an interesting comparison with a previous oil-under-ice experiment in the Canadian Beaufort Sea carried out in 1979/80 (Dickins et al., 1981). Oil from the first spill in that experiment rose through a similar ice thickness (60 to 70 cm) to reach 100% exposure in approximately 40 days from first appearance under the snow, results very similar to the timing of oil appearance documented at Svea.

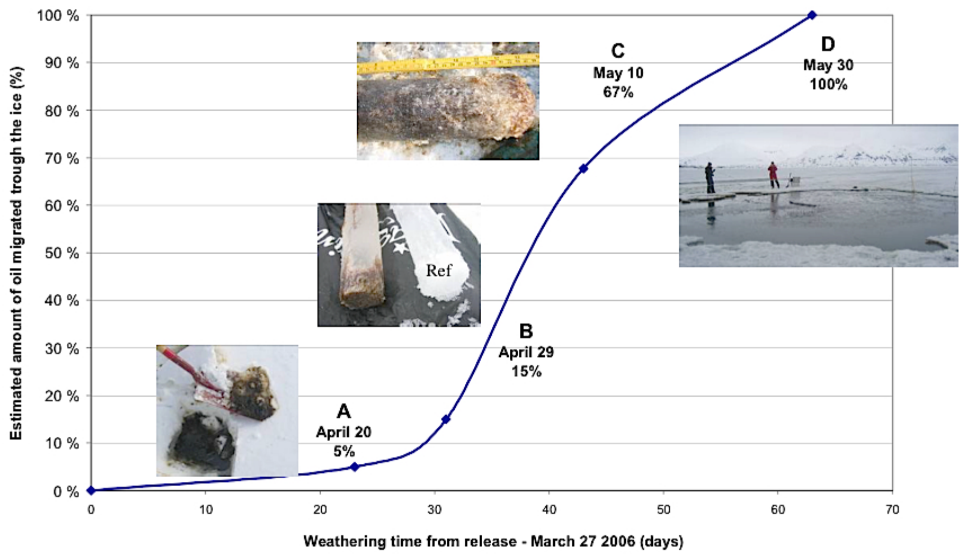

Figure 11: Estimated amount of oil penetrated through the brine channels in the ice and available on the ice surface. Inserted pictures show oil on top of snow (A), cores drilled through the ice to quantify oil captured in the ice (B+C) and the final melt pool (D).

After migrating through the ice and appearing on the ice surface after approximately 23 days, the oil was sampled approximately every second day. Evaporative loss (weight %) was measured on these samples. The evaporative loss in the surface samples was variable but relatively stable in the 30 – 35% range. Towards the end of the experiment the evaporative loss of the bulk surface oil drops from 36 to 27% (63 days after the spill). This shift is most likely caused by fresh oil still being released from the ice and reducing the average evaporative loss of the bulk oil on the surface. Water content of the surface oil in the melt pool was, as expected, very low (0-8 vol.%).

Earlier studies have shown that individual semi volatile organic compounds, (SVOC's) leak out from oil captured in ice and establish a significant concentration gradient trough a 1 m ice layer (Faksness and Brandvik 2005 and Faksness et al. 2006). In this study ice cores were collected both outside the skirted areas (reference samples) and inside to study possible migration of water-soluble oil components and oil droplets (see Fig. 12 below).

The water-soluble components in the ice cores sampled outside the skirted area before and after the oil release had no significant difference in concentration (0.05 to 1.09 ppb sum Water Accommodated Fraction (WAF)). The shallow cores taken inside the skirted area after the oil release showed also no significant difference in concentration of water-soluble components (0.01 to 0.1 ppb sum WAF). However, the reference cores showed increased content of water-soluble components after 24 days, attributed to migration of these components in the porous first-year ice (no bulk oil was present in these cores). By that time, the oil had migrated through the ice and was present in the snow inside the skirted area by April 20 (see Fig. 11 above). Later sampling of reference cores (May 10, 20 and 29) showed the presence of bulk oil components due to spreading of bulk oil through the surface snow/slush/water layer. Further studies should be performed to determine the release rates of water-soluble components in ice from encapsulated oil spills. Such data is important for modeling of the exposure of water-soluble hydrocarbons to Arctic ice fauna as part of future environmental impact assessments.

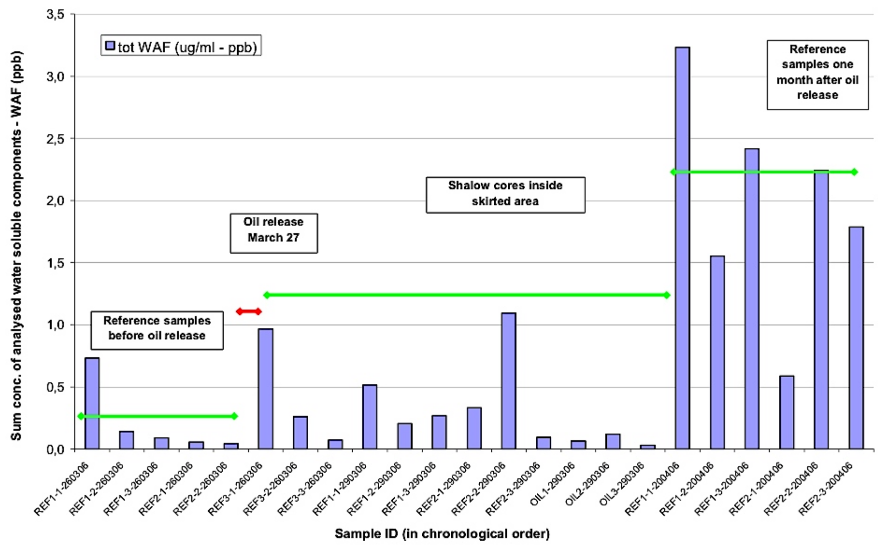

Figure 12: Summary concentration of analyzed water-soluble components from selected ice cores (reference and inside skirted area). The last part of the sampling ID is the sampling date.

In-situ Burning

In-situ burning of the surface oil was performed with a simple hand held igniter (gelled n-hexane). Flame spreading was successful, and approximately 2,500 liters of weathered oil burned down to a solid residue of 106 liters in only 11 minutes (96% effectiveness) with a burn rate of 3.1 mm/min. Table 1 summarizes parameters measured in documenting the in-situ burn.

Table 1: In-situ burning summary

In-situ Burning Summary	
Oil Type	Statfjord crude
Initial oil volume (liters)	3400
Evaporative loss (vol.%)	27
Weathered oil volume (liters)	2482
Oil film thickness (mm)	35
Oil film area (m^2)	69
Burning time (min)	11
Terminal oil thickness (mm)	1
Residue (liters)	106
Density of residue (g/ml)	0.9412
Burning efficiency (%)	96 %
Burning rate (mm/min)	3,1
Burning rate (liters/min)	216

The oil film thickness shown in Table 1 was measured on the oil layer in the melt pool on site (Fig. 13). During the eleven minute burn, the oil spread out and filled the approximate 100 m^2 melt pool. The burning effectiveness was calculated by comparing the actual oil volume burned (weathered oil - residue) with the weathered oil volume. Further details are provided in Daniloff (2006).

The combustion process appeared visually to be starved, and created a dark smoke plume (Fig. 14). The smoke plume could be followed by eye for approximate 500 meters before it diluted completely and could not be distinguished from the background. The appearance of the burn residue is shown in Figure 15.

Figure 13: Oil in the melt pool on the ice May 30, 2006 prior to ignition.

Figure 14: In situ burn on the ice surface 5 min after ignition, May 30.

Figure 15: Burn residue on the melt pool after 2 hours of cooling. Semi solid, 1 mm thickness.

<u>In-situ burn conclusions:</u> This experiment confirmed that in-situ burning is an effective tool to greatly reduce the environmental impact of oil spills in ice-covered waters with minimal logistics demands.

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