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The Interaction of Crude Oil and Natural Gas with Laboratory-grown Saline Ice

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THE INTERACTION OF CRUDE OIL AND NATURAL GAS WITH LABORATORY-GROWN SALINE ICE

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A Report Submitted To:

Research and Development Division
Environmental Emergency Branch
Environmental Impact Control Directorate
Environmental Protection Service
Department of Fisheries and the Environment

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ABSTRACT

Norman Wells crude oil and natural gas were injected under 35 cm of saline ice in the laboratory, and 20 cm of additional ice was grown under the oil and gas. The oil was observed to spread in a thin layer on the under-surface of the gas bubble. When the sheet was thawed, the gas was observed to escape when the minimum temperature in the ice sheet rose to -3.6°C, and this caused the release of a few drops of oil. The bulk of the oil, however, emerged at the same time as a pure oil spill in a control experiment. It is concluded that the presence of gas greatly increases the area over which spilled oil will surface, but does not affect the timing of its appearance.

RÉSUMÉ

Du gaz naturel et du brut de Norman Wells ont été injectés en laboratoire sous 35 cm de glace saline, puis sous cette inclusion, on a fait croître 20 cm de glace. Le brut s'étale en couche mince sous la paroi de la cavité. À la fonte, le gaz s'échappe lorsque la température de la couche de glace s'élève à la température minimale de -3, 6° C, et ceci provoque l'échappement de quelques gouttes de brut. Toutefois, lors d'une expérience témoin, la masse du brut émerge au même moment sous forme pure. On en conclut que la présence de gaz accroît de beaucoup la superficie sur laquelle l'huile va faire surface, mais n'influe pas sur le moment où cela se produira.

FOREWORD

This study was undertaken by Arctec Canada Limited under contract to the Environmental Emergency Branch of the Department of Fisheries and the Environment. Dr. D.E. Thornton of this Branch supervised the work as scientific authority.

Dr. Bernard Michel of Laval University and Dr. Seelye Martin of the University of Washington assisted in this work, and their constructive suggestions are gratefully acknowledged.

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1 INTRODUCTION

The recently completed Beaufort Sea Project has focused attention on the subsea well blowout as a particularly serious potential pollution incident for ice-covered waters. According to the standard blowout scenario developed in that work, oil and gas would be released in a ratio of approximately 1: 100 by volume (at STP), and much of this material might be trapped under the sea ice. The configuration which the blowout products might assume is of great importance as oil on the surface of water forms a layer less than a centimeter thick. Any substantial quantity of oil thus spreads over enormous areas. It is hoped and anticipated that the ice cover would trap the oil in deep under-ice pockets over a relatively restricted area, and estimating this area has been the concern of numerous investigations.

Chen, Keevil and Ramseier (1976) studied the spread of Norman Wells crude oil under smooth fresh-water ice. In a laboratory study, they observed that the oil formed pools 0.3 - 1.0 cm thick when confined only by its own interfacial tensions with the ice and water. They observed that as the ice continues to grow it encapsulates such an oil drop, immobilizing it until the ice melts.

These results were extended to sea ice in the field by Beaufort Sea Project 17 (Norcor, 1975). Here Norman Wells and Swan Hills crude oil was injected under growing sea ice during the winter. The depth of the trapped pools depended on the under-ice topography, but pools averaging 2 cm in depth were formed. As in the laboratory, these pools froze in and were immobilized until spring when the oil migrated to the surface. One injection was carried out under melting ice at -4°C. The oil flowed to the surface through 195 cm of ice in an hour. These results are thus encouraging because they predict that spilled oil will be immobilized by the ice in deep pools that will be released in a predictable way.

This work was tentatively extended to multi-year ice in a porosity experiment recently conducted by Milne et al (1977). He estimated the porosity of multi-year ice by drilling blind holes in a sheet and watching them fill under hydrostatic pressure.

All of this work has focussed strictly on oil distribution and migration. In the case of a well blowout the oil residue is mixed with 100 times its own volume of natural gas. This natural gas can be expected to significantly alter the results of these pure oil studies in two ways. First, the gas will preferentially fill the under-ice topography and present to the oil, not an undulating ice surface, but the perfectly level under-surface of a gas bubble. The oil can spread on this gas-liquid interface much as it would floating freely on calm water. In this case, the concentrating effect of the rough ice under surface would be largely lost.

Figure 1 shows three possible schematic configurations for the resulting ice/oil/gas/water system. Configuration A results in the minimum area of oil/gas interface. Configuration B minimizes oil/water interfacial area, while Configuration C minimizes the area of the gas/water interface. The various interfacial tensions determine which of these configurations will be energetically favoured.

A second effect of the gas might be in pioneering a route to the surface for the oil. All of the work cited above discusses oil as penetrating the ice through brine drainage features enlarged by the oil as it absorbs solar radiation. Rosenegger discusses the pore diameter required for this sort of permeation, and Milne models the process on this basis. The lower-density, lower-viscosity gas should be capable of penetrating less porous ice (in other words, colder ice earlier in the spring). Once cleared in this way, the channels might be penetrated by oil more easily than if the oil alone cleared the channels.

The present work undertook to study these oil and gas effects in the laboratory. Its general objective was to grow a sheet representative of first-year sea ice; to inject a 100:1 gas/oil mixture under the sheet and observe its distribution; to enclose the gas/oil mixture by growing more ice under it; to thaw the sheet and compare the escape of pure oil with that of the mixture; and to determine the configuration of the oil remaining under the ice once the gas had escaped.

On the basis of work by Lake and Lewis (1970), 35 cm was considered sufficient thickness to represent the crystallography of a natural ice sheet. Further, Lake and Lewis report major brine drainage features spaced an average of 13.4 cm apart in natural ice, so 35 cm was considered a sufficiently large bubble diameter to ensure interaction with at least one brine drainage feature.

To relate the experimental observations to the field data on pure oil, a control experiment was set up using pure oil in place of the mixture. Norman Wells crude oil was selected because previous workers had used this material. For comparability, freezing and thawing conditions of temperature and illumination were selected to match the average temperatures and illumination reported in the field experiments with crude oil.

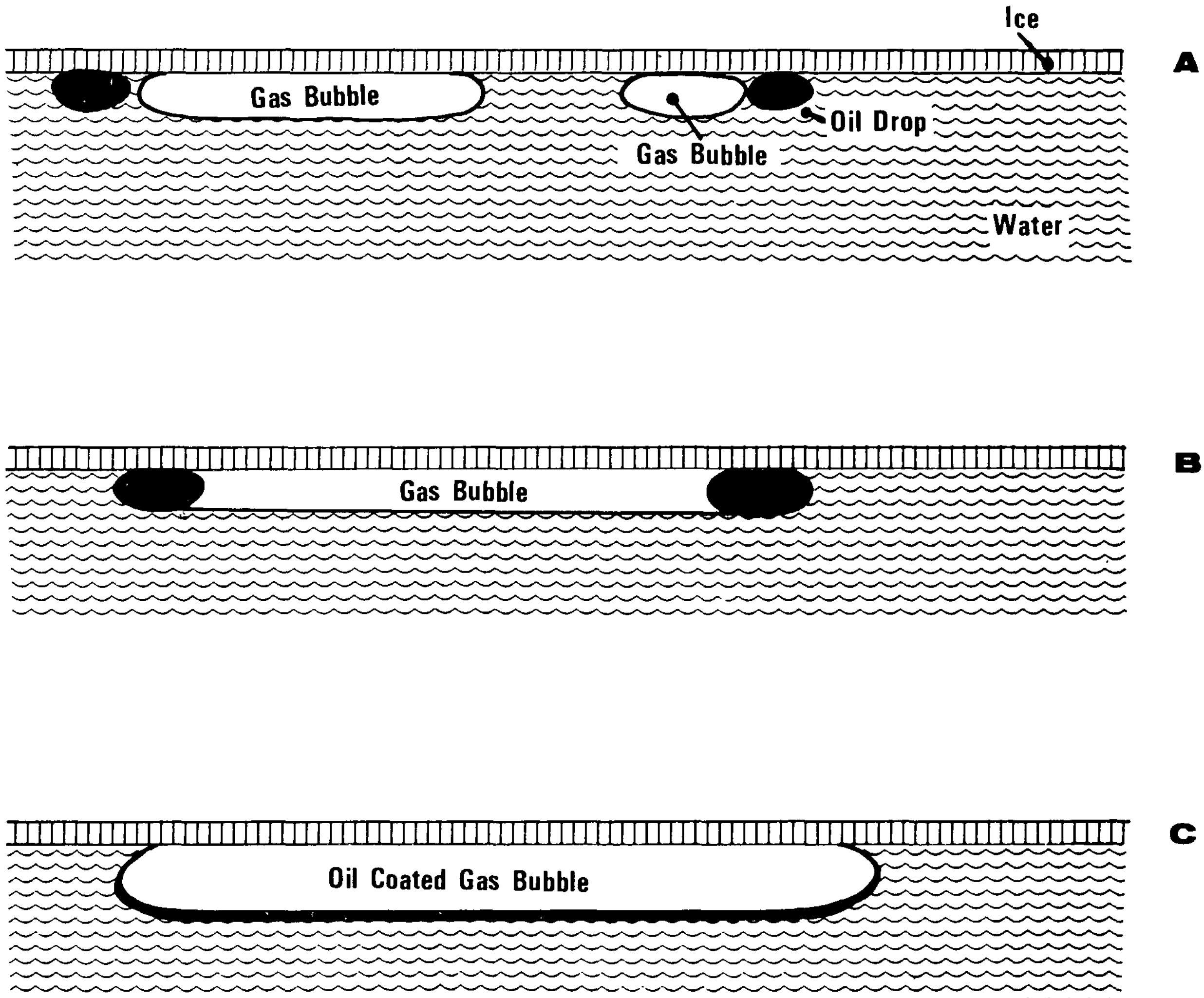


Fig.1 - Possible Configurations of an Ice/Oil/Gas/Water System

The experiment was designed to predict the modifications that the presence of gas imposes on the escape pattern of crude oil. It was hoped that these modifications could then be applied to the field data collected with pure oil and that the result could be used in planning a future field study of both oil and gas under natural sea ice.

2 EXPERIMENTAL WORK

Field studies (e.g. Lake and Lewis 1970) have shown that brine drainage features in first-year sea ice are spaced, on the average, about 13 cm apart. On this basis, an experiment 1 meter in diameter was considered somewhat representative of field conditions. Ice sheets of this size were thus grown and thawed in an environmental room under controlled conditions of temperature and illumination.

2.1 Apparatus

The experiment was conducted in two cubical tanks 1.2 m on a side. Each tank was fitted with two 25 x 60 cm viewing windows - one in the bottom and one set vertically in the side. Figure 2 shows one of these tanks under construction. These were mounted in an environmental chamber on a platform 41 cm high to permit access to the bottom viewing port. The tops were left open but the other 5 faces of each tank were insulated with 21 cm of glass wool insulation which could be removed for access to the viewing ports.

Each box was equipped with an injector system for inserting gas bubbles and/or oil drops under the ice. A 60 cm length of 4 mm ID glass tubing was tapped through the wall of each tank to provide an injection point at the center 15 cm above the bottom viewing window. Once an ice sheet had been grown in the tank, gas and/or oil could be forced through this tube to escape in the center of the tank and rise to the center of the ice sheet.

One of the two tanks was fitted with a string of 9 thermistors mounted vertically 12 cm from one corner. The top-most thermistor of the string was above the ice surface while the others relayed temperatures down through the sheet to a depth of 50 cm.

FIG. 2 - ONE OF THE TEST TANKS UNDER CONSTRUCTION

During the thawing phase of the experiment, both tanks were covered with polyethylene covers to confine a volume of approximately 0.4 m^3 over the surface of the ice sheet. A Westinghouse 75w "Agro-Lite" was set into the center of each cover to roughly simulate the spectral distribution of solar illumination and each light was equipped with a rheostat to adjust the illumination level. The covers were also fitted with mercury-in-glass thermometers to monitor the temperature of the enclosed volume.

The escape of gas through the ice sheet was monitored by measuring the concentration of methane in the air space beneath each cover with a Drager Model 31 gas detector. This detector was capable of detecting gas concentrations as low as 0.5% by volume which corresponds to an escape of 27% of the injected gas bubble.

2.2 Methodology

Each of the tanks described above was charged with 1134 Kg of tap water in which had been disolved 34 Kg of Windsor "High Grade" granulated salt to give a salinity of 30°/₀₀. With the environmental room at -5°C, the two tanks were equilibrated at the freezing point, and the insulation was installed. The room temperature was then lowered to -45°C.

The growth of ice in both tanks was observed through the side windows. In 165 hours, 34 cm had formed, measured at the center of each basin. The sheets were not pierced for these measurements, and the underside was slightly concave, so the thickness is accurate to only ± 1 cm. From above and through the windows both sheets appeared uniform with no large included bubbles. (See Figure 3.)

The room was then brought to -5°C for 8.25 hours during which time oil and gas were inserted under the ice sheets. A 1 m length of 1.4 cm ID clear plastic tubing was attached to each injector fitting. Initially, the first few cm of the glass injection tube was frozen in the proximity of the tank wall. This was thawed by placing a few cc of hot tap water in the plastic tubing. This, plus the hydrostatic pressure differential quickly unblocked the injector.

FIG. 3 - THE ICE SHEET AS SEEN FROM BELOW THROUGH A VIEWING PORT

The injector line of the experimental tank was then connected to a cylinder of methane, and this was gradually bubbled through the injector tube to rise in the center of the slightly domed ice sheet. The bubbles immediately coalesced to form a single large bubble, and this was observed through the windows until its diameter was estimated to be 1 meter. (See Figures 4 and 5.) It had been intended to meter the amount of methane added, but this system failed to function as expected. Instead the volume of the bubble was estimated to be 7.5 liters on the basis of the observed concavity of the ice surface and the bubble's observed diameter. The bubble was quite circular, and no small outlying bubbles remained. Its meniscus edge had a diameter of about 0.5 cm.

The methane injection just described was in the experimental tank only. Norman Wells crude oil was then injected into both the experimental and control tanks. A 125 cc charge (1.7% of the gas volume in the experimental tank) was added to both injector lines and pressured into the tanks with methane. In the control tank, the oil entered smoothly in large drops. In the experimental tank, the injector had initially refrozen, and the first charge of oil escaped from the bulkhead fitting at the tank wall and was caught in the ice on the tank wall at that point. None rose to the underside of the sheet, although later in the experiment this lost oil melted up the wall in front of the window and surfaced at the side of the sheet. It was always confined at the wall with a barrier and not confused with the oil at the center. After this false start, the injector of the experimental basin was again cleared with hot water, and another 125 cc charge was injected. These drops rose in the center of the basin and immediately coalesced in a sessile-appearing pool on the under-surface of the gas bubble. (See Figures 6 and 7.)

The room temperature was then lowered to -45°C for a further 128.5 hours. The total thickness at this point was 59 cm $\pm$ 2. The room was then adjusted to -8°C for 106 hours, during which time the tank covers and lighting systems were installed.

The light intensity at the center of the sheet over the inclusions was adjusted to 555 cal/cm^2-day using the rheostat control and a Gossen "Lunasix 3" light meter. The air temperature was adjusted to a target temperature of +10°C under both covers as measured by a mercury-in-glass thermometer. The thawing process was then observed every two hours.

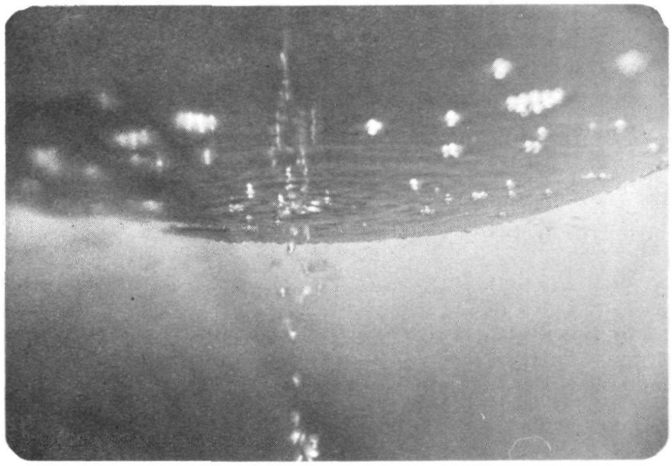


FIG. 4 - FORMING THE GAS BUBBLE

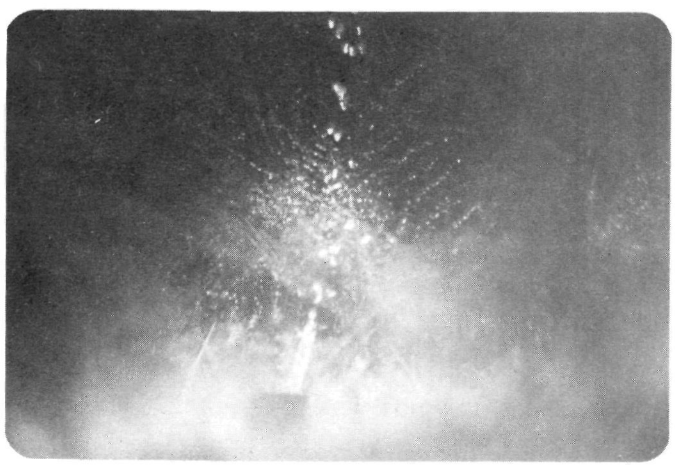


FIG. 5 - FORMING THE GAS BUBBLE

FIG. 6 - OIL UNDER THE GAS BUBBLE

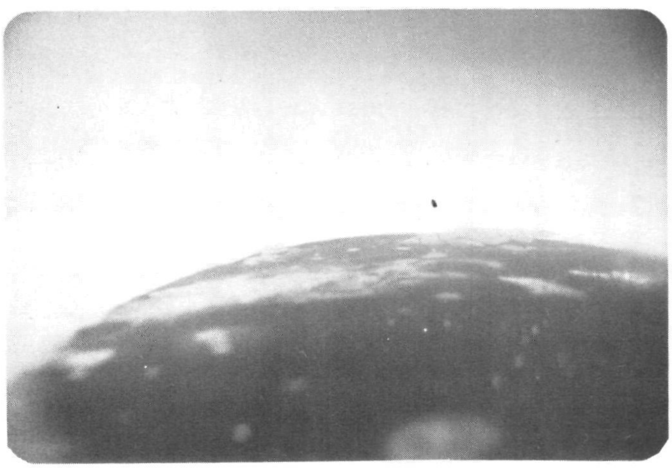


FIG. 7 - OIL UNDER THE GAS BUBBLE

3 OBSERVATIONS

As discussed in Section 1 above, the three critical phenomena to be observed in the experiment were the distribution of oil gas under the ice, the release timing of the oil/gas bi-layer as compared with the pure oil, and the redistribution of the oil on release of the gas.

3.1 Oil and Gas Geometry Under the Ice

The gas injected under the experimental sheet rose in bubbles of mixed sizes mostly from 0.5 - 4 cm in diameter. These impacted the underside of the ice over an area approximately 20 cm in diameter at the center of the sheet and immediately fused into a single circular bubble with a sessile-appearing edge. The large bubble almost covered the ice sheet; its diameter was estimated at a meter and it was confined by the domed shape of the sheet in a pool approximately 2 cm deep at the center. The edges of the bubble appeared typically sessile with a meniscus-like edge about 0.5 cm in diameter. The edge of the bubble was about 10 cm from the tank wall on all sides. The volume of the bubble was estimated at 7.5 liters based on the volume of a spherical segment 2 cm deep. The injection process took about 5 minutes.

The oil drops arrived under the gas bubble or under the ice sheet (in the control tank) in a small area <10 cm in diameter. They thus impacted an existing oil pool and immediately fused to form a single, sessile-appearing oil body. Against the ice interface (in the control tank) this circular pool simply grew in diameter with each drop until the 125 cc formed a pool approximately 15 cm in diameter. (See Figure 8.) Under the gas bubble the large sessile pool was resting against a flat interface, and gradually spread in area with each added drop. This pool was not circular. It grew in lobes and tentacles to eventually coat an estimated 80% of the gas bubble surface. Figure 10 shows the final configuration. The thickness of the oil layer was not measurable without a reference length but the curved edge of the drop was clearly visible.

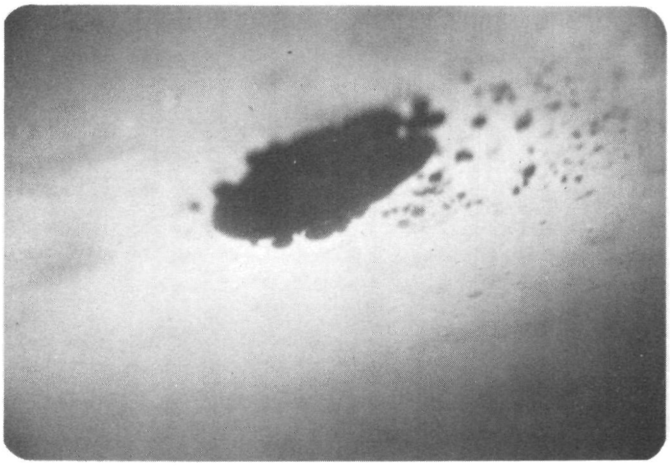


FIG. 8 - THE OIL POOL IN THE CONTROL BASIN

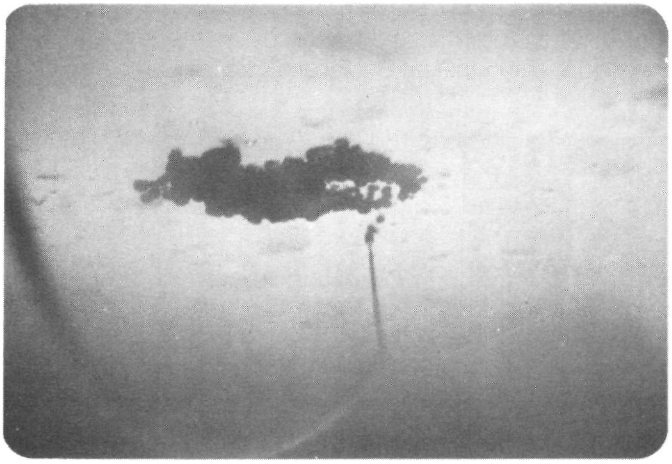
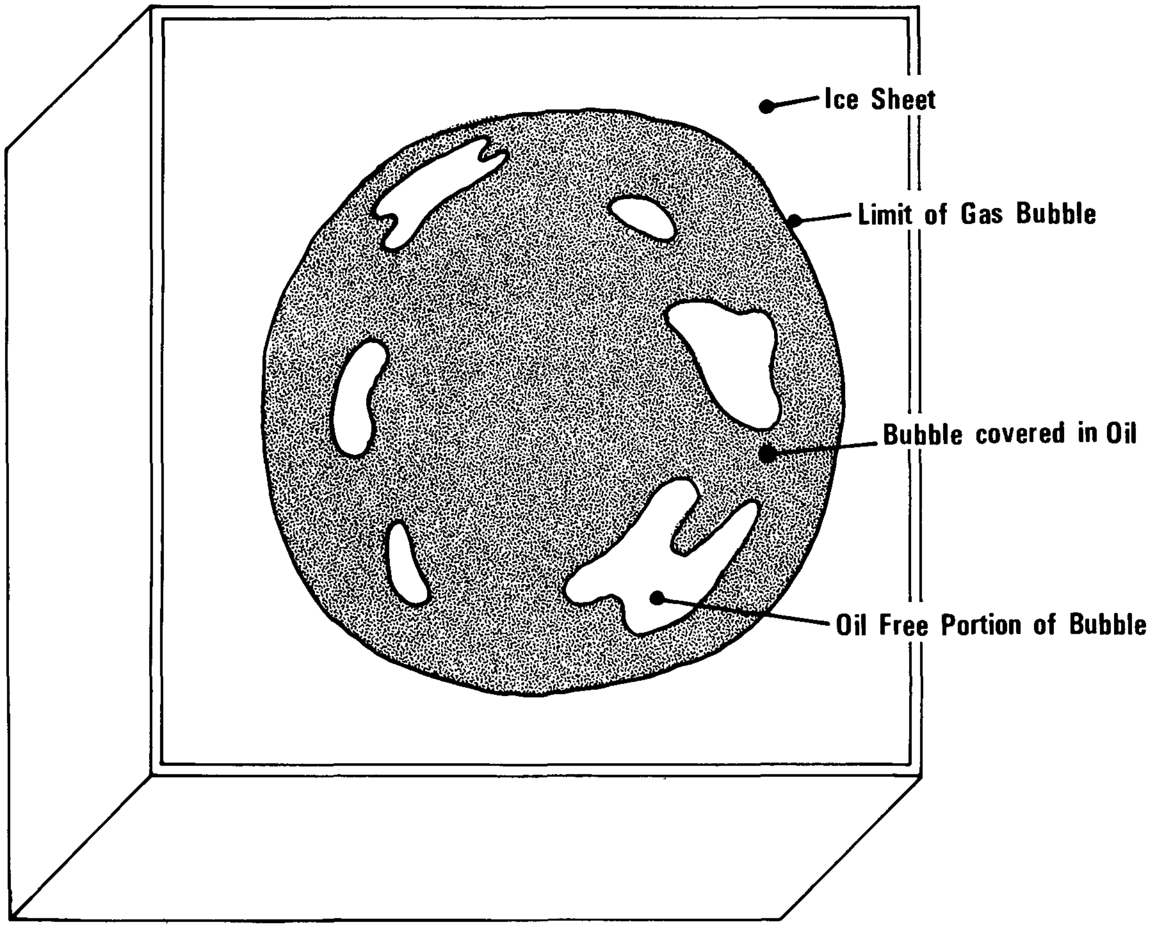


FIG. 9 - THE OIL POOL IN THE CONTROL BASIN



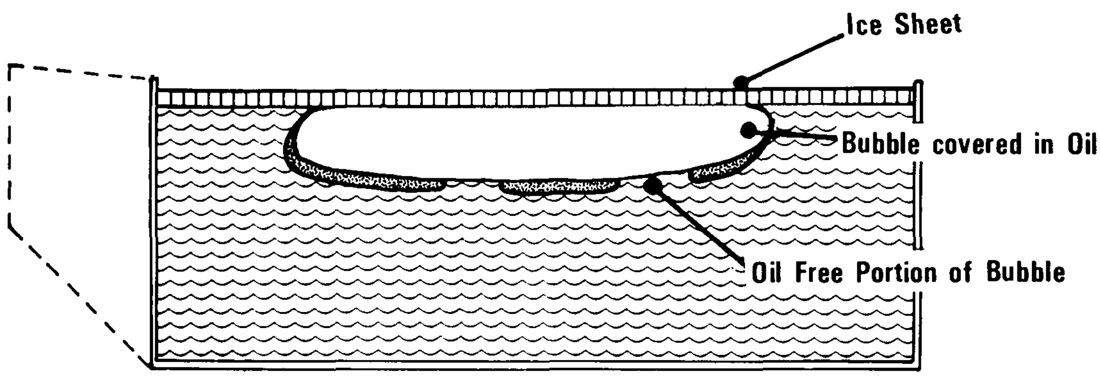


Fig.10 - Distribution of Oil under a Gas Bubble

3.2 Release Timing - Gas

As the air temperature over the two sheets was gradually raised, and particularly in the center under the lights, melt pools began to form within 24 hours. To highlight escaping gas, 3 drops of Palmolive dishwashing liquid were added to the melt pool on the experimental sheet. After a further 3 hours (at 124.4 thawing degree-hours) 5-10, 0.5-1 mm diameter bubbles were observed in a small cluster on the melt pool. The minimum temperature in the sheet at this point was -3.6°C at the mid-plane. Both surfaces were at -2°C.

At 147.8 thawing degree-hours bubbling became rapid enough that bubbles could be observed emerging within a few minutes of observation. At 162.6 thawing degree-hours, 31 of these small bubbles were observed in 90 seconds emerging from approximately 31 different points on the sheet. Some of these points were on the wet, bare surface of the sheet; others were at the edges of melt pools; but no bubbles emerged in melt pools deeper than 0.7 cm. At 174.6 thawing degree-hours, the rate had become sufficient that bubbles could be counted through a 65 cm^2 mask. Based on bubbles 0.75 mm in diameter, the flow was 10^{-5} cc/cm^2-min. The sheet center temperature was -2.2°C.

Shortly thereafter, at 204.2 thawing degree-hours, the flow became concentrated at a single channel in a steady stream of one 1 mm diameter bubble every 7 seconds. This evolved to a pulsing flow of approximately 200 bubbles (4 slugs of 50) in 90 seconds. Then, at 250 thawing-degree hours, the bubbling tapered off quickly, and no further gas escape was observed apart from very occasional bubbles which might have been air trapped in the ice sheet on freezing.

In clock time, the 1 m bubble of 7500 cc of gas was released over a period of 22 hours starting 76 hours after the onset of thawing. The atmosphere over the sheet was sampled with a gas analyzer during this period, but concentrations greater than 0.5% were never obtained. As a result, no rigorous mass balance was possible.

3.3 Release Timing - Oil

Within two hours of the last bubbling (at 266.4 thawing degree-hours) oil appeared on the experimental sheet. The oil was in the form of drops 5×10^{-4} cc to 7 cc in volume widely distributed over the surface melt pools. By 637 thawing degree-hours about 100 of these were apparent, but by 675 thawing degree-hours evaporation and dissolution had reduced the population to 3 or 4 drops of about 5cc each. This situation remained stable until the eventual complete rotting of the sheet.

In clock time the first oil drops appeared on the experimental sheet 55 hours after the onset of thawing, 2 hours after the end of gas release. The population of oil drops rose to about 100 over 68 hours, then the initial release of oil slackened and the population stabilized at less than 10 drops for the next 160 hours. During this period, oil release was not observed but was indicated by the persistence of oil in the face of evaporation and dissolution and by changes from day to day in the positions of the drops on the melt water pool.

Everything described to this point took place in the experimental tank. The first occurrence of note in the control tank occurred at 1768 $\pm$20 thawing degree-hours when a single 1-5 cc drop of oil appeared on the melt pool. This was almost coincident with a resurgence of oil flow in the experimental basin at 1711$\pm$ 188 thawing degree-hours. Thereafter, both sheets released all of their oil over a period of 24 hours.

The release took the form of individual drops 3 mm in diameter which, at the height of release, rose at 1.5-3 second intervals through the melt pool. In the experimental sheet this flow was dispersed over an array of points about 1 cm apart. In the control basin, with its limited oil pool diameter, the flow was concentrated at a single spot. The oil rising in the experimental sheet could be observed as individual drops. The pattern in the control sheet was unobservable as the ice was heavily oiled throughout in the area of the oil pool.

3.4 Redistribution of Oil After Gas Release

It was impossible to discern the oil configuration through either of the viewing ports in the experimental vessels. Nevertheless, the pattern of oil release clearly indicated that the oil originally spread under the gas bubble remained spread over the bubble area after release of the gas.

4 DISCUSSION OF RESULTS

The results clearly show that configuration C of Figure 1 is preferred when a small quantity of Norman Wells crude oil is injected with a large quantity of gas under an ice sheet. The thickness of the layer observed in these experiments can be estimated on the basis of uniform coverage of 80% of a 1 m diameter circular area by 125 cc of oil. The resulting estimated thickness is 0.2 mm. This is much thinner than the 2.5 mm predicted by Rosenegger (1975) for Norman Wells crude on the surface of cold sea water.

The discrepancy cannot be solely attributed to error in estimating the bubble diameter, as a misestimate by a factor of 3 would be required. The estimate of percentage coverage is similarly unsupported, but could not be in error by an order of magnitude. The oil volume was measured by graduated cylinder and precise within a few percent. Rosenegger's calculation of the 2.5 mm minimum thickness for floating Norman Wells crude is based on surface tensions measured in air at 1 atm. The present experiments were conducted at a methane interface under 35 cm of water head. Interfacial tension data are not available for this situation, so this is a possible source of discrepancy. The difference of the component surface tensions enters the spreading coefficient, so small changes in one surface tension can be significant.

This remains a subject for further experimental investigation. On the basis of the present work, it can be said that oil layers less than 0.5 cm thick would probably be encountered in the case of well blowout products accumulating under ice.

Aside from the main experiment, some preliminary tests were conducted injecting motor oil and air under a thin sheet of fresh water ice. In these tests, all of the configurations of Figure 1 were observed, as oil drops and air bubbles coexisted in contact under the ice. There was an opportunity for this type of behaviour in the main experiment but it was not observed. Oil and gas properties are known to strongly affect interfacial tension properties; therefore divergent results should be expected with other oil and gas compositions, other water salinities, and perhaps at other depths.

As discussed in Section 1, it was expected that a gas bubble under the ice would greatly increase the dispersion of a given quantity of oil, and it was feared that this increased dispersion would retard the release of the oil through the ice. These results have confirmed the expectation, but tend to alleviate the fear.

For low-viscosity crude such as Norman Wells, its distribution under a gas bubble can be predicted on the basis of its interfacial tension, and approximated on the basis of its air/oil surface tension.

This gas/oil bi-layer will freeze in, as has been observed with pure oil lenses, and will be stable until (in first-year ice) the minimum temperature in the sheet profile reaches -3.6°C. The gas will then be released through brine channels, drawing with it a few drops of oil through each channel.

The bulk of the oil, however, will remain as a thin layer covering the upper surface of the brine-filled cavity previously occupied by the bubble. This layer, despite its large, thin geometry will be released at approximately the same time and approximately the same rate as if no gas bubble had been present.

These results should be directly applicable to field conditions. The pool of oil in the control was not really large enough to sample a full range of brine channel features, but the simultaneous oil release in the two pools suggests that the results are nonetheless valid. Thicker ice would, of course, lengthen the time intervals involved, but the minimum temperature criterion should be a reliable prediction of release.

A variable not explored here was behaviour in multi-year ice. It was not possible to measure ice salinity profiles in this work, for fear of compromising the entire experiment through disturbing the release. For maximum utility, this experiment should be repeated with ice of varying salinity, so that the sheet temperature criteria can be converted to brine volume criteria. On this basis they could be applied to Milne's model to predict release from ice of any thickness, geometry or freeze-thaw history.

5 CONCLUSIONS

a) Norman Wells crude forms a sessile pool on the underside of a methane bubble held under an ice sheet.

b) At gas to oil ratios of 60:1 or greater, the pool of Norman Wells will not coat the entire bubble surface.

c) Oil layers as thin as 0.2 cm will probably be encountered when well blowout products accumulate under ice.

d) The distribution of the oil phase varies markedly with oil properties.

e) Gas will be released much earlier than oil in the course of thawing a containing sheet.

f) The presence of gas has little or no effect on the release timing of oil trapped under first-year ice.

g) The presence of gas under an ice sheet greatly increases the area contaminated by oil spilled under the ice.

h) The release timing of both gas and oil can possibly be predicted on the basis of ice thickness, salinity profile, and meteorological data.

6 RECOMMENDATIONS

a) The maximum and minimum equilibrium thickness of oil drops under methane bubbles should be measured at pressures up to 3 m of water head.

b) These results should be extended to other oil types and 0 - 30°/₀₀ water salinities.

c) These results should be extended to ice of various salinity profiles in hope of developing release criteria based on brine volume.

d) The generality of the oil/gas distribution observed in this work should be extended in experiments with various oil viscosities and surface tensions and with various gas/oil ratios.

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