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MODELLING OF OIL SPILLS IN SNOW

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ABSTRACT

This study involved developing process equations to model the fate of oil spills in snow. A literature survey was undertaken to assess data gaps. Based on the results of this survey small–scale field experiments were conducted to collect data on oil evaporation rates beneath snow and oil transport by blowing snow and mid–scale experiments were conducted to measure oil spreading beneath snow.

The results of these tests and data from the literature review were used to develop equations describing the spreading and evaporation of oil on or in snow.

RÉSUMÉ

L'étude comportait la constructin d'équations pour modéliser le devenir des hydrocarbures déversés sur la neige. Une étude bibiographiqe ayant permis d'évaluer les lacunes dans les données, on a entrepris, à petite échelle sur le terrain, des expériences afin de mesurer la vitesse d'évaporation des hydrocarbures sous la neige et leur transport par les rafales de neige ainsi que des expériences à échelle moyenne pour mesurer la migration horizontale des hydrocarbures sous la neige.

Les résultats de ces expériences et de l'étude bibliographique ont servi à construire des équations de la migration horizonatale et de l'évaporation des hydrocarbures sur la neige ou sous la neige.

ACKNOWLEDGEMENTS

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1.0 INTRODUCTION

Comprehensive models now exist to predict the movement, fate and behaviour of cold region oil spills on water (e.g., Mackay et al. 1979), on and under ice (e.g., Wotherspoon and Swiss 1985), on land (e.g. S.L. Ross and McBean 1986) and in pack ice leads (S.L. Ross and D.F. Dickins 1987a). This paper describes the development of process equations to predict the fate and behaviour of oil spills on land or ice in or under snow.

1.1 PREVIOUS STUDIES

Studies of oil spill processes in snow conditions began in 1972 with experimental spills of Prudhoe Bay crude oil on Arctic snow and ice (McMinn 1972). At about the same time experimental spills of Norman Wells crude oil on freezing water were conducted in winter near Ottawa (Scott and Chatterjee 1972). Data on the effects of snow on weathering processes are available from these tests.

In 1972, 1973 and 1974 twelve experimental spills of about 1 m^3 of Norman Wells crude on land were conducted in the N.W.T. Of these, two were conducted in snow conditions. Detailed data on spreading and thermal effects are available from these tests as well as some weathering information. A simple computer model for predicting oil spreading, heat transfer, evaporation and viscosity was also developed (Mackay et al. 1974).

In 1975, during the Balaena Bay study (NORCOR 1975), data on the absorption of snow by oil and the effect of snowfall on oil evaporation were collected using Norman Wells crude as the test oil.

During the winter of 1979/80 two spills of oil took place (one experimental and one accidental). The effects of snow on each are documented (Buist et al 1980; Dickins 1980). Combustion tests with these oil/snow mixtures were also carried out (Energetex 1981).

During the winter of 1980–81 a series of experimental spills of Prudhoe Bay crude on snow and sea ice was conducted. These tests involved spraying hot oil onto the snow to simulate a surface oil well blowout during mid–winter (–23°C) and spring (+4°C). Data on oil/snow interaction were collected over a two week period (Nelson and Allen 1982).

A comprehensive study of oil weathering processes was conducted by the U.S. Coast Guard (Tebeau et al. 1982) during the winters of 1979/80 and 1980/81 using Prudhoe Bay crude oil and No. 2, No. 4 and No. 6 fuel oils. Snow played an integral role in the experimental design. Considerable data on evaporative loss and subsequent property changes were amassed. Significantly, this study used the "evaporative exposure" approach to correlate losses and property changes, thus providing an excellent data set.

Comfort and Purves (1982) reported oil weathering results from a sample collected at the site of the Griper Bay, N.W.T. oil–in–multi–year–ice experiments. They also reported the possibility that particularized oil/snow mixtures could be blown about by high winds.

Although not specifically related to oil spills, two studies in 1985 and 1986 at the University of Toronto contain useful data. The first (Kawamura and Mackay 1985) involved outdoor experiments to determine the evaporation of volatile liquids. One of the experiments involved a toluene/snow mixture and provides useful insights into the processes occurring in evaporation of oil in or under snow. The second involved small scale experiments and modelling of the spread of chemicals on ice and snow (Kawamura et al. 1986). Significantly, this study was the first to develop a spreading model that related to snow properties and did not require the use of an empirical "surface roughness" factor to predict spreading rates.

Finally, two recent studies, though not designed to study snow/oil behaviour fortuitously resulted in data on the subject; the recent experimental spills off Cape Breton (S.L. Ross and D.F. Dickins 1987b) confirmed some of the spreading equations developed by Kawamura et al 1986 for oil in thick brash ice and provided good data on oil weathering in thick brash ice. Outdoor tank tests of oil behaviour in leads shed further light on the absorptive capacity of oil for snow and the effect of snowfall on oil behaviour and weathering (S.L. Ross and D.F. Dickins 1987a).

1.2 STUDY APPROACH

Prior to the detailed planning of the experiments it was necessary to retrieve, collate and study the considerable body of data already existing on the behaviour of oil in, under or on snow (see Appendix I). Table 1 shows such an analysis, for the literature sources discussed previously. It is seen that the effects of snow properties and spill type on spreading have been poorly studied and understood.

Once the key data gaps were firmly identified, small and mid–scale outdoor tests were conducted to collect data on spreading and evaporation. Additional tests were conducted at Arctic locations to evaluate snow drifting as an oil transport mechanism. It was necessary to conduct outdoor tests since it is impossible to create realistic snow indoors or even use real snow indoors since excavation and transportation irrevocably changes its properties.

TABLE 1 – LITERATURE DATA ANALYSIS

NUMBER OF STUDIES IN WHICH THE PARAMETER WAS MEASURED OR PREDICTED FOR ITS EFFECT ON:

Parameter	Oil Spreading	Oil Weathering
snow properties	1	0
snow depth	4	1
oil properties	4	9
oil quantity	6	4
oil thickness	6	2
temperature	3	9
wind speed	0	3
weather	3	3
spill type	1	1

Process equations, based on accepted theory, literature and experimental results were then developed to describe the fate and behaviour of oil on, or under snow and on an impermeable surface. A description of Arctic snow conditions was also prepared.

2.0 EXPERIMENTAL METHODS

2.1 THE TEST OIL

The crude oil selected for these tests was Mixed Sweet Western, the properties of which are given in Table 2. This particular oil was selected since it is very close in properties to the EPS standard crude and its properties and spill behaviour in cold climates have been extensively studied and are well known (e.g., S.L. Ross and D.F. Dickins 1986; S.L. Ross and D.F. Dickins 1987; S.L. Ross and DMER 1988).

TABLE 2

PROPERTIES OF MSW CRUDE

	Density	@	0°C	0.858 g/cm^3
	Viscosity	@	0°C	10 mPas
Interfacial Tensions				
	air/oil			25.7 mN/m
	oil/seawater			19.0 mN/m
	oil/water			26.2 mN/m
	Pour Point			−8°C
	Flash Point			7°C
modified ASTM distillation		T_o = 384.9°K		
		T_g = 539.7°K		

2.2 SMALL–SCALE EVAPORATION STUDIES

Pyrex baking trays containing 1 cm of oil initially filled to various depths with snow were placed in an exposed location near Woodlawn, Ontario for two weeks in February. Three trays were filled with 45 mm of snow of different density (created by manually compressing the snow in two of the trays); two trays were filled with different heights of uncompacted snow (100 mm and 200 mm) and the sixth contained no snow, for a control. Wind speeds and air and oil temperatures were recorded using a remote weather station and thermocouples; data were recorded approximately every three hours on a TRS–80 micro–computer.

Evaporative loss was determined periodically by recovering small (20 ml) samples of oiled snow from the bottom of each tray, carefully melting and decanting the water phase. The oil sample's density was then determined at 0°C using a Parr densitometer. Evaporative loss was calculated using a verified density/evaporation calibration curve for the MSW oil.

2.3 MID–SCALE SPREADING AND EVAPORATION STUDIES

These experiments were conducted at the National Research Council of Canada's Outdoor Manoeuvring Basin in Ottawa during February 1988. Two test spills of about 200 L each of MSW crude were conducted from catwalks above the snow (Figure 1). The oil was released into the snowpack at the centre of each test area and its spreading along four radii monitored by timing the appearance of oil in the bottom of bore holes spaced 30 cm apart (Figure 2). The first test was conducted with virgin snow; the second with snow densified and thickened with snow blown onto the test plot from adjacent areas (Figure 3). Snow properties (density, crystal size, stage of metamorphosis and thickness) were determined using a standard NRC snow kit. Oil samples were collected and analysed as described above to determine evaporation rates.

2.4 SMALL SCALE BLOWING SNOW TESTS

A small, portable test kit consisting of three trays (Figure 4) two pre-measured oil samples and sample vials were sent to three Arctic locations (Yellowknife, Inuvik and Iqaluit) to be set up near weather stations to determine if blowing snow transported oil from a surface spill. Arctic locations were necessary for these tests since the extreme cold generates a type of snow not normally found in southern Canada. Oil losses to blowing or drifting snow were to be determined by comparing the weight gains and losses of a control tray (no oil) with those of a tray containing oil; corrections for evaporation losses were to be made based on oil samples from the third tray to be analyzed as described above.

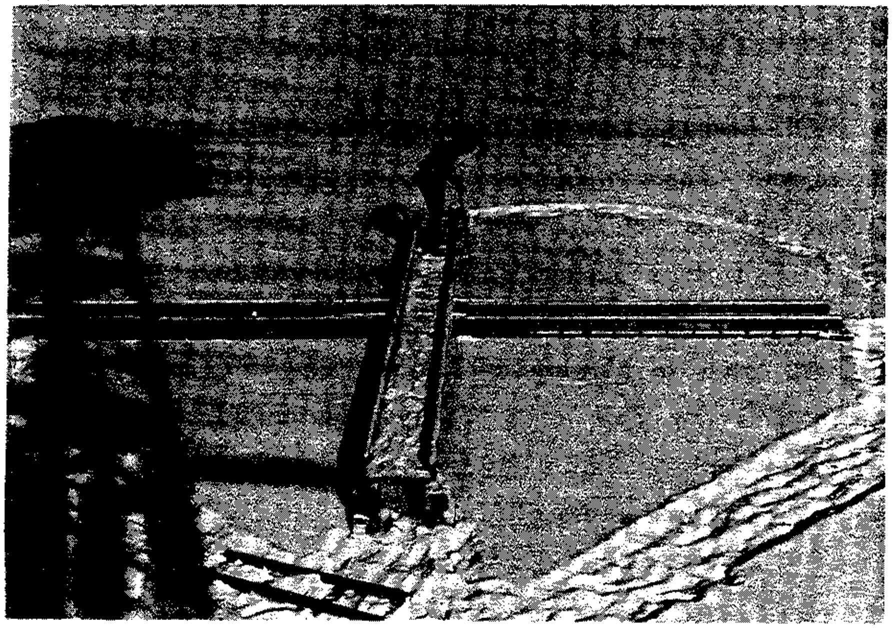


Figure 1 – Mid–scale test site layout

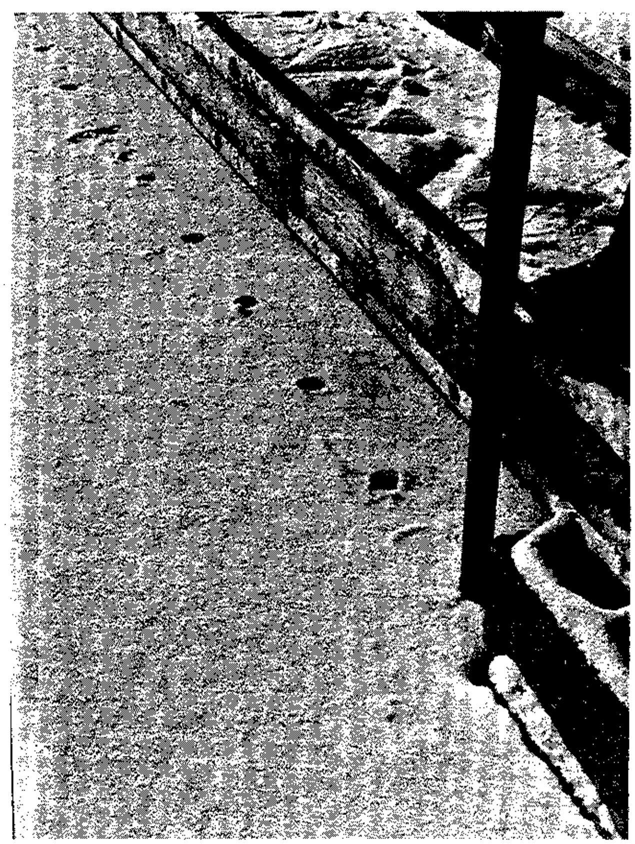


Figure 2 – Bore holes to monitor
oil spreading beneath snow

Figure 3 – Mid–scale test site
with additional snow

Figure 4 – Tray for Arctic tests

3.0 RESULTS AND DISCUSSION

3.1 SPREADING OF OIL ON SNOW

Since the literature review yielded several studies on spreading of oil on ice and snow, no additional experimental studies were felt to be necessary. The data of the previous studies was used to develop and confirm a spreading theory for oil on ice or snow.

3.1.1 Theory

The theoretical spreading model is based on a balance of forces per unit volume of oil, as used by Fay (1969) in analysing oil spreading on water, modified to reflect the physical situations of oil on snow or ice. The three forces involved in the spreading are gravity, viscous and inertia, the first being a driving force and the latter two resistances. Surface tension forces are neglected since oil on ice or snow inevitably ceases spreading at thicknesses (on the order of 5 mm) much greater than those at which surface tension forces become dominant. The forces can be defined as:

	Continuous Source	Instantaneous Spill
Gravity	$= \rho g Qt/r^3$	$= \rho gV/r^3$
Viscous	$= \rho \nu^{1/2} \pi r^3/Qt^{5/2}$	$= \rho \nu^{1/2} \pi r^3/Vt^{3/2}$
Inertia	$= \rho r/t^2$	$= \rho r/t^2$

where
- ρ = oil density (kg/m^3)
- g = gravitational acceleration (m/s^2)
- Q = oil flowrate (m^3/s)
- V = oil volume (m^3)
- t = time (s)
- r = spill radius (m)
- ν = kinematic viscosity of oil (m^2/s)

Equating the driving force to each of the resistances yields the equations that define the two spreading regimes for oil on snow or ice:

	Continuous Source	**Instantaneous Spill**
Gravity–Inertia	$r = (gQ)^{1/4}\, t^{3/4}$	$r = 1.5\, (gV)^{1/4}\, t^{1/2}$
Gravity–Viscous	$r = (gQ^2/\pi\, \nu^{1/2})^{1/6}\, t^{1/2}$	$r = (gV^2/\pi \nu^{1/2})^{1/6}\, t^{1/4}$

Figure 5 shows the continuous source data of McMinn and Golden (1972) and Glaeser and Vance (1971) plotted in non–dimensional format and the theoretical equations for the two spreading regimes. Although the data fit is not perfect, the trend certainly indicates that spreading of continuous oil releases on snow or ice occurs primarily in the gravity–viscous regime. Figure 6 shows the instantaneous release data of Glaeser and Vance (1971) for diesel and crude spilled on snow covered Arctic ice, the data of Kawamura et al. (1986) for the spread of bayol and pentanol on ice and the equation of Chen et al. (1974) based on numerous small scale oil on ice and snow spreading experiments. The fit of these various data to the theoretical equations for the two spreading regimes, though far from perfect, certainly indicates that initial spreading of instantaneous spills on snow or ice is governed by the gravity–inertia regime but, the spreading quickly reverts to the gravity–viscous regime.

In summary, the spreading of oil on snow or ice for a continuous source or instantaneous spill can be adequately modelled by the equations given for gravity–viscous spreading.

3.2 INFILTRATION OF OIL INTO SNOW

Again the literature review revealed several studies of oil infiltration into a snow pack (in fact one standard method for determining the permeability of a snow pack is to use kerosene to measure infiltration rates).

The flow of liquids through a permeable media is governed by the D'Arcy equation which can be written as:

FIGURE 5

NON—DIMENSIONAL SPREADING ON SNOW OR ICE
(continous source)

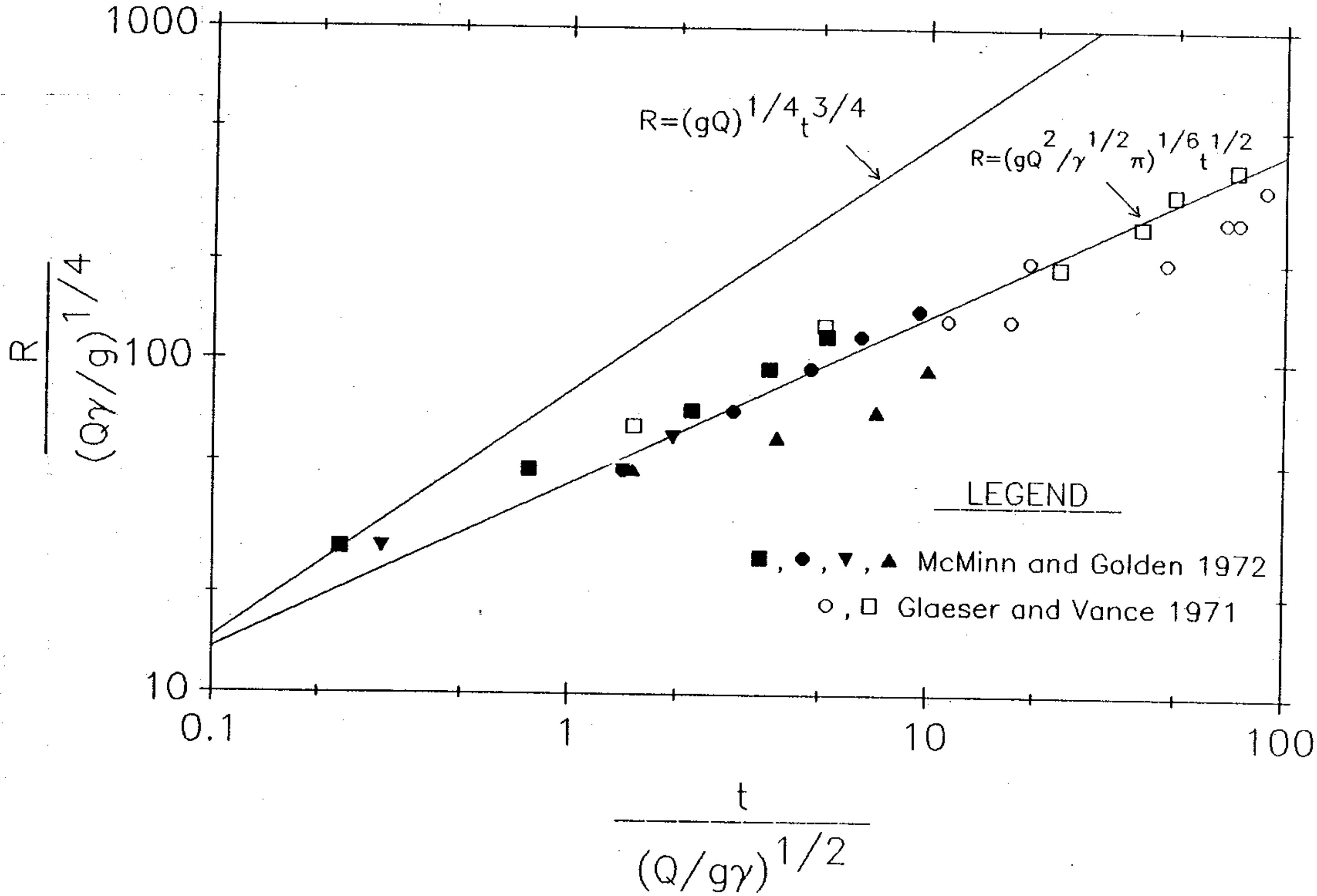
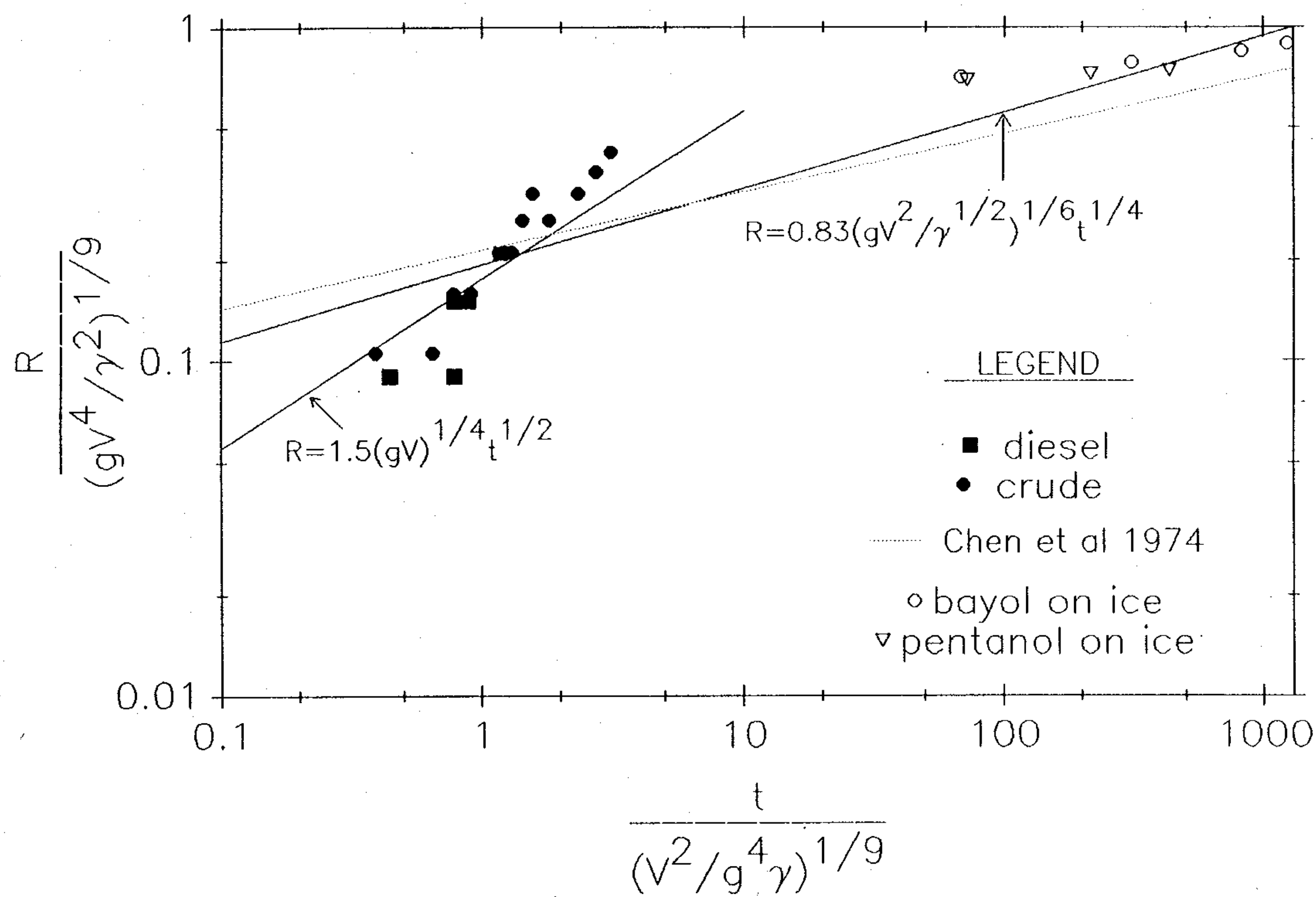


FIGURE 6

NON—DIMENSIONAL SPREADING ON SNOW OR ICE



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

where K = specific permeability of snow (m^2)

A = flow area (m^2)

L = flow path length (m)

ΔP = pressure driving force along flow path (Pa)

μ = dynamic viscosity of fluid (Pas)

Following the derivation of Mackay et al. (1974) for flow into snow beneath a surface spill:

for $P = \rho g\,(x+L)$ where x = thickness of oil on snow (m)

$$Q = KA\rho g\,(1+x/L)/\mu$$

and the linear rate of penetration of oil into snow is

$$dL/dt = (K\rho g/E\mu)\,(1+x/L)$$

where E = void fraction of snow

= porosity

= $1-\rho_s/\rho_i$

ρ_s = snow density (kg/m^3)

ρ_i = ice density

= 917 kg/m^3

The major unknown in these equations is K, the specific permeability of snow which is a function of snow density, crystal size and age. A simple equation for specific permeability is presented in the next section.

3.3 HORIZONTAL FLOW OF OIL IN SNOW

3.3.1 Theory

The horizontal flow of oil in snow at an impermeable layer was modelled as follows, beginning with the D'Arcy equation rewritten as:

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

substituting
$$A = 2\pi Lh,$$
$$V = Qt,$$
$$h = V/E\pi L^2$$

and
$$P = gh = gV/E \quad L^2$$

where h = height of oil layer in snow (m)

yields $L = (2K\rho gV/\pi E^2 \mu)^{1/4} t^{1/4}$ for an instantaneous spill, or similarly

$L = (2K\rho gQ/\pi E^2 \mu)^{1/4}\ t^{1/2}$ for a continuous release

3.3.2 Specific Permeability of Snow

Shimizu (1969) has shown that the specific permeability of snow may be adequately determined from

$$K = 7.7 \times 10^{-2}\ d_o^2 \exp(-7.8 \rho_s/\rho_i)$$

where d_o = mean grain size of snow (m)

For situations where snow properties are unknown, the permeability can be estimated to within a factor of 2 by using d_o = 0.5 mm and $_s$ = 400 kg/m^3 to yield

$$K = 6 \times 10^{-10} \, m^2$$

This is a reasonable approximation since K appears to the power 1/4 in the equation for horizontal flow in snow, and thus a margin of error in K of 200% translates to an error of less than 20% in L.

Mackay et al. (1974) experimentally determined K for snow with a variety of oils. Their results ranged from 1.5 to 7.8 x 10^{-10} m^2.

3.3.3 Experiments

Figure 7 shows the results of the mid–scale experiments of oil spreading under snowpack on ice expressed as radius vs time. The oil temperature was 7°C when it was spilled; the average flowrate during release was 1.4 L/s. The snow at the first test plot (Run 1) was 15 cm thick, had an average density of 173 kg/m^3 and was comprised of crystals ranging in size up to 1 mm and averaging 0.5 mm. the artificially densified and thickened snow at the second test site was 18.5 cm thick, had a density of 272 kg/m^3 (upper half = 296 kg/m^3; lower half = 248 kg/m^3) and was also comprised mainly of 0.5 mm size crystals. Air temperature during the spills was −8 to −10°C; the snow temperature at the ice was −3 to −3.5°C. Winds were light (1 m/s) during the duration of the tests.

Figure 8 shows the height of oiled snow remaining, after spreading ceased, across each test site. Except for the central area (with a diameter of some 2 m) the equilibrium height of oiled snow was constant at about 2–3 cm.

Figure 9 shows the fit of the data to the theoretical models. Although there is considerable scatter, the theory for spreading of an instantaneous release (i.e., equation with V) fits the data, after a time of 150 s (the oil release time), reasonably well. The theory for spreading of a continuous source, although it approximates the data in the time period up to 150 s, does not appear to have the correct slope. This may be due to the fact that the oil was warm (8°C) when poured and could have melted the snow as it spread until it cooled to below 0°C.

FIGURE 7
MID-SCALE
SPREADING UNDER SNOW

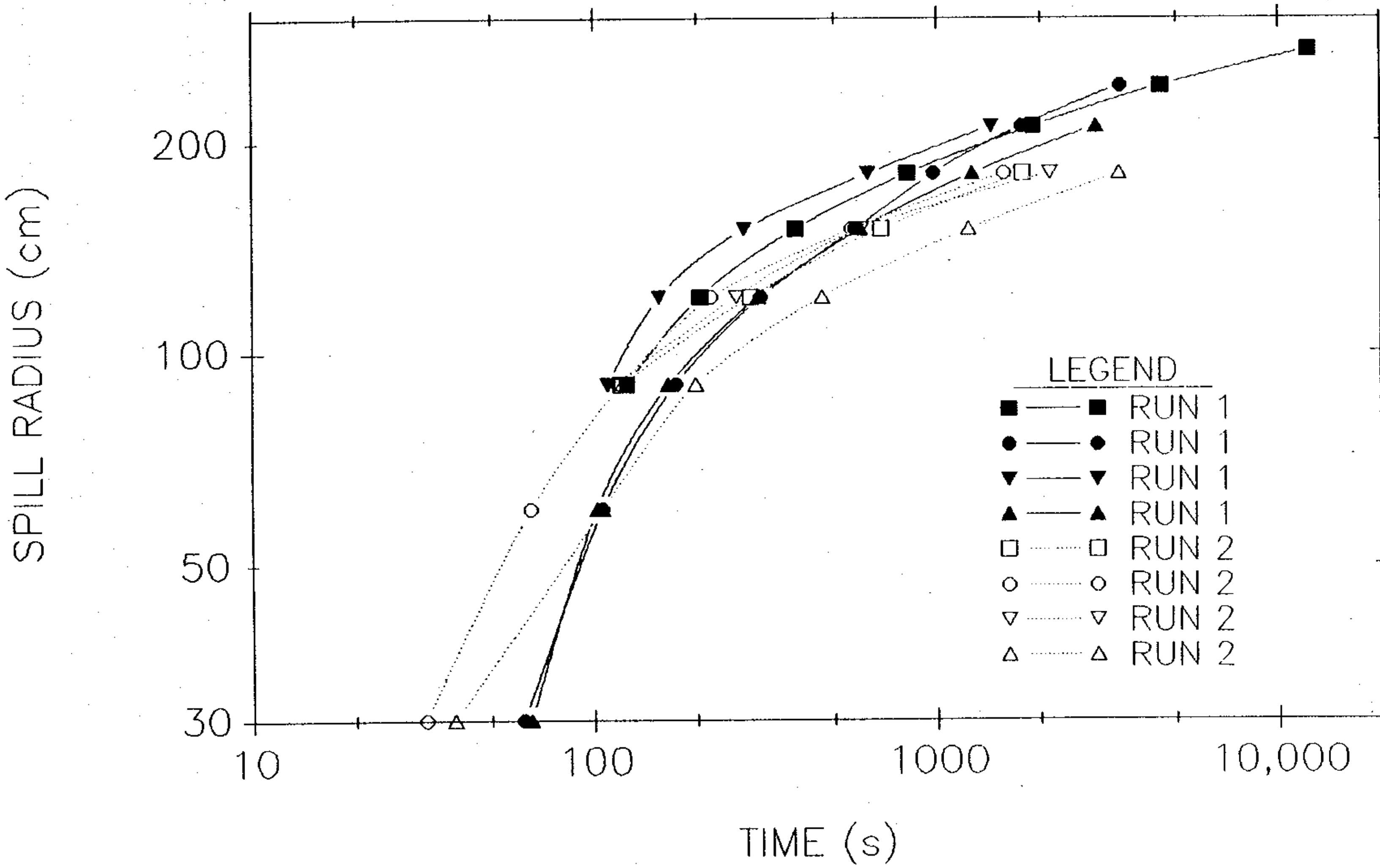
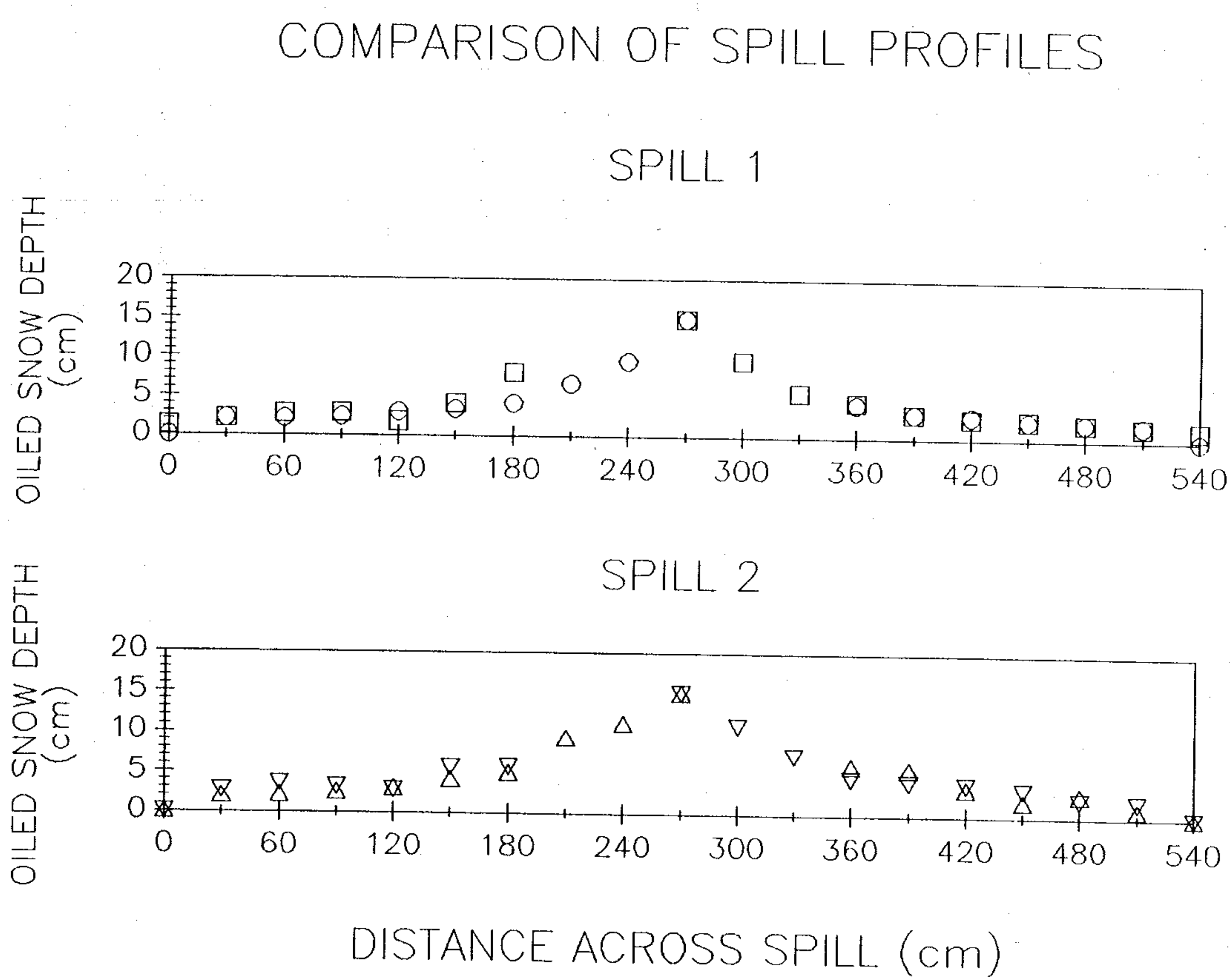


FIGURE 8



COMPARISON OF SPILL PROFILES
SPILL 1
SPILL 2
OILED SNOW DEPTH (cm)
0
5
10
15
20
0
60
120
180
240
300
360
420
480
540
DISTANCE ACROSS SPILL (cm)

FIGURE 9

SPREADING UNDER SNOW — COMPARISON OF THEORY WITH DATA

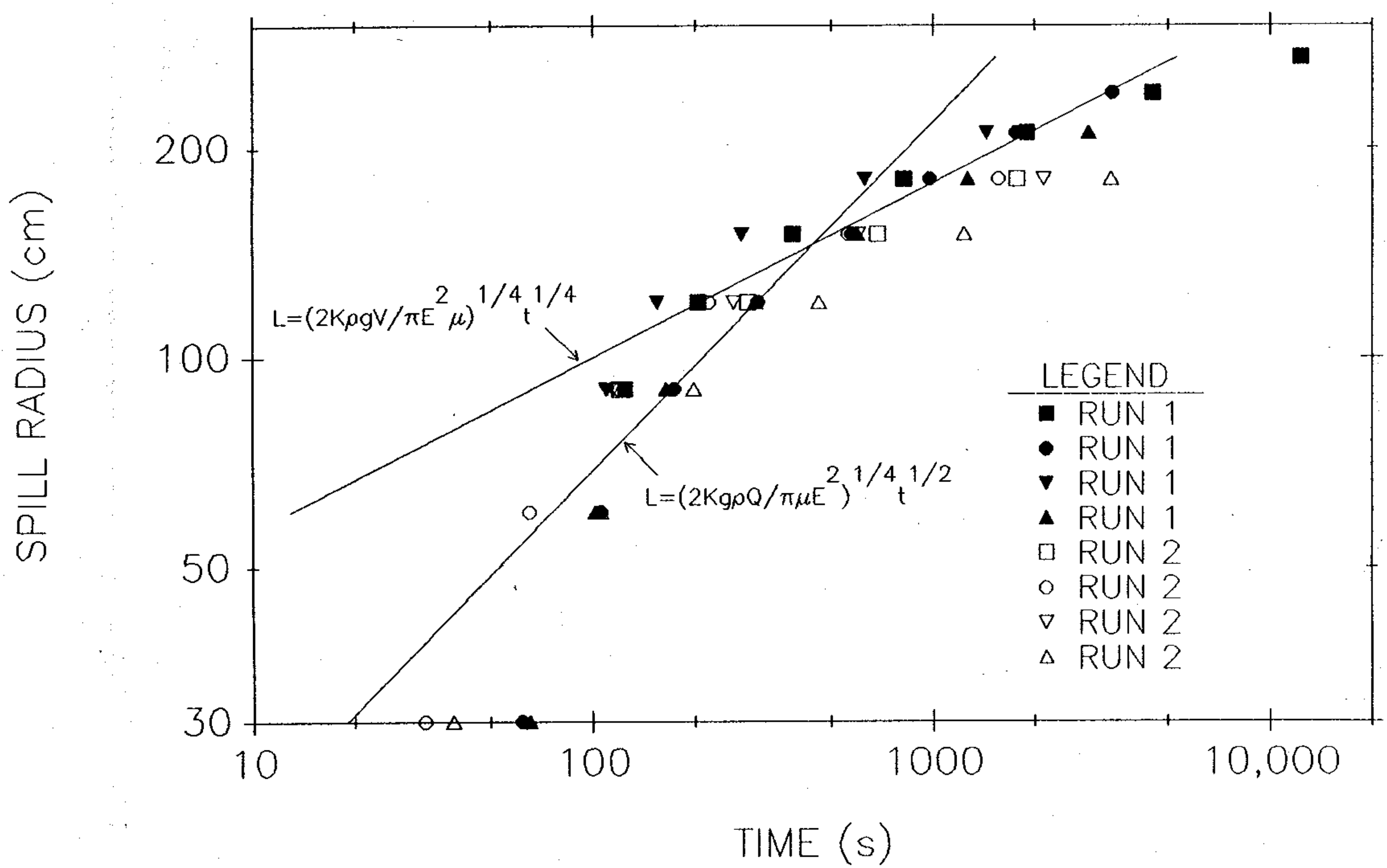


Figure 10 shows the fit of the experimental data to the instantaneous release model in a non–dimensional format. Also shown are the data from a 0.4 m^3 experimental spill reported by Mackay et al. (1974). With the exception of the data collected during the discharge (up to a non–dimensional time of about 5000) the model fits the data reasonably well.

3.4 EVAPORATION OF OIL IN SNOW

The trays containing the oil for evaporation studies were left outdoors for two weeks. A warm spell on the 14th day caused the snow to melt and end the experiments.

Figure 11 shows the oil and air temperatures recorded during the experiments as well as the calculated means for each tray. Figure 12 shows the measured wind speeds at the test site. Since the lowest wind that activated the anemometer was 1.34 m/s, zero readings were arbitrarily assigned a value of 0.67 m/s.

Figure 13 shows the measured volume fraction evaporated for each of the trays as a function of time. Also shown are the data from the two mid–scale experiments. For the small–scale experiments, the control tray (no snow) experienced the greatest evaporative loss. Of the trays containing snow and oil, the one with 45 mm of uncompacted snow had the highest evaporative loss; increasing snow density and thickness reduced evaporation from the oil. At first glance the results from the mid–scale tests seem anomalous; however, it must be kept in mind that the temperature during the mid–scale tests (–3°C) was much higher than during the small–scale tests (–17°C), thus the mid–scale tests could be expected to experience more rapid evaporation. In addition, as will be discussed later, the temperature difference between the two test series spans the pour point of the fresh MSW oil (–8°C). As has been recently discovered (S.L. Ross and DMER 1987) oils at temperatures below their pour points (as is the case with the small–scale tests) evaporate much more slowly than expected due to the development of an internal resistance to mass transfer in the semi–solid oil.

FIGURE 10

NON—DIMENSIONAL SPREADING UNDER SNOW

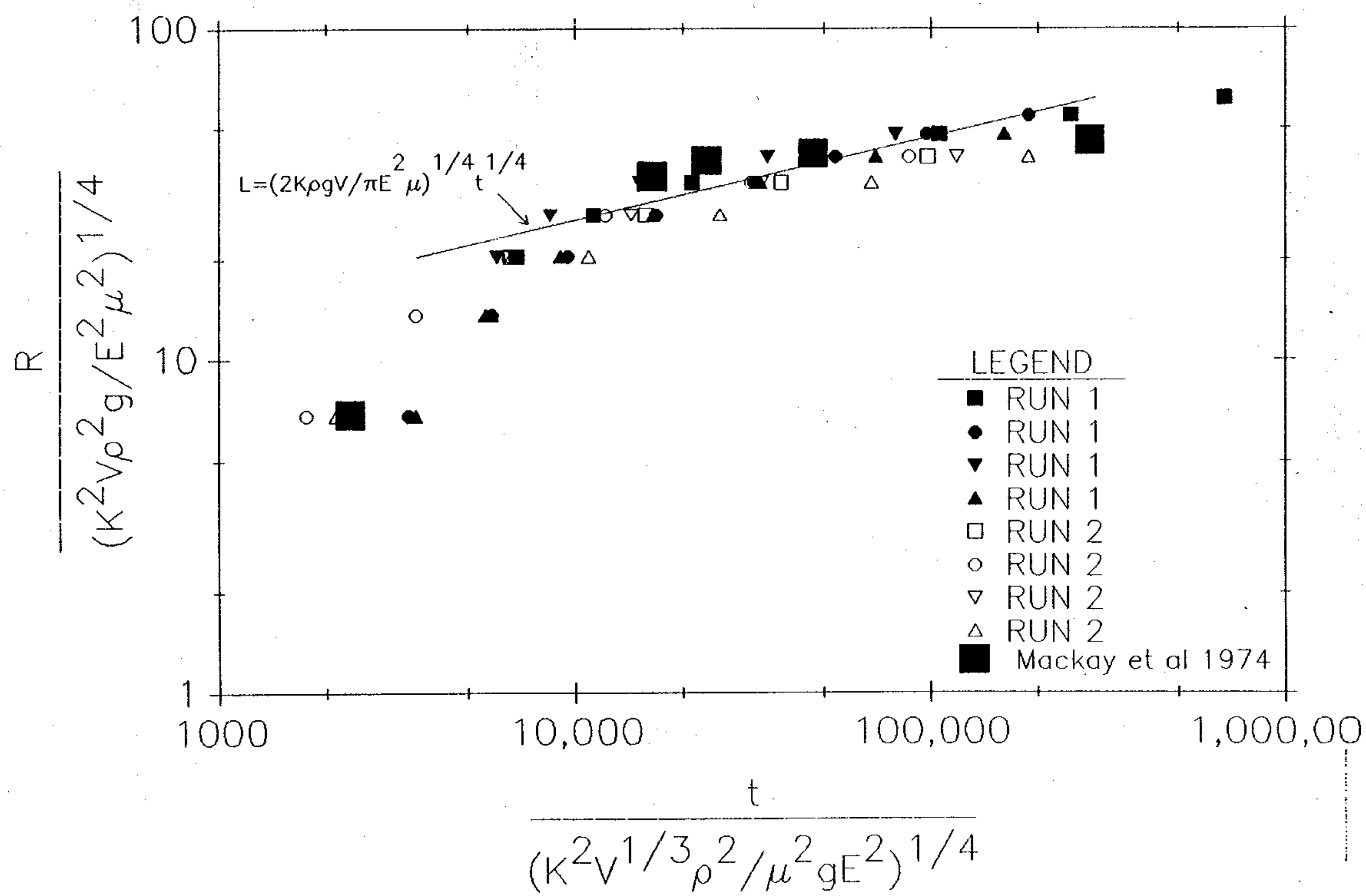


FIGURE 11

SMALL – SCALE EXPERIMENT TEMPERATURES

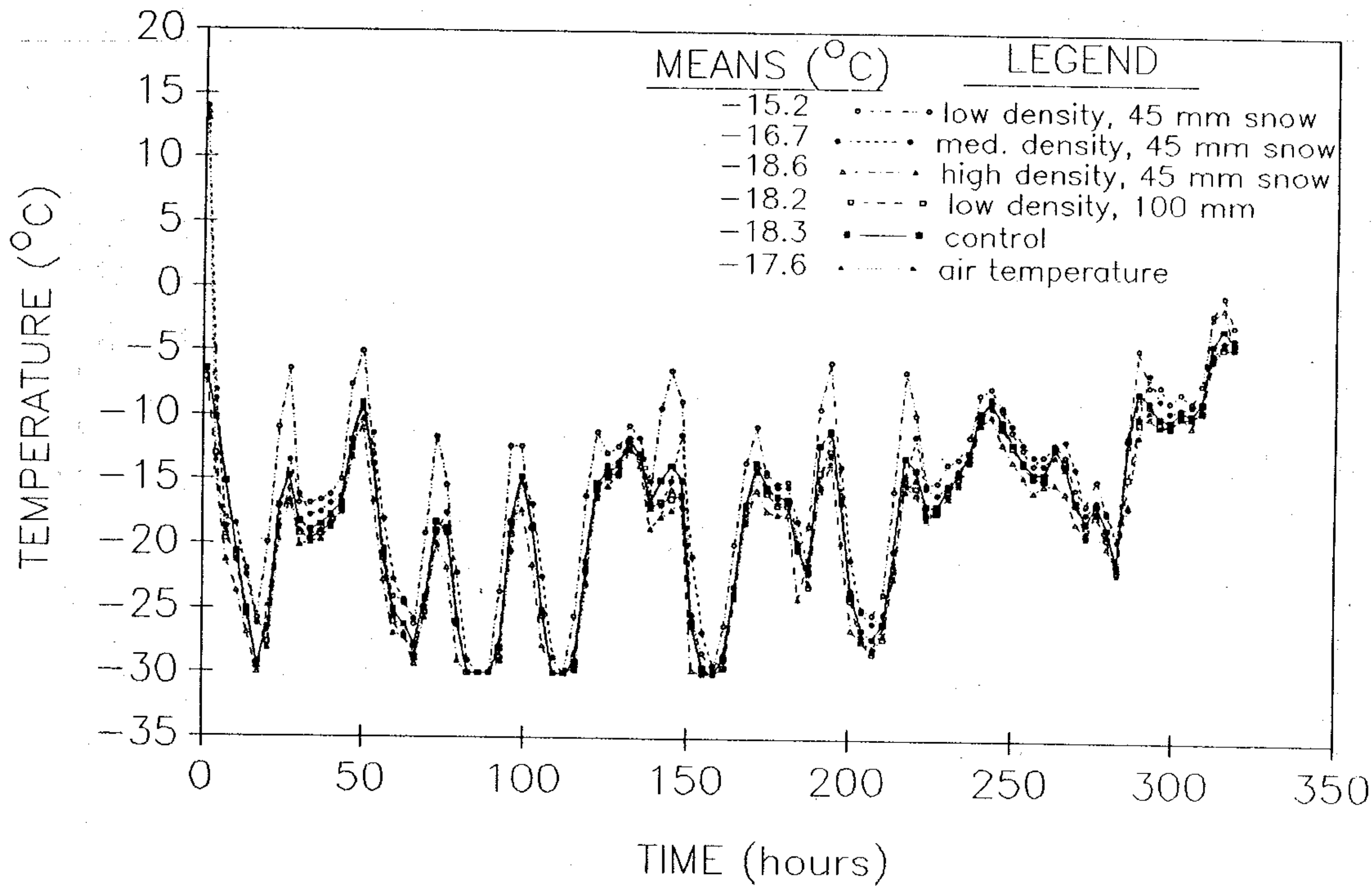


FIGURE 12

SMALL – SCALE EXPERIMENT WINDS

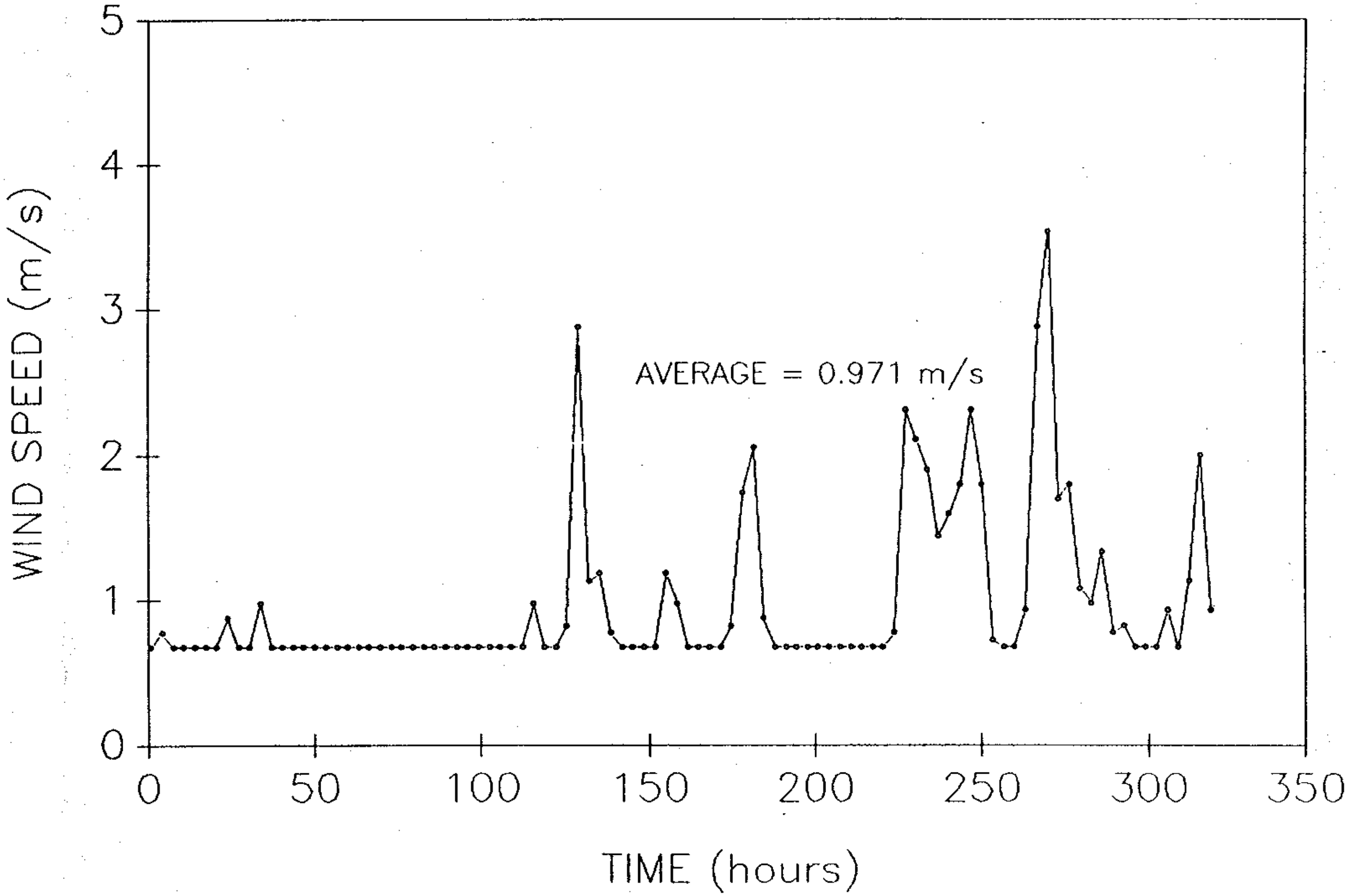
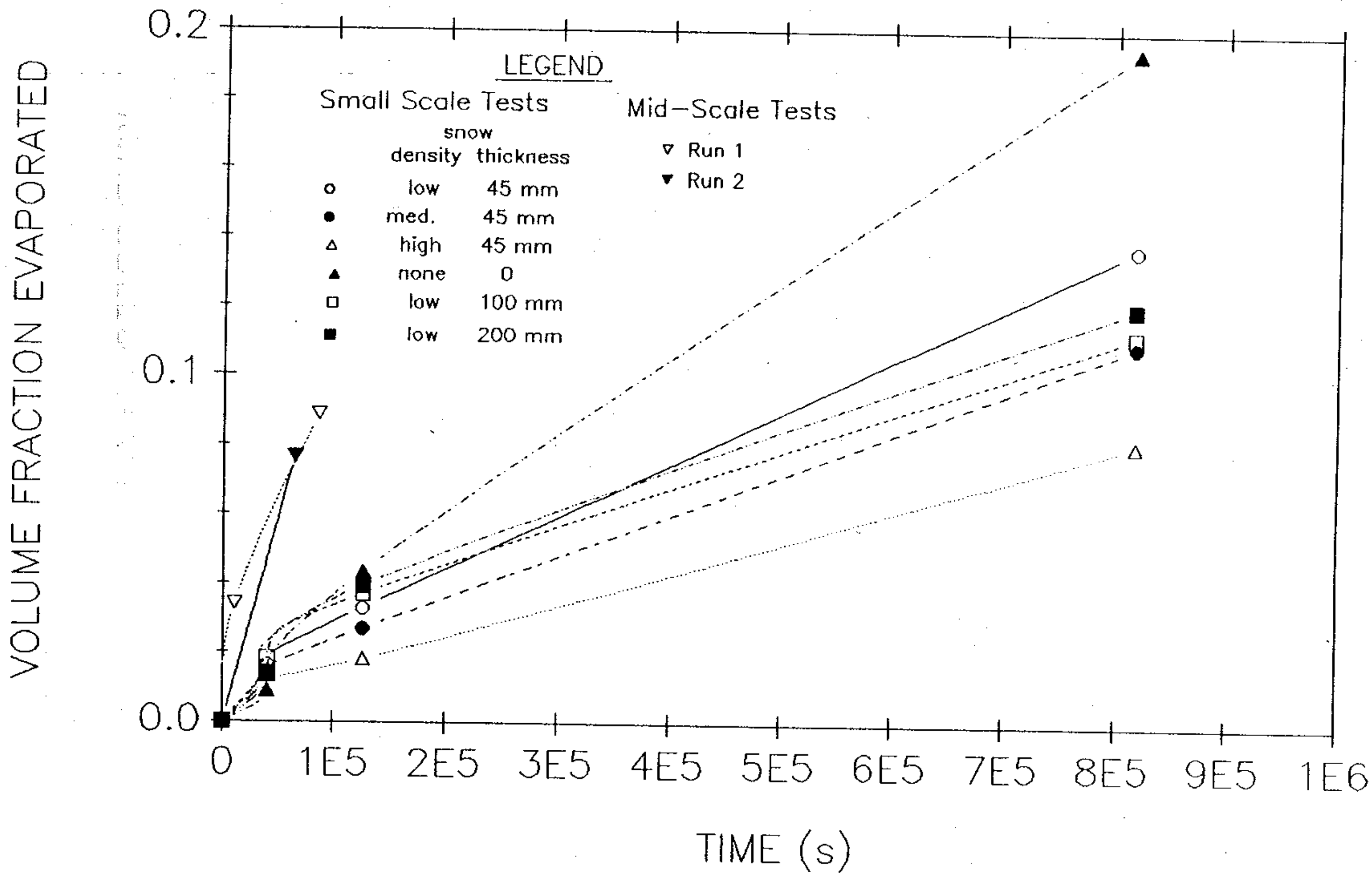


FIGURE 13

EXPERIMENTAL EVAPORATION RESULTS



3.4.1 Determination of the Snow Mass Transfer Coefficient

Using the evaporative exposure approach of Stiver and Mackay (1982) where:

$$F_v = (T/10.3\ T_G)\ \ln\ (1 + (10.3\ T_G/T)\ \ \theta\ \exp\ (6.3 - 10.3\ T_o/T)$$

and $0 = kAt/V = kt/x$

where	F_v	=	volume fraction evaporated
	T	=	environmental temperature (°K)
	T_G	=	slope of modified ASTM distillation curve (°K)
		=	539° K for MSW crude
	T_o	=	intercept of modified ASTM distillation curve (°K)
		=	385° K for MSW crude
	θ	=	evaporative exposure coefficient
	k	=	mass transfer coefficient (m/s)
	A	=	spill area (m^2)
	V	=	spill volume (m^3)
	x	=	slick thickness (m)
	t	=	time (s)

setting $A = (T/10.3\ T_G)$

and $B = (10.3\ T_G/T)\ \exp\ (6.3 - 10.3\ T_o/T)$

gives $F_V = A\ \ln\ (1 + B\theta)$

rearranging yields

$$\theta = (\exp\ (F_v/A) - 1)/B$$

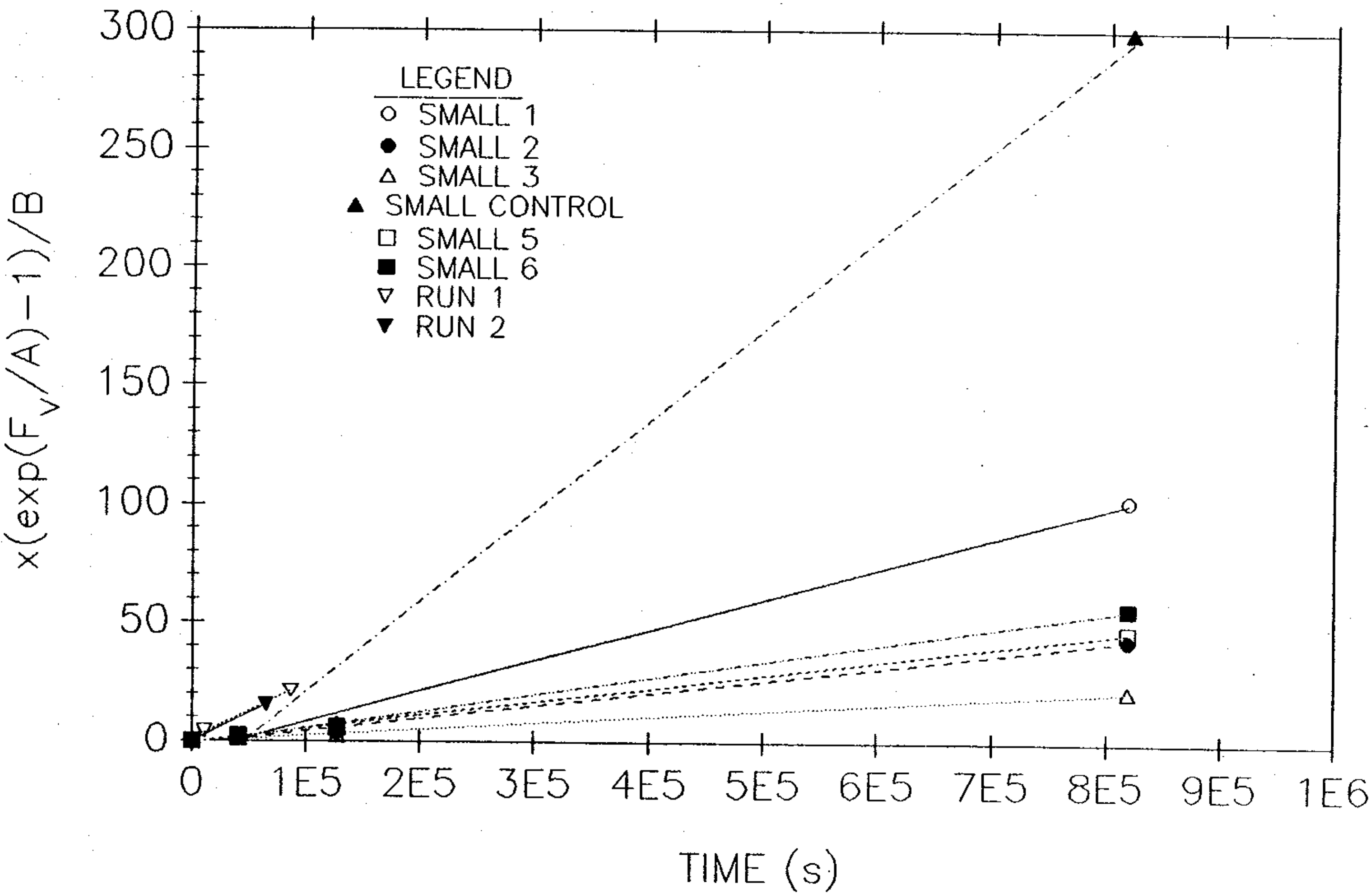
or substituting for 0

$$x\ (\exp\ (F_v/A) - 1)/B = kt$$

thus a plot of $x(\exp\ (F_v/A) - 1)/B$ vs t will have a slope of k, the overall mass transfer coefficient. Figure 14 shows such a plot.

FIGURE 14

Determination of Overall Mass Transfer Coefficient



Using the resistance–in–series approach to mass transfer:

$$1/k = 1/k_w + H/k_o + L/D_s$$

where k_w = air–side mass transfer coefficient (m/s)
= $0.002U^{0.78}$ (Mackay and Matsugu 1973)
k_o = oil internal mass transfer coefficient (m/s)
H = Henry's law constant for the oil
D_s = diffusivity of oil vapours in snow (m^2/s)
L = depth of oil below snow surface (m)

thus a plot of 1/k (the slope of the curves in Figure 14) against snow depth (L) should have a slope of $1/D_s$ and intercept of $1/k_w + H/k_o$. Such a plot is given in Figure 15. The least squares fit to the small–scale data from the trays with uncompacted snow gives a slope of 5.5×10^4 s/m^2 or $D_s = 1.8 \times 10^{-5}$ m^2/s. This is close to reported values of water vapour diffusivities in snow of 6×10^{-5} m^2/s (de Quervain 1972). A line drawn from 500 on the y–axis (equivalent to $1/k_w$ for the mid–scale tests, conducted at temperatures above the pour point), through the two mid–scale data point would have a slope very close 5.5×10^4.

The intercept is 6.4×10^3 equivalent to $(1/k_w + H/k_o)$. With $k_w = 2 \times 10^{-3}$ and H for fresh MSW = 3.5×10^{-5} the internal resistance to mass transfer (k_o) equals 6×10^{-9} m/s. This value is quite close to that determined for waxy oils at temperatures below their pour point (5×10^{-9} m/s).

Although there are insufficient data points to accurately determine the effects of snow density on the diffusivity of the snow, Figure 16 shows the relationship between D_s and the specific gravity of the snow. The values of D_s for the medium and higher density small–scale experiments come from the slope of the line drawn from the control data point (snow depth = 0) to the respective density data point. These data indicate that diffusivity varies inversely with the fourth power of snow specific gravity. Although it makes sense that diffusivity should decrease with increasing snow density, a dependence on the fourth power of density seems excessive. With the present data it is not possible to determine more accurately the true relationship; more experiments are required.

FIGURE 15

DETERMINATION OF DIFFUSIVITY IN SNOW

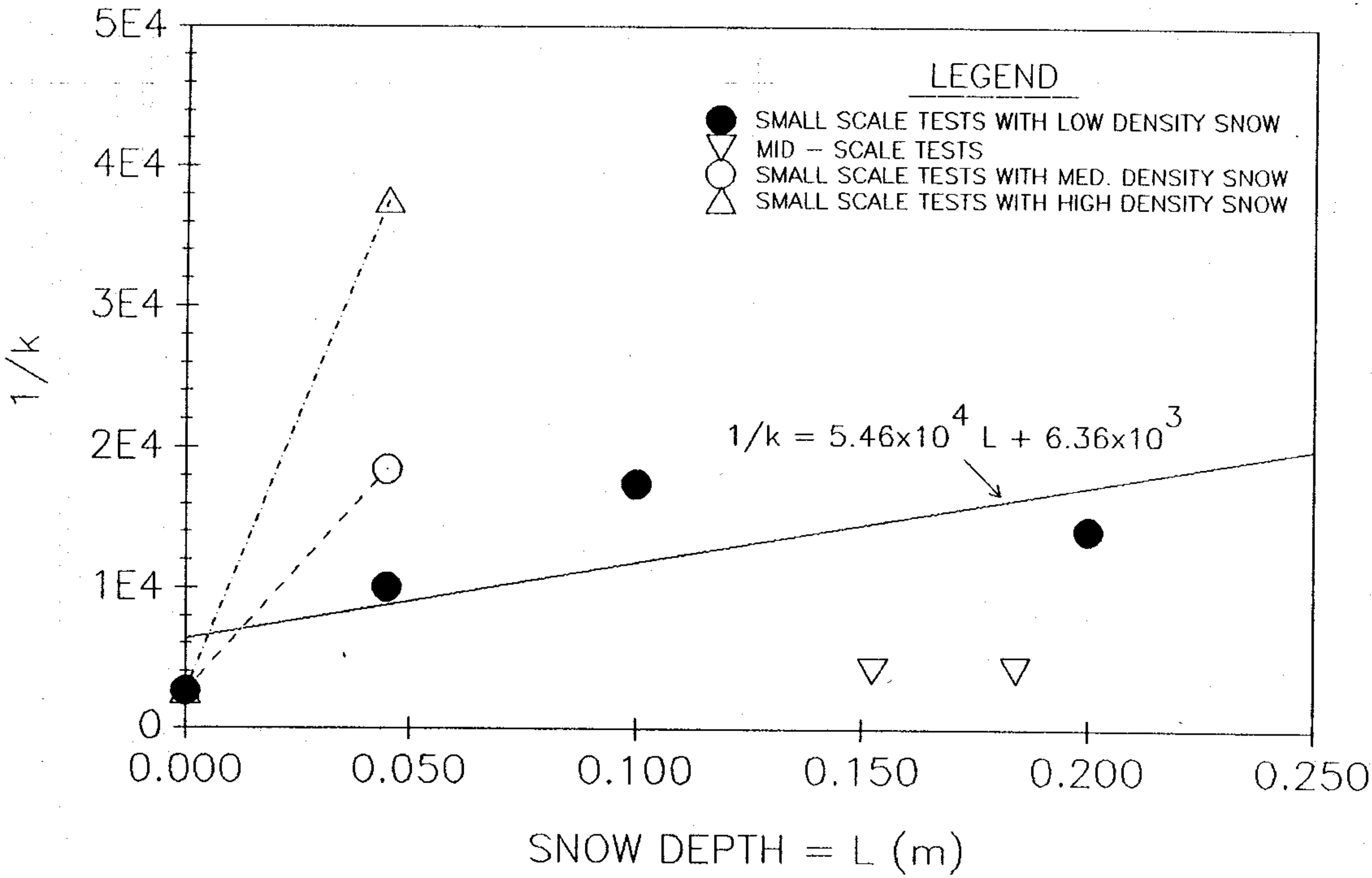
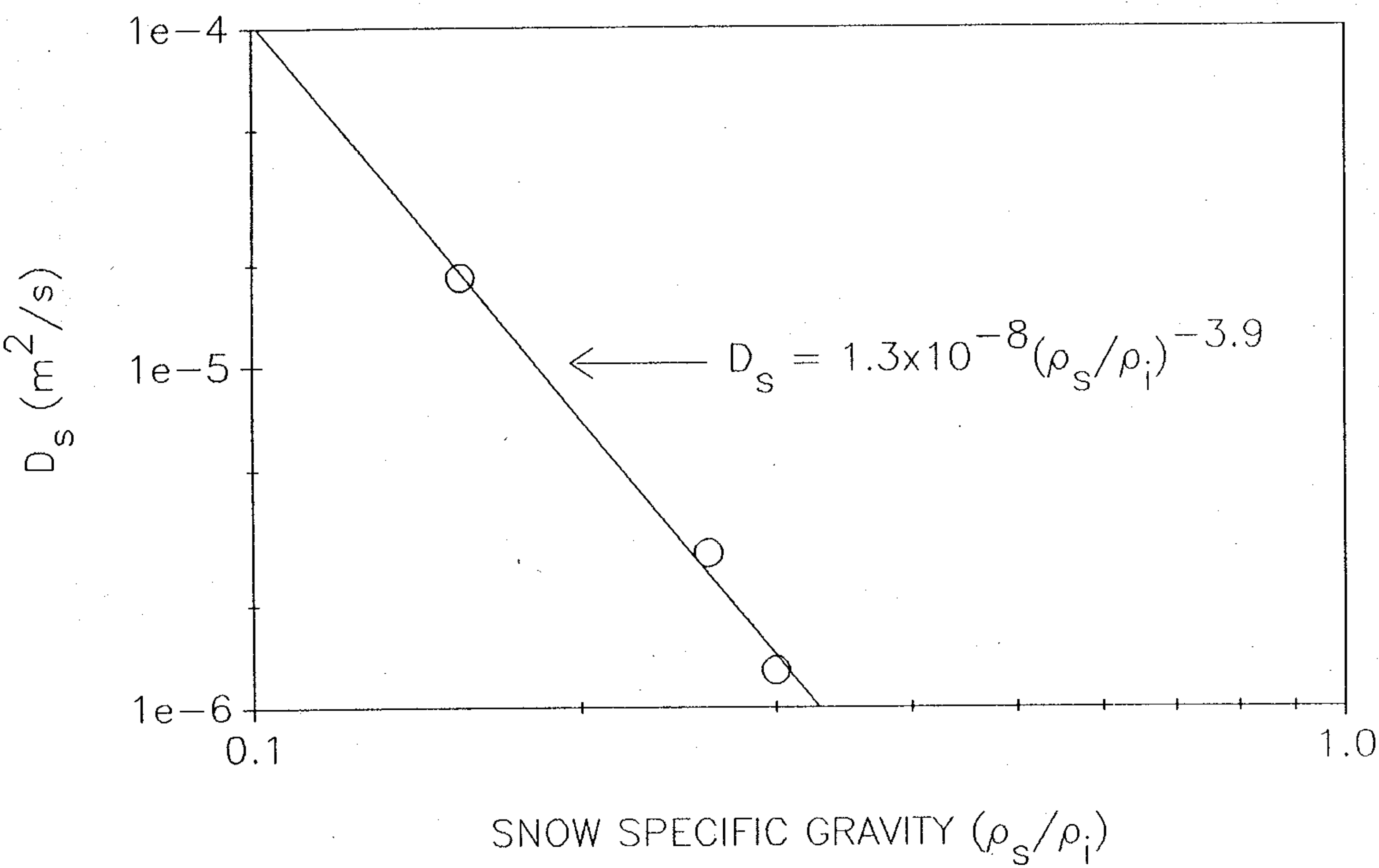


FIGURE 16

VARIATION IN D_s WITH SNOW DENSITY



3.5 OIL TRANSPORT BY BLOWING SNOW

Unfortunately, due to unusually warm, dry conditions in the areas where the experiments were set up no useful data on the transport of oil by blowing snow was collected. The raw data and meteorological records are contained in Appendix II.

During the small–scale evaporation studies it was noted that when snow fell on a fresh pool of oil, the snowflakes would absorb oil. These lightly coated snowflakes could be easily blown off the slick, carrying a small amount of oil with them. This seems to be the most likely mechanism for the transport of oil by snow; oil spilled into or onto snow and absorbed is relatively immobile. Thus, only during fall or spring snowfalls (when fresh oil can be found on a snow–free ice or ground surface) is the transport of oil by blowing snow likely.

4.0 ARCTIC SNOW CONDITIONS

4.1 SNOW DEPTH AND DENSITY

4.1.1 Data Sources

Snow depths measured on ice surfaces have been recorded for various locations throughout the arctic (Atmospheric Environment Service, 1982). The data is reported as mean monthly snow depths. Snow depths for various land stations, listed in other Atmospheric Environment publications (Burns 1974 and Maxwell 1980), are reported as mean aggregate snowfall or as amounts of snowfall at given probability levels for three month intervals and are not presented here.

Snow cover densities in the arctic are among the highest in Canada (Maxwell 1980). Mean monthly snow cover densities for selected arctic locations (listed in Table 3) are from Burns (1974) and Maxwell (1980). The densities are calculated from monthly nomographs for estimating snow cover density and are not actual field measurements. Local relief and vegetation are not taken into account using this method for determining snow densities and the estimates are only useful on a regional scale (Maxwell 1980).

There are few studies that have actually measured snow cover densities in the arctic (Frederking, pers. comm). The most extensive snow density data set was collected at Pond Inlet between 1978 and 1986. This work is unpublished but can be obtained through H. Steltner (pers. comm.). Snow depth and density measurements as a function of time are available for Eclipse Sound, near Pond Inlet (Sinha and Nakawo 1981) and Resolute (Longley 1960). There is essentially no snow density data for the western Canadian arctic. A recent publication on the climate of the Yukon (Wahl et al. 1987) does not report any snow densities as the data set is considered too short term and discontinuous for statistical analysis.

4.1.2 Results

Mean monthly snow depths for selected locations throughout the arctic are presented in Figures 17 to 28. All snow depths were measured on the ice surfaces of the local water bodies and are not land based measurements. The period of record for most locations is greater than 25 years. Snow depth, after the initial accumulation in early winter, is a function of the surface topography and the direction of the last strong winds. Accumulated snow fall does not have a significant effect on the snow cover, except in protected areas (Burns 1974; Longley 1960). Snowfall reflects both the pattern of cyclonic storm trajectories and the local effects of orography and open water. Snow accumulation is proportional to the height and density of vegetation and is also affected by variations in energy factors, such as shading and pollution (Burns 1974). Snow depths are generally greatest in mountainous regions of the eastern arctic, such as Cape Dorset and Resolute (Figures 18 to 27, respectively), and lowest in the exposed tundra of the western arctic, such as Cambridge Bay (Figure 17).

Estimated monthly snow densities for many of the same locations are listed in Table 3.

TABLE 3

ESTIMATED MEAN MONTHLY SNOW COVER DENSITIES FOR SELECTED LOCATIONS

	SNOW COVER DENSITIES (g/cm^3)				
Location	**November**	**December**	**January**	**February**	**March**
Cambridge Bay	0.36	0.33	0.38	0.37	0.35
Cape Parry	0.30	0.28	0.32	0.33	0.33
Coppermine	0.30	0.29	0.33	0.33	0.33
Hall Beach	0.36	0.31	0.36	0.35	0.34
Inuvik	0.24	0.27	0.31	0.30	0.31
Iqaluit	0.24	0.23	0.28	0.27	0.30
Mould Bay	0.34	0.33	0.36	0.36	0.35
Norman Wells	0.24	0.26	0.30	0.26	0.28
Resolute	0.37	0.33	0.37	0.37	0.36
Sachs Harbour	0.34	0.31	0.33	0.33	0.33

Source: Burns 19874 and Maxwell 1980

Figure 17

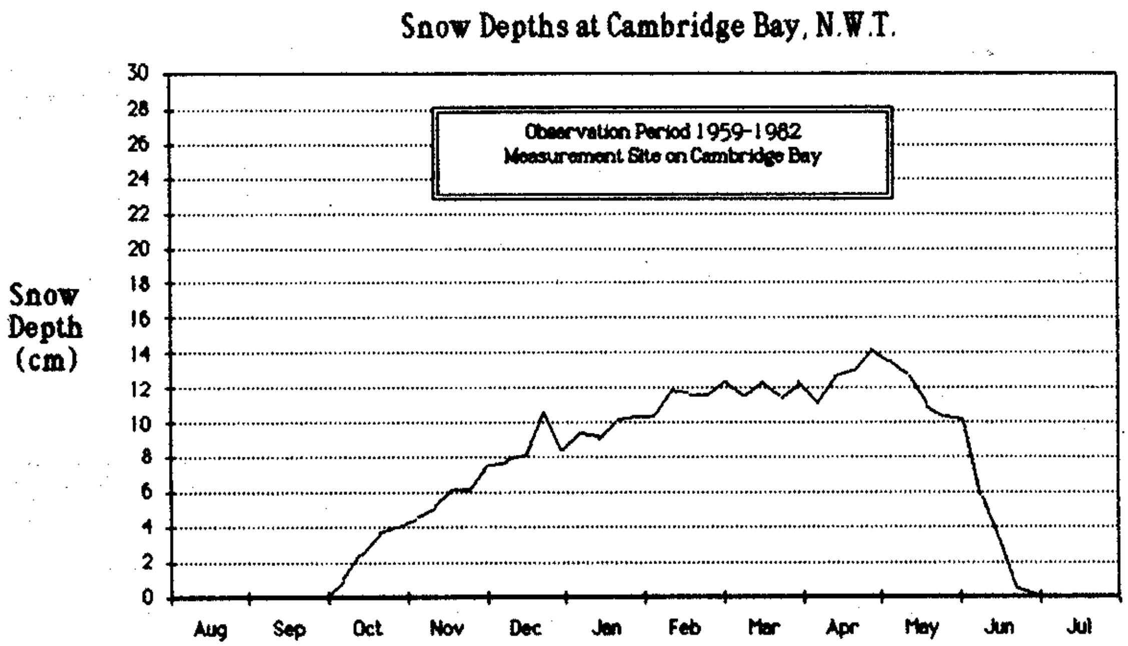


Figure 18

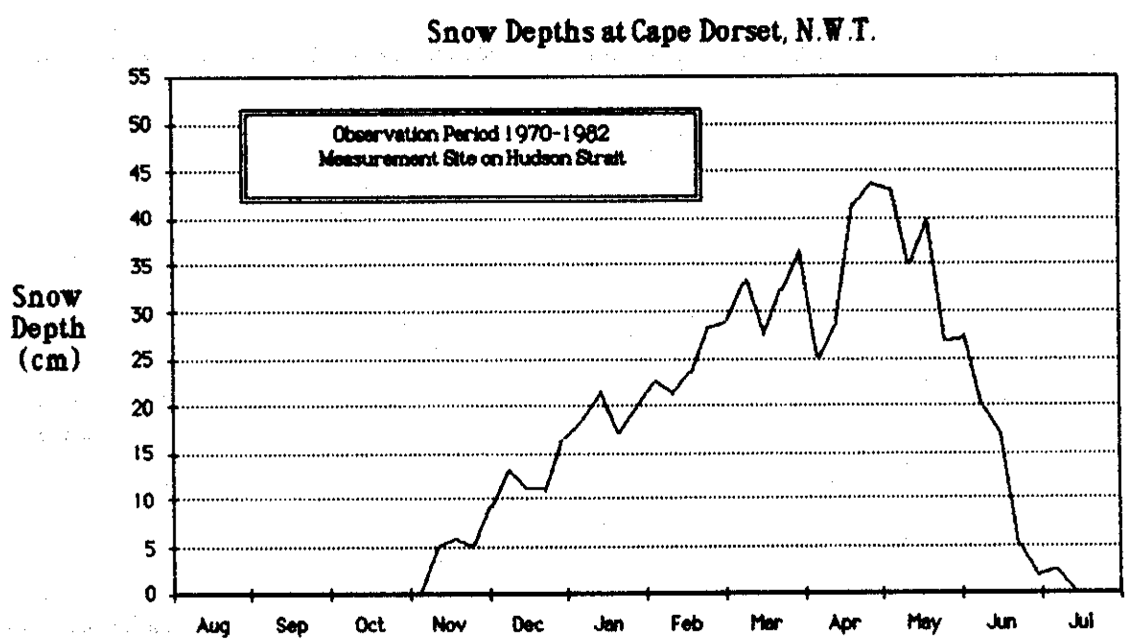


Figure 19

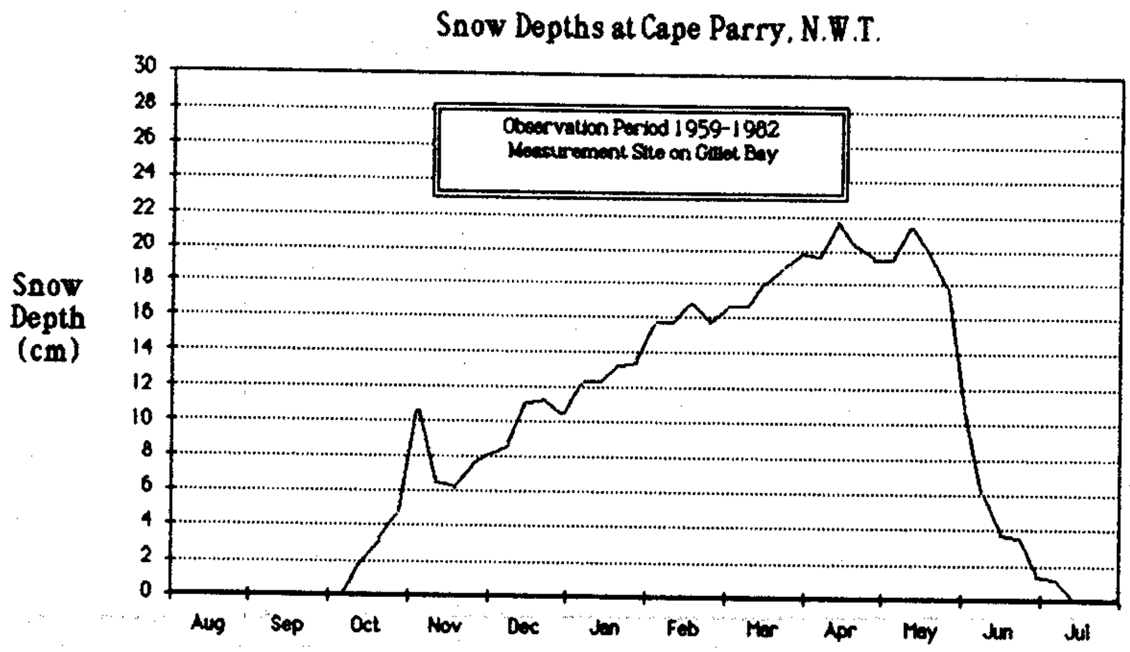


Figure 20

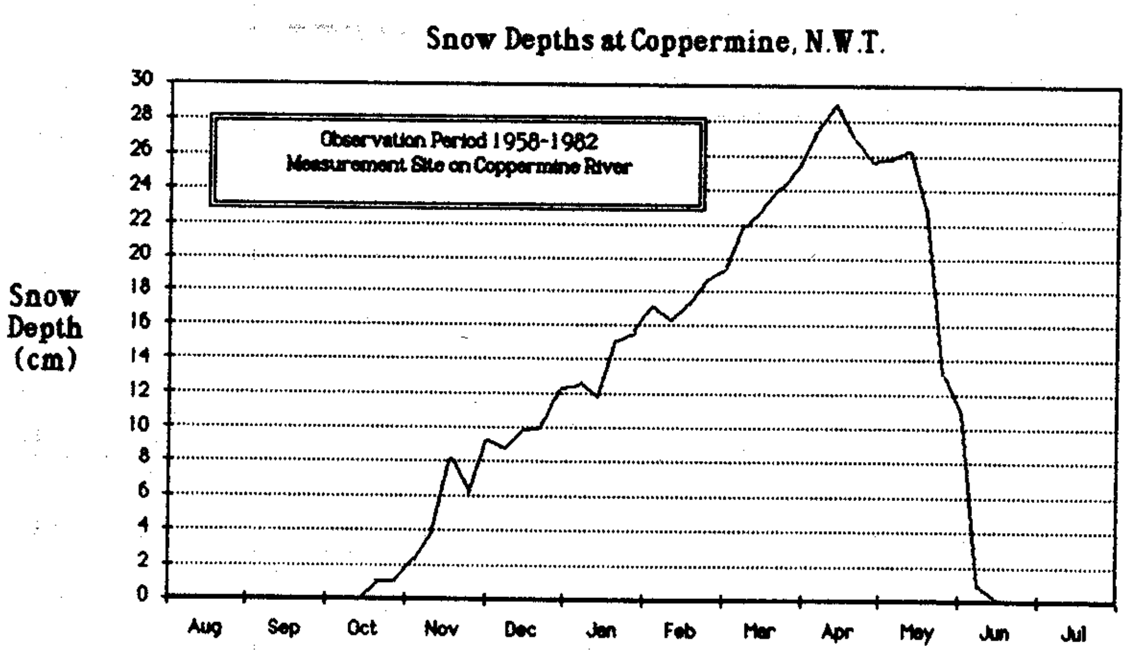
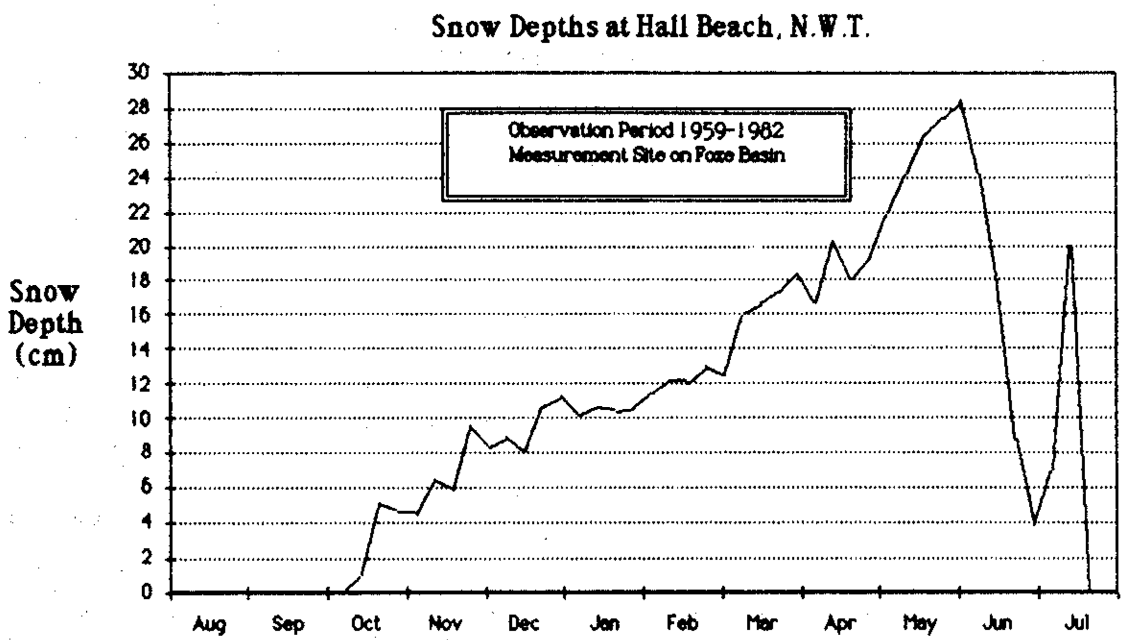


Figure 21



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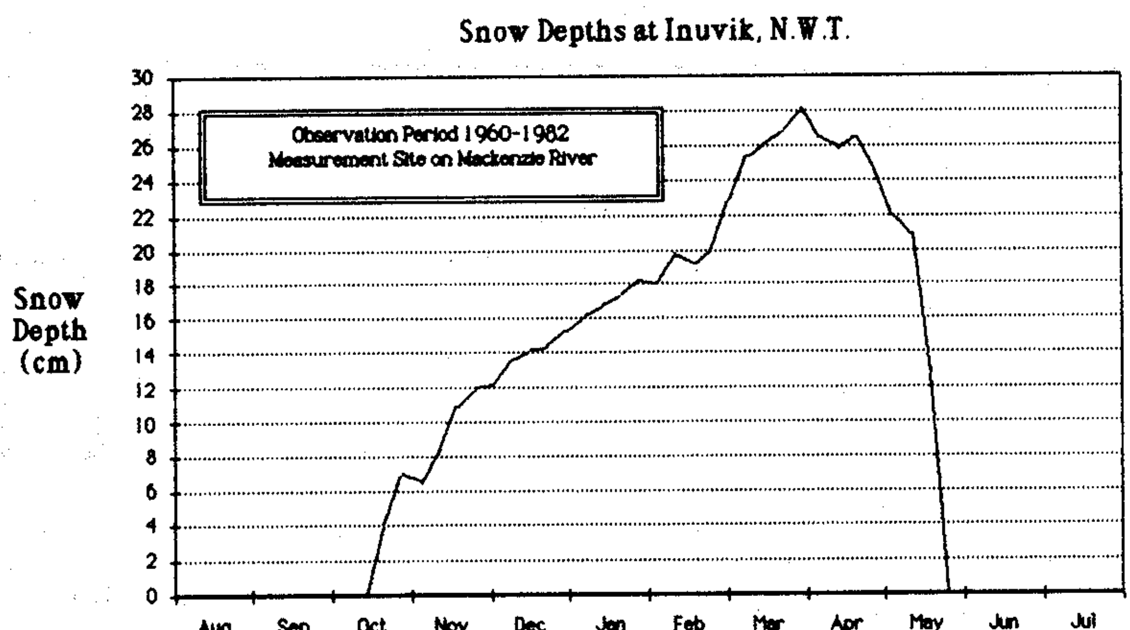
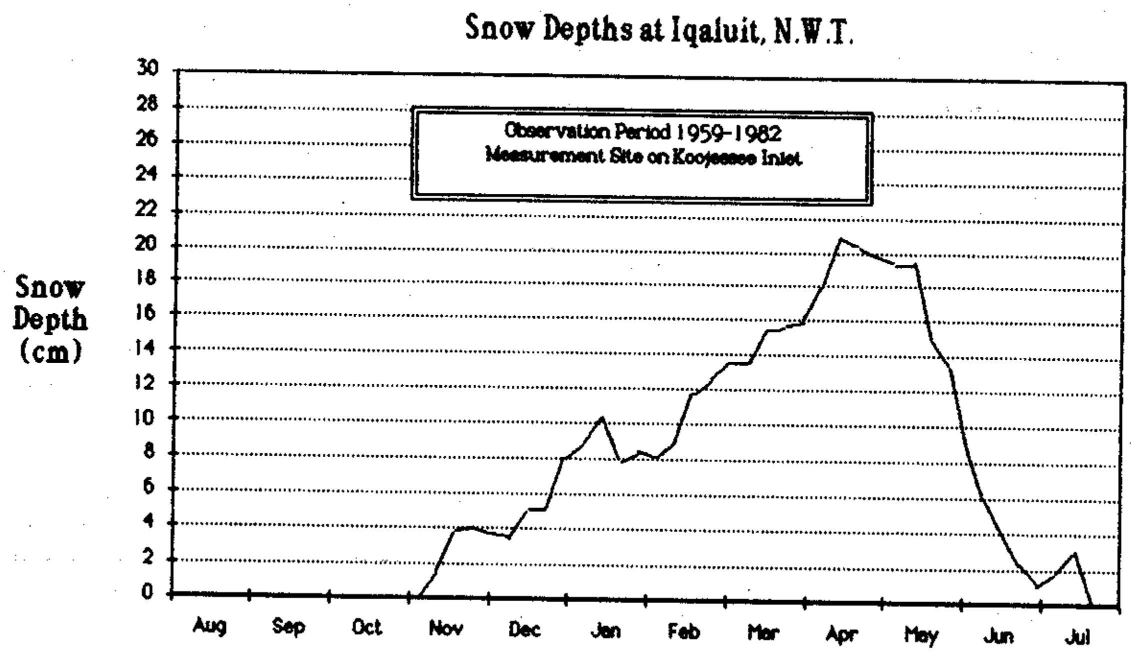


Figure 23



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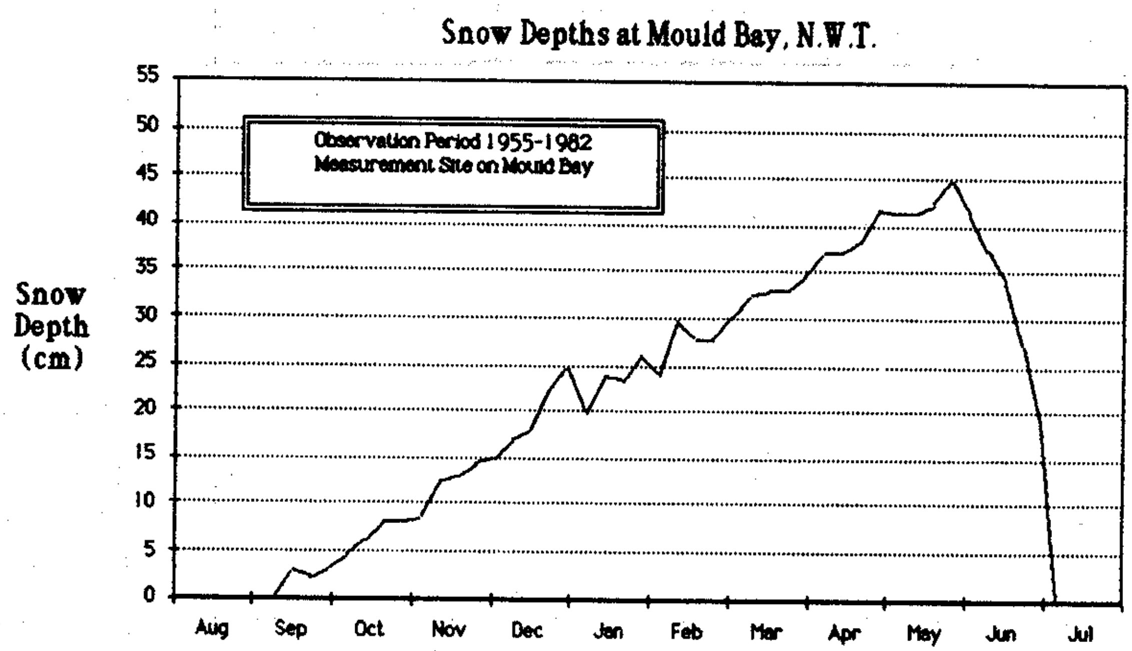


Figure 25

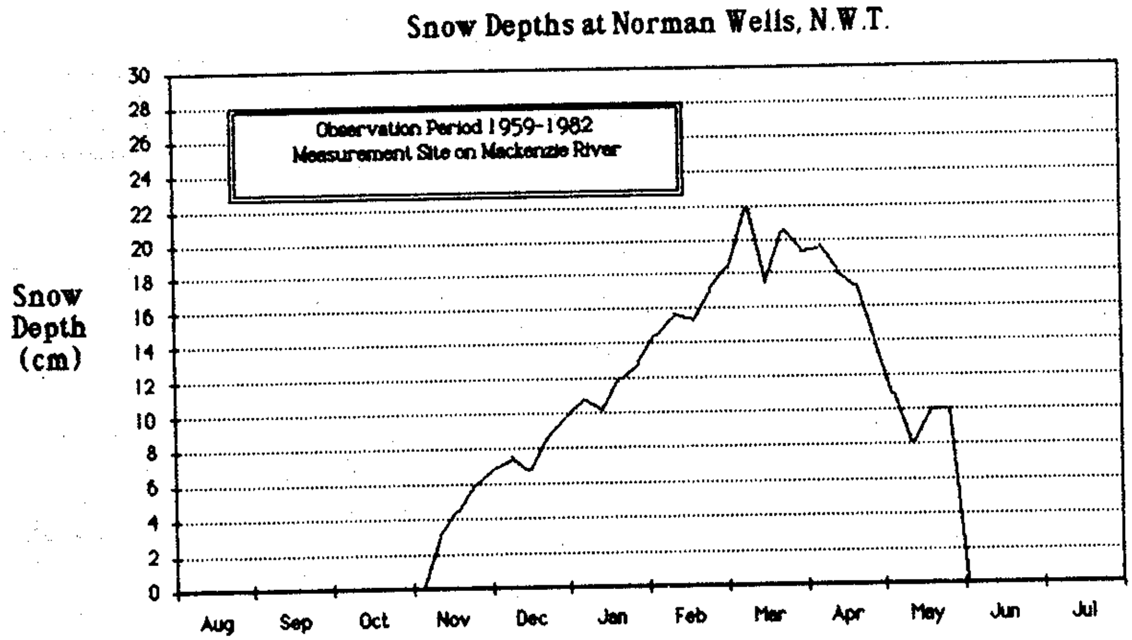


Figure 26

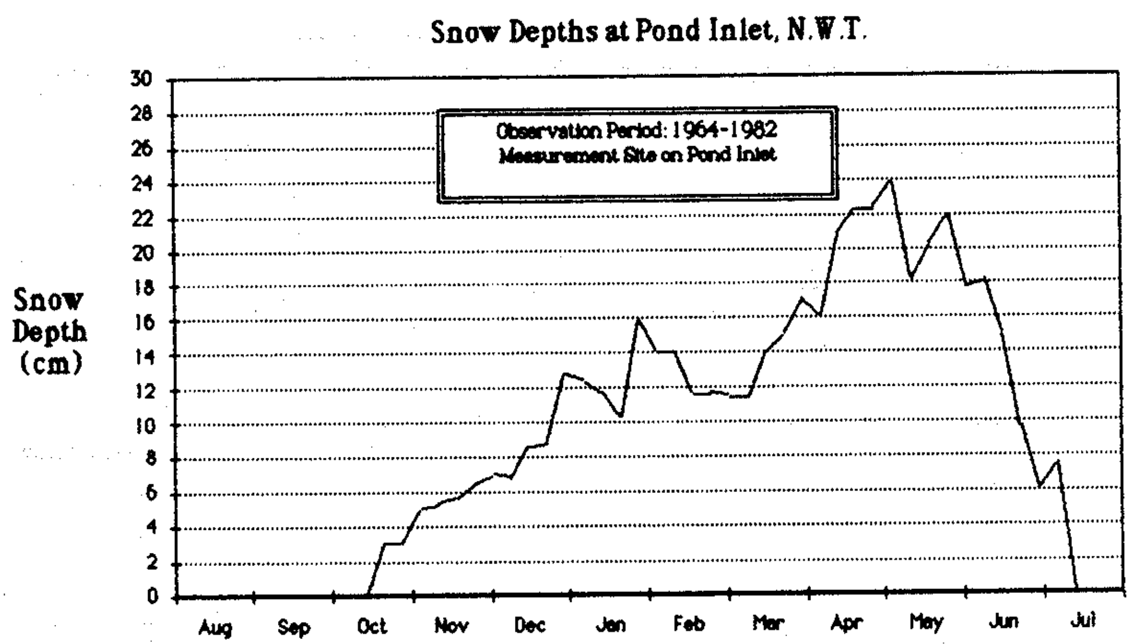


Figure 27

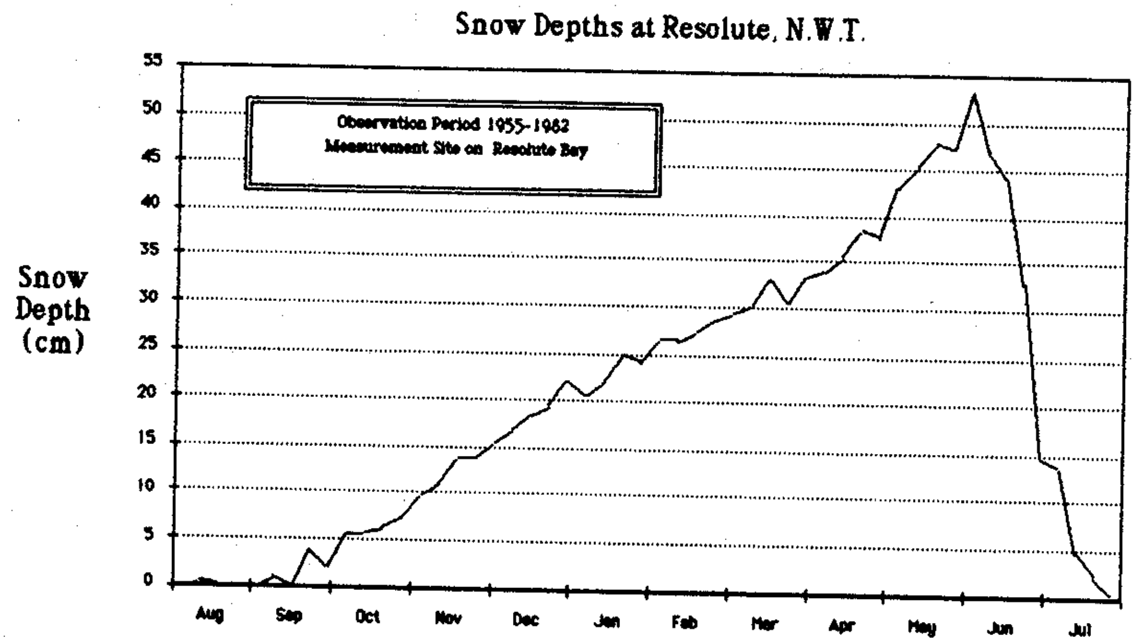
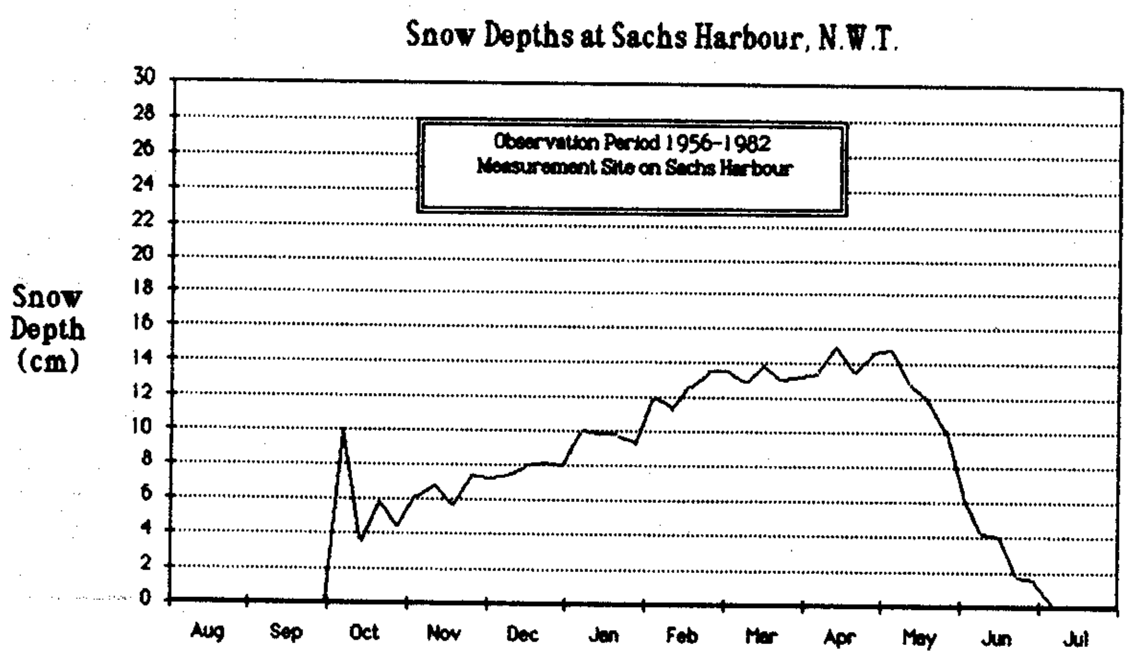


Figure 28



In general, the relationship between snow cover density and air temperature and wind speed is that lower mean monthly air temperatures and/or strong winds correspond to higher mean monthly snow densities. In November, wind speeds were most important in determining snow densities while, in February and March, the stations (listed above in Table 3) with the lowest monthly temperatures had the highest snow densities (Maxwell 1980).

Average, winter snow densities at Aklavik and Resolute, measured over an unspecified period of years, are listed in Table 4 below (Williams and Gold 1958). The results seem to agree with the estimated snow densities for Inuvik (close to Aklavik) and Resolute in Table 3. Snow density measurements at Nanisvik, on Baffin Island, are listed in Table 5 below (Frederking pers. comm).

TABLE 4

CALCULATED MEAN SNOW DENSITIES FOR AKLAVIK AND RESOLUTE

Location	Mean Snow Density (g/cm^3)	Standard Deviation (g/cm^3)	No. Observations
Aklavik	0.242	0.053	93
Resolute	0.356	0.052	261

Source: Williams and Gold 1958.

TABLE 5

SNOW MEASUREMENTS AT NANISIVIK

SNOW DEPTH (cm)	SNOW DENSITY (g/cm^3)	SALINITY (ppt)
5–6	0.4	6
15–20	0.3	3

Measurements taken on Strathcona Sound, 2 km offshore, in March 1986.

Source: Frederking, R. pers. comm.

Two detailed studies of snow depth and densities were conducted at Resolute during the winter of 1957–58 (Longley 1960) and on Eclipse Sound, near Pond Inlet, during the winters of 1977–78 and 1978–79 (Sinha and Nakawo 1981).

Figures 29 and 30 show the snow depth and density measurements at Resolute in the winter of 1957–58. Snow measurements were collected along three transect lines running along the lake shore and over the raised marine beaches. Both snow depth and density varied considerably between sampling locations, even in sites less than 100 m apart. The study concludes that recorded depths of new snow are not too reliable and that choosing a representative site to measure mean snow depth is difficult (Longley 1960). Snow densities varied considerably over a small area, as well as from layer to layer within the snow cover. Density variations can also be diurnal (Burns 1974). Because of this variability, snow densities do not warrant being reported to any accuracy greater than ±0.05 g/cm^3 for arctic locations (Longley 1960).

Figures 31 and 32 present the results of Eclipse Sound study. Snow depths and densities varied between the two seasons. Snow cover varied with time as well as location during the second winter. Although the scatter was different, the average snow depths were the same for both winters. Snow density did not show any particular pattern over time. The average snow density wa 0.35 ±0.04 g/cm^3 in 1977–78 and 0.26 ±0.06 g/cm^3 in 1978–79 (Figure 32). The 1977–78 measurement agrees with the mean snow density measured at Resolute by Williams and Gold (1958, see Table 4). However, the range in snow densities between seasons is similar to that found between locations at Resolute by Longley (1960).

Figure 29

Mean Snow Depths at Resolute, Winter 1957-58

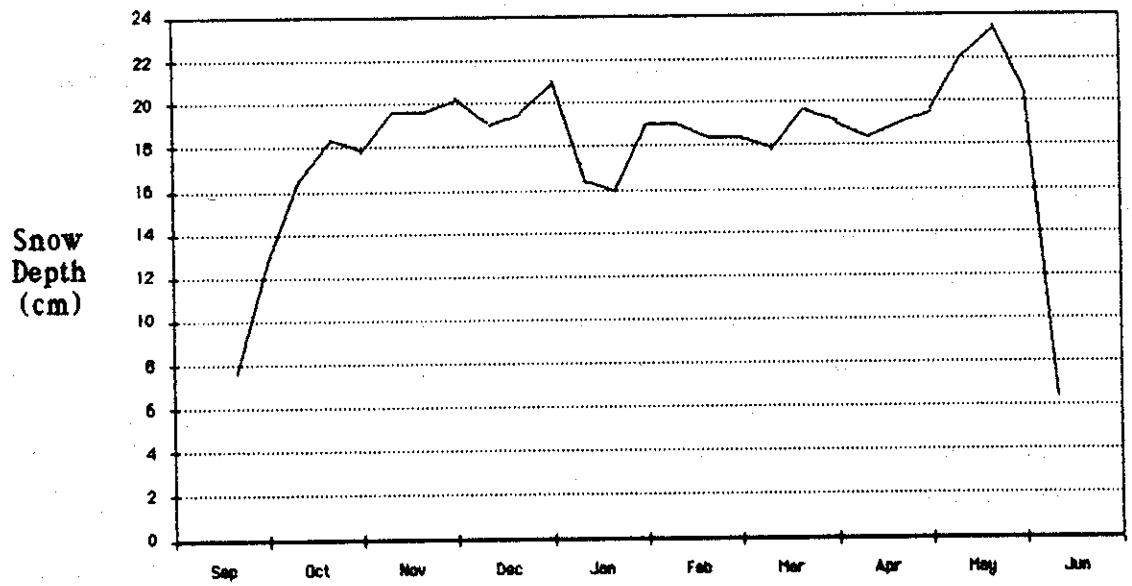


Figure 30

Snow Cover Densities at Resolute, Winter 1957-58

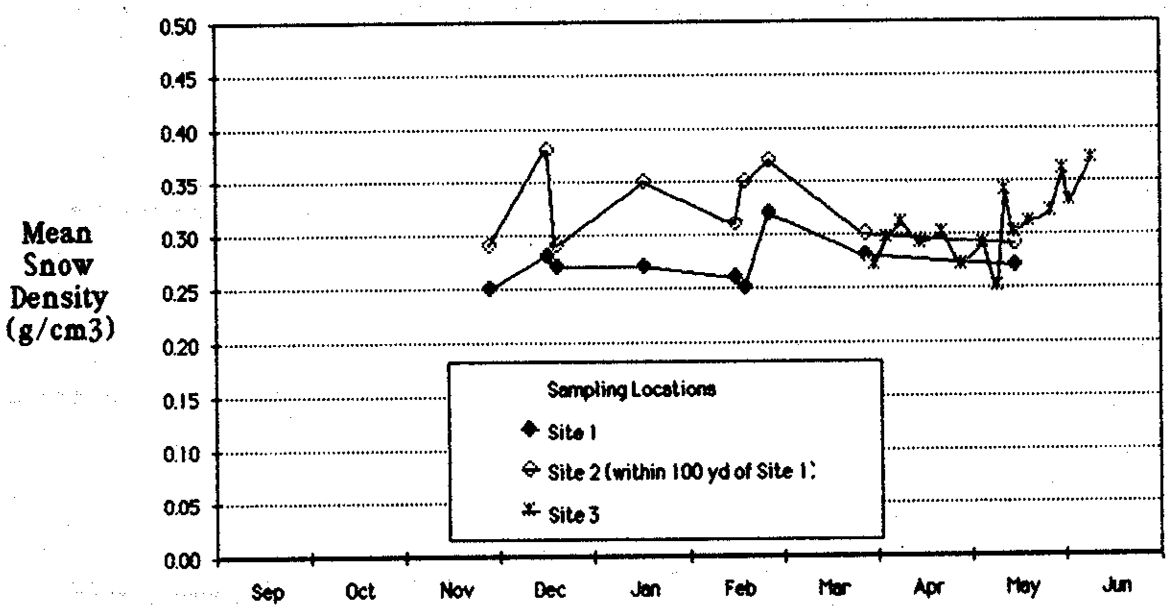


Figure 31

Snow Cover Depths at Pond Inlet

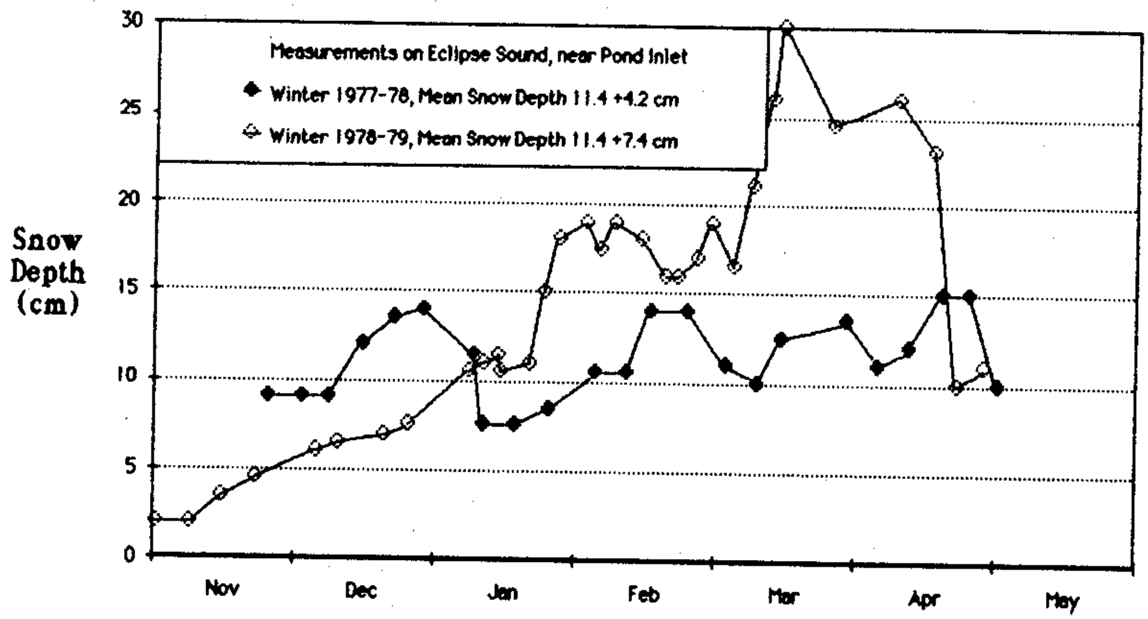
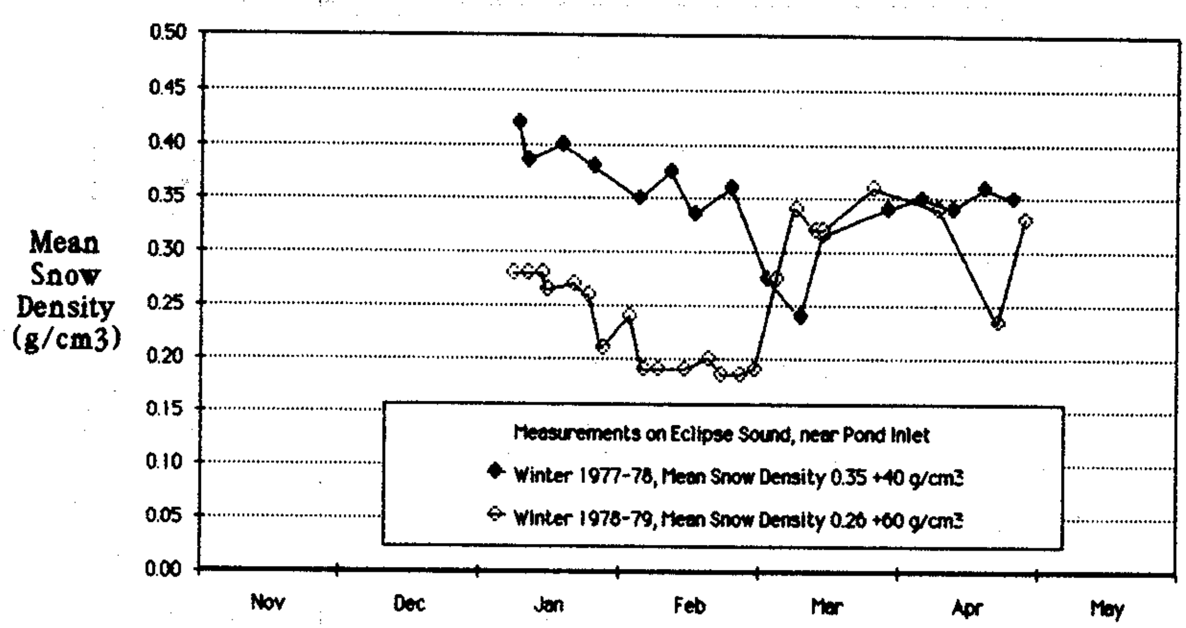


Figure 32

Snow Cover Densities at Pond Inlet



5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

1. Oil spreading on snow or ice can be modelled using the equations for the gravity–viscous spreading regime:

   For a continuous source
   $r = (g\,Q^2/\pi\,\nu^{1/2})^{1/6} t^{1/2}$
   and for an instantaneous spill
   $r = (gV^2/\pi\,\nu^{1/2})^{1/6} t^{1/4}$

2. Oil infiltration into a snowpack can be modelled using the D'Arcy equation:

   $Q = KA\rho g(1 + x/L)/\mu$
   and
   $dL/dt = (K\rho g/E\mu)(1 + x/L)$

3. The horizontal spreading of oil on an impermeable surface beneath a snowpack can be modelled by:

   For a continuous source
   $L = (2Kg\rho Q/\pi E^2\mu)^{1/4} t^{1/2}$
   and for an instantaneous release
   $L = (2Kg\rho V/\pi E^2\mu)^{1/4} t^{1/4}$
   in which
   $K = 7.7 \times 10^{-2}\, d_o^2 \exp(-7.8\, \rho_s/\rho_i)$

4. The evaporation of oil beneath a snowpack can be modelled by the evaporative exposure approach using:

   $1/k = 1/k_w + H/k_o + L/D_s$
   where the diffusivity in snow was found to be
   $D_s = 1.3 \times 10^{-8}\, (\rho_s/\rho_i)^{-3.9}$

5.2 RECOMMENDATIONS

Further work on the effect of snow density on oil evaporative flux should be conducted.

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APPENDIX I

RESULTS OF LITERATURE SURVEY

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BARNES, P.W., E. REIMNITZ, L.J. TOIMIL, and H.R. HILL. 1979. Fast Ice Thickness and Snow Depth Relationships Related to Oil Entrapment Potential, Prudhoe Bay, Alaska. POAC '79: The Fifth International Conference on Port and Ocean Engineering under Arctic Conditions, Norwegian Institute of Technology, August 13-18, 1979. Vol. 2, pp. 1205-1225.

Investigations in early May, 1978, studied the relationship between ice bottom morphology, sea bed morphology, tidal currents, and variations in snow thickness at three sites representing three different fast ice environments - protected bay, deep, open lagoon, and narrow tidal channel. Snow depth and ice thickness exhibit a negative correlation - thin ice coinciding with a thicker insulating snow cover. The results imply a seasonal stability for the snow ridge pattern and that sub-ice oil concentrations would be indicated by surficial snow morphology in the fast ice zone. Spreading directions would be enhanced in the elongate dimensions of the under-ice ridges and troughs, that is, upwind and downwind. In spring, gases will leak to the surface.

BENNETT, E.R., K.D. LENSTEDT, V. NILSGARD, G.M. BATTAGLIA, and F.W. PONTIUS. 1981. Urban Snowmelt Characteristics and Treatment. Journal of Water Pollution Control Federation, Vol. 53, No. 1, pp. 119-125.

The pollutional characteristics of rainfall runoff versus snowmelt have been assessed for two urban sites: one a high housing density, high traffic volume area, the other a typical single family residential area. The higher density site produced greater quantities and concentrations of pollutants than the lower density area. Snowmelt was much lower in nitrogen and phosphorus than rainfall runoff and resulted in higher concentrations of dissolved solids (from de-icing chemicals) and oil and grease (from slush washing the undersides of vehicles). Initial treatability studies on snowmelt showed that coagulation as well as filtration were effective but that plain sedimentation was relatively ineffective because of the noncolloidal nature of the suspended matter.

CHEN, E.C. 1972. Arctic Winter Oil Spill Test: United States Coast Guard. Technical Bulletin, Inland Waters Directorate, No. 68. Ottawa.

As part of an arctic pollution control program, the U.S. Coast Guard conducted a series of tests off the northern coast of Alaska during the summer and winter of 1970 to investigate the behavior of crude oil spills in the Arctic.

COLLINS, C.M. 1983. Long-Term Active Layer Effects of Crude Oil Spilled in Interior Alaska. Permafrost: Fourth Annual International Conference, July 17-22, 1983, Washington, D.C, pp. 175-179.

Two experimental oil spills of 7570 litres each were conducted at a black spruce forested site in February and July of 1976. The long-term effects of the spills on the active layer were directly related to the method of oil movement. The winter spill moved beneath the snow within the surface moss layer, and the summer spill moved primarily below the moss, in the organic soil. The summer spill effected an area nearly one and one-half times that of the winter spill. Only 10% of the 303 m^2 in summer spill area had oil visible on the surface, while 40% of the 188 m^2 winter spill had visible oil. Thaw depths in the summer spill area increased from 1977 to 1980 - average thaw depth was 72 cm versus 48 cm in the control - and remained essentially the same in 1981 and 1982. Thaw depths in the winter spill area continued to increase until 1982 to an average of 92 cm. Presumably the change in albedo due to the surface oil accounts for the increased thaw in the winter spill area.

DESLAURIERS, P.C. 1978. Behavior of the Bouchard 65 Oil Spill in the Ice-Covered Waters of of Buzzard Bay. Proceedings Tenth Annual Offshore Technology Conference, 1978, Dallas, Texas. Vol. 1, pp. 267-276.

The Buzzards Bay spill, which occurred in moving ice, was of particular interest. Initially, the strong tidal currents transported most of the oil leaking from the barge into the broken ice field and beneath the large ice floes. The oil then collected in the crack systems of the rafted ice, hummocks, pressure ridges, and leads, and occupied an area of about 0.1 km^2. Oil pools formed by the rafted ice contained up to 2,000 gal. of pure oil. Some oil in concentrated areas spread onto the ice floe surface primarily by wind forces. The No. 2 oil weathered at different rates, ranging from 6 to 47 percent volume loss, depending upon the degree of oil exposed to the air.

On Feb 5, 0.1 m of snow fell at Buzzards Bay covering most of the oil from view; oil in concentrated pools formed a slush-like mixture containing 30 percent oil by volume. This snow greatly hindered aerial surveillance, research efforts, and cleanup attempts. Several cleanup techniques were used; the most succesful was direct suction from concentrated pools into vacuum trucks accounting for nearly 13,000 gal of recovered oil. The ice began to break up around Feb. 8, releasing the oil contained in the ice in the form of a thin sheen. In addition, oily ice floes were transported by the currents through Cape Cod canal into Cape Cod Bay, where they melted. These processes continued until about Feb. 26, 1977, when Buzzards Bay was essentially free of visible oil.

DESLAURIER, P.C. 1978. Oil Spill Behavior in Ice During the 1977 Buzzards Bay Oil Spill. The Proceedings of the Conference on Assesment of Ecological Impacts of Oil Spills, June 14-17, 1978, Keystone, Colorado. American Institute of Biological Sciences. Vol. 1, pp. 197-215.

On January 28, 1977, the barge BOUCHARD #65 grounded, releasing approximately 81,150 gal of No. 2 home heating oil into Buzzards Bay, which was 90% ice covered. Field measurements and observations were initiated at the spill site on January 29, and continued until February 25, when only negligible amounts of oil remained in the bay. Of particular interest was the initial transport of the oil under the ice, its concentration in the rafted ice, the interaction of the oil with the hummocks and pressure ridges, its spreading from concentrated pools on the surface of ice floes, its penetration into the snow and ice, the weathering of the oil, and its final transport by ice floes during breakup.

FUSSELL, D.R., H. GODJEN, P. HAYWARD, R.H. LILIE, and A. MARCO. 1981. Revised Inland Oil Spill Clean-Up Manual. CONCAWE, The Hague, 159 pp.

The present manual is based on an earlier report of CONCAWE (1975) entitled "Inland Oil Spill Clean-Up Manual", but takes into account more recent developments in hardware and methodology, and also considers in greater detail the problems associated with spills in ice and snow.

GOLDEN, P.C. 1974. Oil Removal Techniques in an Arctic Environment. Marine Technology Society Journal, Vol. 8, No. 8, Dec. 1974, pp. 38-43.

Tests indicate that crude oil (60°F) poured onto ice and snow in the arctic under summer and winter conditions spreads to a minimum thickness of 0.5 cm. On snow and ice the oil flows downslope pooling in depressions. Oil penetrates summer ice. Virtually no oil penetration occurs on winter snow and ice; the temperature difference between the oil and the snow or ice causes an immediate melting and refreezing at the interface. The spread of oil under ice floes is restricted by the depressions and roughness of the bottom face of the ice.

JOHNSON, L.A., E.B. SPARROW, T.F. JENKINS, C.M. COLLINS, C.V. DAVENPORT, and T.T. MCFADDEN. 1980. The Fate and Effects of Crude Oil Spilled on Subarctic Permafrost Terrain in Interior Alaska. Cold Regions Research and Engineering Laboratory, CRREL Report 80-29. Hanover, New Hampshire.

This study was conducted to determine the short- and long-term physical, chemical, and biological effects of spills of hot Prudhoe Bay crude oil on permafrost terrain near Fairbanks, Alaska. Two experimental oil spills, one in winter and one in summer, of 7570 liters (2000 gallons) were made at a forest site. The winter spill oil moved within the surface moss layer beneath the snow. The summer spill oil moved primarily below the moss in the organic soil. The oil moved faster and further downslope in the summer spill. Oil in the winter spill stopped during the first day but remobalized and flowed further downslope in the spring. The total area affected by the summer spill was nearly one and one-half times as large as that affected by the winter spill.

JORDAN, R.E. AND J.R. PAYNE. 1980. Oil Released in Arctic Environments: Oil and Ice/Snow Interactions. Fate and Weathering of Petroleum Spills in the Marine Environment: A Literature Review and Synopsis. Ann Arbor Science, Ann Arbor, pp. 108-114.

Discusses mechanisms of transport and characteristics of the spread of oil spilled in cold water environments with ice cover. Environmental effects on oil weathering rates are noted.

KAWAMURA, P., D. MACKAY, and M. GORAL. 1986. Spreading of Chemicals on Ice and Snow. Environment Canada Report EE-79. Ottawa.

A relatively simple, liquid spill behavior model has been developed which includes terms for the extent and rate of spreading, as well as absorption, evaporation, and snow and ice dissolution. Experiments were performed on snow and ice surfaces to determine the spreading behavior and characteristics and the general phenomena which occur when various chemicals are spilled on these surfaces. The chemicals studied were: m-xylene, n-pentanol, bayol (white mineral oil), and light and heavy mineral oils.

The final spill area and the spreading rate results were correlated with spill volume, chemical viscosity, and snow depth and properties, in dimensional and dimensionless form. These correlations can be viewed as comprising part of the general spreading model, and are believed to enable predictions to be made of the spreading behavior for most chemicals under actual spill conditions.

To document the extent to which a chemical interacts with, or dissolves snow and ice, a classification system was developed. Chemicals were categorized into one of three groups, based on the solubility of water/ice in the chemical. Most of the liquid chemicals on Environment Canada's list of Priority Hazardous Materials were classified into one of three groups by combining the solubility data from the literature and by performing simple experimental solubility measurements.

MACKAY, D., P.J. LEINONEN, J.C.K. OVERALL, and B.R. WOOD. 1975. The Behavior of Crude Oil Spilled on Snow. ARCTIC, Journal of the Arctic Institute of North America, Vol. 28, No. 1, March 1975, pp. 9-20.

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

MACLEOD, W.D., M.Y. UYEDA, A.J. FRIEDMAN, and P.G. PROHASKA. 1978. Weathering Estimatations for Spilled Oil from Bouchard No. 65. The Proceedings of the Conference on Assessment of Ecological Impacts of Oil Spills, June 14-17, 1978, Keystone, Colorado. American Institute of Biological Sciences. Vol. I, pp. 216-228.

Eleven ice and snow samples collected in the vicinty of the No. 2 fuel oil spill from the barge Bouchard No. 65 (Buzzards Bay) were analysed for saturated and aromatic hydrocarbons by high resolution gas chromotography. Similar analysis of samples from the Bouchard No. 65 cargo indicated that the aromatic hydrocarbon level was somewhat less than that of the No. 2 fuel oil spilled from the barge Florida in 1969. Weathering of alkanes and arenes was estimated by comparing quantitative changes in these hydrocarbons relative to the cargo oil. The arenes exhibited greater percent losses than the alkanes. Losses generally correlated with exposure of samples to the atmosphere. Overall oil losses were estimated by taking a weighted average of the alkane and arene loss estimates.

MARTIN, S. 1979. A Field Study of Brine Drainage and Oil Entrainment in First-Year Sea Ice. Journal of Glaciology, Vol. 22, No. 88, pp. 473-502.

From field observations this paper describes the growth and development of first-year sea ice and its interaction with petroleum. In particular, when sea ice initially forms, there is an upward salt transport so that the ice suface has a highly saline layer, regardless of whether the initial ice is frazil, columnar, or slush ice. When the ice warms in the spring, because of the eutectic condition, the surface salt liquifies and drains through the ice, leading to the formation of top-to-bottom brine channels and void spaces in the upper part of the ice. If oil is released beneath winter ice, then the oil becomes entrained in thin lenses within the ice. In the spring, this oil flows up to the surface through the newly-opened brine channels and distributes itself within the brine channel feeder systems, on the ice surface, and in horizontal layers in the upper part of the ice. The paper shows that these layers probably form from the interaction of the brine drainage with the percolation of melt water from surface snow down into the ice and the rise of the oil from below. Finally in the summer, the oil on the surface leads to melt pond formation. The solar energy absorbed by the oil on the surface of these melt ponds eventually causes the melt pond to melt through the ice and the oil is again released into the ocean.

MCMINN, T.J. 1973. Oil Spill Behavior in a Winter Arctic Environment. Proceedings Offshore Technology Conference, 1973, Houston, Texas. Vol. 1, pp. I 233-I 248.

A comprehensive Coast Guard research program was initiated to determine the fate and behavior of crude oil discharges in an arctic environment. Arctic field tests were conducted off Barrow, Alaska, in June 1970 and at Port Clarence, Alaska, in Jan. 1970, in an attempt to quantify oil spreading on and under ice, oil aging on ice, unique interaction characteristics between snow and oil, and the effectiveness of existing oil recovery techniques and treating agents.

MCMINN, T.J. 1973. Behavioral Characteristics and Cleanup Techniques of North Slope Crude Oil in an Arctic Environment. Proceedings Joint Conference on Prevention and Control of Oil Spills, March 13-15, 1973, Washington, D.C. American Petroleum Institute, pp. 263-276.

This paper deals with the physical fate and behavior of crude oil when spilled on winter arctic ice and snow surfaces. The concepts and theories developed are a result of a series of experiments performed by Coast Guard personnel in the Alaskan arctic during January - February, 1972. The paper will develop spreading and aging of oil on ice and snow, the unique interaction phenomena of snow and crude oil, and the effectiveness of various cleanup techniques attempted on crude oil spilled on snow and ice. The paper will also briefly outline the Coast Guard's continuing research plans regarding arctic oil spills. Investigations prove that oil spreading over ice and snow is largely unaffected by oil properties such as density, viscosity, and surface tension. Oil spreading rate is also believed not to be a function of ambient air temperatures. Terminal spreading limit, independent of oil properties, is a function of effective surface roughness and volume of oil spilled. Oil was found to age on arctic ice. The winter aging rate was found to be significant, although reduced from summer aging rates. Migration of oil into the ice or snow surface is minimal. However, snow falling on the surface of a freshly spilled oil pool migrates into the oil, forming a mixture that contains up to 80% snow by volume. An array of sorbents, surfactants, and dispersants were tested with largely negative results.

MCMINN, T.J. 1972. Crude Oil Behavior on Arctic Winter Ice. U.S. Coast Guard 734108. Washington, D.C. NTIS AD-754, 261 p.

Oil spill behavior in an Arctic winter environment is investigated. Several small controlled spills were conducted during January 1972 on the Bering Sea in northwestern Alaska. To duplicate a real world spill as closely as possible, a Prudhoe Bay crude oil was used as the test oil. Investigated were oil spread rate on snow and ice, oil absorption into snow and ice surfaces, aging of oil on snow and ice surfaces, and effectiveness of various cleanup procedures.

NELSON, W.G. and A.A. ALLEN. 1982. The Physical Interaction and Cleanup of Crude Oil with Slush and Solid First Year Sea Ice. Proceedings of the Fifth Annual Arctic Marine Oil Spill Program Technical Seminar, June 15-17, 1982, Edmonton, Alberta, pp. 37-59.

The research summarized in this paper concentrates on studies conducted from the fall of 1980 through the spring of 1982, with occasional reference to the earlier research conducted during the winter of 1979-80. The studies have dealt with oil released during the transitions from open water to solid ice cover when a slush ice cover is often encountered, and with oil released on or under a growing ice sheet.

SCOTT, B.F. and R.M. CHATTERJEE. 1975. Behavior of Oil Under Canadian Climatic Conditions, Part I: Oil on Water Under Ice-Forming Conditions. Scientific Series, Inland Waters Directorate, No. 50. Water Quality Branch. Ottawa.

Oil was poured onto a water surface under ice-forming conditions. Weather conditions were monitored continuously, as were the physical properties of the oil and the effect of the oil on its physical environment. The weathering of the oil and its influence on its environment were correlated with the weather parameters. An estimated 50% of the oil had evaporated before the oil was covered with snow, as determined by gas chromotographic analysis and supported by neutron activation analysis. A biological assessment was conducted during the following summer where the effect of the oil on one pond was compared with the control pond. In the oiled pond, the variety of biological species was substantially less than in the control pond.

APPENDIX II

DATA ON ARCTIC BLOWING SNOW TESTS

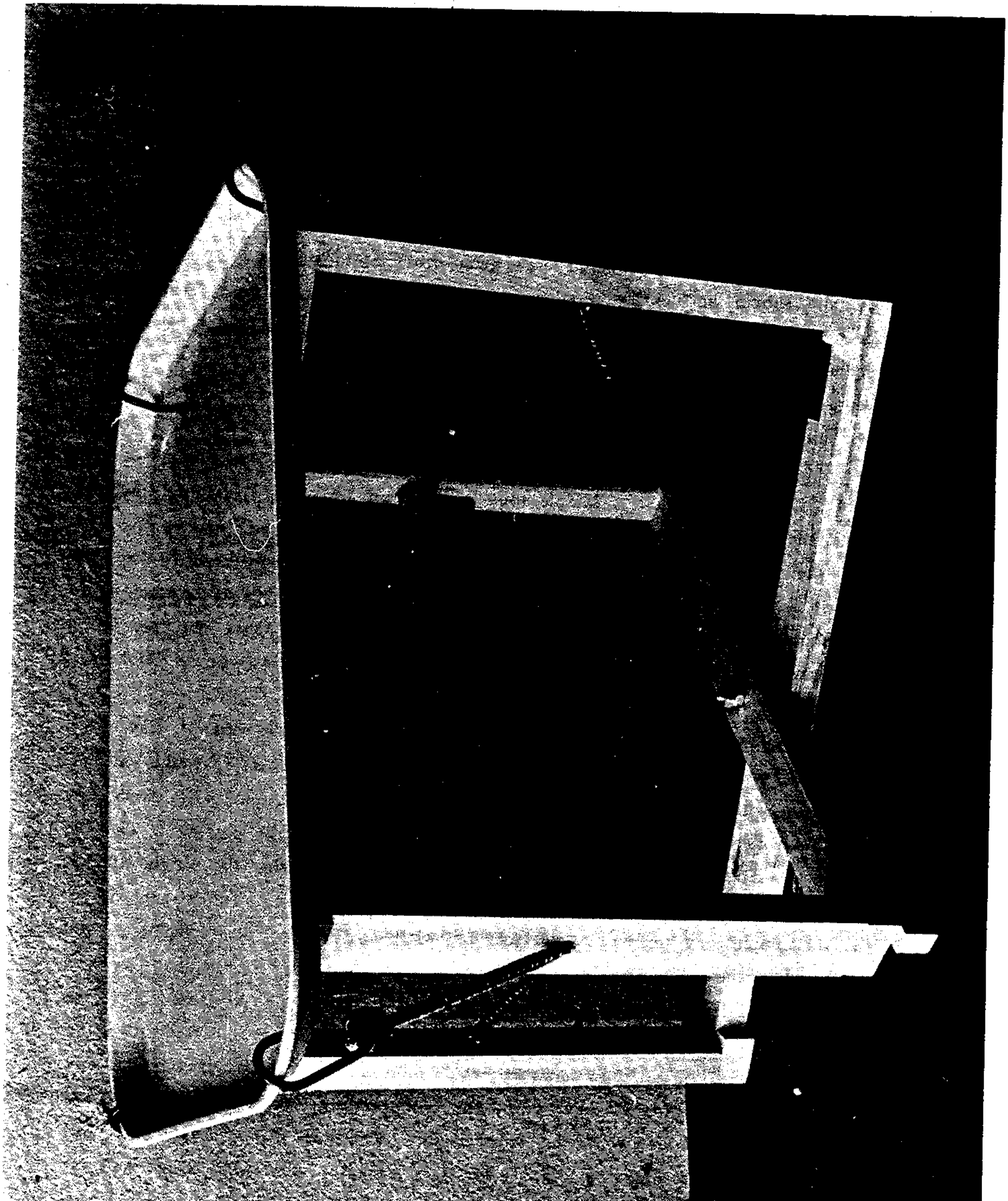
OILED SNOW DRIFTING EXPERIMENT

Procedure

Prior to or during a significant snow fall:

1) Open the 3 wooden frames and lock them into position (see photo).
2) Place the frames in an exposed area away from buildings etc. If possible the test site should be near a weather station (such as at an airport) where wind speed and air temperature are routinely monitored. The platforms should be placed 3 to 5 metres apart to minimize interaction between the trays.
3) Weigh each of the trays and record their weights on the sheet provided.
4) Pour oil into two of the trays: the entire contents of one of the enclosed bottles is added to each of the trays. Re-weigh one of the trays plus oil and record the weight. Take a sample (one vial) of oil from the remaining tray and record the time and date taken on the cap.
5) Lash the trays down onto the supporting frames with the bungy cords. We find that it is best to support the frame by placing a foot on the bottom cross brace and then hook the cords in a cross-corner pattern. Once the tray is in place anchor the frame by placing a weight on the bottom cross-brace (sand bag, cement block, rock etc.).
6) At <u>weekly</u> intervals and after major wind storms weigh the control tray (i.e., tray with no oil) to determine the weight of snow on the trays, weigh one of the trays with oil in it and take a small sample of oil (one vial) from the remaining tray taking care to disturb as little of the snow as possible. The oil sample must be taken from the same tray each time. Knowing the weight of the snow on the trays and the amount of oil evaporated (by our future analysis of the oil sample) the amount of oil lost by wind "erosion" can be calculated with the weight of the undisturbed oil tray.

Store the oil sample in the vials provided (label the caps with the time and date of sample) and record the weight data on the enclosed data form. Comments on the appearance of the oil or oil/snow mixture would also be welcomed. If there is any visible oil blown from the tray onto the surrounding terrain photographs or descriptions of the deposits would be appreciated. Continue the measurements until spring and send samples and data records to Merv Fingas. Any wind speed and air temperature records available from local sources would also be appreciated.



Data Record: Oiled Snow Drifting **Location** ______________

Time and Date of Record	Tray Weights: Tray #1 (control: no oil)	Tray Weights: Tray #2 (undisturbed oil)

Environment Canada Environnement Canada

MEMORANDUM NOTE DE SERVICE

DATE May 16, 1988

FROM: / DE:
Environmental Protection
Conservation and Protection
Inuvik Sub-district
P.O. Box 1086
Inuvik, N.W.T. X0E 0T0

Our file / Notre référence: 4031 001

TO: / À:
Merv Fingas
Head, Chemistry and Physics Section
Environmental Emergencies Technology Division
River Road Environmental Technology Centre

Your file / Votre référence

SUBJECT: / SUJET: Experiment to Measure the Evaporation of Oil on Snow

Here is the data that I promised to forward. All of the data was collected between April 6 - May 4, 1988, at the A.E.S. upper air station - Inuvik.

Included are photos of the sample trays and distribution of trays over site location, along with a mug shot of the "culprit".

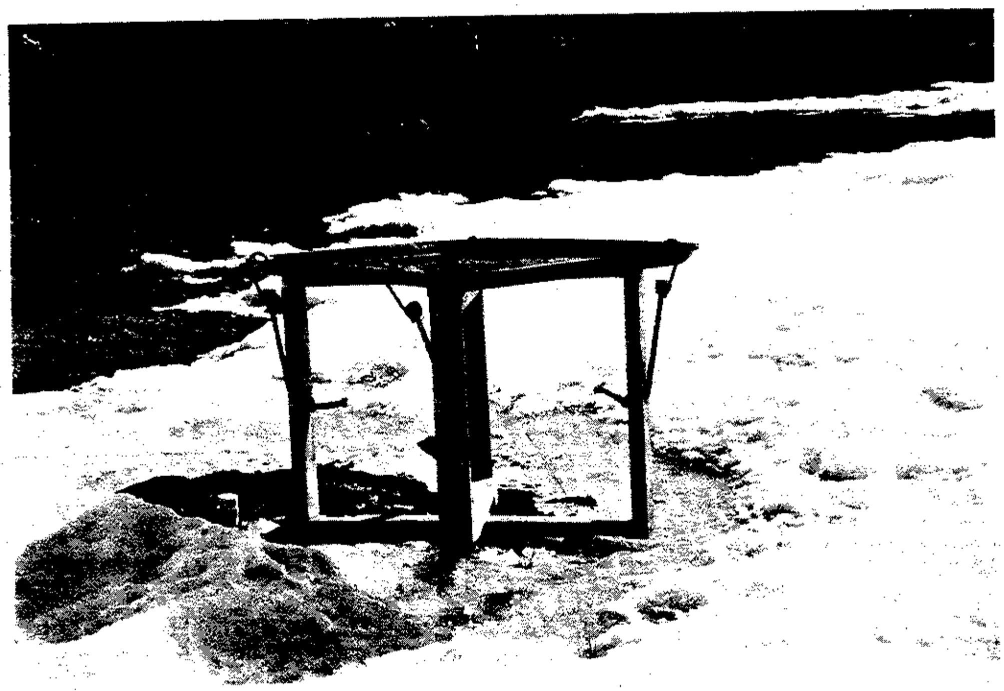
Date Record: Oiled Snow Drifting **Location: Inuvik, N.W.T.**

Date and Time of Record	Tray #1 (Control: no oil)	Tray #2 (undisturbed oil)	Trays #3 (sample)
06/04/88 - 3:00 p.m. -22.3 C, Wind sp. 9 km, Wind dir. N.	755 gm.	1440 gm.	# 1
13/04/88 - 2:00 p.m. 0.0 C, Wind sp. 11 km, Wind dir. SE.	755 gm.	1340 gm.	# 2
20/04/88 - 1:30 p.m. +7.8 C, Wind sp. 4 km, Wind dir. SE.	755 gm.	1260 gm.	# 3
28/04/88 - 1:00 p.m. -2.0 C, Wind sp. 25 km, Wind dir. E.	755 gm.	1000 gm.	# 4
04/05/88 - 1:00 p.m. +4.6 C, Wind sp. 9 km, Wind dir. E.	755 gm.	965 gm.	# 5

Please call if you have any questions Ph. 403-979-2313.

Thank you

Stephen Charlie
Environmental Quality Officer.



Environment Canada Environnement Canada

Environmental Protection
Box 384
Iqaluit, N.W.T.
XOA OHO

Merv Fingas
Head, Chemistry and Physics Section
Environmental Emergencies Technology Divison
River Road Lab
Environment Canada
Ottawa, Ontario
K1A OH3

Your file Votre référence

Our file Notre référence

May 3, 1988

Dear Merv,

Re: Experiment to Measure the Evaporation of Oil with Snow

As per our conversation on April 21, 1988, I have completed the experiment and have enclosed the oil samples, data record and a copy of the Atmoshere Environment Service's Meteorological Summary Report for all of April 1988.

There were a few problems encountered during the experiment with respects to the accuracy of the data obtained. They are as follows...

1) The scale used to weigh the trays gave results with a variance of + or - 10 grams.

2) There was some difficulty in drawing the oil out of the tray and filling the vials, as the oil thickened. As discussed I used a spoon which turned out to be extremely messy and difficult to fill the vials. The use of a large syringe with about a 1/8" or 1/4" opening would have made this task easier.

3) I feel that the time of year this experiment was conducted is not representative of the eastern arctic's weather and may effect the accuracy of the results. The sun melted and evaporated the precipitation from Tray #1 (control tray, no oil) and Tray #2 (oil) trapped a percentage of the precipitation therefore effecting the correlation between the tray weights. I feel the best time of the year to obtain more accurate results for the experiment of effect snow on weathering of oil is November, December January and/or February when our weather is more represented.

I hope this information will be of use to you and your experiment.

If you have any questions or comments, please contact me at (819) 979-6349.

If you ever find yourself passing through or visiting Iqaluit make sure you drop by the office.

Yours truly,

Sandra Green
Manager

cc: Scott Howarth, Acting Manager, YK

Canada

Environment Canada / Environnement Canada
Atmospheric Environment Service / Service de l'environnement atmosphérique

MONTHLY METEOROLOGICAL SUMMARY
SOMMAIRE MÉTÉOROLOGIQUE MENSUEL

MONTH/MOIS APRIL / AVRIL 1988

AT/À IQALUIT A (YFB)

LAT 63° 45' N LONG 68° 32' W ELEVATION/ALTITUDE 33.5 METRES (ASL)/MÈTRES (NMM) STANDARD TIME USED/HEURE NORMALE UTILISÉE EAST/EST

DATE	TEMPERATURE/TEMPÉRATURE Maximum/Maximale °C	Minimum/Minimale °C	Mean/Moyenne °C	DEGREE-DAYS/DEGRÉS-JOURS Heating/De chauffe Base 18.0°C	Growing/De croissance Base 5.0°C	Cooling/De réfrigération Base 18.0°C	REL. HUMIDITY/HUMIDITÉ REL. Maximum/Maximale %	Minimum/Minimale %	Thunderstorm/Orage	PRECIPITATION/PRÉCIPITATIONS Rainfall/Pluie (hauteur) mm	Snowfall/Neige (hauteur) cm	Total precip/Précip totale mm	Snow on ground/Neige au sol cm	WIND/VENT Average speed/Vitesse moyenne km/h	Prevailing direction/Direction dominante	Max 2 min mean speed & direction/Vitesse moyenne max. sur 2 min & direction km/h	Bright sunshine/Insolation effective Hours/Heures
1	-6.6	-18.7	-12.7	30.7			92	79			2.2	2.0	54	4.7	NNW	26 NNW	2.5
2	-17.2	-28.0	-22.6	40.6			76	72			TR	TR	52	16.1	NW	26 NNW	10.7
3	-18.3	-30.5	-24.4	42.4			83	58					50	2.5	WNW	11 NW	12.1
4	-15.3	-29.3	-22.3	40.3			77	58			0.8	0.6	48	1.5	WNW	6 WNW	3.4
5	-12.5	-25.4	-19.0	37.0			84	69			0.6	0.6	49	6.1	NW	17 NW	5.0
6	-15.0	-26.8	-20.9	38.9			83	54			0.8	0.8	49	4.3	NNW	17 NNW	8.2
7	-14.0	-19.0	-16.5	34.5			66	59			0.8	0.8	49	26.1	E	37 ENE	1.8
8	-17.0	-25.8	-21.4	39.4			69	58			TR	TR	49	27.2	NW	41 NNW	12.3
9	-17.0	-26.8	-21.9	39.9			71	58					48	26.1	NW	33 NNW	12.5
10	-12.8	-23.6	-18.2	36.2			76	49					48	21.0	NNW	43 N	12.6
11	-10.8	-26.2	-18.5	36.5			78	56					48	2.2	PLUS	15 SE	9.1
12	-6.5	-12.2	-9.4	27.4			92	61			TR	TR	48	27.9	SE	41 SE	3.0
13	-4.6	-11.9	-8.3	26.3			92	79			TR	TR	48	1.4	S	9 SE	9.0
14	-3.6	-9.4	-6.5	24.5			100	85			2.0	1.8	48	1.8	S	6 S	2.2
15	-2.1	-7.2	-4.7	22.7			93	86			2.0	1.8	51	15.2	SE	30 SE	0.0
16	-1.7	-17.1	-9.4	27.4			100	68			3.0	3.0	52	24.0	SE	44 SSE	1.0
17	-8.2	-18.6	-13.4	31.4			85	62					52	2.3	SSE	9 E	12.9
18	2.3	-11.5	-4.6	22.6			85	64			TR	TR	52	25.6	SE	54 SE	0.0
19	3.0	-1.6	0.7	17.3			75	64			TR	TR	50	27.8	SE	72 SE	0.0
20	-0.4	-6.2	-3.3	21.3			86	63					47	9.2	PLUS	37 E	10.6
21	-1.9	-10.2	-6.1	24.1			86	67			TR	TR	44	5.6	SSE	17 NE	8.0
22	-4.3	-13.2	-8.8	26.8			92	73			TR	TR	43	20.8	PLUS	33 NW	8.9
23	-7.3	-17.0	-12.2	30.2			92	78			TR	TR	41	8.4	NW	28 N	10.8
24	-7.1	-18.9	-13.0	31.0			92	71					40	23.2	NNW	37 NW*	13.0
25	-8.8	-12.5	-10.7	28.7			85	73			TR	TR	40	25.6	NNW	39 NNW	13.6
26	-4.8	-14.3	-9.6	27.6			100	62			TR	TR	40	4.0	PLUS	19 WNW	4.9
27	-4.0	-12.0	-8.0	26.0			85	63			TR	TR	37	10.4	SSE	19 SE*	4.5
28	-3.2	-14.5	-8.9	26.9			85	62					37	18.1	SE	30 SSE	11.7
29	-1.9	-19.7	-10.8	28.8			93	73			0.8	0.8	36	28.5	SE	44 NNW	4.0
30	-8.5	-20.9	-14.7	32.7			85	52					36	5.1	WNW	13 WNW	15.4
MEAN/MOYENNE	-7.7	-17.6	-12.7	TOTAL 920.1	TOTAL	TOTAL	85	66	TOT	TOTAL	TOTAL 13.0	TOTAL 12.2		14.1	PREVAILING/DOMINANTE SE	MAXIMALE 72 SE	TOTAL 223.7
NORMAL/NORMALE	-9.4	-19.1	-14.3	968.5						0.1	28.7	26.4		17.5	NW		235.3

DEGREE-DAY SUMMARY/SOMMAIRE DE DEGRÉS JOURS

Below 18°C/Au-dessous de 18°C	This year/Année en cours	Previous year/Année précédente	Normal/Normale	Above 5°C/Au dessus de 5°C	This year/Année en cours	Previous year/Année précédente	Normal/Normale
TOTAL FOR MONTH/TOTAL DU MOIS	920.1	1026.5	968.5	TOTAL FOR MONTH/TOTAL DU MOIS	0	0	0
ACCUMULATED SINCE JULY 1/ACCUMULÉE DEPUIS LE 1er JUILLET	8825.8	9556.0	8834.3	ACCUMULATED SINCE APRIL 1/ACCUMULÉE DEPUIS LE 1er AVRIL	0	0	0

	Days with total precipitation/Jours avec précipitations totales (mm) 0.2 or more/ou plus	1.0 or more/ou plus	2.0 or more/ou plus	10.0 or more/ou plus	50.0 or more/ou plus	Days with snowfall/Jours avec chute de neige (cm) 0.2 or more/ou plus	1.0 or more/ou plus	2.0 or more/ou plus	10.0 or more/ou plus	50.0 or more/ou plus
	9	4	2	0	0	9	4	4	0	0

UDC 551.506.1 ( )

Note/Avis
1. Climatological Day/Journée climatologique 01 01 E S.T. – 01 00 E S.T.
2. Normal/Normale 1951-1980
3. TR - Trace
4. M - Missing/Manquant
5. No entry/Pas de valeur = No occurrence/Pas d'événement
6. * Indicates first of more than one prevailing direction and/or maximum 2 minute mean speed (see page 4)/Indique la première de plusieurs des directions dominantes et/ou la vitesse moyenne maximale sur 2 minutes (voir page 4).
7. C - Calm/Calme
8. Price single issue 2.65, annual (Jan. to Dec.) 26.25/Prix: numéro individuel 2.65, annuel 26.25 (janv. à déc.)

Canada

Reduce and print image area on 8½ x 11" good quality 20 lb. bond paper allowing for ½" right and left hand margins (DO NOT OVER REDUCE).
Whenever possible, use both sides of paper, i.e. pages 1 and 2 back-to-back, etc.

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Imprimer recto verso dans la mesure du possible (par exemple, pages 1 et 2 recto verso, etc.)

0063-0010 (10/85)

Data Record: Oilded Snow Drifting

Location: Iqaluit, N.W.T. (near AES)

Time and Date of Record	Tray #1 (control, no oil)	Tray #2 (undisturbed oil)	Tray #3 (samples taken)
April 15, 1988 11:00 a.m.	645 grams	600 grams	640 grams sample taken
April 20, 1988 4:30 p.m.	645 grams (precipitation evaporated)	1160 grams*	sample taken
May 2, 1988 1:30 p.m.	700 grams (some melted snow)	1150 grams*	sample taken

* some oil had splattered outside the tray onto the ground

SOMMAIRE QUOTIDIEN

1. Nuageux avec neige.
2. Quelques nuages. Cristaux de glace cessant en matinée.
3. Ensoleillé.
4. Ennuagement suivi de faible neige.
5. Plutôt nuageux. Périodes de faible neige.
6. Passages nuageux avec quelques flocons.
7. Plutôt nuageux avec faible neige ou cristaux de glace.
8. Ensoleillé et vents modérés.
9. Ensoleillé et vents modérés.
10. Ensoleillé. Vents modérés cessant en après-midi.
11. Ensoleillé. Ennuagement en fin d'après-midi.
12. Nuageux avec éclaircies. Quelques flocons de neige.
13. Ensoleillé en journée. Nuageux avec flocons en soirée.
14. Plutôt nuageux avec faible neige.
15. Nuageux avec faible neige. Doux.
16. Neige cessant en fin d'après-midi poudrerie en après-midi. Dégagement par la suite.
17. Ennuagement en fin de soirée.
18. Nuageux. Doux et venteux.
19. Nuageux et doux. Venteux.
20. Nuageux et doux. venteux.
21. Nuageux avec neige. Dégagement en après-midi.
22. Nuageux avec quelques flocons la nuit. Dégagement tôt en matinée.
23. Nuageux avec neige durant la nuit. Dégagement tôt en matinée.
24. Ensoleillé et venteux.
25. Ennuagement suivi de neige en soirée.
26. Nuageux avec éclaircies. Périodes de faible neige.
27. Plutôt nuageux. Quelques flocons.
28. Passages nuageux.
29. Ennuagement suivi de neige. Vents modérés. Dégagement en soirée.
30. Ensoleillé.

DAILY SUMMARY

1. Cloudy with snow.
2. A few clouds. Ice crystals ending in the morning.
3. Sunny.
4. Clouding over followed by light snow.
5. Mostly cloudy. Periods of light snow.
6. Cloudy periods with a few flurries.
7. Mostly cloudy with light snow or ice crystals.
8. Sunny and moderate winds.
9. Sunny and moderate winds.
10. Sunny. Moderate winds ending in the afternoon.
11. Sunny. Clouding over late in the afternoon.
12. Cloudy with sunny breaks. A few flurries.
13. Sunny during the day. Cloudy with a few flurries in the evening.
14. Mostly cloudy with light snow.
15. Cloudy with light snow. Mild.
16. Snow ending in the afternoon. Blowing snow in the afternoon. Clearing later on.
17. Clouding over late in the evening.
18. Cloudy. Mild and windy.
19. Cloudy and mild. Windy.
20. Cloudy and mild. Windy.
21. Cloudy with snow. Clearing in the afternoon.
22. Cloudy with a few flurries during the night. Clearing early in the morning.
23. Cloudy with snow during the night. Clearing early in the morning.
24. Sunny and windy.
25. Clouding over followed by snow.
26. Cloudy with sunny breaks. Periods of snow.
27. Mostly cloudy. A few flurries.
28. Cloudy periods.
29. Clouding over followed by snow. Moderate winds. Clearing in the evening.
30. Sunny.