The Behaviour of Crude Oil Spilled on Snow

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ABSTRACT. Field and laboratory studies of the behaviour of isothermal and hot oil spills on snow are described. Alberta crude oil spilled at 0°C is readily absorbed by snow and contaminates an area of about 0.01 square metres per litre. A hot oil spill melts a channel in the snow and flows along the ground under the snow contaminating an area of about 0.024 square metres per litre. There may be considerable spreading of the oil during thaw. The flow regimes by which oil permeates into snow and the clean-up implications are discussed.

RÉSUMÉ. *Comportement du pétrole brut répandu sur la neige.* Les auteurs décrivent des recherches de terrain et de laboratoire sur le comportement de coulées isothermes et chaudes de pétrole sur la neige. A 0°C, le brut d'Alberta répandu est facilement absorbé par la neige et contamine une surface d'environ 0.01 mètre carré par litre. Un épanchement de pétrole chaud fait fondre la neige et se répand à la surface même du sol pour contaminer une surface d'environ 0.024 mètre carré par litre. Au dégel, la tache de pétrole peut se répandre considérablement. On discute aussi des régimes d'écoulement selon lesquels le pétrole imprègne la neige, et des implications sur le nettoyage.

РЕЗЮМЕ. *Поведение пролитой на снег сырой нефти.* Описывается полевое и лабораторное изучение поведения пролитой на снег изотермической и горячей нефти. Сырая нефть Альберты, пролитая при 0°C, немедленно абсорбируется снегом и загрязняет поверхность приблизительно равную 0,01 кв.*м* на один литр. Пролитая горячая нефть проделывает в снегу канал и течет под снегом по земле, загрязняя поверхность приблизительно равную 0,024 кв.*м* на один литр. Значительное растекание нефти может происходить во время оттепели. Обсуждаются характер проникновения нефти в снег и очистительные операции.

INTRODUCTION

The exploitation of Arctic oil reserves will undoubtedly result in accidental oil spills on snow-covered ground. The Mackenzie Valley is snow-covered for about 200 days of the year with a mean maximum snow depth of 69 cm (Potter 1965). At most locations there is snow cover from October to early May. It is clearly desirable to have a knowledge of the nature of the interaction between crude oil, snow, and ice. Accidental spills in the Canadian Arctic have been discussed by Ramseier (1971) and Barber (1971). Experimental spills made by the U.S. Coast Guard on ice in Alaska have been reported by Glaeser and Vance (1971), McMinn (1972), and Chen (1972). Glaeser (1971), Vance (1971), Barber (1970) and Scott (1973) have discussed the problems of clean-up after oil spills in the Arctic.

It is important to assess how deeply oil will penetrate into snow since this influences the size of the spill area and has significance for the development of

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clean-up technology. In view of the lack of information on this topic, it is necessary to first make field and laboratory observations of a general qualitative nature, to be followed by quantitative analysis, as the problems and processes become defined.

It is hoped that the field and laboratory studies described here may be of use in environmental impact assessments and provide information for clean-up procedures.

Depending on the circumstances, crude oil spills may be at or above ambient temperatures. Pipeline, production and storage facilities are often at about 63 °C, and so the oil, when spilled, causes snow to melt until the oil cools to 0 °C. It is convenient to consider separately the problems of hot oil spills (in which melting is an important effect) and isothermal spills (in which the oil is essentially at the snow temperature). The following studies are described here.

(1) Field, isothermal oil spills at the Beare Road landfill site, Scarborough, Ontario.
(2) Field, isothermal spills at Norman Wells, Northwest Territories.
(3) Field, hot oil spills on University of Toronto land at Dorset, Ontario.
(4) Laboratory studies of oil permeation of snow.

ISOTHERMAL SPILLS AT BEARE ROAD

One hundred and eighty litres of Alberta mixed sour blend crude oil were spilled on 29 February 1972 at the Beare Road site, which consisted of barren sandy soil of gradient 1 in 10. The oil was poured from drums at the ambient temperature of 0 °C on snow 20 cm deep of void fraction 0.5. The oil soaked rapidly into the snow and permeated an area of 1.86 m^2, but caused little or no compaction of the snow. A sample of the oily melted snow consisted of 67% water and 33% oil, by volume. Apparently the oil did not immediately disturb the snow structure significantly and filled about 45% of the void space.

During a subsequent period of freezing rain and thaw, the snow depth was reduced from 20 cm to 15 cm, and more of the oil became visible on the surface as a viscous oily layer. The spill was observed regularly during the next year. For the remainder of the winter, the oil was stationary and was covered by several snow falls up to 10 cm in depth. Solar radiation apparently passed through the ice and snow above the oil and was absorbed preferentially by the oil, causing local heating. This is to be expected since black oil is essentially opaque to short-wavelength radiation, whereas snow is fairly transparent, about half the radiation not reflected penetrating to a depth of 5 cm (Geiger 1966). Melting and sublimation then proceeded upwards, producing a void between the oil and a layer of icy snow. The snow melted more rapidly from the spill than the surrounding area, due presumably to an albedo change. By the end of March the oil was in the form of a thick layer 2-5 cm in depth containing some ice and surface sand. Oil then began to flow down the slope and reached to 4.6 m from the original point of spillage. Cursory examination of the soil under the oil showed negligible penetration into the soil.

During melting and run-off in April and May the site changed considerably and the oil flowed with the melt water over a wide area, eventually contaminating about 33 m^2. The area surrounding the spill dried rapidly, whereas the ground under the oiled surface remained wet. There was still no visible penetration of oil into the ground, apparently because the water trapped under the spill prevented oil penetration. By early May the oil was thick and tarry. Small plants began growing in cracks which developed in the oil-coated sand. Growth of plants in the contaminated region appeared to be more luxuriant, perhaps due to the moisture trapped under the spill.

During May, 114 litres of the same crude oil were spilled on the dry ground beside the site of the winter spill. The oil flowed like water and soaked into the ground within several minutes, covering an area of approximately 9.3 m^2 and penetrating up to 7 cm into the soil. This spill produced a brown discoloration of the ground, with deep penetration of oil. The appearance of the two sites did not change substantially during the summer. It was observed in the fall that considerably more vegetation was growing on and around the site of the winter spill than elsewhere in the area. The tarry material from the winter spill remained on the surface, and the sub-surface soil had only a faint oily smell and slight discoloration.

By the spring of 1973 the oil had weathered considerably and the only trace of oil on the surface consisted of black asphalt-like lumps.

In conclusion, it was found that in winter the snow acted as an excellent absorbent and there was little penetration of oil into the soil. The initial coverage was about 0.01 m^2/litre. During the spring thaw and run-off the spill spread considerably to cover 0.18 m^2/litre. Before the soil under the spill had dried out the oil had weathered considerably and formed a solid tar-like material. The summer spill on dry sandy soil contaminated a smaller area of 0.08 m^2/litre but penetrated into the soil up to 7 cm.

An oil spill on snow thus initially contaminates an area only about one eighth the area affected by a summer spill; however, after thawing has occurred, the area contaminated may exceed the summer spill area by a factor of two. Clearly it is desirable to clean up a winter spill before the thaw.

ISOTHERMAL SPILLS AT NORMAN WELLS, N. W. T.

On 7 March 1973 a total of 630 litres of Norman Wells crude oil was sprayed on two square plots 7.7 m x 7.7 m in a mature spruce forest near Norman Wells. The plots had been selected and marked the previous summer. The oil viscosity was 13 cp at 0°C.

At the time of the spill the snow cover was 50-60 cm and had an average specific gravity of 0.22, corresponding to a void fraction of 0.76. The void fraction was quite variable, being higher at the surface and close to the ground. Close to the ground the snow crystals were larger. This hoar-snow effect is due to sublimation of ice from the ground and lower snow levels to the upper colder snow. As a result the upper levels tend to be harder and may collapse in snowquakes as the lower levels become unable to support the snow mass. The relative warmth and higher void fraction near the ground are important for the survival of small mammals in the winter, and this phenomenon has considerable importance when estimates are being made of the oil-flow characteristics near the ground.

The ambient and oil temperature was −20°C. The oil was applied evenly over the areas at a dosage of 6 litres/m^2 on one plot and 4.5 litres/m^2 on the second. This method of applying the oil evenly over an area rather than from a point was selected to enable botanical studies to be conducted at the same time. (Hutchinson 1974).

Immediately after the spill it was observed that the oil had penetrated the surface snow to a depth of 2-3 cm. After 30 hours it was observed that it had penetrated in places to the ground. This penetration had not occurred over the entire surface, but small vertical rivulets of oil had formed with a random distribution.

After 30 hours a sample of the surface oil-snow mixture was collected. After melting had taken place, the oil-water volume ratio was 60/40. Assuming that the snow was not compressed by the oil spray, the 60/40 ratio indicates that the snow with a void fraction of 0.85 is 25% saturated.

HOT OIL SPILLS AT DORSET

The site selected consisted of a gentle grass-covered north-facing slope of gradient 1 in 25 with a slight central depression. The site was surveyed in the fall and its location marked by stakes driven into the ground. At the time of the spill (6 February 1973) the site was covered with 61 cm of very crystalline snow with several icy layers. The mean specific gravity of the snow was 0.35 (void fraction 0.61).

The heating vessels were two 45-gallon drums mounted on metal racks, each containing approximately 180 litres of Alberta crude oil. The oil viscosity was 12 cp at 0°C. The drums were placed on their sides at a height 30 cm above the snow level and connected through valves to a 3-metre length of PVC pipe of 5 cm diameter. As a safety precaution 15-metre plastic hoses were connected to the drums to provide a remote vent for vapour produced during heating. The drums contained temperature sensing devices, and were insulated with glass fibre and heated by propane burners.

At the time of the spill the air temperature was 0°C with a light wind. The crude oil was heated to 60°C and then immediately spilled by opening both valves. Drainage took 4 minutes. The hot oil immediately melted holes in the snow, reached ground level after 2 minutes and then continued to flow away under the snow. The oil temperature was measured at various points during and after spillage. The oil cooled rapidly, reaching ambient temperature within 5 minutes. The snow downhill of the site was probed to detect the presence of oil in order to estimate the rate of oil flow and to determine the approximate location of the flow front.

Four hours after spillage the oil flow had apparently stopped and the entire site was excavated to determine the final dimensions of the oil-contaminated area. Section dimensions were recorded at 30-cm intervals by photographs and scale drawings. From these measurements the total ground area and volume of snow contaminated were estimated. The data are presented in Table 1.

TABLE 1. Dimensions of hot oil spill at Dorset

Time (min.)	Total ground flow distance (m)	Total ground area contaminated (m^2)	Total snow volume contaminated (m^3)	Total snow volume contaminated by ground flow (m^3)
2	0	0.2	0.34	0
14	4	5.1	0.52	0.18
20	4.5	6.5	0.66	0.32
30	4.9	—	—	—
40	5.2	7.3	0.74	0.40
240	5.8	8.8	0.90	0.56

During the first two minutes of the spill the vertical flow of oil into the snow was controlled by the rate of melting. Approximately two volumes of crude oil at 60°C are required to melt one volume of snow. About 1 cm^3 of oil of density 0.8 gram/cm^3 and heat capacity 0.3 cal. per gram per °C cooled 60°C yields 14.4 cal., whereas 1 cm^3 of snow of density 0.35 gram/cm^3 requires about 28 cal. for melting. The volume of snow melted will thus tend to be less than the volume of oil discharged, and the oil will back up in the hole. At icy layers the heat required per unit volume is even higher, and the melting rate slower, with the result that there is a horizontal flow of oil near the melt hole. Approximately 0.34 m^3 of snow were contaminated around the melt hole — about one third of the total volume eventually contaminated. The melt hole had a final volume of 0.11 m^3. Apparently, as the hot oil melts the snow, the oil-water mixture rapidly penetrates into fresh snow due to both gravity and the impact pressure of the oil being discharged. The melt hole deepens and simultaneously the oil-water mixture permeates the snow horizontally.

If two volumes of oil melt one volume of snow to yield 0.35 volumes of water, the resultant 2.35 volumes of oil-water mixture could permeate fresh snow of void fraction 0.61 and completely fill the void space of 3.9 volumes of snow. Thus 0.18 m^3 of oil (the quantity spilled in two minutes) should form a melt hole of volume 0.09 m^3 and a volume of contaminated snow of about 0.35 m^3. In the experiment the melt hole was 0.11 m^3 in volume, and the volume contaminated adjacent to the melt hole was 0.34 m^3. Good agreement was therefore shown.

At lower temperatures the volume contaminated will be only slightly less, due to sensible heating of the snow to the freezing point. For example, at −40°C about 20% of the oil enthalpy will be used for sensible heating of the snow to 0°C, and two volumes of oil will melt only 0.8 volumes of snow to yield 2.28 volumes of oil-water mixture and so contaminate 3.8 volumes of snow — only a 3% reduction from the 3.9 volumes calculated above.

After two minutes, when the melt hole reached ground level, there was no visible accumulation of oil, and it flowed rapidly under the surface of the snow along the ground. It was detected 4 metres downhill 14 minutes after the spillage, suggesting a mean velocity of about 28 cm/min. An area of 8.8 m^2 was contaminated. The depth of the contaminated snow varied from 6 cm to 10 cm.

Samples of the oil-snow mixture from the ground flow area contained about 55% oil and 45% water by volume when melted — corresponding to 72% of the void space being occupied by oil. Assuming this sample to be typical, then 0.18 m^3 of oil (the volume discharged in the final 2 minutes) should contaminate 0.4 m^3 of snow. By experiment, the volume of ground flow snow contaminated was found to be 0.56 m^3, suggesting that on the average only 53% of the void space was occupied by oil. Sampling is difficult, since the oil-water mixture may separate prior to re-freezing. Further, it should be emphasized that with other snow structures the results may be very different.

Although the ground was porous there was no evidence of oil penetrating into the soil in agreement with the observations at Beare Road. There was evidence of upward flow of oil into the snow in some areas, possibly due to capillary forces.

To summarize: 0.36 m^3 of hot oil created a melt-hole volume of about 0.11 m^3 and a contaminated volume of about 0.90 m^3; two distinct contamination mechanisms were found, the first during melt-hole formation and the second during subsequent flow of oil along the ground under the snow.

An attempt was made to estimate a heat balance for the oil. The enthalpy of the oil was about 5.2 x 10^6 cal. (with 0°C as reference temperature). Heat loss occurred in several ways including snow melting, conduction to the ground, evaporation, conduction and convection to the air. About 3.2 x 10^6 cal. are required to melt the 0.11 m^3 of snow in the melt hole. An approximate calculation of the heat loss due to evaporation and heat transfer to the air suggested that they may account for 0.5 x 10^6 cal., or 10% of the heat input. The direct heat transfer from the oil to the ground at the bottom of the melt hole during spilling was estimated to be about 0.5 x 10^6 cal., or 10% of the heat input. The balance of the heat is presumably used to melt snow during ground flow, the water formed later freezing as heat is slowly transferred to the ground.

Since an oil spill under winter conditions will result in the formation of a large volume of oil-snow mixture, it is of interest to consider methods of cleaning-up this mixture. Burning is one obvious approach. Samples of the oily snow could be ignited easily even one day after the spillage. Once ignited with an oily rag, the mixture burned well, the snow gradually melting and forming a depression with the flame at the bottom. Radiation from the flame melted the oil-snow mixture at the sides and the oil then flowed down into the area of combustion. A burning test was also conducted on a metal trough on to which oily snow was shovelled. The mixture melted by radiation and conduction, and as a result there was a flow of oil into the combustion region. Part of the melted mixture could be removed and the water separated from the oil by gravity, and so the necessity of burning all the oil can be avoided.

After the thaw the site was examined and it was found that the spill area had doubled to 16 m^2 and all the vegetation in the spill area was dead. The initial and final areas contaminated corresponded to 0.024 m^2/litre and 0.044 m^2/litre. A hot oil spill on snow apparently initially covers an area about twice that of an isothermal spill. When the snow melted the oil was less mobile than at Beare Road, possibly due to the presence of vegetation, disturbance during excavation, the formation of a viscous water-in-oil emulsion or differences in the volume of run-off water. The mobility of the oil upon the thawing of a snow pack is thus a complex phenomenon which is not well understood at present. Further work is under way in an effort to elucidate these processes.

LABORATORY STUDIES OF OIL PERMEATION IN SNOW

A series of exploratory semi-quantitative experiments were carried out to study aspects of the behaviour of oil-snow systems.

Oil-ice-air surface effects

The capillary rise of Norman Wells crude oil at $-5\,^{\circ}C$ was measured between two ice plates separated by a known gap and suspended in a pool of oil. The rise was measured with a travelling microscope and the interfacial tension determined using the equation

$$2\gamma \operatorname{Cos}\theta = \rho g h d$$

where γ is the air-oil interfacial tension in dynes/cm, ρ the oil density in gm/cm^8, d the plate gap in cm, h the capillary rise in cm, θ the contact angle, and g the gravitational constant (981 cm/sec^2).

The average value of γ cosθ obtained was 19.6 dynes/cm. The contact angle could not be determined accurately, but it was believed from observation to be close to zero. This experiment provides an approximate measure of the tendency of oil to spread on ice and hence into snow, and shows that oil will be drawn by capillary forces into snow.

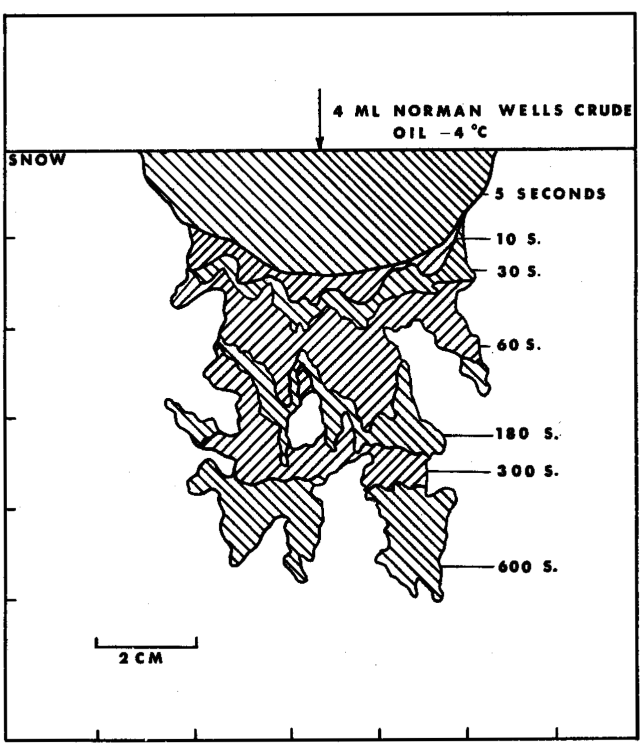

FIG. 1. Oil permeation into snow between glass plates.

In a second experiment a snow-filled glass tube was placed in a pan of Norman Wells crude oil at −10°C and the rise of oil into the snow measured. Results were quite variable due to variations in snow porosity. The capillary rises varied from 2.9 to 4.8 cm, with a mean of 3.6 cm.

Flow of oil in snow between glass plates

Snow was made to fill a gap of known width between two glass plates and compressed to a void fraction of 0.55. The glass plates were clamped vertically and 4 millilitres of crude oil at −5°C were poured onto the surface. Back lighting was used to make visible the permeation of the oil through the snow. Photographs were taken at various times to record the oil movement. This procedure was repeated with Norman Wells and Alberta crude oils at gap widths of 0.32 and 0.64 cm.

Typical results of observations are shown in Fig. 1 which is a composite photograph derived from several taken as the oil permeated the snow. In Fig. 2 the results of four experiments are shown.

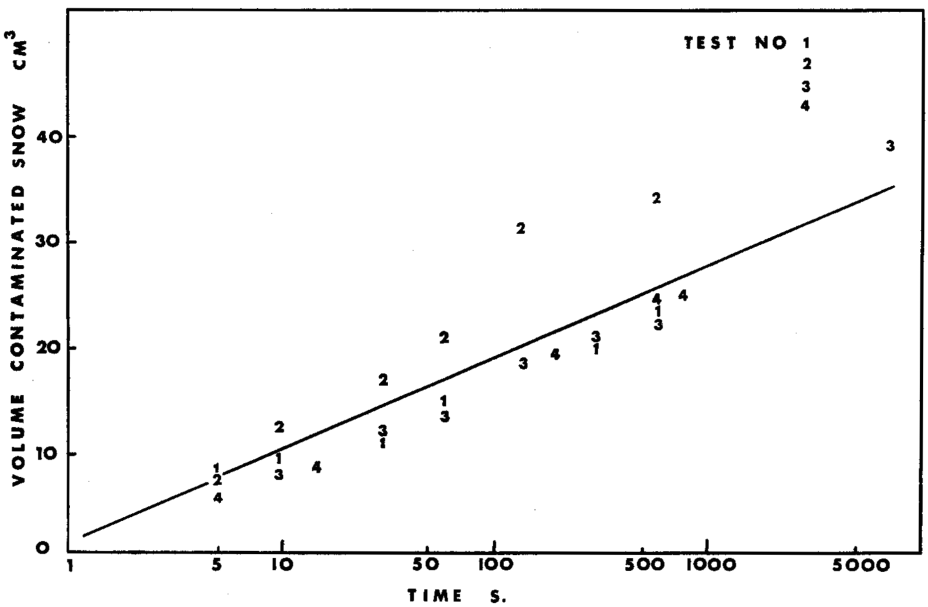

FIG. 2. Rate of oil contamination of snow between glass plates.

When the oil was poured on the surface it soaked into the snow within 5 seconds. This high initial absorption rate occurred while there was still a head of oil on top of the snow and produced a uniformly saturated zone with all the voids filled.

Subsequent drainage of this saturated zone proceeded at a diminishing rate, ultimately producing a volume of contaminated snow of 30-40 cm³. There appeared to be areas of saturation at the bottom, or leading edge, of the oil-snow zone. The final overall saturation of the contaminated snow was about 20% of the void volume.

Steady-state flow of oil in snow

In these experiments an attempt was made to measure the steady-state flow of crude oil through snow.

The apparatus consisted of a glass column, 4.5 cm in diameter, containing snow, connected to an oil-circulating and cooling system. It was contained in an upright refrigerator with a glass door.

After temperature equilibration the oil was pumped on to the snow surface until the snow was completely saturated, the drained oil returning to the pump. A predetermined head of oil was maintained on the snow surface by adjusting the flow rate. The oil-flow rate from the bottom of the column was measured at regular intervals until the run was complete. The results of these experiments are given in Table 2.

TABLE 2. Results of experiments on the steady-state flow of oil in snow

Crude oil type	Temperature (°C)	Viscosity (μ)	Snowbed depth (L) (cm)	Oil head (H) (cm)	Oil flow rate (Q) (cm^3/sec.)	Permeability constant (K) (cm^2) x 10^6
Alberta	−10	0.28	10.2	10.2	0.31	3.2
				5.1	0.17	2.3
				0	0.13	2.6
Alberta	− 7	0.24	6.8	10.2	0.75	4.9
				5.1	0.22	2.3
				0	0.16	2.9
Norman Wells	−10	0.15	9.5	10.0	0.51	2.9
				6.0	0.38	2.7
				1.8	0.51	2.8
Alberta	−10	0.28	11.0	9.0	0.13	1.5
				5.0	0.10	1.5
				2.0	0.09	1.6
Norman Wells	−12	0.15	16.0	5.0	0.83	7.8
				2.0	0.71	7.8

The apparatus was also used to determine the rate of penetration of oil into fresh snow by measuring the depth of penetration at various times. The rate of drainage of saturated snow was also determined by collecting the oil which drained from a previously-saturated volume of snow.

Hot-oil spills

Several experiments were carried out in which hot (65 °C) crude oil was spilled on snow. The results, although only qualitative, are useful in predicting the behaviour of crude oil spills.

When 20 millilitres of hot Alberta oil was poured on to the snow in a glass container (14 cm x 20 cm x 20 cm) it formed a melt hole. A cross-section of a spill of hot oil taken after spreading had stopped appears in Fig. 3. The snow surrounding the channel appeared to have thawed and refrozen. Its porosity had increased, and it was almost saturated with oil. There was an icy layer between the contaminated and uncontaminated snow indicating that refrozen melt water may form a barrier to the spread of oil. This conclusion agrees with the observations

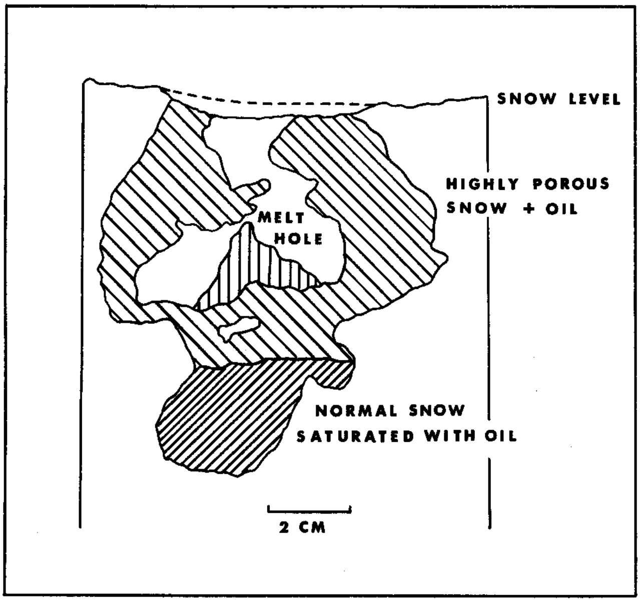

FIG. 3. Cross section of laboratory hot oil spill.

of McMinn (1972) made at the time of the spill made by the U.S. Coast Guard in Alaska. The zone beneath the channel had the appearance of a cold-oil spill and had apparently been permeated by cooled oil flowing from the melted area of the spill.

DISCUSSION

The experimental observations suggest that in an isothermal spill of oil on snow the penetration will tend to take the form of complete filling of the voids until there is a decrease in the hydrostatic head. If the head drops then gravitational flow of oil assisted by capillary forces will occur, draining the saturated region with only partial saturation of the voids in the newly-contaminated snow. Oil viscosity is likely to be the most critical variable. Ultimately the amount of oil remaining as a coating on the drained snow crystals will depend on the nature of the snow, but it appears that it may amount to about 20% of the void volume.

The hot oil spills are very different in that the melting process generates an oil-water mixture which penetrates the snow in advance of the hot oil. Depending on the snow temperature, it may tend to freeze and block further penetration. The total process is very complex, involving fluid flow, heat transfer, phase change and liquid-liquid separation.

The results of field and laboratory experiments suggest that there are at least three regimes of isothermal oil flow in snow.

(a) Steady-state flow of oil through oil-saturated snow.

(b) Unsteady-state penetration of oil into fresh snow .

(c) Unsteady-state oil drainage from oil-saturated snow.

Such flows are commonly quantified by the Darcy equation for flow of fluids through porous media (Darcy 1856; Perry 1963):

$$Q = KA\Delta P/(\mu L)$$

where Q is the oil-flow rate (cm^3/sec.), K is the permeability constant dependent on the structure of the porous medium (cm^2), A is the cross-sectional area of the flow (cm^2), ΔP is the pressure driving force (dynes/cm^2), μ is the viscosity (poise) and L the depth of penetration (cm).

The flow rate of oil into snow could be characterized by this equation in steady- or unsteady-state form, including the effects of interfacial tension as a term in ΔP. The permeability K can presumably be related to the snow structure, this having been done for other media by Bear (1972).

Permeability constants calculated for the experiments into steady-state flow are shown in Table 2. There is good agreement between the values of K obtained by varying the flow rate for each of the five conditions. The variation between the five sets is presumably due to the variation in snow structure which is very sensitive to the nature of prior handling and compaction. The mean value of 3.3×10^{-6} cm^2 enables a rough estimate to be made of rates of oil penetration into snow.

In these calculations the pressure-drop term ΔP is equated to $\rho g(H+L)$ where H is the head of oil above the snow, L the depth of the snow bed, and ρ and g are as already indicated.

When the oil is close to its pour point, and the viscosity several orders of magnitude greater than used here, the flow rates will probably be reduced in proportion. The degree of penetration obtained for example in 30 sec. (Fig. 2) may require 30 hours. It is clearly desirable that this marked difference in behaviour should be predictable.

It should thus be possible to predict the properties of isothermal flow of oil into snow, provided that information is available on the snow and oil properties. Viscosity is likely to be the most important single variable, particularly if the temperature is close to the oil pour point.

The interaction of hot oil with snow is presently only poorly understood, and more quantitative estimation of behaviour must await a better understanding of the effects of heat and phase change, the flow of oil-water mixtures in snow and the subsequent freezing of such mixtures.

It is clear from these studies that more work is needed in these areas, the hope being that the ability to predict hot or isothermal oil-flow behaviour in snow will lead to a better preparedness for oil spills in the Arctic and the development of an appropriate clean-up technology.

ACKNOWLEDGEMENTS

The data for this paper were obtained as a result of investigations carried out under the Environment-Social Program, Northern Pipelines, of the Task Force on Northern Oil Development, Government of Canada.

The research was carried out under contract for the Arctic Land Use Research Program, Northern Natural Resources and Environment Branch, Department of Indian and Northern Affairs, which does not, however, accept responsibility for the results or the interpretation.

We gratefully acknowledge the assistance provided by the Metropolitan Toronto Department of Works in providing the Beare Road Site, and the cooperation of the Faculty of Forestry of the University of Toronto and the Ontario Forest Technical School at Dorset, Ontario. We are indebted to British Petroleum Oil Limited, Shell Canada Limited and Imperial Oil Limited for the gift of crude oil.

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