AD-754 261

# Crude Oil Behavior on Arctic Winter Ice

Coast Guard

SEPTEMBER 1972

Distributed By:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

# DEPARTMENT OF TRANSPORTATION

## UNITED STATES COAST GUARD

Office of
RESEARCH & DEVELOPMENT

•

•

Project 734108

# CRUDE OIL BEHAVIOR ON ARCTIC WINTER ICE

BY

LTJG T. J. McMinn USCGR
Environmental and Transportation Technology Division
Office of Research and Delevopment

• Final Report

• September 1972



Prepared for: COMMANDANT ( DET )
U.S. COAST GUARD HEADQUARTERS
WASHINGTON, D.C., 20590

76

Unclassified
Security Classification

# DOCUMENT CONTROL DATA - R & D

*Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)*

1. ORIGINATING ACTIVITY (Corporate author)
Commandant (GDET)
U. S. Coast Guard Headquarters
400 7th Street, S.W., Washington, D. C. 20590

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP
None

3. REPORT TITLE
CRUDE OIL BEHAVIOR ON ARCTIC WINTER ICE

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final Report

5. AUTHOR(S) (First name, middle initial, last name)
LTJG T. J. McMinn, USCGR

6. REPORT DATE
September 1972

7a. TOTAL NO OF PAGES
75

7b. NO OF REFS
7

8a. CONTRACT OR GRANT NO

b. PROJECT NO.
734108

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
734108

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
None

10. DISTRIBUTION STATEMENT
Availability is unlimited. Document may be released to the National Technical Information Service, Springfield, Virginia 22151 for sale to the public.

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
Commandant (GDET)
U. S. Coast Guard Headquarters
400 7th Street, S.W., Wash., D.C. 20590

13. ABSTRACT


Oil spill behavior in an Arctic winter environment is investigated. Several small controlled oil 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 absorbtion into snow and ice surfaces, aging of oil on snow and ice surfaces, and effectiveness of various cleanup procedures.


I

DD FORM 1 NOV 65 1473 (PAGE 1)
S/N 0101-807-6801

Unclassified
Security Classification

Unclassified
Security Classification

| 14 KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Oil Pollution | | | | | | |
| Arctic Oil Pollution | | | | | | |
| Pollution Control | | | | | | |

II

DD FORM 1 NOV 65 1473 (BACK)
(PAGE 2)

Unclassified
Security Classification

UNITED STATES COAST GUARD

ENVIRONMENTAL & TRANSPORTATION TECHNOLOGY DIVISION

FINAL REPORT

# CRUDE OIL BEHAVIOR ON ARCTIC WINTER ICE

BY


LTJG T. J. MCMINN USCGR

POLLUTION PREVENTION PROJECTS BRANCH

ENVIRONMENTAL & TRANSPORTATION TECHNOLOGY DIVISION


Date : September 26, 1972

Submitted : W E Lehr

W. E. Lehr, CDR, USCG
Chief, Pollution Prevention Projects Branch

Approved : J R Iversen

J. R. Iversen, CAPT, USCG
Chief, Environmental & Transportation Technology Division
Office of Research and Development
U. S. Coast Guard Headquarters
Washington, D.C. 20590

FOREWARD

This report has been generated as a result of tests conducted by the U. S. Coast Guard on the Bering Sea during January-February 1972. The Coast Guard Loran Station Port Clarence, Alaska 65° 15' N, 160° 53'W served as base of operations. The principle investigator was LTJG Thomas J. McMinn, USCGR. The tests were conducted in partial fulfillment of the Coast Guard's program to develop a capability to prevent, combat and cleanup oil spills in the Arctic.

## ACKNOWLEDGEMENTS

The success of this field test was due largely to the cooperation and assistance of the following organizations:

Army Cold Regions Research and Engineering Lab

Port Clarence Loran Station

Seventeenth Coast Guard District

Atlantic Richfield Oil Company

Humble Oil and Refining Company

Hoult, Cross, and Milgram

LTJG Paul Golden,USCGR, was instrumental in the conduct of test site procedures and was responsible for the investigation of the effectiveness of sorbent, dispersant, herding, and burning agents under Arctic conditions.

Dr. E. C. Chen, Canadian Deptartment of the Environment, participated officially as an observer but proved to be an important participant in actual test operations.

LIST OF FIGURES

LIST OF SYMBOLS

$A_t$ - total area
$d$ - diameter of oil slick
$F_i$ - force due to inertia
$F_g$ - force due to gravity
$F_s$ - force due to surface tension
$F_u$ - force due to viscosity
$h$ - thickness
$h_c$ - critical thickness
$g$ - acceleration due to gravity
$\Phi_i$ - porosity of ice
$\Phi_s$ - porosity of snow
$Q$ - oil flow rate
$\overline{Q}$ - average oil flow rate
$\rho$ - density
$r$ - radius of oil slick
$rm$ - maximum radius of oil slick
$\sigma$ - surface tension
$\sigma_r$ - resultant surface tension
$\theta$ - contact angle
$t$ - time
$t_m$ - maximum time
$V$ - volume
$z_o$ - effective roughness height
$f(t)$ - is afunction of t
$f(z_o)$ - is a function of $z_o$

TABLE OF CONTENTS

# I. Introduction

## Background

The discovery of large oil fields in the Alaskan Arctic has brought mixed reactions from the United States public and certain large industries.

Although North Slope production is conservatively estimated at over two million barrels of oil/day by 1980, a serious logistics problem is encountered during crude oil transportation to refining and marketing areas. The primary production area, Prudhoe Bay, is located on the coastal plain of Alaska's North Slope. As in any conventional producing area, crude oil will move to market by either pipeline, waterborne traffic, or both. Water traffic must overcome restrictions due to Arctic pack ice which can close navigation to the North Slope area up to ten months a year. The proposed trans-Alaskan pipeline must cover some 750 miles which includes traversing the rugged Brooks Range.

While most observers recognize the need for added U.S. production and the subsequent minimization of dependence on foreign crude, many are unwilling to tolerate possible adverse environmental effects to America's "last frontier" which may accompany movement of Arctic crude to refining areas.

## Purpose

In anticipation of the possibility of large scale oil spills in Arctic regions, the Coast Guard has initiated a program to determine the potential of accidental Arctic oil spills, investigate the environmental and aesthetic effects of Arctic oil spills, and to develop detection and response systems for dealing with them.

This report, investigating the behavior of crude oil when spilled on Arctic winter ice, is a result of one of a series of studies sponsored by the U.S. Coast Guard, investigating physical, chemical, and biological effects of oil spilled in Arctic regions. The results of the studies provide a fundamental understanding of the fate and behavior of oil spilled under Arctic conditions needed for development of cleanup response systems.

## II. Test Site and Equipment Description

### Test Site

In an attempt to duplicate the environmental areas where crude oil would most likely be spilled, an area adjacent to 1) bay ice 2) pack ice, and 3) tundra was selected as the test site. Located below the Arctic circle at 65° 15'N, 160° 55'W, Port Clarence Loran Station is situated on the point of a narrow spit. To the east is Port Clarence Bay, a sheltered body of salt water approximately fifteen miles across. Directly westward is the Bering Sea, which ice bounds Port Clarence seven months a year. To the south of Port Clarence, on the narrow spit, are numerous fresh water lakes and areas of bare tundra. The weather and daylight characteristics of Port Clarence are illustrated in Figure (1) and Figure (2).

### Equipment

Transporting the test crude from the base of operations to the test site was accomplished using an insulated tank sled (Figure 3) designed specifically for this experiment. The sled was fabricated of aluminum to conserve weight. The sled body was mounted on two runners to facilitate movement over ice/snow surfaces. The body consisted of two major sections. The forward half consisted of an insulated test oil storage tank. The rear half provided space for operating personnel and a compressed air source for discharging oil from the test tank. The insulated tank consisted of an inner and outer shell, with 3 inches of insulation blown in between the two tanks. The inner tank, approximately 100 gallons in volume, was fitted with an oil discharge and an air inlet line. The rear half of the

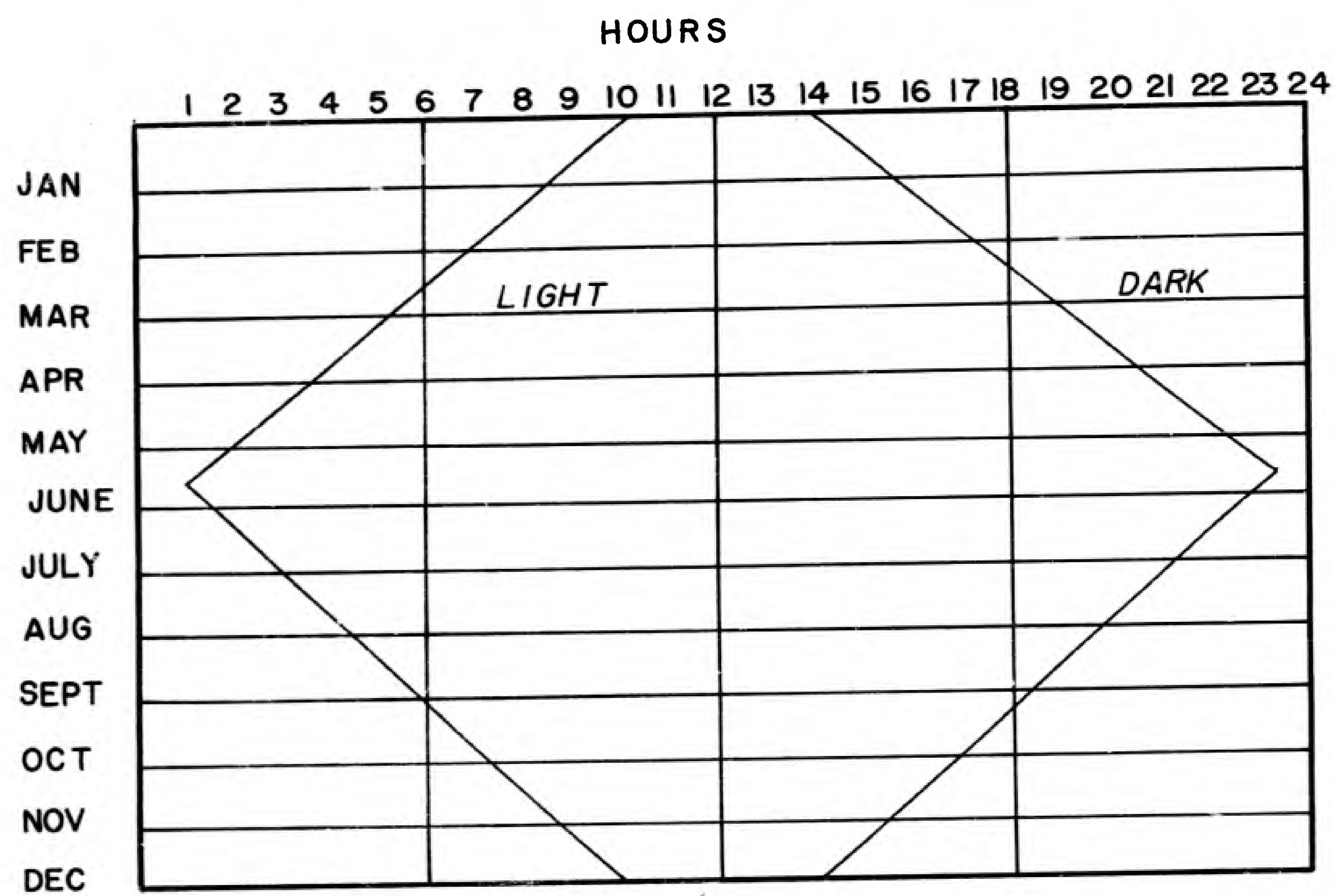
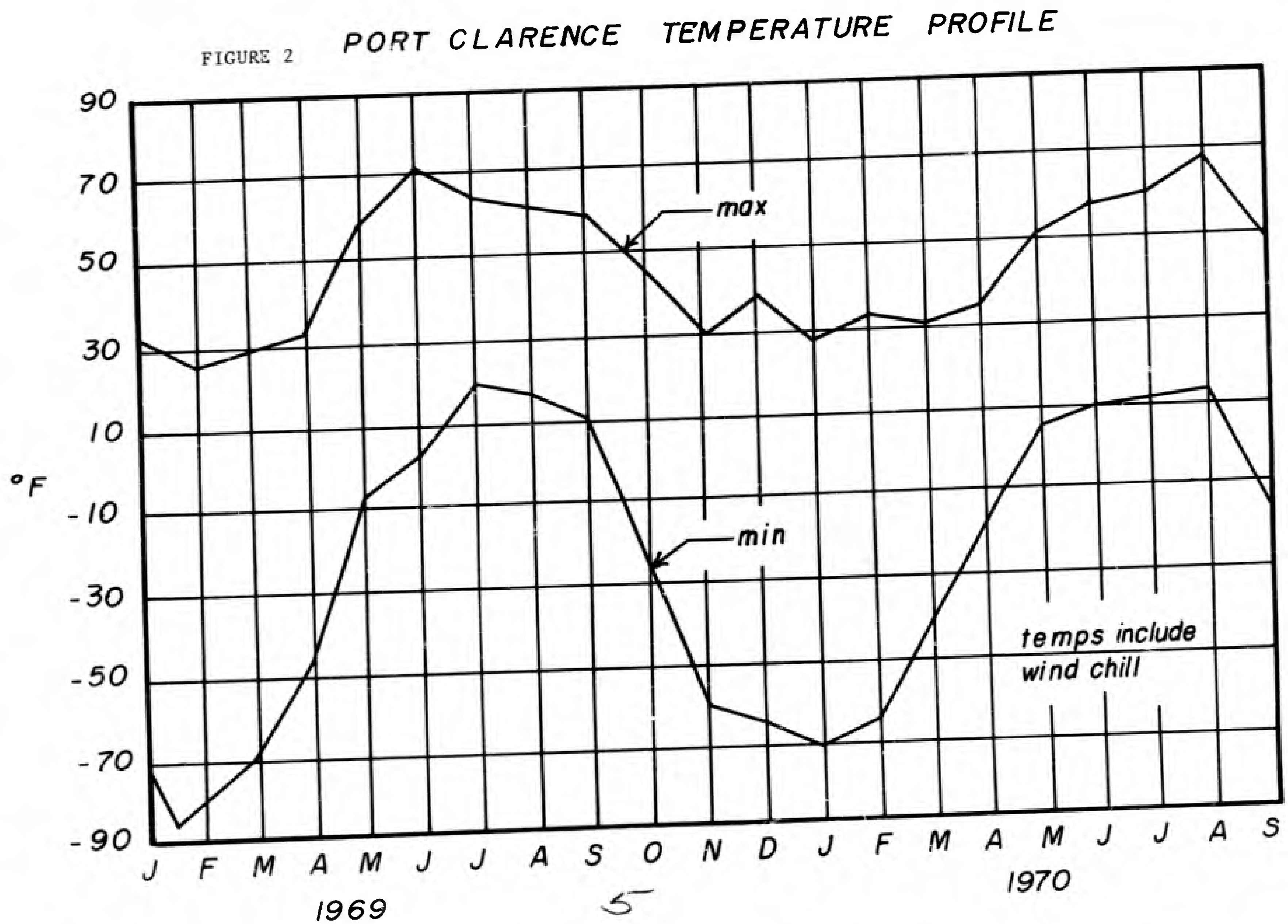





FIGURE 1 PORT CLARENCE DAYLIGHT CHART

FIGURE 2


PORT CLARENCE TEMPERATURE PROFILE
90
70
50
30
10
°F
-10
-30
-50
-70
-90
max
min
temps include
wind chill
J F M A M J J A S O N D J F M A M J J A S
1969
1970

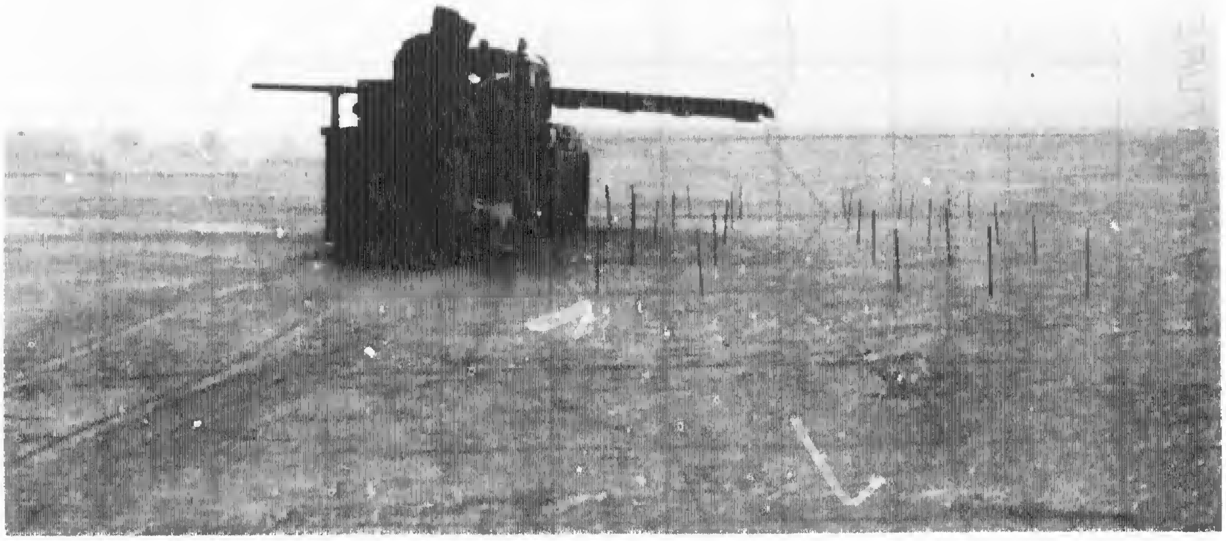
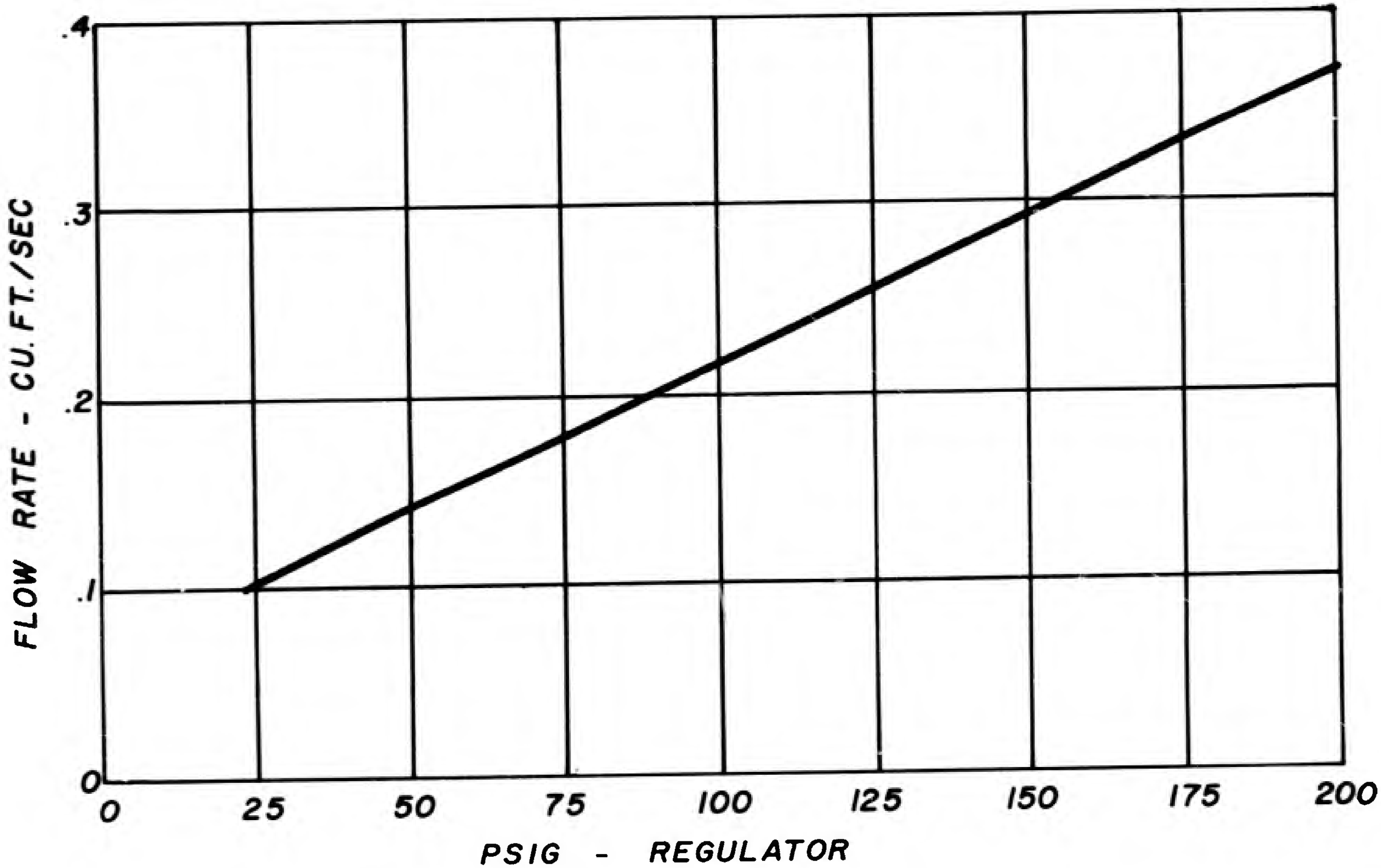


FIGURE 3 - Insulated oil dump tank sled used to experimentally spill oil on the ice surface.

sled was designed as open space for an operator to stand. A regulated compressed air source was installed in a portion of this open area. An air line, connected to the tank air inlet line, was fitted with a fixed sonic orfice. The orfice facilitated controlling oil discharge rate as a function of air flow rate. Upon regulating the air flow into the oil tank, oil could be discharged at constant flow rate (Figure (4).

A twelve foot pinned boom was attached to the oil discharge line allowing a ready manipulation of the oil discharge point. The above described oil tank sled was used in all experiments where oil was discharged onto the snow and ice. Equipment used for operation and data collection will be described in respective sections.

FIGURE 4



.4
.3
.2
.1
0
0
25
50
75
100
125
150
175
200
PSIG - REGULATOR
FLOW RATE - CU. FT./SEC

## III. Oil Spreading

### Introduction

In the event of a large scale oil spill in the Arctic and especially if under adverse weather conditions, knowledge of the areal coverage of the released oil will be valuable information if effective reactionary procedures are to be undertaken. If an accurate prediction of spreading rate and ultimate spreading limits of an oil spill are to be made the mechanics of oil spreading over ice and snow must be understood. The purpose of this experiment is to examine theories developed for oil spreading over ice and snow and to compare these theories with spreading data taken in the field. In this regard the experiment attempted to prove that oil spreading on snow/ice can be accurately predicted and that spreading rate and ultimate pool size are independent of oil properties and ambient air temperature.

### Spill Site Description

In attempting to duplicate a real world spill as closely as possible and to make the data as reliable as possible the spreading experiments were performed in January in the Alaskan Arctic.

The spreading experiments were conducted on both a snow covered ice surface and a windswept ice surface. Surface (1), the snow covered ice surface was located approximately 1/4 mile east of the shoreline into Port Clarence Bay. The ice was sationary, averaging 2-3 feet in thickness and at the outset of the test was covered with 8" of snow. Surface (2), the wind swept ice surface, was the surface of a fresh water inland lake approximately 300 yards across and located 1/5 mile inland from the Bering Sea. The reason for using the inland lake was simply that it was the only ice surface in the area completely bare of a snow cover.

The exact areas of the spilled oil were chosen such that the surface was as horizontal as possible. This hopefully would minimize error due to oil flowing down a gradient.

Aluminum stakes 1/2 inch in diameter were driven into the ice surface at fixed intervals to aid in calibrating the rate of spreading. The stakes were spaced every one foot along a radius extended from the point of release(Figure 5). The crude oil was poured on the ice in the center of the stake pattern at a known rate of flow. The oil was poured using the sled tank apparatus described in section II of this report. As the oil was being poured onto the snow/ice surface an 8mm movie camera recorded the spreading. The film was later analyzed and spreading rate determined by recording the time interval required for the spreading oil to pass successive stakes.

A total of four spills were made for the purpose of analyzing oil spreading. Three of the spills were made on the snow surface with a total stake spacing of 8 feet. The fourth spill was made on the lake ice surface with a total stake spacing of 14 feet. In each case the oil used was North Slope produced crude oil at a temperature of 58°F. An analysis of the oil is provided in appendix (C).

## III Theory

In an attempt to theoretically describe the spreading of oil on snow and ice a simplified theory was developed. This theory is based on the mechanics of oil spreading over water by Fay[2]. According to Fay,

FIGURE 5 - Oil flowing from specially insulated oil tank sled to snow covered ice surface at a predetermined rate.

oil spreading on water is controlled by four physical phenomena; gravity, surface tension, inertia, viscosity. Initially, the oil driving force is due primarily to gravity generated pressure. Since pressure acts in all directions from a single point, forces due to this gravity pressure tend to force the oil outward from the center in all directions. Hence the force due to gravity (Fg) equals:

$$F_g = \int_0^h P dA$$

where $P = \rho g h$ and $A = 2\pi r h$

$$dA = 2\pi r dh$$

therefore $F_g = 2\pi\rho g r \int_0^h h dh$

$$F_g = r\pi g h^2 \qquad (1)$$

(Note: Definition of symbols in front of report)

As the oil continues to spread and the thickness (h) becomes very small, gravity forces become negligent. At this point, forces due to the difference in the oil and water (in our case ice) surface tension dominate spreading forces. Most oils have a surface tenstion value less than that of water or ice and therefore most oils "wet" these surfaces. The point at which surface tension forces begin to control spreading is the point where the force due to gravity equals the force due to surface tension. The spreading force due to surface tension (Fs) equals:

$$F_s = \sigma_r (2\pi r)$$

where $\sigma_r$ is the resultant surface tension vector when oil interfaces an ice surface and $2\pi r$ is the circumference of the oil pool. Equating the surface tension force and the gravity forces $F_s = F_g$

we get $\sigma r(2\pi r) = \pi r \rho g h^2 \qquad (1.1)$

We now solve equation 1.1 for the thickness (h) of the oil at the instant $F_s = F_g$. We shall call this thickness the critical thickness ($h_c$). The critical thickness ($h_c$) where surface tension forces begin to dominate spreading is therefore:

$$h_c = \sqrt{\frac{2\sigma_r}{\rho g}} \qquad (2)$$

Hence in summarizing the positive oil spreading forces we find the following sequence:

(1) Gravity forces dominate spreading until $h = h_c$

(2) At $h_c$, $Fs > Fg$ and surface tension forces dominate

A similiar situation is found when investigating the forces responsible for retarding the spreading of oil. The primary oil spread retarding forces are due to an inertial deceleration force and a viscous drag force.

Let us first consider the inertial forces. Inertia ($F_i$) is a retarding force that by definition equals mass x deceleration. For our purpose

$$F_i = \frac{mdv}{dt} \qquad \text{where} \quad m = \pi r^2 h\rho \qquad \text{and} \qquad v = r/t$$

$$\text{hence} \qquad F_i = \frac{\pi r^2 h\rho r}{t^2}$$

$$F_i = \frac{\pi\rho r^3 h}{t^2} \qquad (3)$$

(Note: See list of symbols in front of report)

The viscosity forces ($F_u$) are essentially friction forces due to the deformation of horizontal layers of the oil. The dynamic viscosity of the oil (u) is by definition the ratio of the shear intensity to the rate of deformation $(\frac{dv}{dh})$ . We represent this by

$$u = \frac{\tau}{\frac{dv}{dh}} \qquad \text{where} \quad \tau = \frac{F_u}{\pi r^2}$$

$$\text{and} \quad \frac{dv}{dh} = \frac{v}{h}$$

for our purposes $v = r/t$

so $\frac{v}{h} = \frac{r}{ht}$

Our definition of viscosity now becomes

$$u = \frac{F_u ht}{\pi r^2}$$

Solving for viscous drag we obtain

$$F_u = \frac{\pi u l^3}{th}$$

If we examine the inertia to viscous force ratio, $\frac{\rho h^2}{ut}$ we see that this ratio, for a particular oil, increases as $h^2/t$ increases. It is evident from the $\frac{1}{t}$ relationship that initially, or when time is small, inertial forces dominate the retarding forces and as time increases and the inertial/viscous ratio becomes smaller, viscous forces dominate retarding forces.

In order to establish the relative significance the aforementioned spreading forces effect oil spreading on ice, a discussion of terminal spreading limit (or the maximum area a spill will cover) is required.

As described in Section I of this report under "sled description", the oil was poured on the ice in a slow continuous manner to simulate a broken pipeline or a slowly leaking surface vessel (ship, barge, etc.) Therefore it is convenient and accurate for us to represent the total volume of oil spilled by:

$$\text{total volume} = V_t = \bar{Q}\,(t) \tag{5}$$

Where $\bar{Q}$ represents the average flow rate and t the total time of oil discharge.

The total volume ($V_t$) also equals:

$$V_t = \pi r^2 h \tag{6}$$

Equating the two volumes (eq. 5&6) and solving for (r) we obtain:

$$r = \sqrt{\frac{\bar{Q}t}{\pi h}} \tag{7}$$

A term, one we shall call "effective roughness height" or $z_o$ is now introduced. $z_o$ is a quantification of effective snow/ice roughness height that it affected by 1) surface roughness, 2) ice permeability and porosity, and 3) viscosity of the fluid (oil). Through research conducted on the spreading of liquids over rough surfaces and statistical investigations into ice roughness [5]. the effective roughness height ($z_o$) has been determined to vary greatly but seldom ranging below a value of 0.1 ft (3.04 cm).

Noting equation (7) and considering the definition of $z_o$, we draw the conclusion that spreading will cease when h (oil thickness) $\cong z_o$ (effective roughness height). Substituting zo for h and renaming r to $r_{max}$ equation (7) becomes:

$$r_{max} \cong \sqrt{\frac{Qt}{\pi z_o}} \tag{8}$$

This equation is plotted in Figure (6) over a range of roughness heights. From this figure a reasonable prediction of terminal pool radius for a given flow rate, time, and $z_o$ can be made. The difficulty associated with the terminal spreading prediction theory is that the effective roughness height of a surface area must be known if the spill area is to be accurately predicted. Work is now underway (Coast Guard Contract DOT-CG-12,438-A) to statistically determine the range of effective roughness height in Arctic areas of high spill potential. However, our determination that the lower limit of $z_o$ is approximately 0.1 ft allows us, at this time, to predict the maximum area a spill of a given volume would ultimately cover.

With the above discussion of terminal spreading limit we can continue with our analysis of the relative importance of the previously described spreading and retarding forces due to gravity surface tension, inertia, and viscosity.

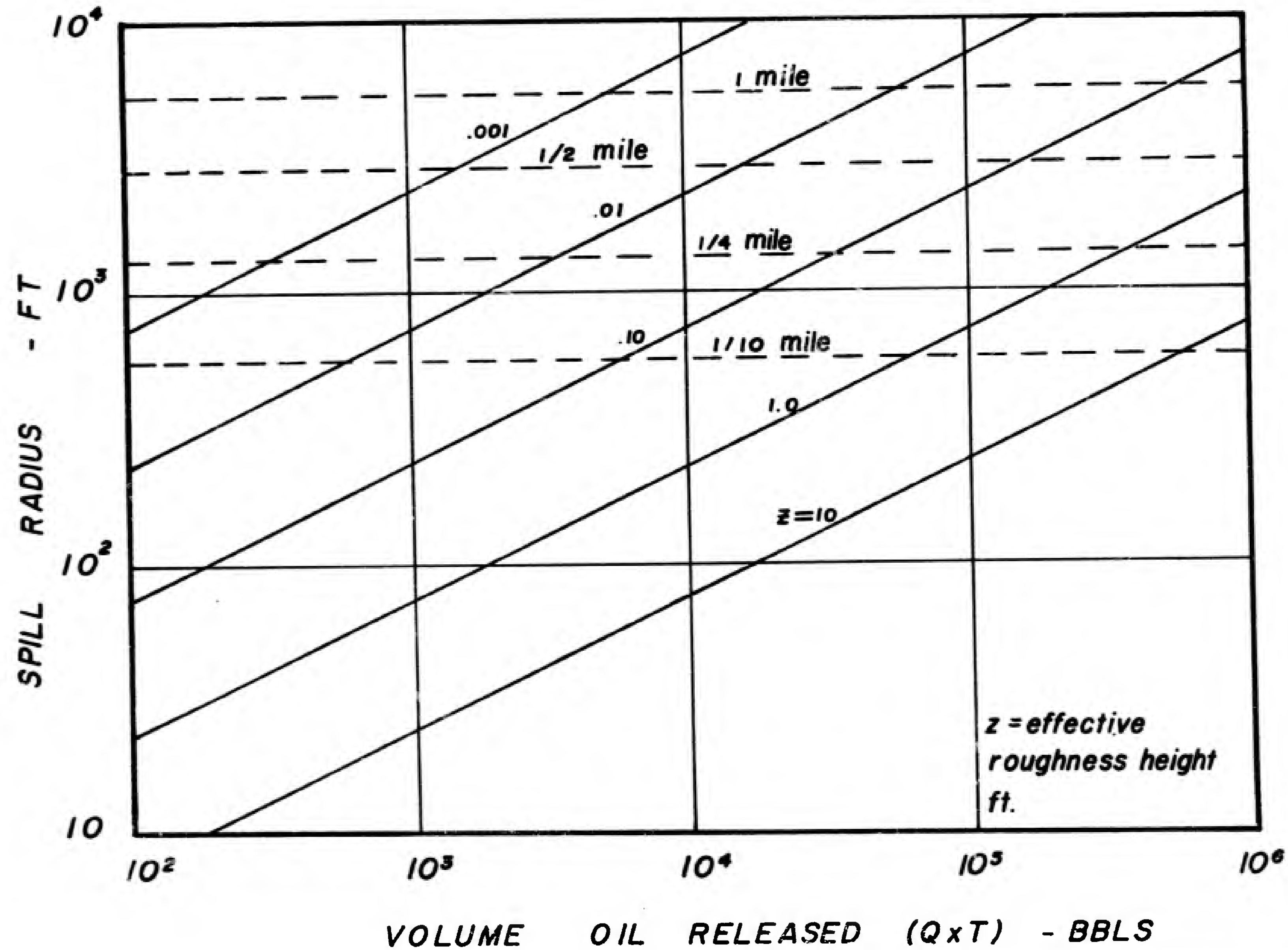
Examining equation (2) we see that the transition point from gravity to surface tension spreading occurs when the oil diminished to a critical thickness ($h_c$) of

$$h_c = \sqrt{\frac{2\sigma_r}{\rho g}}$$

(Note: the surface tension $\sigma_r$ is the resultant surface tension vector when oil is spreading on an ice surface)

We will now attempt to solve for $h_c$ using representitive values of $\rho$ (density) and $\sigma_r$ (surface tension) obtained for the Prudhoe Bay test crude (See Appendix C). A density of .890 gm/cc will be substituted for $\rho$. The resultant surface tension $\sigma_r$ is calculated as being:

FIGURE 6 MAXIMUM AREAL COVERAGE - ICE SPILL



$$\sigma_r = \sigma_r(1 + \cos \Theta) \qquad (9)$$

where $\Theta$ equals the oil contact angle. For a contact angle of 45° (See Note) and an oil surface tension of 30 dynes/cm (measured value of Prudhoe Bay Crude):

$$= 30\ (1+\cos 45°) = 30\ (1.702)$$

$$= 51 \text{ dynes/cm}$$

Using the above mentioned values of $\rho$ and $\sigma_r$ and 980 gm/sec$^2$ as the acceleration due to gravity (g),

$$h_c = \sqrt{\frac{2 \times 51}{.89 \times 980}} = .342\text{cm}$$

From this calculation we can predict that gravity spreading forces will dominate positive spreading forces until an oil thickness of approximately one-third cm is reached. however, as we previously stated in our analysis of terminal spreading limits, oil spreading will cease when h = zo, which has been determined to range down to an oil thickness

(Note: No experimental data was available for the contact angle of oil on ice. For purposes of this discussion it is assumed that oil "wets" ice which indicates a contact angle of between 0° and 90°. A conservative value of 45° was assigned as the contact angle for determining the resultant surface tension. However, as the cosine of angles between 0° and 90° varies only from one to zero, we can see that by using the worst but impossible case of 0° contact angle, the cosine equals 1.0 resulting in a $\sigma_r$ of 60 dny/cm and a "h" of 0.371, which is below the minimum oil thickness of 3.04cm.)

of approximately 3.04cm. It can easily be seen that h will never reach the critical thickness necessary for the transition from gravity to surface tension spreading forces. It can safely be predicted then, that gravity forces are the only significant contributers to positive oil spreading over ice forces and that spreading terminates prior to entering the surface tension spreading regime.

Since the final thickness of an oil spill on ice is quite large when compared to an oil spill on water, and as previously discussed the ratio of inertia to viscous retarding forces vary as $h^2$, we can also make the assumption that viscous retarding forces are negligible contributors to the resultant retarding force.

Neglecting, then, the surface tension spreading forces and the viscous retarding forces, our discussion leaves us with only gravity spreading forces (eq.1) and inertial retarding forces (eq.3) affecting the spreading of oil on ice.

Equating the gravity spreading and inertial retarding forces we obtain

$$\pi r \rho g h^2 = \frac{\pi \rho r^3 h}{t^2} \qquad (10)$$

Again depicting the volume (V) of spilled oil as

$$V = \overline{Q}t = \pi r^2 h$$

and solving for thickness (h) to obtain:

$$h = \frac{\bar{Q}t}{\pi r^2} \tag{11}$$

allows us to represent the oil thickness (h) in terms of average flow rate ($\bar{Q}$), time(t), and spill radius(r).

Substituting h (eq. 11) in equation (10)

$$\pi r \rho g(\bar{Q}t/\pi r^2)^2 = \frac{\pi \rho r^3(\bar{Q}t/\pi r^2)}{t^2}$$

and solving for radius(r) we obtain:

$$r = .756(g\bar{Q})^{1/4}t^{3/4} \tag{12}$$

We conclude therefore, that oil spreading over ice will progress as a function of time and flow rate as described in equation (12) until oil thickness reaches effective roughness height where spreading stops.

## Data Interpretation

As previously mentioned the spreading experiments were recorded on 8mm film which was later analyzed for one dimensional time vs distance.

The data as extracted from the film represents the time in seconds elapsed as the spilled oil passed stakes spaced at a known distance.

The raw data is tabulated in Table I.

Table I

Spreading Data

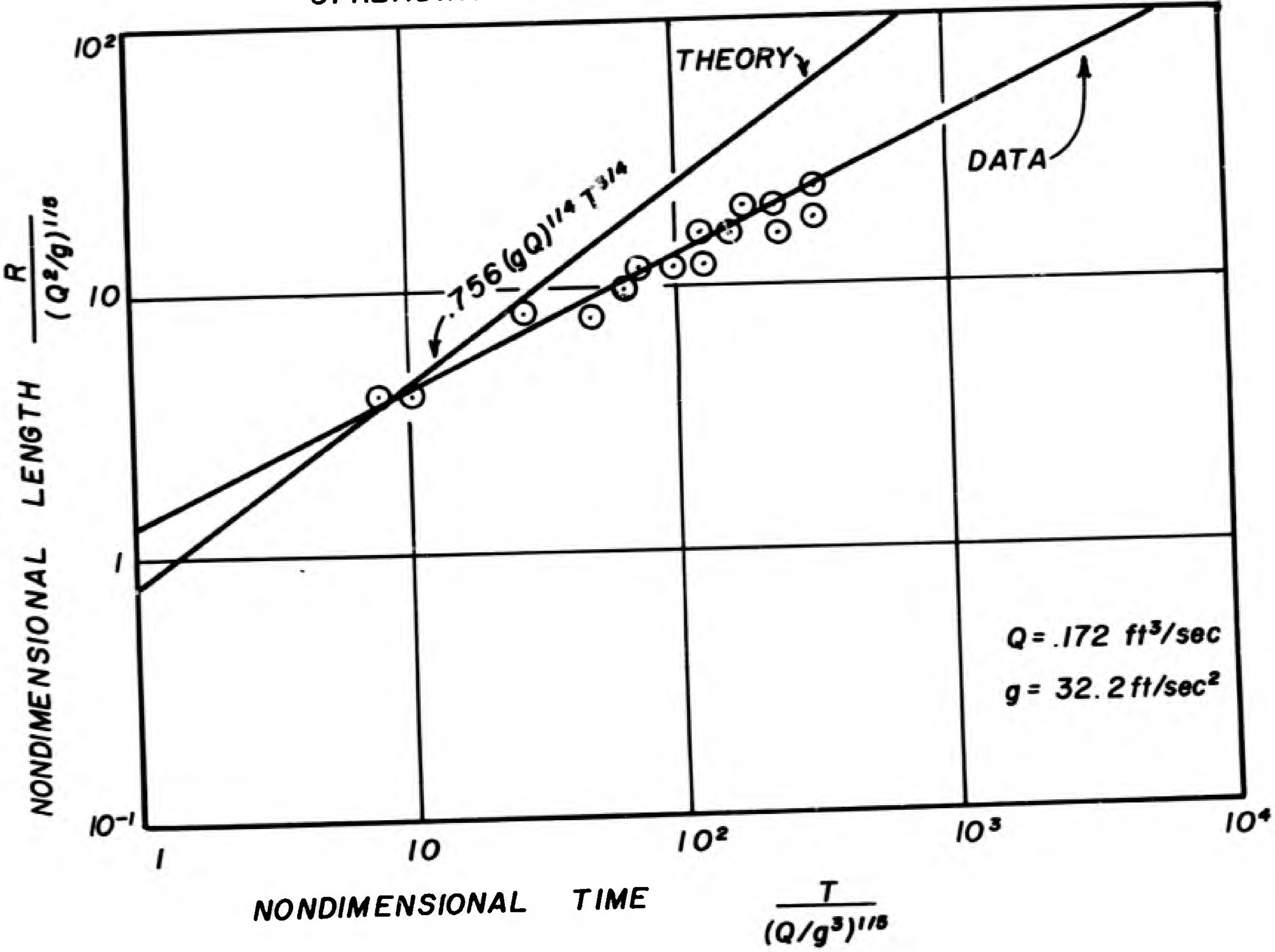
| Radius Ft. | Time - Secs Spill (1) | Spill (2) | Spill (3) | Spill (4) |
|---|---|---|---|---|
| 1.0 | .7 | .7 | .9 | .7 |
| 2.0 | 2.3 | 4.2 | 4.2 | 4.3 |
| 2.5 | — | — | 5.8 | — |
| 3.0 | 6.5 | 8.6 | — | 11.3 |
| 4.0 | 10.6 | 14.0 | — | 21.4 |
| 4.5 | — | — | — | 29.9 |
| 5.0 | 15.6 | 19.5 | — | — |
| 6.0 | — | 28.1 | — | — |

The experimental data is non dimensionalized as per Appendix (B) for comparison with the previously developed theory.

The non-dimensionalized data points are plotted in Figure (7). The data, as can be seen from Figure (7), plots in a straight line on log-log paper with very little scattering. The observation that oil spreading on ice is a single straight line relationship strengthens our assumption that only gravity and inertia forces are significant contributors to spreading and retarding forces. Had surface tension or viscous forces contributed significantly to spreading, the data plot would be expected to be composed of two straight lines of different slopes. Section (1), the gravity -

FIGURE 7

SPREADING RATE - WINTER ICE



inertial spreading, would appear as the data plot illustrated in Figure (7); however the plot would continue on a constant slope until $h=h_c$ where surface tension-viscosity forces would control spreading and the slope of the spreading curve would be reduced. Although the argument that only gravity and inertia forces are involved in the spreading of oil over ice is supported by the field data, the oil spread predicted by theory is not completely validated by the experimental results. As can be seen from Figure (7), the slope of the experimental data is less that that predicted by the simiplified theory. The equation of the field data Figure (7) can be duplicated by the following equation:

$$r = 1.3 \, (Q^3 g)^{.1} T^{1/2}$$

The apparent discrepancy between the theory obtained spreading relationship and the data obtained relationship while interesting is not considered significant. To some extent the discrepancy between theory and experiment is within the range of experimental error. Of greater significance is the fact that the experimental results validate the theoretical assumption that only gravity and inertia forces must be considered when predicting spread rate.

From a practical standpoint, ability to predict the ultimate size of a spill is of greatest importance. It is very probable that the response time for emplacement of spill cleanup equipment at an Arctic oil spill will be such that spreading will terminate before any significant action to control the movement of the oil can be initialed.

## IV. Oil - Ice Interaction

The experiments made evident a number of physical occurances that before hand were not well-defined. Specifically, these occurances dealt with the unique interaction phenomena when oil is spilled on a cold snow or ice surface.

When oil is first subjected to or "spilled" over the ice/snow surface there is very little migration of the oil down the ice column (Figure 8). A slight penetration was expected based on results obtained by Glaeser and Vance and an experimentally determined on scene ice porosity of approximately 30%. Further, the immediate snow surface upon which the oil was spilled was found to have a porosity of approximately 59%. From a cursory examination one would expect the warm (60°F) oil to move, by gravity and capillary forces, down through ice/snow pore channels. However, penetration of oil into the surface did not occur to any substantial degree. As illustrated in Figure (9), the only substantial penetration into the surface is found where a physical surface indentation existed.

The reasons for the lack of penetration into the surface by the oil is theorized as follows.

As measured by test personnel, the snow/ice surface was found to vary in temperature between +5°F and -15°F. Although this is somewhat warmer than the ambient air temperature, it is considerably cooler than the freezing point of saline water. The increased surface temperature is a result of both an upward heat flux generated by the large body of 29°F water immediately below the ice surface and absorption of solar radiation

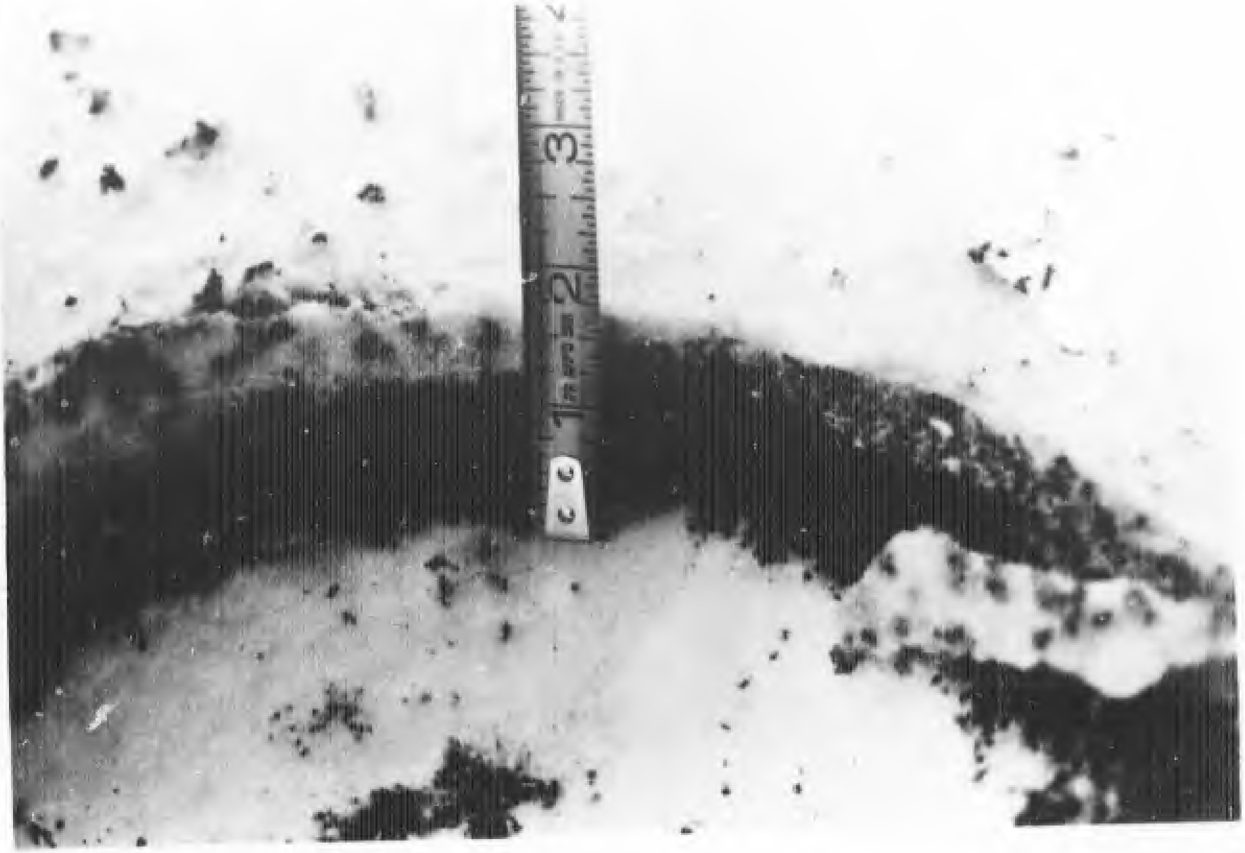


FIGURE 8 - Thickness of oil shortly after being poured on a snow covered ice surface. The oil was poured during a heavy snowstorm.

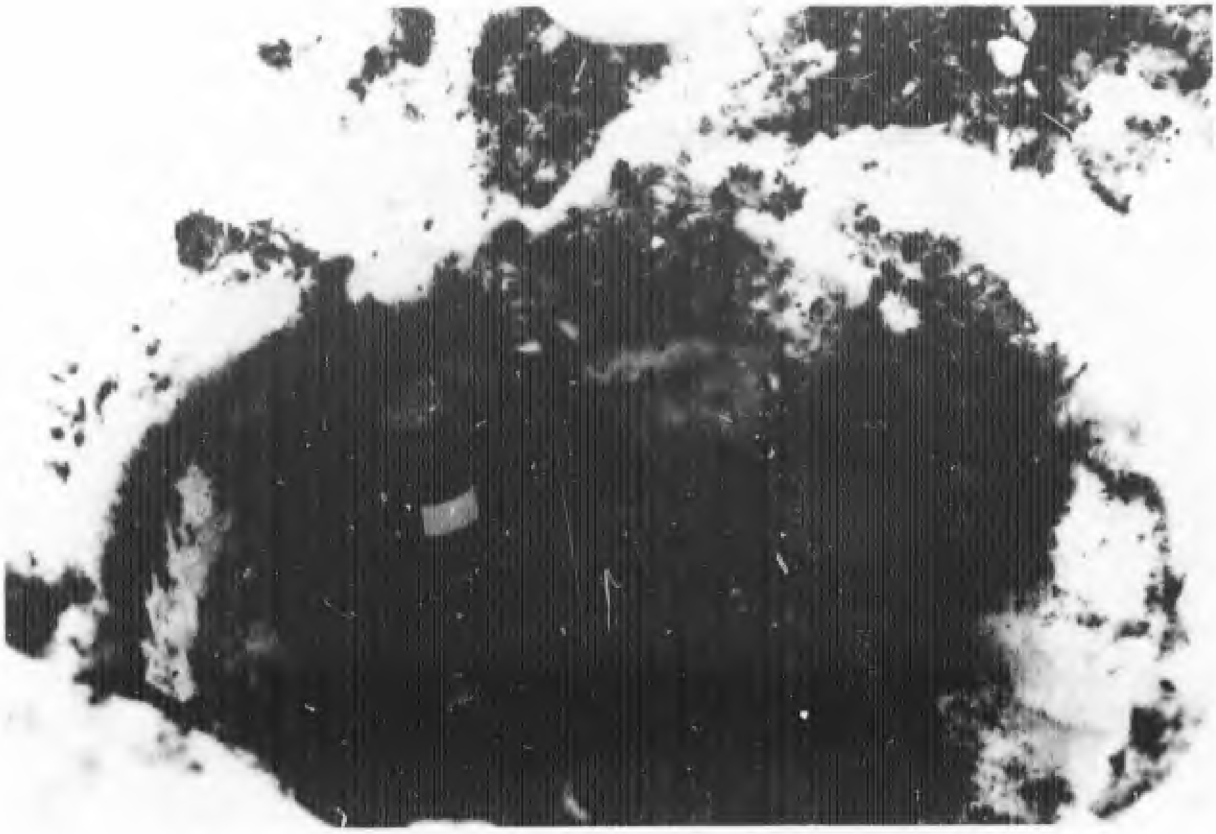


FIGURE 9 - Cross - section of snow/oil/snow/ice column. The heavily oiled snow to the right of the eight ounce sample bottle is the area directly under the oil discharge point.

into the surface.

Immediately after the 60°F oil hits the surface a temperature differential of ~ 70°F is created. The warm oil immediately causes an increase in temperature and subsequent melting of a thin surface layer of snow/ice. The melted snow/ice (water) moves, by gravity and capillary forces, down the snow/ice column a distance on the order of 2mm where the water refreezes thereby blocking many pore channels. The surface then becomes impermeable to any further downward movement of oil.

Effect of Blowing Snow

As high winds and blowing snow are quite common in Arctic regions, it is significant that fresh snow, upon blowing across on an oil surface that has a temperature below the freezing point of water, does not simply lie on the upper oil surface. Fresh snow blowing across the oil tends to stick and migrate downward into the oil. The oil/snow mixture Figure (10) formed by this phenomena was largely crystalline in state. By taking samples and separating the two phases, the mixture was determined to contain up to 80% (by volume) snow. The mixture appeared as a mulch that could easily be handled mechanically. The mixture was quite dry in appearance as long as the temperature remained below the pour point (+15°F) of the oil; however, as the temperature increased above the pour point, the oil within the mixture became more fluid and would physically flow out of or drip from the snow/oil mixture.

FIGURE 10 - Snow/oil "mulch" resulting from snow blowing on a freshly spilled oil pool. The mulch contained up to 80% snow.

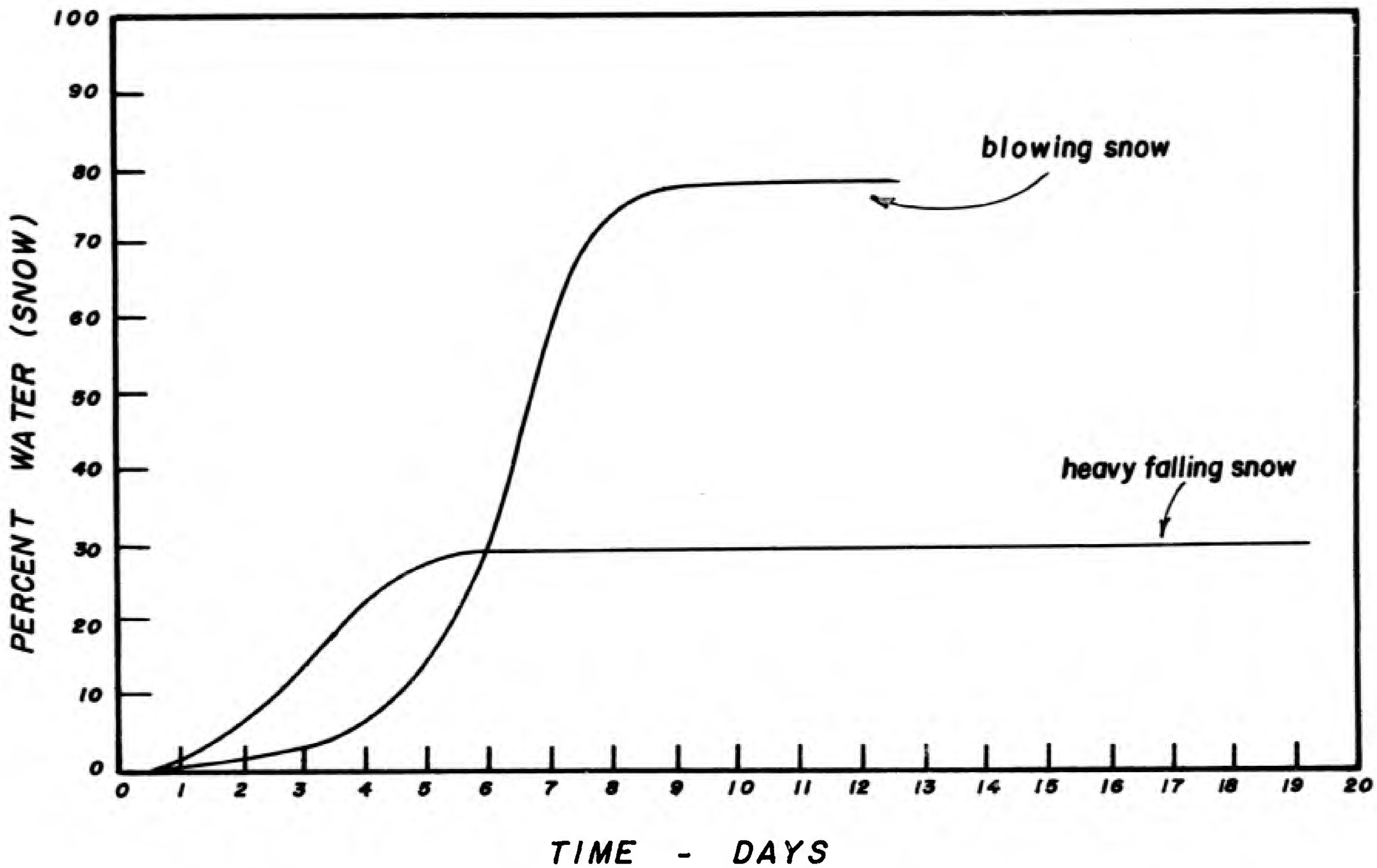
## Effects of Heavy Falling Snow

Although both heavy falling and lightly blowing snow combined with the spilled oil to form the previously described "mulch", it appeared that a heavy snow did not affect the oil as greatly as did the blowing snow. A heavy snow fall resulted in a rapid accumulation of snow upon the surface of the oil which was believed to become compacted at the upper snow/oil interface. It is theorized that this compaction reduced the volume of snow infiltrating the oil. Figure (11) illustrates the effect blowing or heavy falling snow has on the percentage of snow absorbed by the oil.

The curves illustrated in Figure (11) merits some discussion. It must be noted that the time scale is number of days aged for each pool and does not imply, of course, that the oil pools were aged concurrently. First examining the blowing snow curve it is clear that initially there was minimum snow/oil mixing. Between the fifth and eighth day, however, the percent snow (volume) jumped from just over 10% to 80% where a leveling off occured. There was little initial mixing simply because a minimum amount of wind and blowing snow were present the first four days of the spill. On day six (6) (blowing snow curve) high winds accompanied by blowing snow were prevalent, hence the sudden increase in percentage snow. On day eight (8), an extremely heavy snow fall completely inundated the spill area resulting in a leveling off of snow/oil mixing.

Examining Figure (11), the heavy falling snow curve increased at a slope of approximately 1/2 until day five (5) where a leveling of absorption at approximately 30% snow is attained. The oil used for this experiment was subjected to an extremely heavy snowfall the day following the spill. It

FIGURE 11 WATER (SNOW) CONTENT OF OIL-SNOW MIXTURE



is believed that this heavy snowfall was responsible for the reduced leveling off of snow/oil mixture percentage.

Detection Difficulties

After a volume of snow adequate to produce a leveling off of the snow/oil mixture percentage, any further falling or blowing snow will accumulate on the surface of the oil Figure (12). During a heavy snowfall, this covering may occur within hours of the spill. This obviously creates a spill location problem. The experiments indicated that a major spill, if occuring during or before a storm, could go completely undetected from visual observation. It becomes obvious, therefore, that accurate oil spreading predictions must be developed and perfected if the aerial extent of a remotely detected spill is to be accurately assessed. It will also be necessary to establish means of spill detection (other than visual) along high spill potential routes (pipeline, etc.)

V. Oil Aging

Whenever crude oil is openly subjected to the atmosphere the more volatile components will tend to evaporate. This process, sometimes referred to as aging, is dependent upon the partial vapor pressures of the individual components of the oil,the ambient air temperature, and the average wind velocity.

The aging process, depending on the composition of the original oil, can quite drastically alter the oil's properties. The density, viscosity and surface tension are three important properties of oil that increase in magnitude as aging progresses.

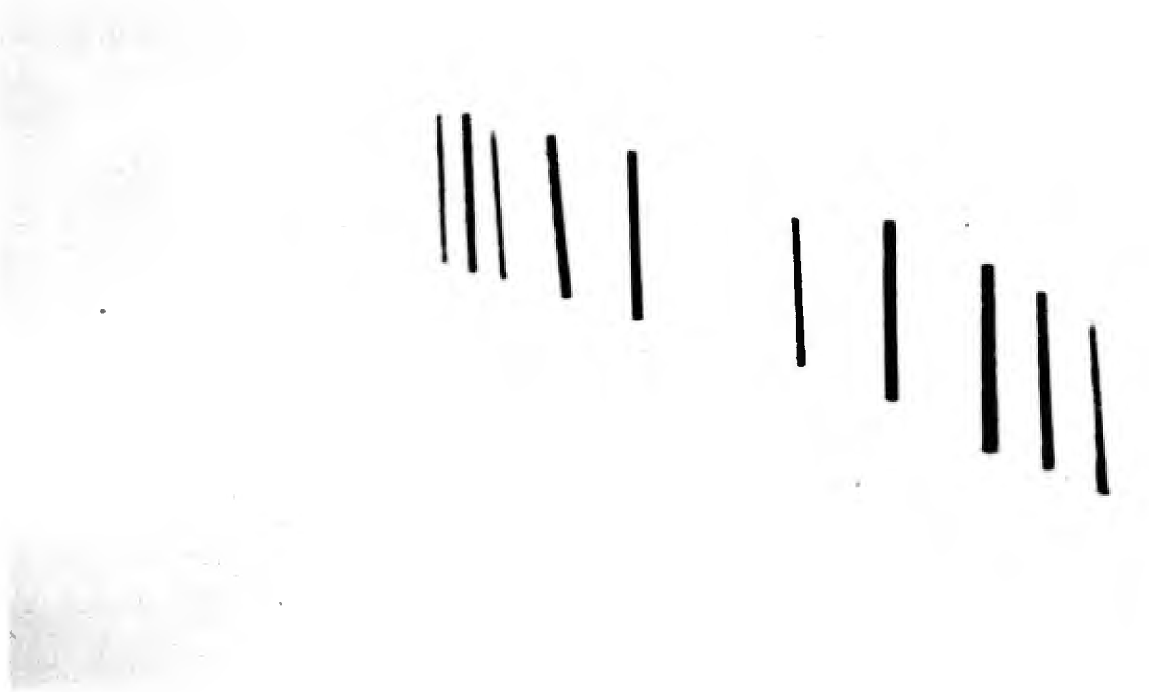


FIGURE 12 - An area of a snow covered oil spill following a heavy snowfall. The oil is completely covered from sight.

In Arctic areas, where ice is continually moving and an annual breakup occurs, alteration of the above mentioned properties will affect the procedures required to minimize oil contamination if and when a major spill occurs. Especially of concern is the density of the oil. The density of undeformed sea ice, which depends upon its salinity and porosity, averages about 0.910 gm/cc. The density of underlying sea water is approximately 1.030 gm/cc. It is obvious that if aging is allowed to progress to the point where the oil density become equal to or greater than the density of sea ice or sea water the oil will be less bouyant than the ice or water and will tend to migrate under the ice (or water depending on degree of aging). The movement of oil under the ice surface was witnessed by the author in Plattsburg, N.Y. (Figure 13) during March of 1971 and by Glaeser and Vance[4].

The purpose of the aging experiments in this test program was to determine the effect the extreme temperature present during the Arctic winter has on the aging rate of oil. Prior to this test, the effect of extreme cold weather on aging was open to speculation.

Aging Experimental Procedure:

Two oil pools of approximately 50 gals in volume and 10' in diameter were used for gathering samples. The oil was spilled using the "oil tank sled" previously discussed. Of the two spills tested for aging one spill (3.1) was made on a smooth ice surface while the other spill (2.3) was created on a snow covered ice surface. Once a day, beginning the day of the spill, two eight ounce samples of the oil were carefully gleaned and stored in teflon gasketed nalgene sample bottles.

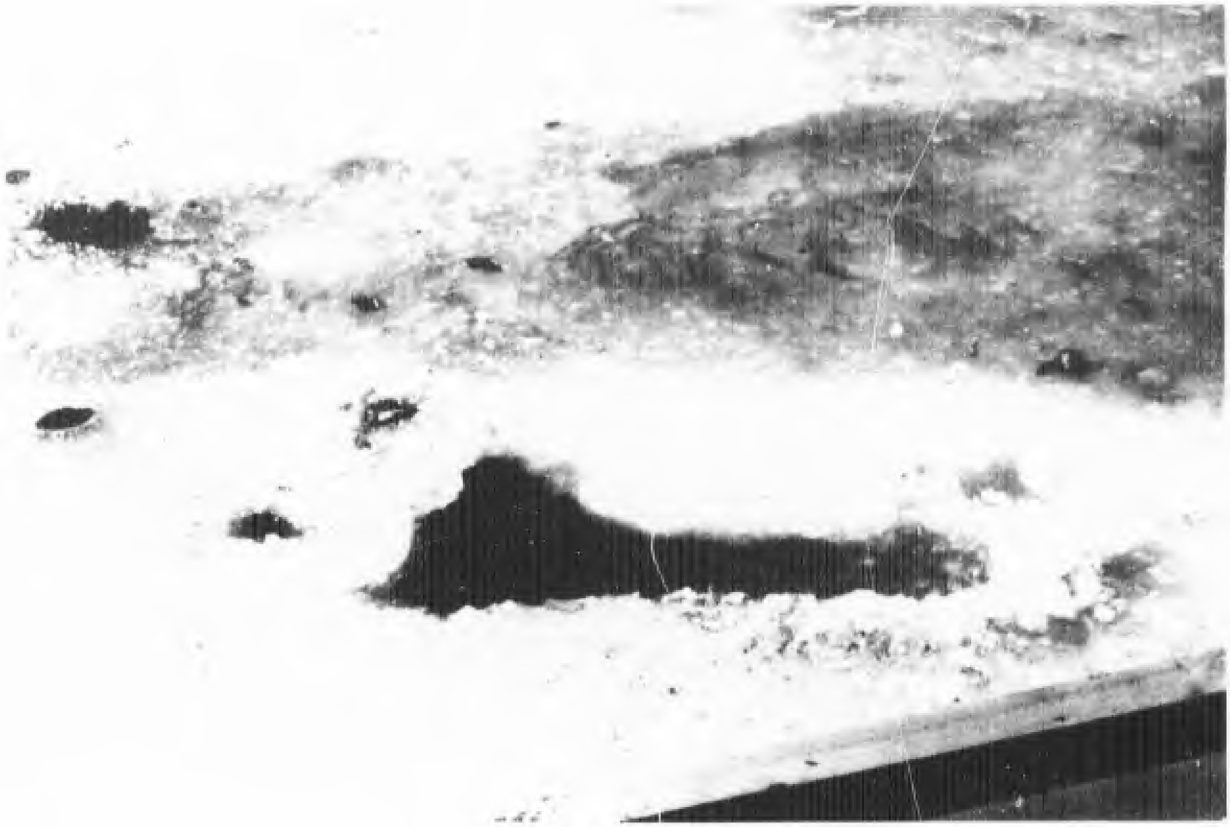


FIGURE 13 - Oil trapped under a thin layer of ice as witnessed by the author at Plattsburg, N.Y. on Lake Champlain during March 1971.

Sample one was evaluated on station for viscosity using a Brookfield model LVF rotational viscometer. The remaining eight (8) ounce samples were forwarded to the ESSO Research and Engineering Company, Baytown, Texas for analysis of 1) density, 2) boiling point distribution, 3) ratio of water to oil in sample, and 4) ratio of saturates to aromatics.

As previously mentioned the oil used was obtained from North Slope oil fields. It was donated by the Atlantic Richfield Oil Company. A typical composition of this crude is found in Appendix (C).

Temperature Effects

Examining the change in density of the oil and comparing it to data obtained by Glaeser and Vance it becomes apparent the aging rate of crude in the winter months is much decreased from summer aging. This decrease in rate was expected. However, it is quite clear that oil does age in the winter months and that North Slope crudes (using analysis Appendix ( C ) as an example) will age to the density of sea ice (.9010 gm/ml) and possibly that of sea water (1.030 gm/ml) if left in place.

Further indications of the extent of winter aging are illustrated in Figures 14, 15, 16, 17, and 18. Although we see again that the aging rate is decreased when ambient air temperature is decreased, the rate is significant and is not to be discounted.

Wind Effects

The data as illustrated in Figures 14-18 requires an explanation. A substantial increase in density of the oil on ice is apparent after the

FIGURE 14 OIL DENSITY vs TIME

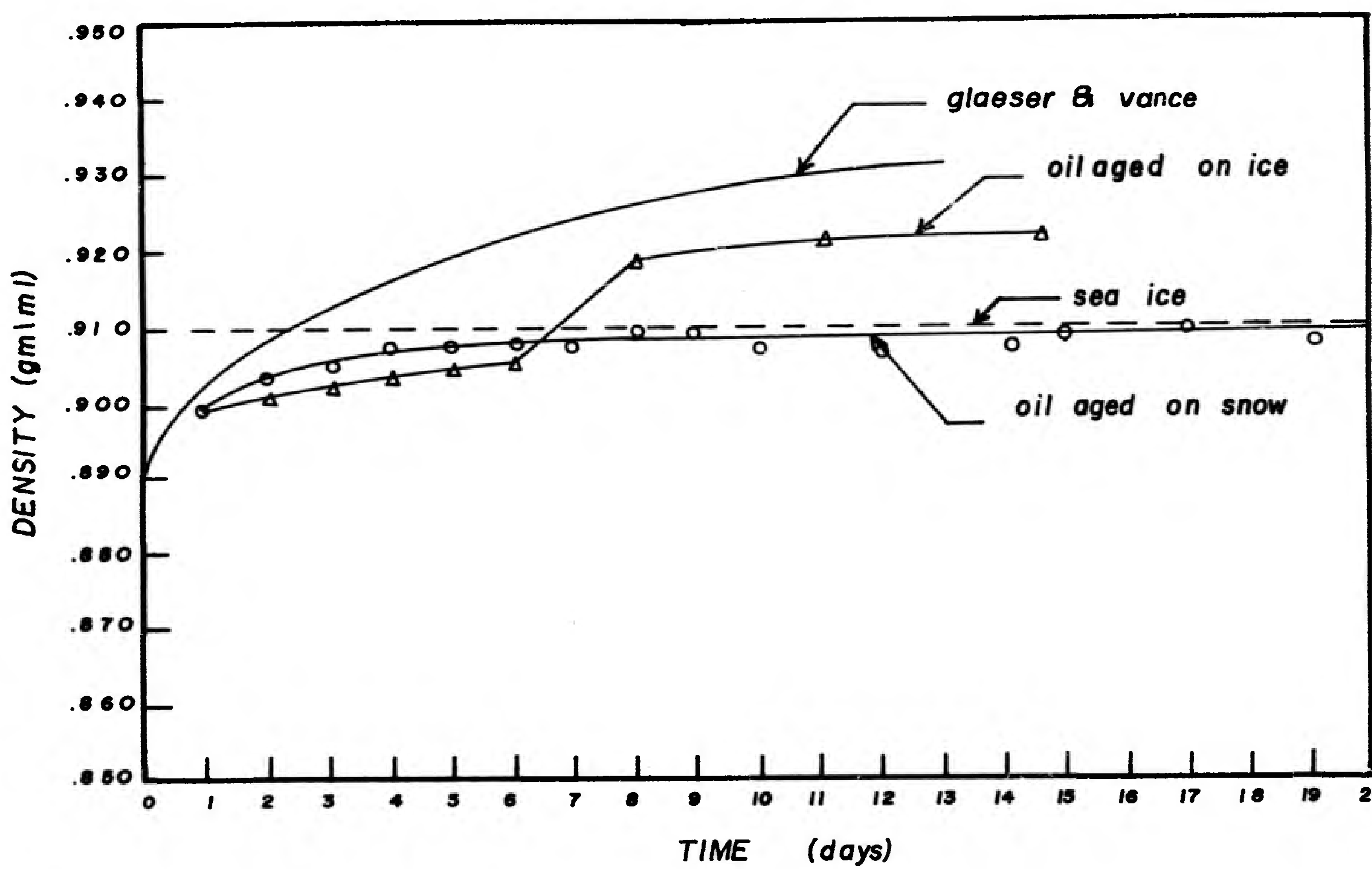


FIGURE 15

DISTILLATION CURVE - OIL WITH HEAVY SNOW

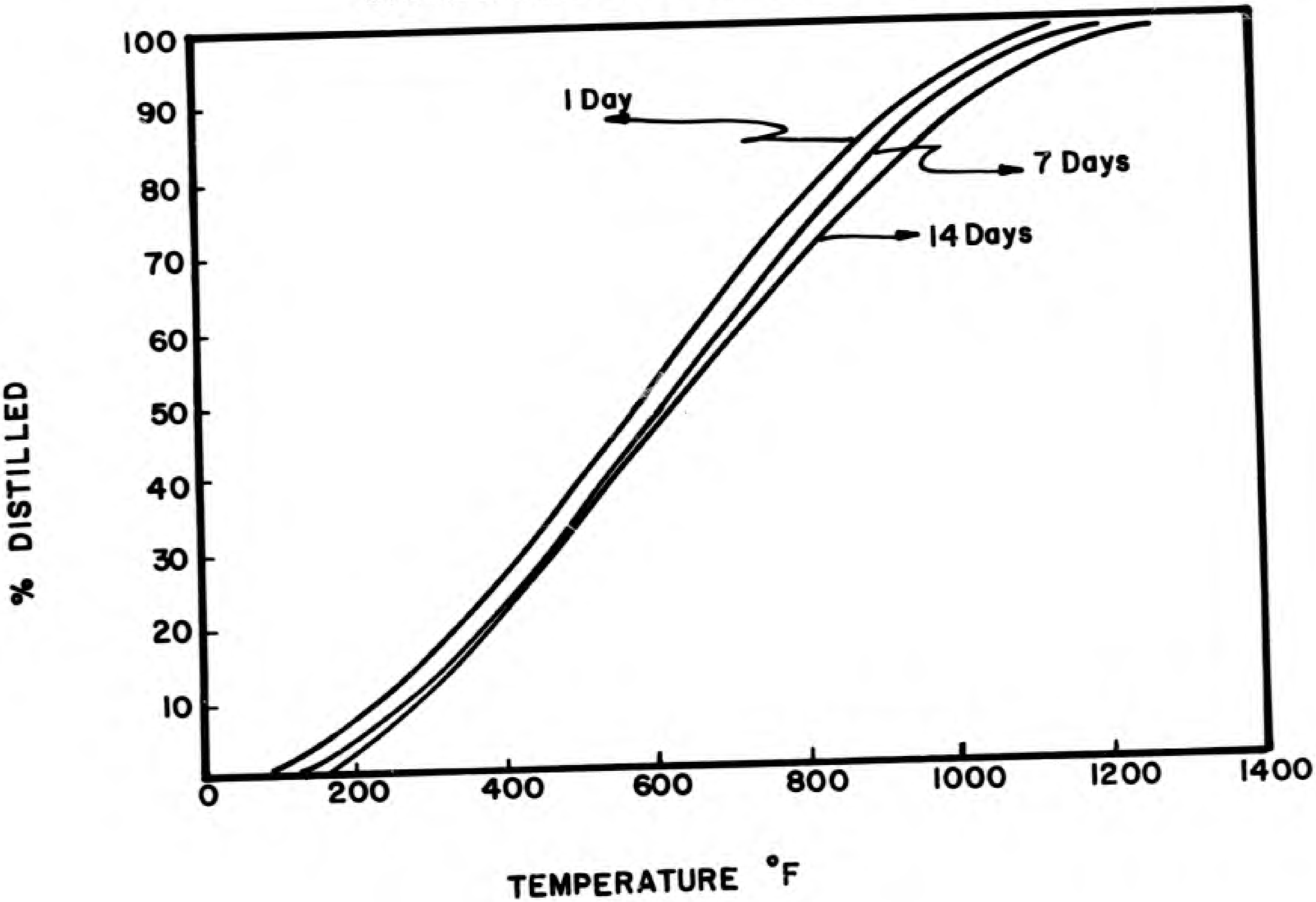
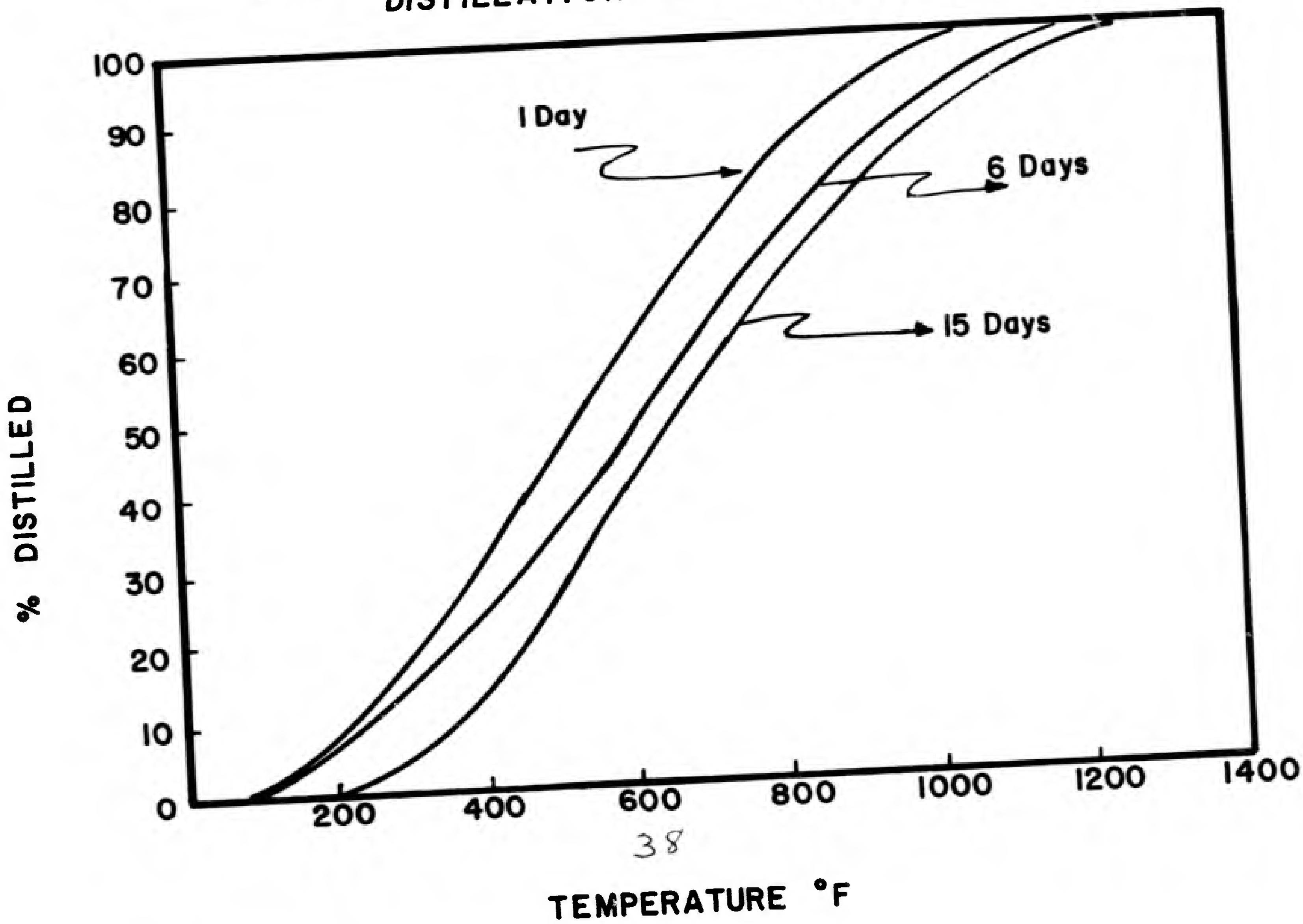


FIGURE 16

DISTILLATION CURVE - OIL WITH BLOWING SNOW



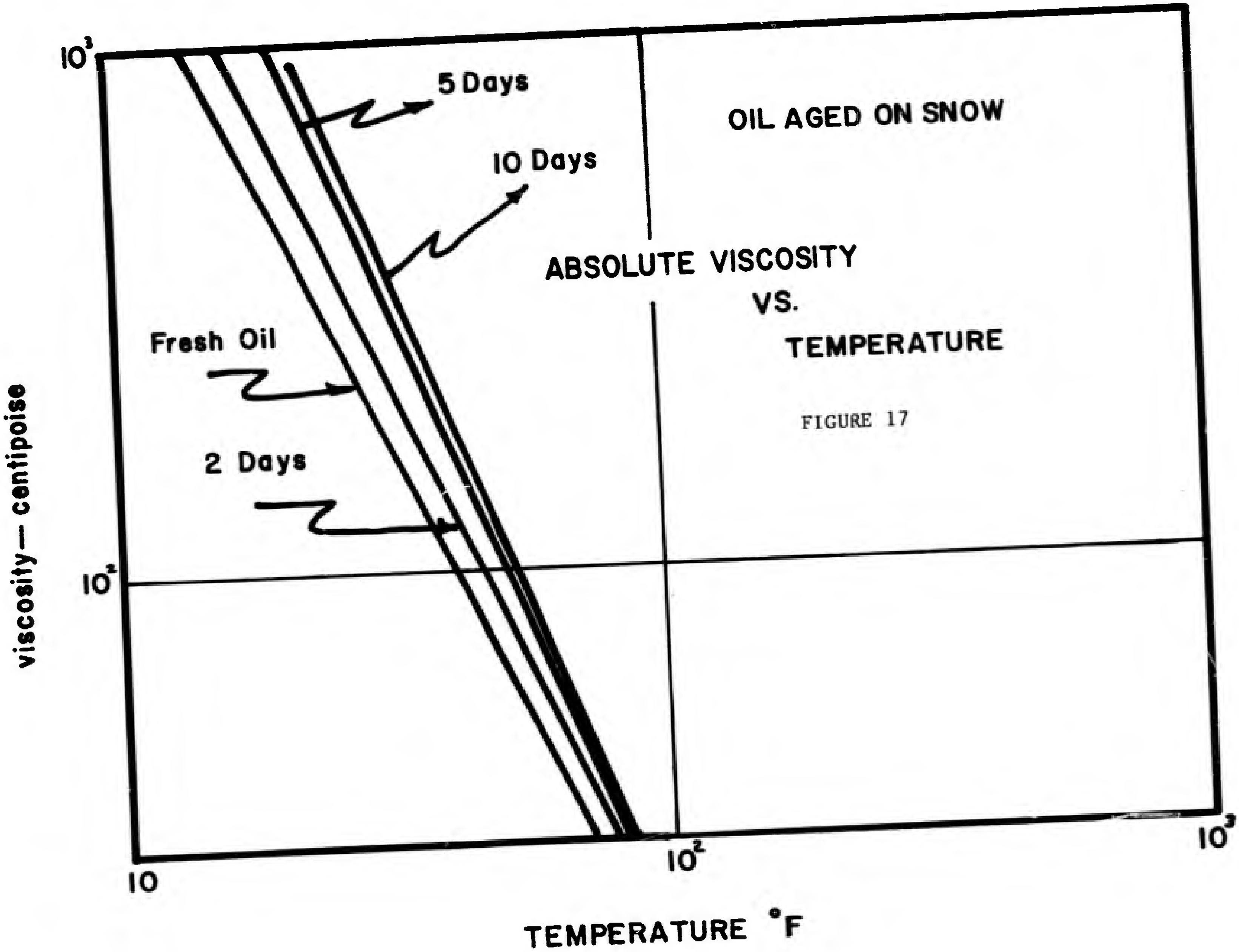
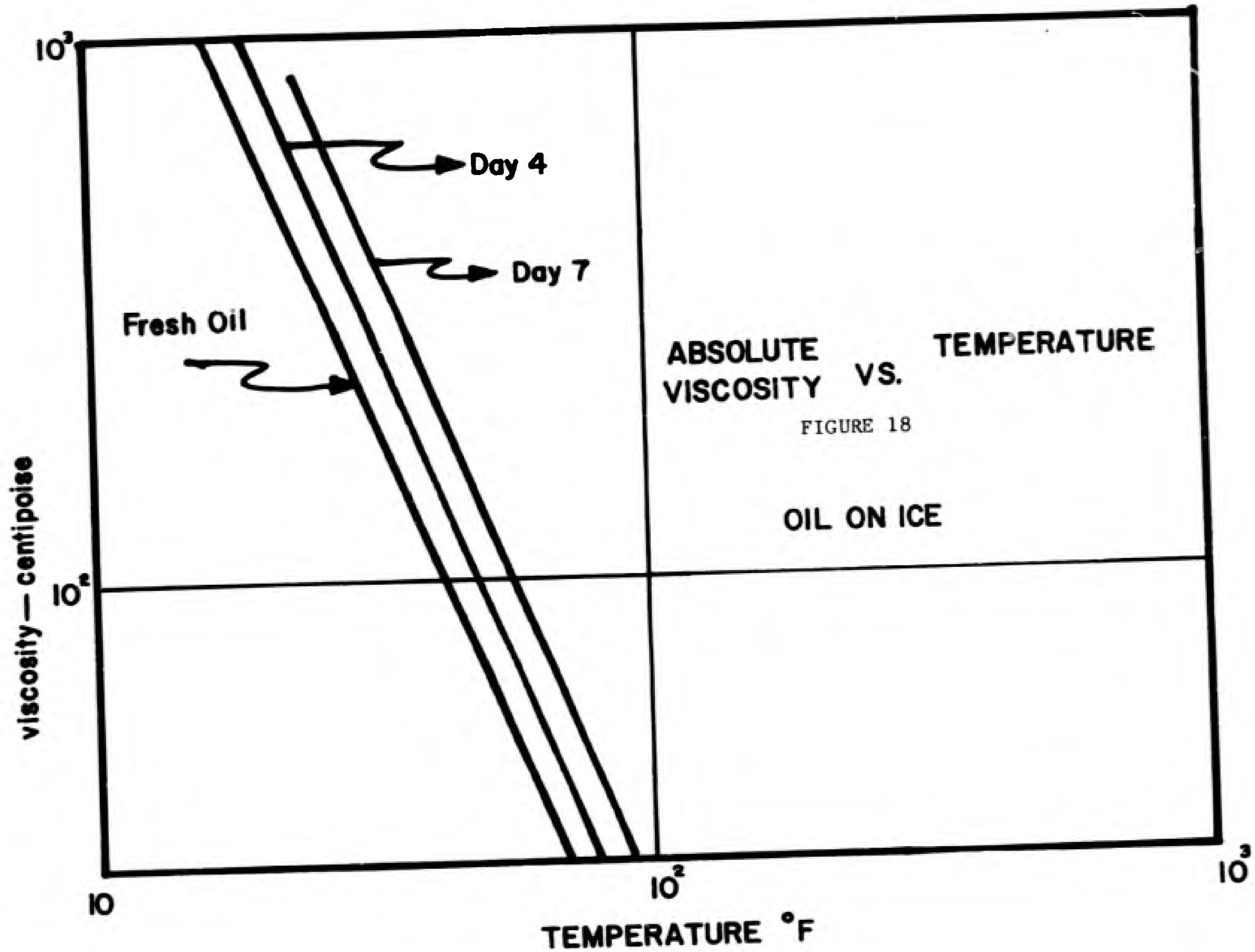

OIL AGED ON SNOW
ABSOLUTE VISCOSITY
VS.
TEMPERATURE
5 Days
10 Days
Fresh Oil
2 Days
viscosity — centipoise
$10^3$
$10^2$
10
$10^2$
$10^3$
TEMPERATURE °F

FIGURE 17


ABSOLUTE VISCOSITY VS. TEMPERATURE
FIGURE 18
OIL ON ICE
Day 4
Day 7
Fresh Oil
viscosity — centipoise
$10^3$
$10^2$
10
$10^2$
$10^3$
TEMPERATURE °F

sixth day. The density of oil aged on snow shows no sudden increase. The evaporation rate (or aging rate) is directly proportional to the rate of removal of the vapors from the area adjacent the oil-air interface. If a system of removing these vapors were not present, the area immediately adjacent to the interface would become saturated and an equilibrium condition would exist. Wind velocity, the chief mechanism for removal of these vapors, is the explanation for the increase in aging rate after the sixth day. A severe storm, accoumpanied by high winds (30-50 knots) passed through the spill area during the seventh day of the aging test. The increased aging rate during this time is believed to be a direct result of this increase in wind velocity. The "oil on snow" aging rate was unaffected primarily because the oil was protected by a 8-10" snow covering. The oil on ice, however, was clear of any snow covering at the storm's initiation.

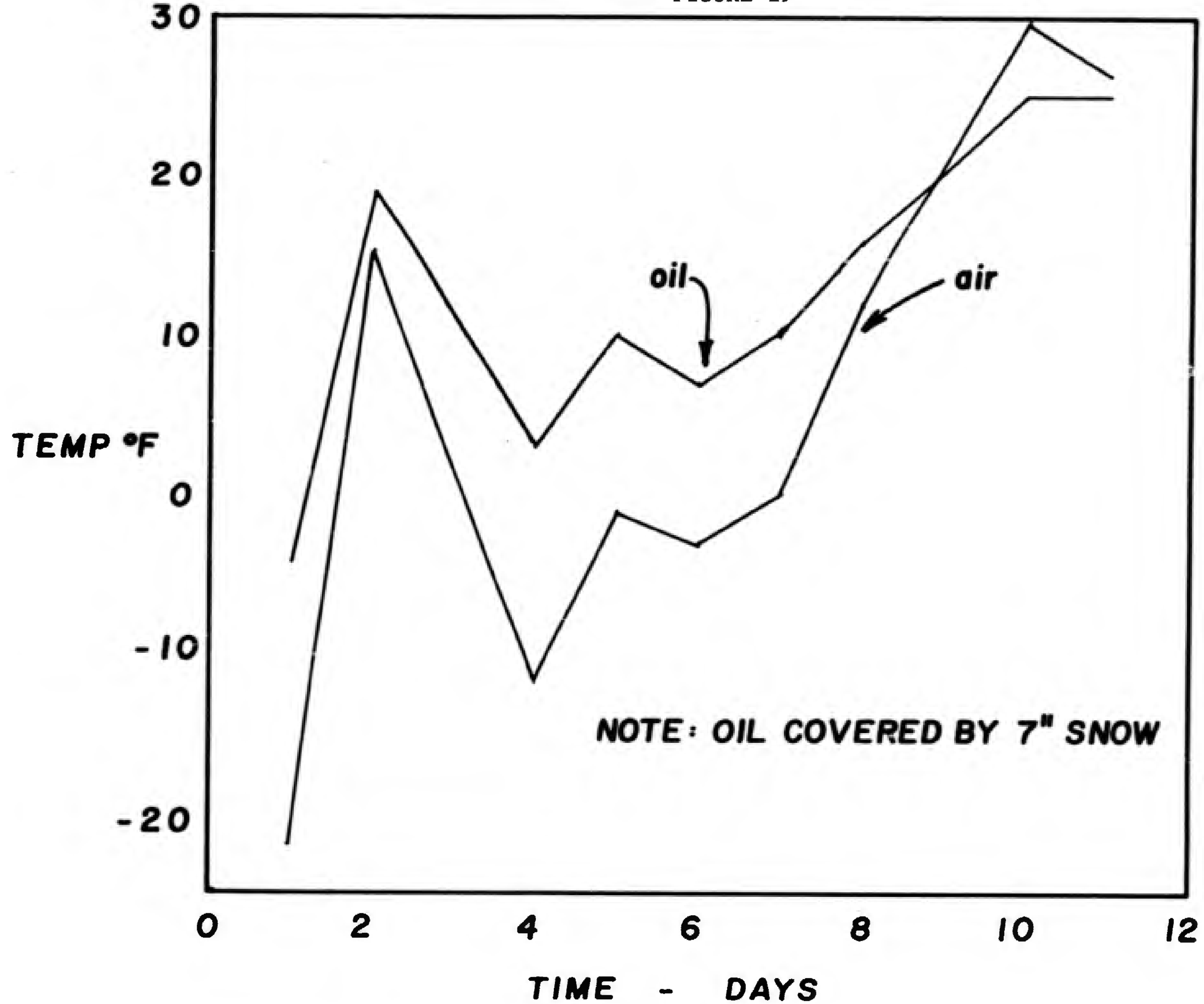
The increased aging rate of the oil aged on ice is also apparent in Figure (15) and Figure (16). The fifteen (15) days distillation curve is much further advanced to the right on ice aging indicating a greater percentage of higher boiling point components comprising the sample aged on ice.

All data indicated that a snow covering significantly decreases the aging rate of oil. It is apparent therefore that moderate wind velocity variations influence aging rate to a greater degree than do moderate temperature variations. The oil aged on snow was sheltered from the wind; however, the snow covering insulated the oil from ambient air temperatures (Figure 19).

The oil that was protected from the wind by an 8" - 10" snow covering aged much slower than the oil exposed to the open wind despite a 20°F to 30°F

OIL TEMP vs AIR TEMP

FIGURE 19



increase in temperature in the snow protected oil. The explanation is that the snow effectively "capped" the oil, not allowing vapors to escape. We can conclude, therefore, that oil ages at a significant rate in the winter Arctic until a snow cover is effected. It is apparent that oil continues to age while heavily covered with snow, but it is not clear if this rate is significant relevant to long or short term oil behavior.

## VI. Cleanup Techniques - LTJG. Paul Golden USCGR

In attempting to understand oil spill recovery constraints in the winter Arctic, various oil recovery treating agents and techniques were evaluated. Two broad categories were studied, 1 ) mechanical techniques and 2 ) treating agents such as sorbents, burning agents, dispersing agents and a surface active agent.

The treating agents were solicited from commercial firms with products that are available in large quantities for use in response to an oil spill. It is emphasized that these products were primarily designed to be used on water under temperate climatic conditions. The observations made on these treating agents in removing oil from snow and ice under sub-zero temperatures in no way reflects on their effectiveness under the normal operating conditions for which they were intended. Further the observations made on the effectiveness of these products were conducted under the extremely difficult field conditions of arctic winter and are subject to significant variations.

Treating agents were used on freshly poured North Slope crude oil covering an area of fresh snow approximately 10' in diameter. The pool was approximately 1/2" in depth, the air temperature was -5°F with an eight knot wind. The oil was allowed to cool for twenty minutes until it steadied at -2F. Two samples of each product were used. All of the sorbent samples failed to absorb oil when placed on the surface of the oil, however, their effectiveness was markedly improved when mixed with a shovel. After the samples were mixed with the oil, they were collected and weighted in the field. In the case of sorbent powders an effort was made to collect only the aggregate oil/sorbent mixture, however, some sorbent was not recovered and some excess fresh oil was collected with the sorbent, both affecting the calculated recovery efficiency. Bulk quantities of each sorbent were then used to determine their respective ease of application. The recovery efficiency and observed effectiveness of the sorbents are included in Table (2).

Dispersants

During the planning phase of the project, it was decided not to request samples of dispersants for field observations. The nature of dispersants (emulsifying agents) do not lend themselves to application in an oil on ice environment. Dispersants are easily applied to a static oil on ice situation however, and could aid in slick disruption during warmer spring/summer seasons when large scale ice breakup occurs. Dispersants, when used as emulsifying agents have no potential for application on an oil covered tundra area.

Prior to the tests, however, four dispersants were donated by commercial firms. The dispersants were applied to small pools of crude oil spilled on both snow and ice. The only visible effect the dispersants had on the oil, depending on the viscosity and freezing temperature of the individual

TABLE II

| SORBENT | TYPE AND FORM | SORBENT WT. GMS. | OIL WT. GMS. | RECOVERY EFFIC. | COMMENTS AND OBSERVATIONS |
|---|---|---|---|---|---|
| A | POLYETHYLENE FIBER (MATTED SHEETS AND SHREDDED) | 96 | 636 | 1:7 | EASY APPLICATION, MECHANICAL MIXING REQUIRED, EASY RECOVERY, SHREDDED FORM OF THIS SORBENT MORE DIFFICULT TO APPLY AND RECOVER |
| B | POLYPROPYLENE (FIBER STRANDS) | 49 | 1963 | 1:40 | EASY APPLICATION, MECHANICAL MIXING REQUIRED, EASY RECOVERY |
| C | CELLULOSE FIBER PERLITE MIXTURE (TYPE I) | 50 | 239 | 1:4 | APPLICATION DIFFICULT IN WINDS DUE TO POWDERED FORM, MECHANICAL MIXING REQUIRED, DIFFICULT TO RECOVER |
| D | CELLULOSE WOOD FIBER SHEETS | 22 | 208 | 1:9 | EASY APPLICATION, MECHANICAL MIXING REQUIRED, EASY RECOVERY |
| E | POLYPROPYLENE SPUN FIBER - SHEET FORM | 57 | 279 | 1:5 | EASY APPLICATION, MECHANICAL MIXING REQUIRED, EASY RECOVERY |
| F | POLYSTYRENE POWDER | 22 | 118 | 1:5 | DIFFICULT TO APPLY IN WINDS, MECHANICAL MIXING REQUIRED, FAIRLY EASY RECOVERY |

TABLE II (cond)

| SORBENT | TYPE & FORM | SORBENT WT. GMS | OIL WT. GMS. | RECOVERY EFFIC. | COMMENTS AND OBSERVATIONS |
|---|---|---|---|---|---|
| G | SYNTHETIC ORGANIC POWDER | 46 | 61 | 1:2 | DIFFICULT TO APPLY IN WIND, MECHANICAL MIXING REQUIRED, FAIRLY EASY RECOVERY |
| H | FIBERBOARD (RECYCLED CELLULOSE) | 100 | NEGL. | NEGL. | BOARDS WERE VERY STIFF, ONLY A VERY THIN COATING WAS ABSORBED ON THE SURFACE OF THE BOARD |
| I | UREA FORMALDEHYDE FOAM IN BLOCK FORM | - | NEGL. | NEGL. | A SMALL AMOUNT OF OIL WAS RECOVERED ON THE SURFACE OF THE BLOCKS |
| J | CELLULOSE FIBER - PERLITE MIXTURE (TYPE 2) | 55 | 191 | 1:4 | DIFFICULT TO APPLY IN WIND, MECHANICAL MIXING REQUIRED, FAIRLY EASY RECOVERY |
| K | UREA FORMALDEHYDE FOAM SHAVINGS | 52 | 369 | 1:7 | APPLICATION EASY, MECHANICAL MIXING REQUIRED, EASY RECOVERY |
| L | ASBESTOS POWDER | - | NEGL. | NEGL. | DIFFICULT TO APPLY IN WIND, MECHANICAL MIXING REQUIRED, BREATHING APPARATUS REQUIRED FOR PROTECTION |

dispersants, was a tendency for the dispersants to mix with and "antifreeze" the oil. In short, it was visually apparent that dispersants lowered the viscosity of the oil, thereby creating a more difficult mechanical cleanup problem. It must be noted that this "antifreeze" effect was observed only when a dispersant: oil ratio of $\sim$ 1:3 was applied. This is an extremely high concentration and would be economically and practically impossible to apply to a major spill. Observed effects of the four dispersents are documented in Table (3).

Surface Active Agents

Surface active agents (SAA) are organic, non-water soluble liquids that spread over water to monomolecular thicknesses. The surface tension of a SAA is much less than that of oil. When a surface active agent is applied to the periphery of an oil slick, surface tension forces will tend to act in the direction of the oil and minimize the area of the slick until the gravity forces are in equilibrium with the surface tension forces. A surface active agent, therefore, has no slick containing capabilities until the slick enters the surface tension spreading regime. As discussed in Section III of this report, oil spreading on ice terminates prior to entering the surface tension regime. Gravity forces alone comprise positive oil on ice spreading forces. Therefore surface active agents should not be effective in reducing the spreading of oil on ice. In spite of the above argument, a surface active agent was tested for its ability to limit spreading on ice. A quantity of a surface active agent was distributed around the perimeter (over ice) of a small spill. There was no apparent decrease in spreading rate or terminal pool size due to the surface covering of surface active agent.

TABLE III

| DISPERSANT | DISPERSANT TEMPERATURE DEG F | OIL TEMPERATURE DEG F | DISP-OIL VOL RATIO | COMMENTS & OBSERVATIONS |
|---|---|---|---|---|
| A | -22 | -10 | 1:5 | No apparent change in oil consistancy after adding and mechanical mixing of dispersant |
| B | -22 | -10 | 1:3 | Mixed with oil to form a dispersant in oil emulsion - result was to decrease apparent viscosity or "antifreeze" oil |
| C | -22 | -10 | 1:3 | No change in oil in oil consistancy |
| D | -22 | -10 | 1:3 | Same result as dispersant "B" |
| | | | | |

## Burning Oil on Ice and Snow

Burning is a method of oil removal that can be used effectively only when the oil is contained in a configuration where pool thickness is adequate to sustain burning and where the heat generated will not pose a danger to life or property. Oil spilled on ice in the Arctic winter meets the first of these criteria and will usually meet the latter.

Burning proved to be an adequate method of removing approximately 80% (by volume) of oil when spilled on ice and water in the arctic summer (Glaeser & Vance 1971). During these summer tests, burning agents proved to be of no value in increasing the percentage of oil removed.

Burning offers the easiest and fastest solution for partial removal of freshly spilled oil from a winter snow or ice surface. With a fresh spill (less than 24 hours old) there is no difficulty involved in igniting the oil by placing fuel soaked rags along the upwind edge of the oil spill. The rags provide a heat and wicking source sufficient for ignition and sustained burning of the crude. Once ignited, the oil gives off an intense flame (Figure 20) accompanied by thick black smoke. The smoke, however, does not leave any ash immediately down wind of the burn and is quickly dissipated. The most effective burns were achieved when the oil was at least 1/4" thick and the wind was blowing between 0 and 14 knots. The temperature of the oil or air did not appear to affect the intensity or efficiency of the burn, however, winds over 14 knots tended to knock the flames down and blow loose snow onto the oil cooling it below ignition temperature.

Differences in the way the oil burned depended on whether the oil was poured on snow or ice. On snow the burning oil would tend to form pits

FIGURE 20 - Oil burning on a snow surface; air temperature @ -25F.

over the hottest areas of the burn. These pits were 4 inches in diameter and 6 to 8 inches deep. Intense burning would take place at the bottom of the pits with oil flowing down into and combining with the oil at the pit bottoms. The maximum size of the pits at the termination of ignition was 3 ft. in diameter and 1.5 feet deep. With the oil concentrated in the bottom of these pits, the oil on the snow surface not immediately adjacent the pits would cool and cease to burn. As a result the burning efficiency of oil on snow is less than that on ice. Over 95% of the oil in the pits would be consumed while only 30% of the surface oil was eliminated. The overall burning efficiency was about 70% burned.

Burning of oil spills on ice does not pose the problems that burning of snow spills do. Fresh oil, when ignited by placing kerosene soaked rags on the upwind edge of the spill, burns intensely, engulfing the entire pool. For ignition and sustained combustion, oil thickness of 1/4 inch or greater were found sufficient. As the intensity of the fire increases a thin layer of ice melts and forms a quarter inch deep pool of water below the burning oil. The water is believed to insulate the ice underneath from the heat of the burning oil. The floating oil may flow down hill (assuming a gradient exists) increasing the area of contamination. The oil burns off with a 90% efficiency leaving a thick tar residue on the melted ice. After a short period of time the water refreezes with much of the tar residue frozen in it, complicating final removal of the residue.

Three burning agents, 1) silicate beads, 2) asbestos powder, and 3) powered calcium carbonate were applied to a fresh oil on ice pool to determine their effect on burning efficiency. Three sections of a 10 ft.

diameter by 1/2 " thick spill were coated with burning agent 1, 2, and 3 respectively. The spill was ignited on the windward side with kerosene soaked rags. The oil burned with an intense flame (Figure 21) and at the termination of the burn, an estimated 80% of the oil had been eliminated. There was no observed advantage in using any of the burning agents as compared to burning the crude in its natural state. Also, an additional residue (remains of the various burning agents) remained in the area where burning agents were applied. This residue increased the final cleanup effort.

It is important to note, however, that oil burns well on snow and ice only if it is relatively free of a snow covering. Once a spill has been subjected to a situation of falling or blowing snow, a snow oil mulch (described in Section IV of this report) forms that contains up to 80% snow by volume. This mulch burns very poorly and is difficult to ignite. Apparently the burning oil cannot supply the heat necessary to melt the high percentage of snow that is well mixed with the oil. We can conclude therefore, that burning oil in the Arctic is effective only if burning procedures can be initiated prior to a snowfall and/or high winds (which cause blowing snow). If burning procedures cannot be initiated before a snowfall, burning will be entirely ineffective and an alternate method of removal (perhaps mechanical) must be utilized.

## VII. Summary and Recommendations

The Coast Guard's efforts to understand the fate and behavior of crude oil spilled in the Arctic have been substantially advanced as a result of this test. The information and insights contained herein, when combined with associated research, should assist in defining the

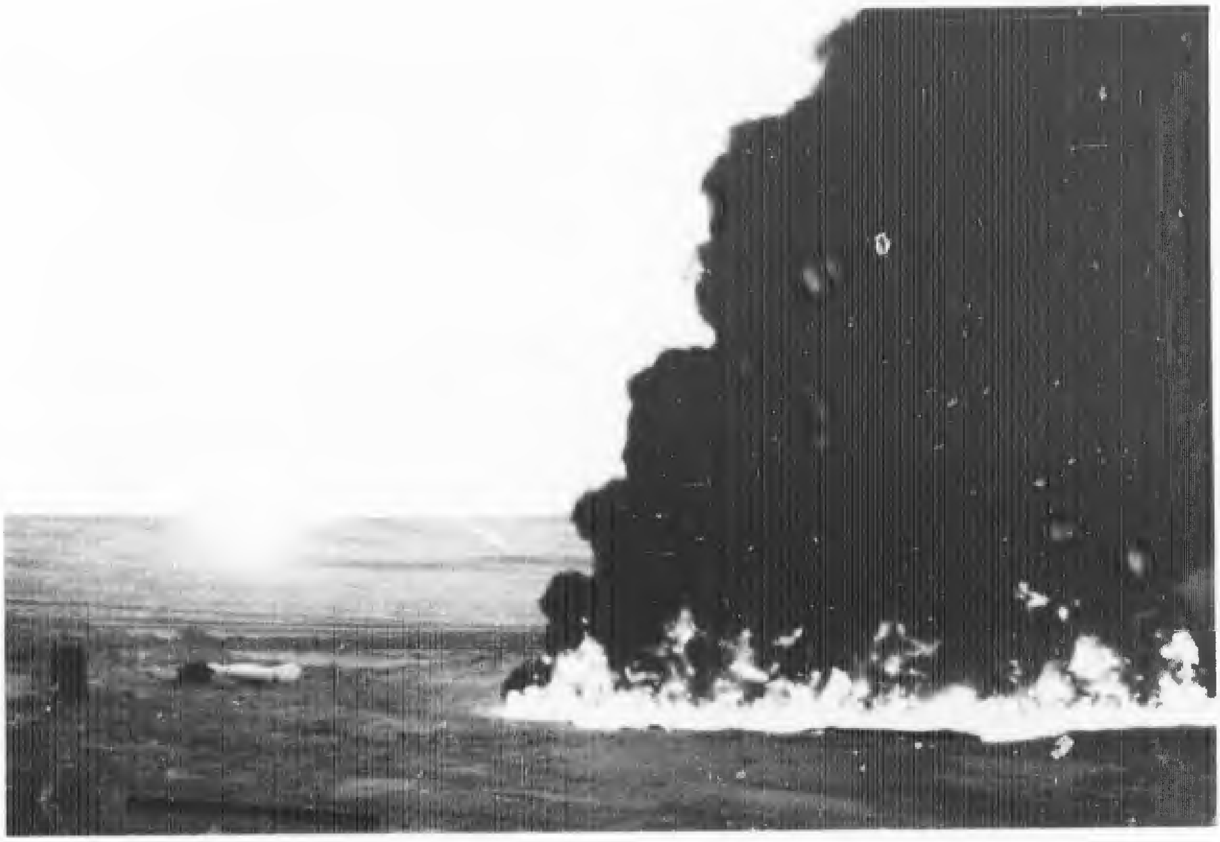


FIGURE 21 - Fresh oil burning on a windswept ice surface; air temperature @ -16F.

requirements for a system to respond to a large scale spill.

Oil spreading cver ice and snow is dominated by gravity and inertia forces. Spreading rate is independent of the properties of the oil and is not affected by temperature. Terminal pool size of a known volume of oil is, however, indirectely related to temperature in that $z_o$=f(t) and $A_t$=f($z_o$). This relationship is explained in Section III of this report.

Basic detection and recovery problems exist when spilled oil is subjected to snow fall or high winds. Snow tends to combine with pooled oil until the oil is effectively saturated with snow crystals. The resulting mixture may be as high as 80% snow. After saturation (which can happen in a few hours time) additional snow covers the oil making visual detection of areal extent impossible. The oil snow mixture is quite easily handled mechanically (shovel, bulldozer, etc.) but cannot be burned or absorbed.

Absorption of oil into the snow or ice surface is minimal. This is because the oil, when initially released (spilled) on the surface, is much warmer than the snow/ice surface (the snow/ice surface stabilizes at ambient air temp. while the oil temp. may vary from ambient air temperature to well head temperature). The temperature differential causes a melting and refreezing of the snow surface, blocking pore channels.

The aging rate of oil on ice is decreased when compared to temperate climate aging. However, the winter aging rate is significant and should not be discounted. It has been determined that the density of crude oil will increase with time, eventually becoming more dense than sea ice (.901 gm/ml) and sea water (1.04 gm/ml).

Artificial cleanup agents such as sorbents, dispersants, surface active agents, and burning agents are of little or no practical use in extreme temperature (cold) conditions found in the Arctic winter. It requires as much energy to apply and physically mix most absorbents than it does to mechanically cleanup the unabsorbed oil. Dispersants and surface active agents, by definition, can not be effective where no open water is involved. Burning agents were found to increase the cleanup effort required due to the additional residue contributed by the agents themselves.

If the oil is spilled in an area of fast ice or over tundra, very little immediate environmental damage will result. The oil will be "sandwiched" between the ice below and the snow above. However, a cleanup operation must be put into effect well before spring "thaws" occur if damage is to be minimized. Even in the event of a very large spill, for example 100,000 BBL oil, it is unlikely that the diameter of the spill will be greater than 1/2 mile (see Figure (6) effective roughness height has been estimated to range between .10 and 1.0). A cleanup problem will be created, however, if the spill is completely covered by snow and the areal configuration cannot be accurately assessed. A remote method of detecting oil underneath a snow or ice covering is desirable. In short, it is apparent that a winter arctic spill will create less immediate problems than an identical spill in the summer. If damage is to be minimized, however, the oil must be eliminated prior to ice breakup or snow melting.

The problem of transporting, applying, mixing and removing large quantities of oil treating agents, as compared to their observed effectiveness, makes these techniques questionable for use against an arctic oil spill. The apparent primary oil recovery techniques are rapid burning and/or mechanical recovery. The immediate burning of the oil, in a dyked in area to prevent additional spreading, can dispose of up to 90% of the oil. However, in burning the oil, short termed air pollution from the resulting smoke must be considered. Weather conditions and logistical capabilities permitting, the mechanical removal of the oil and the oil/snow mulch can result in an almost complete removal of the discharged oil. Light bulldozers and shoveling can accumulate the oil so that it can be barreled and removed by road or air transportation to a disposal or reclamation facility.

## LIST OF APPENDICIES

# APPENDIX A

## OIL AGING DATA

Data on U.S.C.G. oil samples

GC Distillation, Pool 3.1

TEMPERATURE DEG F

| % off | 1/19 | 1/20 | 1/21 | 1/22 | 1/23 | 1/24 | 1/26 | 1/29 | 2/2 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 95 | 95 | 95 | 95 | 98 | 98 | 148 | 155 | 216 |
| 5 | 157 | 124 | 141 | 152 | 158 | 172 | 230 | 233 | 280 |
| 10 | 215 | 191 | 213 | 223 | 216 | 245 | 304 | 304 | 363 |
| 20 | 282 | 302 | 332 | 356 | 302 | 379 | 418 | 409 | 454 |
| 30 | 392 | 423 | 434 | 451 | 399 | 470 | 488 | 480 | 523 |
| 40 | 472 | 503 | 509 | 530 | 471 | 546 | 559 | 546 | 592 |
| 50 | 547 | 578 | 585 | 607 | 536 | 618 | 626 | 615 | 661 |
| 60 | 619 | 654 | 661 | 688 | 600 | 699 | 700 | 692 | 738 |
| 70 | 700 | 737 | 745 | 776 | 672 | 784 | 792 | 775 | 823 |
| 80 | 784 | 830 | 837 | 879 | 754 | 882 | 895 | 871 | 919 |
| 90 | 887 | 852 | 964 | 1019 | 862 | 1003 | 1035 | 1003 | 1042 |
| 95 | 961 | 1038 | 1049 | 1110 | 947 | 1079 | 1132 | 1090 | 1133 |
| 99 | 1050 | 1152 | 1152 | 1238 | 1056 | 1180 | 1285 | 1205 | 1259 |
| S.G.@60F | .8992 | .8993 | .9001 | .9018 | .9013 | .9047 | .9187 | .9194 | .9222 |
| Phases - % | | | | | | | | | |
| water | 0.5 | 0.4 | 0.6 | 4.0 | 14.0 | 30.0 | 72.0 | 68.0 | 72.0 |
| emulsion | 0 | 0 | 0 | 0 | 0 | 7.0 | 2.0 | 2.0 | 3.0 |
| oil | 99.5 | 99.6 | 99.4 | 96.0 | 86.0 | 63.0 | 26.0 | 30.0 | 25.0 |

GC Distillation, Pool 2.3

| | TEMPERATURE DEG F | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| % off | 1/15 | 1/16 | 1/17 | 1/18 | 1/19 | 1/20 | 1/21 | 1/22 | 1/23 | 1/24 | 1/26 | 1/28 | 1/31 | 2/2 |
| 1 | 97 | 97 | 107 | 97 | 92 | 97 | 118 | 125 | 129 | 108 | 97 | 150 | 145 | 140 |
| 5 | 168 | 172 | 210 | 178 | 117 | 170 | 209 | 240 | 217 | 212 | 206 | 222 | 223 | 216 |
| 10 | 221 | 234 | 252 | 206 | 130 | 230 | 250 | 346 | 260 | 245 | 230 | 266 | 285 | 263 |
| 20 | 327 | 347 | 376 | 236 | 166 | 345 | 377 | 470 | 372 | 364 | 336 | 383 | 424 | 389 |
| 30 | 437 | 420 | 466 | 340 | 254 | 426 | 466 | 558 | 453 | 448 | 418 | 475 | 510 | 475 |
| 40 | 513 | 478 | 540 | 426 | 366 | 496 | 542 | 631 | 525 | 521 | 493 | 555 | 592 | 545 |
| 50 | 592 | 548 | 612 | 505 | 440 | 569 | 616 | 706 | 596 | 595 | 571 | 633 | 669 | 616 |
| 60 | 668 | 617 | 592 | 590 | 513 | 650 | 595 | 784 | 671 | 773 | 651 | 719 | 748 | 694 |
| 70 | 752 | 699 | 776 | 686 | 609 | 745 | 777 | 871 | 751 | 758 | 743 | 808 | 830 | 775 |
| 80 | 846 | 792 | 874 | 797 | 727 | 848 | 807 | 799 | 840 | 847 | 848 | 913 | 923 | 865 |
| 90 | 967 | 910 | 997 | 940 | 875 | 975 | 987 | 1095 | 964 | 977 | 985 | 1044 | 1041 | 981 |
| 95 | 1044 | 985 | 1112 | 1035 | 969 | 1052 | 1069 | 1195 | 1064 | 1061 | 1082 | 1136 | 1126 | 1060 |
| 99 | 1135 | 1083 | -- | 1200 | 1101 | 1186 | 1201 | 1325 | 1170 | 1178 | 1243 | 1270 | 1247 | 1177 |
| SP.GR. @60°F | .8994 | .9034 | .9040 | .9066 | .9056 | .9071 | .9051 | .9075 | .9072 | .9040 | .9042 | .9048 | .9083 | .9072 |
| Phases % | | | | | | | | | | | | | | |
| water | 1.2 | 6 | 22 | 37 | 38 | 20 | 30 | 28 | 17 | 24 | 30 | 26 | 25 | 30 |
| emul. | 0 | 0 | 28 | 0 | 0 | 0 | 17 | 12 | 33 | 25 | 5 | 36 | 40 | 22 |
| oil | 98.8 | 94 | 50 | 63 | 62 | 80 | 53 | 60 | 50 | 52 | 68 | 38 | 35 | 48 |

## APPENDIX B

## METHOD OF NON-DIMENSIONALIZING DATA

In order to depict the data in a non - dimensionalized form, the dimensionalized time and length data must be divided by the dimensionalized constants, "Q" and "g" in such a way as to create a time ($T_{nd}$) and length ($L_{nd}$) without dimensions.

$$\text{Let us set} \quad Q = L^3T^{-1}$$

$$\text{and} \quad g = LT^{-2}$$

To non - dimensionalize time and length

$$\text{Time(nd)} = \text{Time(data)}/Q^x g^y$$

$$\text{where} \quad Q^x g^y = T \qquad \text{(C1)}$$

$$\text{Length(nd)} = \text{Length(data)}/Q^a g^b$$

$$\text{where} \quad Q^a g^b = L \qquad \text{(C2)}$$

Solving equation (C1) and (C2) we find that:

$$x = 1/5$$

$$y = -3/5$$

$$a = 2/5$$

$$b = -1/5$$

Hence:

$$T_{nd} = T_d/(Q/g^3)^{.2} \qquad \text{(C3)}$$

and

$$L_{nd} = L_d/(Q^2/g)^{.2} \qquad \text{(C4)}$$

Substituting the values Q = .172cuft/sec and g = 32.2ft/sec$^2$ (which are the values that apply to the experimental procedures) into equation C3 and C4 we obtain:

$$T_{nd} = T_d/.08758 \qquad \text{and}$$

$$L_{nd} = L_d/.24707$$

Thus revising Table I to non - dimensionalized form we obtain:

| RADIUS | | TIME | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| DATA | ND | DATA | ND | DATA | ND | DATA | ND | DATA | ND |
| 1.0 | 4.1 | .7 | 8.0 | .7 | 8.0 | .9 | 10.3 | .7 | 8.0 |
| 2.0 | 8.1 | 2.3 | 26.3 | 4.2 | 50.0 | 4.2 | 50.0 | 4.3 | 49.1 |
| 2.5 | 10.1 | - | - | - | - | 5.8 | 66.2 | - | - |
| 3.0 | 12.1 | 6.5 | 74.2 | 8.6 | 98.2 | - | - | 11.3 | 129.0 |
| 4.0 | 16.2 | 10.6 | 121.0 | 14.0 | 159.9 | - | - | 21.4 | 244.4 |
| 4.5 | 18.2 | - | - | - | - | - | - | 29.9 | 341.4 |
| 5.0 | 20.2 | 15.6 | 178.1 | 19.5 | 222.7 | - | - | - | - |
| 6.0 | 24.3 | | | 28.1 | 380.9 | - | - | - | - |

## APPENDIX C

## CRUDE OIL ANALYSIS

D.1 Routine analysis of Prudhoe Bay crude

D.2 Sadlerochit crude properties

64

## Routine analysis of Prudhoe Bay crude oil[1]

GENERAL CHARACTERISTICS

Gravity, specific, 0.893

Gravity, °API, 27.0

Pour point, °F., 15

Color, brownish black

Sulfur, %, 0.82

Nitrogen, %, 0.230

Viscosity, Saybolt Universal at 77° F. 111 sec, at 100° F. 84 sec

DISTILLATION, BUREAU OF MINES ROUTINE METHOD

Stage 1—Distillation at atmospheric pressure, 741 mm Hg, first drop, 81° F.

| Fraction No. | Cut temp., °F. | % | Sum. % | Sp gr, 60/60° F. | °API, 60° F. | C. I. | Refractive index, $n_D$ at 20° C. | Specific dispersion | S. U. visc., 100° F. | Cloud test, °F. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 122 | 2.1 | 2.1 | 0.693 | 72.7 | | | | | |
| 2 | 167 | 2.6 | 4.7 | 0.723 | 64.2 | | | | | |
| 3 | 212 | 3.5 | 8.2 | 0.752 | 56.7 | 23 | 1.38591 | 127.9 | | |
| 4 | 257 | 3.6 | 11.8 | 0.773 | 51.6 | 27 | 1.40312 | 139.0 | | |
| 5 | 302 | 3.7 | 15.5 | 0.790 | 47.6 | 30 | 1.41922 | 141.9 | | |
| 6 | 347 | 3.5 | 19.0 | 0.801 | 45.2 | 31 | 1.43082 | 147.0 | | |
| 7 | 392 | 4.3 | 23.3 | 0.818 | 41.5 | 30 | 1.43922 | 149.6 | | |
| 8 | 437 | 4.8 | 28.1 | 0.836 | 37.8 | 33 | 1.44626 | 152.1 | | |
| 9 | 482 | 5.0 | 33.1 | 0.851 | 34.8 | 36 | 1.45528 | 154.7 | | |
| 10 | 527 | | | | | 38 | 1.46565 | 157.0 | | |
| Stage 2—Distillation continued at 40 mm Hg. | | | | | | | | | | |
| 11 | 392 | 2.8 | 35.9 | 0.873 | 30.6 | 45 | 1.47467 | 160.5 | 40 | 10 |
| 12 | 437 | 6.5 | 42.4 | 0.881 | 29.1 | 45 | 1.48218 | 161.5 | 45 | 30 |
| 13 | 482 | 6.8 | 49.2 | 0.897 | 26.2 | 49 | 1.48650 | 168.6 | 58 | 50 |
| 14 | 527 | 6.0 | 55.2 | 0.910 | 24.0 | 52 | 1.49477 | 169.4 | 93 | 70 |
| 15 | 572 | 7.4 | 62.6 | 0.919 | 22.5 | 53 | | | 176 | 90 |
| Residuum | | 36.3 | 98.9 | 0.990 | 11.4 | | | | | |

Carbon residue, Conradson: Residuum, 11.6%; crude, 4.7%.

| APPROXIMATE SUMMARY | % | Sp gr | °API | Viscosity |
|---|---|---|---|---|
| Light gasoline | 4.7 | 0.710 | 67.9 | |
| Total gasoline and naphtha | 19.0 | 0.762 | 54.2 | |
| Kerosine distillate | 4.3 | 0.818 | 41.5 | |
| Gas oil | 18.4 | 0.860 | 33.1 | |
| Nonviscous lubricating distillate | 11.0 | 0.887-0.911 | 28.0-23.9 | 50-100 |
| Medium lubricating distillate | 8.1 | 0.911-0.922 | 23.9-22.0 | 100-200 |
| Viscous lubricating distillate | 1.8 | 0.922-0.924 | 22.0-21.6 | Above 200 |
| Residuum | 36.3 | 0.990 | 11.4 | |
| Distillation loss | 1.1 | | | |

[1]Reprinted with permission of OIL & GAS JOURNAL

## Sadlerochit Crude Properties[1]

Range in stock tank oil gravity: 25.2 to 28.4 deg API

Range in viscosity @ 60 deg F and 14.7psia: 23.1 to 60.0 centistokes

| Average Crude Composition | Mole % |
|---|---|
| Nitrogen | 0.28 |
| Carbon dioxide | 8.63 |
| Methane | 44.97 |
| Ethane | 4.98 |
| Propane | 3.27 |
| Iso-butane | 0.57 |
| N-butane | 1.67 |
| Iso-pentane | 0.54 |
| N-pentane | 0.91 |
| Hexanes | 2.01 |
| Heptanes plus | 32.17 |

[1]Courtesy of Atlantic Richfield Oil Company

Surface tension of test crude as determined using a du Nouy ring tensiometer is 29.5 dynes/cm.

## BIBLIOGRAPHY


1. Cursitsch, L. and Moore, H., The Scientific Principles of Petroleum Technology, London, 1932.

2. Fay, J. A., in Oil on the Sea, D. P. Hoult ed., New York, 1969.

3. Garret, William B. and Barger, William R., Control and Confinement of Oil Pollution on Water with Monomoleculor Surface Films, Final Report of Project 724110.1/4./ for the United States Coast Guard, November 1971.

4. Glaeser, John, L. and Vance, George, P., A Study of the Behavior of Oil Spills in the Arctic. Final Report of Project 724108/1.1 for the United States Coast Guard. Feb. 1971.

5. Hoult, D. P., Personal Communication, May 1972.

6. Schatzberg, Paul, Investigation of Sorbents for Removing Oil Slicks from Waters, Final Report 724110.1/2/1 for the USCG, November 1971.

7. Thompson, C. J.; Coleman, H. J.; Dooley, J. E.; and Hirsch D. E. "Bumines Analysis Shows Characteristics of Prudhoe Bay Crude" in The Oil and Gas Journal, October 25, 1971.