ARCTIC
VOL. 31, NO. 3 (SEPT. 1978), P. 305-323.

The Physical, Chemical And Biological Effects Of Crude Oil Spills On Black Spruce Forest, Interior Alaska

T. F. JENKINS, L. A. JOHNSON, C. M. COLLINS and T. T. McFADDEN

INTRODUCTION

In the late 1960's, it became apparent that the large petroleum resources of the Alaskan and Canadian Arctic would soon be developed. Scientists from both the United States and Canada became increasingly concerned that transport of this large volume of crude oil across arctic and subarctic terrains would likely result in periodic spills. Information regarding the environmental effects of these types of terrestrial spills was largely nonexistent.

In the early seventies, several groups initiated small-scale studies documenting the effects of spills on arctic and subarctic vegetation (Deneke *et al.*, 1975; Hutchinson *et al.*, 1974) and identifying natural recovery mechanisms which would tend to restore impacted areas (Hunt, 1972; Cook and Westlake, 1974; McGill, 1977). Other studies directed at artificially enhancing biological recovery by methods such as fertilization were also conducted (Parkinson, 1974; Lehtomäki and Niemelä, 1975; Atlas, 1977). Another group of researchers documented the impacts resulting from past spillages of petroleum fuels from breaks in a military pipeline in southeastern Alaska (Deneke *et al.*, 1975; Rickard and Deneke, 1972; Hunt *et al.*, 1973).

Following the decision to construct the Trans-Alaskan Pipeline System (TAPS), information regarding the area and extent of impact from a potential leakage in the system was sought. While experimentation with small-scale controlled spills was essential to an understanding of the processes involved, it was of limited value in predicting the extent of impact expected from a large volume of oil such as would result from a failure in the pipeline. Except for several studies in the MacKenzie Valley of Canada (MacKay *et al.*, 1974; Hutchinson *et al.*, 1974; Cook and Westlake, 1974), little information was available regarding the spillage of larger amounts of oil on terrestrial sites and none with respect to the interior subarctic portions of Alaska.

It was, therefore, the goal of this study to conduct an experiment more realistic in size and mode of impact, utilizing crude oil from Prudhoe Bay. A temperature was selected that would be representative of the TAPS during full-scale operation. The site chosen was to be one representative of interior Alaska and similar to the terrain encountered by the TAPS south of the Brooks Range. Because of the large seasonal climatic variations in the

---

United States Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire

subarctic, it was decided that two similar spills differing in time of year would be conducted. The first was conducted in mid-winter and the second at the height of the growing season in mid-summer on sites with very similar topography and vegetation. The overall objectives of the study were threefold:

1) To detail the physical effects of crude oil spills in black spruce forests of interior Alaska emphasizing the mode of transport, area of impact vs. time, and effects on the active layer and underlying permafrost;

2) To determine the fate of petroleum contaminants once spilled in subarctic terrestrial environments;

3) To evaluate the effects of crude oil spills on vegetation.

A companion study, conducted simultaneously, describing the effects of the spill on microbial populations and activity is described elsewhere (Sparrow *et al.*, this volume).

SITE DESCRIPTION

The study site chosen lies in the lower reaches of the Caribou-Poker Creeks Research Watershed, 48 km north of Fairbanks, Alaska (McFadden *et al.*, 1977). The site is about 300 m above sea level and situated on a moderate (7-8%) west-facing slope. The closest stream is Poker Creek some 800 m downslope. An abandoned water diversion ditch lies between the study site and Poker Creek guarding against inadvertent oil contamination.

The study site is an open black spruce (*Picea mariana* (Mill.) Britt., Sterns & Pogg.) stand (Fig. 1) with a shrub understory of Labrador tea (*Ledum decumbens* (Ait.) Hult. and *Ledum groenlandicum* (Oeder) Hult.), resin birch (*Betula glandulosa* Michx.,), and blueberry (*Vaccinium uliginosum* L.). A few scattered willows (*Salix spp.*) occur in the area. Mosses and lichens provide 50% or more ground cover. Various herbs can be found. Cottongrass tussocks (*Eriophorum vaginatum* L.) have a scattered distribution but are of local importance (Troth *et al.*, 1975).

The soil on the site is typical of the Saulich series found in the lower slopes of the watershed (Rieger *et al.*, 1972). A typical profile consists of 3 to 13 cm of moss, 0 to 3 cm of reddish-brown peat, a layer of 1 to 3 cm of brown mixed organic and silt loam, and greyish silt loam extending to permafrost. The soil is poorly drained with a depth of active layer ranging from a few centimeters to 75 cm depending on the thickness of the organic mat and proximity to shrubs and trees. The pH of both the organic and mineral soils is strongly acidic, generally below pH 4 (Troth *et al.*, 1975). The cation exchange capacity of the organic layer exceeds that of the mineral soil (Table 1).

TABLE 1. Range of pH and Exchangeable Cations (meq/100 g)

Layer	pH	Ca++	Mg++	K+	Na+
Organic (02,A_1)	3.3-3.8	15-40	4-9	0.4-1.8	0.1-0.2
Mineral (C_2)	3.6-4.0	4-16	1-3	0.1-0.3	0.05-0.1

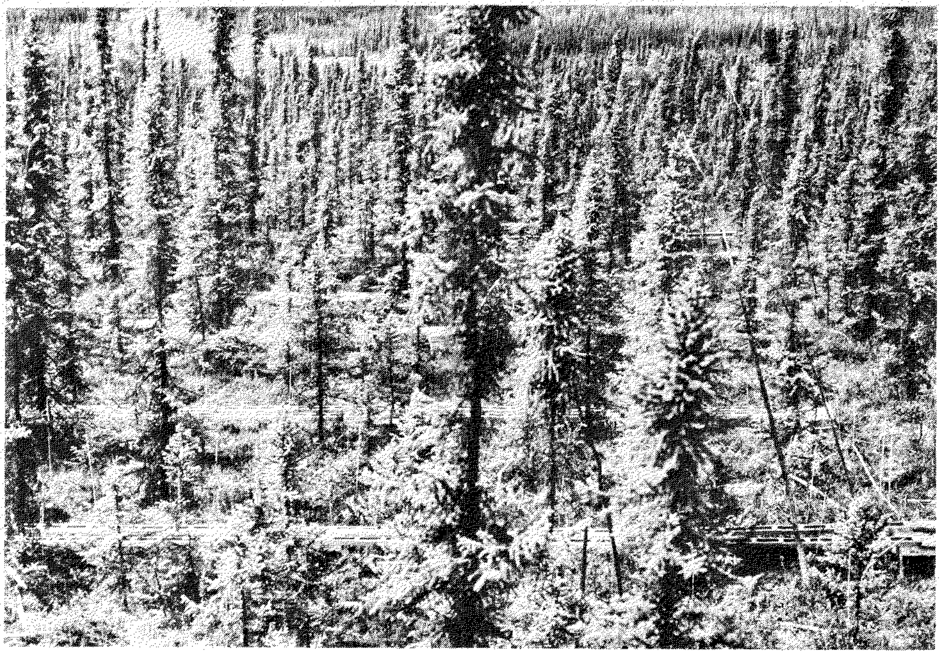

FIG. 1. View looking downslope prior to oil application on summer spill plot.

METHODS

Oil Application

The oil for the study was obtained from Prudhoe Bay and hauled by truck in 55-gal drums to an area near the site. The oil was transferred to a 2000-gal tank and transported to the spill site on a large tracked vehicle. The oil was heated to 57 °C, using heat tapes, in a closed system to preserve the volatile components. The oil was spilled through a 5-m length of perforated pipe at about 170 l/min (45 gal/min) over a 45-minute period. The winter spill was conducted on 26 February 1976 at an ambient termperature of about -5 °C (23 °F). The summer spill was carried out on 14 July 1976. In each test 7570 l (2000 gal) of oil was spilled.

Physical Characterization

The rate of oil flow downslope following the spill was determined by probing with wooden dowels at predetermined locations on a 1-m grid. The presence of the crude oil was readily discerned by sight and smell and confirmed by UV-fluorescence when questionable (Deneke *et al.*, 1975).

Elevated crosswalks were installed at 5 m intervals across the treatment plots to allow direct access to the plots with minimum surface trampling disturbance (Fig. 1).

Thermal Characterization

An extensive thermocouple array was installed at five levels (Fig. 2a), from within the permafrost up to the overlying moss cover, by attaching the thermocouples to 32-mm-diameter wooden dowels and installing in predrilled holes. This vertical array was replicated 36 times in each plot (Fig. 2b) to allow adequate spatial monitoring of thermal effects.

A program of probings to determine changes in the depth of thaw in the plots was conducted during the thaw periods. Six cross sections were laid out at 1, 3, 6, 9, 14 and 20 m downslope from the spill point in each plot with frequent probings taken at 1-m intervals.

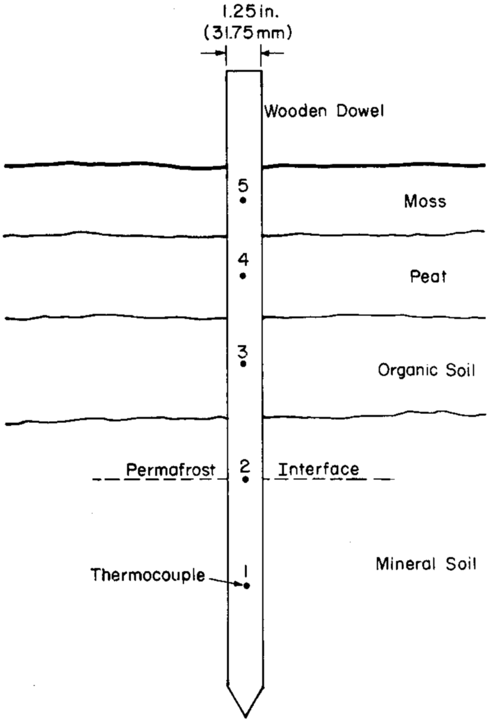

FIG. 2a. Vertical thermocouple assembly.

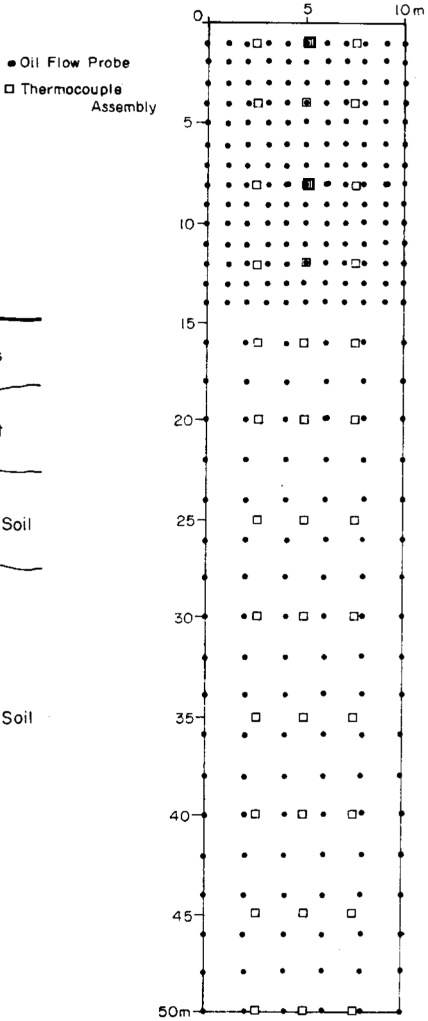

FIG. 2b. Layout of oil detection stakes and thermocouple arrays.

Oil Characterization

Initial oil samples were obtained at the time of the spills, cooled rapidly to preserve their integrity with respect to volatile components, and characterized along with samples collected later by the following techniques:

1) headspace analysis for volatiles by gas chromatography;
2) silica gel/alumina column chromatography to obtain major oil components (% alkanes, aromatics, asphaltenes, and NSO's);
3) characterization of the alkane fractions by capillary flame ionization gas chromatography (Apiezon L and Dexsil SCOT columns);
4) characterization of all oil fractions by scanning infrared spectroscopy.

Soil cores were collected initially and periodically afterwards over a two-year period. Each sample was taken with a 5.7-cm-diameter corer, divided visually into overlying moss (01), brown organic layer (02 and A_1) and greyish-brown silt loam (C_2) and individually stored in prewashed Ball canning jars. The samples were iced immediately and kept frozen until analysis.

The soil samples were analyzed as follows. A sub-sample was taken, placed in a scintillation vial, sealed with a silicone rubber septum material, and equilibrated at room temperature (approximately 22 °C) for 24 hours; the headspace was sampled with a gas-tight syringe, and analyzed by gas chromatography (McAuliffe, 1971). The remainder of the soil sample was manually extracted with chloroform (Mallinckrodt, nanograde). For oily soils, extractions were continued until the color of extract was visually similar to that from a control soil (up to 10 individual extractions). The chloroform was removed by evaporation and the residue, containing material C_{15} and greater, determined gravimetrically. The asphaltene material was removed by precipitation with pentane and the remainder of the material fractionated by silica gel-alumina chromatography in a manner similar to that described by Bailey *et al.*, (1973). In our study, the column was sequentially eluted with pentane, benzene, and methanol (Mallinckrodt, nanograde) with the amount of material in each fraction determined gravimetrically. The alkane fraction was further characterized by gas chromatography and along with the other fractions by infrared spectroscopy.

VEGETATION

Prior to the spill, the vegetation was characterized using a number of 1-m^2 plots within the spill and control plots. Data were collected according to methods of Ohmann and Ream (1971) as previously used in the research watershed (Troth *et al.*, 1975). Nomenclature follows Hultén (1968) for herbaceous species, Viereck and Little (1972) for shrub and tree species, Crum *et al.* (1973) for moss species, and Hale and Culberson (1966) for lichen species.

Pre-spill measurements were made of percentage of cover and frequency of occurrence of vegetation species. Plots were permanently marked and will be resampled at the end of the third growing season following oil application

(1978). The site was visited biweekly during the 1976 and 1977 growing seasons in order to record the time and extent of oil related injuries.

Samples of current year's spruce needles from trees within and outside the winter and summer spills were taken in 1975 and 1976 and were analyzed for total nitrogen, phosphorus, and potassium by a Technicon Autoanalyzer to determine if the spills significantly affected nutrient content.

Dr. Arthur Linkens, Virginia Polytechnic Institute, took several soil cores from both the winter and summer oil spill plots during the 1977 growing season. These were then used to evaluate ectotrophic root respiration for all species including black spruce, blueberry, and Labrador tea. Root respiration rates and respiratory quotients (ratio of carbon dioxide released to oxygen absorbed) were determined in a Gilson differential respirometer using the direct KOH method.

RESULTS AND DISCUSSION

Oil Movement

The winter spill was conducted on 26 February 1976 at 1145 hours AST. The oil was applied from a 5-m-wide header with 6-mm holes spaced every 10 cm. The oil was spilled on top of a snow pack which was approximately 45 cm in depth. The hot oil rapidly melted holes in the snow immediately downstream of the header and moved downslope beneath the snow generally following the microrelief of the frozen soil surface. Most of the movement occurred within the moss layer above the frozen organic and mineral soils. Although, the oil was not visible from the surface, its presence at prelocated points downslope from the header was obtained and is plotted with respect to time in Figure 3. Movement of oil continued at a gradually decreasing rate for 24 hours following the spill before it became immobilized over an area extending 18 m downslope of the header. The oil remained stationary throughout the remainder of the winter and did not remobilize until spring breakup in May 1976. With the onset of warm weather the oil gradually moved an additional 17 m downslope. By the end of the summer, oil movement had ceased and no further movement has been observed. The total area affected by the oil is about 185 m^2 or about 24 m^2/m^3 of oil (41 l/m^2).

The summer spill was conducted on July 1976 in order to approximately coincide with the peak of the growing season. Maximum yearly temperatures were expected around this time.

Air temperature during the summer spill was 25 °C and the moisture content of the organic soil was 171% on an oven-dried basis. The spill was conducted in the same manner as the winter spill. A similar spill rate of 170 l/min was used and the oil temperature at the header was also 57 °C. As the oil spilled onto the surface, it rapidly penetrated to the organic soil and moved downslope beneath the moss. Oil disappeared from view less than a meter below the spill point and was only visible downslope in surface depressions where pools formed. Oil movement continued for approximately 24 hours at which time it had moved 30 m downslope. After the initial 24-hour period the

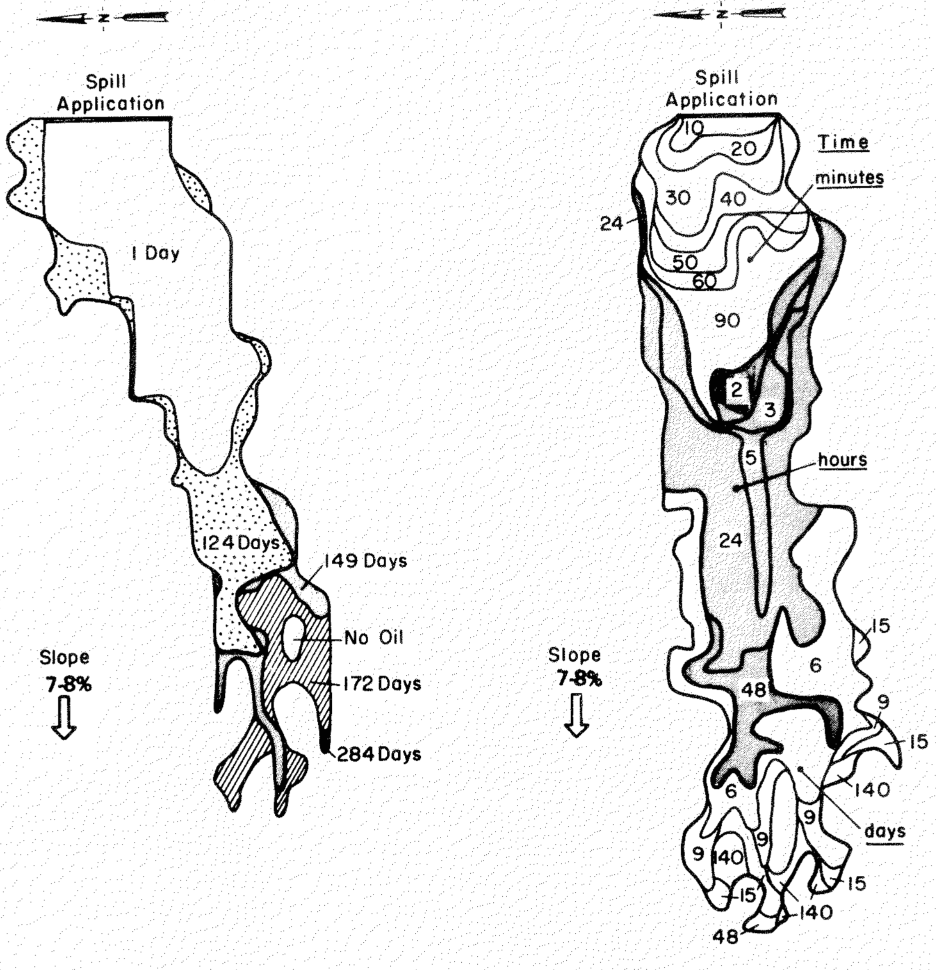

FIG. 3. Downslope movement of oil following winter spill (a, 26, Feb. 1976) and summer spill (b, 14, July, 1976).

oil only moved an additional 11.5 m downslope before winter freeze-up in October 1976. During the spring breakup 1977, little further movement of the oil was observed.

The total area affected by the summer spill was 303 m^2 or 40 m^2/m^3 of oil (25 l/m^2), more than one and a half times the area affected by the winter spill. These values compare favourably with the range of 20 to 100 m^2/m^3 of oil predicted by McKay *et al.* (1974). However, the subsurface flow found in the summer spill differs from that observed by McKay *et al.* (1974), where surface flow over saturated moss occurred. The differences observed are likely a result of lower moisture content in the moss and upper soil layers of this site. A relatively dry moss layer allowed the oil to penetrate quickly to the organic soil where downslope flow occurred. A very wet moss layer at the time of the spill might have caused the oil to float above rather than to penetrate the moss as was observed. Later, however, oil was seen to be wicked upwards into the overlying moss in the summer spill. Penetration of the crude oil in both the winter and summer spills was, for the most part, limited to the organic soil. Very small amounts penetrated to the mineral subsoil and no movement along the permafrost boundary was noted.

A possible cleanup strategy for actual winter spills is suggested by the observation of the test winter spill that oil movement ceased within a few hours and did not recur until warm weather arrived. Cleanup operations might be delayed for days or even weeks while preparations are made, provided the cleanup is completed before spring remobilization occurs. Reaction to a summer spill, however, must be much faster if one seeks to minimize the area of impact.

It is useful to compare the behavior of these controlled spills with two actual spills from the TAPS at Valve 7 (19 July 1977) and Steele Creek (15 Feb. 1978). At Valve 7 more than 300,000 l (80,000 gal) of crude oil were sprayed under high pressure as far as 1200 m downwind, but the oil concentrations were great enough to saturate the vegetation only within an area 230 m from the valve (Walker *et al.*, this volume). In contrast, at Steele Creek more than 1,900,000 l (500,000 gal) of crude oil sprayed down into the gravel workpad. Although some minor amounts sprayed into the air, most of the oil seemed to have flowed on the surface. Some of the oil flowed in the upper organic layers of the soil (similar to the CRREL winter spill) but large amounts flowed over the top of the snow surface. Evidently the oil, which had reached a temperature of only 10 °C (50 °F) in the pipe, cooled sufficiently before reaching the snow so that it could flow over it. Therefore the behavior of these actual spills seems to combine aspects of both the experimental spray conducted by Deneke *et al.* (1975) and experimental point spill studies reported here.

Effects on Permafrost

Very little modification to the permafrost has been noted in the experimental heated spills. The actual mass of oil, even at 57 °C, is so small compared with the underlying mass of permafrost as to be negligible. Some minor depressions were thawed into the permafrost where oil pooled or concentrated on the surface. Some of these pools remained throughout the summer in both spills, increasing solar input, due to the increased albedo, enough to warm the surface substantially above that of the control plot. This resulted in a higher heat flux into the permafrost, thawing small depressions in the top surface.

Compositional Changes

The Prudhoe Bay crude oil used in the study was characterized by a number of chemical methods in order to assess changes due to natural weathering on slope. These included fractionation with respect to major classes of components by silica gel-alumina column chromatography and further characterization of each fraction by methods such as gas chromatography and infrared spectroscopy. Table 2 summarizes some of the pertinent data obtained.

TABLE 2. Initial Characteristics of Prudhoe Bay Crude Oil Used in Study

Specific Gravity	0.89
% Sulfur	1.0%
% Volatiles (C_1-C_{15})	24%
Major Components of Residue (C_{15}-C_{40})	
Alkanes	33%
Aromatics	30%
Asphaltenes	22%
Soluble NSO	11%
Insoluble NSO	4%
Pristane/C_{17} Ratio	0.89
Phytane/C_{18} Ratio	0.77
pH	7.2
Alkane/Aromatic Ratio	1.1

The major processes thought to contribute to weathering of oil after spills are evaporation of volatiles, solubility and translocation of water-soluble components, and microbiological degradation. Of these, the loss of volatiles makes the largest initial impact. Samples of the original oil, oil from pools on slope and oily soil were analyzed by head space gas chromatography to characterize changes in the volatile fraction (C_1 through C_8). Changes in the presence of these components in the equilibrium headspace at a given temperature are a direct reflection of their change in concentration in the liquid (oil) phase. Results of these analyses are shown in Figure 4. These chromatograms, obtained for samples collected from a pool on the winter spill site, show a rapid loss of methane and ethane in the first few hours. Components in the C_3-C_8 range declined through the first day with a reduction by a factor of four in the first two months. Only small amounts of these components (C_3-C_8) were observable in the five-month sample. Volatile analysis of oily soils from the winter spill area demonstrated similar behavior, with losses from oil carried to the mineral soil being slowest of all. This retention of volatiles undoubtedly maintained a rather low viscosity in the oil resulting in substantial further remobilization of the oil downslope at spring breakup. These results, however, disagree with data obtained from experiments conducted in arctic tundra soils (Sexstone and Atlas, 1977) where loss of the volatile fraction ($<C_{10}$) was reported in the first 24 hours. These differences may be explained by differing methods of oil application or may be due to the

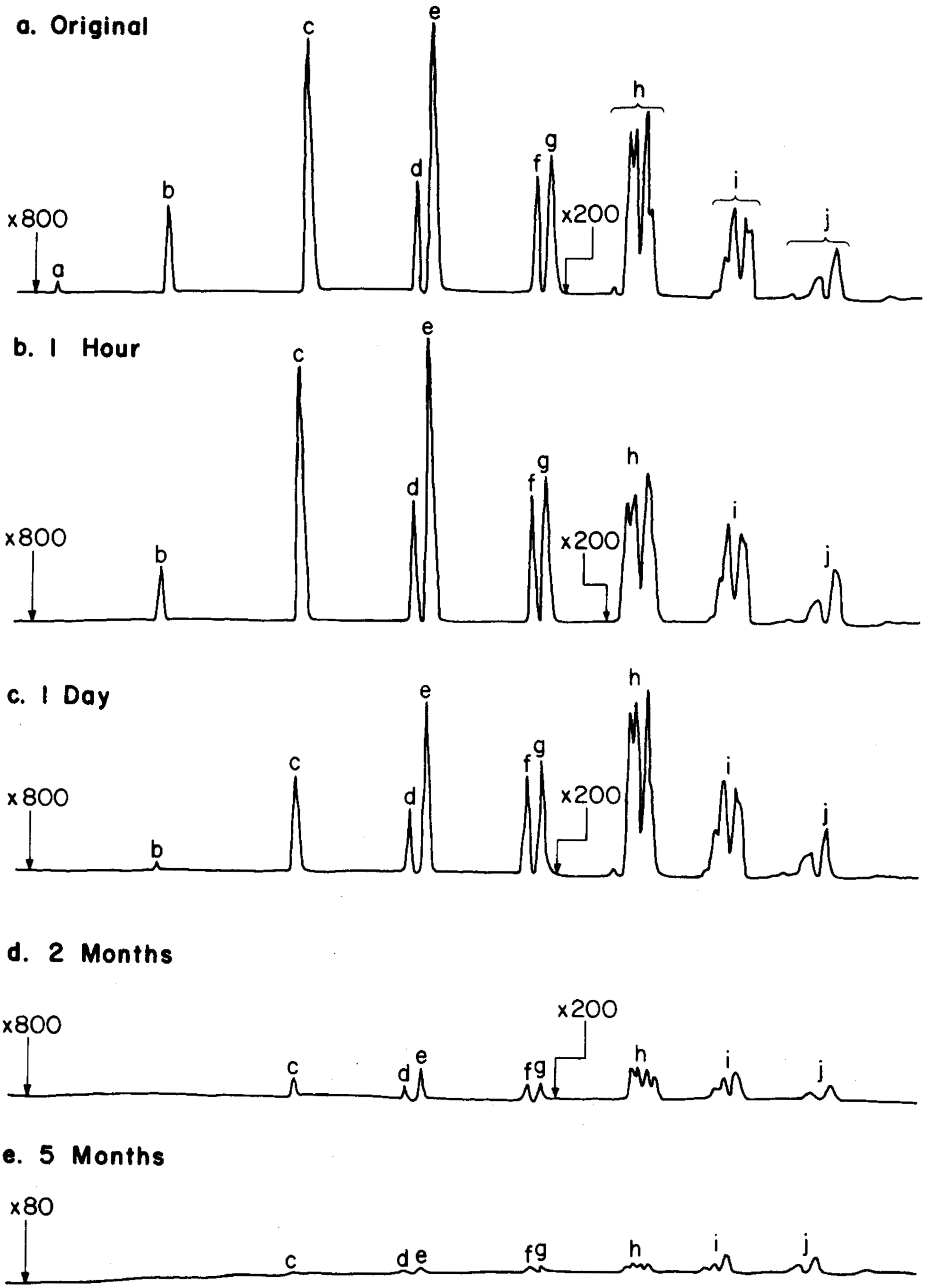

FIG. 4. Chromatograms of volatiles from pooled oil on winter spill site, 1976.

fact that the oil remained in the top 2 cm of the soil in their study. In their example, oil was applied evenly through a perforated plate, resulting in a thin film in more intimate contact with the atmosphere.

Behavior of the volatiles in the summer spill followed that found from the winter site. Samples from the organic soil did, however, retain a detectable volatile fraction even after the first winter.

Translocation of water-soluble material from the spill areas downslope with runoff is undoubtedly occurring to some extent. Attempts at measuring the relative importance of this mechanism were unsuccessful. Water samples collected at locations just downslope of visible oil movement were analyzed by a simplified stripping method based on that used by MacKay *et al.* (1974). In no case were detectable quantities ($>10^{-9}$ g/ml) of individual components found. An attempt at utilizing total organic carbon analysis to look at the total material was also unsuccessful due to large concentrations ($>$ 50 ppm) of organic carbon in natural soil solution in this region.

In general the most water-soluble components of the oil are also the most volatile. The loss rate of equally volatile substances which differ widely in solubility can be used to qualitatively assess the importance of this mechanism relative to volatilization. Losses of two very soluble components of the oil, benzene and toluene, were found to be similar to the losses of alkanes of equal volatility but much lower solubility. Thus the contribution of solubility is less significant than volatilization at least for the lower molecular weight fraction. Results obtained from silica gel-alumina chromatography (to be presented later) indicate that compositional changes of relatively water-soluble material vs. highly insoluble material, in the high molecular weight fractions, is insignificant. This result agrees with that obtained by Raymond *et al.* (1976) in a study in a more temperate climate where no loss of material was observed via runoff or leachate in oiled field plots. It also agrees with results obtained for spills directly onto freshwater (Phillips and Groseva, 1977) and salt water (McAuliffe, 1977) where evaporation was shown to be the predominant process for changes in oil composition after spills.

Several types of microbial organisms, including bacteria, actinomycetes, yeasts and fungi, have been shown to be capable of degrading many of the organic components of crude oils (Davis, 1967). Populations of various organisms and their levels of activity after the spills are reported in a companion study (Sparrow *et al.*, This volume). Compositional changes in the oil due to their activity, however, were investigated as a part of this work.

The method chosen to investigate these changes was fractionation using silica gel-alumina column chromatography. This procedure sub-divides the residue obtained by chloroform extraction of the oily soils into its major organic components: alkanes, aromatics, asphaltenes and NSO's. From laboratory studies (Bailey *et al.*, 1973; Jobson *et al.*, 1972), these individual fractions have been shown to degrade at different rates due to preferential utilization of the alkane fraction by micro-organisms.

Within the alkane fraction, other studies (Kator *et al.*, 1971) have indicated a preferential degradation of straight chain vs. branched chain components. A second method based upon gas chromatographic analysis of the alkane fraction was designed to follow the ratio of straight chain to branched chain material. Results of both of these methods are given in Table 3. Clearly these results show little compositional change in the oil with time in either the summer or winter spills. Results obtained from both the fractionation experiment and analysis of straight chain vs. branched chain alkanes were confirmed by infrared spectroscopy. Thus it appears that microbial degradation is having only a minimal effect on the composition of the residual oil.

TABLE 3. Alkane/Aromatic and Pristane/m-C_{17} Ratios* for Topped Soil Extracts

Sampling Date			Sample			
	Winter Mineral Soil		Winter Organic Soil		Winter Moss	
	a	b	a	b	a	b
7/15/76	1.0	0.81	1.1	0.84	1.2	0.81
9/17/76	1.2	0.82	1.1	0.84	1.2	0.88
3/29/77	—	—	1.0	0.82	1.2	0.85
4/5/77	1.5	0.88	1.2	0.87	1.2	0.88
7/13/77	1.0	0.84	1.2	0.86	1.0	0.90
8/1/77	1.2	0.84	1.1	0.87	—	—
	Summer Mineral Soil		Summer Organic Soil		Summer Moss	
	a	b	a	b	a	b
7/15/76	1.0	0.87	1.0	0.87	1.0	0.82
9/17/76	1.1	0.84	1.0	0.86	1.1	0.88
3/29/77	—	—	1.3	0.82	0.9	0.82
4/5/77	1.0	0.80	1.1	0.83	—	—
7/13/77	0.9	0.79	1.0	0.84	1.0	0.90
8/1/77	0.8	0.93	1.1	0.85	—	—

*Original Topped Prudhoe Bay Oil had ratios of 1:1 for Aklane/Aromatic and 0.89 for Pristane/m-C_{17}.

a Alkane/Aromatic ratio

b Pristane/m-C_{17} ratio

Some recent evidence from field studies (Raymond *et al.*, 1976; Horowitz and Atlas, 1977) indicates that microbiological degradation is less preferential in field conditions than formerly believed. Thus alkanes and aromatics could be degrading at similar rates. It is not possible to evaluate quantitative changes in total oil presence on slope with time in a large field experiment. However, the lack of new functionality appearing in the infrared spectra does not support significant non-preferential degradation.

These results suggest that the crude oil will remain fairly well intact for long periods if no measures to increase degradation, such as fertilization, are employed. Even so, it is hard to imagine that the large amounts of oil present in the subsurface organic soil could be easily degraded even with fertilization since inadequate aeration may well limit the process.

Oil Effects on Vegetation

The detailed results of the pre-spill vegetation analyses are given in Table 4. One can readily notice the close similarity of species composition in the three areas.

Following application of the oil, vegetation damage was assessed visually via changes in leaf color and leaf fall. There were three main time frames for injuries: 1) immediate; 2) occurring during the initial growing season; and 3) cumulative, occurring after the initial growing season.

TABLE 4. Results of Pre-spill Vegetation Analysis

Species	Frequency of Occurrence (%)		
	Winter	Summer	Control
Trees			
Picea mariana	80	75	60
Medium and low shrubs			
Betula glandulosa	90	92	60
Ledum decumbens	70	92	0
Ledum groenlandicum	80	92	100
Vaccinium uliginosum	100	100	100
Vaccinium vitis-idaea L.	100	100	100
Dwarf shrubs and herbs			
Rubus chamaemorus L.	70	100	100
Equisetum sylvaticum L.	80	50	40
Petasites hyperboreus Rydb.	30	0	100
Eriophorum vaginatum	100	100	60
Graminae	0	8	40
Mosses			
Total	100	100	100
Pleurozium schreberi (Brid.) Mitt.	100	100	100
Polytrichum spp.	100	83	100
Dicranum spp.	80	83	80
Sphagnum spp.	40	100	40
Other	10	0	0
Lichens			
Total	100	100	100
Foliose	100	83	100
Fruticose	100	100	100
Cladonia spp.	100	100	100
Cetraria spp.	100	92	100
Peltigera spp.	100	67	100
Mushrooms	10	0	0

Virtually all aboveground foliage that came into contact with the oil was quickly killed. Turgidity was immediately reduced and foliage appeared dead within several days. In the winter spill the foliage was dead when it was first observed in mid-May after snowmelt. Evergreens such as cranberry retained the damaged foliage longer than deciduous species such as birch. The zone of

FIG. 5. Cottongrass tussock growing on winter spill plot despite surrounding oil.

contact was generally limited to the immediate areas below the 5-m wide oil feeder and to areas of low relief in the path of aboveground flowing oil. Lichens and mosses, which tend to be concentrated in low areas and have a low-growth form, suffered particularly heavy mortality. In contrast, cottongrass tussocks with a raised, upright growth form and species growing on areas of higher relief kept most of their aboveground biomass above the oil. These species continued to grow and flower, at least initially, despite their being surrounded by oil (Fig. 5).

Since oil flowed into depressions and low areas, aboveground vegetation on higher relief was not in physical contact with the oil. Belowground contact was difficult to accurately ascertain since the nature of the study would not permit large-scale destructive sampling of roots and soil. An estimate of belowground flow was made with the system of dowels described previously, but the depth and extent of root systems were unknown. Therefore, damage due to root contact could only be inferred.

Damage during the first growing season varied with such factors as species, position on slope, growth form, and season of spill. In general, delayed injuries first appeared on foliage that was above the path of the oil and near the top of the plot. Injuries subsequently appeared farther downslope and in areas of subsurface flow immediately adjacent to surface oil. Deciduous leaves turned brown and abscised prior to evergreen leaves. For example, in the summer spill, resin birch foliage turned brown 5 m downslope two weeks after the spill, but did not turn brown at 10 m until four weeks after the spill. In contrast, Labrador tea and cranberry leaves had only turned partially brown 10 m downslope at the end of the growing season (six weeks). Black spruce had some of the most delayed damage of any species. Although spruce in the upper 2 m of the winter spill began dropping needles by mid-June, the needles had not entirely dropped until September. On the summer spill the needles turned brown on several spruce and many had chlorotic foliage by September. Most needles remained on the trees at that time.

The nutrient analysis of black spruce foliage indicated a significant decrease in the total nitrogen content of the new foliage of trees exposed to oil (Table 5). Total phosphorus and total potassium did not show consistent changes. Although there was significant year-to-year variability in total nitrogen, the magnitude of the nitrogen decrease on the oiled plots was great enough to be statistically significant at the 5% level when compared with either the control plot during the same year or with the same plot from the previous year when it was unoiled. The decrease in nitrogen content may be due either to disruption of the metabolism of root nutrient uptake or to a coating of the roots by a hydrophobic layer of oil which physically interfered with nitrogen uptake.

Cumulative injuries were largely limited to evergreen species. During the second growing season increasing amounts of black spruce foliage became chlorotic, turned brown, and abscised. Similarly, foliage of cranberry and Labrador tea continued to turn red and then brown throughout the second growing season so that some injuries were apparent as far downslope as 25 m on the winter spill and 35 m on the summer spill. Cumulative injuries could be due to a combination of direct oil-caused stress and problems of overwintering. This mechanism has also been suggested by other studies (McCown *et al.*, 1973; Linkins and Antibus, this volume).

TABLE 5. Nutrient content of black spruce foliage

Year	Treatment	Avg/Std. Error %N*	Avg/Std. Error %P*	Avg/Std. Error %K*
1975	Control	0.91 (.03) a	0.07 (.01) a	0.56 (.04) a
(unoiled)	Summer	0.90 (.02) a	0.08 (.01) a	0.54 (.01) a
	Winter	0.94 (.03) a	0.09 (.00) a	0.57 (.01) a
1976	Control	1.05 (.04) a	0.11 (.00) a	0.35 (.00) a
(oiled)	Summer	0.75 (.06) b	0.10 (.01) a	0.32 (.01) b
	Winter	0.86 (.02) b	0.10 (.00) a	0.37 (.00) a

* Figures with a common letter are not significantly different at the 5% level using the t-test. Comparisons are made within years and within columns.

In summary, damage appeared more rapidly and was more extensive on the summer spill. This could have been due to the more rapid flow downslope, the oil remaining hotter for a longer period, or the greater area affected by the oil. In addition, actively growing vegetation was subjected to a higher volatile contact on the summer spill since the vegetation was dormant at the time of the winter spill. Many of the volatile components were lost prior to the start of the growing season on the winter plot (Fig. 4). On both plots deciduous species showed a more rapid browning of foliage, with resin birch being the most susceptible. Blueberry and cloudberry were more delayed. Evergreen species continued to exhibit new injury symptoms throughout the second growing season. Foliage of Labrador tea and cranberry was still alive in the second season in areas where all deciduous foliage was dead. Finally, especially during the second growing season, some foliage of species outside the areas of surface flows turned brown and dehisced.

An important characterstic of both spills is that no regrowth has been seen on any species which lost its foliage as a result of oil damage. This result is in direct contrast to other reported studies (Hutchinson and Freedman, 1975; Wein and Bliss, 1973) and probably is the result of root damage as pointed out by McCown *et al.* (1973).

No regrowth or invasion by new individuals has occurred within areas of surface flow. Observations of an earlier (1971) CRREL crude oil spill at Glen Creek, Alaska, showed a similar situation except that feather mosses had begun to encroach upon part of the surface flow area after six growing seasons. However, the Glen Creek site was considerably wetter than the Poker Creek site.

Root respiration was reduced at all oiled sites, with the summer spill showing the greatest decrease (65%; Table 6). Studies on respiration quotients (RQ), although limited, suggest that these RQ values were raised by exposure to the crude oil in this study in contrast to arctic studies which showed decreased RQ's (Linkins and Antibus, this volume).

TABLE 6. Respiration of Ectotrophic Mycorrhizal Feeder Roots. Data for 0^2 and CO^2 given as the mean of three experiments in μl gas/hr. g dry wt. RQ = Respiratory Quotient (from A. E. Linkins, VPI)

	Control
O_2	219
CO_2	155
RQ	0.71
	Summer (6 m downslope)
O_2	77 (65% decrease)
CO_2	63
RQ	0.81
	Summer (21 m downslope)
O_2	163 (26% decrease)
CO_2	111
RQ	0.68
	Winter (6 m downslope)
O_2	152 (31% decrease)
CO_2	154
RQ	1.02

The results of the vegetation study are consistent with the physical and chemical changes of the oil. It is possible that, although many of the toxic components of the oil were rapidly lost, some remained within the soil. These could account for the delayed, progressive injuries observed during the second growing season. The mechanism of injury would probably be due to disruption of root functions. This type of injury could continue to increase for at least three years following a spill and possibly longer (Freedman and Hutchinson, 1976).

Both the nature of injury and the lack of vegetative recovery have important implications for restoration following oil spills. The lack of reinvasion by seedlings may be due to the hydrophobic surface of the oil-soaked moss layer (Deneke *et al.*, 1975; McGill, 1977). However, even if the hydrophobic surface were disrupted to allow for germination as suggested by McGill (1977) the problem of toxic components of oil within the soil might persist for a number of years. In addition, restorative measures which disrupt the surface organic mat on a permanent site pose a threat to the thermal stability of the area.

CONCLUSIONS

The physical, chemical, and biological effects of large, hot crude oil spills in winter and summer upon a black spruce site have been followed for two years. The major conclusions are given below.

1. In both the winter and summer spills, oil flowed downslope following the microtopography for distances of 35 and 41.5 m, respectively. Movement was more rapid in the summer. In the winter spill, oil moved beneath the surface of the snow and within the moss layer. Movement during the summer spill was primarily below the moss in the organic soil.
2. The total area affected by the summer spill was nearly one and a half times as large as the winter spill (303 m^2 vs. 185 m^2).
3. The effect of the spills upon the underlying permafrost has been minimal up to this time.
4. Compositional changes in the oil after the spill have been primarily a result of volatilization. Little change in composition has been noted that can be definitively attributed to microbiological activity.
5. Vegetation mortality was virtually complete within areas of surface flows. Damage to vegetation overlying subsurface flows was more delayed and less extensive.
6. In general, deciduous species showed the most rapid injury. Evergreen species displayed more delayed symptoms. Injuries have continued to appear up to the present. There is no evidence of recovery by vegetation in areas of surface flows.

The study on the fate and effects of the crude oil will continue through the 1978 growing season. Continued observations of the thermal regime, chemical changes in oil composition, and vegetation injury and recovery will be made. At the end of the 1978 growing season, relative growth rates of oil-affected vs.

control vegetation will be determined and the vegetation analysis of the permanent plots will be repeated.

ACKNOWLEDGEMENTS

We wish to thank Dr. Frederick Deneke, U.S. Forest Service, and Dr. Brent McCown, University of Wisconsin, for assistance in the vegetation portion of the study and Dr. Arthur Linkins, Virginia Polytechnic Institute, for providing information on root respiration. Dr. Charles Slaughter, U.S. Forest Service, is acknowledged for his contributions during the first year of the study in site selection and initial research. Mr. Larry Dietrick, Alaska Department of Environmental Conservation, supplied information on the TAPS oil spills. In addition, we gratefully acknowledge the contribution of Ms. Ellen Foley in preparation of the manuscript and technical assistance in chemical analysis.

This work was supported by the Arctic Environmental Research Laboratory, Environmental Protection Agency, Fairbanks, Alaska, Dr. Frederick Lotspiech and Ms. Charlotte Davenport, project monitors.

REFERENCES

ATLAS, R. M. 1977. Stimulated petroleum biodegradation. *CRC Critical Reviews in Microbiology*. 6, (3): 371-386.

BAILEY, N. J. L., A. M. JOBSON and M. A. ROGERS. 1973. Bacterial degradation of crude oil: Comparison of field and experimental data. *Chemical Geology*. 11:203-211.

COOK, F. D. and D. W. S. WESTLAKE. 1974. Microbiological degradation of northern crude oils. Environmental-Social Committee, Northern Pipelines, Task Force on Northern Oil Development. Report No. 74-1. *Information Canada*, Cat. No. R72-12774. Vancouver, B.C., Canada.

CRUM, H. A., W. C. STEERE and L. E. ANDERSON. 1973. A new list of mosses of North America north of Mexico. *Bryologist*. 76:85-130.

DAVIS, J. B. 1967. *Petroleum Microbiology*. Elsevier Publishing Company, Amsterdam.

DENEKE, F. J., B. H. McCOWN, P. I. COYNE, W. RICKARD and J. BROWN. 1975. Biological aspects of terrestrial oil spills — USACRREL oil research in Alaska 1970-1974. Hanover, New Hampshire: *U.S. Army Cold Regions Research and Engineering Laboratory*. Research Report 346.

FREEDMAN, W. and T. C. HUTCHINSON. 1976. Physical and biological effects of experimental crude oil spills on low arctic tundra in the vicinity of Tuktoyaktuk, NWT, Canada. *Canadian Journal of Botany*. 54:2219-2230.

HALE, M. E., Jr. and W. L. CULBERSON. 1966. A third checklist of the lichens of the continental United States and Canada. *Bryologist*. 69:141-182.

HOROWITZ, A. and R. M. ATLAS. 1977. Continuous open flow-through system as a model for oil degradation in the Arctic Ocean. *Applied and Environmental Microbiology*. 33:647-653.

HULTÉN, E. 1968. *Flora of Alaska and neighbouring territories*. Stanford, California; Stanford University Press, 1008 p.

HUNT, P. G. 1972. The microbiology of terrestrial crude oil degradation. Hanover, New Hampshire: *U.S. Army Cold Regions Research and Engineering Laboratory*, Special Report 168.

HUNT, P. G., W. E. RICKARD, F. J. DENEKE, F. R. KOUTZ and R. P. MURRMANN. 1973. Biological effects — Terrestrial oil spills in Alaska: Environmental effects and recovery. *Reprint* from "Proceedings of Joint Conference on Prevention and Control of Oil Spills, March 13-15, 1973, Washington, D.C." (available) Hanover, New Hampshire: *U.S. Army Cold Regions Research and Engineering Laboratory*.

HUTCHINSON, T. C. and W. FREEDMAN. 1975. The impact of crude oil spills on arctic and subarctic vegetation. *In Proceedings of the Circumpolar Conference on Northern Ecology, September 15-18*. Ottawa. 1:175-182.

HUTCHINSON, T. C., J. HELLEBUST and M. TELFORD. 1974. Oil spill effects on vegetation and soil microfauna at Norman Wells and Tuktoyaktuk, N.W.T. Environmental-Social Committee, Northern Pipelines, Task Force on Northern Oil Development. Report No. 74-14. *Information Canada*, Cat. No. R57-10/1974, Vancouver, B.C., Canada.

JOBSON, A., F. D. COOK and D. W. S. WESTLAKE. 1972. Microbial utilization of crude oil. *Applied Microbiology.* 23:1082-1089.

KATOR, H., C. H. OPPENHEIMER and R. J. MIGET. 1971. Microbial degradation of a Louisiana crude oil in closed flasks and under simulated field conditions. *Proceedings of the Joint Conference on Prevention and Control of Oil Spills, American Petroleum Institute.* Washington, D.C., p. 287-296.

LEHTOMÄKI, M. and S. NIEMELÄ. 1975. Improving microbial degradation of oil in soil. *AMBIO.* 4 (3):126-130.

LINKINS, A. E. and R. K. ANTIBUS. 1978. Impact of surface applied oil on mycorrhizal respiration and cold hardiness. *Arctic* (this volume).

MacKAY, D., M. E. CHARLES, C. R. PHILLIPS. 1974. Physical aspects of crude oil spills on northern terrain (second report). Environmental-Social Committee, Northern Pipelines, Task Force on Northern Oil Development. Report No. 74-25. *Information Canada,* Cat. No. R-57-34/1974. Vancouver, B.C., Canada.

McAULIFFE, C. D. 1971. GC determination of solutes by multiple phase equilibrium. *Chemical Technology.* 1:46-51.

McAULIFFE, C. D. 1977. Evaporation and solution of C_2 to C_{10} hydrocarbons from crude oils on the sea surface. In: Wolfe, D. A. (ed.), *"Fate and Effects of Petroleum Hydrocarbons in Marine Organisms and Ecosystems."* Elmsford, New York; Pergamon Press, p. 363-371.

McCOWN, B. H., F. J. DENEKE, W. E. RICKARD, L. L. TIESZEN. 1973. The response of Alaskan terrestrial plant communities to the presence of petroleum. *In* Proceedings, Symposium on the Impact of Oil Resource Development on Northern Plant Communities. *Occasional Publication on Northern Life No. 1., Univ. of Alaska.* p. 44-51.

McFADDEN, T., T. JENKINS, C. COLLINS, L. JOHNSON, B. McCOWN, and E. SPARROW. 1977. Fate and effects of crude oil spilled on permafrost terrain. Hanover, New Hampshire: *U.S. Army Cold Regions Research and Engineering Laboratory.* Special Report 77-44.

McGILL, W. B. 1977. Soil restoration following oil spills — a review. *Journal of Canadian Petroleum Technology.* April-June 1977, p. 60-67.

OHMANN, L. F. and R. R. REAM. 1971. Wilderness ecology: A method of sampling and summarizing data for plant community classification. *U.S. Forest Service Research Paper NC-49,* 14 p.

PARKINSON, D. 1974. Effects of oil spillage in northern Canadian soils. Environmental-Social Committee, Northern Pipelines, Task Force on Northern Oil Development. Report No. 74-2. *Information Canada,* Cat. No. R72-12874. Vancouver, B.C., Canada.

PHILLIPS, C. R. and V. M. GROSEVA. 1977. The spreading of crude oil spills across a lake. *Water, Air and Soil Pollution.* 8:353-360.

RAYMOND, R. L., J. O. HUDSON and V. W. JAMISON. 1976. Oil degradation in soil. *Applied and Environmental Microbiology.* 31:522-535.

RICKARD, W. E. and F. DENEKE. 1972. Preliminary investigations of petroleum spillage, Haines-Fairbanks military pipeline, Alaska, Hanover, New Hampshire: *U.S. Army Cold Regions Research and Engineering Laboratory,* Special Report 170.

RIEGER, S., C. E. FURBUSH, D. B. SCHOEPHORSTER, H. SUMMERFIELD, Jr., and L. C. GEIGER. 1972. Soils of the Caribou-Poker Creeks Research Watershed, interior Alaska. Hanover, New Hampshire: *U.S. Army Cold Regions Research and Engineering Laboratory.* Technical Report 236.

SEXSTONE, A. and R. M. ATLAS. 1977. Mobility and biodegradability of crude oil in arctic tundra soils. In: *"Development in Industrial Microbiology"*, Vol. 18, Chapter 59. Monticello. New York: Lubrecht and Cramer.

SPARROW, E. B., C. V. DAVENPORT and R. C. GORDON. 1978. Response of microorganisms to hot crude oil on a subarctic taiga soil. *Arctic* (this volume).

TROTH, J. L., F. J. DENEKE and L. M. BROWN. 1975. Subarctic plant communities and associated litter and soil profiles in the Caribou Creek Research Watershed, interior Alaska. Hanover, New Hampshire: *U.S. Army Cold Regions Research and Engineering Laboratory.* Research Report 330.

VIERECK, L. A. and LITTLE, E. L., JR. 1972. Alaska trees and shrubs. U.S. Department of Agriculture, Forest Service. *Agriculture Handbook* No. 410, 165p.

WALKER, S., EVERETT, K. and WEBER, P. 1978. Sensitivity of vegetation to oil spills on the Arctic Coastal Plain of Alaska. *Arctic* (this volume).

WEIN, R. W. and BLISS, L. C. 1973. Experimental crude oil spills on arctic plant communities. *Journal of Applied Ecology.* 10: 671-682.