

Movement of Crude Oil in an Experimental Spill on the SEEDS Simulated Pipeline Right-of-way, Fort Norman, N.W.T.

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ABSTRACT. The Studies of the Environmental Effects of Disturbances in the Subarctic (SEEDS) experimental spill was conducted on a simulated pipeline right-of-way and trench. A total of 3273 L of Norman Wells crude oil was released over a 24 h period at a depth of 100 cm in a simulation of a rupture from a subsurface pipeline. Absorptive qualities of the surface vegetation and organic soil layers in an undisturbed forest produce rates of flow and area of contamination values much lower than the SEEDS experiment. Furthermore, the area of contamination (672.75 m²) was greater than experiments in which the amount of oil and rates of pumping were larger. This resulted from the presence of surface water, a depressed mineral soil-dominated simulated pipeline trench, a cleared right-of-way and slow pumping rates. The SEEDS experiment was a more valid analogue of crude-oil spills associated with a buried pipeline in a subarctic environment.

Key words: oil spill, crude oil, hydrocarbon spill, pipeline, Subarctic, corridor, disturbance

RÉSUMÉ. Le déversement expérimental réalisé dans le cadre de l'étude SEEDS (Studies of the Environmental Effects of Disturbances in the Subarctic) a eu lieu sur le trajet et la tranchée simulés d'un oléoduc. Une quantité de 3273 litres de pétrole brut de Norman Wells a été déversée au cours d'une période de 24 h à une profondeur de 100 cm, pour simuler la rupture d'un oléoduc souterrain. Les qualités absorbantes de la végétation de surface et des couches de sol organique dans une forêt non perturbée, ont donné des taux d'écoulement et des valeurs de contamination de la surface beaucoup plus bas que dans l'expérience SEEDS. De plus, la zone contaminée (672,75 m²) était plus grande que celle où avaient été effectués des déversements expérimentaux dans lesquels la quantité de pétrole et les taux de pompage étaient plus importants. Cela était dû à la présence d'eau de surface, au fait que la tranchée simulée de l'oléoduc était dans une dépression et contenait un sol riche en minéraux, au fait que le passage avait été débroussaillé et que les taux de pompage étaient bas. L'expérience SEEDS était une reproduction plus valide des déversements de pétrole brut associés à un oléoduc enfoui dans le sol dans un environnement subarctique.

Mots clés: déversements de pétrole, pétrole brut, déversements d'hydrocarbure, oléoduc, subarctique, tranchée simulée, perturbation

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INTRODUCTION

The subsurface mode of the Norman Wells–Zama Lake pipeline (the Norman Wells Project) may well be selected for additional mainland crude-oil pipelines from the Beaufort Sea or Arctic Islands. If there were a rupture of a buried pipeline, then crude-oil spills would occur into the active layer and eventually migrate upward onto the pipeline right-of-way. Studies of simulated, thaw-season crude-oil spills in arctic and subarctic environments have been limited primarily to those occurring onto the soil surface in undisturbed forests (Wein and Bliss, 1973; Charles and Mackay, 1974; Mackay *et al.*, 1974; Jenkins *et al.*, 1978; Westlake *et al.*, 1978; Hutchinson, 1980; Collins, 1983). Two methods of oil application have been used: the spraying of a uniform coating on the vegetation and soils (Wein and Bliss, 1973; Hutchinson *et al.*, 1974; Walker *et al.*, 1978), and localized point spills pumped directly onto the surface (Hutchinson and Freedman, 1975; Jenkins *et al.*, 1978). It has been recognized that surface applications by spraying do not closely simulate an oil spill from a pipeline break in terms of intensity, movement of oil or vegetation contamination (Hutchinson and Freedman, 1978; Kershaw and Kershaw, 1986). Although surface point spills more closely simulate an aboveground pipeline failure, they may not provide a valid analogue for a subsurface spill where subsequent spread of oil within the soil may give rise to different impacts. Furthermore, current subsurface line construction practices result in the disruption of the surface organic layer and exposure of the mineral-dominated soil component (Wishart, 1988). In subarctic areas with permafrost, this surface disturbance combined with the effects of right-of-way clearing results in surface subsidence due to

thickening of the active layer and a loss of near-surface ground ice (Viereck, 1982; Evans *et al.*, 1988).

Point-origin experimental surface spills have been conducted in permafrost-affected areas with a tree cover and understory vegetation intact (Charles and Mackay, 1974; Mackay *et al.*, 1975; Johnson *et al.*, 1980). Subsurface spreading of oil, as a result of downward percolation, resulted in a more extensive area affected (Mackay *et al.*, 1974; Jenkins *et al.*, 1978; Collins, 1983). Mackay and others (1974) found that oil in the moss layer was only visible in areas where it was flowing too fast for the capacity of the moss layer to absorb it. They further concluded that oil, following a surface spill, drains from the moss and the visible spill area becomes approximately half the size of the total contamination zone.

OBJECTIVES

The main objective of this study was to determine how oil would behave under conditions that would prevail during a small subsurface crude-oil spill from a buried pipe within a transport corridor in permafrost-affected terrain.

LOCATION

The experiment was initiated at the Studies of the Environmental Effects of Disturbances in the Subarctic (SEEDS) site, 10 km north of Fort Norman, Northwest Territories (Fig. 1). The experimental area was in a decadent *Picea mariana* stand at least 280 years old. Permafrost underlies the site and a number of simulated transport corridor disturbances have been under investigation since their creation in 1985 (Evans *et al.*, 1988; Kershaw, 1988; Gallinger and Kershaw, 1989).

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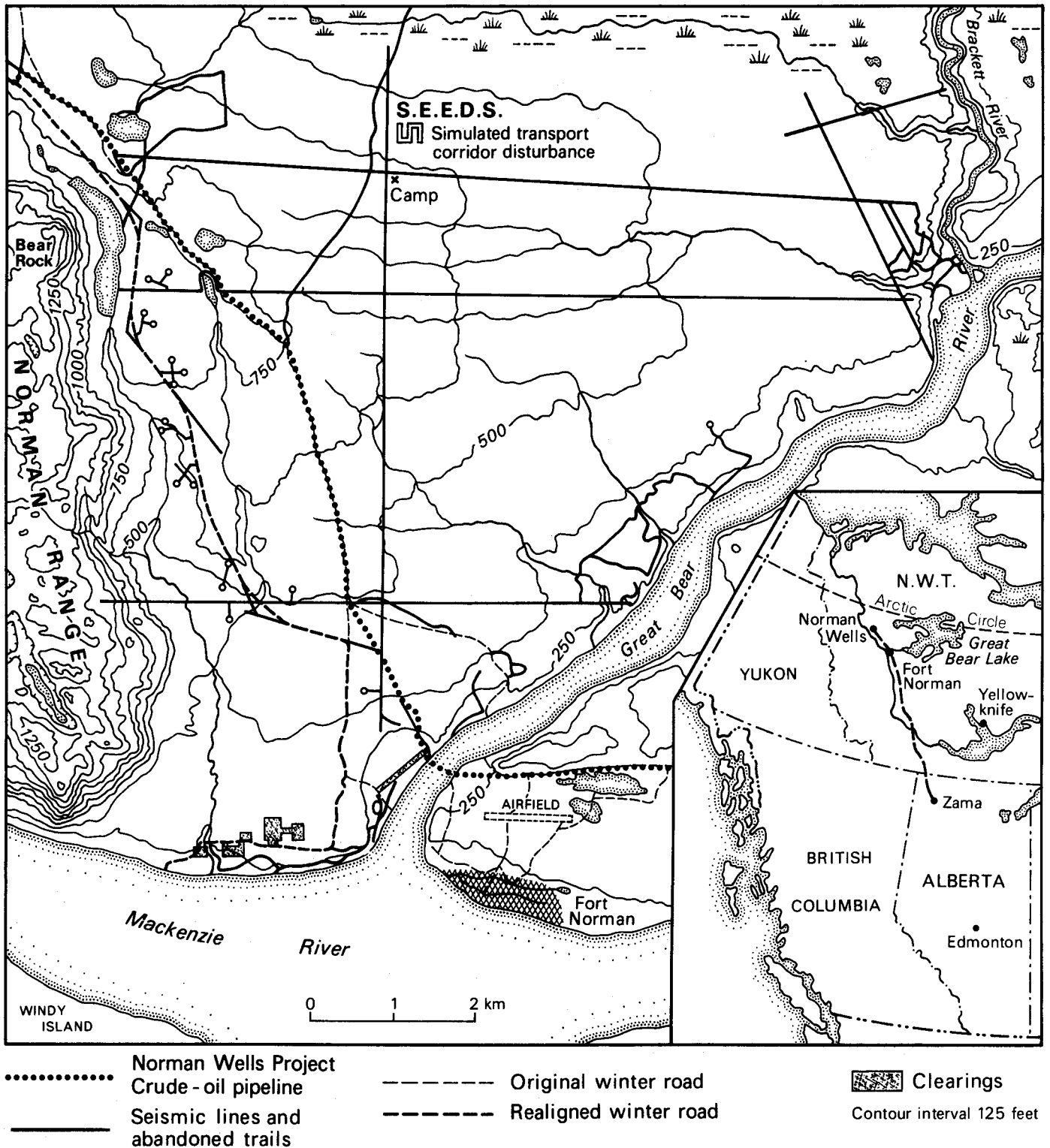


FIG. 1. The SEEDS simulated transport/pipeline corridor is 10 km north of Fort Norman, N.W.T., on a NNE-facing slope of 1.5° in an upland *Picea mariana*-dominated forest.

METHODS

Spill Initiation

An elevated catwalk network (total length of approximately 310 m in September 1988 and extended to 535 m in June 1989) was installed on the site of the spill to ensure

unimpeded access and a minimum of trampling disturbance during the life of the experiment (Fig. 2). Over a period of 24 h, 3.27 m³ (3273 L, or 20 imperial barrels) of Norman Wells crude oil was pumped directly into an open-ended, 100 cm long segment of a 30.5 cm diameter pipe (Table 1) buried at a depth of 100 cm in an existing simulated pipeline trench. The

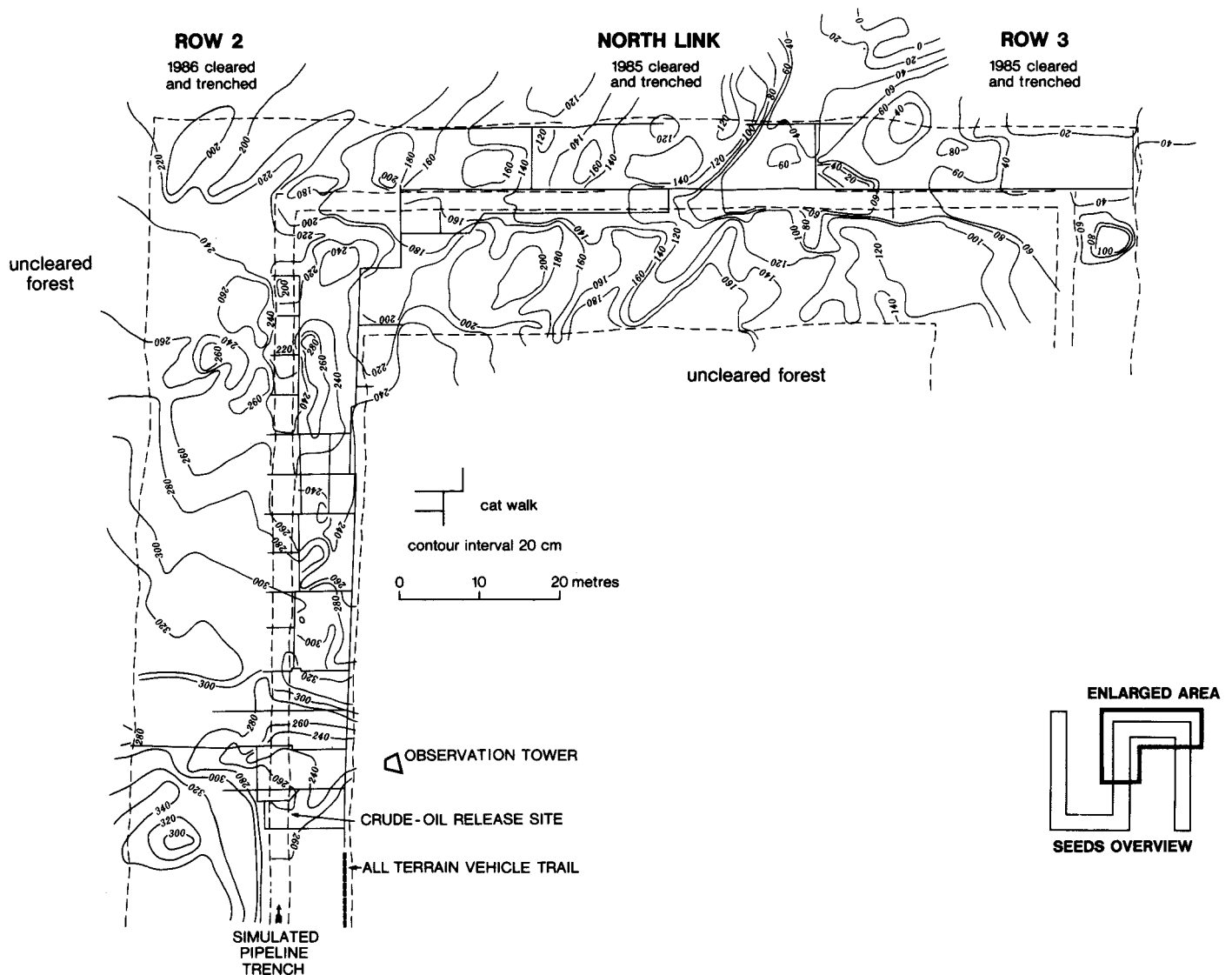


FIG. 2. The site of the experiment was a cleared right-of-way (ROW) with north-south and east-west oriented trenched portions. A catwalk was installed to reduce disturbance due to monitoring activities.

trench was 2 m wide and extended the length of the cleared right-of-way, 14 to 16 m from one side and 9 m from the other. This portion of the simulated pipeline right-of-way extends down the 1–2° slope for approximately 90 m, then turns at 90° and runs across the slope for 100 m (Fig. 2). The pump employed to extract and move the oil from the barrels was a Honda G200 Oil Alert with a Honda Trash Pump WT20 jacket attached to 5 cm diameter hoses. Oil was allowed to escape from the buried pipe commencing at 15:00 h on 28 August 1988 (Table 1).

Consequently, unlike previously reported experiments (Charles and Mackay, 1974; Mackay *et al.*, 1975; Johnson *et al.*, 1980): 1) The oil was slowly released — 136.4 L·h⁻¹ (simulating a leak at a level below detection on modern pipelines). 2) The release point was 70 cm below the moss surface on the adjacent right-of-way within the mineral-dominated active layer (simulating a break in a buried pipeline). 3) The point of release was within a linear, mineral soil-dominated depression (such as would occur in association with a buried pipeline). 4) The simulated pipeline trench was within a cleared right-of-way (similar to an operating pipeline right-of-way at

least two years following construction). 5) The right-of-way location was selected to have sections parallel and normal to the general slope trend. (As with typical northern transport corridors, surface runoff could be trapped and channelled along the depressed simulated pipeline trench.)

Spill Morphology

The three-dimensional geometry of the spill was monitored using a coring and dowel/lath system adapted from Jenkins *et al.* (1978). A sampling grid was established at the time of the surface spill with 1 m cells in a 50 x 17 m plot (encompassing the area downslope and 5 m above the point of the spill). However, shortly after the commencement of the pumping operation it was apparent that the area of the spill was going to be larger than expected. Accordingly, a new grid varying from 1 x 1 m to 5 x 5 m cells (depending on the topography and the presence of oil) was installed (Fig. 2). During the 1989 field season grid points were determined for the perimeter of the spill. These points provided permanent survey markers for monitoring the oil's movement. Wooden laths were inserted at known points to the maximum thaw

TABLE 1. Quantities and rates of flow of an experimental crude-oil spill, SEEDS, Fort Norman, N.W.T.

Date & time (hhmm)	Quantity (L)	Area of spill (m ²)	Cumulative area of spill (m ²)	Average concentration of spill (L·m ⁻²)	Hours since initiation (h)	Increment increase of spill (m ² ·h ⁻¹)	Concentration change (L·m ⁻² ·h ⁻¹)	Increment in concentration change (L·m ⁻² ·h ⁻¹)
1988								
28 Aug 1530	164	33.5	33.5	4.9	2.50	13.4	1.96	1.96
28 Aug 2130	818	41.75	75.25	10.87	8.50	6.96	1.28	1.81
29 Aug 0900	818	13.5	88.75	9.22	20.00	1.17	0.46	0.8
29 Aug 1300	2134	1.75	90.5	23.58	24.00	0.44	0.98	5.9
30 Aug 1300	3273	96.0	186.5	17.55	48.00	4.0	0.37	0.73
31 Aug 1930	3273	43.0	229.5	14.26	78.50	1.41	0.18	0.47
1 Sept 1600	3273	28.75	258.25	12.67	99.00	1.4	0.13	0.62
2 Sept 1300	3273	9.75	268.0	12.21	120.00	0.46	0.10	0.58
1989								
June	3273	404.75	672.75	4.86	281 days	0.06	n/a	n/a

n/a: not appropriate to provide a value due to the extended time period involved.

depth, where they were left for sufficient time to absorb oil from the soil. Oil on the wood was easily detected by sight and smell (Charles and Mackay, 1974; Collins, 1983). In this manner, the depth of oil penetration and its horizontal extent were monitored until 2 September at 13:00 h, when the last measurements were taken at the time of the camp being closed. In February numerous snow pits were excavated in an effort to determine the extent of the spill; however, without complete removal of the snowpack it proved impossible to plot the spill margin along its entire length. During the spring of 1989 a final detailed topographic survey was completed for the area of the spill and its extent was measured during the plane table survey. Further checking was conducted at the end of August 1989.

Soils and Oil Characteristics

Soil sampling was conducted prior to the spill initiation to determine moisture content. Thirty samples were taken from 15 sites within the trench and right-of-way. Sampling was stratified by depth (0–15 cm and 15–30 cm). Ideally volumetric water content would be most appropriate; however, due to the high water and peat content and the technique/tools employed, it was not possible to consistently extract a known volume of soil. Consequently moisture content was expressed

on a dry weight basis following air drying to stable weights. Soils were Gleysolic Turbic Cryosol-silt loams, with an average clay and fine sand content of approximately 20% each, while the remaining 60% was composed of silt (Kershaw and Evans, 1987; Evans *et al.*, 1988).

Most previous Canadian studies have also used Norman Wells crude oil (Table 2). The similarity in viscosity and specific gravity therefore reduces the possibility of variability in crude-oil characteristics affecting the results and therefore permits more direct comparison of the SEEDS spill to previous work.

RESULTS

As a result of saturated soil conditions (>100% within the top 30 cm) and the fine texture of the soils at the site, little oil was confined to the active layer. Oil could not be absorbed or infiltrate the soil. Confining pressures due to overburden were insufficient to confine the oil within the active layer, and so it was forced to the soil surface along the discontinuity provided by the pump hose where it passed through the soil to the buried pipe segment. Upon reaching the surface, oil flowed along the topographically low areas of the site (the simulated pipeline trench and existing depressions and swails; Fig. 2). The subsurface portion of the spill was localized to an

TABLE 2. A comparison of point-origin, experimental crude-oil spills conducted in subarctic environments

	Road allowance	Forest	Forest	Forest	Forest	Forest	Forest	Forest	Simulated pipeline right-of-way
Season	summer	summer	summer	winter	winter	spring	summer	winter	summer
Volume (m ³)	0.72	0.72	10.12	0.90	1.00	1.26	7.57	7.57	3.27
Area affected (m ²)	100.3	118.2	400.0	26.0	49.0	128.5	303.0	188.0	672.75
Concentration (L·m ⁻²)	7.2	6.1	25.3	34.6	20.4	9.8	25.0	41.0	4.86
Coverage (m ² ·m ⁻³)	139.31	164.17	39.53	28.89	49.00	102.00	40.03	24.83	205.54
Surface slope (°)	2.0	ND	ND	2.0	2.0	2.0	4.0	4.0	1.5
Pumping rate (L·min ⁻¹)	114.67	72.00	84.33	112.50	285.71	36.00	170.00	170.00	2.84
Oil temperature (°C)	ND	ND	26	-20	40	15	57	57	16 to 23
Air temperature (°C)	ND	ND	22	-20	-20	15	25	-5	16 to 23
Crude-oil type	N.W.	N.W.	N.W.	N.W.	N.W.	N.W.	P.B.	P.B.	N.W.
Specific gravity	0.83	0.83	0.81	ND	ND	ND	0.89	0.89	ND
Date initiated (ddmmyy)	0772	150772	080773	250274	270274	160574	140776	260276	280888
Source	Charles and Mackay, 1974		Mackay <i>et al.</i> , 1980; Mackay <i>et al.</i> , 1975			Johnson <i>et al.</i> , 1980		This study	

P.B. — Prudhoe Bay crude oil; N.W. — Norman Wells crude oil; ND — no data.

Note: several values had to be estimated based on reported data.

Conversion values: 1 m³ = 220 Imperial gallons = 6.11 Imperial barrels; 1 m³ = 264 U.S. gallons = 8.39 U.S. barrels.

area of less than 1 m³. The size of the aboveground portion of the spill increased rapidly as the oil was released; then, after 24 h the rate of increase in area declined (Table 1). Initially the oil occupied low areas. Then it pooled and remained relatively fixed in its extent and concentration (Table 1). Within the first 24 h after the initiation of pumping it had occupied 13.45% of its ultimate extent (Fig. 4). Within 24 h of the cessation of pumping, the end of the spilling operation, it had occupied 27.7% of its final area. By the fifth day after commencement of pumping, the spill occupied 268 m² and the rate of change in area had dropped from 13.4 m²·h⁻¹ to 0.46 m²·h⁻¹ (Table 1).

Concentration of oil was only estimated based upon the amount released and the areal extent of the contamination zone (Table 1). As such it represents only a gross estimate on which the rate of change in concentration values were based. At the initiation of pumping the rate of change in concentration was the highest, since the oil moved quickly along the confining drainage-ways at a rate of 1.96 L·m⁻²·h⁻¹. This was the maximum rate, and it declined to 0.8 L·m⁻²·h⁻¹ at the time when pumping ceased. Over the next four days it declined to 0.58 L·m⁻²·h⁻¹ when observation ceased. Between 29 and 30 August the rate of change in the concentration increased to 5.9 L·m⁻²·h⁻¹ when it spread out to cover a flat area on the right-of-way (Fig. 3). During the next four days the rate of change in area remained relatively constant as the oil spread onto the trench of the North Link (Fig. 2). Much of the new area added to the spill between September and June was only patchily covered by blobs of concentrated oil residue. Within this portion of the spill were numerous areas without visible oil or with only a light coating of oil.

In February 1989 an attempt was made to delineate the spill margin. This necessitated snow removal, and it proved impractical to precisely follow the spill margin and therefore accurately determine the areal extent of the spill. Since the sites of snow trench excavation were at or near the June margins of the spill, much of its areal extent must have been set by mid-winter. This 404.75 m² was a 151% increase in area over the September values.

DISCUSSION

An assessment of the behaviour of crude oil in the active layer was not possible since the oil came to the surface upon release. A possible method of insuring that, at least initially, the oil remains in the soil is to conduct the spill using an identical approach but in the early winter when the soil surface is frozen, thus preventing its spread to the surface.

In September it was expected that any further increase in area would be small, with much of it occurring along the topographically depressed simulated pipeline trench. This expectation was based upon the behaviour of other experimental crude-oil spills (Table 2) as well as the slow rates of increase observed five days following initiation of the SEEDS spill. With 60.2% of the spill area being added subsequent to the September measurement (Fig. 4), it is apparent that major differences exist between the SEEDS spill and other experimental crude-oil spills.

It is possible to compare the mid-growing season spill conducted by Charles and Mackay (1974) on a cleared, mineral-dominated road allowance near Norman Wells to the SEEDS spill. All other experiments were conducted in forests

with no human-induced disturbances present. The SEEDS spill produced a lower concentration (4.87 vs. 7.2 L·m⁻²), while its area was 6.7 times that of the road allowance spill (Fig. 3, Table 2). Some of the difference may be due to the SEEDS spill volume being almost 4.5 times that used on the road allowance. The saturated condition of the road allowance at the time of the spill was probably similar to the SEEDS simulated pipeline trench; however, the presence of flowing water (even the small amount on the SEEDS site) facilitated the spread of the oil. The slower rates of areal increase occurred once the oil at the SEEDS site flowed onto the cleared right-of-way, with its intact surface organic layer producing flows reduced to rates similar to those experienced by Collins (1983) in a sub-arctic forest site near Fairbanks.

If one considers area-to-volume ratios, it is apparent that the SEEDS spill was the highest of the experimental spills conducted in the Subarctic (Fig. 3). This is particularly significant since three of those with lower ratios were for volumes of two or more times that of the SEEDS spill (Table 2). However, these experiments were conducted on forested sites. In addition, the spills conducted by Charles and Mackay (1974), with the exception of a summer forest spill conducted by Mackay *et al.* (1980, 1975), involved smaller volumes than the SEEDS spill (Table 2). With these low volumes it is difficult to compare among experiments, and Mackay *et al.* (1975) maintain that spill area is not *directly* proportional to spill volume. If the SEEDS crude-oil volume is plugged into the formula of Mackay *et al.* (1975) [1], it predicts that the area will be 153.6 m², or 518.65 m² smaller than the actual area. However, the 672.25 m² area at 4.4 times the predicted value is within the error range of Mackay *et al.* (1975), stated to be a factor of 3 to 6.

$$\text{Spill area (m}^2\text{)} = 53.5 (\text{spill volume (m}^3\text{)})^{0.89} \quad [1]$$

The relatively large area of the SEEDS spill and its consequently high area-to-volume ratio (205.58 m²·m⁻³) or coverage (Table 2) is a result of the channelizing of flow along the mineral soil-dominated simulated pipeline trench and naturally occurring drainage swails on the cleared right-of-way. As a consequence of the movement of the oil, it differed from the road alignment used by Charles and Mackay (1974) and produced a larger area-to-volume ratio (205.58 vs. 139.3 m²·m⁻³). Furthermore, the SEEDS spill concentration was much lower than all other experimental spills, regardless of season or site characteristics (Table 2). These characteristics are presumably due in large measure to absorptive ability of the moss/lichen mat and soil humus layer in both the Alaskan and Norman Wells studies, where release was conducted into an undisturbed forest (Mackay *et al.*, 1974, 1975, 1980; Jenkins *et al.*, 1978; Johnson *et al.*, 1980; Collins, 1983).

Another factor is the rate at which the oil was released. At 2.8 L·min⁻¹ the SEEDS spill was several magnitudes below the next highest rate (Table 2). With slower pumping rates the movement of the oil front should have been relatively slow, maximizing its potential for absorption into the organic surface horizons and moss/lichen layer of the vegetation. However, the SEEDS spill had a relatively low area-to-volume ratio, confirming the low absorption potential of the simulated pipeline trench.

Comparing rates of area increase on the experimental Alaskan summer spill and the SEEDS spill, it is evident that the former rapidly achieved its final size (i.e., 88% within six days) (Figs. 4 and 5). The SEEDS spill was only 39.8% of its ultimate

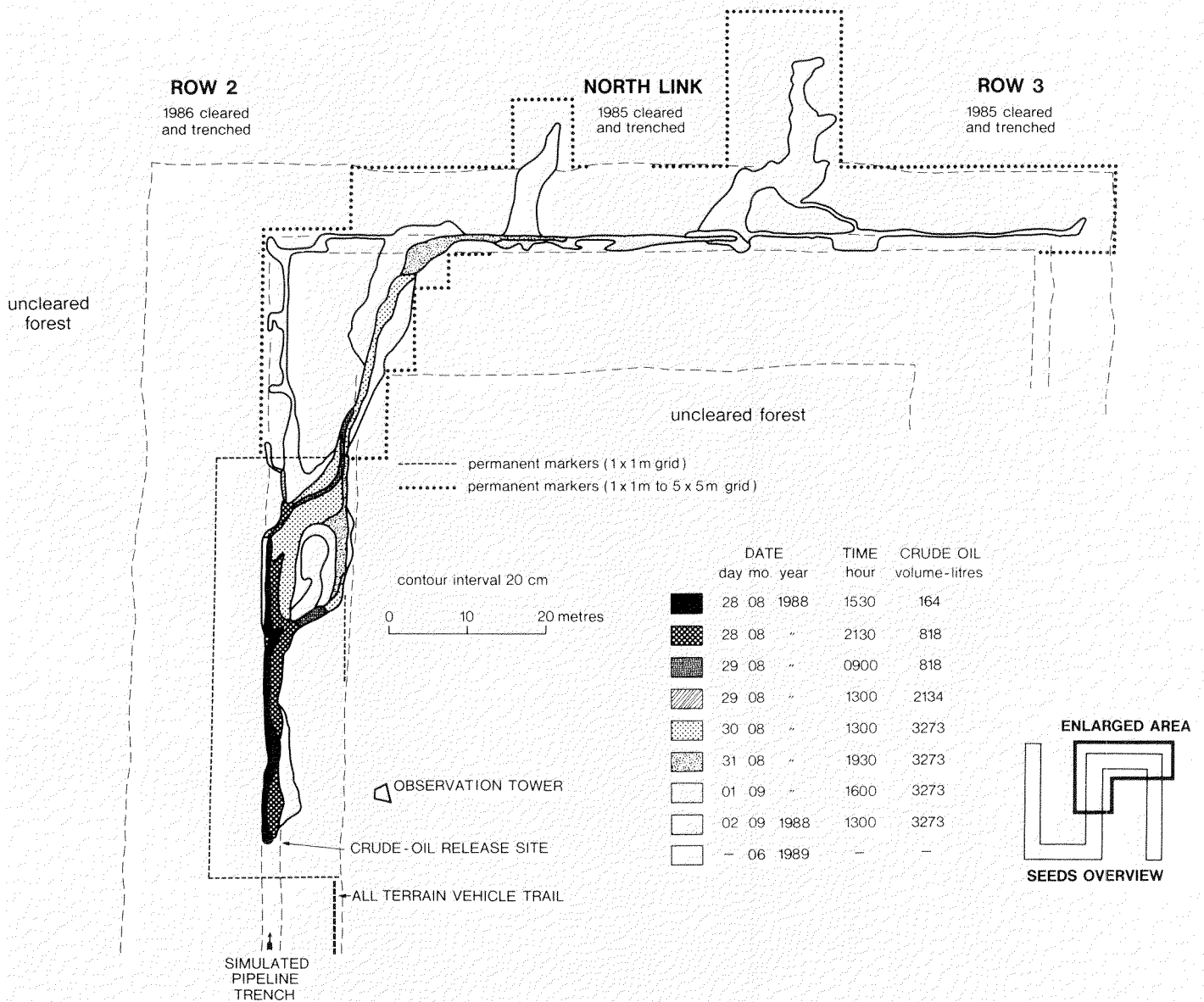


FIG. 3. Initially the oil flowed along the depressed trench portion of ROW 2 until channelled off this area by naturally occurring linear depressions. The oil then moved across the cleared portion of the right-of-way, through a corner of forest, onto the North Link and back into the depressed simulated pipeline trench. By spring the following year it had expanded via naturally occurring depressions into the edge of the uncleared forest, where its extent stabilized for a total of 672.75 m².

area within five days. Again the differences in absorptive capacities of the materials in contact with the oil would help explain this situation.

CONCLUSIONS

The SEEDS spill originated at 100 cm depth and became a surface spill as a result of the active layer's inability to absorb the oil as it was emitted. This was to be expected in fine-grained, saturated soils. However, should the surface be frozen, a condition prevailing during early winter, then the oil may well be trapped within the still unfrozen active layer.

Similarities exist between the SEEDS spill and previously conducted surface, point-origin, experimental crude-oil spills. The areal extent of the oil was controlled by: 1) low volume but continually flowing water in a shallow channel; 2) to-

pographically depressed areas and their degree of interconnectedness; and 3) low absorptive ability of the surfaces in contact with the oil (including moisture content of the substrate).

The SEEDS crude-oil spill deviated from other experimental spills in that: 1) The oil front moved rapidly over saturated mineral soil-dominated surfaces, conditions expected over a buried pipeline. 2) Average concentration values were low, while area-to-volume ratios were high, suggesting that less oil covers larger areas when crude oil moves along mineral-dominated surfaces or naturally occurring depressions, conditions expected on buried pipeline rights-of-way. 3) The areal extent of the spill continued to increase until some time after freeze-up, but certainly much longer time periods were required to achieve stability compared with forest area spills.

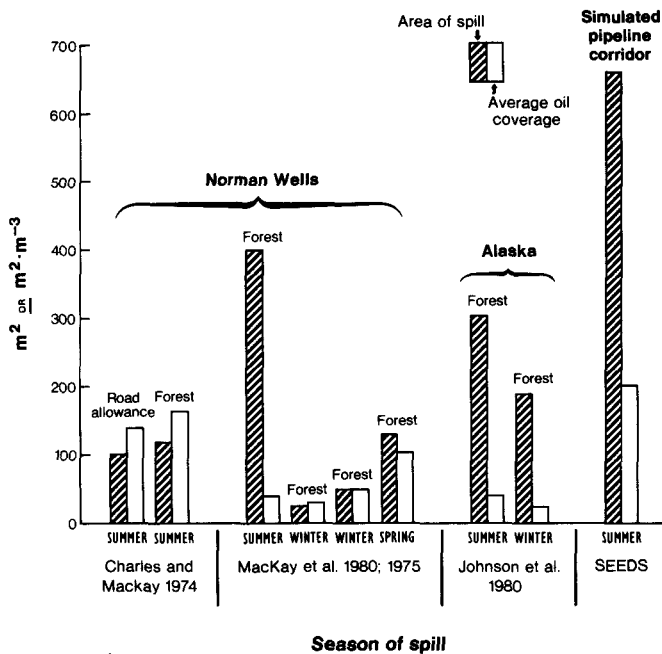


FIG. 4. A comparison of experimental crude-oil spills conducted in subarctic areas. Despite having less than half the oil volume of the Alaskan experiments and one-third the volume of the largest Norman Wells experiment, the SEEDS spill onto a cleared and trenched right-of-way affected the largest surface area.

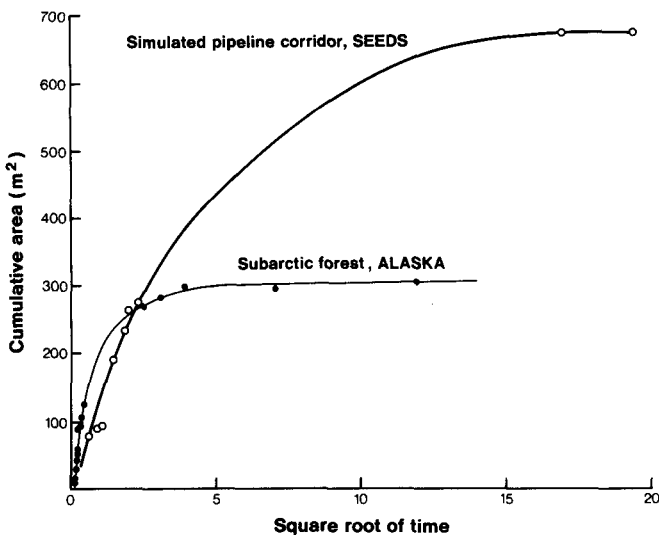


FIG. 5. A comparison of the rate of change in area of experimental crude-oil spills in an undisturbed subarctic forest (Johnson *et al.*, 1980) and on the SEEDS simulated pipeline right-of-way. The spill on the right-of-way took longer to stabilize and covered more than twice the area of the forest spill despite containing less than half the volume used in the Alaskan experiment.

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