Detection and Tracking of Oil Under Ice

Minerals Management Service

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FINAL REPORT

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SUMMARY AND RECOMMENDATIONS

The United States Department of Interior, Minerals Management Service initiated this study to gather and evaluate all available knowledge about the subject of oil-under-ice detection. The overall objective was to identify the most promising technology for further development and testing. The study focuses on the potential for remote sensing systems to perform in an operational arctic spill monitoring role.

The problem of remote sensing in the case of wintertime spills beneath a solid ice sheet is particularly challenging. An operational system will need to accommodate a wide range of oil in ice configurations over an equally broad range of ice conditions and water depths. A major operational issue concerns bottom fast ice which may extend out from shore out to six feet of water by mid-winter. The introduction of a frozen soil layer between the bottom of the ice and the oil adds an extra dimension to an already complicated problem.

In the past, considerable effort has gone into research and development of various methods to detect oil trapped under an ice cover or entrapped as a layer within growing ice. To date none of these technologies have resulted in an operational system. Examples where different systems have been tried on actual spills in ice include: two types of impulse radar(surface and airborne) tested in an effort to map pools of oil trapped within sea ice during Dome's Oil and Gas Under Sea Ice Experiment in the spring of 1980 (Butt et al., 1981); infrared and visual photography used to map oil spilled among broken ice floes in a Canadian experimental spill off Nova Scotia in 1986 (SL Ross and DF Dickins); airborne remote sensing used in an effort to map oil dispersed within pack ice during the Kurdistan tanker spill off Nova Scotia in March 1979 (C-CORE, 1980); and a prototype acoustic system based on a comparison of ultrasonic waves received from the ice under surface, tested on freshwater and salt water ice sheets in laboratory/basin tests and field trials in the NWT (Goodman et al., 1985; Jones et al., 1986a and 1986 b).

Radar technology was the subject of extensive research in the 1980's. Several initially positive indications showing the potential presence of an oil layer in the ice could not be validated. Subsequent theoretical and laboratory/tank studies failed to identify an established mechanism for the radar detection of oil-in-ice. Practical considerations included a concern that natural anomolies in the internal structure of sea ice would attenuate the signals to such an extent that much of the data needed to identify the presence of oil in the ice would be lost.

Extensive efforts in the 1980's were also expended on the application of acoustic methods to detect oil in ice. A great deal of progress was made in this field, and a working prototype was developed. This unit was tested in a laboratory test tank, the Esso test tank in Calgary using salt water ice, over oil seeps on the Mackenzie River and in the Beaufort Sea. The presence of oil under the ice was successfully detected in both the controlled laboratory tests over fresh ice and during the Mackenzie River trials. During the Beaufort tests, the ice was rotting and wet slush on the surface often interfered with coupling of the transducers. Currently, efforts have begun to redesign the original unit using the latest advances in electronics.

All of the available technologies have serious drawbacks, some worse than others. Both radar and acoustic systems may perform poorly or not at all over rough, variable ice. Acoustic systems require bonding of transducers to the ice at each measurement site. Radar may not detect thin oil layers or operate at all with young or thin first-year ice sheets in shallow water. Ambiguous returns may lead to an excessive number of false alarms with any remote sensing system.

There appears to be no new technology with the potential to detect oil in or under ice, or any technology which has not already been considered or tested at least at the feasibility level in previous work. This conclusion is based on contacts with a broad cross section of researchers and agencies in North America and Europe.

Advances in computer capabilities over the past fifteen years, while dramatic, will not directly overturn previous conclusions about the potential of different technologies to detect oil in ice. The latest generation of data processors and software will however allow much lighter and smaller components, faster scan and data processing rates, real time readouts, and potentially some form of expert system to avoid false alarms.

Two avenues still stand out as being the likely focus of future development: acoustics (including the potential use of ultrasound); and electromagnetic (primarily the wave domain systems commonly referred to as impulse radars or ground penetrating radars). Further testing could be pursued in both of these areas. The optimum choice of direction in future development work needs to focus on systems which could evolve into practical operational devices, readily deployed and maintained in extreme conditions. Future tests need to combine both laboratory and field trials with oil spilled under ice. A sole reliance on laboratory or tank tests will not provide an adequate basis for developing operational systems in the future.

It appears that the development of any practical operational system for detecting oil in or under ice will be extremely challenging. The most effective solution may not be a single sensor but could require the integration of several different technologies.

It is recommended that the latest evolution of the acoustic system first tried in the 1980's be tested over a realistic of mix of first year sea ice under field conditions. At the same time, it would be valuable to test the capabilities of the latest generation of ground penetrating radars in areas of bottom fast ice where the interface is directly ice to frozen sediment rather than ice to water. The results of these tests can be used to determine if these GPR systems have any potential for mapping the presence of oil trapped in frozen sediments over a pipeline leak in shallow water areas where the sea ice is in direct contact with the seabed for much of the winter.

Based on previous work, there are limited prospects for developing operational radar based systems to detect oil in floating sea ice (not bottom founded).

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1.0 OBJECTIVES AND PURPOSE

The United States Department of Interior, Minerals Management Service is seeking new and innovative methods and equipment for the purpose of remote sensing and surveillance of oil spilled in and under ice in Arctic areas. This report covers phase 1 of this work. Subsequent phases may lead to prototype development and field or lab testing.

The primary goal of this phase was to gather and evaluate all available knowledge about the subject of oil-under-ice detection with the objective of identifying the most promising technology and/or process for future development and testing. The study focuses on the potential of any given system to fulfill an operational monitoring role in a "real world" environment. Operational applications require reliable detection while operating in a wide range of ice and weather conditions.

This is not a technology assessment aimed at experimental laboratory systems, but rather an attempt to learn as much as possible from past research in order to develop recommendations for future prototype development and testing.

2.0 BACKGROUND AND INTRODUCTION

The phrase "oil in or under ice" has been commonly used in the literature to refer to oil trapped within an ice sheet, oil pooling under ice, oil amongst broken ice and so on (Figure 4.3). In this report, the terms oil-in-ice and oil under ice are used interchangeably. The focus is on situations where the oil is either trapped (encapsulated) as a layer within the ice sheet, or lying in pools or thin films under the ice. There are a number of possible physical situations or scenarios which could lead to oil in or under ice. Examples include subsurface pipeline leaks or ruptures at different times during the ice season (freeze-up to break-up).

The case of oil lying on top of the ice (with and without snow cover) is not covered in this study; a variety of airborne remote sensing methods are available to detect and monitor oil in this situation: optical, infrared, laser fluorosensor etc.

The focus here is on technologies which could result in detection systems applicable to current exploration, development and production activities within the Alaskan Outer Continental Shelf (OCS) region, encompassing the Beaufort and Chukchi Sea areas. Primary examples of the types of ongoing projects where these systems could to be applied in the near future are represented by the Northstar and Liberty developments by BP Exploration (Alaska) Inc (Figure 4.1). Both of these projects involve a buried pipeline extending from shore to an artificial production island within the so called fast or stable ice zone in less than 40 feet of water. Recent (1999) permitting stipulations issued by the Corps of Engineers include requirements to develop and install a prototype leak detection system mounted externally on the buried pipeline, and to investigate other remote systems to detect oil in and under ice (Bryce, 2000).

The overriding operational need for an oil in or under ice detection system centers on the possibility of having a pipeline leak which continues without detection for some time (days to weeks). Larger spills associated with pipe ruptures are detected almost immediately with traditional SCADA or pressure drop systems. There is still an on-site need to map the overall area of contamination resulting from a rupture situation, but the general location of the spill is already known. In the case of chronic leaks below detectable limits, an oil spill could accumulate at any point along the pipeline. Related to this risk, there is an ongoing requirement to be able to detect and map both the aerial extent and exact location of any possible oil spill underneath the fast ice.

Traditionally, chronic leaks can be spotted for both on land and marine pipelines through right of way surveys (sniffers, discoloration of ground cover, soil probes etc.) and/or aerial marine surveys (sheens on the water). In the case of a nearshore arctic marine pipeline, the presence of a continuous ice cover for up to 9 months prevents the use of conventional surveys.

Detection of chronic leaks beneath the ice can be done in one of two ways: (1) a system installed with the pipe itself which allows the detection of leaks below threshold limits commonly associated with traditional systems (flow rates in the order of 0.12% percent of the oil flow rate). The Siemens LEOS system recently installed with the Northstar pipeline is a prime example (Bryce, 2000).; and (2) regular surface surveys to detect the presence of oil either under the ice or within the ice. It may be possible to accomplish this task with some form of remote sensing system (either airborne or surface mounted). The purpose of this report is to explore option 2.

Oil released through a chronic leak or rupture during the winter is expected to rapidly saturate the porous backfill in the pipe trench, and rise through the water column to become trapped in pools underneath the ice. The natural undulations in ice bottom topography provide many effective catchment areas to contain the released oil (Kovacs et al., 1981- CRREL; Barnes et al., 1979 - USGS). As a result, thousands of barrels of oil accumulated over a long period of time can be contained in relatively small areas only hundreds of feet in diameter. This process is described in Dickins and Buist (1999) and elaborated further in Section 4.3 (Figure 4.4).

At present, the only known method of searching for and detecting the presence of oil leaking at low rates from a marine pipeline in the winter period involves drilling holes at frequent intervals along the pipe to expose any oil which could be trapped in or under the ice. Clearly this method is extremely labor intensive and raises serious safety and reliability issues with crews working under highly variable and extreme weather and ice conditions. There is a strong motivation within industry and government agencies to identify and develop a reliable, and safe means of remotely detecting oil in and under the ice.

3.0 STUDY ORGANIZATION

This study aims to not only encapsulate what has been learned in the past, but also to assess how recent technology advances may modify the conclusions reached in past work. Current generations of portable computers and signal processing software could enhance the capabilities of different technologies and/or systems compared to what was possible in the 1980's when much of the previous work in this field was conducted. For example, reduced system noise may allow a much greater signal attenuation while still leaving useful information; and dramatic increases in processing speed may allow real-time results in the field where previous interpretations had to rely on post-processing in the office or lab.

Many past studies focused on simple oil in ice configurations within a controlled test basin or laboratory setting. This study emphasizes the variability in ice conditions and in oil/ice configurations which will affect the performance of operational systems.

In order to accomplish the objectives described above, the study was divided into the following tasks, each of which is the subject of separate headings in Section 4:

1. **Literature Review:** covering all known research into the problems of detecting and surveying (mapping) oil in or under ice, including both surface (e.g., sled or vehicle mounted), and airborne systems (fixed wing and/or helicopter). This review does not cover satellite systems for reasons explained below.

2. **Technical Constraints:** This task revisits the conclusions drawn from past studies. The focus is on techniques which showed promise in the past, but where results may have been constrained by technical limitations not directly related to the basic scientific principle involved. Opinions are provided from technical specialists including potential suppliers of prototype systems.

3. **New Technologies:** This task identifies any new remote sensing theories or techniques developed since 1990 which may have arctic applications with oil in ice. The approach was to canvas key national groups and agencies with a background in arctic ice and oil spill research. The goal was to identify any new developments (past ten years) which may have potential for oil-under-ice detection, but which were not tested or evaluated during the last major research thrust in this field ten to twenty years ago (1979 to 1988).

4. **Operating Environment:** The purpose of this task is to provide a detailed description of the physical environment in which an operational system will have to perform on a regular basis. The environment covers both the landfast ice and the expected configurations of oil under or in the ice which need to be detected. Information here has direct application to the design, deployment and operation of future detection systems.

5. **Related Studies:** The final work task of the study identifies any ongoing or recent studies and projects by other agencies or organizations which may be of direct or peripheral interest to future developers and/or operators of oil in ice detection systems.

4.0 RESULTS

4.1 Literature Review

This review encompasses all known references dealing with the subject of detection (and mapping) of oil trapped beneath or within an ice sheet through some form of remote means (that is without using destructive or manual methods such as drilling and diving). Platforms included surface systems mounted on sleds or vehicles, or airborne systems mounted on aircraft and/or helicopters.

Three technologies and/or methods are not considered in this study: satellites; divers; and drill holes. The current generation of satellite sensors, particularly the Canadian all weather Radarsat, have demonstrated some potential for open ocean slick monitoring; examples include the *Sea Empress* spill in Milford Haven UK, *Nakhodka* tanker spill off Japan, and the Russian Komi pipeline spill (Lunel et al., 1997; Hodgins et al., 1996; Fingas et al., 1996). Unfortunately, available satellite sensors are not capable of detecting or mapping oil trapped under or within solid ice. Although demonstrated in field tests, the detection and mapping of oil under ice with divers is considered to have very limited applications for reasons of safety and practicality (McKindra et al., 1981). Similarly, the use of drill holes to detect oil in ice, while theoretically possible, is considered impractical as a long term solution for arctic spill monitoring.

The following summaries highlight the scope and contents of key references. In some cases, where a single body of work generated a number of similar papers, the group of related references is reviewed together and either combined into a single summary, or limited to the most recent publication. Except where noted, the text constitutes either a direct quote from the original report/paper, or an accurate paraphrasing of the original. Opinions (ed.) which are not contained in the original are noted in [ ]. Primary references are also included in the reference section (6.0) by author name in alphabetical order.

The literature review is organized according to the following hierarchy:

- Research Agency or Organization (e.g., CRREL, C-CORE, Environment Canada etc.)
- Technology or Principle (e.g., acoustics, radar)

An early overview report produced by Intera (1984) summarizes much of the original research in the area of oil in ice detection systems.

State of the Art Survey of Oil Spill Detection, Tracking and Remote Sensing in Cold Climate, by Intera Environmental Consultants for Environment Canada, Ottawa, January 1984 (report series EE-50).

Surface Methods: Remotec (1981) is mentioned in work for Environment Canada trying gamma-ray spectrometry, impulse radar, active radio frequencies, and active acoustic sensing. Apparently, only the acoustic method showed any promise [see paper by Stapleton et al. (1981) reviewed below under "Environment Canada: Various Methods"]. Earlier work by Nordco (1979-full reference missing) considered radio frequencies, acoustics, optical, nuclear and gas sniffer methods., and concluded that only radio waves and acoustics would have any practical chance of success. Jones (1982) is credited with discovering the key to oil detection ice by acoustic methods, going beyond simple reflection and exploiting the differences in attenuation and propagation of shear and compression ultrasound waves by the viscous (oil) and non viscous (ice) media. See reviews of variety of papers on this work below under Environment Canada.

Airborne Methods: One area of laser applications involves the penetration of ice by laser-produced radiation and subsequent excitation of sub-surface oil. R. Goodman is quoted (pers.comm.) as saying that detection of the fluorescence emission by the oil using this method has been detected for an ice thickness of about 2 m. C-CORE (Laidley, 1981) is referenced for their work on trying to raise the temperature of oil in the ice using a CO_2 laser and then detecting the thermal contrast between the oil and the ice or water. Actual detection would use some form of airborne thermal infrared sensor on a low flying helicopter. [See review of the only publication on this method under C-CORE below]. Impulse radar methods are considered promising in terms of penetrating ice and detecting sub-surface oil (references quoted are Mann (1979) and Dean (1981) [see various reviews by these and other authors under C-CORE, Environment Canada and APOA]. Recommended research areas to be looked at for further radar development include: insulation properties of the oil, dielectric effects (phase change of reflected radiation) and constructive interference (thin film effects).

Valuable overviews of the general subject of oil spill remote sensing (not specific to oil in ice) are provided in a number of reports produced by Environment Canada, River Road Technology Centre, Ottawa. Examples are:

Oil Spill Surveillance, Monitoring and Remote Sensing: A Global Review, by C.E. Brown & M. Fingas, Environment Canada, in proceedings 1999 Arctic Marine Oilspill Program Technical Seminar.

A Review of Oil Spill Remote Sensors, by M. Fingas, C. Brown (Environment Canada) and J. Mullin (Minerals Management Service), in proceedings 1999 Arctic Marine Oilspill Program Technical Seminar.

A Review of Oil Spill Sensors, by Fingas, M.F., and C.E. Brown, in proceedings of the third International Airborne Remote Sensing Conference and Exhibition, July 7-10, 1997, Copenhagen (pp. 1-707 to 1-713).

An Assessment of Sensors for Oil Spill Applications, by Fingas, M.F., Brown, C.E., and Fruhwirth, M., June 24-27, 1996, San Francisco (pp. III- 689 to 698).

Review of Remote Sensing For Oil Spills, by Merv Fingas and Carl Brown, Environment Canada, Ottawa, 1995.

The following reviews of papers and reports dealing with the subject of detecting oil under or in ice are grouped primarily according to the research organization which originally conducted or sponsored the work. A number of references are cross-referenced in several different categories, for example work by C-CORE which may have been sponsored by Environment Canada.

C-CORE , St. John's, Newfoundland

A Field Evaluation of Impulse Radar for Detecting Oil in and Under Sea Ice, by K. Butt, P. O'Reilly, and E. Reimer, C-CORE, St. John's, 1981 (Appendix K to Vol II of the Oil and Gas Under Sea Ice Experiment, D. Dickins and I. Buist for Dome Petroleum, Calgary, 1981), APOA Contract report 169

This report describes a field trial conducted as part of Dome Petroleum's Oil and Gas Under Sea Ice Project (Dickins and Buist, 1981). The airborne tests used a 100 MHz unit suspended beneath a helicopter. A GSSI 400 MHz surface unit was also used. Figures shown in the report appear to be all derived from signal returns with the airborne unit. Results showed that it was possible to detect an oil lens with a thickness smaller than the radar pulse wavelength. Distinct reflection anomalies were observed from oil lenses encapsulated at the 60 cm level, and from oil and gas freshly spilled beneath 175 cm thick ice in early April. Figure 7 in the report shows an apparent attenuation in the ice bottom spike with a corresponding increase in the strength of the anomaly associated with oil under ice as the flight profiles moved closer to the spill center (thicker oil).

These trials were conducted over undisturbed fast ice. The authors felt that any detection or identification of oil trapped in rafted or broken ice would be much more difficult. The development of an operational impulse radar system for the detection of oil in ice was considered possible. However, the positive identification of oil-in-ice over a range of conditions would require a significant development effort in terms of signal processing and interpretation capability.

[The conclusions of this report in terms of the potential for using impulse radar devices for oil in ice detection are far more positive than indicated by the outcomes of later analytical work sponsored by Environment Canada and Esso Resources (see for example Tunaley and Moorcroft (1986) and Dean (1983) reviewed below). Mann (1979) also reported what appeared to be positive results in a controlled series of tests (reviewed under APOA below)].

Laser Detection of Oil in Ice, by T. Laidley in C-CORE News 6(1), St. Johns, April 1981.

This one page article describes a research project aimed at using thermal IR techniques to detect oil trapped in or under ice by first raising the temperature of the oil above it's surroundings by heating it in-situ by means of a CO_2 laser, operating at a wavelength of 10.6 microns, so as to be largely unaffected by atmospheric attenuation. The paper describes preliminary results in the laboratory at C-CORE, St. John's where there were noticeable differences between oil and the other targets at an energy threshold of 20 millijoules/cm^2.

[Subsequent attempts to find any published evidence of follow-up work to this paper were unsuccessful, including personal communication with a number of researchers who were active in the field in Newfoundland at the time (E. Reimer, J. Rossiter). Judith Whittick, the present director of C-CORE remembered that the board of directors made a decision at the time discontinue further oil in ice research. Judith conducted a search of the C-CORE library and determined that there was no further publication of results or any documentation relating to follow-on work in this area. R. Goodman is quoted in a report by Intera (1984 - see above), as saying that detection of fluorescence emissions from oil has been detected for an ice thickness of about 2 m.]

Proceedings of the International Workshop on the Remote Estimation of Sea Ice Thickness, ed. J. Rossiter, C-CORE, St. John's, September 1979

This workshop brought together 60 worldwide participants from the US, Canada, Europe and Russia. The focus was on presenting the state of the art in remote sensing of sea ice thickness at the time. The proceedings are valuable as compendium of knowledge about the capabilities of ice thickness radars of the same generation as those systems evaluated in the early 80's for their potential to detect oil in or under ice. Bryan Mercer in the opening address to the workshop, highlighted oil detection under ice as valuable application of ice sounding radar. In that address he indicated that future operational systems would be helicopter-borne with real time processing and a small footprint (see conversations with researchers presently active in this area - Section 4.2).

An Oilspill in Pack Ice - Chapter 8: Remote Sensing of Bunker C in Dynamic Pack Ice, C-CORE Contract Report C80-2 (pp. 77 - 128)

This work discusses the problems of detecting oil mixed in broken pack ice, and discriminating between the oil and other impurities in the ice, based on field observations following the 1979 Kurdistan tanker spill on the Canadian East Coast. This report presents the most comprehensive review of possible techniques for detecting small oil particles mixed with brash and pancake ice. Further details of the full remote sensing program associated with the Kurdistan incident including samples of UV-IR images of oil in ice are provided by O'Neil and Thomson (1980) These results are not directly relevant to the problem of oil in or under solid ice.

Microwave Systems for Detecting Oil Slicks in Ice Infested Waters: Phases 2 and 3, report EPS 3-EC-80-3 for Environment Canada, Ottawa, 1980

This report presents results from analysis of Synthetic Aperture Radar (SAR) imagery obtained at 3000 m over the Labrador sea in a project to determine the potential of microwave systems for detecting oil in different ice regimes: specifically oil in waves in broken pack ice and icebergs. The results are not directly related to problem of oil in or under ice

US Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover NH

Electromagnetic Subsurface Measurements, by A.Dean, CRREL Report 81-23, Hanover, NH, October 1981. - (see below for conference paper on same work)

Investigating the Practical Application of Resonant Scattering Theory for the Detection of Oil Under Sea Ice, by A.Dean, AMOP Technical Seminar, Edmonton, June 1983 (pp. 255-260) - see review below under "Environment Canada ----- Radar"

Remote Sensing of Oil Spills Near the Kolva River, by Chadwick, D.J, Bolus, R.L. and L.E. Link, presented at the 2nd International Oil Spill Research and Development Forum, London, May 1995

This paper, acquired on the chance that it covered the topic of oil in ice detection, deals with the potential for radar and visible satellite systems (ERS and SPOT) to detect and monitor oil on land under snow-free and snow-covered conditions. Spills were not identified with a high degree of confidence with the systems available at the time but the paper points out that newer generation satellites now coming into service offer increased potential.

Electromagnetic Sounding of Sea Ice Thickness, by A. Kovacs, D. Diemand, and J. Bayer, in proceedings 15th International Conference on Port and Ocean Engineering Under Arctic Conditions, August 1999.

This paper presents the results of a 1992 field study in the pack ice north of Alaska. A portable (9 kg) Geonics EM-31-D electromagnetic induction sounding system was demonstrated to accurately (within 5% of drill hole measurements) map sea ice thickness in the range 1.25 to 4.5 m thick. Seawater under winter arctic pack ice has a relatively uniform conductivity of about 2.5 S/m which means that a simple graph or look-up table can be used to estimate sea ice thickness from the apparent conductivity reading of the instrument. The 1992 instrument used a plug-in ice thickness processor module which could operate over a range of seawater conductivity from 2 to 3 S/m. All that is required to calibrate the instrument at the beginning of a survey line is to match the instrument reading to a single drill hole by adjusting the seawater conductivity. No tests were conducted with this instrument and oil under ice. [The author (pers. comm. 03/28/00) feels that EM technology has a limited potential to detect oil under ice but that if field trials were being planned with another form of radar or other technology, it may be worth trying. The EM system does offer the potential to measure average thickness in rougher ice fields than possible with an impulse radar - this could provide valuable background survey data to identify problem areas (underlying rubble or rafting) along a pipeline route where other detection methods may be required.]

Environment Canada and Esso Resources Canada and the Arctic Marine Oilspill Program (AMOP)

Detection of Oil Under Ice - A joint ESSO/EPS Project, R. Goodman and M. Fingas, in proceedings 6th annual AMOP Technical Seminar, Edmonton, June 1983 (pp. 233-240)

This paper provides a valuable summary of the initial approach to evaluating alternative technologies in the search for an attractive and practical means of detecting oil in and under ice. Remotec's (1979) study formed the basis for many of the conclusions presented here (see also paper by Stapleton et al. (1981) reviewed below under Various Methods). The authors go on to postulate reasons for the success or otherwise of different systems based on scientific principles and the known properties of the different materials. Of the four systems tried in the earlier study (GSSI impulse radar normally used for ice thickness measurements, passive VHF radio spectrometer, passive gamma ray spectrometer, and ultrasonic inspection unit), only the ultrasonic system (operating between 500 and 2250 kHz gave clearly different signals when oil was present under freshwater ice).

The radar was projected to show positive results based on previous field experience. One explanation offered for the disappointing results was that oil tends to fill under-ice cavities, generating an apparent smooth flat reflector. [See also field trial results reported by Butt et al. (1981) reviewed above (C-CORE), Dean's investigation of resonant scattering theory (1983), Tunaley and Moorcroft (1986), and a summary of radar results by Goodman et al. (1985) reviewed under Environment Canada, and earlier laboratory/tank tests by Mann (1979) reviewed under APOA.]

Acoustics

The Detection of Oil Under Ice by Ultrasound Using Multiple Element Phased Arrays, by H. Jones, W. Kwan, E. Yeatman, in proceedings 9th annual AMOP Technical Seminar, Edmonton, June 1986 (pp. 475-484)

This paper provides details of the construction and signal processing of the phased arrays and provides preliminary results from a series of field trials on freshwater ice in the Mackenzie River, NWT. Mention is made of further field trials under way at the time on salt ice in the Beaufort Sea near Tuktoyaktuk (spring of 1986). Results of initial tests at the Esso Test Basin in Calgary are provided in Jones et al. (1986b - following).

The acoustic system was used to scan for ice thickness, producing accurate results to within a few cm in ice thickness' ranging from 80-95 cm. Attempts were made to locate natural oil seepage under the ice, a difficult task due to the high under ice currents and very small concentrations of oil. One oil site under the ice was located with the system and anomalous readings made up only about 10% of the data. Most spurious readings occurred close to shore where the ice was severely broken and the bottom highly irregular. The prototype was demonstrated to withstand rough handling and temperatures down to the -30 to -40°C range.

The Detection of Liquids and Viscoelastic Substances Trapped Under Solid Surfaces, Jones, H., Kwan H., Hayman, T., and Yeatman, E.J. Acoustics Society of America, 1986 (79(1): 84-90)

These two similar papers presented in 1986 represent the concluding phase of four years of research into oil spill detection using ultrasound methods leading to prototype development (first AMOP presentation by the same authors was made in 1982). Remotec's initial survey of possible technologies in 1981 concluded that while ultrasound methods showed the most potential, effective transmission through several meters of ice would require the use of relatively low frequencies (100 to 200 kHz).

It is possible to use ultrasonic frequencies of 500 kHz and higher with fresh water ice to detect oil layers 1 to 2 cm thick. In conductive sea ice, the need to use lower frequencies to achieve sufficient penetration of the acoustic signal meant that the problem of finding the oil layer by simple acoustical reflection became quite difficult (water and oil are very close in acoustical impedance). The author's methods utilize the differences in the ratios of reflected and mode converted signals between clean sea ice and ice with an oil layer to detect the presence of oil. Experiments use the compression wave as the incident wave.

Development work assumed a typical operational ice thickness of 1 to 3 m. Experiments used an artificial salt water sheet 80 cm thick grown in Esso's Calgary research center. A depression in the bottom of the ice, 45 cm diameter and 2.5 cm thick was filled with oil. It was estimated that half of this oil migrated up from the lower surface as much as 30 cm through fissures cracks and drainage channels. The resulting scattering of incident beam energy appears at the receiving transducer as masking of the signal from the liquid solid interface. The paper concluded that modern digital techniques in signal processing could assist in discriminating against unwanted artifacts in the measured signals, and that the technique has applications for ice thickness in the range of 30 to 400 cm. The paper concludes that the experiments confirmed the validity of the acoustic method in agreement with the theory, based on the viscoelastic properties of the oil.

The Detection of Oil Under Ice Using Acoustics, R. Goodman, H. Jones, and M. Fingas, in proceedings Vol.2 of the Conference on Port and Ocean Engineering Under Arctic Conditions (POAC), Narssarssuaq, 1985 (pp. 903-916)

The authors assume that the problem of detection of oil under ice is independent of the source, that the configuration of the trapped oil would be similar for pipeline, tanker spills or subsurface blowouts. [No mention is made of the situation of chronic pipeline leaks over extended time periods which could lead to much thicker oil pools under the ice. In theory, this should make the problem of detection much easier.]

Goodman explains the limitations associated with having to use low enough frequencies to both penetrate thick sea ice and have signal attenuation less than 20 db/m (based on 4 m of round trip signal travel in 2 m ice and a maximum allowable attenuation of 80 db). Higher frequencies would allow the use of direct reflection techniques to detect thinner oil films down to the order of a few mm (improved system sensitivity) and would give better spatial resolution. [Current concerns center around the presence of potentially much thicker oil pools under the ice.]

Operating in the 100 kHz range to achieve the necessary penetration, the acoustic detection system utilizes the ratio of the amplitudes of the compressive and shear wave returns to determine the presence of oil at the ice fluid interface. The paper concludes that the operation of the prototype system has a rigorous scientific basis confirmed by lab data. The signal to noise ratio measured in the lab is recognized as probably being much higher than achievable in the field (due to variable properties of the ice among other factors). Operational limitations include the need for careful coupling of the transducers to the ice. A listing of related earlier papers follows.

An Apparatus for the Detection of Oil Under Ice, by Jones, H., Kwan H., Hayman, T., and Yeatman, in proceedings 1985 AMOP (pp. 278 - 286)

On the Design of an Apparatus to Detect Oil Trapped Under Sea Ice, H. Jones, W. Kwan, E. Yeatman, in proceedings 7th annual AMOP Technical Seminar, Edmonton, June 1984 (pp. 295-305)

The Detection of Crude Oil Under Seawater in the Arctic Ocean, H. Jones and H. Kwan, in proceedings 6th annual AMOP Technical Seminar, Edmonton, June 1983 (pp. 241-252)

Experiments in the Detection of Oil Under Ice Using Acoustics, by D. Knudsen, in proceedings 6th annual AMOP Technical Seminar, Edmonton, June 1983 (pp. 253-254) - limited to status report on initial prototype development based on the theories developed by Jones et al. Subsequent results were written up as an internal Environment Canada (EE) report.

The Detection of Oil Spills Under Arctic Ice by Ultrasound, by J. Jones and H. Kwan, in proceedings 5th annual AMOP Technical Seminar, Edmonton, June 1982 (pp. 391-411)

Radar

Aspects of the Detection of Oil Under Sea Ice Using Radar Methods, by J. Tunaley and D. Moorcroft, in proceedings 9th annual AMOP Technical Seminar, Edmonton, June 1986 (pp. 468-474)

This paper encapsulates a series of related studies aimed at exploring the potential for impulse radar systems to detect oil in ice (see earlier papers below). The authors present a pessimistic appraisal, concluding that the positive identification of oil is likely to be frustrated by the scattering of radar signals from the top surface, air bubbles and brine inclusions. Operating the radar at lower frequencies such as a few hundred Mhz could minimize these effects but at the cost of poor spatial resolution. A simple radar detection system may have to rely on the presence of oil to generate a flatter lower surface in order to have a signal anomaly between clean and oiled ice (oil filling in the under ice depressions). The possible use of a SAR radar system is discussed in combination with expert system techniques to discriminate between signal patterns with and without oil. The high variability of ice as a material compounds the problem of discrimination. The paper is highly theoretical and proposes conducting a simulation of a SAR system in this application. It is not known if such a simulations was ever performed - this is the last published paper on the subject by these authors. Earlier papers by the same research group are listed below. [ed. opinion is that this work provides little the way of practical results which can be used to evaluate radar applications in an operational setting]

Electromagnetic Resonance in Layers of Sea Ice and Oil Over Sea Water, by R. Moorcroft and J. Tunaley, in proceedings 8th annual AMOP Technical Seminar, Edmonton, June 1985 (pp. 269-286) - not reviewed - refer to later paper above.

Detection of Oil Under Ice Using Electromagnetic Radiation, by Goodman, R.H., Dean, A.M, and Fingas, M.F., in proceedings 8th International Conference on Port and Ocean Engineering Under Arctic Conditions, Narssarssuaq, Greenland, September 7-14 1985 (pp. II - 895 to 902)

At first glance this paper appears to describe the results of research carried out six years earlier by Mann (1979) and reported below under the heading APOA. Experimental methods are identical except that in the work reported here, the ice tank is larger. It is not clear why the previous study was repeated, and there is no reference to Mann's report as background. Goodman concludes that for any radar unit working at frequencies below 1 GHz, the likely oil thickness in the ice is much less than one wavelength (e.g., 30 cm at 400 MHz). This fact points to the Resonant Scattering Theory (RST) approach as an appropriate analysis tool (see papers by Dean reviewed below). It appears that this work was carried out to obtain actual results to validate Dean's theory developed earlier.

Ice sheets of 0.5 and 1 m were grown in a test tank, and No 2 fuel oil injected under the ice in layers up to 14 cm thick. The data showed a strong absorption peak at about 1 GHz which was a function of the oil thickness under the ice. None of the observed spectral features could be explained by a simple RST, but there was a definite "signature" of the presence of oil at the ice-fluid interface for thick oil films. The authors were not able to estimate the limits of detection at the time. The paper concluded by saying that although the cause of the return signal from the oil was not entirely understood, the experimental data appeared to be unambiguous and reproducible. Subsequent reexamination of the data failed to show positive signs of oil detection in these tests (from review comments on first draft of this report).

I*nvestigating the Practical Application of the Resonant Scattering Theory for the Detection of Oil Under Sea Ice,* by Dean, A.M., in proceedings AMOP 1983 (pp. 255 - 260) - purely analytical, contains no actual results, see later paper by Goodman et al. 1985 (above)

Various Methods

Laboratory Experiments in the Detection of Oil Under Ice, by Remotec Applications for Environment Canada, St. Johns, 1981 (Report EE-26) - see related paper below

Detection of Oil Under Ice - A Laboratory Program, by G. Stapleton, S. Parashar, J. Snellen, R. Worsfold, in proceedings 4th annual AMOP Technical Seminar, Edmonton, June 1981 (pp. 587-605)

Much of this work is also summarized in the paper by Goodman and Fingas (1983) above. The authors also describe a field test program at Prudhoe Bay using an ultrasonic unit over encapsulated oil several cm thick. The oil pockets were at a depth of about 60 cm in an ice sheet with an overall thickness of 160 cm. No echoes showing any interfaces were obtained (same result over non oiled ice 130 cm thick). It was concluded that the high frequency of the ultrasound unit being used did not provide sufficient penetration of the sea ice (see papers by Jones et al. above). It was recognized that efforts to increase penetration by reducing frequency would degrade the ability to detect thin oil layers.[This limitation may not be as critical for the scenario of a chronic leak where a thick oil pool has accumulated under the ice.]

[The results presented in this paper have been widely misinterpreted as confirmation that radar technology is defintitely not useful in detecting oil in ice (Intera 1984), when in fact the original paper concludes simply that the impulse radar could not be properly evaluated in the lab experiments because the ice sheet was not thick enough. The main problem was deduced to be lack of sufficient ice thickness in the experimental flume to resolve the air/ice and ice/water interfaces (only 40 cm was achieved in the tank vs. a minimum practical ice thickness for the radar unit being tested of 50 to 80 cm). It was concluded that further testing of the impulse radar unit would have to be carried out either in the field or in a laboratory environment that could grow ice beyond 0.8 m thick.]

Laser Fluorosensor & Fluorescence

Note: there are many more references dealing with the development of the laser fluorosensor in Canada - the following papers are selected because they specifically mention the detection of oil on or in ice (see also telephone conversation with C. Brown, 03/08/00 in 4.2)

The Detection of Oil Under Ice by Pulsed Ultraviolet Fluorescence, by Moir, M.E, and D.C. Yetman, Imperial Oil Resources, in proceedings 1993 International Oil Spill Conference, March 1993, Tampa (pp. 521)

This paper discusses an experiment where crude oil is introduced under both fresh and synthetic sea ice grown in a cold room. The oil is irradiated with 1 microsecond pulses of 360 nm ultraviolet radiation from a 10 MW Xenon flash lamp suspended above the ice. The returning fluorescence signal was then measured with a photo diode detector. Results show that using this method, oil can be detected under fresh ice up to 100 cm thick and sea ice up to 80 cm thick. However, discontinuities in the ice and the presence of any snow (even 2-3 mm) will prevent detection. This drawback would seem to preclude any practical field use on other than absolutely bare lake and or river ice surfaces (sea ice is rarely if ever truly bare of snow).

First Results of Airborne Trials of a 64-Channel Laser Fluorosensor for Oil Detection, by Dick, R. and Fingas, M., in proceedings 15th annual AMOP Technical Seminar, June 10-12, 1992 (pp. 365-379)

A series of test overflights with the fluorosensor in the spring of 1992 showed that the sensor (LEAF) measured reproducible and distinct signatures from oil and oily material on snow and ice. Oil thickness was a fraction of a millimeter. In a recent summary paper, Fingas and Brown (2000) describe the laser fluorosensor as unique in its unique capability to detect oil on backgrounds including water, ice and snow.

Fisheries and Oceans Canada - Canadian Coast Guard

Principal researchers: Holladay J.S., Prinsenberg, S.J., and Moucha, R.Z. (see also earlier paper by Kovacs and Holladay (1989).

Over the past 10 years (1989-99), the Canadian Coast Guard, Bedford Institute of Oceanography and other organizations have worked to develop an operational airborne system of mapping sea ice thickness through electromagnetic (EM) methods. Low frequency EM signals are transmitted by the antenna in the sensor bird (flown at an altitude of 15 to 20 m off the ice) and excite eddy currents in the sea water beneath the ice. The secondary EM fields generated by these currents are then measured by the receiver which is also in the bird. The distance of the bird to the water/ice interface is then determined by measuring the amplitude and phase of the secondary field relative to the transmitted field. A laser profilometer is used to measure the distance of the bird from the snow/air interface (footprint of less than 0.05 m). The radius of the EM sensor's footprint is much larger (comparable to the height of the sensor above the ice surface).

[Ongoing developments in Canada involve the development of a hand-held ground penetrating radar with a much smaller footprint (this may have applications in the scenario where oil is trapped between the seabed and bottom fast ice (common in many Beaufort areas where water depths are less than 5 feet). The current airborne EM system will not work in areas where water depths are less than 3 m (10 ft). Discussions with the developer (Scott Holladay of Geosensors Inc.) indicate that under one of the common scenarios being considered where a very thick (10's of cm) layer of oil is mixed with slush under the ice, the oil could potentially be detected by the existing airborne system and measured as an ice thickness anomaly. See also discussions with experts in the electromagnetic field in 4.2]

United States Coast Guard

Oil Spill Detection Under Ice - Status Report, M. Fitzpatrick, R. Francois, C. McKindra, in proceedings 6th annual AMOP Technical Seminar, Edmonton, June 1983 (pp. 207-215) An earlier paper by Jackson, Gaunaurd and McKindra was presented on same project at AMOP 1982.

This work builds on the initial tests reported by Stapleton et al. (1981) - see Environment Canada, Various Methods above. In that study, a series of alternative sensors were tried on fresh and salt water ice sheets grown in a flume. Tests were not able to determine the impulse radar capabilities because the flume ice thickness was less than the minimum resolvable ice thickness (50 to 80 cm). Fitzpatrick also refers to the 1980 test with a GSSI 400 Mhz unit over the Dome oil spill test site (see report by Butt et al. reviewed under C-CORE).

In 1981, the US Coast Guard sponsored a study by the US Naval Surface Weapons Center to assess the applicability of resonance scattering theory in the electromagnetic detection of oil under ice The theory was promising, but the practical application would require a variable frequency radar. Ice profiling radar systems at the time were short pulse single center-frequency impulse radar systems where the frequency is fixed by the geometry of the antenna. Resonance scattering also requires that the interface between the different layers is ideally bonded - in the real world, oil seeps up into the skeletal layer and beginning as early as March, up the brine channels, giving rise to a discontinuous boundary (see discussion of the operating environment in 4.3).

According to the authors, any radar system attempting to detect oil will experience the same constraints as a system examining single layers (ice/water): high signal attenuation in saline ice (first-year), signal scattering from rough ice surfaces (particularly true of airborne systems), and a constant trade-off between ice depth penetration (requiring low frequencies) and oil layer resolution (requiring higher frequencies).
The US Coast Guard applied the acoustic approach in quite a different manner than previous researchers (see Jones et al., under Environment Canada). They contracted with the Applied Physics Lab at the University of Washington (Prof. J. Francois) to investigate the use a sonar transducer below the ice to map oil before it became encapsulated, quoting available time windows of 5 to 10 days attributed to Norcor (1975). [Note: these values are very optimistic and do not agree with Norcor's actual results - more realistic times for the oil to encapsulate in mid-winter are in the range of 1 to 3 days]. The objective was to use an acoustic system to rapidly localize an under ice spill whose general location was known. The rationale behind this is difficult to understand without more background than presented in the paper [why try to remotely detect what you already know?] The paper concluded that a suitably designed system could map an area several hundred meters in diameter from one set up.

Use of Acoustics in Localizing Under-Ice Oil Spills, Francois, R., and T. Wen, University of Washington Applied Physics Laboratory, in proceedings OCEANS '83: Vol. 1, 1993 (pp. 16-20) - see review of AMOP paper above describing the same program.

Russia

Studies of the Possibilities of Creation the Remote Optical Systems for Remote Sensing the Under Ice Oil Spills, by Vadim K. Goncharov, in 5th International Conference on Remote Sensing for Marine and Coastal Environments, October 5-7 1998, San Diego (pp. II - 433 to 440)

This paper examines the possibilities of detecting oil in ice through optical methods. It is extremely difficult to make out what the author is saying due to the very rough translation. It appears that the recommended technique involves some form of detection by laser excited fluorescence (basically following the path of the development work in Canada with the laser fluorosensor).

Arctic Petroleum Operators Association (APOA)

A Field Evaluation of Impulse Radar for Detection of Oil in and Under Sea Ice, by Butt K, O'Reilly, P. and E. Reimer, APOA Report 169, 1981 (see review under C-CORE above)

Detection of Oil Trapped Under Ice Using Impulse Radar, by J. Mann for Esso Resources Canada, APOA Report No. 119, 1979, Calgary

This report contains the findings of Phase II of the study (whereabouts of the Phase 1 report are unknown). There is a reference to the earlier phase 1 tank tests as lacking a strongly defined ice-oil interface with poorly shaped pulses (apparently the test ice in Phase 1 did not closely mimic real sea ice). In Phase 2, Geophysical Survey Systems (GSSI) participated with CRREL (A. Dean) to test the feasibility of using off the shelf field types of impulse radar to detect the presence of an oil layer underneath a sheet of sea ice. Two techniques were tried, so called vertical probing and polarization measurement. Vertical probing uses transmit and receive antennas side by side and looks at the relative strength and time offsets between signal returns from the ice-oil and oil-water interface. The strongest reflections from the oil layer are only about 10% of the reflections from the seawater and these reflections follow the much stronger water reflections by only 0.25 nanoseconds per inch of oil. Results were considered unambiguous for oil layers 3 to 4 inches and thicker. With a filter to compress the received pulse in time so there is less overlap between adjacent pulses, it was considered feasible to use the vertical probing to successfully detect oil films less than 3 inches.

For thinner oil layers around one inch, detection of the oil (at least with signal processing technology available in 1979) required a more complicated measurement of the difference in phase of the horizontally and vertically polarized reflected waves. In this case the transmit and receive antennas need to be separated by about twice the ice thickness. Possible complications due to ice anisotropy were mentioned (see also telephone conversations with radar experts in 4.2) but it was considered possible to subtract this effect in areas where the ice is relatively uniform in structure (e.g. landfast ice).

Both the 325 MHz and 700 MHz transducers easily "saw" the ice water interface with ice thickness' of 8 to 24 inches (The ice tank was 8 ft by 8 ft by 4 ft deep). Problems were encountered in two of the three trials: in the first attempt, the ice salinity was three times normal resulting in complete attenuation of the radar energy and preventing penetration.; in the second attempt, the ice was not well bonded to the sides of the tank so that the oil all ran up the space between, leaving almost no oil under the ice. In the final test, the ice salinity was satisfactory in the 6-8 parts per thousand range (slightly higher than normal, representing a worse than average case for the radar), but the ice thickness was highly variable from only 8.5 inches at the center to 20 inches near the edge. The vertical probing for oil in the center of this third test was successful but due to the ice thickness variation, the shape of the oil lens tended to be a wedge, defeating attempts to fully test the polarization effect (enough was learned to be able to see large changes in polarization when the oil was present).

[This report appears to indicate that under ideal circumstances (relatively uniform ice) impulse radars operating in the 300 to 700 MHz range can successfully detect oil layers down to 7.6 cm (3 inches) thickness under ice as thin as 20 cm. In spite of some promise shown in field trials in McKinley Bay (Butt et al., 1981) there is still considerable uncertainty in the application of radar technologies to the detection of oil layers trapped in ice. Problems include the lack of repeatability (laboratory tests were inconclusive) and the difficulty in making an unambiguous interpretation in a field setting with natural irregularities and discontinuities in the ice cover.] Refer to further discussion of the physical environment in 4.3.3.

4.2 Technical Constraints and New Technologies

The main purpose of this task was to revisit the conclusions drawn from past studies (1980's) in the light of current technology. The intent here was to focus on techniques which showed promise in the past, but where results may have been constrained by technical limitations not directly related to the basic scientific principle involved (e.g., radar where the ability to discriminate between oil and ice may have been limited by system noise or the allowable attenuation in the signal).

At the same time, the opportunity was taken to contact known agencies and research organizations around the world to determine if they know of any previous work in this field or have any ongoing programs using existing or new technologies.

The main purpose was achieved by holding a number of telephone interviews with researchers in Canada and the United States who had experience either with the technologies themselves (e.g., EM, radar, acoustics) or with previous trials and test programs. Individuals were asked for their opinions as to the capabilities of state of the art systems in achieving the desired goal of operationally detecting oil in ice. Results of these discussions are summarized below.

No new technologies were identified which have not already been considered in previous studies and tests (see 4.1). As a result of contacting the following groups, no new technologies could be identified beyond those already described in the literature (4.1):

- National Institute of Polar Research, Tokyo
- University of Lapland, Finland
- Swedish Polar Research Secretariat
- British Antarctic Survey, Cambridge
- Geophysical Institute, University of Alaska, Fairbanks
- Polar Science Center, Seattle

- Lanzhou Institute of Glaciology and Geocryology (LIGG), China
- Nansen Remote Sensing Center, Norway
- National Research Council, Ottawa
- Danish Polar Centre, Greenland
- Danish Hydraulic Institute
- Scott Polar Research Institute, Cambridge University, Cambridge UK
- CRREL (US Army), Hanover, New Hampshire
- Environment Canada, River Road Environmental Technology Centre, Ottawa
- C-CORE, St. John's
- SINTEF, Norway
- Canada Centre for Remote Sensing, Ottawa
- Imperial Oil, Calgary

Telephone contact was made with the following individuals covering a range of expertise::

Scott Holladay, Goesensors Inc., Toronto (supplier of operational EM ice thickness systems to the Canadian Coast Guard)

Austin Kovacs, Lebanon, NH (expert in ice thickness measurement by impulse radars & EM systems, previous research includes measurements of under ice oil holding capacities in the Prudhoe Bay area)

Dan Delea, GSSI, NH (systems engineer with long time manufacturer of impulse radar systems used for ice thickness measurement, among many other applications)

Les Davis, Sensors and Software, Inc., Ontario (expert in radar system design and applications)

Louis Lalumiere, Sensors by Design, Ltd., Ontario (expert in GPR radar system design and applications)

Merv Fingas, Environment Canada, Ottawa (expert in remote sensing including sponsorship and management of previous programs involving radar and acoustic systems for oil in ice detection)

Ron Goodman, Imperial Resources, Calgary (expert in remote sensing including sponsorship and management of previous programs involving radar and acoustic systems for oil in ice detection)

Hugh Jones, Nova Scotia (expert in acoustic systems and designer of prototype system tested by Environment Canada and Esso)

The following text contains a synthesis of conversations held with these individuals. Out of professional courtesy, it was considered inappropriate to assign specific opinions by name.

Electromagnetic Induction (EM) Systems:

The Geodat EM "bird" is suspended beneath the helicopter and provides real time measurements of total ice thickness. A Laser is used to profile the snow-air interface. The ice thickness is derived from a combination of the EM measurement of the distance from the bird to the ice underside and the laser measurement of the distance from the bird to the ice surface.

Sea ice is virtually transparent to radiation at frequencies where EM systems operate (around 100 KHz). There are several opinions as to the applicability of EM technology in detecting oil in ice. One view is that an airborne EM bird similar to the Canadian Aerodat may be able to detect a thick pool of oil and slush expected following an extended chronic leak beneath the ice (4.3). Another view by an expert with extensive experience testing EM systems in the field is that this technology will not "see" the oil and would likely register similar values for equivalent thickness between oiled and unoiled ice.

There are several major drawbacks to these systems: the existing airborne system is seriously affected by static discharge buildup in blowing snow, and the EM system is limited to areas with more than ten feet of water underneath the ice (EM systems experience a systematic error in shallow water because they start "seeing" the bottom in depths less than about 3 m). This water depth limitation effectively eliminates large areas of nearshore ice in the Alaskan Beaufort Sea. EM systems are also characterized by a large footprint (compared to impulse radars). These measurement footprints are typically 30 m for an airborne system flying at 15 m altitude to achieve a 90% reliability level, down to about 3 m for a handheld surface system as tested by Kovacs (1999). The Canadian Coast Guard is presently working with Geosensors to develop a fixed mount EM system which will allow the helicopter to land or hover and collect point samples with a smaller footprint (tests are planned for the Gulf of St Lawrence, winter 1999/2000). The final system development will integrate video, laser, EM ice and EM snow thickness to achieve the full capability to map ice thickness, snow depth and ice morphology all at once. This development ongoing in Canada is probably still several years away from being a functional unit.

One suggestion was to integrate ground penetrating radar (GPR) with an airborne EM system. In this way, the airborne system could conduct a wide area sweep to identify areas which could be surveyed in more detail with the GPR.

Several experts felt that EM systems, while valuable as means of obtaining meaningful thickness measurements in areas of rough ice which would confuse impulse radars, have a limited potential of being able to detect oil trapped under or in ice, regardless of the thickness of the oil layer. It was noted that while radar is the most common term, it would be more accurate to describe systems under the general category of Electromagnetic with sub headings of EM induction and wave domain (radars).

Impulse Radars (including airborne and GPR surface systems)

There is a need to examine the potential for using GPR to look at oil sandwiched between the ice and the seabed in the bottom fast zone. The problem in this case is the lack of a definite oil/ice interface. In this situation (common in the nearshore areas of the Beaufort Sea) the oil could be mixed with partially frozen sediments or trapped under a cap of frozen soil in the trench.

One expert felt that chances today for detecting oil in ice with the latest generation of surface impulse radars are better than 15 years ago because of strides made in reducing the noise in the system itself (this means that greater signal attenuation can be tolerated before the signal becomes unusable). Compared with the previous generation of radars, the newest systems offer significant improvements in electronics including: stability and accuracy, signal drift, reliability and hardening for field use.

The "desirable" frequency range of surface impulse radars optimized for sea ice thickness falls between 300 MHz and 500 MHz. It may be desirable to go down as low as 100 MHz to get penetration of the pulse with warm high brine content ice where conductivity goes way up. On the other hand, when ice is this warm, the oil will be rapidly migrating to the surface and it may not be necessary to do any remote sensing surveys (see description of this natural process in 4.3 below).

It is possible to perform useful tank tests if they are well designed but it is always difficult to avoid interference effects. Field tests are desirable to really test the capabilities of any system. The key problem is that oil and ice dielectrics are very close. There may be some way of taking advantage of the unusually smooth surface provided by the oil/seawater interface.

One opinion by an experienced researcher, was that impulse radar units were not evaluated sufficiently in past studies to fully determine their actual capability to detect (or not detect) oil in ice. The same individual also cited the significant problem of having to cope with highly variable ice conditions in a field setting [ed. the same argument can also be used as a reason why radar systems will not work either].

Ground penetrating radars are commonly used to look at the "vados" zone around leaking underground storage tanks (transition from saturated to unsaturated soils containing petroleum products, liquid and vapor). One expert in radar applications thought that it was feasible to detect oil beneath a frozen sediment layer under bottom fast ice (see 4.3). With a normal GPR used on floating sea ice, the pulse essentially dies at the seawater ice interface due to huge dielectric losses (in the absence of seawater, this pulse could potentially continue to penetrate the sediments bonded to the ice in shallow water).

Several experienced radar systems engineers and designers felt that with the significant technological advances since radar units were last tested with oil in ice (past 15 years), current generation systems (particularly surface GPR units) would have a better chance of detecting oil in ice under a certain range of conditions such as thick oil films under level mid-winter ice in water depths over 10 feet. Advances in technology include dramatically lower signal to noise ratios (20-40 dB better), much faster scan rates, real time signal processing, and a wide range of vertical/low/high pass filters. The dynamic range of new radar systems is double or triple what would have been possible in the mid-1980's. Interestingly, the technological advances in airborne systems has not kept pace with surface radars (see further comments below).

Most ground penetrating radars run in the 10 MHz to 1 GHz range. A one GHz system could measure ice as thin as about 6 inches (15 cm), while the 300 MHz frequencies commonly used in sea ice thickness applications are limited to ice thicker than about 2 feet (60 cm). In order to cover the full spectrum of oil in ice configurations, it may be necessary to develop a variable frequency system or separate systems for early and mid-winter applications.

Radar signal absorption depends on the conductivity of the medium which explains why lower frequencies are required to penetrate highly saline or warm ice. The resolution depends on the radar pulse length while the footprint depends largely on the antenna length.

It should be noted that the condition of warm ice is not relevant to the question of oil in ice detection; in a spring condition, most if not all of the encapsulated oil will naturally rise to the ice surface and be clearly visible (Norcor, 1975).

One designer went into considerable detail in describing the basic principles and possible application to the oil-in-ice problem Radar works by propagating a wave through a medium: there has to be an interface, as well as some physical property which will allow the system to differentiate between layers or interfaces. At the relatively low frequencies used for past ice thickness radars (100 to 400 MHz) the oil layer would need to be quite thick to be detected (6 inches or more). A single off the shelf radar system may not be useful for high salinity (i.e., first year ice). It may be necessary to look at an array of radars with multiple receiver/transmitters (similar to other comments noted above). It was noted that GSSI used to manufacture a cross polarized sea ice antenna; the same effect can be achieved by using a two channel system today.

The original application of cross dipole antennas for sea ice mapping was a means of canceling the natural anisotropy of sea ice (preferred C-axis alignment common in fast ice - refer to discussion of this feature in 4.3 below). There may be some means of taking advantage of this anisotropy rather than always seeking to cancel the effect. For example, oil within the ice would not display the same anisotropy as the surrounding ice. The isotropic effect could be retained by sticking with a straight dipole antenna (this means that only surveys in certain directions aligned with the ice crystal orientations, would produce results). Although not desirable for an operational system, this natural effect could be extremely useful in a basic research program as a means of better interpreting what is actually happening to the radar energy as it passes through the oil layer.

One method of increasing radar penetration at higher frequencies (corresponding to better resolution and thinner oil films) is to increase the transmit power. There are physical limitations to doing this. Another alternative is so called "stacking" where you sit in one place for a period of time and average a large number of successive wave forms. This type of approach would have been difficult with the older systems due to the inherent system noise, but may be worth exploring with the current generation of systems.

With a rough ice field, normal radar loses its signal due to the multiple reflectors in all directions. Both EM and airborne radar have large footprints (10's of meters). The real advantage of EM is its ability to average over this footprint in rough ice and produce some meaningful value. On the other hand, radar in this situation sees numerous point targets throughout the footprint and the result is garbage. On a flat plane, radar effectively measures the ice thickness from a very small footprint (single target). In general, ice thickness radars work best on multi-year ice (low salinity), and worst on rubble and brash ice. First-year ice falls in the middle of the difficulty range. Radar is generally much more reliable and easier to work with than EM technology, without the continuing problems of drift and static build-up mentioned earlier.

A major hurdle in developing an operational oil in ice detection system will be to avoid too many false alarms. This is a key problem with all leak detection systems (how high can the sensitivity be set without triggering an excessive number of false alarms?)

One designer felt that the technology involved with airborne radars has not improved significantly in the past 15 years. Radar manufacturers claim that the signal to noise ratios have dramatically improved, but in reality off-the-shelf systems that can be flown today are 4 times worse than a custom system put together from 10 year old components (this comment confirms to the need for dedicated designs in developing radars for specialized applications). Manufacturers have not really changed anything in their components which could be used in an airborne mode in the past 15 years (opinion).

The real technological improvements in the past ten years have been in surface systems which have seen much reduced system noise with almost no ringing in the antennas. The result is seen in much better GPR systems for shallow surveying in the ground.

One designer offered the opinion that the most important factor in developing a new radar system for oil in ice detection will be the geometry of the equipment. There is a need for multiple antennas and multiple transmitters to measure the different dielectric properties. As an example of the advantage of multiple arrays, HF systems have small antennas which limit the power going out. An array of multiple HF antennas can transmit more power. The array can be used to focus the antenna beam better and average the side echoes to concentrate on one point. The ability to fairly easily build a real time array is one of the most significant improvements in new vs. older systems.

Acoustics

A number of questions were put to agencies, organizations and designers who worked extensively with acoustics technology in the 1980's in developing a working system for detecting oil in ice (refer to literature review of papers on this subject under Environment Canada and Esso Resources).

What is the status of new program developments in this area?

The original designer of the first acoustics oil-in-ice detection system prototype in the mid 1980's, Dr. Hugh Jones, recently (late 1999) completed a technology review for Environment Canada (not publicly available). The report topics included:

Review of research since 1986
Review of physical theories
Review of available publications
Review of processing systems
Review of transducer design and development
Review of limitations of state of the art electronics

A new prototype acoustics system is in the early planning stages with the possibility of putting together hardware by the summer of 2000, and of local (Ottawa) testing later in 2000.

Are there any target performance parameters for the new system?

There are too many unknowns and variables to establish definite performance parameters. Any new system which is built today will concentrate on hardening of components to deal better with cold temperatures. The new system is viewed by Environment Canada as an update to the original with more compact new technology electronics. Fundamental principles and operating characteristics remain essentially unchanged from the late 80's. The proposed new prototype would still require transducer bonding to the ice surface. System performance parameters which would be of interest for a new system include: min/max ice thickness, min/max oil layer thickness, differences between free (i.e., oil under ice) vs. encapsulated oil in ice. There is no information on the ability of an acoustic system to work in shallow water (less than 6 feet), and detect oil potentially trapped under a layer frozen sediment attached to the bottom of the ice. This unknown also applies to any other technology.

The point was made that very little is known about the acoustic properties of ice. For example, there is a lack of understanding about the causes of attenuation of acoustic signals under field conditions. It was agreed that newer generations of signal processors and electronics can generally tolerate a higher level of system noise.

Past work in the area of acoustics based detection systems demonstrated that relatively low acoustic frequencies are required to penetrate 1-2 m of ice (e.g., 100 to 200 KHz). Such a system would be able to resolve oil layers in the 1-2 cm range.

Higher ultrasound frequencies (unsuccessful in past trials with oil) could theoretically resolve much thinner oil films over a smaller footprint with simple reflection techniques. In contrast, the previous prototype uses differences in the ratios of the amplitudes of reflected shear and compression waves to detect the presence of oil. Older acoustics systems could only tolerate signal attenuation of about 20 dB per meter which translates to a total maximum allowable attenuation of 80 dB with 2 m of ice and a return path. It may be possible to improve on these figures with new electronics and system design which could work at a higher level of attenuation.

Are there any published results from the original field trials held on the Mackenzie River and in the Canadian Beaufort Sea in the late 1980's?

Reports were prepared internally within Imperial Oil on these trials (carried out jointly with Environment Canada) but the information has never been released or published in its entirety. Summary information was provided in presentations at the AMOP conference series. Much of the data either remains unanalyzed or has been lost over the past decade.

Acoustics represents the only available technology to achieve the target of reliable oil in ice detection and that acoustics is the only technology worth developing further (individual opinion). The fully engineered prototype build in the mid 80's was state of the art at the time. It's main drawback was the weight and size of the electronics which could easily be overcome with modern components. Future generation systems would be much lighter, faster and more capable of withstanding cold operations in a field environment.

The developer remembered three lots of tests, 2 in fresh water at Norman Wells and one series in the Arctic (Beaufort Sea). Apparently, the sea ice tests were somewhat unsatisfactory, particularly in situations of snow ice with a hard slush layer overlaying the sea ice. (review comments on the draft report related these difficulties to the fact that the ice sheet was already rotting). Porous or rough ice presented problems for the system. Reliable results depended on a fairly homogeneous, solid ice sheet.

4.3 Operating Environment

4.3.1 Introduction and Background

This section summarizes the key parameters and features of the nearshore ice zones and the expected oil in ice configurations and geometry affecting the practical deployment and operation of oil under or in ice detection systems. The discussion covers the range in ice conditions and ice properties which any working system will need to accommodate, focusing on the Alaskan coastal area (see study region description below). Example scenarios are described in terms of how the spilled oil will most likely be deposited and contained under and in the ice sheet. The discussion focuses on situations where oil could be deposited either beneath solid, stable ice in the so called "landfast zone", including the sub-region known as bottom-fast ice.

Although the following discussion would apply generally to a variety of spill sources, the text is oriented to situations where a marine pipeline either ruptures (leading to a batch release) or leaks over a period of time (days to weeks), at rates which are not immediately detected by the installed monitoring systems. Examples of other low probability events which could result in a spill beneath winter ice are a subsurface blowout in the vicinity of a production facility, or a sunken barge or vessel containing oil.

The volumes of oil involved in the types of scenarios considered here are in the order of thousands of barrels. The actual volume associated with any given incident depends on a complex set of variables including the oil flow rates in the pipeline, response times to shut down of a line from the point of first detection, time interval between leak surveys, seabed slopes at the point of the spill etc.

The geographic area being considered for the description of the ice operating environment encompasses the nearshore region surrounding Prudhoe Bay to the east and west, including the current producing fields with the potential for a marine incident, and sites of proposed offshore fields which would utilize a buried marine pipeline from shore (Figure 4.1). While the general study area is not limited by any defined water depth, current development efforts are focused on the area of landfast (contiguous with shore) winter ice out to approximately 60 feet of water. For example, two new offshore developments by BP Exploration (Alaska) are in approximately 19 feet (Liberty) and 38 feet of water (Northstar).

Much of the material describing the ice environment and oil in ice configurations is derived from public documents prepared by K. Vaudrey and/or D. Dickins as part of the Northstar planning and permitting process (this being the most detailed description of a representative offshore Alaskan oil field development available to date). Other material has also been extracted from recent publications in conference proceedings and journals (Dickins and Buist, 1999).

Figure 4.1 shows the oil fields in the Prudhoe Bay area from the Kuparuk field in the west to the proposed Liberty field in the east (Source: BP cartography, Anchorage). Areas with risk exposure to marine spills include Niakuk, Pt. McIntyre, Milne Point, Northstar, Endicott and Liberty. Two of these developments, Northstar and Liberty involve a buried pipeline from shore to the offshore production facility.

The operating period when it may be necessary to deploy oil-in-ice detection systems on a regular basis stretches from freeze-up to break-up. This period will vary by several weeks or more, depending on proximity to shore, and actual location (see discussion below), but typically stretches from mid October to late June. For a detailed discussion of the variability in break-up and freeze-up dates at different sites, the reader is referred to Dickins, Vaudrey and Ross (2000).

The intent here is to provide sufficient background for future developers and systems engineers to use in developing performance specifications, deployment procedures, and reliability estimates for different systems in an operational setting.

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4.3.2 Important Environmental Factors

A clear statement of the operating environment is critical to not only determine whether a given technology will work in the first place (is there a fundamental physical constraint such as ice thickness, ice salinity or depth etc.), but also to determine whether or not a particular system is likely to provide an acceptable level of reliability over the full range of natural environments to be encountered. Localized ice characteristics such as a refrozen snow layer at the surface, excessive voids or air pockets within the sheet, fractures and cracks, and deformed ice (rafting and rubble) could seriously downgrade the practical operating performance of many systems which produce favorable results in a lab environment.

Important aspects of the physical environment and the oil in ice configuration are listed below according to whether they affect either the choice of sensor technology (acoustics, EM etc.) and/or the application of the technology in a reliable, routine field setting (e.g., extreme temperatures).

Examples of important environmental conditions affecting design and operations are listed below.

1. Sensor Selection/Design (possible effect in brackets)
   - level ice thickness (signal penetration)
   - deformed ice such as rafting and rubble (multiple targets)
   - ice temperature and salinity (conductivity affecting attenuation)
   - water depth beneath the ice (confusing returns, secondary interface)
   - other factors (e.g., blowing snow creating EM static problems)
   - oil layer thickness (detectability vs. minimum resolution)
   - geometry of oil in ice lens or pocket (detectability vs. footprint)
   - sharpness of oil/ice/water interface boundaries (unambiguous returns)
   - air pockets or voids (attenuation of signals)
   - timing of new ice formation beneath the oil (interface interpretation)configuration of interfaces, signal interpretation vs. time)

2. Sensor Deployment/Operation
   - visibility, air temperature, winds (flying conditions, reliability of airborne surveys)
   - extreme temperatures (electronics, packaging, power supplies etc.)
   - surface roughness (feasibility of towed surface systems, transducer to ice bonding, need for and extent of surface preparation)
   - ice stability (safety of on-ice survey methods)
   - ice thickness vs. time (commencement of safe surface operation)
   - available operating window (first stable ice to river overflood)

4.3.3 The Physical Environment: Ice Climate

This section provides an overview of sea ice conditions in the study area, starting with a basic orientation to sea ice as a material. Additional statistics on Prudhoe Bay weather (winds, temperature, visibility) can be found in Dickins, Vaudrey and Ross (2000).

Ice Structure (from Sanderson, 1988, edited to include items most relevant to this study)

Ice is characterized by oxygen atoms well bonded within layers of hexagonal symmetry, but less firmly attached from layer to layer. The so called "basal" plane parallel to these layers is referred to the crystal "c-axis", the orientation of which in different ice forms gives rise to differing physical properties. Ice crystals are usually of extremely high purity. Although formed from a strong saline solution solid ice contains a negligible amount of salt. Arctic surface waters are commonly in the range 30 - 34 parts per thousand (ppt), locally less (15-25 ppt) in areas influenced by river outflow. Any saltiness of the ice is due only to trapped salt solution or crystals, but not to any incorporation of salts into the ice crystal structure.

During the freezing process, young ice appears as the first continuous sheet some 5 to 30 cm thick (following frazil, grease ice and pancake ice). This young ice consists of crystals about 1 mm diameter frozen randomly together, and is categorized as granular form or frazil ice after its crystal origin. Brine is incorporated into the ice structure in the form of fluid or gas pockets. The gross salinity of this young ice layer is in the range of 5 to 10 ppt early in the winter (subsequent brine drainage later in the winter can lead to lower surface salinities). Young ice is generally moist at the surface with very high salinities in the first few mm.

Once the young ice has reached a stable condition (no longer broken by winds and waves) subsequent freezing occurs much more slowly (no longer being a conglomerate of individual crystals and fragments thrown randomly together) in the order of 1 cm per day. This process results in the formation of large regular crystals in the order of 1 to 10 cm in size. In their early stages of growth these crystals appear as thin plates extending down beneath the ice (skeletal layer). These crystals are elongated in the vertical direction (corresponding to the direction of heat flux) with a substructure of platelets having horizontal c-axes. As the crystals form, salt is expelled at the ice-water interface of growing platelets and cold briny streamers fall from the surface to be replaced by warmer, fresher water from below. This ice formed with predominantly horizontal c-axes is known as columnar ice. When sea ice grows in this fashion as drifting floes, the crystals grow with no preferred direction in the horizontal plane - such ice has uniform properties in all directions.

In landfast conditions of most interest in this study, a preferred orientation of columnar crystals can develop in response to unidirectional under ice currents. Such anisotropic alignments have been observed off Alaska (Weeks and Gow, 1978; Langhorne, 1983). The degree of alignment generally improves with depth so that a typical winter ice cover may look like 30 cm of granular ice, followed by 50 cm of more or less randomly oriented columnar ice, followed finally by preferentially oriented columnar ice. This lower ice level may show consistent c-axis alignment to better than ± 5°. Offshore ice in the seasonal pack zone is often a complex composite of frazil and non-aligned columnar ice at different depths. The preferred alignment properties of sea ice in the nearshore zone could be used to advantage in for example providing another point of signal comparison between ice and oil.

Sea ice types can be broadly divided into the following categories (Table 2.1 in Cammaert and Muggeridge, 1988).

• Primary Ice	first to form (eg. granular, frazil)
• Secondary Ice	forms under the primary ice (columnar)
• Superimposed Ice	forms at the top of the ice cover (e.g., snow ice)

Figure 4.2 shows the typical structure of first year sea ice with the different categories of ice (after Weeks, 1982).

Figure 4.2

Typical Structure Of First-Year Sea Ice

Ice Roughness

In reality, all first-year ice can take on a variety of forms, depending mainly on the degree of mechanical action it has been subjected to. Near the coast, for example inside the Barrier Islands, the fast ice is typically very flat and uniform for miles at a time, the uniformity broken only by occasional long-range tensile cracks. Even in this relatively protected area, there can be areas of minor rubble left over from fall storms. Although there is no actual data, first hand experience (Vaudrey pers. comm.) shows that is unlikely that such roughness would cover more than 5% of the overall ice surface.

Rubble consists of small blocks (20 to 60 cm) bonded in a randomly oriented fashion to form a highly irregular material with numerous voids and irregularities. Early in the season, shortly after the rubble forms, the ice underside will be very jagged with many deep pockets to hold spilled oil. With minor rubble of limited draft, new ice forming later in the winter may smooth out some of this extreme bottom surface roughness. Rubble having even two meters of draft would not be smoothed out to any great extent and would retain its rough under surface through the winter. Rafting is another form of ice deformation where two or more young ice sheets ride over each other early in the season, October to November (it is possible for rafting to contain four or more ice layers in a local area). Within a short period of time, rafted features can be completely obscured on the surface by drifting snow and within a few months obscured on the under surface by new ice growth.

Outside of the Barrier Islands and out to approximately 20 feet of water, the landfast ice is still relatively smooth but the probability of encountering large patches (hundreds of meters in extent) of moderate rubble with surface elevations in the 1 to 2 m range increases substantially with an average in the order of 10% of the ice surface having some form of roughness. It may be necessary to implement some form of surface smoothing to enable such activities as surface travel (e.g., towing an impulse radar system) and bonding of any transducer requiring intimate contact with the ice (acoustics). At the same time, such roughness features could make the discrimination between an oil layer in the ice and reflections from multiple radar targets very difficult.

Beyond 20 feet of water out to 36 feet of water (some four miles in the case of the pipeline route to Northstar) the proportion of rough ice would gradually increase to approximately 20% by area. Immediately around the production facility itself, severe rubble piles can form in preferential directions depending on the timing and duration of fall storms breaking the young ice and piling it against the sides of the island.

Nearshore ice often contains significant concentrations of entrained sediments especially in shallow areas such as the Beaufort Sea. The fine grain sediments often show up within the first 30 cm of the ice as discrete bands. Large sediment loads may be deposited on the nearshore ice by the spring overflood and left behind when the flood waters drain. This sediment can create confusing visual images where oiled and dirty ice look very similar in June.

Ice temperatures

Sea ice temperature profiles are generally linear during much of the winter (Jan to March) The upper ice surface (10 - 20 cm) remains within ±10° C of the mean daily air temperature, while the bottom of the ice remains steady at close to -1.8 °C (for water at 35 ppt). A typical gradient in mid-late winter for 1.5 m of ice would then be approximately 12 degrees per meter (surface at -20). In the spring (April-May) the rapid rise in air temperature and solar heating of the ice surface will lead to a reversed temperature curve where the surface and bottom may be 5° or more warmer than the ice center. As explained below, this condition will give rise to the simultaneous expulsion of liquid brine to the top and bottom surfaces of the melting ice.

Brine and Gas Pockets

Sea ice salinity has a major effect on the penetration of many remote sensing systems, (particularly radar). This salinity is almost entirely due to trapped pockets of briny water. Gas, mainly air, also exists in the form of bubbles trapped during the freezing process. Typical gas concentrations may be in the range of 0.5 to 5% by volume, with the concentration decreasing with depth. The density effects of brine and gas tend to cancel each other out such that a typical density value for sea ice at the mid-depth would be in range of 0.915 to 0.92 kg/cubic meter, very close to that of bubble free freshwater ice. The upper layers of first-year sea ice may show densities down to 0.89 or lower.

The amount of salt trapped within the ice at any given depth is primarily a function of the rate of freezing. Surface salinities in granular ice are often in the range of 8-12 ppt. At lower levels with much slower freezing rates, the bulk salinity drops to the 5 -8 ppt range. With time, the brine pockets tend to migrate slowly downwards during the freezing period as a result of the temperature gradient. During spring and early summer brine will be expelled to top and bottom surfaces and the gross salinity of the ice then decreases with time. In April and May, the bulk salinity of the material may decrease by about 0.5 ppt per month. Empirical equations exist to calculate the gross volume of the brine pockets within the ice as function of temperature and salinity.

Other Properties

Goodman et al. (1985) summarized several of the electromagnetic properties of materials involved in oil in ice detection as follows (conductivity values are as quoted from Kovacs (1999)):

Table 4.1

Electromagnetic Properties

Material	Real Component of Dielectric Constant	Conductivity (Siemens/m)	Sound Velocity x 10^9 cm/sec	Wave Length @ (1GHz) cm
Air	1	0	3	30
Sea Water	80	2 to 3	absorbed	270
Sea Ice	4-8	typ 0.01	1.68	50
Oil	2		2.12	42

The estimated ice properties in field situations may depend greatly on localized variations in ice morphology. Examples of such cases would include the situation where a high snow load early in the winter has depressed the sea ice below sea level and created a layer of snow saturated with highly conductive seawater. Rafted ice sheets may be separated by loose ice blocks or slush ice which would also greatly affect the bulk conductivity of the ice. These regions of high conductivity could create problems in using standard software modules used to interpret for example EM or impulse radar returns as a real time display of true sea ice thickness.

Work at McGill University in the 1960's documented the attenuation of sound in sea ice (Langleben and Pounder, 1970). These results were used by Goodman et al. (1985) to plot the attenuation co-efficient of acoustic compression waves as a function of frequency. This type of representation allows acoustic system designers to select an operating frequency for a given system performance (allowable attenuation of signal) and ice thickness. Research by Jones et al. in the 1980's quantified many of the important physical characteristics of ice and oil involved in the development of acoustic systems: velocity differences for compressive and transverse waves as a function of ice salinity, effects of ice temperature on the propagation of compressive and transverse waves, attenuation of shear waves in crude oil and so on). For details, the reader is referred to the original paper on this subject presented at POAC 1985 and other related papers presented at AMOP conferences (see literature reviews in 4.1 under Environment Canada - Acoustics).

Alaskan Beaufort Sea Nearshore Ice Regimes

The previous text deals with sea ice a material, in terms of its initial formation and crystal structure. This section provides an introduction into the general ice cycle or season in the nearshore waters of the Beaufort Sea in the vicinity of Prudhoe Bay (Vaudrey, 1996 & 1999). Within this area, there can be localized ice features or behavior trends related to river runoff, bathymetry, shoals, barrier islands and so on. The intent here is to provide a regional overview of the important distinctions in the timing of ice formation and decay and characteristics of winter fast ice out to approximately 40 feet of water. This description excludes the highly deformed area in deeper water known as the shear zone where massive grounded ice features cause annual reworking of the sediments on the shelf break, as well as the so called "seasonal" pack ice zone where apart from unpredictable short periods of immobility in deeper water (outside of 70 feet) the ice is normally in a state of constant motion throughout the winter.

Petroleum activities in the southern portions of the Alaskan Beaufort Sea are occurring on gravel islands and structures, which in winter are surrounded by solid, immobile, landfast ice. Only the months of August and September can truly be characterized as open water and even at this time drift ice from the offshore pack can invade shallow water areas with northerly winds. In many years, the nearshore waters are not clear of ice until the end of July and freeze-up can start near shore in late September.

In this study, the focus is on situations where oil could be trapped under or in solid ice which for the most part limits this discussion to that period when the area from shore out to approximately 40 feet of water (that region being considered for potential production development in the foreseeable future), is covered with a stable sheet of what is termed landfast ice (ice contiguous with the land).

Freeze-up and Initial Ice Stability: The rapid drop in average air temperatures in early October is generally accompanied by the formation of fluid-like frazil and grease ice nearshore and in inshore and backwater areas inside of the Barrier Islands (e.g., Simpson Lagoon and Stefansson Sound). This area is normally covered with a thin but stable, continuous sheet of ice within a week of the first appearance of ice.

Stable ice covers take longer to establish in deeper water. Depending on the wind and sea conditions, the first continuous ice forms such as nilas and grey ice can extend beyond the Barrier Islands within a few weeks of initial freeze-up. These early stages of first-year ice are susceptible to break-up by fall storms. In most years, 30 to 40 days will elapse (from the initial stages of freeze-up) before a stable solid ice cover exists out to sites such as Northstar. This condition is usually reached in mid November at which point the ice is 10 to 12 inches thick. Currents beneath the ice at this time decrease to 0.1 knots or less and remain at that level in most regions until spring breakup (refer to additional discussion below on the issue of whether sub-ice currents in the region are capable of transporting oil under the ice).

It is interesting to consider the point at which the landfast ice attains sufficient thickness to be mapped reliably by impulse type radars at the surface. A commonly quoted threshold for the minimum thickness capable of measurement with this technology is in the range of 50 to 60 cm. Off Prudhoe Bay, this thickness is surpassed in most years by late November and in some years as early as mid November. The ice reaches the minimum threshold thickness required for existing impulse radar surveys about the same time that crews are able to travel safely on the ice to offshore sites such as Northstar. In shallow water sites inshore of the Barrier Islands, the ice will stabilize at lower thickness values. The situation could arise where crews could conceivably gain access to the ice surface in early November, several weeks before it was thick enough to use radar systems.

Winter Conditions: The mid-winter period extends from late December to mid-May. There is almost no ice movement during this time within the study area (less than a few feet maximum). The ice grows at a typical rate of 1 foot per month and attains a maximum thickness of between 70 and 85 inches (avg. 77 inches) by May 1. During the April to May period, the ice is subject to various types of stress cracks as a result of rapid temperature changes, tidal action and storm surges. These cracks heal very rapidly to become solid ice (overnight).

There is another form of mid-winter ice within the landfast zone which will greatly effect the configuration of any spill from the seabed during the mid winter period (see further discussion in 4.3.4). In the shallow water lagoon areas, large portions of the fast ice rest directly on the seabed by early February (sooner in shallower areas). This condition known as *bottom fast* or *bottom founded* ice is commonly encountered between the shore and the barrier islands after mid-February. By early April, most of the ice out to the one fathom (6 ft) isobath is solidly grounded.

Periods of westerly storms can create a one to two foot increase in water levels and lift the ice sheet off the bottom temporarily during mid-winter (Coastal Frontiers in Intec, 1996a). Otherwise, much of the ice within this bottom fast zone (particularly in areas inside the Barrier Islands such as Simpson Lagoon) rests firmly on the seabed with an attached layer of frozen sediment at the ice/bottom interface after March. This condition persists until June when the nearshore ice lifts free of the bottom following drainage of the river overflood (see below).

During the months of May and June, the ice is warmed rapidly by increasing air temperatures and lengthening periods of sunlight. In late May or early June, the surge in river flow from snow melt in the upland areas leads to large scale overflooding of the freshets out onto the ice offshore of the delta areas (Sag, Kuparuk, Colville etc.). A typical overflood from Kuparuk begins on May 29 and rapidly extends to cover the ice out to the 25 to 30 foot water depth range. Following natural drainage of these overflood waters through openings in the floating ice (seal holes, cracks etc.) the remaining nearshore bottom fast ice is left with a heavy layer sediment on the surface. This ice melts rapidly from the surface down. Within a period of 2 to 3 weeks after the flooding has ceased, most of the landfast ice within the overflood zone will have melted in place from a combination of the fresh, relatively warm, water and the increased heat absorption by the dirty ice.

The nearshore lagoon areas are the first to clear of ice, often by late June. Offshore areas may take another month or more before the ice is substantially gone. During this period of decay, 100% ice coverage persists until the ice deteriorates to the point of breaking up under the influence of winds and currents. Following the onset of breakup, the ice cover begins to shift, crack, and deteriorate further into a field of ice cakes and brash ice and floes of varying sizes.

At this point, mid to late July in the vicinity of Seal Island for example, there is no longer any solid ice cover in the region of interest and the problem of oil detection becomes quite different. While theoretically, some oil can still be deposited under the large moving floes of ice during the break-up period, the porosity of the ice is such that the oil will surface very rapidly. Once the ice has become permeable in terms of vertical oil migration, the problem of detection becomes one of looking for oil on ice or among floes.

Ice Bearing Capacity

It is important to understand the limits of ice bearing capacity when planning any routine over ice operations with vehicles, personnel and equipment such as helicopters. The safe bearing capacity of ice sheets has traditionally been derived from empirical results with the allowable load being estimated as a simple function of the square of the ice thickness (e.g., Gold, 1971). Vaudrey (1977) used a finite element analysis to calculate the required thickness of sea ice to support a given load based on such factors as ice temperature, time of load application, and the physical properties of ice as an engineering material.

Approximately twenty inches of sea ice is recommended as a starting thickness to begin conventional (wheeled) vehicle operations with conventional wheeled vehicles such as small trucks. Lighter equipment such as ditch witches, snow machines and special terra tired vehicles called Rolligons can operate on thinner ice (12 to 20 inches) as long as the sheet is continuous and stable and operators accept the increased risk. Strong winds can lead to rapid break-up of young sea ice, and such early season operations will require strict safety measures, continuous ice monitoring and evacuation plans. It is strongly recommended that any operations over ice less than twenty inches be limited to areas inside the barrier islands with water less than four feet in depth.

The table below gives dates and safe ice thickness associated with two types of helicopters common on the North Slope. This information is important for planning possible airborne surveys which would require landing for spot sampling or calibration.

Table 4.2

Recommended Ice Thickness For Selected Helicopters

(Note: actual weights may vary with different options and model numbers)

Aircraft	**Gross Weight (lb)**	**Payload est. (lb)**	**Winter Ice Thickness (in)**	**Average Earliest Date on the Ice**
Bell 212	11,000	5,000	16	Nov 8
BV-107	19,000	11,500	20	Nov 17

4.3.4 Configurations of Oil in and Under Ice

(derived from material in Buist and Dickins, 2000; and Dickins and Buist, 1999)

Overview

The purpose of this section is to outline the possible geometry and configurations of oil which may be trapped under solid ice or encapsulated as a layer in the ice following a subsurface release in the landfast zone (see ice description above). For a detailed review of the state of knowledge concerning the behavior of oil in all types of ice the reader is referred to Dickins and Fleet (1992). Figure 4.3 shows a number of possible oil configurations under, among, in and on ice at different times of the year (after Bobra and Fingas, 1986).

Figure 4.3
Illustration Of Oil And Ice Configurations

It is convenient to divide the ice season into two distinct periods when considering oil configurations in and under ice:

- Winter spreading under ice & oil encapsulation (October to April, and
- Oil migration and surface appearance (May to June).

The fate and behavior of oil beneath a solid sheet of ice is governed by a number of important processes which control the geometry of the oil layer under and in the ice:

Initial Spreading. In general, oil spilled under stable landfast ice will not spread beyond hundreds of feet from the spill source, based on currents and the projected under-ice storage capacity (see discussion below). Cox and Schultz (1980) determined that the minimum threshold current to move crude oil under a smooth sheet of ice was in the order of 0.5 ft/sec (15 cm/sec), increasing to approximately 0.7 ft/sec under slightly rougher ice. The maximum expected under-ice currents in the Beaufort Sea nearshore are extremely low. In a March 1996 study inside the barrier islands near Prudhoe Bay, no currents were detected under the ice over a period of five days (Intec, 1996a).

Two experimental spills with crude oil were conducted under smooth first year ice in the presence of a 10 cm/sec current in April 1975 (Norcor, 1975). These results are interesting in that in spite of the ice under surface being extremely smooth (gradual variations of less than a few cm, not discernible to the divers), the oil , although influenced initially by the current in the direction it flowed away from the discharge point, ceased to spread further once the pumping stopped.

The conclusion from a large body of field observations and laboratory testing is that oil spilled under solid ice in the Beaufort Sea will remain spatially in the immediate vicinity (hundreds of feet) of the release point. This feature of oil spills in ice has important and beneficial implications for planning leak detection surveys, and for determining the minimum sensor footprint area required to "see" an oil pool under the ice.

Encapsulation and rapid immobilization of oil spilled beneath growing ice. This is the process whereby new ice quickly forms beneath oil trapped under the ice and acts to immobilize the spill within a very small area (see also discussion of natural ice containment following chronic leaks below). This new ice layer introduces a new interface (ice/oil/ice) soon after the spill (typically within 12 to 72 hours depending on time of year). Ref. Norcor (1975; Dickins and Buist (1982).

Ice Storage. Normal variations in first-year ice thickness provide huge natural “reservoirs” to effectively contain oil spilled underneath the ice within a small area. The implication here is that any mid-winter spill beneath the ice will be naturally contained within a relatively small area when compared to an identical volume spill on open water.

Ice naturally develops an undulating bottom surface in response to preferred snow drift patterns on the surface. Researchers have investigated the holding capacity of ice covers by mapping the under-ice topography and calculating the potential for oil containment (e.g., -winter surveys near West Dock). Results show typical under-ice containment capacities for first-year landfast ice representative of the Prudhoe Bay area starting at 0.007 bbl/ft^2 under very smooth young ice in November (Goodman and Holoboff, 1987), increasing to 0.012 barrels per square foot (bbls/ft^2) for 30-inch thick ice in December, and eventually reaching 0.026 bbls/ft^2 for 60-inch thick ice in April (equivalent to about one million barrels per square mile). Ref. Kovacs et al. (1981)

Vertical migration of oil through the melting ice starts in the spring when the expulsion of brine from the warming ice opens pathways to the surface (Norcor, 1975; Buist and Dickins, 1981). Beginning as early as April and continuing through June, oil will naturally rise to the surface from wherever it is trapped within or beneath the ice. The timing of vertical migration effectively changes the entire character of how the oil is distributed within the ice sheet in terms of detection. Oil during the active migration period is no longer present in a sharply defined layer with a clear interface between different materials. At some point in late May the ice becomes extremely porous. In one example, oil released under six feet of ice in the Beaufort Sea on May 21 rose to the surface within one hour. By this time of year, the problem of oil detection has become one of mapping oil on ice rather than detecting oil in ice.

Most detection systems require a clearly defined oil layer where either the acoustic, radar or other system will hopefully record an unambiguous anomaly in the signal being returned. While this clear definition is available from October to February (the vertical penetration of the oil in this period is limited to a few cm above the initial point of contact with the ice), the boundary or interface becomes progressively more blurred and eventually indistinct as the migration begins. This process first becomes noticeable in March when some oil can rise approximately 10 cm vertically with the gradual warming of the ice sheet. In April and May the migration accelerates until by mid-May, much of the ice sheet can become saturated with oil at different levels (Norcor, 1975). At this point, the concept of detecting an oil layer within the ice may become unworkable or unrealistic.

There are two situations where either the configuration of oil under ice is radically altered from the normal winter case in floating fast ice, or when the mobility of the ice itself may rapidly transport oil trapped in ice away from the spill site:

(1) The first situation involves the nearshore region with water depths less than six feet. Much of the ice in this area will become bottom fast (grounded to the seabed) during the period February to early June.

    While there is no direct information on how a subsurface spill in this ice zone will behave, it is possible to develop the following hypothesis. Immediately beneath the ice resting on the seabed is a layer of hard frozen sediment. As the winter progresses, the cold front would be expected to penetrate deeper into the sediments. Oil released, for example from a buried pipeline, under these conditions will likely to rise through the part of the trench backfill material which remains unfrozen, and then become trapped beneath the frozen soil layer until the spring melt. At some time in June, the bottom fast ice melts sufficiently from the surface that it pops free of the bottom, lifting some of the frozen sediment with it. Trapped oil will then be quickly released, rise up to the bottom of the rotting ice and either surface through cracks and holes or surface directly through the sheet itself (see process of vertical migration described above).

(2) Ice during October and November is still highly mobile depending on the year and location. At this time response teams could be faced with detecting oil trapped under or in pans of new or young ice moving in response to wind forces. It is assumed that any oil still under the ice during the other period of high ice mobility (June or July) will quickly surface to become oil on ice.

Because of the importance of defining the likely oil in ice configurations additional discussion is provided here with regard to spreading and under ice containment:

Two physical factors act to naturally limit the area contaminated by oil under ice: (1) natural depressions related to variability in snow depth, and (2) rapid incorporation of the oil by new ice growth around and beneath the oil layer.

Barnes et. al. 1979) postulates that there is a stable pattern of hard drifts aligned with the prevailing winds which form early in the season and remain in place throughout the winter Barnes goes further to propose that this pattern of stable hard drifts leads to a consistent pattern of shallow troughs in the ice under surface corresponding to the ridges of these sastrugi or wind formed drifts on the surface. Although highly variable, an order of magnitude dimension for the typical wavelength of these drifts is in the range 40 to 60 feet. The dominant pattern of east-west winds during the winter will lead to snow drifts and corresponding under-ice depressions which are roughly oriented in the same direction (east-west). As a result, oil under ice will tend (in the most simplistic generalization) to lie in troughs of thinner ice between the drifts. Due to the undulating character of the ice under surface, it is assumed that approximately half of the ice within any contaminated area will actually contain oil.

As the natural containment increases with ice thickness, the area needed to contain a given spill volume decreases steadily throughout the winter, as shown in Figure 4.4.

Based on these ice containment capacities, a 1,325-barrel spill from a source beneath the ice surface in December will be contained within a diameter of approximately 380 feet, decreasing to a diameter of approximately 260 feet for spills of equal volume in April or May. The associated average oil layer thickness in the ice will range from three inches in early winter to seven inches in April, with the maximum thickness in the deepest pools varying from five to 14 inches. It should be noted that these pool depths are far greater than the natural equilibrium thickness of oil spilled under an idealized flat ice sheet (less than one cm). Previous research into oil in ice detection systems have focused on the need to detect very thin films of oil in the ice. This is not a realistic scenario or requirement for relatively large releases (hundreds to thousands of barrels under naturally variable first year ice).

Figure 4.4
Predicted Radii Of Spills Of A Given Volume
Spilled Under Landfast Ice
Dickins and Buist (1999)

A chronic leak needs to be considered very differently from a batch release in terms of the likely oil in ice configuration for detection. With a low flow rate over a long period of time (days to weeks) new ice is unlikely to form directly beneath the oil pool due to the continuing arrival of fresh oil from the leak. Ice crystals (frazil) present in the water at the oil/ice interface may be incorporated to provide a slush/oil mixture that becomes deeper the longer the spill source remains undetected. Local pockets of oil may be encased by new ice but much of the contaminated area is expected to contain oil in a slushy state mixed with ice crystals. There is no direct experience with such a spill but observations have been made of slush/oil mixtures within solid ice by coring through past spills under ice (Buist et al., 1983). Around the perimeter of this oil pool, uncontaminated ice will continue to grow, effectively containing the trapped (but not encapsulated) oil pool over the leak site. Eventually, when the natural ice growth rate slows in April, the contaminated area will increase (see examples below). If the leak is interrupted or stopped at some point during the ice growth period, new ice will form beneath the oil within a few days. When the sheet warms sufficiently in May, the trapped oil will surface naturally in the same manner as described previously for batch spills.

The oil spill response information document prepared for the Northstar Environmental Assessment (BP, 1998) contains a number of sample calculations of the possible dimensions of an oil pocket in the ice resulting from an extended chronic leak at approximately 0.12% of flow. A similar procedure can be used to determine dimensions of leaks over any desired period of time. For example, with a leak over 60 days between

November and February, 40,000 bbl would be contained within an area of 200 foot radius and height of 1.75 ft (corresponding to 60 days of ice growth during this period).

Leaks beginning in late April when the ice sheet is close to its maximum thickness will potentially spread to cover an area which is limited by the natural holding capacity of the under ice surface. Using values of .026 bbl/square foot computed for the Prudhoe Bay area in late winter by Kovacs et al. (1981), a 30 day leak commencing on April 25 and continuing undetected for 30 days would theoretically spread to cover an irregular shaped area equivalent to a circle 500 feet in radius. This dimension is considered a worst case for two reasons: (1) a longer leak would be detected visually and stopped when the oil begins to appear naturally on the surface in late May; and (2) a leak beginning earlier in late March would still be partly contained by some growth in the surrounding ice for the first two to three weeks of the leak.

4.4 Ongoing Studies

The objective of this task was to identify and summarize where possible, the results of recent or ongoing studies connected either with the subject of direct interest here, the remote detection of oil in solid ice, or the related subject of pipeline spill or leak detection under arctic conditions.

The principal method used to identify such studies was to contact research agencies worldwide with an interest in the subject. This phase of the work was combined with requests sent out at the same time to inquire about any knowledge of historical work or references.

Worldwide agencies and organizations with a potential interest in this subject were listed in 4.2. The response from these groups is listed below:

National Institute of Polar Research, Tokyo
- no reply

University of Lapland, Finland
- searched database of the Technical Research Centre of Finland (VTT) with no results

Swedish Polar Research Secretariat
- not aware of any research in Sweden in this field

British Antarctic Survey, Cambridge
- not aware of any research in Antarctica or the UK on this subject

Geophysical Institute, University of Alaska, Fairbanks
- no ongoing work or knowledge of previous work in this area

Polar Science Center, University of Washington, Seattle
- not aware of any references or research in the field

Lanzhou Institute of Glaciology and Geocryology (LIGG), China
- no reply

Nansen Remote Sensing Center, Norway
- no reply

National Research Council, Ottawa
- no knowledge of any work in this field

Danish Polar Centre, Greenland
- not aware of any work in this area

Technical University of Denmark (Leif Toudal Pedersen)
- message received as follows:

  "Unfortunately I do not know of any remote sensing technique that allows detection of oil trapped beneath sea ice. Most of the signals we use to observe sea ice will not penetrate the entire thickness of the ice, and therefore contains no information of what is below the ice. The only case I can think of is using high resolution visible imagery to detect oil between ice-floes. Radar techniques also generally will detect oil between floes, but the signature will be very much the same as the signature of frazil/grease ice"

Scott Polar Research Institute, Cambridge University, Cambridge UK
- not aware of any references in the field

CRREL (US Army), Hanover, New Hampshire
- no active research. Previous work covered in Literature review and disc. with A. Kovacs (4.2)

Environment Canada, River Road Environmental Technology Centre, Ottawa
- active research into acoustic systems (see 4.1 for past work and 4.2 disc. with M. Fingas for ongoing activities). Research through this organization is covered through telephone discussion with M. Fingas and a literature search for historical material published at AMOP and elsewhere (Task 1a). Note: Ongoing development of the scanning laser fluorosensor has great potential for detecting and mapping oil on ice and among broken ice (in slush or water) but this system is considered to have a very low potential for detecting oil trapped under or in ice (Carl Brown, tel. con., 03/07/00).

C-CORE, St. John's
- discussions with director Judith Whittick yielded no information beyond references already reviewed in 4.2 No work in this field since the late 70's

SINTEF, Norway
- no known work in this area

Canada Centre for Remote Sensing, Ottawa
- no current programs in this area

Ron Goodman, Imperial Oil, Calgary

  Esso is working with Environment Canada on development of a new generation oil in ice detection system using acoustic methods (no further information publicly available). All reports on previous research in this area sponsored in the past by Esso Resources are considered intellectual property (not available).

A number of recent initiatives in Alaska relate generally to the issue of pipeline leak detection, but not specifically to the problem of detecting oil in ice. A number of interesting technologies covered in these reports are listed below.

The Alaska Department of Environmental Conservation (DEC) commissioned two studies in 1999 to provide a Technical Review of Leak Detection Technologies as summarized in selected extracts below:

Vol. 1 Crude Oil Transmission Pipelines

- Acoustic Emissions: In this application of acoustics, a baseline acoustic map of the pipeline (internal noise levels under normal operation) is compared with readings monitored from sensors fixed directly to the outside of the pipe. The theory is that escaping oil will cause an unusual acoustic signature and signal an alarm.

- Fiber Optic Sensing: This system requires fiber optic sensing probes to be driven into the soil beneath or adjacent to the line. In the presence of hydrocarbons, the sensor covering changes its refractive index (not clear how this could be used in a marine environment).

- Liquid Sensing: This system uses liquid sensing cables buried beneath or alongside the line. Any hydrocarbon entering the cable alters the impedance of the cable which in turn alters the reflection pattern of the energy signal returning to the microprocessor. Again not sure how such a system would work in a marine environment where permeability to oil would also mean permeability to sea water.

The report also discusses the potential benefits of some form of rules-based logic or expert systems (artificial intelligence) in reducing the proliferation of often meaningless alarms based on simple high and low limits. Potentially, this type of software could also aid in reducing false alarms with a remote oil in ice detection system when it reached the operational stage of development.

A set of criteria for evaluating leak detection technologies are developed from established practices such as API. These criteria as stated in Chapter 4 of the report include:

- Applicability and Availability: combination of "is the system designed for the intended use?" and "is the system and it's components commercially available?".

- Effectiveness: covers expected system performance as a combination of sensitivity, accuracy, reliability and robustness. These terms are self explanatory except the latter which in this context means an ability to perform the principal functions of leak detection under less than ideal conditions (e.g. loss of a component, ability to distinguish between normal transient line conditions and a real leak, ability to disable certain functions when required etc.)

- Transferability/Feasibility: refers to whether a system which may have performed in one application is going to work in another (includes operational situations to be avoided for each technology)

- Compatibility/System Requirements: This covers operating requirements such as instrumentation, communications, sampling frequency and training

> Vol. 2 <u>Above Ground Bulk Oil Storage Tanks.</u>
>
> This report largely contains material of limited relevance to the subject of oil in ice. One section (3.7) is interesting in that it discusses passive acoustic sensing using acoustic sensors in the tank itself or externally around the tank circumference. The detection system then searches for an out of character acoustic signature in a consistent location (same concept as discussed in the first report for pipelines).

In addition to the technology reviews sponsored by DEC, BP Exploration, together with Intec Engineering, recently conducted their own review of the best available technology for pipeline leak detection. This work was an outgrowth of item # 18 in the Letters of Authorization for Incidental Care of Polar Bears during Project (Northstar) Operations: "The permittee shall design, construct, install during pipeline trenching operations, and maintain a prototype oil spill leak detection system, external to the carrier pipeline to detect an oil spill below current threshold detection limits (Pressure Point Analysis and mass balance)". The outcome of this requirement was a decision to proceed with procurement of a commercially available system (Siemens LEOS) for installation on the Northstar line. The system functions on the basis of molecular diffusion and the rapid change in resistivity of sensors exposed to the sampling air stream (Bryce, 2000).

The Minerals Management Service (MMS) was interested (1999) in funding work into under-ice acoustics and ambient noise which could have a significant bearing on the effectiveness of a number remote sensing systems being considered for oil-in-ice detection. The status of any ongoing work in this area is not known.

5.0 CONCLUSIONS AND OVERVIEW

The problem of remote sensing in the case of wintertime spills beneath a solid ice sheet is particularly challenging. Not only can the oiled area occur anywhere along a pipeline for example, but the resulting area of contamination area is likely to be highly localized (implying that any system will need a small sensing footprint to "see" the oil). Ice conditions are not uniform, even within the stable landfast zone of most interest in terms of projected new developments. An operational system will need to accommodate a wide range of oil in ice configurations over an equally wide range of ice conditions.

In the past, considerable effort has gone into research and development of various methods to detect oil trapped under an ice cover or entrapped as a layer within growing ice. To date none of these technologies have resulted in an operational system, although a number of prototype devices have been tested including acoustic and radar systems.

Radar technology was the subject of extensive research in the 1980's (Butt et al., 1981; Mann 1979; Goodman and Fingas, 1985). Much of this work was directed at determining if scattering or radar waves at the ice bottom surface would be altered enough by the presence of oil to allow reliable detection. Several initially positive indications showing the potential presence of an oil layer in the ice could not be validated in subsequent re-examination of the results. Theoretical and laboratory/tank studies failed to identify an established physical mechanism for the radar detection of oil-in-ice. Practical considerations included a concern that natural anomalies in the internal structure of sea ice (cracks, voids and discontinuities) would attenuate the signals to such an extent that much of the data needed to identify the presence of oil in the ice would be lost. This concern applies to all of the technologies which have any potential for detecting oil in ice.

Much of the effort expended in the 1980's was focused on using acoustic principles to detect oil in ice. The acoustic method makes use of the phenomenon that oil appears as a solid to a sound wave. By searching for the telltale differences in the relative amplitudes of shear and pressure waves reflected from the ice/water and a potential ice/oil interface, it is possible to detect the presence of oil trapped in or under the ice. A great deal of progress was made in this direction, and a working prototype was built and successfully tested both over fresh ice in the laboratory and over river ice in the NWT. Subsequent tests over salt water ice in the Beaufort Sea were inconclusive as the ice was already in the melt phase when the work was carried out. There is no technical reason why the system will not work over solid, cold sea ice in mid winter. Concerns about the future use of this type of system in a field environment center on the need for close physical bonding between the transducers and the ice surface, and the proportion of anomalous readings in rough, irregular ice (this problem is common to other technologies as well).

From discussions with researchers and agencies connected with arctic and remote sensing disciplines, there appears to be no new technology with the potential to detect oil in or under ice, or any technology which has not already been considered or tested at least at the feasibility level in previous work. This conclusion is based on contacts with a broad cross section of researchers in North America and Europe.

Electromagnetic induction methods are used routinely for operational ice thickness monitoring as well as other applications such as geotechnical and underground storage tank leaks. Although EM systems have greater capabilities in rough ice than conventional impulse radars there appears to be little merit in pursuing this technology as a potential oil in ice detector.

Advances in computer capabilities over the past fifteen years, while dramatic, will not directly overturn previous conclusions about the potential of different technologies to detect oil in ice. The latest generation of data processors and software will allow lighter and smaller components, faster scan and data processing rates, real time readouts of critical values such as ice thickness, and an enhanced ability to filter noise and spurious signals (false alarms).

Two avenues stand out as being the likely focus of future development: acoustics (including the potential use of ultrasound); and electromagnetic (primarily the wave domain systems commonly referred to as impulse radars or ground penetrating radars).

Acoustic methods are still being actively pursued by Environment Canada and Imperial Oil Limited (the original developers and promoters of this technology in the 80's). The current focus is on improved packaging and cold temperature "hardening".

Radar systems have been proven through numerous tests and operational exercises as a reliable off the shelf tool to accurately map ice thickness in relatively smooth ice areas (such as the landfast zone of most interest in this study). Ground penetrating radars (GPR) are routinely used to detect and map hydrocarbon contamination in soils. Previous research into radar detection of oil spilled in ice focused on the case of oil trapped under floating ice with inconclusive results.

Further testing could be pursued in two avenues: (1) to carry out field tests of the latest generation of acoustic system with oil trapped underneath and within sea ice; and (2) to determine whether the latest generation of impulse radars have any potential for detecting oil-in-ice over a range of configurations which have not been tested in the past (including thick oil pools and the important case of oil in frozen sediments beneath grounded ice). The choice of direction in future development work needs to focus on systems which could evolve into practical operational devices, readily deployed and maintained in extreme conditions.

An important issue in assessing the potential of any available technologies is one of identifying realistic oil-in-ice scenarios. Much of the previous research focused on the ideal situation of a thin perfectly defined oil layer encapsulated in a solid homogeneous ice layer. In practice, the most common scenario may be one of a series of thick oil pools (covering an area tens to hundreds of meters in diameter) under the ice: a result of chronic discharge from a buried marine pipeline over a period of weeks to months.

It appears that the development of any practical operational system for detecting oil in or under ice will be extremely challenging. The most effective solution may not be a single sensor but could require the integration of several different technologies: for example, airborne EM to map areas of rough and thicker ice along the pipeline route (not for oil-in-ice detection), followed by higher resolution sampling with a towed surface GPR and/or spot checks with an acoustic system. This sequence is given as a purely hypothetical example and not necessarily as a recommended course of action.

Each type of system needs to be used in an application suited to its capabilities. For example, an acoustic system could provide a reliable means of continuously monitoring a localized area where the transducers could be maintained in a continuously bonded state through the winter. For large area surveys over tens of miles along a pipeline corridor, some other solution is needed where the remote sensing instrument can be maintained free of the ice surface. At present there appears to be no obvious technology which can provide this survey capability with an acceptable degree of reliability.

Future tests need to combine both laboratory and field trials of prototypes with actual crude oil (or near substitute materials) spilled under ice. With sufficient lead time, it may possible to obtain permits to allow the discharge of oil within secure containment skirts inserted through the ice. These skirts have been used in previous oil spill experiments and have proven effective in preventing spreading of oil beyond a known area (e.g., Norcor 1975). Failing U.S. approvals for live oil testing, it may be necessary to explore other options such as Canada and Norway. A sole reliance on laboratory or tank tests is not an adequate basis for developing an operational system in the future.

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