IN SITU COMBUSTION: AN OIL SPILL COUNTERMEASURE FOR ARCTIC SHORELINES

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INTRODUCTION

When oil is released to the ocean as a result of an error, either from ships at offshore drilling sites or during transfer operations, contamination of an adjacent shore area is usually the end result. Before this occurs and thereafter a multiplicity of factors come into play (i.e. sediment composition, ice, waves, tides, oil volume, and winds). These factors along with the type of coastal environment will determine to a large extent the degree of oil degradation and dispersion. Cleanup methods employed to remove the beached oil will, to a large extent, be influenced by the type of coastal environment as well as by the adverse working conditions which are likely to be encountered in the Arctic.

Oil Spill Compositional and Physical Changes

Before the actual contamination of a shoreline, the oil slick will undergo a series of compositional and physical changes. These changes will alleviate, to a certain extent, the harmful effects of the oil and will usually precede the available cleanup methods. A list of the natural processes consists of:

1. Evaporation;
2. Dissolution;
3. Emulsification;
4. Elution;
5. Biodegradation; and
6. Chemical Oxidation.

The physical changes include only emulsification and elution, and the rest are compositional changes (see Figure 1).

In open waters the processes of evaporation, dissolution, and emulsification will affect the oil slick the most, along with some sinking of the oil. Chemical and

Environment Canada. Arctic and Marine Oilspill Program (AMOP) Technical Seminar, 3rd. Proceedings. June 3-5, 1980, Edmonton, Alberta, Canada, Environment Canada, Ottawa, Ontario, 385-401 pp, 1980.

biological degradation will play a much smaller role in affecting the oil, largely because of the cold temperatures and limited sunlight characteristic of the Arctic climate. Beached oil, on the other hand, will be mainly subjected to evaporation and emulsification. Elution or washing out will play a certain role especially in high tidal areas. However, dissolution, biodegradation and chemical oxidation will be limited in their effects, especially if there is deep oil penetration into the sand. Thus, the main effects on beached oil will be the result of the physical processes, and the chemical process of evaporation which will increase the viscosity of the oil, subsequently making in situ combustion of the oil easier due to smaller penetration of the oil into beach and a thicker oil layer on beach surface.

Factors Affecting Shoreline Oil Distributions

The behaviour of oil spills on different types of coastal areas will be influenced by many factors including sediment conditions, ice, waves, tides, oil volume, and winds.

The penetration depth of an oil spill landing on a beach will vary as to the granular size of the beach sediment. The finer grained sediments allow less penetration than the coarse grained ones such as gravel (Deslauriers et al., 1979). Also the viscosity of the oil will determine the penetration depth, which increases as the oil viscosity decreases. Thus, in general, the thickness of oiled sediment increases as grain size increases (Gundlach and Hayes, 1978) making removal more difficult on coarse-sand and gravel beaches than on fine-sand or silt beaches.

The presence of ice on the shoreline has two basic effects:

1) It modifies littoral processes caused by winds, wave action, tides, and coastal currents; and
2) It can prevent or restrict spilled oil from reaching the shore or penetrating into the sediment.

Generally, ice can be present on the shore in the form of shorefast ice, ice feet, and frost between sediments. The presence of shorefast ice, (a solid sheet from the shore to a point bounded by open water or free-floating ice), will usually serve as the best containment mechanism, preventing the oil from spreading to shore. On ice free beaches, however, individual ice floes will play an important role since they can be driven by wind action onto the beach, causing sediments to be pushed landward and at the same time mixing and burying the oil into the beach (Lewis and Green, 1977).

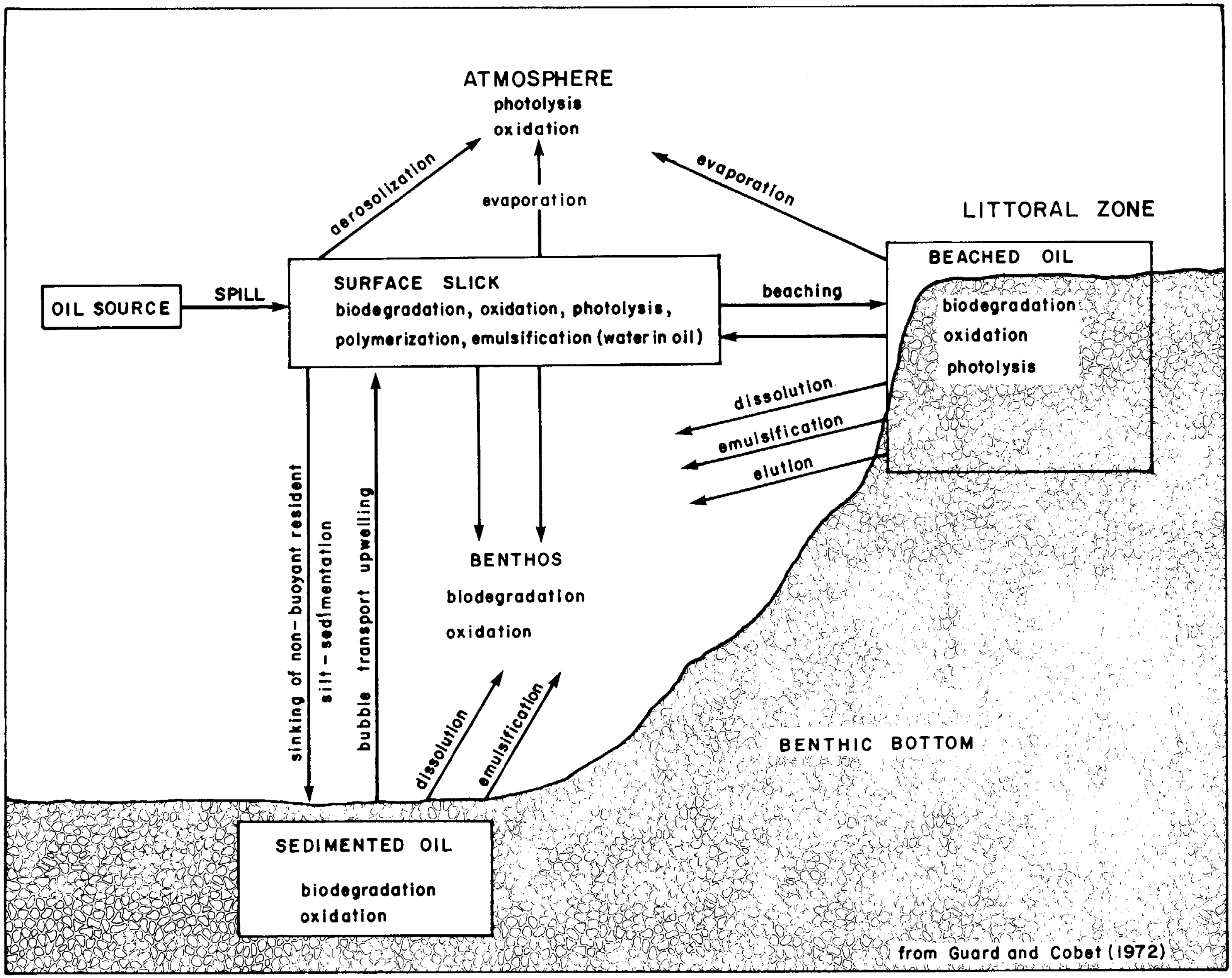

FIGURE 1 NATURAL DISPERSION AND DEGRADATION OF SPILLED OIL

Aside from the influence of ice, wave energy also plays an important role in dispersing, mixing, and burying the oil. The breaking up of an oil slick into smaller oil particles will occur much more readily in a high-energy environment, one which has the coasts open to swell and/or storm waves, as opposed to sheltered environments which have low energy levels. Therefore, the sensitivity of a shoreline to oil will be greatly influenced by the type of coastal environment. In biologically productive environments such as lagoons and marshes, the impact of oil will be great. On the other hand, rock or cliff shorelines in high energy environments will have lower ecological and geological sensitivity, due to the high rates of natural dispersion and degradation of the oil (see Table 1).

TABLE 1 SHORELINE SENSITIVITY

Decreasing Sensitivity ↓		
	I	Marshes Lagoons
	II	Sheltered Environments Pocket Beaches
	III	Exposed Beaches Mud Flats Sand Flats
	IV	Exposed Rock or Cliff Environments

(Department of the Environment, 1978)

Wave action is also important with respect to dispersal and redistribution of sediments. Thus, a shoreline having a large seasonal difference in wave energy levels, will have erosion predominating in one season, and construction (or accretion) in another. The importance of this is that during an erosion phase, sediments and oil on the beach would be removed and transported into the nearshore area. However, if the oil was deposited on a beach immediately following the erosion phase, but before recovery has commenced, the oil on the beach would be buried as constructive waves return the sediment. Aside from this process, the longshore movement of sediment or beach drift will also cause the beached oil to be transported along the shore area.

The variation in water level due to tides is among one of the most important controls on the distribution of wave energy on a shoreline. Environments characterized by low tides have the wave energy transmitted to the shoreline in a small range of elevation. Therefore, the effectiveness of wave action to erode will decrease as the tidal range increases, due to the wave energy being dissipated over an increasingly larger vertical section of the shoreline (Hayes and Gundlach, 1975).

The volume of oil is also important since it will influence both the surface distribution of oil on the beach, and also the duration for which oil shoreline interactions will be maintained (such as burial and mixing).

Winds, aside from transporting oil slicks on water, can also cause the burial of oil by sediment or snow. An increase in wind velocity will also increase the oil aging rate.

Available Beach Cleanup Methods

For any Arctic shoreline cleanup to be effective, the countermeasures employed should meet certain criteria. They should be flexible, not labour intensive and make maximum use of conventional equipment and readily available materials. The countermeasures should also take into account oil distributed in comparatively small separate accumulations scattered over very large areas (Meikle, 1978). In the Arctic, it is also most desirable to dispose of oil immediately rather than to store it and confront the possibility of a secondary spill and face the danger of re-contamination (Leary, 1975).

The wide range of presently available beach cleanup methods includes the following:

1. *In situ* combustion;
2. Mechanical removal;
3. Manual removal;
4. Hydraulic flushing (high or low pressure);
5. Steam cleaning;
6. Sandblasting;
7. Incineration;
8. Chemical Treatment (dispersants, coating agents, etc.); and
9. Groundwater skimming and suction.

With regards to the previous criteria, *in situ* combustion of oil spills on Arctic shorelines is considered to be the most promising disposal by many investigators (Peterson et al., 1975; Leary, 1975; Freiberger and Byers, 1971). A description of the advantages of in situ combustion includes the following characteristics:

1. Speed - Once decided upon as desirable, a burn can be initiated and completed within a relatively short time. Accessibility by helicopter to remote Arctic regions would be relatively rapid compared to land or sea transport.
2. Economy - The limited requirement in equipment and manpower, as well as the low cost of igniters, places in situ combustion among the more economical methods for oil spill cleanup.
3. Ecology - There is no evidence to date, to indicate that burning has a harmful effect upon the ecology of the shoreline and ocean floor, even in the area directly beneath the burn. Although air pollution would be an unfavourable by-product of combustion, the efficiency of the burn could be increased by adding combustion promoters prior to the burn.
4. Toxicity - Combustion can be accomplished without the addition of toxic or polluting materials.

The main foreseeable problems with in situ combustion would be that of achieving ignition and maintaining combustion, which has been reported to cease when the source of heat was removed (Sittig, 1974). This will happen most likely under the following conditions: a) small oil thickness; b) aged oil; c) high water or snow concentration; and d) high wind velocity with blowing snow. Further research in these areas should thus be the primary concern at this stage for developing the process of in situ combustion. Therefore, the main objective of this project is the evaluation of the following parameters:

a) beach slope;
b) type of beach surface;
c) oil type and its thickness; and
d) application of combustion promoted.

Another possible countermeasure method is the mechanical removal of beached oil using heavy construction equipment (e.g. motorized graders, elevating scrapes, front-end loaders and bulldozers). This method, however, can only be recommended for sandy beaches and possibly for coarse sediment beaches where trafficability would permit their use. However, in remote Arctic regions the cost of transporting equipment, and the difficulty in operating under adverse weather conditions would make this method economically unfeasible (Deslauriers et al., 1979).

Manual removal, using rakes, pitchforks or shovels can also be ruled out as a possible countermeasure, due to the great manpower requirements and the adverse working conditions encountered in the Arctic (Logan et al., 1975).

With the hydraulic flushing method, using both high pressure and low pressure dispersion, a potential exists for more extensive damage to the polluted area. Hydraulic high pressure cleanup is most effective on rock surfaces and man-made structures but if used on permafrost, damage to that area may occur. It is also not recommended for marshes and oil-contaminated sediments, thus making it inappropriate for Arctic shorelines. Low pressure flushing, although being more biologically preferred than high pressure, would present a threat of recontamination of unaffected areas if runoff from the flushing operation was not properly channeled and collected. The logistic problems in deploying both of these countermeasures and the required skilled personnel would further make it inapplicable in the Arctic regions.

With regard to steam cleaning and sand blasting, these methods are used mainly for removing oil coatings from boulders, rocks, and man-made structures. Although certain areas of the Arctic have exposed rocky shorelines, these would be least sensitive to any oil spill due to the high rates of natural dispersion and degradation of the oil (Department of the Environment, 1978). Therefore, in such high-energy environments the use of cleanup or protection would generally not be required, and from this point alone cleanup methods might not be worthwhile. In addition, the presence of danger to intertidal flora and fauna with the use of these methods, further decreases their usefulness with respect to beach cleanup techniques (Department of the Environment, 1978).

The process of incineration, although being the least polluting method of burning when a closed chamber is employed (Ewing, 1978), is the most costly. Transportation costs involved in moving the equipment to isolated Arctic regions would make it impractical, especially since only limited quantities of soil could be handled (Leary, 1975).

Use of chemical agents (dispersants, coating agents, etc.) in shallow waters and on the beach has been widely criticized in the past, mainly because of the toxicity problem. Dispersants, especially, are not recommended for use on beaches, particularly marshes and deltas (Lamp'l and Rhodes, 1969; Department of the Environment, 1978). Their use on beaches has also been reported to increase oil penetration into the sand. Coating agents, however, which would prevent oil penetration into the beach sediment, and consequently reduce the volume of contaminated beach, are still relatively unknown but could conceivably play a greater role in the cleaning up process of beaches.

Finally, the use of groundwater skimming and suction which requires the construction of wells and ditches, is more designed for terrestrial spills rather than coastal ones (Deslauriers et al., 1979). Therefore, this method would have no application as an oil spill countermeasure on remote Arctic shorelines.

In conclusion, the relatively new beach cleanup countermeasure of in situ combustion, has been judged to be one of the most promising disposal methods available (Peterson et al., 1975; Freiberger and Byers, 1971), and is worthy of further development, particularly as it appears to work well under cold-weather conditions. The proposed method of burning would use air deployable igniters (Energetex, 1978, 1980) which are small, light, and easily manufactured. It is a simple and straight-forward approach and one which can have an important impact on future cleanup of Arctic shorelines.

The method of in situ combustion was therefore further investigated in this project and will be an extension of the work performed by Hardy Associates, 1979; with the main addition being a beached slope along with its effect on the process of combustion and its eventual efficiency.

PRELIMINARY TESTS

Test Objectives

The depth of oil penetration can influence the efficiency and cost of oil cleanup; thus, it was one of the main parameters evaluated in this project. The specific objectives of the preliminary tests were:

1. To determine the penetration rates of aged and fresh Weyburn-Midale crude oil into sand.
2. To compare the penetration rates of fresh and aged W.M. on different beach slopes, and locations along the slope.
3. To evaluate the effect of a water table presence on penetration rates.

Experimental Setup

A wooden box (48 x 40 x 35 cm) was used for the tests. Sand was then placed inside and shaped to the required slope levels. At the start of the test the box was filled with water and then covered with a 1 cm layer of oil. To deposit the oil on the beach surface the water was drained and the oil subsequently penetrated into the sediment. The following parameters were varied:

1. Oil type (fresh or one-week aged Weyburn-Midale crude oil).
2. Beach slopes (0°,5°, 10°,20°, and 25°).
3. Position of water table (high water table or water drained out).
4. Position of sampling cores (A, B, and C. A being at the top of the beach, B in the middle, and C at the bottom.)
5. Times for penetration depth measurements (1, 3, 6, 12, and 24 hours).

Results and Conclusions

The results for the penetration rates are shown in Tables 2 - 4. They indicate a greater initial penetration rate (first hour) than in the succeeding hours, e.g. in Table 2, 5° slope, the penetration depth at point A was 7.5 mm after 1 hour, but in the next 2 hours the penetration depth increased by only 2.1 mm to a total depth of 9.6 mm. The significance of this result is that it indicates the necessity for a quick response to an oil spill, to ensure a higher probability of ignition before oil penetration is too extensive.

The penetration depth on a horizontal beach is greater than for a sloped beach. Table 2 indicates that after 24 hours of penetration time the penetration depths at point A were: 0° - 95 mm; 5° - 17 mm; 10° - 3.9 mm; and 20° - no penetration. This tendency of oil to penetrate less on a sloped beach would aid the combustion process on these beaches, since the oil would tend to collect at the bottom of the slope, thus increasing the probability of ignition and total amount of oil burned.

There is a decrease in penetration rate due to the increased viscosity of the oil (a characteristic of aged oils). Table 4 shows that for aged oil on a 5° slope the penetration depth after 24 hours at point A was 7.1 mm but for fresh oil (Table 2) it was 17 mm. The water table was found to have a strong effect on the penetration rate and depth of aged oil. If the water table was high, the penetration depth at the top of the beach was greater than in the middle, e.g. after one hour, A = 4.4 mm; B = 2.5 mm (Table 3). However, when water was completely drained (Table 4), the top of the beach had a lower penetration depth than the middle or bottom portions, e.g. after 24 hours, A = 7.1 mm, B = 19.8 mm, C = 42-56 mm. Therefore the reduced availability of pore spaces within the sediment (filled with water) prevents any significant portion of the oil to penetrate it.

TABLE 2 OIL PENETRATION RATES ON SAND: FRESH WEYBURN - MIDALE CRUDE OIL WITH WATER DRAINED OUT.

0° Slope						
Time (hours)		1	3	6	12	24
Penetration (mm)		24	28	27	32	95
Temperature (°C)		18	17	16	15	16
5° Slope						
Time (hours)		1	3	6	12	24
Penetration (mm)						
Location:	A	7.5	9.6	10.9	16.4	17
	B	10.3	9.8	13.5	16.4	15
	C	20.5	25.3	31.1	36.6	40
10° Slope						
Time (hours)		1	3	6	12	24
Penetration (mm)						
Location:	A	3.2	3.7	3.8	3.9	3.9
	B	4.5	4.7	4.8	5.1	5.6
	C	3.3	8.4	20.2	33.2	34.2
20° Slope						
Time (hours)		1	3	6	12	24
Penetration (mm)						
Location:	A					
	B	1.5	8.7	10.7	11.6	13
	C	2.3	9.5	17.5	17.2	14.3

TABLE 3 OIL PENETRATION RATES ON SAND: ONE WEEK AGED W.M. CRUDE OIL WITH A WAVE GENERATED HIGH WATER TABLE.

5° Slope					
Time (hours)		1	3	6	24
Temperature (°C)		15	15	15	17
Penetration (mm)					
Location:	A	4.4	3.8	5.8	6.5
	B	2.5	2.4	2.0	3.5

TABLE 4 OIL PENETRATION RATES ON SAND: ONE WEEK AGED W.M. CRUDE OIL WITH WATER DRAINED OUT

5° Slope						
Time (hours)		1	3	6	12	24
Temperature (°C)		15	15	15	15	15
Penetration (mm)						
Location:	A	6.4	6.9	7.1	6	7.1
	B	11.2	12.9	13.2	14	19.8
	C					42-56

The results also indicate that as the beach drains, the oil moves more down the slope rather than into the beach. This is shown by the increased amounts of oil at point C as compared to points A and B. Therefore, there is greater penetration down the slope due to the decreased movement and greater proportion of oil at that point. In view of these results combustion would be more effective if carried out as close to the bottom of the slope as possible, because of the greater availability of oil in that area.

IN SITU COMBUSTION TESTS

Test Objectives

The objectives of in situ combustion tests were:

1. To evaluate the combustion process on sand with different beach slopes;

2. To determine the penetration depths at different locations of the beach slope, before and after in situ combustion; and
3. To compare the effect of high vs. low water table on in situ combustion.

Experimental Setup

This part of the project involved working outside, using 2.4 x 2.4 x 0.5 m wooden boxes, filled with sand to appropriate slope levels. The boxes were filled with water, and one week aged Sour Blend crude oil was poured on top. The water was then allowed to drain and the oil, as in the preliminary testing, subsequently penetrated the sand. In some of the tests peat moss (a combustion promoter) was placed on the beach prior to the application of the oil. The following parameters were varied:

1. Beach slopes (2.5°, 5°, 10°, and 20°).
2. Height of water table (high or low).
3. Water draining rate (2.5 cm in 10 min or 10 cm in 30 min).
4. Presence of a combustion promoter (peat moss) or not.
5. Wave generated on beach or not. A long wooden piece of plywood was used by hand to generate the waves.

The unburned oil residue was collected after combustion and measured to establish the combustion efficiency. When peat moss was used the oil and peat moss were separated to establish the amount of oil left. The oil and peat moss were separated simply by squeezing the mixture and letting the oil drip out. Core samples were taken before and after combustion to compare the oil penetration depth, and to compare the effect of combustion on the penetration depth.

Results and Conclusions

Results of the in situ combustion tests are shown in Table 5. It was found that penetration of Sour Blend crude oil into the sand beach occurred within hours on all beach slopes (2.5°, 5°, 10°, and 20°), and no combustion on the beach itself was possible at first. However, after emulsification due to rain in test run No. 2 combustion was possible, mainly at the bottom of the 10° beach slope; close to the water and on the water surface. This was due to the decreased viscosity because after ignition the oil on the beach was preheated and was able to flow down to the water surface.

The addition of peat moss in a 1:1 ratio with the oil, resulted in easy ignition on the beach surface on both 20° and 5° slopes (test runs No. 5 and 6). Caking, however, occurred on top of the oil-peat moss mixtures and if not disturbed prevented the underlying oil to burn. Due to this caking and the good holding characteristics of peat moss the combustion process took a considerable time to complete, e.g. test run No. 5, combustion time was 2 hours, 24 min and for test run No. 6 it was 58 min. In general, combustion of crude oil Sour Blend and Weyburn-Midale (one week aged) based on preliminary results, is not possible on a sloped beach surface, unless a trench or fireproof boom is used near the shore surface to collect the oil. This will then allow combustion to take place, which will predominate on the water surface. Even emulsified crude oil when ignited on a beach surface, (due to the high temperature generated during the combustion process, and the change in its viscosity) will subsequently flow down to the water surface where most of the combustion will take place. Based only on preliminary results, a trench or fire-proof boom would also be required in this case, involving emulsified oil. When peat moss is used for both oils (Sour Blend and Weyburn-Midale) combustion is possible and ignition is quite easy. However, the efficiency is low (around 50%) for a 1:1 peat moss to oil ratio. Various peat moss loadings will be tested in the near future and the combustion efficiency will be evaluated. Nevertheless, based only on preliminary results it would appear that if the mixture of peat moss and oil were collected first and then disposed of, in an incinerator or other mobile combustion unit, the efficiency would be much higher.

SUMMARY

The results of laboratory and field experiments conducted in Waterloo, Ontario between November, 1979 and April, 1980 are summarized in this report. The project is incomplete at this stage; however, the oil penetration rates for sand using fresh and one week aged Weyburn-Midale crude oil plus the combustion tests with one week aged Sour Blend crude oil, have been completed. The properties for oils tested may be found in Table 6.

During the preliminary testing on a small laboratory scale, penetration rates were determined in order to understand the physical behaviour of beached oils. It was originally planned to carry out tests involving three sediment types; silt, gravel, and sand, however, after initial testing it was decided to perform the tests on sand only. With gravel the oil penetrated too quickly, and with silt there was no noticeable penetration resulting in a rapid flow down the slope. Using sand as the only composition, the

TABLE 5 RESULTS OF THE IN SITU COMBUSTION TESTS

Test Run No.	Oil Type	Beach Slope and Type	Initial Oil Thickness (cm)	Penetration After 24 hours (Before Ignition) (cm)			Penetration After Combustion (cm)			Water Table	Drainage Rate (cm/min)	Comments
				A	B	C	A	B	C			
1	1 week Aged sour Blend	20° slope sand	1	5	1	0.5	5	1	0.5	High*	0.33	After generation of a wave to move oil up the slope some sand was washed out. No combustion was possible on the beach.
2	1 week Aged sour Blend	10° slope sand	1	2	1	0.5	2	1	0.5	High	0.25	Emulsification due to rain occurred during the night, before attempting ignition. Ignition was easy, but most combustion took place on water. Oil flowed down to water level after it was preheated.
3	1 week Aged Sour Blend	5° slope sand	1	1	0.5	0.0	1	0.5	0.0	High	0.25	No ignition possible on beach.
4	1 week Aged Sour Blend	2.5° slope sand	1	1	0.5	0.0	1	0.5	0.0	High	0.25	No ignition possible on beach.
5	1 week Aged Sour Blend	20° slope sand	1	2	2	2	2	2	2	Low*	0.33	Peat moss was applied on top of the oil in a 1:1 volume ratio with the oil, and then water was drained out. Ignition was easy. Not a very strong flame. Surface caked and some oil was left unburned. Combustion time was 2 hr 24 min. No oil flow observed.
6	1 week Aged Sour Blend	5° slope sand	1	2	2	2	2	2	2	Low	0.33	Peat moss applied as before in a 1:1 volume ratio. Ignition was easy. Intense flame for 2 min, then weak flame. Some oil was left unburned. Combustion time was 58 min. No oil flow was observed.
7	1 week Aged Sour Blend	10° slope sand	1	5	2	1	5	2	1	Low	0.40	No ignition was possible on beach.

A = top of beach slope
B = middle of beach slope
C = bottom of beach slope

High Water Table = water level half way up the beach slope
Low Water Table = water completely drained out

TABLE 6 OIL PROPERTIES

Oil Type	Specific Gravity	Viscosity (Centipoise)	Pour Point (°C)	Fire Point (°C)
Sour Blend				
1 week aged	0.94	87-2000	-13	110
Weyburn-Midale				
1 week aged	0.96	200-1250	+3	106

conditions that were varied included beach slope (2.5°, 5°, 10°, 20° or 25°); the height of the water table (high or low); and the age of oil (fresh or 1 week aged W.M. crude).

Results showed that with both oil types (fresh and aged) penetration was greater initially (1st hour) than in the succeeding hours, e.g. in Table 2 with fresh oil for 5° slope, penetration depth at point A (top of slope) was 7.5 mm after 1 hour, but in the next 2 hours it increased by only 2.1 mm; likewise in Table 4 with aged oil, the penetration after 1 hour at point A was 6.4 mm, but in the next 2 hours increased by only 0.5 mm. Also, it was observed that the steeper the beach slope, the smaller was the penetration, e.g. Table 2.1, the penetration depths at point B (mid slope) after 1 hour were: 0° = 24 mm, 5° = 10.3 mm; 10° = 4.5 mm; and 20° = 1.5 mm. This tendency to flow down a steep slope is one factor which would account for the oil tending to collect at the bottom of the beach slope (the other factors would be age of oil, viscosity, sediment porosity, and height of water table).

The water table level was found to have the most influence on oil penetration. When it was high (water level half way up the beach slope) the penetration depth was low, e.g., at point B it was 2.5 mm (Table 3). However, with a low water table (water completely drained out) penetration was high, e.g., at point B it was 11.2 mm (Table 4). The reason for this increase in penetration is due to the increase of available pore spaces within the sediment, once the water is removed from the sediment.

During the in situ combustion tests carried out at the North Campus Research Station in Waterloo, the Energetex built igniters were placed on top of the beached oil located in large wooden boxes (3 x 3 x 0.5 m). It was found that the low viscosity oil (i.e. one week aged Sour Blend) penetrated into the sand beach within hours on all beach slopes, 2.5°, 5°, 10°, 20°, and 25°, making in situ combustion impossible. However, this same oil, when emulsified by rainfall, was possible to burn due to the reduced viscosity.

With the addition of peat moss to the Sour Blend crude oil (one week aged) in situ combustion was also possible. This peat moss-oil-mixture however, formed a cake at the surface and if not disturbed prevented the underlying oil to burn. The combustion process was therefore prolonged as a result of the caking process and the strong holding characteristics of peat moss. Unburned oil residue always remained after combustion.

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