APPENDIX H

GE-AK 80

RU-267

STUDIES OF THE BEHAVIOR OF OIL IN ICE, CONDUCTED BY THE OUTER CONTINENTAL SHELF ENVIRONMENTAL ASSESSMENT PROGRAM

by

William J. Stringer

and

Gunter Weller

Geophysical Institute
University of Alaska
Fairbanks, Alaska

July, 1980

Prepared for NOAA - OCS

2531

Studies of the behavior of oil in ice, conducted by the Outer Continental Shelf Environmental Assessment Program

William Stringer
and
Gunter Weller

Arctic Project Office
Outer Continental Shelf Environmental Assessment Program
University of Alaska
Fairbanks, Alaska 99701

Abstract

The Outer Continental Shelf Environmental Assessment Program has studied the behavior of oil in ice over a number of years. Early work in tanks in which ice was grown under the action of winds and waves was followed by research on the behavior of oil under ice of various degrees of roughness in a flume, simulating different current velocities. Satel - lite, laser profilometer, impulse radar and drilling data have allowed an assessment of the natural underside roughness of ice in the Beaufort and Chukchi Seas, and drifting buoys and satellite observation have given bulk displacements of the ice. From all these observations and some numerical modeling a picture of oil behavior in ice has been synthesized. A summary of the major results to date is presented.

1.0 Introduction

Petroleum exploration and development is proceeding rapidly in the ice-covered waters of the arctic continental shelves. As a consequence of this development, environmental risks associated with oil spills are anticipated. The Outer Continental Shelf Environmental Assessment Program (OCSEAP) conducted for the U.S. Bureau of Land Management by NOAA - the National Oceanic and Atmospheric Administration - attempts to evaluate such risks in a multidisciplinary research program. This program started in 1975 and continues to date; studies are conducted in the Gulf of Alaska, the Bering Sea and the Chukchi and Beaufort Seas. As part of this research, the behavior of oil spilled in ice is addressed by OCSEAP. Oil spills in ice are a potential environmental problem along half of the Alaskan coastline for 6-10 months each year.

2.0 Small-scale behavior of oil in ice

This section discusses the small-scale (micro-scale) behavior of oil in ice. The spatial scale of processes discussed ranges from individual crystals to the crystal matrix of sea ice including brine drainage channels and to grease, frazil and pancake ice. Perhaps the most comprehensive knowledge of oil in ice on this scale is that of stable, stationary first-year ice. Martin (1980) gives a detailed description of oil entrainment by smooth first year ice, based on both OCSEAP data and a field experiment carried out for the Canadian Beaufort Sea Project. Oil behavior in the Beaufort Sea region can be divided into the following three characteristic periods:

a. November-February. When oil is first released under smooth first-year ice, it collects in natural undulations beneath the ice, which are caused by snowdrift-induced insulation. These undulations have an amplitude of order 0.1 m and a length scale of order 10 m. Some oil also flows a short distance up into the ice through the brine drainage channels.

b. March-May. In the spring as the ice warms, top-to-bottom brine channels open up in the ice and the oil rises through these channels to the ice surface where it spreads laterally, both under the snow and within the first few porous cm of the ice surface. The oil on the surface then absorbs solar radiation through the snow causing the snow above the oil to melt.

c. June-August. In the early part of the summer, the trapped oil continues to rise through the ice to the surface, where above the trapped oil melt ponds with oil surfaces form. Because the sun heats the oil and the winds blow the oil on the melt pond surfaces against the edges of the ponds, the oiled melt ponds grow both laterally and in depth faster than the un-oiled ponds. As the ice continues to decay throughout the summer, much of this oil in a weathered form will flow back into the ocean either off the tops of the floes or by melting through the ice bottom.

The description of the behavior of oil in growing ice which is stirred by wind and waves is a more difficult matter. Martin, et al., (1978) have examined this process by generating waves in a laboratory tank in which they produced grease ice. The experiments showed that most of the oil introduced into the ice ends up on the ice surface beyond a "dead zone". The dead zone marks the transition from liquid to solid behavior of the grease ice. Field observations (Martin, 1980; see section 3) confirm that if oil were spilled in the various polynya zones of a freezing ice front, some of the oil would end up on the grease ice surface, some would accumulate in the local dead zones, and a small fraction would be emulsified into oil droplets by wave breaking, where these droplets would then circulate around within both the grease ice and the ocean circulation at the ice front.

When grease ice freezes further it develops into pancake ice. Martin, et al., (1978) showed in the laboratory that when grease ice becomes so thick that the circulation within the ice is suppressed, the surface freezes into chunks of pancake ice floating over a grease ice layer. They also found that oil released under long linear pancakes came to the ice surface between the oscillating cakes and that the oscillating motion pumped about 50% of the oil onto the pancake surface. Because long linear cakes do not appear in nature the test was repeated in a two-dimensional wavefield, so that nearly circular cakes were formed. Despite ridges formed around the rims of the pancakes, oil was pumped over the rims onto the pancake interior. Approximately 25% of the spilled oil reached the surface of the pancakes in this manner. The rest was bound up in small droplets in grease ice under the pancakes.

Another interesting problem is the movement of oil by ocean currents under a rough or smooth solid ice cover. OCSEAP has investigated this problem set through a contract with ARCTEC (Schultz, 1980). ARCTEC, using a long, glass-walled flume constructed in a cold room was able to study the equilibrium thickness of an oil film beneath smooth freshwater ice and the current conditions required to cause that film to move. They found that the equilibrium thickness was linearly dependent on the difference in density between the oil and water beneath the ice. For the range of densities to be expected for crude oil this slick thickness ranges from one half to one cm.

Measurements of currents required to move an oil slick showed a marked dependence on small-scale roughness. Under smooth ice, as might be expected to be found after melting has begun in late spring, slick threshold velocities were between 3 and 7 cm/sec. However, with ice of 1 cm amplitude roughness, as might be found under growing salt ice from November to late May, the threshold velocity increased to the the vicinity of 25 cm/sec.

These results which are discussed in greater detail by Cox and Schultz (1980) indicate that a relatively large volume of oil can be spread beneath the ice cover in the form of a 0.5-1 cm thick slick and that for many months this slick can be immobile in the Beaufort Sea and perhaps other areas such as Kotzebue and Norton Sounds and some nearshore areas of the Chukchi Sea where underice current velocities are below the threshold required to cause the slick to move.

3.0 Meso-scale behavior of oil in ice

The previous section discussed the behavior of oil in ice on the microscale (individual crystals to pancake ice); the present section will examine oil behavior on the meso-scale (floes of -pack ice to ice ridges and ice plumes near an open ice front). Ice characteristics, both static and dynamic, will be discussed and related to the observed and projected behavior of oil introduced into or under the ice.

One of the important characteristics of shore-fast ice is its underside configuration since this determines the amount of oil that can be stored under the ice in the absence of currents; this is referred to as the oil storage potential. In broken and moving pack ice this oil storage potential is less important, particularly if the ice floes are small, since it is likely that the bulk of the oil will flow into the leads between the floes. The underice contours can be determined by drilling holes and measuring ice thickness, by correlating ridge heights with keel depths (Wadhams, 1976; Tucker, et al., 1979), by examining the thickness of the snow cover on the ice (Barnes, et al., 1979) or by using remote-sensing techniques such as the use of impulse radar.

All the above methods have been used by OCSEAP. Correlating snow thickness with ice thickness, Barnes, et al., (1979) found some interesting results by cutting trenches parallel and perpendicular to sastrugi and snow ridges on shore-fast ice near Prudhoe Bay. Snow depth and ice thickness varied about 30-40 cm and exhibited a negative correlation -- thin ice coinciding with a thicker insulating snow cover. Elongate ridge and trough patterns on the under-ice surface paralleled the surface snow ridge pattern on wavelengths typically 10 m wide, yielding sub-ice voids of 0.02-0.047 m^3/m^2 (600-1200 barrels per acre). Diving observations indicated a smaller set of depressions 5 cm or less in depth, oriented parallel to the ice crystal fabric. The results imply that there is a seasonal stability to the snow ridge pattern and that oil concentrations under the ice would be indicated by surficial snow morphology in the fast ice zone.

The quickest and most reliable method of routinely determining under-ice contours is provided by impulse radar which has now been perfected to give reliable results over relatively large areas and with good resolution (Kovacs, 1977). The radar can provide profiles of annual as well as multiyear ice. Kovacs (1977) data show that annual ice of 1.91 m mean thickness had a storage potential above the mean ice thickness of 0.027 m^3/m^2; that of multiyear ice of 4.31 m thickness was 0.293 m^3/m^2. The results for annual ice are close to those obtained by Barnes, et al., (1979), as described above. Multiyear ice could theoretically hold approximately 1.8 million barrels of oil in a one square kilometer area. A variety of different ice types have been sampled since then with the impulse radar (Kovacs, 1980).

The above calculations of potential oil containment of multiyear ice have assumed that the oil will remain stationary under the ice. As has. already been shown in section 2, it requires only a relatively small current to set at least some of the oil in motion. Measurements by current meters placed under the ice in shallow water show (Matthews, 1980) that velocities are generally small during most of the winter; around 5-10 cm/sec in waters less than 20 m deep in the vicinity of Prudhoe Bay. Continuous current measurements in these shallow waters are threatened by moving ice, particularly in spring, and it has been found to be very difficult to obtain good year-round current values. Weeks and Gow (1979) have discovered a unique, quick and cheap method to get prevailing current directions at least. Their findings show that ice crystals grow with their c-axis parallel to the prevailing current. Analysis of ice cores below 30 cm depth to determine crystal orientations show very good correlations with measured current directions. " Similar results were obtained by Cherepanov (1971) in the Kara Sea. A quick survey of prevailing currents along the coastline, around islands and capes, is thus possible. In addition there is some indication that aligned ice is capable of entrapping more spilled oil than non-aligned ice (Martin, 1977) although it is not clear why this should be so. Strength properties of the ice, incidentally, are also affected by the crystal orientation (Shapiro, 1980) .

Oil can also be moved by winds and currents in open water stretches between ice floes and can be swept under the ice. For example, the oil spill in Buzzards Bay, Massachusetts in January 1977 showed that tidal currents swept oil under the ice and collected it in the lee of rafted ice, eventually filling shallow surface ponds on the ice to a depth of 100-150 mm (Deslauriers, et al., 1977). Estimates from aerial photographs suggested that such ponds contained as much as 30% of the spilled oil.

Apart from currents moving oil under the ice and between ice floes, the ice itself can be displaced under the action of wind, water and other stresses. Oil entrained in the ice or located in pockets under the ice will move with the ice. The Buzzards Bay spill showed that oiled floes moved considerable distances before they melted and the oil was released. In the Arctic Ocean oiled floes may move hundreds of kilometers before releasing the oil. Large-scale bulk displacement of pack ice and any contained oil will be discussed in the next chapter, but the meso-scale process of shorefast ice displacement, transport of the oil in leads (including “lead pumping”), incorporation of oil into pressure ridges and the behavior of oil along an open ice front are the subjects of discussion in this section.

Shore-fast ice is relatively stable but horizontal movements up to 100m are occasionally possible (Weeks, et al., 1977). Pack ice displacements of several tens of kilometers per day are possible in the Beaufort Sea (Untersteiner and Coon, 1977}. When leads close, two processes may occur that affect the dispersal of the oil:

1. Oil in the open leads will be compressed to greater film thicknesses and lateral flow along the leads will occur from areas of thick oil films to unoiled parts of the leads. This process will continue until obstructions in the leads cause the oil to overflow over the surrounding ice. Campbell and Martin (1973) have hypothesized that long linear leads can transport oil very rapidly over long distances; the effectiveness of this “lead pumping” has been questioned, however, by Lewis (1976) who points out that leads are rarely long and linear without bends and projections which would stop the oil flow when they make contact with the other side of the lead.

Very large leads, on the other hand are a regular feature of the Beaufort Sea ice, particularly in spring, as seen on LANDSAT satellite imagery. Lead pumping on a small scale undoubtedly can occur, as discussed in chapter 2, quoting the results of Martin, et al. (1978).

2. The second process occurs when the leads close up completely and the ice on either side of the lead is deformed into pressure ridges. Before the leads close up, the bulk of the contained oil is spilled over the surrounding ice. As the ridge is formed, the oiled ice will be broken up and incorporated into the ridge. Some of the oil will be retained in the ridges, possibly over several years, but there are no reliable numbers of how much oil will be entrapped and when it will be released and how much will remain free in the initial ridging process. The process of ice ridging itself has been described in some detail by Parmeter and Coon (1972) and is now the starting-off point for studies by OCSEAP (Coon, et al., 1980) adding oil into the ridging process.

Quite different conditions exist for the interaction of oil and ice along an open ice front, 'such as exists in the Beaufort Sea at the beginning of freeze-up or during ice decay in spring. These processes were studied for OCSEAP by Martin (1980b) in the Bering Sea. The Bering Sea location was chosen for convenience of logistics support and for the longer operating period that is possible in those waters. In the lee-shore regions of the Bering Sea, ice formation is dominated by the presence of wind, waves and swell. Laboratory experiments (Martin, et al., 1978) and field observations (Martin, 1980b) showed that the kinds of ice which form in these regions are grease and pancake ice. The laboratory experiments also showed (see section 2) that much of the oil spilled within these kinds of ice accumulates on the surface.

LANDSAT satellite imagery In the Bering Sea showed freezing sea fronts often to consist of long linear ice plumes approximately parallel to the wind and extending 10-40 km downwind. Downwind of the ice plume accumulations of new grey ice were usually observed (Martin, 1980b). Dunbar and weeks (1974) suggest that oceanic Langmuir circulation leads to the formation of the grease ice plumes. If any oil in this zone were to be emulsified into small droplets' by wave breaking, these droplets circulate around in the Langmuir rotors, which may have down-welling velocities of between 20-60 mms^{-1} (Pollard, 1978). This could lead to oil being distributed throughout the water column,

Another factor of oil-ice Interaction near an open ice front that needs to be considered is the motion of ice floes under the action of ocean swell. The case of pancake ice in a wind-and wave-agitated tank was already discussed in the previous section and showed that oil will be pumped onto the floe surfaces by the oscillating motion of the ice. The amount of oil pumped to the surface was approximately 25% of the total oil. We can thus expect that a sizeable fraction of the oil will be deposited on the surface, with the remainder bound-up in the grease ice-pancake ice mixture. Experiments in the Bering Sea suggest that a similar effect will occur in nature in this region (Martin, 1980b).

Other meso-scale considerations involve the interaction of oil with obstructions under a solid ice cover as found in the extensive fast ice areas of the Beaufort and Chukchi Seas. Direct, full scale spills are difficult to manage and often it is not possible to perform such experiments under a variety of conditions. Flume tests by Arctec similar to those described in section 1 (Schultz, 1980) were therefore performed *to* measure the effect of small but abrupt under-ice obstructions on oil slick motion. The obstructions were triangular and rectangular in cross section and on the order of 30 cm deep. The experimentors have presented arguments that the mechanisms active at this scale are valid all the way to large scale obstructions -- such as ridge keels extending to 30 m depths or more.

Their results indicate that oil trapped upstream of such obstructions can be “flushed out” by currents with velocities in the 15 to 25 cm/sec range. Hence, small obstructions as found in many ice fields and even large ridge keels will not obstruct the motion of a slick if current velocities are sufficient to cause the slick to move under small-scale rough ice. (presumably these velocities would also be sufficient to “flush out” the undulating underice pockets measured in the Beaufort Sea by Kovacs, 1980).

Many areas of the Beaufort and Chukchi Seas and Norton Sound appear to be immune from 25 cm/sec underice currents under normal conditions. In these areas some deep pooling might be expected to take place if obstructions are close to the source of spilled oil. However, even in the absence of obstructions the equilibrium thickness (0.5 to 1.0 cm) is so great that large amounts of spilled oil can be contained in a relatively small area due to that mechanism alone. For instance, a 1 cm thick film represents 300 bbl/acre or 1.9×10^5 bbl/sq. mile.

4.0 Large scale transport of oil in ice

In order to understand the bulk transport of oil in ice, both static and dynamic aspects of sea ice on a large scale must be known. At the outset of OCSEAP little was known about Alaskan nearshore ice conditions except that during winter and spring fast ice generally extended to water depths of twenty meters or so and was usually bounded by grounded ice ridges. Beyond fast ice was the “shear zone” forming the boundary between fast ice and pack ice. The pack ice was thought to be generally in motion, constantly breaking and refreezing. In order to determine these characteristics more closely, Stringer (1978) mapped nearshore ice conditions along the Beaufort, Chukchi and Bering coasts of Alaska using Landsat imagery at 1:500,000 scale. These maps, produced for representative periods between February and September have been analyzed in terms of nearshore ice characteristics.

In particular, the location of the edge of fast ice was determined as a function of time for all three coastal areas. These results indicate that within statistical bounds the fast ice provides a stable reservoir for spilled oil for much of the year. Although these bounds generally coincide with the 20-m isobath in the Beaufort Sea region, in portions of the Chukchi coastal area and along the entire Bering coast this is not true. However, it was also found that for long periods of time (up to six or eight weeks' duration) fast ice in the Beaufort Sea can extend well beyond the twenty meter isobath. These periods are generally during February-March. During these months it is entirely possible that oil spilled beneath Beaufort Sea ice will remain completely beneath the ice (except for small quantities rising in thermal cracks and breathing holes made by marine mammals).

The situation along the Chukchi coast is quite different: the boundary of shorefast ice is defined by a constantly active flaw lead from Barrow to Cape Lisburne. The fast ice edge is much closer to shore along the Chukchi Sea coast than the Beaufort Sea. In addition, currents in the nearshore area are much stronger. As a result it is likely that an under-ice oil spill will not be entirely contained under fast ice, but will also be incorporated into newly-forming ice in the active flaw lead and will be transported as this ice is advected away from the coast.

When one considers coastal areas south of Cape Lisburne and in the Bering Sea a wide variety of nearshore ice conditions are encountered which again will have quite different effects on the oil-ice interaction problem. Generally the fast ice extent is limited to increasingly shallower waters as one proceeds southward. This behavior results from a combination of three factors:

1. moderation of climate with decreasing latitude
2. increased tidal action breaking nearshore ice
3. advection of ice away from the coast

As a result mobile pack ice and newly-forming ice is often found in very shallow areas. The likelihood that petroleum development activities will be confined to stable fast ice areas is very small. As a consequence, an oil spill will almost certainly involve interaction with a combination of ice floes, newly-forming ice and open water. Bering Sea ice is quite mobile and spilled oil is likely to be transported relatively quickly to the ice edge (Pease, 1980; McNutt, 1980) where it will be released in the ice-water transition zone (Martin, 1980b).

There is evidence that ice in the Bering Sea region is generally advected to the south while oceanic currents are northward. As a result, less buoyant weathered petroleum released from the ice may be transported back beneath the ice cover.

Satellite imagery and drifting buoys can be used to monitor ice motions to oil spill trajectories. As part of the OCSEAP studies satellite-interrogated and tracked buoys were placed in nearshore pack ice at various locations along the Beaufort Sea coast (Untersteiner and Coon, 1977). The trajectories obtained showed that while the general trend of ice movement is to the west, short duration reversals do take place, and for relatively long periods of time the pack ice can remain nearly motionless. OCSEAP extended these observations into the Chukchi Sea with buoys being deployed in pack ice at locations between Barrow and Cape Lisburne during March 1977 and 1978. By April 1 they had all been displaced southward towards Bering Strait over distances up to 80 km. However, after that date their drift was westward or northwestward. These results (Pritchard, 1978; Colony, 1979) indicate that oiled ice in the Chukchi during the spring of 1977 and 1978 would not have been transported into the Bering Sea but instead would drift northward and westward. Colony concluded that the probable fate of the surviving buoys was to be incorporated into the transpolar drift streams and exit into the Greenland Sea after two or three years.

As part of the OCSEAP 1977 Synthesis Meeting (OCSEAP, 1978), a working group chaired by K. Aagaard, constructed a scenario for an instantaneous 25,000 barrel crude oil release in the pack ice of the Beaufort Sea. The scenario summarizes the results and information available to OCSEAP at that time. Oil is introduced into the main shear zone or moving pack ice off Prudhoe sometime after the fall freeze up. The oil would undergo a net westward translation together with the ice, but the movement would probably not exceed 50 km through February. Some of the oil would be trapped by the ice topography and some would also appear at the surface of both the leads and the ice as the ice field was constantly deformed. As the oil would come to the surface, it would become extremely viscous at temperatures below its pour point, which for Prudhoe crude is about -1OC. Nonetheless, it would not be unreasonable to expect some lateral oil dispersion in association with blowing snow. This would continue intermittently throughout the winter and spring. Once at the lead surface, the oil might be transported long distances downwind, as some of the leads are very long indeed. However, except for windblown material, the oil would not appear inshore of the grounded ridge zone.

In April the westward ice drift would increase, moving the oil some 100-150 km to the west of the spill site by late May. Brine channels would bring oil to the ice surface, which, as before, would promote melting and drainage back into the water. Biodegradation would also be underway at this time, although the rate would still be relatively slow.

By late June, oil transported with the ice could be expected as far as Cape Simpson. The remaining oil fractions would by then have become quite dense, and some sinking should be expected. Oil within the water column over the outer shelf would probably move eastward with the Bering Sea water. In general, the oil would be very widely dispersed.

Some of the oil would probably have encountered the Colville River plume. As a result, some portion might have been moved further offshore due to the currents, and some would have settled to the bottom by bentonite adhesion.

Finally, any oil in open water in July and August is capable of coming onto the western Beaufort Sea beaches under the influence of summer winds. Ice with oil still entrained would move relatively rapidly northwest and become part of the pack ice.

5.0 Synthesis of Results

The overall direction of OCSEAP oil-ice interaction studies has been determined by a series of workshops involving OCSEAP principal investigators, and administrators, BLM environmental assessment personnel, representatives of the petroleum industry and local residents of the Beaufort Sea coastal region. The workshops synthesized current research findings and other results such as Canadian work in the eastern Beaufort Sea as reported by Milne and Simley (1976). The objective of the workshops has been to develop realistic arctic oil spill senarios in order to pinpoint research gaps and to provide BLM environmental assessment personnel with the most up-to-date oil spill fate and trajectory analyses. These senarios are being revised and considerably refined by Coon, et.al. (1980) as part of the OCSEAP research effort.

Acknowledgements:

This study was supported by the Bureau of Land Management through inter-agency agreement with the National Oceanic and Atmospheric Administration, under which a multi-year program responding to needs of petroleum development of the Alaskan continental shelf is managed by the Outer Continental Shelf Environmental Assessment Program (OCSEAP) Office.

References

Barnes, P.W., E. Reimnitz, L. Toimil and H. Hill. Fast ice thickness and snow depth in relation to oil entrapment potential, Prudhoe Bay, Alaska. USGS Open-File Report 79-539, Menlo Park, CA. 30 pp. 1979.

Campbell, W.J. and S. Martin. Oil and ice in the Arctic Ocean: Possible large-scale interactions. Science, 181, 56-58. 1973.

Cherepanov, N.V. Spatial arrangement of sea ice crystal structure (in Russian]. Publ. Arktiki i Antarctiki, 38, 137-140. 1971.

Colony, R. Dynamics of Near Shore Ice. Final Report. Outer Continental Shelf Environmental Assessment Program, NOAA/Arctic Project Office (University of Alaska), Fairbanks, AK 99701. 1980.

Coon, M. and R. Pritchard. The transport and behavior of oil spilled in and under sea ice. OCSEAP Annual Report. Outer Continental Shelf Environmental Assessment Program, NOAA/Arctic Project Office (University of Alaska), Fairbanks, AK 99701. 1980.

Cox, J.C. and L.A. Schultz. The transport and behavior of spilled oil under ice. Proceedings of Third Annual Technical Seminar, Arctic Marine Oilspill Program, Edmonton, June 80 (this volume). 1980.

Deslauriers, P.C., S. Martin, B. Morson and B. Baxter. Bouchard #65 oil spill in ice covered waters of Buzzards Bay. OCSEAP Report, Outer Continental Shelf Environmental Assessment Program, NOAA. Boulder, CO 80302. 1977.

Dunbar, M. and W.F. Weeks. Interpretation of young ice forms in the Gulf of St. Lawrence using side-looking airborne radar and infrared imagery. U.S. Army CRREL Research Report 337. 1975.

Kovacs, A. Sea ice thickness profiling and under ice oil entrapment. Proceedings of 9th Annual Offshore Technology Conference, Houston, Texas, May 1977, 547-550. 1977.

Kovacs, A. Oil pooling under ice. OCSEAP Annual Report. Outer Continental Shelf Environmental Assessment Program, NOAA/Arctic Project Office (University of Alaska), Fairbanks, AK 99701. 1980.

Lewis, E.L. Oil in sea ice. Institute of Ocean Sciences, Victoria B.C., Pacific Marine Science Report 76-12, 26 pp. 1976.

Martin, S. The interaction of oil with sea ice. OCSEAP Annual Report. Outer Continental Shelf Environmental Assessment Program, NOAA/Arctic Project Office (University of Alaska), Fairbanks, AK 99701. 1977.

Martin, S. A field study of brine drainage and oil entrainment in first-year sea ice. Journal of Glaciology {in press). 1980a.

Martin, S. Anticipated oil-ice interactions in the Bering Sea. in The Eastern Bering Sea, its Oceanography and Resources. OCSEAP, Outer Continental Shelf Environmental Assessment Program. NOAA, P. O. Box 1808, Juneau, AK 99802 (in press). 1980b.

Martin, S., P. Kauffman and P.E. Welander. A laboratory study of the dispersion of crude oil within sea ice grown in a wave field. in West, G.C. ed. Proceedings of the 27th Alaska Science Conference, AAAS, P. O. Box 80271, Fairbanks, AK 99708. 1978.

Matthews, J.B. Characterization of the nearshore hydrodynamics of an arctic barrier island-lagoon system. OCSEAP Annual Report. Outer Continental Shelf Environmental Assessment Program, NOAA/ Arctic Project Office (University of Alaska), Fairbanks, AK 99701. 1980.

McNutt, S.L. Remote Sensing Analysis of Ice Growth and Distribution in the Eastern Bering Sea. in The Eastern Bering Sea, its Oceanography and Resources. OCSEAP, Outer Continental Shelf Environmental Assessment Program. NOAA, P. O. Box 1808, Juneau, AK 99802 (in press). 1980b.

Milne, A.R. and 8. D. Smiley. Offshore drilling for oil in the Beaufort Sea: A preliminary environmental assessment. Beaufort Sea Project, Technical Report No. 39, Dept. of Environment, Victoria, 43 pp. 1976.

OCSEAP. Outer Continental Shelf Environmental Assessment Program. Interim Synthesis: Beaufort/Chukchi. NOAA, Boulder, CO 80302. 362 pp. 1978.

Parmeter, R.R. and M.D. Coon. Model of pressure ridge formation in sea ice. Journal of Geophysical Research, 77_, 6565-6575. 1972.

Pease, C.H. Eastern Bering Sea Ice Dynamics and Thermodynamics. in The Eastern Bering Sea, its Oceanography and Resources. OCSEAP, Outer Continental Shelf Environmental Assessment Program. NOAA, P. O. Box 1808, Juneau, AK 99802 (in press). 1980b.

Pollard, R.T. Observations and models of the structure of the upper ocean. in Krause, E.B. ed. Modelling and Prediction of the Upper Layers of the Ocean, Pergamon Press, pp. 102-117. 1977.

Pritchard, R.S. Dynamics of Near Shore Ice. OCSEAP Annual Report. Outer Continental Shelf Environmental Assessment Program, NOAA/ Arctic Project Office (University of Alaska, Fairbanks, AK 99701. 1980.

Schultz, L. The transport and behavior of oil spilled in and under sea ice. OCSEAP Annual Report. Outer Continental Shelf Environmental Assessment Program, NOAA/Arctic Project Office (University of Alaska), Fairbanks, AK 99701. 1980.

Shapiro, L.H. In-situ measurements of the mechanical properties of sea ice. OCSEAP Annual Report. Outer Continental Shelf Environmental Assessment Program. NOAA/Arctic Project Office (University of Alaska), Fairbanks, AK 99701. 1980.

Stringer, W.J. Morphology of Beaufort, Chukchi and Bering Seas Near-shore Ice Conditions by Means of Satellite and Aerial Remote Sensing. Final Report, NOAA/Arctic Project Office (University of Alaska), Fairbanks, AK 99701. 1978.

Tucker, W.B., W.F. Weeks and M. Frank. Sea ice ridging over the Alaskan Continental Shelf. Journal of Geophysical Research, 84, C8, 4885-97. 1979.

Untersteiner, N. and M. Coon. Dynamics of nearshore ice. OCSEAP Annual Report. Outer Continental Shelf Environmental Assessment Program. NOAA/Arctic Project Office (University of Alaska), Fairbanks, AK 99701. 1977.

Wadhams, P. Sea ice topography in the Beaufort Sea and its effect on oil containment. AIDJEX Bulletin #33, University of Washington, 1-52. 1976.

Weeks, W.F., A. Kovacs, S.J. Mock, W.D. Hibler and A.J. Gow. Studies of the movement of coastal sea ice near Prudhoe Bay, AK. Journal of Glaciology, 19, 533-546. 1977.

Weeks, W.F. and A.J. Gow. Crystal alignment in the fast ice of arctic Alaska. U.S. Army CRREL Report 79-22, 21 pp. 1979.