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OCEAN-ICE OIL-WEATHERING COMPUTER PROGRAM USER'S MANUAL

by

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Applied Environmental Sciences Department Science Applications International Corporation 10260 Campus Point Drive San Diego, California 92121

Final Report Outer Continental Shelf Environmental Assessment Program Research Unit 664

October 1987

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Because the Oil in Ice Program is an extension of our ongoing oil weathering investigations, the contributions of numerous individuals over many years and months have been critical to its successful development. As in our open-ocean oil-weathering research, Professor D. Mackay of the University of Toronto has contributed extensively through his decade of experience in oil weathering, and we draw upon this vast experience for mass transfer, slick spreading, and water-in-oil emulsification. Professor Seelye Martin at the University of Washington was extremely helpful through his assistance in the design and execution of cold room/wave tank studies at Kasitsna Bay. Lt. Cmdr. Tebeau, Environmental Technology Branch, Peter A. USCG. is gratefully acknowledged for his interest and support in the areas of vertical migration of oil in brine channels, evaporation, and emulsification. The continued and sustained efforts of Russell and Linda Geagel in completing the design and fabrication of the cold room and wave tank system at NOAA's Kasitsna Bay Laboratory are gratefully acknowledged. Mr. George Lapiene and Lt. Cmdr. Mike Meyer are also thanked for their assistance in expediting activities at Kasitsna Bay. Mabel O'Byrne, Laurie Hughey, Lucy Kaelin and Jimmie Stone produced the final copy of this document on the word processor.

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OCEAN-ICE OIL-WEATHERING COMPUTER PROGRAM USER'S MANUAL

MODEL OVERVIEW

The ocean-ice oil-weathering code is written in FORTRAN as a series of stand-alone subroutines that can easily be installed on most any computer. All of the trial-and-error routines, integration routines, and other special routines are written in the code so that nothing more than the normal system functions such as EXP are required. The code is user-interactive and requests input by prompting questions with suggested input. Therefore, the user can actually learn about the nature of crude oil and oil weathering by using this code. A complete code listing of the ocean-ice oil-weathering code is presented in the Appendix to this report.

The ocean-ice oil-weathering model considers the following weathering processes:

-- evaporation
-- dispersion (oil into water)
-- mousse (water into oil)
-- spreading

These processes are used to predict the mass balance and composition of oil remaining in the slick as a function of time and environmental parameters. Dissolution of oil into the water column is not considered as part of the main code because this weathering process is not significant with respect to the overall material balance of the oil slick. The companion document to this User's Manual (Final Report for RU 664, Payne et al. 1987)* contains computer code for stand-alone models which consider component-specific dissolution from oil slicks and from dispersed droplets.

An important assumption required in order to write material balance equations for evaporation is the state of mixedness of the oil in the slick. The ocean-ice oil-weathering model is based on the assumption that the oil is well mixed. This might not always be true, but data have been taken and

^{*}See pages 147-465 of this volume.

interpreted as if the plantane and compositional observations that the oil is not thought based on physical and compositional observations that the oil is not always well mixed. As the oil weathers, its viscosity increases (measured and known to be true), resulting in a slab-like oil phase. Clearly, the mass transfer within the oil will change drastically in going from a well-mixed to a slab-like phase.

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The other three weathering processes are not explicitly component specific as is evaporation. However, the dispersion process is a function of the oil viscosity; oil viscosity is a function of composition. Thus the dispersion process does depend on the evaporation process. Mousse formation also alters the oil viscosity but the present knowledge of this process does not point to any quantifiable compositional dependence. The spreading of the slick results in an ever-increasing area for mass transfer.

The composition of the oil is described in terms of pseudocomponents that are obtained by fractionating the oil in a true-boiling-point distillation column. This procedure yields cuts of the oil which are characterized by boiling point and density. This information is then used to calculate many more parameters about the cut. The most important calculated parameters pertain to vapor pressure and molecular weight. The evaporation process is driven by vapor pressure and system partial pressures are calculated assuming Raoult's law.

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Sample runs of the model are included in this User's Manual in the following manner. Examples of the various input options are presented and described on pages 17 through 39. Examples of various calculated results appear on pages 40 through 81. Each output or run of the computer model always echoes the input to the output. In other words, what was entered as input is documented in the output. Therefore, the calculated results appearing on pages 40 through 81 contain all the user-entered parameters. The illustrations of input are intended to illustrate all the options available and a real computer run would (probably) not invoke all these options (i.e., spreading versus no spreading, dispersion versus increased dispersion, and many other on-off examples).

The pseudo-component characterization of crude oil for the open-ocean oil-weathering model is described in detail (Payne et al., 1984a). The specific detail presented in oil characterization can vary depending upon exactly which literature references are used. Those references used to write the current open-ocean oil-weathering model are all essentially contained in a standard text (Hougen, Watson and Ragatz, 1965).

The pseudc-component evaporation model and the over-all mass-transfer coefficient required for evaporation has also been described in detail (Payne, Kirstein, et al., 1983 and 1984a). The fundamental process of evaporation is described in many texts, such as Mass Transfer Operations (Treybal, 1955) and in papers in the open literature. A paper on this subject relevant to oil weathering is that by Liss and Slater (Liss and Slater, 1974).

The equation which describes slick spreading has also been described (Payne et al., 1983). The spreading equation is based on observations due to Mackay (Mackay et al., 1980) and is not based on the many publications which describe oil spreading due to gravity-viscosity-surface tension. The phenomenological approach to oil spreading does not pertain to a rough ocean surface, and the empirical approach at least reflects reality.

The viscosity prediction used in early oil-weathering model calculations is based on a (mole fraction).(cut viscosity) summation (Reid, et al., 1977). This viscosity prediction has been found to be inadequate in that the predicted viscosity is always too low. This viscosity prediction has been replaced with one due to Tebeau and Mackay (Tebeau, Mackay et al., 1981) where the viscosity at 25°C is a function of the fraction of oil evaporated on a dispersion-free basis. The functional relationship is $\exp(K_4F)$ where K_4 is an oil-dependent constant and F is the fraction evaporated. The viscosity is scaled with respect to temperature according to the Andrade equation (Gold and Olge, 1969).

The prediction of water-in-oil emulsification is based on four parameters (Mackay, et al., 1980) appearing in the following equation:

$$(1 - K_2 W) \exp\left[\frac{-2.5W}{1-K_1 W}\right] = \exp\left(-K_5 K_3 t\right)$$

where W is the weight fraction water in the oil-water mixture, K_1 is a constant in a viscosity equation due to Mooney (Mooney, 1951), K_2 is a coalescingtendency constant, K_3 is a lumped water incorporation rate constant, and K_5 is a factor by which the mousse formation rate is increased during broken- ice field weathering.

The change in visiosity due to mousse formation is predicted by:

$$\mu = \mu_0 \exp\left[\frac{-2.5W}{1-K_1W}\right]$$

where μ° is the parent oil viscosity. K_1 is usually around 0.62 to 0.65 and apparently does not change much with respect to different types of oils. The constant K_2 above must satisfy the relation $K_2W < 1$ in order for the water incorporation rate term (right-hand side) to be > 0. Thus, K_2 is the inverse of the maximum weight fraction water in the mixture. K_3 is the water incorporation rate constant and is a function of wind speed in knots.

The dispersion (oil into water) weathering process is described by two equations (Mackay, et al., 1980). These equations are:

$$F = K_{a} K_{c} (U + 1)^{2}$$
$$F_{B} = (1 + K_{b} \mu^{0.5} \delta_{X})^{-1}$$

where F is the fraction of sea surface subject to dispensions per second, U is the wind speed in m/sec, K_a is constant, and K_c is a factor by which dispersion is increased during broken-ice field weathering. F_b is the fraction of droplets of oil below a critical size which do not return to the slick, K_b is a constant, μ is the viscosity in centipoise, x is the slick thickness in meters, and δ is the surface tension in dynes/cm. The mass fraction that leaves the slick as dispersed droplets is (F_b) . (F) and this fraction applies to each cut of oil.

USER INPUT DESCRIPTION

The initial input required to perform an oil-weathering calculation is the distillation characterization of the crude oil. The desired input is termed a true-boiling-point (TBP) distillation and consists of distillate cuts of the oil with each cut characterized by its average boiling point and API gravity. For a description of the TBP distillation see Van Winkle (1967). An example of a TBP distillation is shown in Table 1. The petroleum product characterized in this table is a whole crude oil. The reason for choosing this example is that it is a text-book example of a true-boiling-point distillation. The introduction of the true-boiling-point distillation to characterize crude oil and products for environmental predictions is a new concept. Therefore, the objective in using this example is to illustrate that the concept is common in another branch of engineering. By providing this example, the reader has access to a readily available reference that actually used a TBP (i.e., Van Winkle, 1967).

TBP distillations of crude oils are not always readily available. The more common inspection on crude oil is termed an ASTM (D-86) distillation. The ASTM distillation (Perry, R. H., and C. H. Chilton, 1973) differs in that the ASTM distillation is essentially a flask distillation and thus has no more than a few theoretical plates. The TBP distillation (ASTM D- 2982, 1977) is performed in a column with greater than 15 theoretical plates and at high reflux ratios. The high degree of fractionation in this distillation yields an accurate component distribution for the crude oil (mixture). Another type of crude oil inspection available is the equilibrium flash vaporation (EFV) which

% Distilled	T, °F	API Gravity
0	105	first drop
5	230	63.5
10	300	46.7
20	392	39.0
30	458	34.5
40	505	32.0
50	542	30.8
60	585	27.5
70	640	23.5
80	720	20.4
90	880	13.1
99	1090	

Table 1.--Example of True Boiling Point (TBP) Distillation of Crude Oil (Van Winkle, 1967).

differs from both the ASTM and TBP distillation in that the vapor is allowed to equilibrate with the liquid, and the quantity vaporized reported. In the distillations vapor is continuously removed from the still pot.

Both the ASTM distillation and EFV can be converted to a TBP distillation (API, 1964). However, at the present the ASTM D-86 distillation results can be used directly in the oil-weathering calculations because it is a reasonable approximation to the TBP-distillation result at the light end of the barrel. The differences between the two distillations at the heavy end of the barrel are noticeable but since the heavy ends of the barrel do not evaporate in oil weathering, this difference is of little consequence.

Currently, the best sources of distillation data are "Evaluation of World's Important Crudes" (O&GJ, 1973) where a tremendous number of distillations and other characterizations are reported. The distillations reported are a mix of ASTMs and TBPs. Another excellent source of distillation data is "Analyses of 800 Crude Oils from United States Oilfields" (Coleman, et al., 1978). The distillations reported by Coleman are not TBP distillations but are essentially ASTM distillations and can be used in the oil-weathering calculations when the boiling points are all converted to one atmosphere total pres-The reason parts of the ASTM or TBP distillations are conducted at sure. sub-atmospheric pressure is that cracking begins to occur in the still pot at temperatures around 700F. Thus, the data reported by Coleman are around atmospheric pressure up to 527F, and for fractions boiling above this temperature the distillation is performed at 40 mm Hg. In order for the entire distillation to be used as input to the oil-weathering calculation, the cut data must be converted to one atmosphere total pressure. The procedure for converting sub-atmosphere boiling points to atmospheric boiling points is described in many places (Edmister and Okamoto, 1959; ASTM D-2892, 1977; API, 1964). An example of the sub-atmospheric boiling-point conversion is shown in Table 2 for Prudhoe Bay Crude Oil. The reported distillation pressure for Prudhoe Bay crude oil in (Table 2), which is near atmospheric but not exactly at one atmosphere, is not critical for the oil-weathering calculations.

Table 2.--Distillation Data for Prudhoe Bay Crude Oil Showing Conversion of Sub-Atmosphere Boiling Points to Atmospheric Boiling Points (see text) (Coleman et al., 1978).

Prudhae Bay field Sadlerachit, Triassic 8, 890 - 9, 008 feat

Alaska North Slape

GENERAL CHARACTERIERCS

Gravity, specifir,	0.893	Gravity, * AP1, 27.0	Pour point, * P. 15
Vincensy, Saviols ("nevernal as	77° F, 111 me; 100° F, 84 me	Color, brownish black Nitragen, percent, 0.230

DISTILLATION, BUREAU OF MINES ROUTINE METHOD

Strag 1-Dutiligion & atmospherig provides. 741 nom lig First desp										
Francisco No	Cat	l'erreni	tim Interne	Sit na" F	111 All* P	c t	Refractise suder n. at 20° C	specific disperants		Chrond trent.
1 . 2 . 3 . 4 . 5 . 6 . 7 . 8 . 7 . 8 . 9 .	123 167 212 257 302 347 392 487 488	2.1 2.6 3.5 3.6 3.7 3.5 4.3 4.8	2.1 4.7 8.2 11.8 15.5 19.0 23.3 28.1 33.1	0.693 723 752 773 750 801 818 836 851	72.7 64.2 56.7 51.6 47.6 45.2 41.5 37.8	23 27 30 31 30 33 36	1.38591 1.40312 1.41922 1.43082 1.43922 1.44626 1.45528 1.45528	127.9 139.0 141.9 147.0 149.6 152.1 154.7 154.7		
				hane 2-1344	iligtone comer		inin Hg			
) 2 3 4 5 Resolution	392 437 442 527 572	2.8 6.5 6.0 7.4 36.3	35.9 42.4 49.2 55.2 62.6 98.9	0.873 .881 .977 .910 .919 .990	30.6 29.1 26.2 24.0 22.5 11.4	45 45 49 52 53	1.48218 1.48450 1.49477	161.5 168.6 169.4	40 45 58 93 176	10 30 50 70 90

Carlina residues Constition Reliduum 11.6 pireses; ande 4.7 present.

Carlona resultat, Connection - Residuum	11.6 percent; and 4.7 percent. APPROXIMATE SUMM	ARY	Rendium; Sulfur, percuns, Nisragun, percuns,	
·		'mme	No pr. API	Vinterty
Light gaming		4.7	0.710 67,9	
Total gasaine and namiths	· -	19.0	0.762 54.2	
Kernune dutuliete		4.3	818 41.5	
Gas and		18.4	. 840 33.1	
Nus arous laboration distribute		11.0	. 887 911 28, 0-23, 9	58-108
Marburn Jubrantine destiliste		8.1	.911922 23.9-22.0	108-205
Lucence internation destribute		1.8	. 922 924 22.0-21.6	Abeve 200
Rendund		36.3	.990 11.4	
Distrilation loss		1,1	· · · · · · · · · · · · · · · · · · ·	-

Fraction no.	Cut temperature, °F at 1 atmosphere
10	580
11	638
12	638
13	738
14	790
Residuum	

An example of the use of the distillation data as input for the oilweathering calculation is shown in Table 3. This table is an actual computer display of what the user sees beginning with code execution. In this example the user is using data that is programmed into data statements and will not have to enter the distillation characterization data. The TBP cuts echoed to the user in Table 3 were obtained from the data of Coleman (Coleman et al., 1978) in Table 2, and illustrate the transfer of these data to the oilweathering calculation. Notice that cut 1 (fraction 1) in Table 2 has been deleted and the cuts renumbered. The reason cut 1 was deleted is because it is not the first cut with any measurable volume. Also note that the residuum cut is assigned a boiling point of >850F. This assigned boiling point is fictitious and used to indicate that this cut is indeed a residuum.

It can be noted that the true boiling point data presented here (e.g., Table 3) differ from values presented in the open-ocean oil weathering model (Payne et al., 1984a). Reasons for these differences can be explained as follows. The distillation data in Table 2 are presented as cumulative-cut temperatures and are to be interpreted as follows: Fraction #4 (for example) has a cut temperature of 257° F, which means the distillate receiver was changed at this temperature and Fraction #5 began being collected. Thus, the Fraction #4 temperature tabulated is the upper temperature at which that fraction was collected. The temperature used to characterize the entire fraction is the average temperature that is (rounded up to) 235° F.

A similar example of the use of distillation data from Coleman (Coleman et al., 1978) is illustrated in Tables 4 and 5. Table 4 again is the published data and Table 5 illustrates how these data appear as input to the oil-weathering calculation.

The distillation cut data for non-library oils can be entered by the user. The user can either enter this data via the keyboard or use data from a disk file created from a previous execution of the model. An example of keyboard input is illustrated in Table 7 using TBP data for a gasoline cut (O&GJ, 1973, pg. 57) which is presented in Table 6.

Table 3.--Distillation Cut Data as Used in Oil-Weathering Calculation (data obtained from Table 2).

ENTER THE NUMBER OF TBP CUTS TO BE CHARACTERIZED ON 12 IF YOU HAVE NO INPUT DATA JUST ENTER 99 A 99 ENTRY WILL USE A LIBRARY EXAMPLE 99 CHOOSE A CRUDE ACCORDING TO: 1 - PRUDHOE BAY, ALASKA 2 - COOK INLET, ALASKA 3 - WILMINGTON, CALIFORNIA 4 - MURBAN, ABU DHABI 5 - LAKE CHICOT, LOUISIANA 6 - LIGHT DIESEL CUT 1

YOU CHOSE: FRUDHOE BAY, ALASKA

CUI	Г	TB	API	VOL
1		150.0	72.7	2.1
2		190.0	64.2	2.6
3		235.0	56.7	3.5
4		280.0	51.6	3.6
5		325.0	47.6	3.7
6		370.0	45.2	3.5
7		415.0	41.5	4.3
8		460.0	37.8	4.8
9		505.0	34.8	5.0
10		554.0	30.6	2.8
11		609.0	29.1	6.5
12		662.0	26.2	6.8
13		712.0	24.0	á.Û
14		764.0	22.5	7.4
15		850.0	11.4	36.3
DO N	YOU	WANT TO	CHANGE ANY?	

Table 4.--Distillation Data for Wilmington Field Crude Oil (Coleman et al., 1978).

Wilmington field Reporte, Lower Miscons and Puerte, Miacene

Califamia Los Angeles County

GENERAL CHARACTERISTICS

Gravity, specific 0.938	Gravity, * API.	19,4	Pour point . F . be	ow 5
Viernety, Sevenit Universe	il at 100° F, 470 mg; 130° I	F, 229 mc.	Color: Brownish bl Nisrogen, percent,	0, 597

DISTILLATION, BUREAU OF MINES ROUTINE METHOD _

Frantsin	Ca	Percent	Seema parternat	1911 - 1917 - 1944 - 148 ⁻ 19	(1)) All ^a F	ст	Hefenetics mater	-greste dispersion	N U	Cloud L reg.
	122			•				· ·		
2	167						,	1		
3	212	2.J	2.3	0.707	68.6	•	1.39794	122.7		
•	257	2.4	4.7	. 744	58.7	24	1.41215	125.7		
3	302	2.4	7. I	. 767	53.0	27	1,42308	127.1		
6	347	2.5	9.6	. 786	48,1	30	1.43480	128.8		
7	192	2.8	- 12.4	. 810	43.2	34	1.44451	133.3		
	437	3.6	16.0	. 831	38.8	39	1.45771	148.6		1
•	482	4.4	20.4	. 848	35.4	41	1.46754	150.5		
19	\$27	5.3	25.7	. 864	32.3	44	1.47736	152.9		
				TANE 2 -Desi	listen contri		min Hg			
11	342	4.7	30,4	0.894	26.8	55	1.48843	155.3	42	Below 5
12	437	6.3	36.7	. 907	24.5	57	1,49878	163.8	56	i do.
13	482	4.1	40.8	. 920	22.3	60			87	de.
14	527	5.5	46.3	. 932	20.3	· 62			172	do.
15	572									1
Rendunm	-	SJ. J	99.6	1.008	8.9					
Carbon resi	han, Can	ngdona Res		permit, an		PITTIN.	Bendun 19 Sulfu Nite	n: Je. percent. Jern. percent	- . 1.0	243
						- 1'++			<u> </u>	Visensity
Light semi-	*	:				2		07 6	. 0	
						13	A			

Kers والد ومداد Ges ed ν. 10.100 م اعاد اه 5. 100 м. .936 .939 Ł. مدماك بسبار ¥ 4 53.3 1,008 8.9 1 . . 4

1/ Distillation discontinued at 527° F.

Distribution in

Table 5.--Distillation Data for Wilmington Field Crude Oil Illustrating Use in Oil-Weathering Calculations. (See Table 4 for published data.)

ENTER THE NUMBER OF TBP CUTS TO BE CHARACTERIZED ON 12 IF YOU HAVE NO INFUT DATA JUST ENTER 99 A 99 ENTRY WILL USE A LIBRARY EXAMPLE 97 CHOOSE A CRUDE ACCORDING TO: 1 = FRUDHOE BAY, ALASKA 2 = COOK INLET, ALASKA 3 = WILMINGTON, CALIFORNIA 4 = MURBAN, ABU DHABI 5 = LAKE CHICOT, LOUISIANA 6 = LIGHT DIESEL CUT 3

YOU CHOSE: WILMINGTON, CALIFORNIA

CUI	Г	TB	API	VOL
1		195.0	68.6	2.3
2		235.0	58.7	2.4
3		280.0	53.0	2.4
4		325.0	48.1	2.5
5		370.0	43.2	2.8
6		415.0	38.8	3.6
7		460.0	35.4	4.4
6		505.0	32.3	5.3
9		554.0	26.8	4.7
10		609.0	24.5	6.3
11		662.0	22.3	4.1
12		712.0	20.3	5.5
13		850.0	8.9	53.3
00 N	YOU	WANT TO	CHANGE ANY?	
00	YOU	WANT TH	E MACKAY CONS	TANTS?

Cut	Cut Temp., °F	Vol. %	API Gravity
		* * -* - ** - ** ** ** ** ** ** *	
1	137	1.5	71.6
2	196	2.1	69.7
3	228	2.0	55.0
4	256	2.0	53.8
5	283	2.0	49.6

Table 6.--True Boiling Distillation Data for a Gasoline Cut (O&GJ, 1973, pg. 57).

Table 7.--Illustration of User Input of Data for a Gasoline Cut. (See Table 6 for published data.)

ENTER THE NUMBER OF TBP CUTS TO BE CHARACTERIZED ON 12 IF YOU HAVE NO INPUT DATA JUST ENTER 99 A 99 ENTRY WILL USE A LIBRARY EXAMPLE S IS THE CRUDE ON A FILE ? N ENTER THE NAME OF THE CRUDE GASOLINE CUT ENTER AN IDENTIFICATION NUMBER FOR THIS CRUDE ON 15 11111 ENTER A SAMPLE NUMBER ON IS 22222 ENTER THE BULK API GRAVITY 55. YOU MUST ENTER THE TRUE BOILING POINT CUT DATA STARTING WITH THE MOST VOLATILE CUT AND GOING TO THE BOTTOM OF THE BARREL ENTER THE BOILING FOINT AT 1 ATM IN DEG F FOR CUT 1 137. ENTER API GRAVITY FOR CUT 1 71.6 ENTER VOLUME PER CENT FOR CUT 1 1.5 ENTER THE BOILING POINT AT 1 ATM IN DEG F FOR CUT 2 176.

```
Table 7.--(Continued)
```

ENTER API GRAVITY FOR CUT 2 59.7 ENTER VOLUME PER CENT FOR CUT 2 2.1 ENTER THE BOILING POINT AT 1 ATM IN DEG F FOR CUT 3 228. ENTER API GRAVITY FOR CUT 3 55. ENTER VOLUME PER CENT FOR CUT 3 2. ENTER THE BOILING POINT AT 1 ATM IN DEG F FOR CUT - 4 256. ENTER AFI GRAVITY FOR CUT 4 53.8 ENTER VOLUME PER CENT FOR CUT - 4 2.0 ENTER THE BOILING POINT AT 1 ATM IN DEG F FOR CUT 5 283. ENTER API GRAVITY FOR CUT 5 49.6 ENTER VOLUME PER CENT FOR CUIT 5 2. CUT AFI VOL TB 137.0 1.5 71.6 1 2 196.0 59.7 2.1 3 228.0 55.0 2.0 4 256.0 53.8 2.0 5 283.0 49.6 2.0 DO YOU WANT TO CHANGE ANY? N THIS CRUDE WILL NOW BE WRITTEN TO A FILE. WHAT WOULD YOU LIKE TO CALL IT ? DSK:FOR38.DAT at MAIN.+526 (PC 14421)] CERSNAM OPEN unit 38 [FRSEFS Enter correct file specs] *GASCUT.OIL DO YOU WANT THE MACKAY CONSTANTS? N

Each time an input is required the user is prompted with an appropriate question. Since it is nearly impossible to enter many numbers into the oil-weathering calculation without an error, the distillation cut data are always echoed to the user for review. In the event an input error is discovered or it is desired to change an entry, the user's response to DO YOU WANT TO CHANGE ANY? is yes. The error recovery is illustrated in Table 8 where the gasoline-cut data from Table 6 is entered. Note the input error for TB (boiling temperature) for cut 3 where 22.8 was entered instead of 228. The user is prompted for the error-recovery information and the final data is echoed to the user. In the event another error is to be corrected, a "YES" would be entered in response to the very last question in Table 8.

Following keyboard data entry, the user will be prompted for a name to be assigned to a disk file which will contain the TBP data for the oil of interest. The format for this name is one to six characters followed by an optional period and one to three letter extension. In the example (Table 7), the file was named GASCUT.OIL.

An example of disk file input is illustrated in Table 9. In this example, the disk file created in the previous example (Table 7) is used as input for the model.

After the TBP data required as input have been specified, the user is asked if the Mackay Constants are desired. These constants are input constants for the Mackay evaporation model (Mackay, 1982). The calculation of these constants are an "add-on" calculation and do not affect the "weathering" portion of the model.

Table 8.--Illustration of Input-Error Recovery. (Note error for cut 3 boiling temperature.)

S

ENTER THE BOILING POINT AT 1 ATM IN DEG F FOR CUT 283. ENTER API GRAVITY FOR CUT 5 49.6 ENTER VOLUME PER CENT FOR CUT 5 2. CUT TB API VOL 1 137.0 71.6 1.5 2 2.1 196.0 59.7 3 22.8 55.0 2.0 4 256.0 53.8 2.0 2.0 5 283.0 49.6 TO YOU WANT TO CHANGE ANY? Y ENTER THE CUT NUMBER TO BE CHANGED ON 12 3 ENTER 1 TO CHANGE TB, 2 FOR API, 3 FOR VOL% 1 ENTER THE CHANGED DATA 228. CUT API VOL TB 137.0 1.5 1 71.ó 3 196.0 59.7 2.1 2.0 3 55.0 228.0 2.0 4 256.0 53.8 5 2.0 283.0 49.6 DO YOU WANT TO CHANGE ANY? N

Table 9.--Illustration of Disk-file Input of TBP Distillation Data.

ENTER THE NUMBER OF TBP CUTS TO BE CHARACTERIZED ON 12 IF YOU HAVE NO INPUT DATA JUST ENTER 99 A 99 ENTRY WILL USE A LIBRARY EXAMPLE 5 IS THE CRUDE ON A FILE ? Y WHAT IS THE FILE NAME? EFRSNAM OPEN unit 36 DSK:FOR36.DAT at MAIN.+156 (FC 14051)] [FRSEFS Enter correct file specs] *GASCUT.OIL CUT ТВ AFI VOL 1 137.0 71.6 15.6 2 176.0 59.7 21.9 3 228.0 55.0 20.8 4 256.0 53.8 20.8 5 283.0 49.6 20.8 DO YOU WANT TO CHANGE ANY? N TO YOU WANT THE MACKAY CONSTANTS? N

At this point the calculation can be stopped. The crude oil characterization and, if desired, the Mackay Constants are all that will have been calculated. However, in order to "weather the crude", the user types "YES" in response to DO YOU WANT TO WEATHER THIS CRUDE?

The user input required for an oil-weathering calculation begins with a YES in response to the question DO YOU WANT TO WEATHER THIS CRUDE? The user is then prompted for the spill size in barrels.

Following this, the user is "led" through a series of three "compartments" of possible oil weathering. These three compartments are:

- 1. Oil weathering in pools on top of ice.
- 2. Oil weathering on the ocean surface in a broken-ice field.
- 3. Open ocean oil weathering.

The user is allowed to "mix and match" combinations of these three environmental configurations in order to design a scenario that will best match the actual or hypothetical conditions for which an oil weathering prediction is desired. Individual compartments can be skipped and environmental parameters such as temperature, wind speed, etc. can be changed from compartment to compartment. An example of user input for a scenario that involves all three compartments using a library crude oil is illustrated in Table 10. Following the spill size specification the user is asked WILL THE WEATHERING SCENARIO INCLUDE SEA ICE? If the user responds with "N", the first two compartments are not used and open ocean weathering follows. If the user enters 'Y', as in the example, all three weathering compartments are offered.

For weathering of oil on top of ice the required input data are: the number of hours for oil weathering, the temperature, the depth of the oil pools, the mass-transfer coefficient code, the wind speed, and, if desired, new viscosity constants.

Table 10.--Illustration of User Input for Oil-Weathering Calculation with a Library-Specified Crude.

ENTER THE NUMBER OF TBP CUTS TO BE CHARACTERIZED ON 12 IF YOU HAVE NO INPUT DATA JUST ENTER 99 A 99 ENTRY WILL USE A LIBRARY EXAMPLE 99 CHOOSE A CRUDE ACCORDING TO: 1 = PRUDHOE BAY, ALASKA 2 = COOK INLET, ALASKA 3 - WILMINGTON, CALIFORNIA 4 = MURBAN, ABU DHABI 5 - LAKE CHICOT, LOUISIANA 6 = LIGHT DIESEL CUT 1 YOU CHOSE: PRUDHOE BAY, ALASKA CUT TB AFI VOL 150.0 72.7 2.1 1 2 64.2 2.6 190.0 3 3.5 235.0 56.7 280.0 4 51.6 3.6 5 325.0 47.6 3.7 45.2 3.5 6 370.0 7 41.5 4.3 415.0 8 460.0 37.8 4.8 9 5.0 505.0 34.8 30.6 2.8 10 554.0 29.1 6.5 11 609.0 6.8 12 662.0 26.2 6.0 13 712.0 24.0 14 764.0 22.5 7.4 15 850.0 11.4 36.3 DO YOU WANT TO CHANGE ANY? N DO YOU WANT THE MACKAY CONSTANTS? Y AT WHAT TEMPERATURE, DEG F? 32. FLEASE WAIT TO YOU WANT TO WEATHER THIS OIL? Y WHAT IS THE SPILL SIZE IN BARRELS? 10000 WILL THE WEATHERING SCENARIO INCLUDE SEA ICE? Y WHEN THE OIL REACHES THE OIL SURFACE, WILL IT WEATHER IN FOOLS ON TOP OF THE ICE? Y

```
AT WHAT TEMPERATURE, DEG F?
20.
FOR HOW MANY HOURS?
24.
HOW DEEP WILL THE POOLS BE IN CN?
                                    TRY 2
2
ENTER THE MASS-TRANSFER COEFFICIENT CODE: 1, 2, OR 3 WHERE:
1-USER SPECIFIED OVER-ALL MASS-TRANSFER COEFFICIENT
2-CORRELATION MASS-TRANSFER COEFFICIENT BY MACKAY & MATSUGU
3-INDIVIDUAL-PHASE KASS-TRANSFER COEFFICIENTS
2
ENTER THE WIND SPEED IN KNOTS
10
DO YOU WANT TO ENTER NEW VISCOSITY CONSTANTS?
N
FLEASE WAIT
WILL THE OIL NOW WEATHER IN THE BROKEN ICE FIELD?
Y
FOR HOW MANY HOURS?
100.
AT WHAT TEMPERATURE, DEG F?
32.
ENTER THE FRACTION OF ICE COVER, I.E. 0.7
• 66
DO YOU WANT TO ENTER NEW MOUSSE FORMATION CONSTANTS?
N
DO YOU WANT TO ENTER A NEW OIL-WATER SURFACE TENSION (DYNES/CM)?
N
ENTER THE MASS-TRANSFER COEFFICIENT CODE: 1, 2, OR 3 WHERE:
1-USER SPECIFIED OVER-ALL MASS-TRANSFER COEFFICIENT
2-CORRELATION MASS-TRANSFER COEFFICIENT BY MACKAY & MATSUGU
3-INDIVIDUAL-PHASE MASS-TRANSFER COEFFICIENTS
2
ENTER THE WIND SPEED IN KNOTS
15.
DO YOU WANT THE SLICK TO SPREAD?
γ
DO YOU WANT TO ENTER NEW VISCOSITY CONSTANTS?
N
DO YOU WANT THE WEATHERING TO OCCUR WITH DISPERSION?
Y
DO YOU WANT TO ENTER NEW DISPERSION CONSTANTS?
N
```

PLEASE WAIT

Table 10.--(Continued)

WILL OPEN OCEAN WEATHERING NOW OCCUR? Y FOR HOW MANY HOURS? 240. AT WHAT TEMPERATURE, DEG F? 40. TO YOU WANT TO ENTER NEW MOUSSE FORMATION CONSTANTS? N DO YOU WANT TO ENTER A NEW OIL-WATER SURFACE TENSION (DYNES/CM)? N ENTER THE MASS-TRANSFER COEFFICIENT CODE: 1, 2, OR 3 WHERE: 1-USER SPECIFIED OVER-ALL MASS-TRANSFER COEFFICIENT 2-CORRELATION MASS-TRANSFER COEFFICIENT BY MACKAY & MATSUGU 3-INDIVIDUAL-PHASE MASS-TRANSFER COEFFICIENTS 2 ENTER THE WIND SPEED IN KNOTS 20. DO YOU WANT THE SLICK TO SPREAD? Y DO YOU WANT TO ENTER NEW VISCOSITY CONSTANTS? N TO YOU WANT THE WEATHERING TO OCCUR WITH DISPERSION? Y DO YOU WANT TO ENTER NEW DISPERSION CONSTANTS? N PLEASE WAIT CFU time 19.73 Elapsed time 2:36.35
The mass-transfer coefficient is for the evaporation weathering process, not dissolution. There are three possible mass-transfer coefficient input specifications, and the one recommended is 2 as illustrated in Table 10.

The wind speed, which is in knots, should be less than 40 knots because oil-weathering processes at and above this wind speed are not quantified. Also, the lowest wind speed used in the calculation is 2 knots and any value entered lower than this is reset to 2.

For now, new viscosity constant are not entered. The procedure for specifying new constants will be detailed later in this manual.

After all of the required data have been entered, the user is asked to wait while the numerical integration routine is executed. Following this pause, the user is asked if broken ice field weathering will take place. In the example (Table 10), the answer is "YES" so the input parameters for brokenice field weathering are now requested. For <u>library oils</u> the required data are the same for broken-ice and open-ocean weathering (with one minor exception noted below) so the following discussion applies to both of these compartments of the model.

The required data at this point are: the number of hours for weathering to occur, the temperature, new mousse formation constants (if desired), new oil-water surface tension (if desired), the mass-transfer coefficient code, the wind speed, whether or not the slick is to spread (YES) or (NO), new viscosity constants (if desired), whether or not the slick is to disperse (YES) or (NO), and new dispersion constants (if desired). For broken-ice weathering one other parameter is required, the fraction of ice cover.

As shown in Table 10, dispersion and spreading are "on" for the example and no new constants have been specified to replace the library values.

The same guidelines for mass-transfer coefficient code and wind speed outlined above apply for the last two compartments as well.

The fraction of ice cover is used to calculate the reduction in spreading rate due to the broken ice. The spreading equation (or algorithm) used in the oil weathering code(s) is a correlation based on observation. At present, there is not a mechanistic model (except possibly Elliot, 1986) that applies to the open ocean, and especially the situation where ice occurs or where ice cover changes as a function of time. The correlation algorithm for spreading can be changed quite readily in the oil-weathering codes in the event a useable algorithm is published. The search for a more realistic and mechanistic spreading model for all situations is on-going.

The preceding input description illustrates a straightforward use of the information programmed in the oil-weathering code. Illustrations of how the programmed information can be changed are presented in the following discussion. Altering the programmed information allows other crudes or petroleum cuts to be entered into the calculation, or actual spills and experiments can be analyzed to find the best physical properties or rate constants which predict observed data. Such alteration can be used in each of the three compartments of the model so the following discussion applies to each of those compartments.

The first input information that can be changed by the user is the mousse-formation constants as illustrated in Table 11. The mousse constants appear in an equation which quantifies the rate of water incorporation into the oil with respect to time. This rate equation is (Mackay, et al., 1980).

$$(1 - K_2 W) \exp\left[\frac{-2.5W}{1-K_1 W}\right] = \exp\left(-K_3 K_5 t\right)$$

where W is the weight fraction water is mousse. K_1 is a constant in the viscosity equation, K_2 is a coalescing-tendency constant, K_3 is a lumped water incorporation rate constant, and K_5 is the factor included in the equation to increase the mousse formation rate in the broken-ice field. K_1 appears in a stand-alone equation for the apparent viscosity of the emulsion as (Mooney, 1951).

Table 11.--Illustration of User-Specified Mousse-Formation Constants.

TO YOU WANT TO ENTER NEW MOUSSE FORMATION CONSTANTS? Y 1. ENTER THE MAXIMUM WEIGHT FRACTION WATER IN OIL .60 2. ENTER THE MOUSSE-VISCOSITY CONSTANT, TRY 0.65 .65 3. ENTER THE WATER INCORPORATION RATE CONSTANT, TRY 0.001 .001 4. ENTER THE BROKEN ICE FIELD MULTIPLIER FOR MOUSSE FORMATION 5. DO YOU WANT TO ENTER A NEW OIL-WATER SURFACE TENSION (DYNES/CH)? Y TRY 30. 30.

$$\mu = \mu_0 \exp\left[\frac{-2.5W}{1-K_1W}\right]$$

where μ° is the parent oil viscosity. K₁ is usually around 0.62 to 0.65 and apparently does not change much with respect to different types of oils.

The constant K_2 must satisfy the relation $K_2^W < 1$ in order for the water incorporation rate to be > 0. Thus, K_2 is the inverse of the maximum weight fraction water in mousse. K_3 is the water incorporation rate constant and is a function of wind speed in knots. Currently the oil-weathering code calculates K_3 from

 $K_3 = 0.001 \text{ (WIND SPEED)}^2$

and the constant actually entered by the user is the 0.001 constant above.

Thus, referring to Table 11, the first mousse formation constant entered is the maximum weight fraction water in the mousse. The reciprocal of this number is used for K_1 . The second constant entered is the viscosity constant in Mooney's equation and this number should be 0.62 to 0.65 unless experimental evidence suggests otherwise. The third constant entered is the multiplier of the (wind speed)² which then yields K_3 . This number is around 0.001 as indicated. There is limited data available for K_5 but some evidence points to a typical value of about 10 for broken-ice fields, which is the default value. In the open ocean, K_5 is by definition 1.0 so input is not required for this constant in the open-ocean section of the code. Note that most of the prompting for input also prints suggested values for each constant.

The next input parameter that the user can change is the masstransfer coefficient for evaporation. The input illustration in Table 10 uses the correlation mass transfer coefficient as developed by Mackay and Matsugu (Mackay and Matsugu, 1973). Table 12 illustrates the three possible input

Table 12.--Illustration of Three Input Options for the Mass Transfer Coefficient for Evaporation.

ENTER THE MASS-TRANSFER COEFFICIENT CODE: 1, 2, OR 3 WHERE: 1=USER SPECIFIED OVER-ALL KASS-TRANSFER COEFFICIENT 2=CORRELATION MASS-TRANSFER COEFFICIENT BY MACKAY & MATSUGU 3-INDIVIDUAL-PHASE KASS-TRANSFER COEFFICIENTS 1 ENTER THE WIND SPEED IN KNOTS 10. DO YOU WANT THE SLICK TO SPREAD? Y ENTER THE OVER-ALL MASS-TRANSFER COEFFICIENT, CM/HR, TRY 10 10. DO YOU WANT TO ENTER NEW VISCOSITY CONSTANTS? ENTER THE MASS-TRANSFER COEFFICIENT CODE: 1, 2, OR 3 WHERE: 1-USER SPECIFIED OVER-ALL MASS-TRANSFER COEFFICIENT 2=CORRELATION MASS-TRANSFER COEFFICIENT BY MACKAY & MATSUGU 3-INDIVIDUAL-PHASE KASS-TRANSFER COEFFICIENTS ENTER THE WIND SPEED IN KNOTS 10. DO YOU WANT THE SLICK TO SPREAD? Y ENTER THE MASS-TRANSFER COEFFICIENT CODE: 1, 2, OR 3 WHERE: 1-USER SPECIFIED OVER-ALL MASS-TRANSFER COEFFICIENT 2-CORRELATION MASS-TRANSFER COEFFICIENT BY MACKAY & MATSUGU 3-INDIVIDUAL-PHASE KASS-TRANSFER COEFFICIENTS 3 ENTER THE WIND SPEED IN KNOTS 10. DO YOU WANT THE SLICK TO SPREAD? Y ENTER THE DIL-PHASE MASS-TRANSFER COEFFICIENT IN CM/HR, TRY 10 10. ENTER THE AIR-PHASE MASS-TRANSFER COEFFICIENT IN CM/HR, TRY 1000 1000. ENTER THE MOLECULAR WEIGHT OF THE COMPOUND FOR K-AIR ABOVE, TRY 200 200. DO YOU WANT TO ENTER NEW VISCOSITY CONSTANTS? N

options for the evaporation mass transfer coefficient. The first input option shown in Table 12 allows the user tp input the mass-transfer coefficient directly, in contrast to the second input option where the coefficient is calculated as a function of wind speed and slick diameter. In the third input option the user can enter individual-phase mass transfer coefficients. In this last option the entered coefficient is scaled according to the square root of the molecular weight of each cut to yield a coefficient specific to each cut (Liss and Slater, 1974). The coefficient in this last option is also scaled according to wind speed according to Garratt's drag coefficient (Garratt. 1977).

After specifying the mass-transfer coefficient options the user can specify if the slick is to spread or not. This option is illustrated in Table 13 by entering YES or NO to the prompt. In this particular illustration the user has specified that the slick does not spread. This option is useful for investigating evaporation from spills on solid surfaces such as ice or land. When the no-spreading option is selected the user is prompted for a starting thickness, unless previous weathering has occurred in which case the remaining thickness is used. In the illustration in Table 13 the entered thickness is 2 cm.

The final physical property <u>optional input</u> that can be specified by the user is the viscosity. The viscosity-prediction for the bulk weathered oil is important when dispersion of oil into water occurs, since viscosity appears in the rate equation for dispersion. The current methaod of viscosity prediction is based on the viscosity of the initial crude at 25°C, a temperaturescaling constant, and a fraction-oil-weathered constant. The viscosity predicted at this stage of optional input is for oil only, and must not be interpreted as that viscosity when a water-in-oil emulsion is present. The further change in viscosity due to water-in-oil emulsification (mousse formation) was described on page 12.

The viscosity at 25°C is scaled to other temperatures by the Andrade equation (Gold and Olge, 1969), which is

$$\ln\left[\frac{\mu_{1}}{\mu_{0}}\right] = B\left[\frac{1}{T_{1}} - \frac{1}{T_{0}}\right]$$

and the temperature-scaling constant is B. This viscosity of the weathered oil is calculated according to $\exp(K_4F)$ where F is the fraction weathered (Tebeau, Mackay, et al., 1982) i.e., fresh crude oil has F = 0. As weathering proceeds, the parent oil viscosity increases exponentially with respect to F.

The user can enter the three viscosity constants by answering YES to the prompt illustrated in Table 14. In this illustration suggested input viscosity constants are printed along with the prompt.

The constants which appear in the dispersion process can also be specified by the user. The dispersion of oil into the water column is described by two equations (Mackay, et al., 1980):

$$F = K_a K_c (U + 1)^2$$

and

$$F_{B} = (1 + K_{b} \mu^{0.5} \delta_{\chi})^{-1}$$

where F is the fraction of sea surface subject to dispensions per second, U is the wind speed in m/sec, and K_a is a constant, typically 0.1 hr⁻¹. F_B is the fraction of droplets of oil below a critical size which do not return to the slick, K_b is a constant, around 50, μ is the viscosity in centipoise, x is the slick thickness in meters, w is the surface tension in dynes/cm, and K_c is the constant which determines the increase in dispersion for broken-ice fields. Little experimental data is available for K_c , however some limited data suggests a value of 10, which is the default value. In open-ocean weathering, K_c is by definition 1.0, so input for this variable is not required in the Table 13.--Illustration of the "No-Spreading" Option and Starting Thickness Specification.

ENTER THE MASS-TRANSFER COEFFICIENT CODE: 1, 2, OR 3 WHERE: 1-USER SPECIFIED OVER-ALL MASS-TRANSFER COEFFICIENT 2=CORRELATION MASS-TRANSFER COEFFICIENT BY MACKAY & MATSUGU 3-INDIVIDUAL-PHASE MASS-TRANSFER COEFFICIENTS 2 ENTER THE WIND SPEED IN KNOTS 10 DO YOU WANT THE SLICK TO SPREAD? N SINCE THE SLICK DOES NOT SPREAD, ENTER A STARTING THICKNESS IN CM 2.

Table 14.--Illustration of Viscosity-Constant Input Options.

DO YOU WANT TO ENTER NEW VISCOSITY CONSTANTS? Y 1. ENTER THE BULK CRUDE VISCOSITY AT 25 DEG C, CENTIPOISE, TRY 35. 40. 2. ENTER THE VISCOSITY TEMPERATURE SCALING CONSTANT (ANDRADE), TRY 9000. 9000. 3, ENTER THE VISCOSITY-FRACTION-OIL-WEATHERED CONSTANT, TRY 10.5 10.5 DO YOU WANT THE WEATHERING TO OCCUR WITH DISPERSION? Y TO YOU WANT TO ENTER NEW DISPERSION CONSTANTS? Ϋ́ ENTER THE WIND SPEED CONSTANT, TRY 0.1 .1 ENTER THE CRITICAL DROPLET SIZE CONSTANT, TRY 50 50. ENTER THE BROKEN ICE FIELD DISPERSION MULTIPLIER 8. DO YOU WANT THE WEATHERING TO OCCUR WITH DISPERSION?

open-ocean portion of the model. Ths mass fraction that leaves the slick as dispersed droplets is (F_b) .(F) and this fraction applies to each cut of oil. Table 15 illustrates the user input of the constants K_a , K_b , and K_c .

OUTPUT DESCRIPTION

The output generated by the ocean-ice oil-weathering code is written to four disk files: OILICE.OUT, OILICE.TYP, OILICE.PLT, and MACKAY.DAT. These files contain the calculated results in various forms. The OILICE.OUT file is 130 columns wide and intended to be printed on an appropriate high speed printer. The OILICE.TYP file is an abbreviated version of OILICE.OUT. The OILICE.PLT is a numbers-only raw data file and intended to be read by a plotting routine or other data processing routines which must be supplied by the user. The MACKAY.DAT file contains the input parameters for the MACKAY evaporation model.

An example of the OILICE.OUT file (130 column) is presented in Table 16 where the calculated results for an oil-weathering calculation for Prudhoe Bay crude are presented. The first page of this output (page 40) is crude characterization information for fresh Prudhoe Bay crude oil as calculated according to previous descriptions (Payne et al., 1983, 1984a). Page 41 presented the mass-transfer coefficients, the input parameters and constants, and the beginning of the results of the calculations for weathering in pools on top of ice. Pages 42 through 45 are the remainder of these calculations. Page 46 presents characterization of the oil after "pool-weathering." The intermediate characterization is used automatically as input for further weathering as directed by the user. (Note that the volume percents and bulk API gravity have changed.)

For the scenario presented in Table 16, weathering in the broken-ice field at 32°F was chosen next. Page 47 presents the input constants and the beginning of the results for this weathering.

One important aspect of the code output to notice is the deletion of very volatile cuts. The information presented for various times is self

Table 15.--Illustration of Dispersion Constants Input.

DO YOU WANT THE WEATHERING TO OCCUR WITH DISPERSION? Y DO YOU WANT TO ENTER NEW DISPERSION CONSTANTS? Y ENTER THE WIND SPEED CONSTANT, TRY 0.1 .2 ENTER THE CRITICAL DROPLET SIZE CONSTANT, TRY 50 50. ENTER THE BROKEN ICE FIELD DISPERSION MULTIPLIER 89.

PLEASE WAIT

Table 16.--Illustration of Output from Oil-Weathering Calculations: Fresh Prudhoe Bay Crude Oil Characterization.

SUMMARY OF THE CUTS CHARACTERIZATION FOR: PRUDHOE BAY, ALASKA

CODE VERSION IS CUTICA OF NAY 84 ITEN 9, SAMPLE 71011

	TB	API	SPCII	VOL.	MW	TC	PC	VC	Α	В	T10	VIS	NC	NS
1	1.50E+02	7.27E+01	6.81E-01	2.12E+00	8.35E+01	9.14E+02	3.95E+01	3.66E+02	3.17E+00	1.90E-01	4.478+02	3.80E-01	3	1
2	1.90E+02	6.42E+01	7.11E-01	2.63E+00	9.39E+01	9.63E+02	3.791:+01	4.071.102	3.24E+00	2.03E-01	4.748:+02	4.488-01	3	
3	2.35E+02	5.67E+01	7.392-01	3.54E+00	1.06E+02	1.02E+03	3.64E+01	4.546+02	3.31E+00	2.15E-01	5.13E+02	5.44E-01	3	1
4	2.00E+02	3.162+01	7.60E-01	3.64E+00	1.198+02	1.071:+03	3.4861+01	5.07E+02	3.41E+00	2.27E-01	5.49E+02	6.73E-01	3	
5	a.25E+02	4.76E+U1	7.77E-01	3.74E+00	1.348+02	1.12E+03	3.328+01	5.658.+02	3.52E+00	2.39E-01	5.868+02	8.46E-01	3	1
6	1.70E+02	4.528+01	7.876-01	8.54E+00	1.51E+02	1.16E+03	3.16E+01	6.328+02	3.671.+00	2.50E-01	6.23£+02	1.07E+00	3	1
7	4.1510+02	4.15E+01	8.04E-01	4.35E+00	1.678+02	1.21E+03	3.031:+01	6.948+02	(L. 80)E+90	2.59E-01	6.60E+02	1.38E+00	3	1
- A	4.601:+02	3.78E+01	8.22E-01	4.435E+00	1.45E+02	1.26E+03	2.916+01	7.671:02	0.94E+00	2.671-01	6.98E+02	1.81E+00	3	1
9	5.05E+02	3.486+01	8.36E-01	5.06E+00	2.008+02	1.311+03	2.84E+01	8.28E+02	4.06E+00	2.74E-01	7.368+02	1.75E+00	3	1
10	5.54E+02	3.06E+01	8.58E-01	2.83E+00	2.218+02	1.35E+03	2.74E+01	9.098+02	4.22E+00	2.82E-01	7.771.+02	2.48E+00	3	
11	6.09E+02	2.911+01	8.662-01	6.57E+00	2.52E+02	£.40E+03	2.508:+01	1.038+03	4.491:+00	2.928-01	8.26E+02	4.002+00	3	1
12	6.62E+02	2.621.+01	8.82E-01	6.88E+00	2.84E+02	1.45E+03	2.47E+01	1.15E+03	4.73E+00	2.998-01	8.73E+02	7.18E+00	3	1
13	7.12E+02	2.491:+01	8.94E-01	6.072+00	a. (3E+02	1.498+03	2.36£+01	1.278+03	5.00E+00	3.06E-01	9.198+02	1.36E+01	3	1
14	7.641.+02	2.251.+01	9.03E-01	7.48E+00	3.51E+02	1.5312+03	2.256+01	1.43E+03	5.35E+00	3.13E-01	9.68£+02	2.81E+01	:1	i
15	4.50E+02	1.14E+01	9.73E-01	8.672+01	6.00E+02	0.00E+00	0.001:+00	0.00E+00	0.00E+00	0.001:+00	0.00E+00	1.812+02	4	

	DOL R	CORNELATION INDEX
1	1.246+01	L.16E+01
2	1.226+01	1.662+01
ā	1.20E+01	2.126+01
4	1.198+01	2.322+04
5	1.196+01	2.432+01
6	1.196+01	2.326+01
7	1.198+01	2.561+01
Å.	1.1446.+01	2.90E+01
ä	1.146.+01	3.458+01
	1 178+41	3.735+01
	A 14464-01	3.668.101
		A 44-26-444
12	1.101.101	
13	1.106+01	4.27E+01
14	1.18E+01	4.368+01
15	1.12E+01	7.212+01

HULK API CHAVITY = 28.9

MEAN MOLECULAR WEIGHT OF THE CHUDE - 2-593E+02

Table 16.--Output from Oil-Weathering Calculations (Continued): Prudhoe Bay Crude Oil, Time versus Calculated Results of Weathering in Pools on Top of Ice at 32°F.

WEATHERING OF OIL IN POOLS ON TOP OF ICE

OVER-ALL MASS-TRANSFER COEFFICIENTS BY INPUT CODE 2.

OVER-ALL MASS-TRANSFER COEFFICIENT FOR COMENE - 2.079E+01 M/HR

CUT	M/HIL	GN=NOLESZ(III)(ATTA)(M**2)
4	2.245E+01	1.0244E+03
2	2.212E+01	1.013E+03
3	2. LIGE+01	9、994起+62
4	2.156E+01	9.873E+02
5	2.13316+01	9.7678+02
6	2.112E+01	9.6698+82
7	2.095E+01	9.5912+02
43	2.000E+01	9.525E+02
4	2.0692+01	9.474E+02
10	2.057E+01	9.4198+02
11	2.042E+01	9.351E+02
12	2.0312+01	9.300E+02
13	2.022E+01	9.2676+02
14	2.012E+01	9.2138+02

FOR THIS SPILL OF 1.000E+04 BARRELS, THE MASS IS 1.395E+03 METRIC TORNES VOLUME FROM SUMMING THE CUTS = 1.6E+03 M**3, OR 1.000E+04 BARRELS WIND SPEED = 1.000E+01 KNOTS, OR 1.853E+04 M/HR INITIAL SLICK DIAMETER = 3.182E+02 M, OR AREA = 7.950E+04 M**2 THIS SLICK DOES NOT SPREAD FOR THIS CALCULATION

KINEMATIC VISCOSITY OF THE BULK CRUDE FROM THE CUTS = 4.0E+00 CENTISTOKES AT 122 DEC F

KINEMATIC VISCOSITY OF THE BULK CRUDE FIRM THE CUTS = 1.1E+00 AT T = 32.0 DEC F, SCALE FACTOR = 2.8E-01

VISCOSITY ACCONDING TO MASS EVAPONATED: VIS25C = 3.50E+01, ANDRADE = 9.00E+03, FRACT WEATHERED = 1.05E+01, VSLEAD = 1.25E+03 CP

MOUSSE CONSTANTS: MOUNEY= 0.00E+00, MAX H20=-1.00, WIND**2= 0.00E+00

THE FRACTIONAL SLICK AREA SUBJECT TO DISPERSION IS 0.0E+00 PER HOUR

COUNT THE CUTS IN THE FOLLOWING OUTPUT FROM LEFT TO RIGHT

THE INITIAL CHAM MOLES IN THE SLICK ARE: 2.740E+05 3.140E+05 3.907E+05 3.660E+05 3.433E+05 2.923E+05 3.304E+05 3.414E+05 3.340E+05 1.741E+05 3.576E+05 3.412E+05 2.745E+05 3.042E+05 9.420E+05 THE INITIAL MASSES (GRAMS) IN THE SLICK ARE:

2.284E+07 2.956E+07 4.100E+07 4.375E+07 4.596E+07 4.407E+07 5.530E+07 6.308E+07 6.690E+07 3.443E+07 9.005E+07 9.594E+07 8.505E+07 1.009F+08 5.652E+08 THE TUTAL MASS FROM THESE CUTS IS 1.395E+09 CRAMS

STEP SIZE OF 0.047E-02 IS BASED ON CUT 1

TIME - 0.0E+00 HOURS, MASS FRACTION OF EACH CUT HEMAINING: 1.0E+00 MASS HEMAINING = 1.395E+09, MASS DISPENSED = 0.000E+00, MASS EVAPORATED = 0.000E+00, SUM = 1.395E+09 FRACTION (BASED ON MASS) HEMAINING IN THE SECO. (0.000E+00, AHEA- 7.9E+04 M##2, THICKNESS 2.0E+00 CM, HOLE WT-259.3 METCHT FRACTION (BASED ON MASS) HEMAINING IN THE SECO. (0.000E+00, AHEA- 7.9E+04 M##2, THICKNESS 2.0E+00 CM, HOLE WT-259.3 METCHT FRACTION WATER IN OTL = 0.0E+00, VISCOSTTY = 1.3E+03 CENTISTOKES, DISPENSION TERM = 0.0E+00 WEICHT FEACTION/BR MASS AHEA- 1.8E+04 CMS/M#M, SPCR- 8.BE OF, TOTAL VOLUME- 1.0E+04 BBL, DISPENSION TERM = 0.0E+00 WEICHT FEACTION/BR Table 16.--Output from Oil-Weathering Calculations (Continued): Prudhoe Bay Crude Oil, Time versus Calculated Results at 32°F for Weathering in Pools on Top of Ice. TIME = 1.0E+00 HOURS, MASS FRACTION OF EACH CUT REMAINING: 2 5.8E=01 8.4E=01 9.6E=01 9.9E=01 1.0E+00 1.01:+00 MASS HEMAINING = 1.379E+09, MASS DISPERSED = 0.000E+00, MASS EVAPOHATED = 1.673E+07, SUM = 1.395E+09 FRACTION (BASED ON MASS) BENAINING IN THE SLICE= 9.9E-01, AREA= 7.9E+04 M**2, THICKNESS= 2.0E+00 CN, NOLE WT=265.4 WEIGHT FRACTION WATER IN OIL = 0.0E+00, VISCOSITY = 1.4E+03 CENTISTORES, DISPERSION TERM = 0.0E+00 WEIGHT FRACTION/HR NASSZAREA: 1.7E+04 CMSZMAN, SPCR: 0.0E-01, TOTAL VOLUME: 9.0E+03 BBL, DISPERSION: 0.0E+00 CMSZMAMZNB, EVAP RATE: 1.7E+02 CMSZMANZHR TIME = 2.1E+00 HOURS, MASS FRACTION OF EACH OUT REMAINING: 3 3.38-01 7.0E-01 9.2E-01 9.8E-01 1.0E+00 1.01:+00 MASS BEMAINING = 1.367E+09, MASS DISPERSED = 0.000E+00, MASS EVAPORATED = 2.864E+07, SUM = 1.395E+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICE= 9.8E-01, AREA= 7.9E+04 M##2, THICENESS= 1.9E+00 CH, MOLE WT=270.0 WEIGHT FRACTION WATER IN OIL = 0.00+00, VISCOSITY = 1.60+03 CENTISTORES, DISPERSION TERM = 0.00+00 WEIGHT FRACTION/HR MASS/AREA= 1.7E+04 CMS/M*M, SPCB= 8.8E-01, TOTAL VOLUME= 9.7E+03 BBL, DISPERSION= 0.0E+00 CMS/M+M/BB, EVAP RATE= 1.3E+02 CMS/M+M/BB TIME = 3.11:+00 HOURS, MASS FRACTION OF EACH OUT REMAINING: 1.9E-01 5.8E-01 8.8E-01 9.7E-01 9.9E-01 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.08+00 MASS BEMAINING = 1.358E+09, MASS DISPERSED = 0.000E+00, MASS EVAPORATED = 3.755E+07, SUN = 1.395E+09 FRACTION (BASED ON MASS) BENAINING IN THE BLICK= 9.7E-01, AREA= 7.9E+04 M**2, THICENESS= 1.9E+00 CN, HOLE WE=273.4 WEIGHT FRACTION WATER IN DIL = 0.0E+00, VISCOSITY = 1.7E+03 CENTISTOEFS, DISPERSION TERM = 0.0E+00 WEIGHT FRACTION/HR MASS/AREA= 1.7E+04 CMS/N+M, SPCH= 8.8E-01, TOTAL VOLUME= 9.7E+03 BBL, DISPERSION= 0.0E+00 CMS/N+M/HR, EVAP RATE= 9.5E+01 CMS/N+M/HR TIME = 4.2E+00 HOURS, MASS FRACTION OF EACH OUT REMAINING: 5 1.0E+00 1.01.+00 MASS BEMAINING = 1.351E+09, MASS DISPENSED = 0.000E+00, MASS EVAPORATED = 4.447E+07, SUN = 1.395E+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICE = 9.7E-01, ANEA= 7.9E+04 M##2, THICKNESS= 1.9E+00 CH, HOLE WT=276.0 VEICHT FRACTION WATER IN OIL = 0.0E+00, VISCOSITY = 1.8E+03 CENTISTORES, DISPERSION TERM = 0.0E+00 WEICHT FRACTION/III MASS/AREA= 1.7E+04 CRS/N#M, SPCR= 0.0E-01, TOTAL VOLUME= 9.6E+03 BBL, DISPERSION= 0.0E+00 CRS/N#M/HR, EVAP RATE= 7.5E+01 CRS/N#N/HR TIME = 5.2E+00 HOURS, MASS FRACTION OF EACH OUT HEMAINING; 6 5.4E-02 6.0E-01 8.0E-01 9.5E-01 9.9E-01 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.01:+00 MASS REMAINING = 1.345E+09, MASS DISPENSED = 0.000E+00, MASS EVAPONATED = 5.005E+07, SUN = 1.395E+09 FHACTION (BASED ON MASS) REMAINING IN THE SLICE= 9.6E-01. AREA= 7.9E+04 N**2, THICKNESS= 1.9E+00 CN, MOLE VT=278.2 VELOUT FRACTION WATER IN OIL = 0.0E+00, VISCOSITY = 1.8E+03 CENTISTORES, DISPERSION TERM = 0.0E+00 WEIGHT FRACTION/HR MASS/AREA= 1.7E+04 CMS/M+H, SPCR= 8.9E-01, TOTAL VOLUME= 9.6E+03 BBL, DISPERSION= 0.6E+00 CMS/M+M/HR, EVAP RATE= 6.2E+01 CMS/M+M/IIR TIME = 6.3E+00 HOURS, MASS FRACTION OF EACH CUT BEMAINING: 7 3.2E-02 3.3E-01 7.7E-01 9.4E-01 9.9E-01 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.01.40 MASS REMAINING = 1.341E+09, MASS DISPERSED = 0.000E+00, MASS EVAPORATED = 5.471E+07, SUM = 1.395E+09 FHACTION (BASED ON MASS) REMAINING IN THE SLICK: 9.6E-01, ANEA: 7.9E+04 M##2, THICKNESS: 1.9E+00 CM, HOLE VT-200.0 VEICHT FRACTION WATER IN OIL = 0.0E+00, VISCOSITY = 1.9E+03 CENTISTOKES, DISPERSION TERM = 0.0E+00 WEICHT FRACTION/HR MASS/AREA = 1.7E+04 CMS/M+M, SPCR= 0.9E-01, TOTAL VOLUME= 9.5E+03 BBL, DISPERSION= 0.0E+00 CMS/M+M/IIH, EVAP RATE= 5.2E+01 CMS/M+M/IIH TIME = 7.3E+00 HOURS, MASS FRACTION OF EACH CUT REMAINING: 48 1.48-02 2.7E-01 7.3E-01 9.4E-01 9.9E-01 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.01:+00 MASS REMAINING - 1.007E+09, MASS DISPERSED = 0.000E+00, MASS EVAPORATED = 5.070E+07, SUM = 1.095E+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICE= 9.6E.01. ANDA- 7.9E+04 N**2, THICKNESS= 1.9E+00 CM, MOLE MT=201.5 WEICHT FRACTION WATER IN OIL . 0.0E+00, VISCOSITY = 2.0E+03 CENTISTOKES, DISPERSION TERM = 0.0E+00 WEICHT FRACTION/HR

MASS/AREA: 1.7E+04 GMS/M+M, SPGR= 8.9E-01, TOTAL VOLUME 9.5E+03 BBL, DISPERSION= 0.0E+00 GMS/M+M/HR, EVAP BATE: 4.5E+01 GMS/M+M/HR

STEP SIZE OF 2.656E 01 IS BASED ON CUT 2

Calculated Results at 32°F for Weathering in Pools on Top of Ice. TIME = 8.4E+00 HOURS, MASS FRACTION OF EACH CUT REMAINING: 9 9.7E-03 2.2E-01 7.0E-01 9.3E-01 9.9E-01 1.0E+00 MASS REMAINING = 1.333E+09, MASS DISPERSED = 0.000E+00, MASS EVAPORATED = 6.219E+07, SUN = 1.395E+09 FHACTION (BASED ON MASS) BENATHING IN THE SLICK: 9.6E-01, ANEA: 7.9E+04 M##2, THICKNESS: 1.9E+09 CH, MOLE W2:282.8 WEIGHT FRACTION WATER IN OIL = -9.0E+00, VISCOSITY = 2.0E+03 CENTISTOEES, DISPERSION TERM = 0.0E+00 WEIGHT FRACTION/HR MASS/AREA= 1.7E+04 GNS/N#N, SPCR= 0.9E-01, TOTAL VOLUME= 9.4E+03 BDL, DISPERSION= 0.0E+00 CNS/N#N/AR, EVAP RATE= 4.0E+01 CNS/N#N/MR TIME = 9.4E+00 HOURS, MASS FRACTION OF EACH CUT REMAINING: 19 5.2E=03 1.8E=01 6.7E=01 9.8E=01 9.8E=01 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.9E+00 1.0E+00 1.9E+00 1.9E+00 1.01.+00 MASS REMAINING = 1.330E+09, MASS DISPERSED = 0.000F+00, MASS EVAPORATED = 0.535E+07, SUM = 1.395E+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 9.5E-01, AREA= 7.9E+04 M##2, THICKNESS= 1.9E+00 CM, NOLE WT=284.0 WEIGHT FRACTION WATER IN OIL = 0.0E+00, VISCOSITY = 2.1E+03 CENTISTOKES, DISPERSION TERM = 0.0E+00 WEIGHT FRACTION/HR MASS/AREA= 1.7E+04 CMS/M*M, SPCR= 8.9E-01, TUTAL VOLUME= 9.4E+03 BBL, DISPERSION= 0.0E+00 CMS/M+M/HB, EVAP RATE= 3.6E+01 CMS/M+M/HB TIME = 1.0E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 11 2.8E-03 1.5E-01 6.4E-01 9.1E-01 9.8E-01 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.01.+00 MASS REMAINING = 1.327E+09, MASS DISPERSED = 0.000E+00, MASS EVAPORATED = 0.819E+07, SUM = 1.395E+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 9.5E-01, AREA= 7.9E+04 M**2, THICKNESS= 1.9E+00 CM, NOLE WT=205.1 WEIGHT FRACTION WATER IN OIL = 0.0E+00, VISCOSITY = 2.1E+03 CENTISTOKES, DISPERSION TERM = 0.0E+00 WEIGHT FRACTION/HR MANSZAREA= 1.7E+04 GNSZM*M, SPCR= 8.9E+01, TUTAL VOLUNE= 9.4E+03 BBL, DISPERSION= 0.0E+00 CNSZM*MZHR, EVAP HATE= 3.3E+01 CNSZM*NZHR STEP SIZE OF 2.619E-01 IS BASED ON CUT 2 TIME = 1.2E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING; 12 1.5E-03 1.2E-01 6.1E-01 9.0E-01 9.8E-01 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.01:+00 MASS REMAINING = 1.324E+09, MASS DISPERSED = 0.000E+00, MASS EVAPORATED = 7.076E+07, SUN = 1.395E+09 FRACTION (BASED ON MASS) HEMAINING IN THE SLICK= 9.5E-01, ANEA= 7.9E+04 N##2, THICKNESS= 1.9E+00 CN, MOLE WT=206.0 VEICHT FRACTION WATER IN OIL = 0.0E+00, VISCOSITY = 2.1E+03 CENTISTOKES, DISPERSION TERM = 0.0E+00 WEIGHT FRACTION/HR MASS/AREA= 1.7E+04 CNS/N+N, SPCR= 8.9E-01, TUTAL VOLUME= 9.4E+03 BBL, DISPENSION= 0.0E+00 CNS/N+M/HR, EVAP RATE= 3.0E+01 CNS/N+M/HR STEP SIZE OF 2.606E-01 IS BASED ON CUT 2 TIME = 1.3E+01 HOURS, MASS FRACTION OF FACH CUT REMAINING: 13 8.2E-04 9.9E-02 5.8E-01 8.9E-01 9.8E-01 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.05:+00 MASS REMAINING = 1.322E+09, MASS DISPERSED = 0.000E+00, MASS EVAPORATED = 7.310E+07, SUN = 1.395E+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 9.5E-01, AREA= 7.9E+04 M**2, THICKNESS= 1.9E+00 CN, MOLE WT=206.9 VEIGHT FRACTION WATER IN 011. = 0.0E+00, VISCOSITY = 2.2E+03 CENTISTOKES, DISPERSION TERM = 0.0E+00 WEIGHT FRACTION/IIR MASS/AREA= 1.7E+04 CMS/M*N, SPCR= 8.9E-01, TOTAL VOLUME= 9.4E+03 BBL, DISPERSION= 0.0E+00 CMS/M*M/HR, EVAP RATE= 2.8E+01 CMS/M*M/HR STEP SIZE OF 2.594E-01 IS BASED ON CUT 2 TIME = 1.4E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 14 4.4E-04 8.1E-92 5.5E-91 8.8E-01 9.8E-01 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+09 1.0E+09 1.0E+09 1.0E+09 1.01:+00 MASS REMAINING = 1.320E+09, MASS DISPENSED = 0.000F+00, MASS EVAPORATED = 7.525E+07, SUM = 1.395E+09

Table 16.--Output from Oil-Weathering Calculations (Continued): Prudhoe Bay Crude Oil, Time versus

FRACTION (BASED ON MASS) REMAINING IN THE BLICK* 9.5E-01, AREA- 7.9E+04 N**2, THICKNESS* 1.9E+00 CM, NOLE VT*207.7 WEIGHT FRACTION WATER IN OIL * 0.0E+00, VISCOSITY * 2.2E+03 CENTISTOKES, DISPERSION TERM * 0.0E+00 WEIGHT FRACTIONZUR HASSZAREA* 1.7E+04 CMSZN*M, SPCR* 0.9E-01, TOTAL VOLUME* 9.3E+03 BBL, DISPERSION* 0.0E+00 CMSZN*MZHR, EVAP RATE* 2.6E+01 CMSZN*MZHR Table 16.--Output from Oil-Weathering Calculations (Continued): Prudhoe Bay Crude Oil, Time versus Calculated Results at 32°F for Weathering in Pools on Top of Ice.

TIME = 1.5E+01 HOURS, MASS FRACTION OF EACH OUT BEMAINING: 15 2.4E=04 6.6E=02 5.3E=01 8.7E=01 9.7E=01 1.0E+00 MASS BEMAINING = 1.318E+09, MASS DISPERSED = 0.000E+00, MASS EVAPORATED = 7.725E+07, SUN = 1.395E+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICE: 9.4E-01, AREA: 7.90:004 M**2, THICENESS: 1.90:00 CM, HOLE WT:200.4 WEIGHT PRACTION WATER IN DIL = 0.0E+00, VISCOSITY = 2.2E+03 CENTISTOKES, DISPERSION TERM = 0.0E+00 WEIGHT FRACTIONZIR MASS/AREA= 1.7E+04 GNS/N+N, SPGR= 0.9E+01, TOTAL VOLUME= 9.3E+03 BBL, DISPERSION= 0.0E+00 CMS/N+N/HR, EVAP RATE= 2.4E+01 CMS/N+N/HR STEP SIZE OF 2.572E-01 IS BASED ON CUT 2 TIME - LOGE+OI HOURS, MASS FRACTION OF EACH OUT REMAINING: 16 1.382-04 5.48-**02** 5.08-01 8.6<mark>8-01 9.78-0</mark>1 9.98-01 1.08+00 1.08+00 1.08+00 1.08+00 1.08+00 1.08+00 1.08+00 1.08+00 4 494 + 4949 MASS BENAINING = 1.316E+09, MASS DISPENSED = 9.000E+00, MASS EVAPORATED = 7.911E+07, SUM = 1.395E+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 9.4E-01, AREA= 7.90+04 N##2, THICENESS= 1.9E+00 CN, MOLE VT=209.1 SEIGHT FRACTION WATER IN OIL = 0.0E+00, VISCOSITY = 2.3E+03 CENTISTORES, DISPERSION TERM 0.0E+00 WEIGHT FRACTION/IR MASSZAREA= 1.7E+04 CHSZMAN, SPCN= 8.9E-01, TOTAL VOLUME: 9.3E+03 BBL, DISPENSION= 0.0E+00 CHSZMAN, EVAP RATE= 2.2E+01 CHSZMAN/HR STEP SIZE OF 2.562E-01 IS BASED ON CUT 2 TIME = 1.7E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 17 6.9E-05 4.4E-02 4.8E-01 8.5E-01 9.7E-01 9.9E-01 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.01:+00 NASS REMAINING = 1 314E+09, MASS DISPERSED = 0.000E+00, MASS EVAPORATED = 8.086E+07, SUN = 1.395E+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 9.4E-01, AREA= 7.9E+04 M**2, THICKNESS= 1.9E+00 CM, HOLE VT=289.8 VEIGHT FRACTION WATER IN OIL = 0.0E+00, VISCOSITY = 2.3E+03 CENTISTOKES, DISPERSION TERM = 0.0E+00 WEIGHT FRACTION/IR MASSZAREA= 1.7E+04 CMSZN#H, SPCR= 8.9E-01, TOTAL VOLUME= 9.3E+03 BBL, DISPERSION= 0.0E+00 CMSZN#MZHR, EVAP RATE= 2.1E+01 CMSZN#MZHR STEP SIZE OF 2.553E-01 IS BASED ON CUT 2 TIME = 1.8E+01 HOURS, MASS FRACTION OF EACH OUT REMAINING: 14 3.7E-05 3.6E-02 4.6E-01 8.4E-01 9.7E-01 9.9E-01 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.01.+00 MASS REMAINING = 1.313E+69, MASS DISPERSED = 0.000E+00, MASS EVAPOHATED = 8.250E+07, SUM = 1.395E+09 FRACTION (BASED ON HASS) REMAINING IN THE SLICK= 9.4E-04, AREA= 7.9E+04 M**2, THICKNESS= 1.9E+00 CN, NOLE VT-290.4 VEIGHT FRACTION WATER IN OIL = 0.0E+00, VISCOSITY = 2.3E+03 CENTISTOKES, DISPERSION TERM = 0.0E+00 WEIGHT FRACTIONZHR MASSZAREA: 1.7E+04 CMSZMAM, SPCR: 0.9E-01, TOTAL VOLUME: 9.3E+03 BBL, DISPERSION: 0.0E+00 CMSZMAMZHR, EVAP RATE: 2.0E+01 CMSZMAMZHR STEP SIZE OF 2.545E-01 IS BASED ON CUT 2 TIME = 1.9E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 19 2.0E-05 3.0E-02 4.3E-01 8.4E-01 9.7E-01 9.9E-01 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.01:+00 MASS REMAINING = 1.311E+09, MASS DISPERSED = 0.000E+00, MASS EVAPORATED = 0.405E+07, SUM = 1.395E+09 FRACTION (BASED ON MASS) REMAINING IN THE BLICK= 9.4E-01, ANEA= 7.9E+04 N##2, THICKNESS= 1.9E+00 CM, HOLE WT=291.0 VEIGHT FRACTION WATER IN OIL = 0.0F+00, VISCOSITY = 2.4E+03 CENTISTOKES, DISPERSION TERM = 0.0E+00 VEIGHT FRACTION/UR MASSZAREA= 1.66+04 CMS/N+M, SPCR= 8.9E-01, TOTAL VOLUME= 9.3E+03 BBL, DISPERSION= 0.0E+00 CMS/N+M, BR, EVAP RATE= 1.9E+01 CMS/N+M/BR STEP SIZE OF 2.537E-01 IS BASED ON CUT 2 TIME = 2.0E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 20 TTTE-05 2.4E-02 4.TE-01 8.3E-01 9.0E-01 9.9E-01 T.0E+00 T.0E+00 T.0E+00 T.0E+00 T.0E+00 T.0E+00 T.0E+00 T.0E+00 1.01.00 MASS REMAINING = 1.310E+09, MASS DISPENSED 0.000E+00, MASS EVAPORATED = 8.552E+07, SUM = 1.395E+09

MASS REMAINING = 1.310E+09, MASS DISPINSED = 0.0000E+00, MASS EVAPORATED = 0.352E+07, SUM = 1.395E+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICE 9.4E 01, AREA= 7.9E+04 M+42, THICKNESS LIBE+00 CM, MOLE VT+291.5 MEDGUE FRACTION WATER IN 011. = 0.0E+000, VISCOSITY = 2.4E+03 CENTISTORES, DISPERSION TEAM = 0.0E+000 WEIGHT THACTION/UN Table 16.--Output from Oil-Weathering Calculations (Continued): Prudhoe Bay Crude Oil, Time versus Calculated Results at 32°F for Weathering in Pools on Top of Ice.

MASS/AREA= 1.6E+04 GMS/M*M, SPCR= 8.9E=01, TOTAL VOLUME= 9.2E+03 BBL, DISPERSION= 0.0E+00 GMS/M*M/BB, EVAP RATE= 1.8E+01 GMS/M*M/BB

STEP SIZE OF 2.530E-01 IS BASED ON CUT 2

TINE = 2.1E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 5.9E-06 2.0E-02 3.9E-01 8.2E-01 9.6E-01 9.9E-01 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 MASS REMAINING = 1.30RE+09, MASS DISPERSED = 0.000E+00, MASS EVAPORATED = 8.693E+07, SUM = 1.395E+09 FRACTION (BASED ON MASS) REMAINING IN THE SILCK= 9.4E-01, AREA= 7.9E+04 N##2, THICKNESS=1.8E+00 CM, MOLE WT=292.0 WEICHT FRACTION WATER IN OIL = 0.0E+00, VISCOSITY = 2.4E+03 CENTISTORES, DISPERSION TERS I.0E+00 WEICHT FRACTION/HR MASS AREA= 1.6E+04 CMS/M#M, SPCH= 8.9E=01, TOTAL VOLUME= 9.2E+03 BBL, DISPERSION= 0.0E+00 CMS/M#M/HR, EVAP RATE= 1.7E+01 CMS/M#M/HR

STEP SIZE OF 2.522E-01 IS DASED ON CUT 2

TIME = 2.2E+01 HOURS, MASS FRACTION OF EACH CUT HEMAINING: 3.2E=06 1.6E=02 3.8E=01 8.1E=01 9.6E=01 9.9E=01 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 MASS REMAINING = 1.307E+09, MASS DISPERSED = 0.000E+00, MASS EVAPORATED = 8.826E+07, SUM = 1.395E+09 FUACTION (BASED ON MASS) REMAINING IN THE SLICK= 9.4E=01, AREA= 7.9E+04 M**2. THICKNESS= 1.8E+00 CM, MOLE VT=292.5 WEICHT FRACTION WATER IN OIL = 0.0E+00, VISCOSITY = 2.4E+03 CENTISTORES, DISPERSION TERM = 0.0E+00 WEICHT FRACTION/HR MASS/AREA= 1.6E+04 GNS/N*N, SPCR= 8.9E=01, TUTAL VOLUME= 9.2E+03 BBL, DISPERSION = 0.0E+00 GNS/N#M/HR, EVAP RATE= 1.6E+01 CNS/M*M/HR

STEP SIZE OF 2.516E-01 IS BASED ON CUT 2

TIME = 2.3E+01 HOURS, MASS FRACTION OF EACH CUT HEMAINING: 1.7E=06 1.3E=02 3.6E=01 B.0E=01 9.6E=01 9.9E=01 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 MASS REMAINING = 1.306E+09, MASS DISPERSED = 0.000E+00, MASS EVAPORATED = 8.954E+07, SUM = 1.395E+09FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 9.4E-01, AHEA= 7.9E+04 M**2, THICKNESS= 1.4E+00 CM, MOLE WF=293.0 WEIGHT FRACTION WATER IN 01L = 0.0E+00, VISCOSITY = 2.5E+03 CENTISTOKES, DISPERSION TERN = 0.0E+00 WEIGHT FRACTION/HR MASS/AREA= 1.6E+06 CMS/M*M, SPCH= 8.9E+01, TYFAL VOLUME= 9.2E+03 BBL, DISPERSION = 0.0E+00 CMS/M*M/HR, EVAP RATE= 1.6E+01 CMS/M*M/HR

STEP SIZE OF 2.509E-01 IS BASED ON CUT 2

TIME = 2.4E+01 HOURS, MASS FRACTION OF EACH GUT REMAINING: 24 9.0E=07 1.1E=02 0.4E=01 7.9E=01 9.6E=01 9.9E=01 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 MASS REMAINING = 1.004E+09, MASS DISPERSED = 0.000E+00, MASS EVAPORATED = 9.076E+07, SUM = 1.095E+09 FRACTION (BASED ON MASS) REMAINING IN THE BLICE= 9.0E=01, AREA= 7.9E+04 M**2, THICKNESS= 1.0E+00 CH, MOLE=VT=290.4 WEICHT FRACTION WATER IN 01L = 0.0E+00, VISCOSITY = 2.5E+00 CENTISTORES, DISPERSION TERN = 0.0E+00 WEICHT FRACTION/HR MASS/AREA= 1.6E+04 CHS/M*M, SPCR= 0.9E=01, TOTAL VOLUME= 9.2E+00 BBL, DISPERSION= 0.0E+00 CHS/M*M/HR, EVAP RATE= 1.5E+01 CMS/M*M/HR

25

STEP SIZE OF 2.503E-01 IS BASED ON CUT 2

THE COT NUMBERING BEGINS WITH A BASED ON THE ORIGINAL CUT NUMBERS

THE FINAL MASS FRACTIONS FOR THE SLICK AT 2:44+01 HOURS ARE: 6:042E-07 9:000E+03 3:344E-01 7:906E-01 9:549E-01 9:921E-01 9:907E-01 9:998E-01 1:000E+00 1:000E+00 1:000E+00 T:000E+00 1:000E+00 1:000E+00 1:000E+00 FRACTION (BASED ON MASS) REMAINING IN THE SLICE: 9:3E-01, AREA: 7:9E+04 M**2, THECENESS: 1:8E+00 CM, MOLE WF*293:4 MASS REMAINING : 1:304E+09, MASS DISPENSED : 0:000E+00, MASS EVAPORATED : 9:136E+07, SUM = 1:395E+09

Table 16.--Output from Oil-Weathering Calculations (Continued): Characterization of Prudhoe Bay Crude Oil After Weathering in Pools on Top of Ice.

SUMMARY OF THE CUTS CHARACTERIZATION FOR: PRUDHOE BAY, ALASKA

ICE POOL WEATHERING FOR 2.400E+01 HOURS

CODE VERSION IS CUTICA OF NAY 84 ITEM 9, SAMPLE 71011

	TB	API	SPCR	VOI.	NW	TC	PC	VC	۸	B	T10	VIS	nc'	IS.
1	1.50E+02	7.27E+01	6.81E-01	1 . SHE-06	H.35E+01	9.14E+02	3.95E+01	3.66E+02	3.17E+00	1.90E-01	4.47E+02	3. HILE-01	3	
2	1.908+02	6.42E+01	7.11E-01	2.83E-02	9.39E+01	9.63E+02	3.791:+01	4.078+02	3.241+00	2.03E-01	4.788+02	4 4442-01		
3	2.35E+02	3.67£+01	7.39E-01	1.29E+00	1.06E+02	1.028+03	3.641.+01	4.541.+02	3.31E+00	2.15E-01	5.13E+03	5 448-01	ä	
4	2.80E+02	5.16E+01	7.60E-01	3.13E+00	1.196+02	1.071:+03	3.48E+01	5.07E+02	3.415+00	2.276-01	5 495+62	6 738-61		
5	3.25E+02	4.76E+01	7.77E-01	3.89E+00	1.34E+02	1.128+03	3.326+01	5.65E+02	3.52E+00	2.396-01	5.866+02	H 465-01		
6	3.70E+02	4.52E+01	7.876-01	3.82E+00	1.51E+02	1.161+03	3.165+01	6.326+02	3.67E+00	2.506-01	6.23E+02	1.075+44		
7	4.15E+02	4.15E+01	8.04E-01	4.72E+00	1.678+02	1.216+03	3.031.+01	6.986+02	3. 8491.+040	2 598-01	6 6411 + 61*	1 (186)+464		- 1
8	4.608+02	3.788+01	8.221-01	5.28E+00	1.85E+02	1.26E+03	2.918+01	7.671.02	3.941+00	2.678-01	6.9415+02	1 4115+64		;
9	5 03E+02	3.488.+01	11.36E-01	5.50E+00	2.00E+02	1.311+03	2.841+01	8.206+02	4.005+00	2.74F-01	7 365+02	1 755+00		
10	5.548+02	3.06E+01	8.58E-01	3.08£+00	2.218+02	1.35E+03	2.746+01	9.09E+02	4.2211+00	2 426-61	7 775+01	2 485+44		
11	6.09E+02	2.91E+01	4.66E-01	7.15E+00	2.52E+02	1.401.+03	2.500+01	1.031.+03	4.441.+00	2.426-01	A 265+62	4 661.400		- 1
12	6.62E+02	2.62E+01	8.822-01	7.48E+00	2.811+02	1.45E+03	2.471+01	1.15E+03	4.731.+00	2.99E-41	11.735+02	7 185+00		
13	7.12E+02	2.40E+01	8.946-01	6.60E+00	3.13E+02	1.498+03	2.36E+01	1.27E+03	5 . 49426 + 4949	3 468-41	4 145+442	1 34.6 +414		
14	7.64E+02	2.25E+01	9.03E-01	8.14E+00	3.51E+02	1.53E+03	2.251.+01	1.438+03	5.351+00	3 135-01	4 1.115 +417	2 815+41		
15	4. SOE+02	1.142+01	9.73E-01	3.99E+01	6.00E+02	0.00E+00	0.001:+00	0.001.100	0.00E+00	0.001.+00	0.00E+00	1.412+02		

	UOP Y	CORRELATION INDEX
1	1.24E+01	1.16E+#1
2	1.22E+01	1.66E+01
3	1.202+01	2.128+01
4	1.198+01	2.326+01
5	1.198+01	2.438+01
6	1.198+01	2.326+01
7	1.19E+01	3.56起+01
8	1.1482+01	2.902+01
9	1.106+01	3.156+01
10	1.17E+01	3.73E+#1
11	1.186.+01	3.66 <u>8</u> +#1
12	1.18E+01	4.022+01
13	1.188.+01	4.278+01
14	1.18E+01	4.36E+01
15	1.12E+01	7.218+01

BULK API GRAVITY = 26.4

TH = NORMAL BOILING TEMPERATURE, DEC F API = API GRAVITY VOL = VOLUME PER CERT OF TOTAL CRUDE RW = MOLECULAR WEIGHT TC = CRITICAL TEMPERATURE, DEC RANKINE PC = CRITICAL PRESSURE, ATMOSPHERES VC = CRITICAL VOLUME, CC/MOLE A AND B ARE PARAMETERS IN THE VAPOR PRESSURE EQUATION TIO IS THE TEMPERATURE IN DEC R WHERE THE VAPOR PRESSURE IS 10 NM HC VIS IS THE KINEMATIC VISCOSITY IN CENTISTOKES AT 122 DEC F UOOP E IS THE U.O.P. K CHARACTERIZATION FACTOR COMBELATION INDEX IS DEFINED IN COLEMAN, 1970) RC = ERROR CODE, SHOULD BE LESS THAN 20 NS = ERROR CODE, SHOULD BE EQUAL TO 1 ICRORE THE EDROR CODES FOR COMPONENT NUMBER 15 IF IT IS A RESIDUUM

MEAN MOLECULAR WEIGHT OF THE CHUDE - 2.937E+02

Table 16.--Output from Oil-Weathering Calculations (Continued): Beginning of Calculated Results for Broken Ice Field Weathering at 32°F. (Note deletion of cut 1 and renumbering of cuts).

WEATHERING DATA FOR OIL IN A BROKEN ICE FIELD AFTER ICE POOL WEATHERING FOR 2.400E+01 HOURS

OVER-ALL MASS-TRANSFER COEFFICIENTS BY INPUT CODE 2

OVER-ALL MASS-TRANSFER COEFFICIENT FOR CUMENE = 1.957E+01 M/HR

CUL	M×HR	CM-MOLESZ (IIII) (ATM) (M**2)
1	2.112E+01	9.4356+02
2	2.082E+01	19.299E+02
a	2.054E+01	9.174E+02
4	2.029E+01	9.0638+02
5	2.007E+01	8.965E+02
6	1.987E+01	8.876E+02
7	1.971E+01	8.8646+02
- Å	1.9578+01	8.743E+02
4	1.9478+01	8.6972+02
10	1.9351+01	8.646E+02
11	1.9228+01	8.584E+02
12	1.911E+01	8.5376+02
iā	1.9028+01	8.4972+02
14	1.8932+01	8.4572+02

FOR THIS SPILL OF 9.195E+03 BARRELS, THE MASS IS 1.304E+03 METRIC TONNES VOLUME FROM SUMMING THE CUTS = 1.5E+03 N##3, OR 9.195E+03 BARRELS WIND SPEED = 1.200E+01 KNOTS, OR 2.224E+04 M/HR INITIAL SLICK DIAMETER = 3.182E+02 M, OH AREA = 7.950E+04 M##2 KINEMATIC VISCOSITY OF THE BULK CRUDE FROM THE CUTS = 6.4E+00 CENTISTOKES AT 122 DEC F KINEMATIC VISCOSITY OF THE BULK CRUDE FROM THE CUTS = 1.2E+01 AT T = 32.0 DEC F, SCALE FACTOR = 1.8E+00 VISCOSITY ACCORDING TO MASS EVAPORATED: VIS25C = 3.50E+01, ANDRADE = 9.00E+03, FRACT WEATHERED = 1.05E+01, VSLEAD = 5.50E+02 CP NOUSSE CONSTANTS: MODNEY= 6.20E-01, MAX H20= 0.70, WIND##2= 1.00E+02 THE FRACTIONAL SLICK AREA SUBJECT TO DISPERSION IS 5.5E+01 PER HOUR COUNT THE CUTS IN THE FOLLOWING OUTPUT FROM LEFT TO RIGHT

THE INITIAL CRAN MOLES IN THE SLICK ARE: 1.875E=01 3.113E+03 1.307E+05 2.900E+05 3.278E+05 2.899E+05 3.299E+05 3.413E+05 3.339E+05 1.741E+05 3.576E+05 3.412E+05 2.745E+05 3.042E+05 9.420E+05

THE INITIAL MASSES (GRAMS) IN THE SLICK ARE: 1.566+01 2.926+05 1.004E+07 3.450E+07 4.009E+07 4.072E+07 5.523E+07 6.007E+07 6.609E+07 3.040E+07 9.005E+07 9.594E+07 8.505E+07 1.069E+08 5.652E+08 THE TOTAL MASS FROM THESE CUTS IS 1.004E+09 (DRMS

CUT A COES AWAY IN MANUTES, THEREFORE IT WAS DELETED AND THE CUTS RENUMBERED

STEP SIZE OF 1.457E-01 IS BASED ON CUT 1

TIME = 0.01.00 HOURS, MASS FRACTION OF EACH CUT REMAINING: 1.0E+00 MASS REMAINING = 1.304E+09, MASS DISPERSED = 0.000E+00, MASS EVAPORATED = 0.000E+00, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE STICK = 1.0E+00, AREA 7.9E+04 N#42, THICKNESS = 1.0E+00 CN, MOLE WT-293.7 WEIGHT FRACTION WATER IN OIL = 0.0F 05, VISCOSITY = 1.1E+05 CENTISTORES, DISPERSION TERM = 4.6E+03 WEIGHT FRACTION/HR MASS AREA = 1.6E+04 CMS/M/H, STGR = 0.9E 01, TOTAL VOLUME = 9.2E+03 BDL, DISPERSION = 7.6E+04 CMS/M+M/HR, EVAP RATE = 0.0E+00 CMS/M+M/HR

TIME = 1.0E+00 BOURS, MASS FRACTION OF EACH CUT REMAINING: 2 6.5E-01 8.9E-01 9.7E-01 9.9E-01 9.9E-01 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 1.0E+00 MASS REMAINING = 1.295E+09, MASS DISPENSED = 6.121E+06, MASS EVAPORATED = 2.650E+06, SUM = 1.304E+09 FRACTION (BASED ON MASS) BEMAINING IN THE SLICK: 9.9E-01, AREA: LIE+05 M##2, THICKNESS: LIBE+00 CM, MOLE WT=294.6 WEICHT FRACTION WATER IN OIL = 3.0E-01, VISCOSITY = 1.2E+03 CENTISTOKES, DISPERSION TERM = 6.3E-03 WEIGHT FRACTION/HR MASS/AREA= 1.2E+04 CHS/N+N, SPCR= 8.9E-01, TOTAL VOLUME= 9.1E+03 BBL, DISPERSION= 7.3E+01 CHS/N+N/HR, EVAP HATE= 2.5E+01 CHS/N+N/HR TIME = 2.0E+00 HOURS, MASS FRACTION OF EACH OUT REMAINING: 3 3.4E-01 7.7E-01 9.3E-01 9.4E-01 9.9E-01 MASS REMAINING = 1.204E+09, MASS DISPERSED = 1.437E+07, MASS EVAPORATED = 5.734E+06, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE BLICK= 9.8E-01, AREA= 1.4E+05 M*+2. THICKNESS= 1.1E+00 CM, MOLE WT=295.8 WEIGHT FRACTION WATER IN OIL = 4.9E-01, VISCOSITY = 3.2E+03 CENTISTORES, DISPERSION TERM = 4.7E-03 WEIGHT FRACTION/HR MASS/AREA= 9.5E+03 CMS/N+N, SPCR= 8.9E-01, TUTAL VOLUME= 9.0E+03 BBL, DISPERSION= 4.4E+01 CMS/N+N/IIR, EVAP RATE= 2.3E+01 CMS/N+N/IR TIME = 3.1E+00 HOURS, MASS FRACTION OF EACH CUT REMAINING: 2.0E-01 6.5E-01 9.0E-01 9.7E-01 9.8E-01 MASS REMAINING = 1.274E+09, MASS DISPERSED = 2.045E+07, MASS EVAPORATED = 9.005E+06, SUM = 1.304E+09 FRACTION (BASED ON MASS) BENAINING IN THE BLICK= 9.8E-01, ANEA= 1.6E+05 M##2, THICKNESS= 9.2E-01 CN, HOLE VT=297.0 WEICHT FRACTION WATER IN OLL = 6.1E-01, VISCOSITY = 0.0E+03 CENTISTOKES, DISPERSION TERM = 3.4E-03 WEICHT FRACTION/HR MASS/AREA= 8.2E+03 CMS/N+M, SPCR= 8.9E-01, TUTAL VOLUME= 9.0E+03 BBL, DISPERSION= 2.0E+01 CMS/N+M/HR, EVAP RATE= 2.1E+01 CMS/N+M/HR TIME = 4.1E+00 HOURS, MASS FRACTION OF EACH CUT REMAINING: -5 9.6E-02 5.4E-01 8.6E-01 9.5E-01 9.8E-01 MASS REMAINING = 1.267E+09, MASS DISPERSED = 2.4UNE+07, MASS EVAPORATED = 1.202E+07, SUN = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE BLICK: 9.7E-01, AREA: 1.7E+05 M**2, THICKNESS: 8.2E-01 CM, MOLE WE:298.2 VEICHT FRACTION WATER IN OIL = 6.7E-01, VISCOSITY = 1.7E+04 CENTISTOKES, DISPERSION TERM = 2.6E-03 WEICHT FRACTION/IR MANS/AREA= 7.3E+03 CMS/M+M, SPCH= 8.9E-01, TOTAL VOLUME= 8.9E+03 BBL, DISPENSION= 1.9E+01 CMS/M+M/HA, EVAP RATE= 1.9E+01 CMS/M+M/HA TIME = 5.1E+00 HOURS, MASS FRACTION OF EACH OUT REMAINING: 4.3E-02 4.3E-01 8.1E-01 9.4E-01 9.7E-01 9.8E-01 9.8E-0 FRACTION (BASED ON MASS) REMAINING IN THE BLICK= 9.7E-01, AREA= 1.9E+05 M##2, THICKNESS= 7.4E-01 CM, MOLE WT=299.5 WEIGHT FRACTION WATER IN 011. = 6.9E-01, VISCOSITY = 2.7E+04 CENTISTOKES, DISPERSION TERM = 2.3E-03 WEIGHT FRACTION/IR MASS/AREA= 6.7E+03 CNS/N+N, SPCR= 8.9E-01, TOTAL VOLUME= 8.9E+03 BBL, DISPENSION= 1.5E+01 CNS/N+N/HA, EVAP RATE= 1.7E+01 CNS/N+N/HA

TINE = 6.1E+00 HOURS, MASS FRACTION OF EACH CUT BENAINING: 1.BE=02 3.5E=01 7.7E=01 9.BE=01 9.7E=01 9.7E=01 9.BE=01 9.BE=01 9.BE=01 9.BE=01 9.BE=01 9.BE=01 9.BE=01 9.BE=01 MASS REMAINING = 1.254E+09, MASS DISPERSED = 3.121E+07, MASS EVAPORATED = 1.876E+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 9.6E=01, AREA= 2.0E+05 N##2, THICKNESS= 6.9E=01 CN, MOLE WT=300.7 WEICHT FRACTION WATCH IN OIL = 7.0E=01, VISCOSITY = 3.5E+04 CENTISTOKES, DISPERSION FERM = 2.2E=03 WEICHT FRACTION/DR MASS/AREA= 6.1E+03 CNS/N#N, SPCR= 8.9E=01, TOTAL VOLUME= 8.8E+03 BBL, DISPERSION= 1.3E+01 CNS/N#M/HR, EVAP HATE= 1.5E+01 CNS/N#M/HR

STEP SIZE OF 2.030E-01 IS BASED ON CUT 2

TIME = 7.3E+00 HOURS, MASS FRACTION OF FACH CUT REMAINING: 6.2E+03 2.6E+01 7.2E+01 9.2E+01 9.6E+01 9.7E+01 9.7E+01 9.7E+01 9.7E+01 9.7E+01 9.7E+01 9.7E+01 9.7E+01 9.7E+01 MASS REMAINING = 1.247E+09, MASS DISPERSED = 3.432E+07, MASS EVAPORATED = 2.214E+07, SUN = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SILCK = 9.6E+01, AREA = 2.2E+05 M##2, TRICKNESS= 6.4E+01 CM, MOLE MT=301.9 WEIGHT FRACTION WATER IN 011. = 7.0E+01, VISCOSITY = 3.9E+04 CENTISTORES, DISPERSION FERM = 2.2E+03 WEIGHT FRACTION/HR MASS/AREA = 5.7E+03 CMS/M+M, SPCR= 8.9E+01, TOTAL VOLUME= 8.0E+03 BBL, DISPERSION= 1.3E+01 CMS/M+M/HR, EVAP RATE= 1.3E+01 CMS/M+M/HR

STEP SIZE OF 1.960E-01 IS BASED ON CUT 2

TIME = 0.4E+00 HOURS, MASS FRACTION OF EACH CUT REMAINING: 1.9E+00 1.9E+01 6.7E 01 9.0E+01 9.6E+01 9.7E 01 9.7E+01 9.7E+01 9.7E+01 9.7E+01 9.7E+01 9.7E+01 9.7E+01 9.7E+01 MASS REMAINING = 1.24TE+09, MASS DISPERSED = 0.76TE+07, MASS EVAPORATED = 2.547E+07, SUM = 1.004E+09 FRACTION (BASED ON MASS) REMAINING IN THE SITCE 9.5E 01, ANEA+ 2.0E+05 M+42, THECKNESS= 5.9E+01 CM, MOLE WT-003.2

WEICHT FRACTION WATER IN OIL = 7.0E-01, VISCOSITY - 4.2E+04 CENTISTOEES, DISPERSION TERM = 2.3E-03 WEICHT FRACTIONZHR MASSZAREA= 5.3E+03 CHSZN*M, SPCR= 9.0E+01, TOTAL VOLUME= 8.7E+03 BBL, DISPERSION= 1.2E+01 CHSZN*MZHB, EVAP RATE= 1.2E+01 CHSZN*MZHR

STEP SIZE OF 1.05HE-01 IS BASED ON CUT 2

TIME = 9.6E+00 HOURS, MASS FRACTION OF EACH CUT REMAINING: 5.00:04 1.4E=01 6.3E=01 8.9E=01 9.5E=01 9.7E=01 9.7E=01 9.7E=01 9.7E=01 9.7E=01 9.7E=01 9.7E=01 9.7E=01 9.7E=01 MASS REMAINING = 1.235E+09, MASS DISPERSED = 4.000E+07, MASS EVAPORATED = 2.843E+07, SUN = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SILCK= 9.5E=01, AREA= 2.5E+05 M**2, THICKNESS= 5.6E=01 CN, MOLE WT=304.3 WEIGHT FRACTION WATER IN OIL = 7.0E=01, VISCOSITY = 4.4E+04 CENTISTORES, DISPERSION TERM = 2.4E=03 WEIGHT FRACTION/HI MASS/AREA= 5.0E+03 CMS/M*M, SPCN= 9.0E=01, TOTAL VOLUME= 0.7E+03 BBL, DISPERSION= 1.2E+01 CMS/M*M/HI, EVAP RATE= 1.1E+01 CMS/M*M/HR

STEP SIZE OF 1.730E-04 IS BASED ON CUT 2

TIME = 1.1E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 1.0E=04 1.0E=01 5.0E=01 8.7E=01 9.5E=01 9.6E=0; 9.7E=01 9.7E=01 9.7E=01 9.7E=01 9.7E=01 9.7E=01 9.7E=01 9.7E=01 MASS REMAINING = 1.229E+09, MASS DISPERSED = 4.3UHE+07, MASS EVAPORATED = 3.10HE+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE BLICK= 9.4E=01, AREA= 2.6E+05 M*+2. THICKNESS= 5.3E=01 CM, MOLE WT=305.3 MELCUT FRACTION WARS) REMAINING IN THE BLICK= 9.4E=01, AREA= 2.6E+05 M*+2. THICKNESS= 5.3E=01 CM, MOLE WT=305.3 MELCUT FRACTION WARS IN THE BLICK= 9.4E=01, VISCOSITY = 4.6E+04 CENTISTORES, DISPERSION TERM = 2.4E=03 WEICHT FRACTION/HR MASS/AREA= 4.8E+03 CMS/M*N, SPCR= 9.0E=01, TOTAL VOLUME= 8.6E+03 BBL, DISPERSION= 1.2E+01 CMS/M*M/HR, EVAP RATE= 9.6E+00 CMS/M*M/HR

STEP SIZE OF 1.647E-01 IS BASED ON CUT 2

TIME = 1.2E+01 HOURS, MASS FRACTION OF EACH CUT HEMAINING: 4.5E=05 7.2E=02 5.4E=01 8.5E=01 9.4E=01 9.6E=01 9.6E=01 9.6E=01 9.6E=01 9.6E=01 9.6E=01 9.6E=01 9.6E=01 9.6E=01 MASS REMAINING = 1.223E+09, MASS DISPERSED = 4.73GE+07, MASS EVAPORATED = 3.3B5E+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SILCK= 9.4E=01, AHEA= 2.7E+05 M##2, THICKNESS= 5.1E=01 CM, MOLE WT=306.4 WEICHT FRACTION WATER IN 01L = 7.0E=01, VISCOSITY = 4.9E+04 CENTISTOFES, DISPERSION TEAM = 2.5E=03 WEICHT FRACTION/HR MASS/AREA= 4.5E+03 CMS/N+N, SPCR= 9.0E=04, TOTAL VOLUME= 8.6E+03 BBL, DISPERSION= 1.1E+01 CMS/N+M/HR, EVAP RATE= 8.7E+00 CMS/N+M/HR

STEP SIZE OF 1.566E-01 IS DASED ON CUT 2

TIME = 1.3E+01 HOURS, MASS FRACTION OF EACH CUT HEMAINING: 1.1E-03 5.1E-02 4.9E-01 8.4E-01 9.4E-01 9.6E-01 9.6E-01 9.6E-01 9.6E-01 9.6E-01 9.6E-01 9.6E-01 9.6E-01 9.6E-01 MASS REMAINING = 1.217E+09, MASS DISPERSED = 3.074E+07, MASS EVAPORATED = 3.636E+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SILCE 9.3E-01, AREA = 2.8E+05 M**2. THICKNESS= 4.8E-01 CM, MOLE WT=307.3 WEICHT FRACTION WATER IN 011. = 7.0E-01, VISCOSITY = 5.2E+04 CENTISTORES, DISPERSION TEAM = 2.6E-03 WEICHT FRACTION/HR MASS/AREA = 4.3E+03 CMS/M*M, SPCR = 9.0E-01, TOTAL VOLUME= 8.5E+03 BBL, DISPERSION= 1.1E+01 CMS/M*M/HR, EVAP RATE = 7.9E+00 CMS/M*M/HR

STEP SIZE OF 1.490E-01 IS BASED ON CUT 2

TIME = 1.4E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 2.9E=06 3.5E=02 4.6E=01 8.2E=01 9.3E=01 9.5E=01 9.6E=01 9.6E=01 9.6E=01 9.6E=01 9.6E=01 9.6E=01 9.6E=01 9.6E=01 MASS REMAINING = 1.211E+09, MASS DISPERSED = 3.402E+07, NASS EVAPORATED = 3.864E+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SILCK= 9.3E=01, AREA= 2.9E+03 N#+2, THICKNESS= 4.6E=01 CM, MOLE WT=3008.2 WEIGHT FRACTION WATER IN 011, = 7.0E=01, VISCOSITY = 5.4E+04 CENTISTOPERS, DISPERSION TERM = 2.0E=03 WEIGHT FRACTION/HR MASS/AREA= 4.2E+03 CMS/M+M, SPCR= 9.0E=01, TOTAL VOLUME= 8.5E+03 BBL, DISPERSION= 1.1E+01 CMS/M+M/HR, EVAP RATE= 7.3E+00 CMS/M+M/HR

STEP SIZE OF 1.441E-01 IS BASED ON CUT 2

TIME - 1.5E+01 HOURS, MASS FRACTION OF FACH CUT REMAINING: 7.5E 07 2.5E+01 4.2E 01 8.TE 01 9.GE+01 9.5E+01 9.5E+01 9.6E+01 9.6E+01 9.6E+01 9.6E+01 9.6E+01 9.6E+01 9.6E+04 MASS REMAINING = 1.20E+09, MASS DISPUSED - 5.720E+07, MASS EVAPORATED - 4.074E+07, SUM = 1.304E+09 FRACTION (RASED ON MASS) REMAINING IN THE SITCE 9 2F 01, AREA+3 0E+05 M*+2, THICKNESS 4.5E 01 CH, MOLE WT-309.0

WEIGHT FRACTION WATER IN OIL = 7.0E-01, VISCOSITY = 5.7E+04 CENTISTORES, DISPERSION TERM = 2.6E-03 WEIGHT FRACTION/HR MASS/AREA= 4.0E+03 CMS/N#M, SPCR= 9.0E-01, TOTAL VOLUME= 8.5E+03 BBL, DISPERSION= 1.1E+01 CMS/N#M/HR, EVAP RATE= 6.8E+00 CMS/N#M/HR

STEP SIZE OF 1.390E-01 IS BASED ON CUT 2

TIME = 1.6E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 1.6E+07 1.6E+02 3.6E+01 7.9E+01 9.2E+01 9.5E+01 9.

STEP SIZE OF 1.340E-01 IS BASED ON CUT 2

TIME = 1.7E+01 HOURS, MASS FRACTION OF EACH CUT HEMAINING: 3.3E=08 1.1E=02 3.5E=01 7.7E=01 9.1E=01 9.4E=01 9.5E=01 9.5E=01 9.5E=01 9.5E=01 9.5E=01 9.5E=01 9.5E=01 9.5E=01 MASS REMAINING = 1.195E+09, MASS DISPERSED = 6.416E+07, MASS EVAPORATED = 4.500E+07, SUN = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICK = 9.2E=01, ARFA= 3.2E+05 N##2, THICKNESS= 4.2E=01 CM, MOLE VT=310.6 VEICHT FRACTION WATER IN OIL = 7.0E=01, VISCOSITY = 6.3E+04 CENTISTORES, DISPERSION FEM = 2.7E=03 WEICHT FRACTION/HR MASS/AREA= 3.8E+03 CMS/N#M, SPCN= 9.0E=01, TUTAL VOLUME= 0.4E+03 BDL, DISPERSION = 1.0E+01 CMS/N#M/HR, EVAP RATE= 5.9E+00 CMS/N#N/HR

STEP SIZE OF 1.295E-01 IS BASED ON CUT 2

TINE = 1.8E+01 BOURS, MASS FRACTION OF EACH CUT REMAINING: 6.9E-09 7.3E-03 3.2E-01 7.5E-01 9.1E-01 9.4E-01 9.5E-01 MASS REMAINING = 1.190E+09, MASS DISPERSED = 6.74HE+07, MASS EVAPORATED = 4.690E+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 9.1E-01, AREA= 3.3E+05 M##2, THICKNESS= 4.1E-01 CM, MOLE MT=311.3 WEIGHT FRACTION WATER IN 01L = 7.0E-01, VISCOSITY = 6.6E+04 CENTISTOKES, DISPERSION TERM = 2.7E-03 WEICHT FRACTION/HR MASS/AREA= 3.6E+03 (CMS/M#N, SPCH= 9.6E-01, TUTAL VOLUME= 8.3E+04 BEL, DISPERSION TERM = 2.7E-03 WEICHT RACTION/HR MASS/AREA= 3.6E+03 (CMS/M#N, SPCH= 9.6E-01, TUTAL VOLUME= 8.3E+04 DISPERSION TERM = 2.7E-03 WEICHT RACTION/HR

TIME = 1.9E+01 HOURS, MASS FRACTION OF EACH CUT BEMAINING: 0.0E+00 4.BE=03 2.9E=01 7.4E=01 9.0E=01 9.4E=01 9.4E=01 9.4E=01 9.4E=01 9.4E=01 9.4E=01 9.4E=01 9.4E=01 9.4E=01 MASS REMAINING = 1.1B4E+09, MASS DISPERSED = 7.0B1E+07, MASS EVAPORATED = 4.872E+07, SUN = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SELCK= 9.1E=01, AREA= 3.4E+05 M**2, THICKNESS= 3.9E=01 CN. MOLE VT=312.0 MEICHT FRACTION WATER IN OIL = 7.0E=01, VISCOSITY = 0.9F+04 CENTISTORES, DISPERSION TERM = 2.7E=03 WEICHT FRACTION/IR MASS/AREA= 3.5E+03 CMS/N*M, SPCR= 9.0E=01, TUTAL VOLUME= 8.3E+03 BBL, DISPERSION= 9.6E+00 CMS/N*M/MR, EVAP RATE= 5.2E+00 CMS/N*M/HR

TIME = 2.0E+01 HOURS, MASS FRACTION OF EACH CUT HEMAINING: 0.0E+00 3.1E+03 2.6E+01 7.2E+01 9.0E+01 9.3E+01 9.4E+01 9.4E+01 9.4E+01 9.4E+01 9.4E+01 9.4E+01 9.4E+01 9.4E+01 MASS REMAINING = 1.179E+09, MASS DISPERSED = 7.414E+07, MASS EVAPORATED = 5.040E+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICKE 9.0E+01, AREA= 3.4E+05 M##2, THICKNESS= 3.8E+01 CM, MOLE WT=312.7 WEIGHT FRACTION WATER IN 011. = 7.0E+01, VISCOSITY = 7.2E+04 CENTISTOKES, DISPERSION TERM = 2.7E+03 WEIGHT FRACTION/HR MASS/AREA= 3.4E+03 CMS/M#M, SPCH= 9.0E+01, TOTAL VOLUME= 8.3E+03 BBL, DISPERSION= 9.4E+00 CMS/M#M/HR, EVAP RATE= 4.9E+00 CMS/M#M/HR

TIME = 2.1E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 6.0E+00 2.0E+03 2.3E+01 7.0E+01 8.9E+01 9.3E 01 9.4E+01 9.4E+01 9.4E+01 9.4E+01 9.4E+01 9.4E+01 9.4E+01 9.4E+04 MASS REMAINING = 1.174E+09, MASS DISPERSED = 7.747E+07, MASS EVAPORATED = 5.217E+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SIJCK= 9 0E+01, AREA= 3.5E+05 M##2, TRICKNESS= 3.7E+01 CM, MOLE WT-313.4 WEIGHT FRACTION WATER IN 011 = 7.0E+01, VISCOSITY = 7.0E+04 CENTISTOFES, DISPERSION TERM = 2.7E+03 WEIGHT FRACTION/IR MASS/AREA= 3.3E+03 CMS/M#M, SPCR= 9.0E+01, TOTAL VOLUME= 8.2E+03 BBL, DISPERSION= 9.2E+00 CMS/M#M/HR, EVAP RATE= 4.6E+00 CMS/M#M/HR

TIME = 2.2E(0) HOURS, MASS FRACTION OF EACH CUT REMAINING: 22 0.0E(00) 1.3E(03) 2.1E 01 6.9E(01) B.9E(01) 9.3E(01) 9.4E(01) 9.4E(

MASS/AREA= 3.3E+03 CMS/N*N, SPCR= 9.0E-01, TOTAL VOLUME= 8.2E+03 BBL, DISPERSION= 9.0E+00 CMS/N*N/HR, EVAP RATE= 4.3E+00 CMS/N*N/HR

TIME = 2.3E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 23 0.0E+00 8.0E+04 1.9E+01 6.7E+01 8.8E+01 9.2E+01 9.3E+01 9.3E+01 9.3E+01 9.3E+01 9.3E+01 9.3E+01 9.3E+01 9.3E+01 MASS REMAINING = 1.164E+09, MASS DISPERSED = 8.412E+07, MASS EVAPORATED = 5.537E+07, SUN = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SILFF # 8.9E+01, AREA= 3.7E+05 M**2, THICKNESS= 3.5E+01 CM, MOLE # T=314.6 MEICHT FRACTION WATER IN OIL = 7.0E+01, VISCOSITY = 8.3E+04 CENTISTOFES, DISPERSION TERM = 2.8E+03 WEICHT FRACTION/IR MASS/AREA= 3.2E+03 CMS/M*M, SPCR= 9.0E+01, TOTAL VOLUME= 8.1E+03 BBL, DISPERSION= 8.8E+00 CMS/M*M/IB, EVAP RATE= 4.1E+00 CMS/M*M/HB

TIME = 2.4E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 0.0E+00 5.0E+04 1.7E+01 6.6E+01 0.7E+01 9.2E+01 9.3E+01 9.3

TIME = 2.5E+01 HOURS, MASS FRACTION OF EACH CUT HEMAINING: 0.0E+00 3.1E+04 1.5E+01 6.4E+01 8.7E+01 9.2E+01 9.3E+01 9.3E+01 9.3E+01 9.3E+01 9.3E+01 9.3E+01 9.3E+01 9.3E+01 MASS REMAINING = 1.155E+09, MASS DISPERSED = 9.074E+07, MASS EVAPORATED = 5.834E+07, SUN = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE BLICK= 8.9E+01, AREA= 3.6E+05 N**2. THICKNESS= 3.4E+01 CM, MOLE WF=315.8 METCHT FRACTION MATER IN OIL = 7.0E+01, VISCUSITY = 9.1E+04 CENTISTORES, DISPERSION TERM = 2.8E+03 WEICHT FRACTION/HR MASS/AREA= 3.0E+03 CMS/N*M, SPCR= 9.0E+01, TOTAL VOLUME= 8.1E+03 BBL, DISPERSION= 8.4E+09 CMS/N*M/HH, EVAP RATE= 3.7E+00 CMS/N*N/HR

TIME = 2.6E+01 HOURS, MASS FRACTION OF EACH CUT HEMAINING: 0.0E+00 1.9E=04 1.4E=01 6.2E=01 8.6E=01 9.1E=01 9.2E=01 9.3E=01 9.3E=01 9.3E=01 9.3E=01 9.3E=01 9.3E=01 9.3E=01 MASS HEMAINING = 1.150E+09, MASS DISPERSED = 9.403E+07, MASS EVAPORATED = 5.974E+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) HEMAINING IN THE BLICK= 0.8E=01, AHEA= 3.9E+05 M**2. THICKNESS= 3.3E=01 CM, MOLE MT=316.3 WEIGHT FRACTION WATER IN OIL = 7.0E=01, VISCOSITY = 9.5E+04 CENTESTOKES, DISPERSION TERM = 2.8E=03 WEIGHT FRACTION/IR MASS/AREA= 3.0E+03 CMS/M*M, SPCR= 9.0E=01, TOTAL VOLUME= 8.0E+03 BDL, DISPERSION= 8.2E+00 CMS/M*M/HR, EVAP RATE= 3.5E+00 CMS/M*M/HR

TIME = 2.7E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 0.0E+00 1.1E=04 1.2E=01 6.1E=04 8.5E=01 9.1E=01 9.2E=01 9.2E=01 9.2E=01 9.2E=01 9.2E=01 9.2E=01 9.2E=01 9.2E=01 MASS REMAINING = 1.145E+09, MASS DISPERSED = 9.731E+07, MASS EVAPORATED = 6.110E+07, SUN = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 8.8E=01, AREA= 3.9E+05 M**2, TRICKNESS= 3.2E=01 CN, MOLE WT=316.9 WEICHT FRACTION WATER IN 011 = 7.0E=01, VISCOSITY = 9.9E+04 CENTISTOKES, DISPERSION TERM = 2.4E=03 WEICHT FRACTION/IR MASS/AREA= 2.9E+03 CMS/M*M, SPCR= 9.0E=01, TOTAL VOLUME= 8.0E+03 BBL, DISPERSION= 8.0E+09 CMS/M*M/HR, EVAP RATE= 3.3E+00 CMS/M*M/HR

STEP SIZE OF 4.346E-01 IS BASED ON CUT 3

TIME = 2.9E+01 HOURS, MASS FRACTION OF EACH CUT HEMAINING; 0.0E+00 6.3E=05 1.1E=01 5.9E=01 0.5E=01 9.1E=01 9.2E=01 9.2E=01 9.2E=01 9.2E=01 9.2E=01 9.2E=01 9.2E=01 9.2E=01 MASS REMAINING = 1.141E+09, MASS DISPERSED = 1.009E+00, MASS EVAPORATED = 6.252E+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 0.7E=01, AREA= 4.0E+05 M**2, THICKNESS= 3.2E=01 CM, MOLE VT=317.4 WEICHT FRACTION WATER IN 01L = 7.0E=01, VISCOSITY = 1.0E+05 CENTISTOKES, DISPERSION TERM = 2.7E=03 WEICHT FRACTION/HR MASS/AREA= 2.9E+03 CMS/M*M, SPCR= 9.0E=01, TOTAL VOLUME= 8.0E+03 BBL, DISPERSION= 7.8E+09 CMS/M*M/HR, EVAP RATE= 3.1E+00 CMS/M*M/HR

STEP SIZE OF 4.237E-01 IS BASED ON CUT 3

TIME = 3.0E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 0.0E+00 3.3E=05 9.1E=02 5.7E=01 8.4E=01 9.0E=01 9.2E=01 9.2E=01 9.2E=01 9.2E=01 9.2E=01 9.2E=01 9.2E=01 9.2E=01 MASS REMAINING = 1.135E+09, MASS DISPERSED = 1.049E+08, MASS EVAPORATED = 6.407E+07, SUM = 1.304E+09 FRACEION (BASED ON MASS) REMAINING IN THE SLICK= 8.7E 01, AREA= 4.1E+05 M##2, THICKNESS= 3.1E=01 CN, MOLE VT-318.0 WEICHT FRACTION WATER IN OIL = 7.0E=01, VISCOSITY = 1.1E+05 CENTISTOKES, DISPERSION TERM = 2.7E=03 WEICHT FRACTION/HR MASS / AREA= 2.8E+03 CNS=M+M, SPGR= 9.0E=01, TOTAL VOLUME= 7.9E+03 BBL, DISPERSION= 7.6E+00 CMS=M+M/HR, EVAP BATE= 2.9E+00 CMS=M+M/HR

STEP SIZE OF 4.137E-01 IS BASED ON CUT - 3

TIME = 3.1E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 0.0E+00 1.7E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 0.0E+00 1.7E+01 7.8E+02 5.5E+01 B.3E+01 9.0E+01 9.1E+01 9.1E+01 9.1E+01 9.1E+01 9.1E+01 9.1E+01 9.1E+01 9.1E+01 MASS REMAINING = 1.130E+09, MASS DISPERSED = 1.00HE+08, MASS EVAPORATED = 6.553E+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE BITCK = 8.7E+01, AREA = 4.1E+05 M##2, THICKNESS= 3.0E+01 CM, MOLE WT=318.6 METCHT FRACTION WATER IN 01L = 7.0E+01, VISCOSITY = 1.2E+05 CENTISTORES, DISPERSION TERM = 2.7E+03 WEICHT FRACTION/HR MASS/AREA = 2.7E+03 CMS/M#M, SPCR = 9.0E+01, TUTAL VOLUME = 7.9E+03 BBL, DISPERSION = 7.4E+00 CMS/M#M/HR, EVAP RATE = 2.8E+00 CMS/M#M/HR

STEP SIZE OF 4.043E-01 IS BASED ON CUT 3

TIME = 3.2E+01 HOURS, MASS FRACTION OF EACH CUT HEMAINING: 0.0E+00 8.7E=06 6.7E=02 5.3E=01 8.3E=01 9.0E=01 9.1E=01 9.1E=01 9.1E=01 9.1E=01 9.1E=01 9.1E=01 9.1E=01 9.1E=01 MASS REMAINING = 1.124E+09, MASS DISPERSED = 1.125E+08, MASS EVAPORATED = 0.6H9E+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE BLICK= 8.6E=01, AREA= 4.2E+05 M##2, THICKNESS= 3.0E=01 CM, MOLE WT=319.1 WEIGHT FRACTION WATER IN OIL = 7.0E=01, VISCOSITY = 1.2E+05 CENTISTOFES, DISPERSION TERM = 2.7E=03 WEIGHT FRACTION/HR MASS/AREA= 2.7E+03 CMS/N#M, SPCR= 9.0E=01, TUTAL VOLUME= 7.9E+03 BBL, DISPERSION= 7.3E+00 CMS/N#M/HR, EVAP RATE= 2.6E+00 CMS/N#M/HR

STEP SIZE OF 3.960E-01 IS BASED ON CUT 3

TIME = 3.4E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 0.0E+00 4.5E+06 5.8E-02 5.1E-01 8.2E+01 8.9E+01 9.1E+01 9.1E+01 9.1E+01 9.1E+01 9.1E+01 9.1E+01 9.1E+01 9.1E+01 MASS REMAINING = 1.120E+09, MASS DISPERSED = 1.162E+08, MASS EVAPORATED = 6.817E+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE BLICK= 8.6E+01, AREA= 4.3E+05 N*+2, THICKNESS= 2.9E+01 CM, MOLE WT=319.7 WEICHT FRACTION WATER IN 01L = 7.0E+01, VICOSITY = 1.3E+05 CENTISTORES, DISPERSION TERM = 2.7E+03 WEICHT FRACTION/HR MASS/AREA= 2.6E+03 CMS/N*M, SPCR= 9.0E+01, TOTAL VOLUME: 7.0E+03 BBL, DISPERSION= 7.1E+00 CMS/N*N/HR, EVAP RATE= 2.5E+00 CMS/N*N/HR

STEP SIZE OF 3.88(E-0) IS BASED ON CUT 3

TIME = 3.5E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 33 0.0E+00 2.3E=06 5.0E=02 5.0E=01 8.1E=01 8.9E=01 9.0E=01 9.0E=01 9.1E=01 9.1E=01 9.1E=01 9.1E=01 9.1E=01 9.1E=01 MASS REMAINING = 1.115E+09, MASS DISPERSED = 1.197E+08, MASS EVAPORATED = 6.939E+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SILCK= 8.5E=01, AREA= 4.4E+05 M**2, TRICKNESS= 2.8E=01 CM, MOLE WT=320.1 MELCHT FRACTION WATER IN OIL = 7.0E=01, VISCOSITY = 1.3E+05 CENTISTORES, DISPERSION TERM = 2.7E=03 WEICHT FRACTION/NR MASS/AREA= 2.6E+03 CMS/N*M, SPCR= 9.0E=01, TOTAL VOLUME= 7.8E+03 BBL, DISPERSION= 6.9E+00 CMS/N*N/HR, EVAP RATE= 2.4E+00 CMS/N*N/HR

STEP SIZE OF 3.800E-01 IS BASED ON CUT 3

TIME = 3.6E+01 HOURS, MASS FRACTION OF FACH CUT REMAINING: 0.0E+00 1.2E=06 4.3E=02 4.8E=01 8.0E=01 8.8E=01 9.0E=01 9.0E=01 9.0E=01 9.0E=01 9.0E=01 9.0E=01 9.0E=01 9.0E=01 MASS REMAINING = 1.110E+09, MASS DISPERSED = 1.232E+00, MASS EVAPORATED = 7.054E=07, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SILCK= B.5E=01, AREA= 4.4E+05 M##2, THICKNESS= 2.8E=01 CM, MOLE WT=320.6 WEICHT FRACTION WATER IN 01L = 7.0E=01, VISCOSITY = 1.4E+05 CENTISTORES, DISPERSION TERM = 2.7E=03 WEICHT FRACTION/HR MASS/AREA= 2.5E+03 CMS/N#M, SPCH= 9.0E=01, TUTAL VOLUME= 7.7E+03 BDL, DISPERSION= 6.0E+00 CMS/N#M/HR, EVAP RATE= 2.3E+00 CMS/N#M/HR

STEP SIZE OF 3.739E-01 IS BASED ON CUT 3

TIME = 3.7E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 35 0.0E+00 6.2E=07 3.7E+02 4.6E+01 B.0E+01 B.0E+01 9.0E+01 9.0E+01 9.0E+01 9.0E+01 9.0E+01 9.0E+01 9.0E+01 9.0E+01 MASS REMAINING = 1.100E+09, MASS DISPERSED = 1.265E+00, MASS EVAPORATED = 7.163E+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICK+ B.5E+01, ANFA+ 4.5E+05 N##2, THICKNESS+ 2.7E+01 CM, MOLE WT=321+0 WEIGHT FRACTION WATER IN 011 = 7.0E+01, VISCOSITY = 1.5E+05 CENTISTORES, DISPERSION TEIM = 2.7E+03 WEIGHT FRACTION/HR MASS_ABEA+ 2.5E+01 GRS/M#M, SPGR= 9.0E+01, TOTAL VOLUME+ 7.7E+03 BBL, DISPERSION= 6.6E+00 CMS/M#M/HR, EVAP BATE+ 2.2E+00 CMS/M#M/HR

STEP SIZE OF 3.675E-01 IS BASED ON CUT 3

TIME = 3.0E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 0.0L+00 3.2E+07 3.1E+02 4.5E+01 7.9E+01 0.0E+01 0.9E+01 9.0E+01 9.0E+01 9.0E+01 9.0E+01 9.0E+01 9.0E+01 9.0E+01 9.0E+01 9.0E+01 MASS REMAINING = 1.101E+09, MASS DISPERSED = 1.298E+00, MASS EVAPORATED = 7.267E+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE BLICK= 0.4E+01, AREA= 4.5E+05 0.4*42, THICKNESS= 2.7E+01 CM, MOLE WT=321.4 WEIGHT FRACTION WATER IN 01L = 7.0E+01, VISCOSITY = 1.5E+05 CENTISTOKES, DISPERSION TERM = 2.7E+03 WEIGHT FRACTION/HB MASS/AREA= 2.4E+03 CMS/M*M, SPCR= 9.0E+01, TOTAL VOLUME= 7.7E+03 BBL, DISPERSION= 6.5E+00 CMS/M*M/MB, EVAP RATE= 2.1E+00 CMS/M*M/HR

STEP SIZE OF 3.614E-01 IS BASED ON CUT 3

TIME = 3.9E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 0.0E+00 1.7E=07 2.7E=02 4.3E=01 7.8E=01 8.7E=01 8.9E=01 8.9E=01 8.9E=01 8.9E=01 8.9E=01 8.9E=01 8.9E=01 8.9E=01 MASS REMAINING = 1.097E+09, MASS DISPERSED = 1.330E+08, MASS EVAPORATED = 7.367E+07, SUN = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SILCK = 0.4E=01, AHEA= 4.6E+05 M**2, THICKNESS= 2.7E=01 CM, MOLE WT=321.8 METCHT FRACTION WATER IN OIL = 7.0E=01, VISCOSITY = 1.6E+05 CENTISTORES, DISPERSION TERM = 2.6E=03 WEICHT FRACTION/HR MASS/AHEA= 2.4E+03 CMS/M*M, SPCR= 9.0E=01, TUTAL VOLUME= 7.7E+03 BBL, DISPERSION= 6.3E+00 CMS/M*M/HR, EVAP RATE= 2.0E+00 CMS/M*M/HR

STEP SIZE OF 3.557E-01 IS BASED ON CUT 3

TIME = 4.0E+01 HOURS, MASS FRACTION OF EACH CUT HEMAINING: 0.0E+00 = 8.5E+08 = 2.3E+02 = 4.2E+01 = 7.4E+01 = 8.7E+01 = 8.9E+01 = 8.9E+01 = 8.9E+01 = 8.9E+01 = 8.9E+01 = 8.9E+01 = 1.304E+09MASS REMAINING = 1.093E+09, MASS DISPERSED = 1.361E+08, MASS EVAPORATED = 7.462E+07, SUM = 1.304E+09FRACTION (BASED ON MASS) REMAINING IN THE SITCK = 8.4E+01, AREA = 4.6E+05 M**2, THICKNESS = 2.6E+01 CM, MOLE WT=322.2 WEICHT FRACTION WATER IN 01L = 7.0E+01, VISCOSITY = 1.7E+05 CENTISTOKES, DISPERSION = 2.6E+03 WEICHT FRACTION/HR MASS/AREA = 2.4E+03 CMS/M*M, SPCR = 9.0E+01, TOTAL VOLUME = 7.6E+03 BBL, DISPERSION = 6.2E+00 CMS/M*M/HR, EVAP HATE = 1.9E+00 CMS/M*M/HR

STEP SIZE OF 3.503E-01 IS BASED ON CUT 3

TIME = 4.1E+01 HOURS, MASS FRACTION OF EACH OUT HEMAINING: 39 0.0E+00 4.4E+00 2.0E+02 4.1E+01 7.7E+01 0.7E+01 0.9E+01 0.9E+01 0.9E+01 0.9E+01 0.9E+01 0.9E+01 0.9E+01 0.9E+01 MASS REMAINING = 1.0H9E+09, MASS DISPERSED = 1.392E+00, MASS EVAPORATED = 7.553E+07, SUN = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SILCK= 0.4E+01, AREA = 4.7E+05 N##2, THICKNESS= 2.6E+01 CM, MOLE VT=322.6 VEICHT FRACTION WATER IN 011. = 7.0E+01, VISCOSITY = 1.7E+05 CENTISTOKES, DISPERSION TERM = 2.6E+03 CMS/N#M/HR, EVAP HATE= 1.4E+00 CMS/N#M/HR

STEP SIZE OF 3.451E-01 IS BASED ON CUT 3

 TIME = -4.22+01 HOURS, MASS FRACTION OF EACH CUT REMAINING:
 40

 0.0E+00
 2.3E+08
 1.7E+02
 3.9E+01
 7.6E+01
 8.4E+01
 8.9E+01
 8.9E+01

STEP SIZE OF 3.402E-01 IS BASED ON CUT 3

TIME - 4.31*01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 41 0.00+00 1.2E-00 1.5E 02 3.0E-01 7.0F 01 0.6E-01 0.0E 01 0.0E-01 0.0E-01 0.0E-01 0.0E-01 0.0E-01 0.0E-01 0.0E-01 MASS REMAINING = 1.002E+09, MASS DISPERSED - 1.450E+00, MASS EVAPORATED = 7.720E+07, SUM = 1.304E+09 FRACTION (BASED ON NASS) REMAINING IN THE SLICK = 0.3E-01, AREA - 4.0E+05 M##2, THICKNESS = 2.5E-01 CM, MOLE WT-323.3 WEICHT FRACTION WATER IN 01E = 7.0E-01, VISCOSITY - 1.9E+05 CENTISTOKES, DISPERSION TERM = 2.26E-03 WEICHT FRACTION/UR MASS:AREA = 2.3E+03 CMS/MEM, STORE 9.0E-01, TOTAL VOLUME - 7.5E+03 UNL, DISPERSION TERM = 2.26E-03 WEICHT FRACTION/UR

STEP SIZE OF 3.356E-01 IS BASED ON CUT 3

TIME = 4.4E+01 HOURS, MASS FRACTION OF EACH CUT HEMAINING: 0.0E+00 = 6.1E+09 = 1.3E+02 = 3.7E+01 = 7.5E+01 = 8.6E+01 = 8.

TIME = 4.5E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 0.0E+00 0.0E+00 1.1E-02 3.5E=01 7.4E=01 8.6E=01 8.8E=01 8.8E=01 8.8E=01 8.8E=01 8.8E=01 8.8E=01 8.8E=01 8.8E=01 MASS REMAINING = 1.074E+09, MASS DISPERSED = 1.506E+00, MASS EVAPORATED = 7.887E+07, SUN = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SILCE = 8.2E=01, ARFA= 4.9E+05 M#+2, THICENESS= 2.4E=01 CM, MOLE WT=323.9 WEIGHT FRACTION WATER IN OIL = 7.0E=01, VISCOSITY = 2.0E+05 CENTISTOFES, DISPERSION TERM = 2.0E=03 WEICHT FRACTION/HR MASS, AREA= 2.2E+03 CMS/N+M, SPCH= 9.0E=01, TUTAL VOLUME= 7.5E+03 BBL, DISPERSION= 5.0E+00 CMS/N+M/HR, EVAP RATE= 1.6E+00 CMS/N+M/HR

TIME = 4.6E+01 HOURS, MASS FRACTION OF EACH CUT REPAINING: 0.0E+00 9.4E+03 3.4E+01 7.4E+01 8.5E+01 8.7E+01 8.8E+01 8.8E+01 8.8E+01 8.8E+01 8.8E+01 8.8E+01 8.8E+01 8.8E+01 MASS REMAINING = 1.07TE+09, MASS DISPERSED = 1.534E+08, MASS EVAPORATED = 7.964E+07, SUM = 1.004E+09 FRACTION (BASED ON MASS) REMAINING IN THE SILCK= 8.2E+01, AREA= 4.9E+05 M**2, TRICKNESS= 2.4E+01 CM, MOLE WT=324.2 WEIGHT FRACTION WATER IN OIL = 7.0E+01, VISCOSITY = 2.1E+05 CENTISTOFES, DISPERSION FERM = 2.5E+03 WEIGHT FRACTION/IR MASS/AREA= 2.2E+03 CMS/M*M, SPCN= 9.0E+01, TUTAL VOLUME= 7.5E+03 BBL, DISPERSION= 5.5E+00 CMS/M*M/IR, EVAP RATE= 1.6E+09 CMS/M*M/IR

TIME = 4.7E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING; 0.0E+00 0.0E+00 8.0E-03 3.3E-01 7.3E-01 8.3E-01 8.7E-01 8.7E-01 8.8E-01 8.8E-01 8.8E-01 8.8E-01 8.8E-01 8.8E-01 MASS HEMAINING = 1.067E+09, MASS DISPERSED = 1.561E+08, MASS EVAPORATED = 8.041E+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) HEMAINING IN THE SICK = 8.2E-01, ARFA = 5.0E+05 M **2, THICKNESS = 2.4E-01 CH, MOLE WT=324.6 WEIGHT FRACTION WATER IN 01L = 7.0E-01, VISCOSITY = 2.2E+05 CENTISTOPES, DISPERSION TERM = 2.5E-03 WEIGHT FRACTION/HR MASS/AREA = 2.1E+03 CHS/M*M, SPCR = 9.0E-01, TUTAL VOLUME = 7.4E+03 8BL, DISPERSION = 5.4E+00 CHS/M*M/HR, EVAP RATE = 1.5E+00 CHS/M*M/HR

TIME = 4.8E+01 HOURS, MASS FRACTION OF EACH OUT REMAINING: 0.0E+00 0.0E+00 6.8E-03 3.2E-01 7.3E-01 8.3E-01 8.7E-01 8.7E-01 8.7E-01 8.7E-01 8.7E-01 8.7E-01 8.7E-01 8.7E-01 MASS REMAINING = 1.064E+09, MASS DISPERSED = 1.50HE+08, MASS EVAPORATED = 0.115E+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 8.2E-01, AREA= 5.0E+05 N##2, THICKNESS= 2.3E-01 CM, MOLE WT=324.9 WEICHT FRACTION WATER IN OIL = 7.0E-01, VISCOSITY = 2.3E+05 CENTISTOKES, DISPERSION TERM = 2.5E+03 WEICHT FRACTION/BR MASS/AREA= 2.1E+03 CMS/M#M, SPCR= 9.0E-01, TOTAL VOLUME= 7.4E+03 BBL, DISPERSION= 5.3E+00 CMS/M#M/BR, EVAP RATE= 1.5E+00 CMS/M#M/BR

TIME = 4.9E+01 HOURS, MASS FRACTION OF FACE CUT BEMAINING: 0.0E+00 0.0E+00 5.8E-03 3.1E-01 7.2E-01 8.4E-01 8.7E-01 8.7E-01 8.7E-01 8.7E-01 8.7E-01 8.7E-01 8.7E-01 8.7E-01 MASS BEMAINING = 1.060E+09, MASS DISPERSED = 1.615E+001, MASS EVAPORATED = 8.189E+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) BEMAINING IN THE SICK+ 8.1E-01, AREA= 5.1E+05 M**2, THICKNESS= 2.3E-01 CM, HOLE WT=325.2 WEIGHT FRACTION WATER IN 01L = 7.0E-01, VISCOSITY = 2.4E+05 CENTISTOKES, DISPERSION FERM = 2.5E-03 WEIGHT FRACTION/HR MASS/AREA= 2.1E+03 CMS/M*M, SPCR= 9.0E-01, TOTAL VOLUME= 7.4E+03 88L, DISPERSION= 5.2E+00 CMS/M#M/HR, EVAP RATE= 1.4E+00 CMS/M*M/HR

TIME = 5.002+00 HOURS, MASS FRACTION OF EACH CUT REMAINING: 0.002+00 0.002+00 4.92-03 3.02-01 7.12-01 0.42-01 0.02-01 0.72-01 0.72-01 0.72-01 0.72-01 0.72-01 0.72-01 0.72-01 MASS REMAINING = 1.0572+09, MASS DISPERSED = 1.6422+00, MASS EVAPORATED = 0.2612+07, SUN = 1.3042+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 0.12+01, ANEA: 5.12+05 M**2, THICKNESS: 2.32-01 CM, MOLE VT:325.4 WEIGHT FRACTION WATER IN 011. = 7.02-01, VISCOSITY = 2.42+05 CENTISTOKES, DISPERSION FERM = 2.52-03 WEIGHT FRACTION/UR MASS/AREA: 2.12+03 CMS/N+M, SPCR: 9.02-01, TOTAL VOLUME: 7.42+03 BBL, DISPERSION: 5.12+00 CMS/N+M/HR, EVAP RATE: 1.42+00 CMS/N+M/HR

TIME = 5.11*01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 0.0E+00 0.0E+00 4.2E-03 2.9E+01 7.1E=01 8.4E=01 8.6E=01 8.7E=01 8.7E=01 8.7E=01 8.7E=01 8.7E=01 8.7E=01 8.7E=01 MASS REMAINING = 1.054E+09, MASS DISPERSED = 1.66BE+00, MASS EVAPORATED = 8.331E+07, SUN = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SITCH = 8.1E+01, AREA 5.2E+05 N#*2, THICKNESS= 2.3E=01 CN, MOLE NT-325.7 NFICHT FRACTION WATER IN 011. 7.0E 01. VISCOSITY = 2.5E+05 CENTISTOKES, DISPERSION TERM = 2.5E=03 NEICHI TRACTION/HR MASS AREA 2.0E+03 CMS/M/M, SPCR = 9.0E=01, TOTAL VOLUME= 7.3E+03 BBL, DISPERSION 5.0E+00 CBS/M/M/HR, EVAP RATE 1.4E+00 GMS/M*M/HR

TIME = 6.2E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 0.0E+00 0.0E+00 7.3E-04 2.0E-01 6.5E-01 8.1E-01 8.4E-01 8.4E-01 8.5E-01 8.5E-01 8.5E-01 8.5E-01 8.5E-01 8.5E-01 MASS REMAINING = 1.022E+09, MASS DISPERSED = 1.925E+08, MASS EVAPORATED = 8.972E+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 7.0E-01, AREA= 5.6E+05 M**2, THICKNESS= 2.0E-01 CM, MOLE WT=320.4 WEICHT FRACTION WATER IN 01L = 7.0E-01, VISCOSITY = 3.7E+05 CENTISTORES, DISPERSION TERM = 2.3E-03 WEICHT FRACTION/HR MASS/AREA= 1.8E+03 CMS/N*M, SPCR= 9.0E-01, TUTAL VOLUME= 7.1E+03 BBL, DISPERSION= 4.2E+00 CMS/N*M/HR, EVAP RATE= 1.1E+00 CMS/N*M/HR

STEP SIZE OF 5.000E-01 IS BASED ON CUT 4

TIME = 7.2E+01 HOURS, MASS FRACTION OF FACH CUT REMAINING: 0.0E+00 0.0E+00 1.0E-04 1.3E-01 5.9E-01 7.8E-01 8.2E-01 8.2E-01 8.3E-01 8.3E-01 8.3E-01 8.3E-01 8.3E-01 8.3E-01 MASS REMAINING = 9.926E+08, MASS DISPERSED = 2.161E+08, MASS EVAPORATED = 9.522E+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SILCK = 7.6E-01, AREA = 5.9E+05 M##2, THICKNESS= 1.8E-01 CM, MOLE WT=330.7 WEIGHT FRACTION WATER IN OIL = 7.0E-01, VISCOSITY = 5.2E+05 CENTISTORES, DISPERSION TERM = 2.1E-03 WEIGHT FRACTION/HR MASS/AREA = 1.7E+03 CMS/M#M, SPCR = 9.0E-01, TOTAL VOLUME = 6.9E+03 BBL, DISPERSION = 3.5E+00 CMS/M#M/HR, EVAP RATE = 8.4E-01 CMS/M#M/HR

STEP SIZE OF 5.000E-01 IS BASED ON CUT 4

TIME = 8.2E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 0.0E+00 0.0E+00 1.3E=05 8.2E=02 5.3E=01 7.3E=01 8.0E=01 8.1E=01 8.1E=01 8.1E=01 8.1E=01 8.1E=01 8.1E=01 8.1E=01 MASS REMAINING = 9.674E+00, MASS DISPERSED = 2.367E+08, MASS EVAPORATED = 9.979E+07, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 7.4E=01, AREA= 6.3E+05 M##2, TRICKNESS= 1.7E=01 CM, MOLE WT=332.7 WEIGHT FRACTION WATER IN 01L = 7.0E=01, VISCOSTY = 7.1E+05 CENTISTORES, DISPERSION TERM = 2.0E=03 WEIGHT FRACTION/HR MASS/AREA= 1.3E+08 CMS/M#N, SPCR= 9.1E=01, TOTAL VOLUME= 6.7E+03 BBL, DISPERSION= 3.0E+00 CMS/M#M/HR, EVAP RATE= 6.8E=01 CMS/M#M/HR

STEP SIZE OF 5.000E-01 IS BASED ON CUT 4

TIME = 9.2E+01 HOURS, MASS FRACTION OF EACH CUT HEMAINING: 53 0.0E+00 0.0E+00 1.3E=06 5.0E-02 4.BE=01 7.3E=01 7.BE=01 7.9E=01 7.9E=01 7.9E=01 7.9E=01 7.9E=01 7.9E=01 7.9E=01 MASS REMAINING = 9.44BE+0B, MASS DISPERSED = 2.554E+0B, MASS EVAPORATED = 1.037E+0B, SUM = 1.304E+09 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 7.2E=01, AHEA= 6.6E+05 M##2. THICKNESS= 1.6E=01 CM, MOLE VF=334.4 WEICHT FRACTION WATER IN 01L = 7.0E=01, VISCOSITY = 9.5E+05 CENTISTOKES, DISPERSION TERM = 1.8E=03 WEICHT FRACTION/HR MASS/AREA= 1.4E+03 CMS/N#M, SPCR= 9.1E=01, TOTAL VOLUME= 0.6E+03 BBL, DISPERSION= 2.6E+00 CMS/M#M/HR, EVAP RATE= 5.6E=01 CMS/M#M/HR

STEP SIZE OF 5.000E-01 IS BASED ON CUT 4

THE CUT NUMBERING BEGINS WITH 2 BASED ON THE ORIGINAL CUT NUMBERS

THE FINAL MASS FUACTIONS FOR THE STICK AT 1.0F+02 HOURS ARE: 9.000E+00 0.000E+00 1.517E+07 3.181E+02 4.338E=01 7.054E+01 7.682E=01 7.785E=01 7.802E+01 7.803E=01 7.803E=01 7.803E=01 7.803E=01 7.403E+01 7.803E=01 7.803E=01 7.403E+01 FUACTION (BASED ON MASS) REMAINING IN THE SUICK 7.1E 01, AREA: 6.0E+05 N**2, THICENESS=1.5E=01 CM, MOLE NT=334.4 MASS REMAINING = 9.264E+01, MASS DISTERSED = 2.706E+08, MASS FVAPORATED = 1.060E+08, SUM = 1.304E+09

Table 16.--Output from Oil-Weathering Calculations (Continued): Characterization of Prudhoe Bay Crude Oil After Weathering in Pools on Top of Ice and Weathering in a Broken Ice Field.

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SUMMARY OF THE CUTS CHARACTERIZATION FOR: PRUDHOE BAY, ALASKA
AFTER:
ICE POOL WEATHERING FOR 2.400E+01 HOURS
BROKEN ICE FIELD WEATHERING FOR 1.000E+02 HOURS
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CODE VERSION IS CUTICA OF MAY 84 ITEN 9, SAMPLE 71011

	TB	API	SPCR	VOI.	MW	TC	PC	VC	۸	8	T10	VIS	NC	NS
1	2.80E+02	3.16E+01	7.69E-01	6.79E~07	1.19E+02	1.07E+03	3.400+01	5.078+02	3.41E+00	2.27E-01	5.49E+02	6.73E-01	3	1
2	a.25E+02	4.76E+01	7.77E-01	1.778-01	1.346+02	1.12E+03	3.326+01	5.65E+02	3.52E+00	2.398-01	5.86E+02	8.46E-01	3	i
3	3.70E+02	4.52E+01	7.87E-01	2.37E+00	1.516+02	1.168+03	3.168:+01	6.32E+02	3.67E+00	2.501-01	6.23£+62	1.07E+00	3	ī
4	4.15E+02	4.15E+01	8.04E-01	4.77E+00	1.67E+02	1.21E+03	3.03E+01	6.986+02	3.00E+00	2.59E-01	6.601:+02	1.38E+00	- 3	i
5	4.60E+02	3.78E+01	8.228-01	5.80E+00	1.85E+02	1.26E+03	2.918+01	7.071+02	3.94E+00	2.67E-01	6.98E+02	1.81E+00	- 3	- i
6	5.05E+ 0 2	3.48E+01	8.36E-01	6.12E+00	2.00E+02	1.31E+03	2.84E+01	8.28E+02	4.068.+00	2.74E-01	7.36E+02	1.75E+00	3	- i
7	5.54E+02	3.06E+01	8.58E-01	3.44E+00	2.21E+02	1.35E+03	2.74E+01	9.098+02	4.22E+00	2.82E-01	7.77E+02	2.48E+00	3	i
8	6.09E+02	2.91E+01	H. 66E-01	7.98E+00	2.52E+02	1.40E+03	2.58E+01	1.03E+03	4.49E+00	2.92E-01	4.268+02	4.001.+00	3	i
9	6.628+02	2.621:+01	8.82E-01	8.35E+00	2.812+02	1.45£+03	2.471:+01	1.15E+03	4.73E+00	2.998-01	#.73E+02	7.188+00	3	i
10	7.32E+02	2.401+01	8.94E-01	7.36E+00	3.43E+02	1.498+03	2.36E+01	1.271.+03	5.00E+00	3.06E-01	9.198+02	1.368+01	3	ī
	7.64E+02	2.258+01	9.03E-01	9.88E+00	3.51E+02	1.53E+03	2.25E+01	1.43E+03	5.35E+00	3.13E-01	9.68E+ 6 2	2.818+01	3	1
12	4.50E+02	1.146+01	9.73E-01	4.46E+01	6.00E+02	1.45E+03	2.476+01	1.15E+03	4.7:11:+00	2.998-01	8.27E-01	1.81E+02	3	i

	UOP K	CORRELATION INDEX
1	1.196+01	2.326+01
2	1.198+01	2.43栏+单1
3	1.198+01	2.326+01
4	1.198+01	2.36E+01
5	1.18E+01	2.90亿+01
6	1.18E+01	3.15E+#1
7	1.176+01	3.73E+01
8	1.18E+01	3.66E+01
9	1.1882+01	4.428+01
10	1.18E+01	4.27E+#1
11	1.18E+01	4.36E+#1
12	1.126+01	7.218+01

BULK API CRAVITY = 23.8

TB = NORMAL BOILING TEMPERATURE, DEC F API = API CRAVITY VOL = VOLUME PER CERT OF TOTAL CRUDE MW = MOLECULAR MELICIT TC = CRITICAL TEMPERATURE, DEC BANKINE PC = CRITICAL TEMPERATURE, DEC BANKINE PC = CRITICAL TEMPERATURE, DEC BANKINE VC = CRITICAL VOLUME, CC/MOLE A AND B ARE PARAMETERS IN THE VAFOR PRESSURE EQUATION TIO IS THE TEMPERATURE IN DEC R MIERE THE VAPOR PRESSURE IS 10 MM HC VIS IS THE KINEMATIC VISCOSTEY IN CERTISTOKES AT 122 DEC F UOP K IS THE U.O.P. K CHARACTERIZATION FACTOR COMMELATION INDEX IS DEFINED IN (COLEMAN, 1978) NC = ERROR CODE, SHOULD HE EAVAL TO A NS = ERROR CODE, SHOULD HE EAVAL TO A

MEAN MOLECULAR WEIGHT OF THE CRUDE - 0.358E+02

Table 16.--Output from Oil-Weathering Calculations (Continued): Beginning of Calculated Results for Open-Ocean Weathering at 40°F.

WEATHERING DATA FOR OLL ON THE OPEN OCEAN APTER:

TEE FOOL WEATHERING FOR 2.400E+01 HOURS BROKEN ICE FIELD WEATHERING FOR 1.000E+02 HOURS

OVER-ALL MASS-TRANSFER COEFFICIENTS BY INPUT CODE 2

OVER-ALL MASS-TRANSFER COEFFICIENT FOR COMENE = 2.590E+01 N/IR

CUT	MZILK	CH-HOLES/(III()(ATH)(N**2)
1	2.6858+01	1 . 1 BOE+03
2	2.6568+01	1.168E+03
3	2.6:101:+01	1.1568+03
4	2.6091:+01	1.1478+03
5	2.590E+01	1.1398+03
t	2.577E+01	1.133E+03
7	2.5628+01	1.126E+03
4	2.5438:+01	1.1186+03
9	2.5298+01	1.1126+03
10	2.517E+01	1.1072+03
11	2.506E+01	1.1012+03

FOR THIS SPILL OF 6.420E+03 BARRELS, THE MASS IS 9.264E+02 METRIC TONNES VOLUME FROM SUMMING THE CUTS = 1.0E+03 M**3, OR 6.428E+03 BARRELS WIND SPEED = 2.000E+01 KNOTS, OR 3.706E+04 M/HR INITIAL SLICK DIANETER = 9.315E+02 N, OR AREA = 6.811E+05 M**2 KINEMATIC VISCOSITY OF THE BULK CRUDE FROM THE CUTS = 1.1E+01 CENTISTOKES AT 122 DEC F KINENATIC VISCOSITY OF THE BULK CRUDE FROM THE CUTS = 1.9E+01 AT T = 40.0 DEC F, SCALE FACTOR = 1.7E+00 VISCOSITY ACCORDING TO MASS EVAPORATED: VIS25C = 3.50E+01, ANDRADE = 9.00E+03, FRACT WEATHERED = 1.05E+01, VSLEAD = 3.24E+02 CP MOUSSE CONSTANTS: MOUNEY: 6,20E-01, MAX H20: 0.70, WIND**2: 1.00E-03 THE FRACTIONAL SLICK AREA SUBJECT TO DISPERSION IS 1.4E+01 PER HOUR COUNT THE CUTS IN THE FOLLOWING OUTPUT FROM LEFT TO RIGHT THE INITIAL GRAM MOLES IN THE SLICK ARE: 4.400E-02 1.043E+04 1.250E+05 2.327E+05 2.622E+05 2.600E+05 1.358E+05 2.790E+05 2.662E+05 2.142E+05 2.374E+05 7.351E+05 THE INITIAL MASSES (GRAMS) IN THE SLICK ARE: 5.247E+00 1.396E+06 1.497E+07 3.496E+07 4.445E+07 5.208E+07 2.998E+07 7.027E+07 7.487E+07 6.699E+07 8.343E+07 4.4101-08 THE TOTAL MASS FROM THESE CUTS 15 9.264E+08 CRAMS

STEP SIZE OF 9.670E-02 IS BASED ON CUT 1

TIME = 0.002+00 HOURS, MASS FRACTION OF FACH CUT REMAINING: 1.002+00 1.002+00 1.002+00 1.002+00 1.002+00 1.002+00 1.002+00 1.002+00 1.002+00 1.002+00 1.002+00 MASS REMAINING = 9.26402+00, MASS DISPERSED = 0.000000000, MASS EVAPORATED = 0.00002+00, SUM = 9.26402+00 FRACTION (BASED ON MASS) REMAINING IN THE SIJCE= 1.002+00, AREA: 6.002+05 M+#2, THICKNESS= 1.502+01 CM, MOLE WT=335.8 WEIGHT FRACTION WATER IN OIL = 7.002+01, VISCOSITY = 3.302+04 CENTISTORES, DISPERSION TERM = 2.602+03 WEIGHT FRACTION/UR MASS/AREA= 1.402+03 CMS/M+M, SPCR= 9.104+01, TOTAL VOLUME: 6.402+03 BBL, DISPERSION= 3.5000 CMS/M+M/RH, EVAP RATE: 0.002+00 CMS/M+M/RH

TIME - LIFTOD HOURS, MASS FRACTION OF FACH OUT RENAINING: 5.7F*01 0.9E*01 9.7E*01 9.9E*01 L.0E*00 1.0E*00 1.0E*00 L.0E*00 1.0E*00 1.0E*00 1.0E*00 1.0E*00 1.0E*00 1.0F*00 MASS REMAINING = 9.231E*00, MASS DISPLASED = 2.517E*00, MASS EVAPORATED = 7.750E*05, SUM = 9.264E*00 Table 16.--Output from Oil-Weathering Calculations (Continued): Prudhoe Bay Crude Oil, Time versus Calculated Results at 40°F for Open-Ocean Weathering. FRACTION (BASED ON MASS) REMAINING IN THE SLICK+ LIDE+00, AREA= 6.9E+05 M##2, THICKNESS= 1.5E-01 CM, MOLE WT=336.1 WEIGHT FRACTION WATER IN OIL - 7.0E-01, VISCOSITY = 3.4E+04 CENTISTOKES, DISPERSION TERM = 2.6E-03 WEIGHT FRACTION/HR MASS/AREA: 1.3E+03 GNS/N+N, SPGR: 9.1E-01, TOTAL VOLUME: 6.4E+03 BBL, DISPERSION: 3.4E+00 GNS/N+N/HR, EVAP HATE: 1.0E+00 GNS/N+N/HR TIME = 2.11.400 HOURS, MASS FRACTION OF EACH OUT REMAINING: 3 3.3E=01 7.8E=01 9.5E=01 9.9E=01 MASS REMAINING = 9.199E+08, MASS DISPERSED = 5.019E+06, MASS EVAPORATED = 1.532E+06, SUM = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SLICKS 9.9E-01, AREAS 7.0E+05 M**2, THICKNESSS 1.5E-01 CN, MOLE WESG6.5 WEICHT FRACTION WATER IN OIL = 7.0E-01, VISCOSITY = 3.5E+04 CENTISTORES, DISPERSION TERM = 2.5E-03 WEICHT FRACTION/HR MASS/ARFA= 1.32+03 CMS/M+M, SICH= 9.1E-01, TOTAL VOLUME= 6.4E+03 BBL, DISPERSION= 3.4E+00 CMS/M+M/BR, EVAP RATE: 1.0E+00 CMS/M+M/BR TIME = 3.2E+00 HOURS, MASS FRACTION OF EACH CUT REMAINING: 4 1.482-01 6.92-01 9.32-01 9.82-01 9.92-01 9.92-01 9.92-01 9.92-01 9.92-01 9.92-01 9.92-01 9.92-01 9.92-01 MASS REMAINING = 9.167E+08, MASS DISPERSED = 7.504E+06, MASS EVAPORATED = 2.272E+06, SUN = 9.264E+08 FRACTION (BASED ON MASS) BEMAINING IN THE SLICK= 9.9E-01, AREA= 7.1E+05 M#+2, THICKNESS= 1.4E-01 CM, HOLE WT=036.8 WEIGHT FRACTION WATER IN OIL = 7.0E-01, VISCOSITY = 3.7E+04 CENTISTORES, DISPERSION TERM = 2.5E-03 WEIGHT FRACTION/HR MASS/AREA= 1.3E+03 CMS/M+N. SPCR= 9.1E-01. TUTAL VOLUME= 6.4E+03 BAL, DISPERSION= 3.3E+00 CMS/M+M/AR, EVAP RATE= 9.8E-01 CMS/M+M/AR TIME = 4.38+00 HOURS, MASS FRACTION OF EACH OUT HEMAINING: 5 1.0E-01 6.1E-01 9.0E-01 9.7E-01 9.9E-01 9.9E-01 9.9E-01 9.9E-01 9.9E-01 9.9E-01 9.9E-01 9.9E-01 9.9E-01 MASS BEMAINING = 9.135E+08, MASS DISPERSED = 9.973E+06, MASS EVAPORATED = 2.997E+06, SUN = 9.264E+08 FRACTION (BASED ON MASS) BENATHING IN THE BLICK= 9.9E-01, AREA= 7.1E+05 M##2, THICKNESS= 1.4E-01 CM, NOLE VT=337.1 WEICHT FRACTION WATER IN 011. = 7.0E-01, VISCOSITY = 3.8E+04 CENTISTORES, DISPERSION TERM = 2.5E-03 WEICHT FRACTION/HR MASS/AREA= 1.3E+03 CMS/N#M, SPCH= 9.1E-01, TUTAL VOLUME= 6.3E+03 BBL, DISPERSION= 3.3E+00 CMS/N#M/HH, EVAP RATE= 9.5E-01 CMS/N#M/HH TIME = 5.3E+00 HOURS, MASS FRACTION OF EACH CUT REMAINING: 6 5.6E-02 5.3E-01 8.8E-01 9.7E-01 9.8E-01 9.9E-01 9.9E-01 9.9E-01 9.9E-01 9.9E-01 9.9E-01 9.9E-01 MASS REMAINING = 9.103E+00, MASS DISPERSED = 1.242E+07, MASS EVAPORATED = 3.706E+06, SUN = 9.264E+00 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 9.8E-01. AREA= 7.2E+05 M##2. THICKNESS= 1.4E-01 CM, MOLE WT=337.5 WEIGHT FRACTION WATER IN 011. = 7.0E-01, VISCOSITY = 0.9E+04 CENTISTORES, DISPERSION TERM = 2.5E-03 WEIGHT FRACTION/IIR MASS/AREA= 1.3E+03 CNS/N+N, SPCR= 9.1E-01, TUTAL VOLUME= 6.3E+03 BBL, DISPERSION= 3.2E+00 CNS/N+M/HB, EVAP RATE= 9.2E-01 CNS/N+N/HR TIME = 6.4E+00 HOURS, MASS FRACTION OF EACH OUT REMAINING: 7 3.1E-02 4.7E-01 8.5E-01 9.6E-01 9.8E-01 MASS REMAINING = 9.072E+00, MASS DISPENSED = 1.406E+07, MASS EVAPONATED = 4.401E+06, SUM = 9.264E+00 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 9.0E-01, AREA= 7.3E+05 N##2, THICKNESS= 1.4E-01 CN, MOLE WT=337.8 WEIGHT FRACTION WATER IN OIL = 7.0E-01, VISCOSITY = , 4.1E+04 CENTISTOKES, DISPERSION TERM = 2.5E-00 WEIGHT FRACTION/IR MASS/AREA= 1.2E+03 CRS/M*M, SPCR= 9.1E-01, TUTAL VOLUME= 6.3E+03 BBL, DISPERSION= 3.1E+00 CRS/M*M/IR, EVAP RATE= 8.9E-01 CRS/M*M/RR TIME = 7.4E+00 BOURS, MASS FRACTION OF EACH CUT REMAINING: 8 1.7E-02 4.1E-01 8.3E-01 9.5E-01 9.8E-01 9.8E-01 9.8E-01 9.8E-01 9.8E-01 9.8E-01 9.8E-01 9.8E-01 9.8E-01 MASS REMAINING = 9.041E+08, MASS DISPERSED = 1.727E+07, MASS EVAPORATED = 5.082E+06, SUM = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SLICK: 9.8E-01, ANEA: 7.4E+05 M##2, THICKNESS: 1.4E-01 CM, MOLE VT=358.1 WEIGHT FRACTION WATER IN OIL = 7.0E-01, VISCOSITY = 4.2E+04 CENTISTOKES, DISPERSION TERM = 2.5E-03 WEIGHT FRACTION/HR MASS/AREA= 1.2E+03 CMS/N+M, SPCR= 9.1E-01, TOTAL VOLUME= 6.3E+03 BRL, DISPERSION= 3.1E+00 CMS/N+M/RR, EVAP RATE= 8.6E-01 CMS/N+M/RR STEP SIZE OF 3.929E-01 IS BASED ON CUT 2

TINE = 0.002+00 00008, MASS FRACTION OF EACH CUT HEMAINING: 7.6E-03 3.5E+04 0.0E+04 9.4E+04 9.7E+04 9.0E+04 9.0E+04 9.0E+04 9.0E+04 9.0E+04 9.0E+04 9.0E+04 MASS HEMAINING = 9.0022+008, MASS DISPERSED = 2.034E+07, MASS EVAPORATED = 5.935E+06, SUN = 9.264E+00 FRACTION (BASED ON MASS) BENAINING IN THE SILCE = 9.7E+01. AHEA+ 7.5E+05 M#+2, THICKNESS=1.3E+04 CM, MOLE WT=330.4 WEIGHT FRACTION WATER IN 041.4 7.0E 01, VISCOSITY = 4.4E+04 CENTISTORES, DISPERSION TERM = 2.5E+03 WEIGHT FRACTION/HB MASS/AHEA+ 1.2E+03 GMS/M+M, SPCR+ 9.1E 01, TOTAL VOLUME= 6.2E+03 BDL, DISPERSION= 3.0E+00 CMS/M+M/HB, EVAP RATE+ 8.4E+01 CMS/M+M/HB

STEP SIZE OF (3. B91E-01) IS BASED ON CUT 2

TIME = 1.0E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 3.0E+03 3.0E+01 7.8E+04 9.4E+01 9.7E+01 9.7E+01 9.0E+01 9.8E+01 9.8E+01 9.8E+01 9.8E+01 9.8E+01 9.8E+01 9.8E+01 MASS REMAINING = 0.968E+08, MASS DISPERSED = 2.295E+07, MASS EVAPORATED = 6.653E+06, SUM = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SLICF = 9.7E+01, AREA= 7.5E+05 M#+2, THICENESS= 1.3E+01 CM, MOLE WT=300.8 WEICHT FRACTION WATER IN 01L = 7.0E+01, VISCOSITY = 4.0E+04 CENTISTOPES, DISPERSION TERM = 2.5E+03 WEICHT FRACTION/HR MASS/AREA= 1.2E+03 GMS/N*M, SPCR= 9.1E+01, TOTAL VOLUME= 6.2E+03 BBL, DISPERSION= 2.9E+00 GMS/N*M/HR, EVAP RATE= 0.1E+01 CMS/N*M/HR

STEP SIZE OF 3.8835E-01 IS BASED ON CUT 2

TIME = 1.1E+01 HOURS, MASS FRACTION OF EACH CUT HEMAINING: 1.9E-03 2.6E-01 7.5E-01 9.3E-01 9.7E-01 9.7E-01 9.7E-01 9.7E-01 9.7E-01 9.7E-01 9.7E-01 9.7E-01 9.7E-01 MASS REMAINING = 0.936E+00, MASS DISPERSED = 2.550E+07, MASS EVAPORATED = 7.349E+06, SUM = 9.264E+00 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 9.6E-01, AREA= 7.6E+05 N**2, THICKNESS= 1.3E-01 CN, MOLE WT=339.1 WEICHT FRACTION WATER IN OIL = 7.0E-01, VISCOSITY = 4.8E+04 CENTISTOFES, DISPERSION FERM = 2.5E-03 WEICHT FRACTION/HR MASS/AREA= 1.2E+03 CMS/N*M, SPCR= 9.1E-01, TOTAL VOLUME= 6.2E+03 BBL, DISPERSION= 2.9E+00 CMS/N*M/HR, EVAP RATE= 7.9E-01 CMS/N*M/HR

STEP SIZE OF 3.783E-01 IS BASED ON CUT 2

TIME = 1.2E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 9.5E-04 2.2E+01 7.3E+04 9.2E+01 9.6E+01 9.7E+01 9.7E+01 9.7E+01 9.7E+01 9.7E+01 9.7E+01 9.7E+01 9.7E+01 MASS REMAINING = 0.904E+08. MASS DISPERSED = 2.000E+07, MASS EVAPORATED = 0.023E+06, SUM = 9.264E+00 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 9.6E+01, AREA= 7.7E+05 M*+2. THICKNESS= 1.3E+01 CM, MOLE WT=339.4 WEICHT FRACTION WATER IN 01L = 7.0E+01, VISCOSITY = 5.0E+04 CENTISTOFES, DISPERSION TERM = 2.4E+03 WEICHT FRACTION/RR MASS/AREA= 1.2E+03 GMS/M*M, SPCR= 9.1E+01, TOTAL VOLUME= 6.2E+03 BBL, DISPERSION= 2.8E+00 CMS/M*M/RR, EVAP RATE= 7.6E+01 CMS/M*M/RR

STEP SIZE OF 3.732E-01 IS BASED ON CUT 2

TIME = 1.3E+01 BOURS, MASS FRACTION OF EACH CUT REMAINING: 4.7E-04 1.9E-01 7.1E-01 9.1E-01 9.6E-01 9.7E-01 9.7E-01 9.7E-01 9.7E-01 9.7E-01 9.7E-01 9.7E-01 9.7E-01 MASS REMAINING = B.873E+0B, MASS DISPERSED = 3.045E+07, MASS EVAPORATED = 8.677E+06, SUM = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SLICE = 9.6E-01, AREA= 7.8E+05 M##2, THICKNESS= 1.3E-01 CM, MOLE WT=339.7 WEIGHT FRACTION WATER IN OIL = 7.0E-01, VISCOSITY = 5.2E+04 CENTISTOKES, DISPERSION FERSTER 1.3E-03 WEICHT FRACTION/HR MASS/AREA= 1.1E+03 CMS/M#M, SPCR= 9.1E-01, TOTAL VOLUME= 6.1E+03 BBL, DISPERSION= 2.8E+06 CMS/M#MAR, EVAP RATE= 7.4E-01 CMS/M#M/HR

STEP SIZE OF 3.684E-01 IS BASED ON CUT 2

TIME = 1.5E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 14 2.4E-04 1.6E-01 6.9E-01 9.1E-01 9.5E-01 9.6E-01 9.6E-01 9.6E-01 9.6E-01 9.6E-01 9.6E-01 9.6E-01 MASS REMAINING = 0.043(E+00), MASS DISPERSED = 3.204E+07, MASS EVAPORATED = 9.311E+06, SUM = 9.264E+00 FRACTION (BASED ON MASS) REMAINING IN THE SILCE = 9.5E-01, AREA = 7.9E+05 M**2, THICKNESS= 1.2E-01 CM, MOLE WT=340.0 WEIGHT FRACTION WATER IN 011. = 7.0E-01, VISCOSITY = 5.4E+04 CENTISTORES, DISPERSION TERM = 2.4E-03 WEIGHT FRACTION/HR MASS/AREA = 1.1E+03 CMS/M*M, SPCR= 9.1E-01, TOTAL VOLUME= 6.1E+03 BBL, DISPERSION= 2.7E+00 CMS/M*M/HM, EVAP RATE= 7.3E-01 CMS/M*M/HM

STEP SIZE OF 3.63BE-01 IS BASED ON CUT 2

TIME = 1.6E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 1.2E=04 1.4E=01 6.7E 01 9.0E=01 9.5E=01 9.6E=01 9.6E=01 9.6E=01 9.6E=01 9.6E=01 9.6E=01 9.6E=01 MASS REMAINING = 8.813E+00, MASS DISPERSED = 3.517E+07, MASS EVAPORATED = 9.927E+06, SUM = 9.264E+00 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 9.5E 01, AREA= 7.9E+05 M*#2, THICKNESS= 1.2E=01 CM, MOLE WT=340.2 WEIGHT FRACTION WATER IN 01L = 7.0E=01, VISCOSITY = 5.6E+04 CENTISTORES, DISPERSION TERM = 2.4E=03 WEIGHT FRACTION/HR MASS/AREA= 1.1E+03 CMS/M*M, SPCB= 9.1E 01, TOTAL VOLUME= 6.1E+03 BBL, DISPERSION= 2.7E+00 GMS/M+M/HR, EVAP RATE= 7.1E=01 GMS/M*M/HR

TIME = 1.7E+01 HOURS, MASS FRACTION OF EACH CUT HEMAINING: 5.9E+05 1.2E+01 6.5E+01 0.9E+01 9.5E+01 9.6E+01 9.6E+01 9.6E+01 9.6E+01 9.6E+01 9.6E+01 9.6E+01 9.6E+01 MASS REMAINING = 0.704E+00, MASS DISPERSED = 3.746E+07, MASS EVAPORATED = 1.053E+07, SUM = 9.264E+00 FRACTION (BASED ON MASS) BEMAINING IN THE SLICK= 9.5E+01, AREA= 0.0E+05 M*+2, THICKNESS= 1.2E+01 CM, MOLE WT=340.5 WEICHT FRACTION WATER IN 01L = 7.0E+01, VISCOSITY = 5.0E+04 CENTISTORES, DISPERSION TERN = 2.4E+03 WEICHT FRACTION/HR MASS/AREA= 1.1E+03 CMS/M*M, SPCR= 9.1E+01, TOTAL VOLUME= 6.1E+03 BBL, DISPERSION= 2.6E+00 CMS/M*W/HR, EVAP RATE= 6.9E+01 CMS/M*M/HR

STEP SIZE OF 3.552E-01 IS BASED ON CUT 2

TIME = 1.80:+01 BOURS, MASS FRACTION OF EACH CUT REMAINING: 2.91:-05 1.00:-01 6.30:-01 8.90:-01 9.50:-01 9.60:-01 9.60:-01 9.60:-01 9.60:-01 9.60:-01 9.60:-01 9.60:-01 MASS REMAINING = 8.7560:-00, MASS DISPERSED = 3.9700:+07, MASS EVALORATED = 1.1110:+07, SUM = 9.2640:+00 FRACTION (BASED ON MASS) REMAINING IN THE SILCK = 9.50:-01, AREA: 8.10:+05 M*#2, THICKNESS: 1.20:-01 CM, MHE WT::340.8 WEIGHT FRACTION WATCH IN 01L = 7.00:-01, VISCOSITY = 6.00:+04 CENTISTORES, DISPERSION TERM = 2.40:-03 WEICHT FRACTION/NR MASS/AREA: 1.10:+03 CMS/M*M, SPCR: 9.10:-01, TUTAL VOLUME: 6.10:+03 BBL, DISPERSION: 2.60:00 CMS/M*M/MIL, EVAP HATE: 6.80:-01 CMS/M*M/HR

STEP SIZE OF 3.5IIE-01 IS BASED ON CUT 2

TINE = 1.9E+01 HOURS, MASS FRACTION OF EACH CUT HEMAINING: 1.5E-05 B.9E-02 6.1E-01 B.8E-01 9.4E-01 9.5E-01 9.5E-01 9.5E-01 9.5E-01 9.5E-01 9.5E-01 9.5E-01 9.5E-01 MASS REMAINING = 8.729E+08, MASS DISPERSED = 4.190E+07, MASS EVAPORATED = 1.168E+07, SUN = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 9.4E-01, AREA= 8.1E+05 M**2. THICKNESS= 1.2E-01 CM, MALE WT=341.0 WEICHT FRACTION WATER IN 01L = 7.0E-01, VISCOSITY = 6.2E+04 CENTISTOKES, DISPERSION TERM = 2.4E-03 WEICHT FRACTION/IR MASS/AREA= 1.1E+03 CMS/M*M, SPCR= 9.1E-01, TOTAL VOLUME= 6.0E+03 BBL, DISPERSION= 2.5E+00 CMS/M*M/IR, EVAP RATE= 6.6E-01 CMS/M*M/RR

STEP SIZE OF 3.472E-01 IS BASED ON CUT 2

TIME = 2.00+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 7.3E-06 7.5E-02 5.9E-01 8.7E-01 9.4E-01 9.5E-01 9.5E-01 9.5E-01 9.5E-01 9.5E-01 9.5E-01 9.5E-01 9.5E-01 MASS REMAINING = 8.702E+08, MASS DISPERSED = 4.405E+07, MASS EVAPORATED = 1.223E+07, SUN = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SILCK= 9.4E-01, AREA= 8.2E+05 M##2, THICKNESS= 1.2E-01 CM, MOLE WT=341.3 WEICHT FRACTION WATER IN OIL = 7.0E-01, VISCOSITY = 6.4E+04 CENTISTORES, DISPERSION TERM = 2.3E-03 WEICHT FRACTION/HR MASS/AREA= 1.1E+03 CMS/N#M, SPCR= 9.1E-01, TUTAL VOLUME= 6.0E+03 BBL, DISPERSION= 2.5E+00 CMS/N#M/HB, EVAP RATE= 6.3E-01 CMS/N#M/HB

STEP SIZE OF 3.435E-01 IS BASED ON CUT 2

TIME = 2.1E+01 HOURS, MASS FRACTION OF EACH CUT HEMAINING: 20 3.7E-06 6.6E-02 5.7E-01 B.7E-01 9.4E-01 9.5E-01 9.5E-01 9.5E-01 9.5E-01 9.5E-01 9.5E-01 9.5E-01 9.5E-01 MASS REMAINING = 8.675E+08, MASS DISPERSED = 4.616E+07, MASS EVAPORATED = 1.277E+07, SUM = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SILCK = 9.4E-01, AREA = 8.3E+05 M##2, THICKNESS= 1.2E-01 CM, MOLE WT=341.5 WEIGHT FRACTION WATER IN 01L = 7.0E-01, VISCOSITY = 6.6E+04 CENTISTORES, DISPERSION TERM = 2.3E-03 WEIGHT FRACTION/RR MASS/AREA = 1.1E+03 CMS/M#M, SPCR= 9.1E-01, TOTAL VOLUME= 6.0E+03 BBL, DISPERSION = 2.5E+00 CMS/M#M/RR, EVAP RATE= 6.3E-01 CMS/M#M/RR

STEP SAZE OF 3.398E-04 IS BASED ON CUT 2

TIME = 2.2E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 21 1.8E=06 5.6E=02 5.5E=01 B.6E=04 9.2E=01 9.5E=01 9.5E=01 9.5E=01 9.5E=01 9.5E=01 9.5E=01 9.5E=01 MASS REMAINING = B.649E+08, MASS DISPERSED = 4.823E+07, MASS EVAPORATED = 1.830E+07, SUM = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SLICK = 9.3E=01, AREA = 8.3E+05 M**2, THICENESS = 1.1E=01 CM, MOLE WT=344.8 WEICHT FRACTION WATER IN OIL = 7.0E=01, VISCOSITY = 6.8E+04 CENTISTORES, DISPERSION TERM = 2.3E=03 WEICHT FRACTION/RR MASS/AREA = 1.0E+03 CMS/M+M, SPCR= 9.1E=01, TOTAL VOLUME= 6.0E+03 BBL, DISPERSION= 2.4E+00 CMS/M+M/RR, EVAP RATE= 6.2E=01 CMS/M+M/RR

TIME = 2.3E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 22 9.1E=07 4.9E=02 5.4E=01 8.5E=01 9.3E=01 9.3E=01 9.5E=01 9.5E=01 9.5E=01 9.5E=01 9.5E=01 9.5E=01 MASS REMAINING = 0.624E+00, MASS DISPERSED = 5.026E+07, MASS EVAPORATED = 1.382E+07, SUM = 9.264E+00 FRACTION (BASED ON MASS) REMAINING IN THE SLICE= 9.3E-01, AREA: 0.4E+05 M*+2, THICENESS: 1.1E-01 CM, HOLE WE:342.0 WEIGHT FRACTION WATER IN OIL = 7.0E-01, VISCOSATY = 7.1E+04 CENTISTOEES, DESPERSION TERN = 2.3E-03 WEIGHT FRACTIONZHR MASSZAREA= 1.0E+03 CHSZMAAN, SPCR= 9.1E+01, TOTAL VOLUME= 6.0E+03 BBL, DISPERSION= 2.4E+00 CHSZMANZHR, EVAP RATE= 6.1E+01 CHSZMANZHR

STEP SIZE OF 3.330E-01 IS BASED ON CUT 2

TIME = 2.4E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 23 4.6E-07 4.2E-02 5.2E-01 8.5E-01 9.3E-01 9.4E-01 9.4E-01 9.4E-01 9.4E-01 9.4E-01 9.4E-01 9.4E-01 9.4E-01 MASS REMAINING = 0.599E+00, MASS DISPENSED = 5.225E+07, MASS EVAPORATED = 1.432E+07, SUM = 9.264E+00 FRACTION (BASED ON MASS) BENAINING IN THE SLICK= 9.3E-01, AREA= 8.4E+05 M**2, THICKNESS= 1.1E-01 CM, MOLE WT=342.2 WEIGHT FRACTION WATER IN OIL = 7.0E-01, VISCOSITY = 7.3E+04 CENTISTOEFS, DISPERSION TERM = 2.3E-03 WEIGHT FRACTION/HR MASSZAREA= 1.00+03 CMSZM#M, SPCR= 9.1E-01, TOTAL VOLUME= 6.00+03 BBL, DISPERSION= 2.3E+00 CMSZM#M/HR, EVAP HATE= 6.00-01 CMSZM#M/HR

STEP SIZE OF 3.297E-01 IS BASED ON CUT 2

TIME = 2.5E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 24 1.8E-07 3.4E-02 5.0E-01 8.4E-01 9.2E-01 9.4E-01 9.4E-01 9.4E-01 9.4E-01 9.4E-01 9.4E-01 9.4E-01 9.4E-01 MASS REMAINING = 8.566E+08, MASS DISPERSED = 5.485E+07, MASS EVAPORATED = 1.498E+07, SUM = 9.264E+08 FRACTION (BASED ON HASS) REMAINING IN THE SLICK= 9.2E-01, AREA= 8.5E+05 M**2, THICKNESS= 1.1E-01 CN, MOLE WE=342.6 WEIGHT FRACTION WATER IN OIL = 7.00-01, VISCOSITY = 7.6E+04 CENTISTOKES, DISPERSION TERM = 2.3E-03 WEIGHT FRACTION/HR MASSZAREA= 1.0E+03 CMSZM*M, SPCR= 9.1E-01, TOTAL VOLUME= 5.9E+03 BBL, DISPENSION= 2.3E+00 CMSZM*MZHR, EVAP HATE= 5.8E-01 CMSZM*MZHR

STEP SIZE OF 3.255E-01 IS BASED ON CUT 2

TIME = 2.7E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 25 7.1E-00 2.8E-02 4.8E-01 8.3E-01 9.2E-01 9.3E 01 9.4E-01 9.4E-01 9.4E-01 9.4E-01 9.4E-01 9.4E-01 9.4E-01 MASS REMAINING = 0.334E+00, MASS DISPENSED = 3.739E+07, MASS EVAPORATED = 1.562E+07, SUM = 9.264E+00 FRACTION (BASED ON MASS) NEMAINING IN THE SLICK= 9.2E-01, AREA= 8.6E+05 M**2, THICKNESS= 1.1E-01 CM, MOLE WT=342.8 WEICHT FRACTION WATER IN 011. = 7.0E-01, VISCOSITY = 7.9E+04 CENTISTOKES, DISPERSION TERM = 2.3E-03 WEICHT FRACTION/UR MASSZAREA= 9.9E+02 CMSZN+M, SPCR= 9.1E-01, TOTAL VOLUME= 5.9E+03 BBL, DISPERSION= 2.2E+00 CMSZN+MZHR, EVAP RATE= 5.7E-01 CMSZN+NZHR

STEP SIZE OF 3.215E-01 IS BASED ON CUT 2

TIME = 2.8E+01 HOURS, MASS FRACTION OF FACH OUT REMAINING: 26 2.1HE-0B 2.3E-92 4.6E-01 B.2E-01 9.3E-01 9.3E-01 9.3E-01 9.3E-01 9.3E-01 9.3E-01 9.3E-01 MASS REMAINING = 0.503E+00, MASS DISPERSED = 5.907E+07, MASS EVAPORATED = 1.624E+07, SUN = 9.264E+00 FHACTION (BASED ON HASS) REMAINING IN THE SLICK= 9.2E-01, ANEA= 8.7E+05 M##2, THICKNESS= 1.1E-01 CN, HOLE WT=343.1 VEICHT FRACTION WATER IN 041. = 7.0E-01, VISCOSITY = 0.2E+04 CENTISTOKES, DISPERSION TERM = 2.2E-03 WEIGHT FRACTION/UR MASS/AREA: 9.8E+92 CMS/M#N, SPCR: 9.1E-01, TOTAL VOLUME: 5.9E+03 BBL, DISPERSION: 2.2E+00 CMS/M#M/RR, EVAP RATE: 5.5E-01 CMS/M#N/RR

STEP SIZE OF 3.176E-01 IS BASED ON CUT 2

TIME = 2.9000 HOURS, MASS FRACTION OF EACH CUT REMAINING: 27 1.1E=08 4.9E+02 4.4E=01 8.2E+01 9.4E+01 9.3E=01 9.3E=01 9.3E=01 9.3E=01 9.3E=01 9.3E=01 9.3E=01 MASS REMAINING = 8.473E+08, MASS DISPERSED = 6.230E+07, MASS EVAPORATED = 1.684E+07, SUM = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SLICES 9.1E-01, AREAS 8.7E+05 M##2, THICKNESSE 1.1E-01 CM. MOLE WT=343.4 WEIGHT FRACTION WATER IN OIL - 7.0E-01, VISCOSITY - 8.6E+04 CENTISTOEFS, DISPERSION TERM = 2.2E-03 WEIGHT FRACTION/HR MASS/AREA- 9.7E+02 CHS M+M, SPGR- 9.1E 01, TOTAL VOLUME: 5.9E+03 BBL, DISPERSION= 2.2E+00 CHS/M+H/0R, EVAP RATE- 5.4E-01 CHS/M+H/0R

TIME = 3.0E+01 HOURS, MASS FRACTION OF EACH OUT REMAINING: 28 4.4E+09 1.5E+02 4.2E+01 8.1E+01 9.1E+01 9.3E+01 9.3E+01 9.3E+01 9.3E+01 9.3E+01 9.3E+01 9.3E+01 9.3E+01 9.3E+01 MASS BEMAINING = 0.443E+00, MASS DISPENSED = 0.466E+07, MASS EVAPORATED = 1.743E+07, SUM = 9.264E+00 FRACTION (BASED ON MASS) REMAINING IN THE SLICE= 9.1E-01, ABEA= B.BE405 M##2, THICKNESS= 1.1E-01 CM, NOLE WT=343.7 VEIGHT FRACTION WATER IN DIL 3 7.0E-01, VISCOSITY = 8.9E+04 CENTISTORES, DISPERSION TERM = 2.2E-03 WEIGHT FRACTION/HR MASS/AREA= 9.6E+02 CMS/M#M, SPCH= 9.1E-01, TOTAL VOLUME= 5.8E+03 BBL, DISPERSION= 2.1E+00 CMS/M#M/IR, EVAP RATE= 5.3E-01 CMS/M#M/HR TIME = 3.2E+01 HOURS, MASS FRACTION OF FACE OUT REMAINING: 29 0.0E+00 1.2E-02 4.1E-01 8.0E-01 9.1E-01 9.3E-01 9.3E-01 9.3E-01 9.3E-01 9.3E-01 9.3E-01 9.3E-01 9.3E-01 MASS REMAINING = 0.414E+08, MASS DISPERSED = 6.700E+07, MASS EVAPORATED = 1.000E+07, SUM = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 9.1E-01, AREA= 0.9E+05 M##2, THICENESS= 1.0E-01 CN, HOLE WT=344.0 WEICHT FRACTION WATER IN OIL = 7.00-01, VISCOSITY = 9.32+04 CENTISTORES, DISPERSION TERM = 2.22-03 WEICHT FRACTION/IR MASS/AREA: 9.5E+02 CHS/M+N, SPCR: 9.1E-01, TUTAL VOLUME: 5.0E+03 BBL, DISPERSION: 2.1E+00 CHS/M+M/BR, EVAP RATE: 5.2E-01 CHS/M+M/BR TIME = 3.3E+01 HOURS, MASS FRACTION OF EACH OUT REMAINING: :10 0.0E+00 1.0E-02 3.9E-01 7.9E-01 9.0E-01 9.2E-01 9.2E-01 9.2E-01 9.2E-01 9.2E-01 9.2E-01 9.2E-01 9.2E-01 9.2E-01 MASS REMAINING = B.306E+08, MASS DISPERSED = 6.930E+07, MASS EVAPORATED = 1.857E+07, SUM = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 9.1E-01, AREA= 8.9E+05 M#+2, THICENESS= 1.0E-01 CN, HOLE WE=344.2 VEICHT FRACTION WATER IN OIL = 7.00-01, VISCOSITY = 9.66+04 CENTISTORES, DISPERSION TERM = 2.2E-03 VEICHT FRACTION/HR MASSZARFA= 9.4E+02 CMS/M+M, SPCN= 9.1E-01, TOTAL VOLUME= 5.0E+03 BBL, DISPERSION= 2.0E/00 CMS/N+M/III, EVAP NATE= 5.0E-01 CMS/N+M/HR TIME = 3.4E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 31 0.0E+00 8.3E-03 3.8E-01 7.9E-01 9.0E-01 9.2E-01 9.2E-01 9.2E-01 9.2E-01 9.2E-01 9.2E-01 9.2E-01 MASS REMAINING = 0.357E+00, MASS DISPERSED = 7.15HE+07, MASS EVAPORATED = 1.913E+07, SUM = 9.264E+00 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 9.0E-01. ABEA: 9.0E+05 M##2. THICKNESS= 1.0E-01 CM. MOLE VT=344.5 WEICHT FRACTION WATER IN OIL = 7.0E-01, VISCOSITY = 1.0E+05 CENTISTOKES, DISPERSION TERM = 2.2E-03 WEICHT FRACTION/IR MASS/AREA= 9.3E+02 CNS/N+N, SPCR= 9.1E-01, TOTAL VOLUME= 5.8E+03 BBL, DISPERSION= 2.0E+00 CNS/N+N/DB, EVAP DATE= 4.9E-01 CNS/N+N/HR TIME = 3.5E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 32 0.0E+00 6.7E+03 3.6E+01 7.8E+01 8.9E+01 9.2E+01 9.2E+01 9.2E+01 9.2E+01 9.2E+01 9.2E+01 9.2E+01 9.2E+01 MASS REMAINING = 8.329E+00, MASS DISPERSED = 7.384E+07, MASS EVAPORATED = 1.968E+07, SUM = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SLICE= 9.0E-01, AREA= 9.1E+05 M**2, THICKNESS= 1.0E-01 CM, NOLE VT=344.0 WEICHT FRACTION WATER IN OIL = 7.0E-01, VISCOSITY = 1.0E+05 CENTISTOKES, DISPERSION TERM = 2.1E-03 WEICHT FRACTION/HR MASN/AREA = 9.22+02 CMS/N+M, SPCR= 9.1E-01, TOTAL VOLUME= 5.8E+03 BBL, DISPERSION= 2.0E+00 CMS/N+M/HH, EVAP RATE= 4.4E-01 CMS/N+M/HR TIME = 3.7E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 33 0.0E+00 5.4E+03 3.4E+01 7.7E+01 8.9E+01 9.1E+01 9.2E+01 9.2E+01 9.2E+01 9.2E+01 9.2E+01 9.2E+01 MASS REMAINING = 8.301E+00, MASS DISPENSED = 7.607E+07, MASS EVAPORATED = 2.022E+07, SUM = 9.264E+00 FHACTION (BASED ON MASS) REMAINING IN THE SLICE: 9.0E-01, ANEA: 9.1E+05 M##2, THICKNESS: 1.0E-01 CM, MOLE VT=345.0 WEICHT FRACTION WATER IN DIL = 7.00-01, VISCOSITY = 1.10+05 CENTISTOKES, DISPERSION TERM = 2.10-03 WEICHT FRACTION/UR MASN/AREA: 9.1E+02 CNS/N+N, SPCH= 9.1E-01, TOTAL VOLUME= 5.7E+03 BBL, DISPERSION= 1.9E+00 CNS/N+N/RR. EVAP NATE= 4.7E-01 CNS/N+N/RR TIME = 3.8E+01 HOURS, MASS FRACTION OF EACH OUT REMAINING: 34 0.0[+00 4.4E-03 3.3E-01 7.6E-04 8.9E-01 9.1E-01 9.1E-01 9.1E-01 9.1E-01 9.1E-01 9.1E-01 9.1E-01 MASS REMAINING = 8.274E+00, MASS DISPENSED = 7.027E+07, MASS EVAPONATED = 2.076E+07, SUM = 9.264E+00 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 8.9E-01, ANEA= 9.2E+05 M**2, THICKNESS= 9.9E-02 CM, MOLE MT=345.3 WEIGHT FRACTION WATER IN 011 = 7.0E-01, VISCOSITY = 1.1E+05 CENTISTOKES, DISPERSION TERM = 2.1E-03 WEIGHT FRACTION/IIR MASS/AREA: 9.0E+02 CMS/M+M, SPCR- 9.1E-01, TOTAL VOLUME- 5.7E+03 BBL, DISPERSION- 1.9E+00 CMS/M+M/IR, EVAP RATE- 4.6E-01 CMS/M+M/IR TIME = 3.9E+01 HOURS, MASS FRACTION OF EACH OUT REMAINING: 35 0.0E+00 3.5E+03 3.2E+01 7.5E+01 8.0E+01 9.1E+01 9.1E+01 9.1E+01 9.1E+01 9.1E+01 9.1E+01 9.1E+01

0.01:00 3.5E-03 3.2E-01 7.5E-01 8.00:01 9.1E-01 9.1E-01 9.1E-01 9.1E-01 9.1E-01 9.1E-01 9.1E-01 9.1E-01 MASS REMAINING = 0.247E+00, MASS DISPERSED = 0.045E+07, MASS EVAPORATED = 2.120E+07, SUM = 9.264E+00 FRACTION (BASED ON MASS) REMAINING IN THE SLICE-0.04.000 AREA=9.26405 M**2, THICKNESS=9.0E-02 CM, MOLE WE-345.5 WEIGHT FRACTION WATER IN OIL = 7.0E-01, VISCOSITY = 1.2E+05 CENTISTOKES, DISPERSION TERM = 2.1E-03 WEIGHT FRACTION/HR MASS/AREA=0.9E+02 CMS/M*M, SPCR=9.1E-01, TOTAL VOLUME= 5.7E+03 BDL, DISPERSION=1.9E+00 CMS/M*M/HR, EVAP RATE=4.5E=04 CMS/M*M/HR

TIME - 4.000001 HOURS, MASS FRACTION OF EACH OUT REMAINING:

0.00+00 2.80=03 3.00=01 7.50=01 8.80=01 9.10=01 9.10=01 9.10=01 9.10=01 9.10=01 9.10=01 9.10=01 MASS REMAINING = 8.2200+08, MASS DISPERSED = 8.2610+07, MASS EVAPORATED = 2.1800+07, SUM = 9.2640+08 FRACTION (BASED ON MASS) REMAINING IN THE SILCE = 8.90+0, AREA = 9.30+05 M**2, THICKNESS= 9.70+02 CM, MOLE WT=345.8 Weicht Fraction Water in 011 = 7.00+01, Viscosity = 1.20+05 centistofes, Dispersion Trum = 2.10+03 Weicht Fraction/HR MASS/AREA = 8.80+02 CMS/M+M, SPCR= 9.10+01, TOTAL VOLUME 5.70+03 BBL, DISPERSION= 1.80+00 CMS/M+M/HR, EVAP RATE = 4.40+04 CMS/M+M/HR

TIME = 4.2E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 0.0E+00 2.3E+03 2.9E+01 7.4E+01 B.BE+01 9.0E+01 9.1E+01 9.1E+01 9.1E+01 9.1E+01 9.1E+01 9.1E+01 9.1E+01 MASS REMAINING = B.194E+0B, MASS DISPERSED = B.473E+07, MASS EVAPORATED = 2.231E+07, SUM = 9.264E+0B FRACTION (BASED ON MASS) REMAINING IN THE SILCK= B.4B+01, AREA= 9.4E+05 M##2. THICKNESS= 9.6E+02 CM, MOLE WT=346.0 WEICHT FRACTION WATER IN 01L = 7.0E+01, VISCOSITY = 1.2E+05 CENTISTOFES, DISPERSION TERM = 2.0E+03 WEICHT FRACTION/HR MASS/AREA= B.7E+02 CMS/M#M, SPCR= 9.1E+01, TOTAL VOLUME= 5.7E+03 BBL, DISPERSION= 1.0E+00 CMS/M#MAR, EVAP RATE= 4.3E+01 CMS/M#M/HR

TIME = 4.3E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: (B) 0.0E+00 1.0E+03 2.8E+01 7.3E+01 8.7E+01 9.0E+01 9.0E+01 9.0E+01 9.1E+01 9.1E+01 9.1E+01 9.1E+01 9.1E+01 MASS REMAINING = 8.160E+08, MASS DISPERSED = 8.604E+07, MASS EVAPORATED = 2.281E+07, SUN = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 8.8E+01, ANFA= 9.4E+05 M#+2, THICENESS= 9.5E+02 CM, MOLE WT=346.3 METCHT FRACTION WATER IN 01L = 7.0E+01, VISCOSITY = 1.3E+05 CENTISTORES, DISPERSION TERM = 2.0E+03 WEICHT FRACTION/HR MASS/ANFA= 8.7E+02 CMS/M#M, SPCR= 9.1E+01, TUTAL VOLUME= 5.6E+03 BBL, DISPERSION= 1.8E+00 CMS/M#M/HR, EVAP RATE= 4.2E+01 CMS/M#M/HR

TIME = 4.4E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 0.0E+00 1.4E+03 2.6E+01 7.3E+01 8.7E+01 9.0E+01 9.0E+01 9.0E+01 9.0E+01 9.0E+01 9.0E+01 9.0E+01 9.0E+01 MASS REMAINING = 8.142E+08, MASS DISPERSED = 8.092E+07, MASS EVAPORATED = 2.331E+07, SUN = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 8.8E+01, AREA= 9.5E+05 N#*2, THICKNESS= 9.4E+02 CM, MDLE WT=346.5 WEICHT FRACTION WATER IN OIL = 7.0E+01, VISCOSITY = 1.3E+05 CENTISTOKES, DISPERSION TERM = 2.0E+03 WEICHT FRACTION/HR MASS/AREA= 8.6E+02 CMS/N*N, SPCH= 9.1E+01, TOTAL VOLUME= 5.6E+03 BBL, DISPERSION= 1.7E+00 CMS/N*M/HR, EVAP RATE= 4.1E+01 CMS/N*M/HR

TIME = 4.5E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 0.0E+00 1.2E-03 2.5E-01 7.2E-01 8.7E-01 9.0E-01 9.0E-01 9.0E-01 9.0E-01 9.0E-01 9.0E-01 9.0E-01 9.0E-01 MASS REMAINING = 0.117E+08, MASS DISPERSED = 9.0098E+07, MASS EVAPORATED = 2.380E+07, SUM = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SILCK= 8.8E-01, AREA= 9.6E+05 M**2, THICKNESS= 9.3E-02 CM, MOLE WT=346.7 WEIGHT FRACTION WATER IN 01L = 7.0E-01, VISCOSITY = 1.4E+05 CENTISTOKES, DISPERSION TERM = 2.0E-03 WEIGHT FRACTION/HR MASS/AREA= 8.5E+02 CMS/M*M, SPCR= 9.1E-01, TOTAL VOLUME= 5.6E+03 BBL, DISPERSION= 1.7E+00 CMS/M*M/HR, EVAP RATE= 4.1E-01 CMS/M*M/HR

TIME = 4.7E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 0.0E+00 9.2E=04 2.4E=01 7.1E=01 8.6E=01 0.9E=01 9.0E=01 9.0E=01 9.0E=01 9.0E=01 9.0E=01 9.0E=01 9.0E=01 MASS REMAINING = 8.091E+00, MASS DISPERSED = 9.301E+07, MASS EVAPORATED = 2.420E+07, SUN = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SILCK= 8.7E=01, AREA= 9.6E+05 N**2, THICKNESS= 9.2E=02 CM, MOLE VT=347.0 WEICHT FRACTION WATCH IN OIL = 7.0E=01, VISCOSITY = 1.4E+05 CENTISTUKES, DISPERSION TERM = 2.0E=03 WEICHT FRACTION/HR MASS/AREA= 8.4E+02 CMS.M*M, SPCR= 9.1E=01, TOTAL VOLUME= 5.6E+03 BBL, DISPERSION= 1.7E+00 CMS/M*M/HR, EVAP RATE= 4.0E=01 CMS/N*M/HR

 TIME = 4.8E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING:
 42

 0.0E+00
 7.3E=04
 2.3E=01
 7.0E=04
 8.9E=01
 9.0E=01
 9.0E=01

TIME = 4.9E+01 HOURS, MASS FRACTION OF FACH CUT HEMAINING: 0.0E+00 5.8E=04 2.2E=01 7.0E+01 8.6E=01 8.9E=01 8.9E=01 8.9E=01 8.9E=01 8.9E=01 8.9E=01 8.9E=01 MASS REMAINING = 8.042E+08, MASS DISPERSED = 9.701E+07, MASS EVAPORATED = 2.522E+07, SUM = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SILCK= 8.7E+01, AHEA= 9.7E+05 M##2, THICKNESS= 9.1E=02 CM, MOLE WT=347.4 WEICHT FRACTION WATER IN 011. = 7.0E=01, VISCOSITY = 1.5E+05 CENTISTOKES, DISPERSION TERM = 1.9E=03 WEICHT FRACTION/HR MASS/AHEA= 8.3E+02 CMS/M#M, SPCR= 9.1E=01, TOTAL VOLUME= 5.6E+03 BBL, DISPERSION= 1.6E+00 CMS/M#M/HR, EVAP RATE= 3.8E=01 CMS/M#M/HR

TIME = 5.00+001 BOURS, MASS FRACTION OF EACH CUT REMAINING: 0.00+00 4.00:04 2.1E-01 0.9E-01 8.5E 01 8.9E-01 8.9E 01 8.9E 01 8.9E-01 8.9E-01 8.9E-01 8.9E-01 8.9E-01 MASS REMAINING = 8.018E+08, MASS DISPERSED = 9.89B+07, MASS EVAPORATED = 2.56BE+07, SUM = 9.264E+08

FRACTION (BASED ON MASS) RENAINING IN THE SLICKS 8.7E-01, AREAS 9.0E+05 M##2, THICKNESSS 9.0E-02 CH, HOLE WIS347.7 WEIGHT FRACTION WATER IN OIL = 7.0E-01, VISCOSITY = 1.6E+05 CENTISTOEES, DISPERSION TERM = 1.9E-03 WEIGHT FRACTION/IR MASS/AREA= 8.2E+02 CMS/M#M, SPCH= 9.1E-01, TOTAL VOLUME= 5.5E+03 BBL, DISPERSION= 1.6E+00 CMS/M#M/HB, EVAP BATE= 3.7E-01 CMS/M#M/HB

TIME = 5.20+01 HOURS, MASS FRACTION OF EACH OUT REMAINING: 45 0.0E+00 3.6E+04 2.0E+01 6.8E+01 8.5E+01 8.8E+01 8.9E+01 8.9E+01 8.9E+01 8.9E+01 8.9E+01 8.9E+01 MASS REMAINING = 7.994E+08, MASS DISPERSED = 1.009E+08, MASS EVAPORATED = 2.613E+07, SUM = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SLICK: B.GE-OL, ABEA: 9. BE+05 M++2, THICKNESS: B.9E-O2 CH, HOLE WE:347.9 MEIGHT FRACTION WATER IN OIL = 7.0E-01, VISCOSITY = 1.7E+05 CENTISTORES, DISPERSION TERM = 1.9E-03 WEIGHT FRACTIONZHR MASS/AREA: 8.12+02 CMS/M*N, SPCR: 9.12-01, TOTAL VOLUME- 5.5E+03 BBL, DISPERSION: 1.6E+00 CMS/M*M/BR, EVAP RATE: 3.7E-01 CMS/M*N/MR

STEP SIZE OF 5.000E-01 IS BASED ON CUT 3

TIME = 6.2E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING; 46 0.0E+00 4.7E-01 1.3E-01 6.2E-01 8.3E-01 8.6E-01 8.7E-01 8.7E-01 8.7E-01 8.7E-01 8.7E-01 8.7E-01 8.7E-01 MASS HEMAINING = 7 804E+00, MASS DISPERSED = 1.165E+00, MASS EVAPORATED = 2.960E+07, SUN = 9.264E+00 FRACTION (BASED ON MASS) REMAINING IN THE BLICK= 8.4E-01, ARFA= 1.0E+06 M##2, THICKNESS= 8.3E-02 CH, HOLE WT=349.6 WEIGHT FRACTION WATER IN OIL = 7.0E-01, VISCOSITY = 2.2E+05 CENTISTORES, DISPERSION TERM = 1.8E-03 WEIGHT FRACTION/HR MASS/AREA= 7.6E+02 CHS/N+N, SPCR= 9.1E-01, TUTAL VOLUME- 5.4E+03 BBL, DISPERSION= 1.4E+00 CHS/N+M/IIH, EVAP RATE= 3.1E-01 CHS/N+M/HR

STEP SIZE OF 5.000E-01 IS BASED ON CUT 3

TIME = 7.2E+01 HOURS, MASS FRACTION OF EACH OUT REMAINING: 47 0.0E+09 5.8E-06 8.9E-02 5.7E-01 8.0E-01 8.5E-01 8.6E-01 8.6E-01 8.6E-01 8.6E-01 8.6E-01 8.6E-01 MASS BEMAINING = 7.636E+08, MASS DISPERSED = 1.303E+08, MASS EVAPORATED = 3.263E+07, SUM = 9.264E+08 FHACTION (BASED ON MASS) BEMAINING IN THE BLICK= 8.2E-01, AHEA= 1.1E+06 M##2. THICKNESS= 7.8E-02 CM, HOLE WT=051.1 WEIGHT FRACTION WATER IN OIL = 7.0E-01, VISCOSITY = 2.8E+05 CENTISTOKES, DISPERSION TERN = 1.7E-03 WEIGHT FRACTION/HR MASS/AREA= 7.1E+02 CMS/N*N, SPCR= 9.1E-01, TOTAL VOLUME= 5.3E+03 BBL, DISPENSION= 1.2E+00 CMS/N*N/HH, EVAP RATE= 2.7E-01 CMS/N*N/HH

STEP SIZE OF 5.000E-01 IS BASED ON CUT 3

TIME = 8.2E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 0.0E+00 6.2E-07 5.7E-02 5.2E-01 7.8E-01 8.3E-01 8.4E-01 8.4E-01 8.4E-01 8.4E-01 8.4E-01 MASS BEMAINING = 7.482E+08, MASS DISPERSED = 1.429E+08, MASS EVAPORATED = 3.536E+07, SUM = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SLICK: 8. IE-01, AREA: 1. IE+06 N##2, THICKNESS: 7.4E-02 CN, MOLE WT: 352.6 WEICHT FRACTION WATER IN OIL = 7.0E-01, VISCOSITY = 3.6E+05 CENTISTOKES, DISPERSION TERM = 1.6E-03 WEICHT FRACTION/HR MASS/AREA: 6.8E+02 CNS/M#M, SPCH: 9.1E-01, TOTAL VOLUME: 5.2E+03 BBL, DISPERSION: 1.1E+00 CNS/M#M/HR, EVAP RATE: 2.4E-01 CNS/M#M/HR

STEP SIZE OF 5.000E-01 IS BASED ON CUT 3

TIME = 9.2E+01 HOURS, MASS FRACTION OF EACH CUT REMAINING: 49 0.0E+00 5.8E-08 3.6E-02 4.7E-01 7.6E-01 8.3E-01 8.3E-01 8.3E-01 8.3E-01 8.3E-01 8.3E-01 8.3E-01 MASS REMAINING = 7.341E+00, MASS DISPERSED = 1.545E+00, MASS EVAPORATED = 3.707E+07, SUM = 9.264E+00 FRACTION (BASED ON MASS) REMAINING IN THE SLICK: 7.9E-01, ANEA: LIE+06 M**2, THICKNESS: 7.0E-02 CM, MOLE WT:353.9 WEIGHT FRACTION WATER IN 011. = 7.00-01, VISCOSITY = 4.50+05 CENTISTOKES, DISPERSION TERM = 1.50-00 WEIGHT FRACTION/HR MASS/AREA= 6.4E+02 CMS/N+M, SPCH= 9.1E-01, TUTAL VOLUME= 5.1E+03 BBL, DISPERSION= 9.4E-01 CMS/N+M/HR, EVAP RATE= 2.1E-01 CMS/N+M/HR

STEP SIZE OF 5.000E-01 IS BASED ON CUT 3

TIME = 1.0E+02 HOURS, MASS FRACTION OF EACH CUT REMAINING: 50 0.0E+00 4.9E-09 2.2E 02 4.3E 01 7.4E 01 8.0E-01 8.2E-01 8.2E-01 8.2E-01 8.2E-01 8.2E-01 MASS BEMAINING = 7.211E+08, MASS DISPERSED 1.651E+08, MASS EVAPORATED = 4.019E+07, SUM = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SLICK: 7.0E-01, AREA: 1.2E+06 M**2, THICKNESS: 6.7E-02 CM, MOLE WT:355.1 SETCHT FRACTION WATER IN OIL - 7.0E-01, VISCOSITY - 5.6E+05 CENTISTORES, DISPERSION TERM - 1.4E-03 WEIGHT FRACTION/BR MASS/AREA+ GLIE+02 CMS/M/M, SPCR+ 9. LE 01, TOTAL VOLUME- 5.00+03 BBL, DISPERSION+ B.4E-01 CMS/N/M, BVAP BATE+ 1.9E-01 CMS/M+M/BB

TIME = 1.1E+02 HOURS, MASS FRACTION OF FACH CUT BEMAINING: 0.0E+00 0.0E+00 1.3E-02 3.9E-01 7.2E-01 7.9E-01 8.0E-01 8.1E-01 8.1E-01 8.1E-01 8.1E-01 8.1E-01 MASS REMAINING = 7.091E+08, MASS DISPERSED = 1.750E+00, MASS EVAPORATED = 4.235E+07, SUM = 9.264E+08 FHACTION (BASED ON MASS) REMAINING IN THE SLICE 7.7E-01, AHEA= 1.2E+06 M**2, THICKNESS= 6.4E-02 CM, MOLE WT=356.2 WEICHT FRACTION WATER IN 01L = 7.0E-01, VISCOSITY = 7.0E+05 CENTISTOKES, DISPERSION TERM = 1.3E-03 WEICHT FRACTION/HR MASS/AREA= 5.9E+02 CMS/N*N, SPCR= 9.1E-01, TOTAL VOLUME= 4.9E+03 BBL, DISPERSION= 7.6E-01 CMS/N*M/HR, EVAP RATE= 1.7E-01 CMS/N*M/HR

TIME = 1.2E+02 HOURS, MASS FRACTION OF EACH CUT HEMAINING: 52 0.0E+00 0.0E+00 7.9E-03 3.5E-01 7.0E-01 7.8E-01 7.9E-01 8.0E-01 8.0E-01 8.0E-01 8.0E-01 8.0E-01 8.0E-01 MASS REMAINING = 6.9B0E+08, MASS DISPERSED = 1.041E+08, MASS EVAPORATED = 4.43BE+07, SUM = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 7.5E-01, AREA= 1.2E+06 M##2, THICKNESS= 6.2E-02 CM, MOLE WT=357.4 WEIGHT FRACTION WATER IN OIL = 7.0E-01, VISCOSITY = 8.5E+05 CENTISTOFES, DISPERSION TERM = 1.2E-03 WEIGHT FRACTION/HR MASS/AREA= 5.6E+02 CMS/M#M, SPCR= 9.1E-01, TOTAL VOLUME= 4.8E+03 BBL, DISPERSION= 0.9E-01 CMS/M#M/BR, EVAP RATE= 1.6E-01 CMS/M#M/BR

TIME = 1.3E+02 HOURS, MASS FRACTION OF EACH CUT HEMAINING: 53 0.0E+00 0.0E+00 4.6E-03 3.1E-01 6.8E-01 7.7E-01 7.8E-01 7.9E-01 7.9E-01 7.9E-01 7.9E-01 7.9E-01 7.9E-01 7.9E-01 MASS REMAINING = 6.876E+08, MASS DISPERSED = 1.926E+08, MASS EVAPORATED = 4.629E+07, SUN = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 7.4E-01, AHEA= 1.3E+06 M**2, THICKNESS= 5.9E-02 CM, MOLE WT=358.4 WEICHT FRACTION WATER IN 01L = 7.0E-01, VISCOSITY = 1.0E+06 CENTISTOFES, DISPERSION TERM = 1.2E-03 WEICHT FRACTION/HR MASS/AHEA= 5.4E+02 CMS/N*M, SPCR= 9.1E-01, TUTAL VOLUME= 4.7E+03 BBL, DISPERSION= 6.3E-01 CMS/N*M/HR, EVAP RATE= 1.5E-01 CMS/N*M/HR

TIME = 1.4E+02 HOURS, MASS FRACTION OF EACH CUT HEMAINING: 54 0.0E+00 0.0E+00 2.6E=03 2.8E=01 6.6E=01 7.6E=01 7.7E=01 7.8E=01 7.8E=01 7.8E=01 7.8E=01 7.8E=01 MASS REMAINING = 6.77HE+00, MASS DISPERSED = 2.005E+00, MASS EVAPORATED = 4.8HE+07, SUM = 9.264E+00 FRACTION (BASED ON MASS) REMAINING IN THE SICK= 7.3E=01, ARFA= 1.3E+06 M##2, THICKNESS= 5.7E=02 CM, MOLE WT=359.4 WEIGHT FRACTION WATER IN 01L = 7.0E=01, VISCOSITY = 1.2E+06 CENTISTOKES, DISPERSION TERM = 1.1E=03 WEIGHT FRACTION/HR MASS/AREA= 5.2E+02 CMS/N#M, SPCH= 9.1E=01, TOTAL VOLUME= 4.7E+03 BBL, DISPERSION= 5.7E=01 CMS/N#M/HR, EVAP RATE= 1.4E=01 CMS/N#M/HR

TIME = 1.5E+02 BOURS, MASS FRACTION OF EACH CUT REMAINING: 55 0.0E+00 0.0E+00 1.4E-03 2.5E-01 6.4E-01 7.5E-01 7.7E-01 7.7E-01 7.7E-01 7.7E-01 7.7E-01 7.7E-01 7.7E-01 MASS REMAINING = 6.6B7E+00, MASS DISPERSED = 2.079E+00, MASS EVAPORATED = 4.9B3E+07, SUN = 9.264E+00 FRACTION (BASED ON MASS) REMAINING IN THE SILCK = 7.2E-01, AREA = 1.3E+06 M**2, THICKNESS = 5.5E-02 CM, MOLE WT=360.4 WEIGET FRACTION WATER IN OIL = 7.0E-01, VISCOSITY = 1.5E+06 CENTISTOKES, DISPERSION TERN = 1.0E-03 WEIGHT FRACTION/UR MASS/AREA = 5.1E+02 CMS/M*M, SPCR = 9.1E-01, TOTAL VOLUME = 4.6E+03 BBL, DISPERSION = 5.3E-01 CMS/M*M/UR, EVAP RATE = 1.3E-01 CMS/M*M/IR

TIME = 1.6E+02 HOURS, MASS FRACTION OF EACH CUT HEMAINING; 56 0.0E+00 0.0E+00 7.8E-04 2.2E=01 6.2E=01 7.4E=01 7.6E=01 7.6E=01 7.6E=01 7.6E=01 7.6E=01 7.6E=01 7.6E=01 MASS REMAINING = 6.602E+08, MASS.DISPERSED = 2.140E+00, MASS EVAPORATED = 5.147E+07, SUM = 9.264E+00 FRACTION (BASED ON MASS) REMAINING IN THE SILCK= 7.1E=01, AREA= 1.3E+06 M##2, TRICKNESS= 5.4E=02 CM, MOLE VT=301.4 WEIGHT FRACTION WATER IN 01L = 7.0E=01, VISCOSITY = 01.7E+06 CENTISTOKES, DISPERSION TERM = 9.9E=04 WEIGHT FRACTION/HR MASS/AREA= 4.9E+02 CMS/M#M, SPCR= 9.1E=01, TOTAL VOLUME= 4.5E+03 BBL, DISPERSION= 4.8E=01 CMS/M#M/HR, EVAP RATE= 1.2E=01 CMS/M#M/HR

TIME = 1.7E+02 HOURS, MASS FRACTION OF EACH CUT HEMAINING: 57 0.0E+00 0.0E+00 4.2E=04 2.0E=01 6.1E=01 7.3E=01 7.5E=01 7.5E=01 7.5E=01 7.5E=01 7.5E=01 7.5E=01 7.5E=01 MASS REMAINING = 6.322E+00, MASS DISPERSED = 2.212E+00, MASS EVAPORATED = 5.303E+07, SUM = 9.264E+00 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 7.0E=01, AREA= 1.4E+06 M#+2, THICKNESS= 5.2E=02 CM, NOLE WT=362.3 METCHT FRACTION WATER IN 011. - 7.0E=01, VISCOSITY = 2.0E+06 CENTISTOFES, DISPERSION TERM = 9.4E=04 WEICHT FRACTION/HH MASSZAREA= 4.7E+02 CMS:M*M, SPCR= 9.2E=01, TOTAL VOLUME= 4.5E+03 BBL, DISPERSION= 4.5E=01 CMSZM*MZHR, EVAP RATE= 1.1E=01 CMSZM*MZHR

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STEP SIZE OF 5.000E-01 IS BASED ON CUT 4

TIME - LIBE+02 HOURS, MASS FRACTION OF EACH CUT REMAINING: 0.01+00 0.00000 2.22004 1.71.01 5.9001 7.22001 7.4001 7.5001 7.5001 7.5001 7.5001 7.5001 7.5001 MASS REMAINING = 0.4460+08, HASS DISPERSED = 2.2731+08, MASS EVAPORATED = 5.4510+07, SUM = 9.2640+08 FRACTION (BASED ON MASS) RUBAINING IN THE STICLE 7.000000 AREA T.400000442, THICENESS 5.00000 (M.0010 ME363.2 METCHT FRACTION WATER IN OTHE 7.00001, VISCOSTEY = 2.41+0000011STORES, DISPERSION TERM = 9.000000 FRACTION/HR
Table 16.--Output from Oil-Weathering Calculations (Continued): Prudhoe Bay Crude Oil, Time versus Calculated Results at 40°F for Open-Ocean Weathering.

MASS/AREA= 4.6E+02 CMS/M*N, SPCR= 9.2E-01, TOTAL VOLUME= 4.4E+03 BBL, DISPERSION= 4.1E-01 CMS/M*M/HR, EVAP RATE= 1.0E-01 CMS/M*M/HR

STEP SIZE OF 5.000E-01 IS BASED ON CUT 4

TIME = 1.9E+02 HOURS, MASS FRACTION OF EACH CUT REMAINING: 59 0.0E+00 0.0E+00 1.1E=04 1.5E=01 5.7E=01 7.1E=01 7.4E=01 7.4E=01 7.4E=01 7.4E=01 7.4E=01 7.4E=01 MASS REMAINING = 6.374E+00, MASS DISPERSED = 2.331E+00, MASS EVAPORATED = 5.591E+07, SUN = 9.264E+00 FRACTION (BASED ON MASS) REMAINING IN THE SELCK= 6.9E=01, AREA= 1.4E+06 M##2, THICKNESS= 4.9E=02 CN, MOLE WT=364.0 MEICHT FRACTION WATER IN OIL = 7.0E=01, VISCOSITY = 2.7E+06 CENTISTOKES, DISPERSION TERM = 8.6E=04 WEICHT FRACTION/IR MASS/AREA= 4.5E+02 CMS/M#N, SPCR= 9.2E=01, TUTAL VOLUME= 4.4E+03 BDL, DISPERSION= 3.0E=01 CMS/M#M/DR, EVAP RATE= 9.7E=02 CMS/M#M/HR

STEP SIZE OF 5.000E-01 IS BASED ON CUT 4

TIME = 2.0E+02 BOURS, MASS FRACTION OF EACH CUT.HEMAINING: 0.0E+00 0.0E+00 5.6E-05 1.3E-01 5.6E-01 7.0E-01 7.3E-01 7.3E-01 7.3E-01 7.3E-01 7.3E-01 7.3E-01 7.3E-01 MASS REMAINING = 6.307E+08, MASS DISPERSED = 2.385E+08, MASS EVAPORATED = 5.725E+07, SUN = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SILCK = 6.8E-01, AREA = 1.4E+06 M##2, THICKNESS = 4.8E-02 CM, MOLE WT=364.8 WEICHT FRACTION WATER IN 01L = 7.0E-01, VISCOSITY = 3.2E+06 CENTISTOKES, DISPERSION TERM = 8.2E-04 WEIGHT FRACTION/HR MASS/AREA = 4.4E+02 CMS/N#N, SPCR = 9.2E-01, TUTAL VOLUME = 4.3E+03 BBL, DISPERSION = 3.0E-01 CMS/N#N/HR, EVAP RATE = 9.0E-02 CMS/N#N/HR

STEP SIZE OF 5.000E-01 IS BASED ON CUT 4

TIME = 2.1E+02 HOURS, MASS FRACTIÓN OF EACH CUT REMAINING: 0.0E+00 0.0E+00 2.8E-03 1.2E-01 5.4E-01 6.9E-01 7.2E-01 7.3E-01 7.3E-01 7.3E-01 7.3E-01 7.3E-01 MASS REMAINING = 6.243E+08, MASS DISPERSED = 2.436E+08, MASS EVAPORATED = 5.852+07, SUN = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SLICK = 6.7E-01, AREA = 1.5E+06 M**2, THICKNESS = 4.6E-02 CM, MOLE WT=365.6 WEICHT FRACTION WATER IN 01L = 7.0E-01, VISCOSITY = 3.6E+06 CENTISTORES, DISPERSION TERM = 7.8E-04 WEICHT FRACTION/HR MASS/AREA = 4.3E+02 CMS/N*M, SPCR = 9.2E-01, TOTAL VOLUME = 4.3E+03 BBL, DISPERSION = 3.3E-01 CMS/N*N/HR, EVAP RATE = 8.5E-02 CMS/N*N/HR

STEP SIZE OF 5.000E-01 IS BASED ON CUT 4

TIME = 2.2E+02 HOURS, MASS FRACTION OF EACH CUT REMAINING: 62 0.0E+00 0.0E+00 1.4E-05 1.0E-01 5.3E-01 6.9E-01 7.2E-01 7.2E-01 7.2E-01 7.2E-01 7.2E-01 7.2E-01 7.2E-01 7.2E-01 MASS REMAINING = 6.1RE2+00B, MASS DISPERSED = 2.4R5E+00B, MASS EVAPORATED = 5.973E+07, SUN = 9.264E+00B FRACTION (BASED ON MASS) REMAINING IN THE SILCK= 6.7E-01, AREA= 1.5E+06 M##2, TRICKNESS= 4.5E-02 CM, MOLE WT=366.4 WEIGHT FRACTION WATER IN 01L = 7.0E-01, VISCOSITY = 4.2E+06 CENTISTOKES, DISPERSION TERM = 7.5E-04 WEIGHT FRACTION/RR MASS/AREA= 4.2E+02 CMS/M#M, SPCH= 9.2E-01, TOTAL VOLUME= 4.2E+03 BBL, DISPERSION= 3.1E-01 CMS/M#M/HR, EVAP RATE= 7.9E-02 CMS/M#M/RR

STEP SIZE OF 5.000E-01 IS BASED ON CUT 4

TIME = 2.3E+02 HOURS, MASS FRACTION OF FACH CUT REMAINING: 63 0.0E+00 0.0E+00 6.5E-06 9.0E-02 5.1E-01 6.8E-01 7.1E-61 7.2E-01 7.2E-01 7.2E-01 7.2E-01 7.2E-01 7.2E-01 MASS REMAINING = 6.124E+08, MASS DISPERSED = 2.531E+08, MASS EVAPORATED = 6.0400E+07, SUN = 9.264E+08 FRACTION (BASED ON MASS) REMAINING IN THE SILCK= 6.6E-01, AREA= 1.5E+06 M**2, THICKNESS= 4.4E-02 CM, MOLE WT=367.1 WEICHT FRACTION WATER IN 011. = 7.0E-01, VISCOSITY = 4.7E+06 CENTISTOKES, DISPERSION TERM = 7.2E-04 WEICHT FRACTION/UR MASS/AREA= 4.1E+02 CMS/M*M, SPCR= 9.2E-01, TOTAL VOLUME= 4.2E+03 BBL, DISPERSION= 2.9E-01 CMS/M*M/UR, EVAP RATE= 7.5E-02 CMS/M*M/UR

STEP SIZE OF 5.000E-01 IS BASED ON CUT 4

THE CUT NUMBERING BECINS WITH A BASED ON THE ORIGINAL CUT NUMBERS

THE FINAL MASS FRACTIONS FOR THE SLICE AT 2.4E(02 HOURS ARE: 0.000E+00.0.000E+00.0.4191.06.7.975E.02.4.987E=01.6.735E=01.7.072E=01.7.114E=01.7.116E=01.7.117E=01.7.117E=01. Table 16.--Output from Oil-Weathering Calculations (Continued): Prudhoe Bay Crude Oil, End of Calculated Result, Including Final Mass Balance.

7.117E-01 FRACTION (BASED ON MASS) REMAINING IN THE SLICK= 6.6E-01, AREA= 1.5E+06 N**2, THICKNESS= 4.3E-02 CN, NOLE VT=367.1 MASS REMAINING = 6.077E+00, MASS DISPENSED = 2.569E+08, MASS EVAPORATED = 6.181E+07, SUM = 9.264E+08

****** FINAL OVERALL MASS BALANCE FOR PARENT OIL **********

FINAL MASS FRACTIONS OF CUTS: 0.000E+00 0.000E+00 0.000E+00 0.000E+00 1.471E-06 5.619E-02 3.830E-01 5.243E-01 5.518E-01 5.551E-01 5.553E-01 5.553E-01 5.553E-01 5.553E-01 5.553E-01 FRACTION (BASED ON MASS) HEMAININC= 4.356E-01 MASS HEMAININC= 6.077E+08 MASS DISPERSED= 5.275E+08 MASS EVAPORATED= 2.600E+08 MASS DELETED= 1.566E+01 TUTAL= 1.395E+09 ORIGINAL MASS= 1.395E+09 explanatory but some care must be taken in order to identify the cuts at each time step. There are cases where the first cuts can be so volatile that they evaporate away immediately (less than 1 hour). In this case the cut(s) will be deleted from the calculation and the remaining cuts renumbered.

Page 47 illustrates the output where a cut has been deleted because it evaporates too fast to be considered in the calculation. The cut renumbering occurs immediately before the time integration begins and will always be noted on the output before the time - 0 print. The user must know that a cut has been deleted or interpretation of the results will be shifted by one (or more) cut. The deletion of a cut is also noted before the final mass fractions are printed by telling the user the number of the first cut printed. This is illustrated on page 55 where it is noted that the cut numbering begins with 2.

After pool-weathering and broken-ice field weathering, open ocean weathering at 40°C was chosen. Page 56 shows another intermediate characterization of the oil. Note that in this characterization only twelve cuts are shown. This is because the first three cuts have weathered away. The remaining cuts are renumbered and characterized in the usual manner. Thus, if a user desires to follow a particular cut through a scenario, care must be taken to correctly identify the desired cut. This is most easily accomplished by following the boiling point of the component (which does not change) through the various output.

As with the two previous weathering "compartments," the oil characterization data are followed by the input constants and the results of the weathering calculations (pages 57 through 67). Page 67 presents the end of the weathering calculations and the final overall mass balance for the <u>parent oil</u>. This mass balance serves as a means of checking that the sum of the mass evaporated, mass dispersed, mass remaining, and mass deleted (very volatile cuts) is equal to the original mass.

An example of the 80-column output is presented in Table 17. This output was generated at the same time as the output in Table 16. Note that the

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Table 17--Illustration of 80-Column Output from Ocean-Ice Oil-Weathering Code: Prudhoe Bay Crude Oil, Weathering of Oil in Pools on Top of Ice at 32°F.

WEATHERING OF OIL IN POOLS ON TOP OF ICE

OIL: PRUDHOE BAY, ALASKA TEMPERATURE: 32.0 DEG F. WIND SPEED: 10.0 KNOTS SPILL SIZE: 1.000E+04 BARRELS MASS-TRANSFER COEFFICIENT CODE: 2

FOR THE OUTPUT THAT FOLLOWS, MOLES=CRAM MOLES CMS=CRAMS, VP=VAPOR PRESSURE IN ATMOSPHERES BP=BOILING POINT IN DEC F, API=CRAVITY MW=MOLECULAR WEIGHT

CUT	MOLES	GMS	VP	BP	ΔΡΙ	MW
1	2.74E+05	2.29E+07	4.09E-02	1.50E+02	7.27E+01	83
2	3.1 3E+05	2.96E+07	t.35E-02	1.90E+02	6.42E+01	93
3	3.91E+05	4.14E+07	3.25E-03	2.35E+02	5.67E+01	105
4	3.67E+05	4.37E+07	7.05E-04	2.80E+02	5.16E+01	119
- 5	3.43E+05	4.60E+07	1.40E-04	3.25E+02	4.76E+01	133
6	2.92E+05	4.41E+07	2.44E-05	3.70E+02	4.32E+01	1 50
7	3.30E+05	5.53E+07	3.98E-06	4.15E+02	4.15E+01	167
8	3.41E+05	6.31E+07	5.86E-07	4.60E+02	3.78E+01	184
9	3.34E+05	6.69E+07	8.22E-08	5.05E+02	3.48E+01	200
10	L.74E+05	3.84E+07	8.24E-09	5.54E+02	3.06E+01	220
11	3.58E+05	9.01E+07	4.12E-10	6.09E+02	2.91E+01	251
12	3.41E+05	9.59E+07	2.02E-11	6.62E+ 92	2.62E+01	281
13	2.75E+05	8.59E+07	8.60E-13	7.12E+02	2.40E+01	312
14	3.04E+05	1.07E+08	1.96E-14	7.64E+02	2.25E+01	351
15	9.42E+95	5.65E+08	0.00E+00	8.50E+02	1.14E+01	600

MOUSSE CONSTANTS: MOONEY: 0.00E+00, MAX H20=-1.00, WIND**2: 0.00E+00 DISPERSION CONSTANTS: KA: 1.08E-01, KB: 3.00E+01, S-TENSION: 1.00E+00 VIS CONSTANTS: VIS23C: 3.30E+01, ANDRADE = 9.00E+03, FRACT = 1.05E+01

FOR THE OUTPUT THAT FOLLOWS, TIME=HOURS BBL=BARRELS, SPCR=SPECIFIC CRAVITY, AREA=M*M THICKNESS=CM, W=PERCENT WATER IN OIL (MOUSSE) DISP=DISPERSION RATE IN CMS/M*M/HR ERATE=EVAPORTION RATE IN CMS/M*M/HR M/A=MASS PER M*M OF OIL IN THE SLICK I=FIRST CUT WITH CREATER THAN 1% (MASS) REMAINING J=FIRST CUT WITH CREATER THAN 1% (MASS) REMAINING DISPERSION WAS TURNED OFF SPREADING WAS TURNED OFF

TIME BE	il sp	'CR	AREA	THICKNESS	W	DISP	ERATE	M/A	I	J
0 I.OE	.+04 0.	88 7	.9E+04	2.0E+00	0	0.0E+00	0.UE+00	1.8E+04	1	1
1 9.88	.+03 0.	88 7	.9E+04	2.0E+00	0	0.0E+00	1.7E+02	1.7E+04	1	1
2 9.7E	.+03 0.	88 7	.9E+04	1.9 E+00	0	0.0E+00	1.3E+02	1.7E+04	1	2
3 9.7E	.+03 0.	88 7	.9E+04	1.9E+00	0	0.0E+00	9.5E+01	1.7E+04	1	2
4 9.6E	.+03 0.	88 7	.9E+04	1.9E+00	0	0.0E+00	7.3E+0L	1.7E+04	t	3
5 9.6E	.+03 0.	89 7	.9E+04	1.9 E+00	0	0.0E+00	6.2E+01	1.7E+04	1	3
6 9.5E	C+03 0.	89 7	.9E+04	1.9 E+00	0	0.0E+00	5.2E+01	1.7E+04	1	3
7 9.5E	:+03 0.	89 7	.9E+04	1.9 E+00	Ø	0.0E+00	4.5E+01	1.7E+04	1	3
8 9.4E	.+03 0.	89 7	.9E+04	1.92+00	0	0.0E+00	4.0E+01	1.7E+04	2	3
99.4E	.+03 0.	89 7	.9E+04	1.9E+00	0	0.0E+00	3.6E+01	1.7E+04	2	3
10 9.4E	2 +03 0.	89 7	.9E+04	i.9 E+00	0	0.0E+00	3.36+01	1.7E+04	2	3
11 9.48	:+ 03 0.	89 7	.9E+04	1.9E+00	0	0.0E+00	3.0E+01	1.7E+04	2	3
12 9.48	:+03 0 .	89 7	.9E+04	L.9 E+00	0	0.0E+00	2.8E+01	1.7E+04	2	3
13 9.38	:+03 0.	89 7	.9E+04	1.9 E+00	0	0.0E+00	2.6E+01	1.7E+04	2	3
14 9.3E	:+03 0.	89 7	.9E+04	1.9 E+00	0	0.0E+00	2.4E+01	1.7E+04	2	3
15 9.3E	.+03 0.	89 7	.9E+04	1.9 E+00	θ	0.0E+00	2.2E+01	1.7E+04	2	3
16 9.3E	:+03 0.	89 7	.9E+04	1.9 E+00	0	0.0E+00	2.1E+01	1.7E+04	2	4
17 9.38	:+03 0.	89 7	.9E+04	1.9E+ 00	0	0.0E+00	2.0E+01	1.7E+04	2	4
18 9.38	:+03 0.	89 7	.9E+04	1.9 E+00	0	0.0E+00	1.9E+01	1.6E+04	2	4
19 9.26	C+03 0.	89 7	.9E+04	1.8 E+00	Ø	0.0E+00	1.8E+01	l.6E+04	2	4
20 9.28	2+03 0.	89 7	.9E+04	1.8E+00	0	0.0E+ UO	1.72+01	1.6E+04	2	4
21 9.28	C+03 0.	89 7	.9E+04	1.8E+90	0	0.0E+00	l.6E+01	1.6E+04	2	4
22 9.2E	C+03 0.	89 7	.9E+04	1.8 E+00	0	0.0E+00	1.6E+01	i.6E+04	2	4
23 9.25	C+03 0.	89 7	.9E+04	1.8E+00	0	0.0E+00	1.5E+01	1.6E+ 04	2	4

WEATHERING OF OIL IN A BROKEN ICE FIELD AFTER ICE POOL WEATHERING FOR 2.400E+01 HOURS

8 8.7E+03 0.90 2.3E+05 5.6E-01 9 8.7E+03 0.90 2.5E+05 5.6E-01 10 8.6E+03 0.90 2.7E+05 5.3E-01 11 8.6E+03 0.90 2.7E+05 5.1E-01 12 8.5E+03 0.90 2.8E+05 4.8E-01 13 8.5E+03 0.90 2.9E+05 4.6E-01 14 8.5E+03 0.90 3.0E+05 4.5E-01

16 8.4E+03 0.90 3.1E+05 4.3E-01

17 8.4E+03 0.90 3.2E+05 4.2E-01

OIL: PRUDHOE BAY, ALASKA TEMPERATURE: 32.0 DEC F. WIND SPEED: 12.0 KNOTS TEMPERATURE: 32.0 DEG F, WIND SPILL SIZE: 9.195E+03 BARNELS MASS-TRANSFER COEFFICIENT CODE: 2 FOR THE OUTPUT THAT FOLLOWS, MOLES=CRAM MOLES CMS=CRANS, VP=VAPOR PRESSURE IN ATMOSPHERES BP=BOLLING POINT IN DEC F. API=CRAVITY MW=MOLECULAR WEIGHT MOLES CITT CMS VP RP API MW 5.99E-02 1.87E-01 1.57E+01 1.50E+02 7.27E+01 83 3.11E+03 2.92E+05 2.06E-02 1.90E+02 6.42E+01 93 2 1.31E+05 5.42E-03 1.38E+07 3 2.35E+02 5.67E+01 165 2.90E+05 2.80E+02 1.24E-03 4 3.46E+07 5.16E+01 119 5 3.28E+05 4.39E+07 2.59E-04 3.25E+02 4.76E+01 133 2.90E+05 4.37E+07 4.81E-05 3.70E+02 4.52E+01 150 6 3.30E+05 5.52E+07 4.15E+02 8.33E-06 4.15E+01 167 7 3.78E+01 184 ត 3.41E+05 6.31E+07 1.31E-06 4.60E+02 1.95E-07 9 3.34E+05 6.69E+07 5.05E+02 3.48E+01 200 1.74E+05 3.84E+07 5.34E+02 2.12E-08 3.06E+01 220 10 11 3.58E+05 9.01E+07 1.17E-09 6.09E+02 2.91E+01 251 3.41E+05 9.59E+07 6.39E-11 6.62E+02 2.62E+01 281 12 2.40E+01 312 3.03E-12 2.75E+05 8.59E+07 7.12E+02 13 2.25E+01 351 3.04E+05 1.07E+08 7.87E-14 7.64E+02 14 15 9.42E+05 5.65E+08 0.00E+00 8.50E+02 1.14E+01 600 MOUSSE CONSTANTS: MOONEY= 6.20E-01, MAX H20= 0.70, WIND**2= 1.00E-02 K4=1.000E+01 DISPERSION CONSTANTS: KA= 1.08E-01, KB= 5.00E+01, S-TENSION= 3.00E+01 KC=1.000E+01 FRACTION OF ICE COVER=6.600E-01 VIS CONSTANTS: VIS25C= 3.50E+01. ANDRADE = 9.00E+03. FRACT = 1.05E+01 FOR THE OUTPUT THAT FOLLOWS, TIME=HOURS BBL=BARRELS, SPCR=SPECIFIC CRAVITY, AREA*M*M THICKNESS=CM, W=PERCENT WATER IN OIL (MOUSSE) DISP=DISPERSION RATE IN CMS/M*M/HR ERATE=EVAPORTION RATE IN CMS/M*M/HR M/A=MASS PER M*M OF OIL IN THE SLICK I=FIRST CUT WITH GREATER THAN 1% (MASS) REMAINING J=FIRST CUT WITH CREATER THAN 30% (MASS) REMAINING CUT I GOES AWAY IN MINUTES, THEREFORE IT WAS DELETED AND THE CUTS RENUMBERED TIME BBL SPGR AREA THICKNESS W DISP ERATE M⁄A T .1
 Internet
 BBL
 Stor
 AREA
 Internets

 0
 9.2E+03
 0.89
 7.9E+04
 1.8E+00

 1
 9.1E+03
 0.89
 1.1E+05
 1.3E+00

 2
 9.0E+03
 0.89
 1.4E+05
 1.3E+00

 3
 9.0E+03
 0.89
 1.4E+05
 1.1E+00

 3
 9.0E+03
 0.89
 1.4E+05
 9.2E-01
 0 7.3E+01 2.5E+01 1.2E+04 1 48 4.4E+01 2.3E+01 9.5E+03 1 1 2 60 2.8E+01 2.1E+01 8.2E+03 1 2 8.9E+03 0.89 1.7E+05 8.2E-01 66 1.9E+01 1.9E+01 7.3E+03 1 2 5 8.9E+03 0.89 1.9E+05 7.4E-01 6 8.8E+03 0.89 2.0E+05 6.9E-01 7 8.8E+03 0.89 2.2E+05 6.4E-01 8 8.7E+03 0.99 2.3E+05 5.9E-01 69 1.5E+01 1.7E+01 6.7E+03 1 3 70 1.3E+01 1.5E+01 6.1E+03 - 1 3 70 1.3E+01 1.3E+01 5.7E+03 2 3

 $\mathbf{70}$

70 1.2E+01 1.2E+01 5.3E+03 2

70 1.2E+01 1.1E+01 5.0E+03 2 70 1.2E+01 9.6E+00 4.8E+03 2

70 1.1E+01 8.7E+00 4.5E+03 2

70 1.1E+01 7.9E+00 4.3E+03 2 70 1.1E+01 7.3E+00 4.2E+03 2

70 1.1E+01 6.8E+00 4.0E+03 2

70 1.0E+01 6.3E+00 3.9E+03 2 70 1.0E+01 5.9E+00 3.8E+03 2

3

3 3

3

4 4

4

4

4

18	8.3E+03	0.90	3.3E+05	4.1E-01	70	9.8E+00	5.5E+00	3.6E+03	3	4
19	8.3E+03	0.90	3.4E+05	3.9E-01	70	9.6E+00	5.2E+00	3.5E+03	3	4
20	8.3E+03	0.90	3.4E+05	3.8E-01	70	9.4E+00	4.9E+00	3.4E+03	3	4
21	8.2E+03	6.90	3.3E+05	3.7E-01	70	9.2E+00	4.6E+00	3.3E+03	3	4
22	8.2E+03	0.90	3.6E+05	3.6E-01	70	9.0E+00	4.3E+00	3.3E+03	3	4
23	8.1E+03	0.90	3.7E+05	3.5E-01	70	8.8E+00	4.1E+00	3.2E+03	3	4
24	8.1E+03	0.90	3.7E+05	3.5E-01	70	8.6E+00	3.9E+00	3.1E+03	3	4
25	6.1E+03	9.90	3.8E+05	3.4E-01	70	8.4E+00	3.7E+00	3.9E+03	3	4
26	8.0E+03	0.90	3.9E+05	3.3E-01	70	8.2E+00	3.5E+00	3.0E+03	3	4
27	8.0E+03	0.90	3.9E+05	3.2E-01	70	8.0E+00	3.3E+00	2.9E+03	3	4
28	8.0E+03	0.90	4.0E+05	3.2E-01	70	7.8E+00	3.1E+00	2.9E+03	3	4
29	7.9E+03	0.90	4.1E+05	3.1E-01	70	7.6E+00	2.9E+00	2.8E+03	3	4
31	7.9E+03	0.90	4.1E+05	3.0E-01	70	7.4E+00	2.8E+00	2.7E+03	3	4
32	7.9E+03	0.90	4.2E+05	3.0E-01	70	7.3E+00	2.6E+00	2.7E+03	3	4
33	7.8E+03	Ø.90	4.3E+05	2.9E-01	70	7.1E+00	2.5E+00	2.6E+03	3	4
34	7.8E+ 0 3	0,90	4.4E+05	2.8E-01	70	6.9 E+00	2.4E+00	2.6E+03	3	5
35	7.7E+03	0.90	4.4E+05	2.8E-01	70	6.8E+00	2.3E+00	2.5E+03	3	5
37	7.7E+03	0.90	4.5E+05	2.7E-01	70	6.6E+ 00	2.2E+00	2.5E+03	3	5
38	7.7E+03	0.90	4.3E+05	2.7E-01	70	6.5E+ 00	2.1E+00	2.4E+03	3	5
39	7.7E+03	0.90	4.6E+05	2.7E-01	70	6.3E+00	2.0E+00	2.4E+#3	3	5
40	7.6E+03	0.90	4.6E+05	2.6 E-0 1	70	6.2E+00	1.9E+00	2.4E+03	3	5
4 L	7.6E+ 0 3	0.90	4.7E+05	2.6E-01	70	6.1E+00	1.8E+00	2.3E+03	3	5
42	7.6E+03	0.90	4.7E+05	2.5E-01	70	6.0 E+00	1.8E+00	2.3E+03	3	5
43	7.5E+03	0.90	4.8E+05	2.5E-01	70	5.8E+00	1.7E+00	2.3E+03	3	5
44	7.5E+03	0.90	4.8E+05	2.5E-01	70	5.7E+00	1.7E+00	2.2E+03	3	5
45	7.5E+ 0 3	0.90	4.9E+05	2.4E-01	70	5.6E+00	1.6E+00	2.2E+03	3	5
46	7.5E+03	0.90	4.9E+05	2.4E-01	70	5.5E+ 00	1.6E+00	2.2E+03	4	5
47	7.4E+03	0.90	5.0E+05	2.4E-01	70	5.4E+00	1.5E+00	2.1E+03	4	5
48	7.4E+03	0.90	5.0E+05	2.3E-01	70	5.3E+00	1.5E+00	2.1E+03	4	5
49	7.4E+03	0.90	5.1E+05	2.3E-01	70	5.2E+ 00	1.4E+00	2.1E+03	4	5
50	7.4E+03	0.90	5.1E+05	2.3E-01	70	5.1E+00	1.4E+00	2.1E+03	4	5
5 L	7.3E+03	0.90	5.2E+05	2.3E-01	70	5.0E+ 00	1.4E+00	2.0E+03	4	5
61	7.1E+03	0.9 0	5.6E+05	2.0E-01	70	4.2E+00	1.1E+00	1.8E+03	4	5
71	6.9E+03	0.90	5.9E+05	1.8E-01	70	3.5E+00	8.4E-01	1.7E+03	4	5
81	6.7E+03	0.91	6.3E+05	1.7E-01	70	3.0E+00	6.8E-01.	1.5E+03	4	5
91	6.6E+ 0 3	0.91	6.6E+ 05	1.6E-01	70	2.6E+00	5.6E-01	1.4E+03	4	6

.

OPEN OCEAN WEATHERING AFTER: ICE POOL WEATHERING FOR 2.400E+01 HOURS BROKEN ICE FIELD WEATHERING FOR 1.000E+02 HOURS - .a.

OIL: PRUDHOE BAY, ALASKA TEMPERATURE: 40.0 DEC F, WIND SPEED: 20.0 KNOTS SPILL SIZE: 6.428E+03 BARRELS MASS-TRANSFER COEFFICIENT CODE: 2

FOR THE OUTPUT THAT FOLLOWS, MOLES=CRAM MOLES CMS=CRAMS, VP=VAPOR PRESSURE IN ATMOSPHERES BP=BOILING POINT IN DEC F, API=GRAVITY MW=MOLECULAR WEIGHT

~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~		• •	MCR.				MER /	
CUI	i nortes) G	ns	٧P	BP	API	MIN	
1	1 4.40E-	•02 5.2	3E+00	1.77E-03	2.80E+02	5.16E+01	119	
		لم 1 است	45104	A0-310 C	2 255-42	4 765-41	100	
						4.105.01	100	
- 3	3 1.2664	1.9	0E+07 -	7.492-05	3.70E+02	4.52E+01	150	
4	L 2.33E4	05 3.9	9E+07	1.33E-05	4.15E+02	4.15E+01	167	
			45.07	0 105-04	4 605.00	0 705.01	104	
i,) 2.5261	-00 4.a	HE+07	2.10E-00	4.00L+02	3. (OF401	184	
•	5 2.60E4	05 5.2	1E+07 :	3.40E-07	5.05E+02	3. 48E+0 1	200	
-	7 1 3664	65 3 6	05+07	3 865-88	5 548+07	3 965+91	220	
						0.0000000	240	
- E	3 2.7961	-140 7.0	SE+07	2.296-09	6.09E+02	2.916+01	251	
q) 2.66E+	05 7.4	9E+07	1.33E-10	6.62E+02	2.62E+01	281	
		AR 67	AF-07	6 76E-19	7 125+02	2 405-01	212	
10	تعالية و	00 0.1	06701	0.106-14	(. 1 <u>.</u>	2. TULTUI	014	
11	L = 2.37€+	•05 8.3	4E+07	L.91E-13	7.64E+02	2.25E+01	351	
1.2	2 7 35E4	05 4.4	1E+08	A . GAF+6A	8.50E+02	1.14E+01	600	
			10.00	0.000.00	0.001.00			
MOUS	SSE CONST	TANTS: M	OONEY =	6.20E-01	. MAX H20=	0.70, WIN	(D**2* 1.(90E-03
DISP	PERSION C	ONSTANT	S. KA=	1 085-01	KB= 5 001	F+01 S-TF	INSION= 3	005+01
0131								
VIS	CONSTANT	S: V152	SC= 3.5	0E+01, A	NDRADE = 9	.006+03, r	MACT = 1	. 05E+01
FOD	THE AUTE		FOLLOW		INDE			
r Un	INE OUT	UL INAL	f ULLUW	9, IIAE-	auuns			
BBL=	BARRELS,	SPGR=S	PECIFIC	GRAVITY	. AREA=M≭M			
THIC	WNESS=C	I W=PFR	CENT VA	TER IN O	LL (MOUSSE))		
1010						•		
DISP	·= DISPERS	SION HAT	E IN GM	5∕п≭п∕нк				
ERAT	CE=EVAPOR	TION RA	TE IN G	MS/M×M/H)	R			
M / A -	MACO DED		OTT IN	THE SIL	C.K.			
	11A33 FE			INE SLI				
[=F]	RST CUT	WITH CR	EATER T	HAN 17	(MASS) REMA	AINING		
$f = S^{-1}$	BST CUT	WITH CR	FATER T	HAN SAR	(MASS) REMA	A EN ENC		
5 - r i	101 .001							
TIME	E BBL	SPCR A	REA TH	ICKNESS	W DISP	ERATE	M/A I	J
TIME	E BBL	SPCR A	REA TH	ICKNESS	W DISP 70 3 5F+00	ERATE	M/A I 4E+03 1	J
TIME 0	E BBL 6.4E+03	SPCR A 0.91 6.	REA TH 8E+05 1	ICKNESS	W DISP 70 3.5E+00	ERATE 0.0E+00 1	M/A I .4E+03 1	J
TIME 0 I	E BBL 6.4E+03 6.4E+03	SPCR A 0.91 6. 0.91 6.	REA TH 8E+05 1 9E+05 1	ICKNESS .5E-01 .5E-01	W DISP 70 3.5E+00 70 3.4E+00	ERATE 0.0E+00 1 1.0E+00 1	M∕A I .4E+03 1 .3E+03 1	J 1 1
TIME 0 1 2	E BBL 6.4E+03 6.4E+03 6.4E+03	SPCR A 0.91 6. 0.91 6. 0.91 7.	REA TH 8E+05 1 9E+05 1 0E+05 1	ICKNESS .5E-01 .5E-01 .5E-01	W DISP 70 3.5E+00 70 3.4E+00 70 3.4E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1	M/A I .4E+03 1 .3E+03 1 .3E+03 1	J 1 1 2
TIME 0 1 2	E BBL 6.4E+03 6.4E+03 6.4E+03	SPCR A 0.91 6. 0.91 6. 0.91 7.	REA TH 8E+05 1 9E+05 1 0E+05 1	ICKNESS .5E-01 .5E-01 .5E-01	W DISP 70 3.5E+00 70 3.4E+00 70 3.4E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1 9.9E-01 1	M/A I .4E+03 1 .3E+03 1 .3E+03 1	J 1 2 2
TIME 0 1 2 3	E BBL 6.4E+03 6.4E+03 6.4E+03 6.4E+03 6.4E+03	SPCR A 0.91 6. 0.91 6. 0.91 7. 0.91 7.	REA TH 8E+05 1 9E+05 1 0E+05 1 1E+05 1	ICKNESS .5E-01 .5E-01 .3E-01 .4E-01	W DISP 70 3.5E+00 70 3.4E+00 70 3.4E+00 70 3.3E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1 9.8E-01 1	M/A I .4E+03 1 .3E+03 1 .3E+03 1 .3E+03 1	J 1 2 2
TIME 0 1 2 3 4	E BBL 6.4E+03 6.4E+03 6.4E+03 6.4E+03 6.4E+03 6.3E+03	SPCR A 0.91 6. 0.91 6. 0.91 7. 0.91 7. 0.91 7.	REA TH 8E+05 1 9E+05 1 0E+05 1 1E+05 1 1E+05 1	ICKNESS .5E-01 .5E-01 .3E-01 .4E-01 .4E-01	W DISP 70 3.5E+00 70 3.4E+00 70 3.4E+00 70 3.3E+00 70 3.2E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1 9.8E-01 1 9.5E-01 1	M∕A I .4E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1	J 1 2 2 2
TIME 0 1 2 3 4 5	E BBL 6.4E+03 6.4E+03 6.4E+03 6.4E+03 6.3E+03 6.3E+03	SPCR A 0.91 6. 0.91 6. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7.	REA TH 8E+05 1 9E+05 1 0E+05 1 1E+05 1 1E+05 1 2E+05 1	ICKNESS .5E-01 .5E-01 .3E-01 .4E-01 .4E-01 .4E-01	W DISP 70 3.3E+00 70 3.4E+00 70 3.4E+00 70 3.3E+00 70 3.2E+00 70 3.2E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1 1.0E+00 1 9.8E-01 1 9.3E-01 1 9.2E-01 1	M∕A I .4E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1	J 1 2 2 2 2
TIME 0 1 2 3 4 5	E BBL 6.4E+03 6.4E+03 6.4E+03 6.4E+03 6.3E+03 6.3E+03 6.3E+03	SPCR A 0.91 6. 0.91 6. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7.	REA TH 8E+05 1 9E+05 1 0E+05 1 1E+05 1 1E+05 1 2E+05 1	ICKNESS .5E-01 .5E-01 .3E-01 .4E-01 .4E-01 .4E-01	W DISP 70 3.3E+00 70 3.4E+00 70 3.4E+00 70 3.3E+00 70 3.2E+00 70 3.2E+00 70 3.2E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1 9.8E-01 1 9.5E-01 1 9.2E-01 1	M/A I .4E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1	J 1 1 2 2 2 2 2
TIME 0 1 2 3 4 5 6	E BBL 6.4E+03 6.4E+03 6.4E+03 6.4E+03 6.3E+03 6.3E+03 6.3E+03 6.3E+03	SPCR A 0.91 6. 0.91 6. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7.	REA TH 8E+05 i 9E+05 i 0E+05 i 1E+05 i 1E+05 i 2E+05 i 3E+05 i	ICKNESS .5E-01 .5E-01 .3E-01 .4E-01 .4E-01 .4E-01 .4E-01 .4E-01	W DISP 70 3.3E+00 70 3.4E+00 70 3.4E+00 70 3.3E+00 70 3.2E+00 70 3.1E+00 70 3.1E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1 9.8E-01 1 9.3E-01 1 9.2E-01 1 8.9E-01 1	M/A I .4E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .2E+03 1	J 1 1 2 2 2 2 3
TIME 0 1 2 3 4 5 6 7	E BBL 6.4E+03 6.4E+03 6.4E+03 6.3E+03 6.3E+03 6.3E+03 6.3E+03 6.3E+03 6.3E+03	SPCR A 0.91 6. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7.	REA TH 8E+05 1 9E+05 1 0E+05 1 1E+05 1 1E+05 1 2E+05 1 3E+05 1 3E+05 1	ICKNESS .5E-01 .5E-01 .4E-01 .4E-01 .4E-01 .4E-01 .4E-01	W DISP 70 3.3E+00 70 3.4E+00 70 3.4E+00 70 3.3E+00 70 3.2E+00 70 3.2E+00 70 3.1E+00 70 3.1E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1 9.8E-01 1 9.5E-01 1 9.2E-01 1 8.9E-01 1 8.9E-01 1 8.6E-01 4	M∕A I .4E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .2E+03 1 .2E+03 1 .2E+03 1	J 1 1 2 2 2 3 3
TIME 0 2 3 4 5 6 7	E BBL 6.4E+03 6.4E+03 6.4E+03 6.4E+03 6.3E+03 6.3E+03 6.3E+03 6.3E+03 6.3E+03	SPCR A 0.91 6. 0.91 6. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7.	REA TH 8E+05 1 9E+05 1 1E+05 1 1E+05 1 1E+05 1 2E+05 1 3E+05 1 4E+05 1	ICKNESS .5E-01 .5E-01 .4E-01 .4E-01 .4E-01 .4E-01 .4E-01 .3E-01 .5E-01	W DISP 70 3.5E+00 70 3.4E+00 70 3.4E+00 70 3.3E+00 70 3.2E+00 70 3.2E+00 70 3.1E+00 70 3.1E+00 70 3.4E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1 9.8E-01 1 9.5E-01 1 9.2E-01 1 8.9E-01 1 8.6E-01 1 8.4E-01 1	M/A I .4E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .2E+03 1 .2E+03 1 .2E+03 2	J 1 1 2 2 2 3 3 3
TIME 0 1 2 3 4 5 6 7 8	E BBL 6.4E+03 6.4E+03 6.4E+03 6.4E+03 6.3E+03 6.3E+03 6.3E+03 6.3E+03 6.3E+03 6.3E+03 6.3E+03	SPCR A 0.91 6. 0.91 6. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7.	REA TH 8E+05 1 9E+05 1 1E+05 1 1E+05 1 1E+05 1 2E+05 1 3E+05 1 3E+05 1	ICKNESS .5E-01 .5E-01 .4E-01 .4E-01 .4E-01 .4E-01 .4E-01 .4E-01 .3E-01	W DISP 70 3.3E+00 70 3.4E+00 70 3.4E+00 70 3.3E+00 70 3.2E+00 70 3.1E+00 70 3.1E+00 70 3.1E+00 70 3.1E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1 9.8E-01 1 9.3E-01 1 9.2E-01 1 8.9E-01 1 8.6E-01 1 8.4E-01 1	M/A I .4E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .2E+03 1 .2E+03 1 .2E+03 2	J 1 1 2 2 2 3 3 3 3
TIME 0 1 2 3 4 5 6 7 8 9	E BBL 6.4E+03 6.4E+03 6.4E+03 6.4E+03 6.3E+03 6.3E+03 6.3E+03 6.3E+03 6.3E+03 6.2E+03 6.2E+03	SPGR A 0.91 6. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7.	REA TH 8E+05 1 9E+05 1 1E+05 1 1E+05 1 2E+05 1 3E+05 1 3E+05 1 5E+05 1	ICKNESS .5E-01 .5E-01 .4E-01 .4E-01 .4E-01 .4E-01 .4E-01 .3E-01 .3E-01	W DISP 70 3.5E+00 70 3.4E+00 70 3.4E+00 70 3.3E+00 70 3.2E+00 70 3.1E+00 70 3.1E+00 70 3.1E+00 70 3.0E+00 70 2.9E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1 9.8E-01 1 9.5E-01 1 9.2E-01 1 8.9E-01 1 8.4E-01 1 8.4E-01 1	M∕A I .4E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .2E+03 1 .2E+03 1 .2E+03 2	J 1 1 2 2 2 2 3 3 3 3
TIME 1 2 3 4 5 6 7 8 9	E BBL 6.4E+03 6.4E+03 6.4E+03 6.4E+03 6.3E+03 6.3E+03 6.3E+03 6.3E+03 6.2E+03 6.2E+03 6.2E+03	SPCR A 0.91 6. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7.	REA TH 8E+05 1 9E+05 1 1E+05 1 1E+05 1 2E+05 1 3E+05 1 3E+05 1 5E+05 1 5E+05 1	ICKNESS .5E-01 .5E-01 .4E-01 .4E-01 .4E-01 .4E-01 .4E-01 .3E-01 .3E-01	W DISP 70 3.3E+00 70 3.4E+00 70 3.3E+00 70 3.3E+00 70 3.3E+00 70 3.2E+00 70 3.1E+00 70 3.1E+00 70 3.1E+00 70 2.9E+00 70 2.9E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1 9.8E-01 1 9.3E-01 1 9.2E-01 1 8.9E-01 1 8.6E-01 1 8.4E-01 1 8.1E-01 1 7.9E-01 1	M∕A I .4E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .2E+03 1 .2E+03 1 .2E+03 2 .2E+03 2	J 1 1 2 2 2 3 3 3 3 3 3
TIME 0 1 2 3 4 5 6 7 8 9 11	E BBL 6.4E+03 6.4E+03 6.4E+03 6.3E+03 6.3E+03 6.3E+03 6.3E+03 6.3E+03 6.2E+03 6.2E+03 6.2E+03 6.2E+03	SPCR A 0.91 6. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7.	REA TH 8E+05 1 9E+05 1 1E+05 1 1E+05 1 1E+05 1 3E+05 1 3E+05 1 3E+05 1 5E+05 1 5E+05 1 6E+05 1	ICKNESS .5E-01 .5E-01 .4E-01 .4E-01 .4E-01 .4E-01 .3E-01 .3E-01 .3E-01 .3E-01	W DISP 70 3.3E+00 70 3.4E+00 70 3.4E+00 70 3.2E+00 70 3.2E+00 70 3.1E+00 70 3.1E+00 70 3.1E+00 70 3.0E+00 70 2.9E+00 70 2.9E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1 9.8E-01 1 9.5E-01 1 9.2E-01 1 8.9E-01 1 8.6E-01 1 8.4E-01 1 7.9E-01 1 7.9E-01 1 7.9E-01 1	M∕A I .4E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .2E+03 1 .2E+03 1 .2E+03 2 .2E+03 2 .2E+03 2 .2E+03 2	J I I 2222333333333
TIME 0 1 2 3 4 5 6 7 8 9 11 12	E BBL 6.4E+03 6.4E+03 6.4E+03 6.4E+03 6.3E+03 6.3E+03 6.3E+03 6.3E+03 6.3E+03 6.2E+03 6.2E+03 6.2E+03 6.2E+03 6.2E+03	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	REA TH 8E+05 1 9E+05 1 1E+05 1 1E+05 1 1E+05 1 2E+05 1 3E+05 1 3E+05 1 5E+05 1 6E+05 1 7E+05 1	ICKNESS .5E-01 .5E-01 .4E-01 .4E-01 .4E-01 .4E-01 .4E-01 .3E-01 .3E-01 .3E-01 .3E-01	W DISP 70 3.5E+00 70 3.4E+00 70 3.4E+00 70 3.3E+00 70 3.2E+00 70 3.1E+00 70 3.1E+00 70 3.1E+00 70 3.0E+00 70 2.9E+00 70 2.9E+00 70 2.8E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1 9.8E-01 1 9.5E-01 1 9.2E-01 1 8.9E-01 1 8.6E-01 1 8.4E-01 1 8.1E-01 1 7.9E-01 1 7.6E-01 1	M∕A I .4E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .2E+03 1 .2E+03 1 .2E+03 2 .2E+03 2 .2E+03 2 .2E+03 2	J 1 1 2222333333
TIME 1 2 3 4 5 6 7 8 9 11 12 13	E BBL 6.4E+03 6.4E+03 6.4E+03 6.4E+03 6.3E+03 6.3E+03 6.3E+03 6.3E+03 6.3E+03 6.2E+03 6.2E+03 6.2E+03 6.2E+03 6.2E+03 6.1E+03	SPGR A 0.91 6. 0.91 6. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7.	REA TH 8E+05 1 9E+05 1 1E+05 1 1E+05 1 2E+05 1 3E+05 1 3E+05 1 5E+05 1 6E+05 1 7E+05 1	ICKNESS .5E-01 .5E-01 .4E-01 .4E-01 .4E-01 .4E-01 .4E-01 .3E-01 .3E-01 .3E-01 .3E-01 .3E-01	W DISP 70 3.3E+00 70 3.4E+00 70 3.3E+00 70 3.3E+00 70 3.2E+00 70 3.1E+00 70 3.1E+00 70 3.1E+00 70 3.1E+00 70 3.9E+00 70 2.9E+00 70 2.8E+00 70 2.8E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1 9.8E-01 1 9.3E-01 1 9.2E-01 1 8.9E-01 1 8.4E-01 1 8.4E-01 1 7.9E-01 1 7.4E-01 1	M∕A I .4E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .2E+03 1 .2E+03 1 .2E+03 2 .2E+03 2 .2E+03 2 .2E+03 2 .2E+03 2 .2E+03 2 .2E+03 2 .2E+03 2	J t 1 2 2 2 2 3 3 3 3 3 3 3 3
TIME 1 2 3 4 5 6 7 8 9 11 12 13 14	E BBL 6.4E+03 6.4E+03 6.4E+03 6.4E+03 6.3E+03 6.3E+03 6.3E+03 6.3E+03 6.2E+03 6.2E+03 6.2E+03 6.2E+03 6.2E+03 6.1E+03	SPCR A 0.91 6. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7.	REA TH BE+05 1 9E+05 1 1E+05 1 1E+05 1 2E+05 1 3E+05 1 3E+05 1 5E+05 1 5E+05 1 6E+05 1 7E+05 1 8E+05 1 9E+05 1	ICKNESS .5E-01 .5E-01 .4E-01 .4E-01 .4E-01 .4E-01 .4E-01 .3E-01 .3E-01 .3E-01 .3E-01 .3E-01 .3E-01 .3E-01	W DISP 70 3.5E+00 70 3.4E+00 70 3.4E+00 70 3.3E+00 70 3.2E+00 70 3.1E+00 70 3.1E+00 70 3.1E+00 70 3.0E+00 70 2.9E+00 70 2.9E+00 70 2.8E+00 70 2.8E+00 70 2.8E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1 9.8E-01 1 9.5E-01 1 9.2E-01 1 8.9E-01 1 8.4E-01 1 8.1E-01 1 7.9E-01 1 7.4E-01 1 7.3E-01 1	M∕A I .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .2E+03 1 .2E+03 1 .2E+03 1 .2E+03 2 .2E+03 2 .2E+03 2 .2E+03 2 .2E+03 2 .2E+03 2	J 1 1 22 2 2 3 3 3 3 3 3 3 3 3 3 3 3 3 3
TIME 0 1 2 3 4 5 6 7 8 9 11 12 13 14 -	$\begin{array}{c} \text{BBL} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.2E+03} \\ \textbf{6.2E+03} \\ \textbf{6.2E+03} \\ \textbf{6.2E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \end{array}$	SPCR A 0.91 6. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7.	REA TH 8E+05 1 9E+05 1 1E+05 1 1E+05 1 1E+05 1 3E+05 1 3E+05 1 5E+05 1 5E+05 1 7E+05 1 8E+05 1 9E+05 1	ICKNESS .5E-01 .5E-01 .4E-01 .4E-01 .4E-01 .4E-01 .4E-01 .3E-01 .3E-01 .3E-01 .3E-01 .3E-01 .3E-01 .3E-01 .3E-01	W DISP 70 3.3E+00 70 3.4E+00 70 3.3E+00 70 3.3E+00 70 3.3E+00 70 3.2E+00 70 3.1E+00 70 3.1E+00 70 3.1E+00 70 3.9E+00 70 2.9E+00 70 2.8E+00 70 2.8E+00 70 2.8E+00 70 2.7E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1 9.8E-01 1 9.3E-01 1 9.2E-01 1 8.9E-01 1 8.6E-01 1 8.4E-01 1 8.1E-01 1 7.6E-01 1 7.4E-01 1 7.3E-01 1 7.3E-01 1	M∕A I .4E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .2E+03 1 .2E+03 2 .2E+03 2 .2E+03 2 .2E+03 2 .2E+03 2 .1E+03 2 .1E+03 2	J t t 22223333333333
TIME 0 1 2 3 4 5 6 7 8 9 11 12 13 14 13	$\begin{array}{c} \text{BBL} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.2E+03} \\ \textbf{6.2E+03} \\ \textbf{6.2E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \end{array}$	SPCR A 0.91 6. 0.91 7.	REA TH BE+05 1 9E+05 1 1E+05 1 1E+05 1 1E+05 1 3E+05 1 3E+05 1 5E+05 1 5E+05 1 6E+05 1 6E+05 1 9E+05 1 9E+05 1	ICKNESS .5E-01 .5E-01 .4E-01 .4E-01 .4E-01 .4E-01 .3E-01 .3E-01 .3E-01 .3E-01 .3E-01 .3E-01 .2E-01 .2E-01	W DISP 70 3.5E+00 70 3.4E+00 70 3.4E+00 70 3.3E+00 70 3.2E+00 70 3.1E+00 70 3.1E+00 70 3.1E+00 70 3.0E+00 70 2.9E+00 70 2.8E+00 70 2.8E+00 70 2.8E+00 70 2.7E+00 70 2.7E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1 9.8E-01 1 9.3E-01 1 9.2E-01 1 8.9E-01 1 8.4E-01 1 8.4E-01 1 7.9E-01 1 7.6E-01 1 7.3E-01 1 7.1E-01 1	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	J = 1 22223333333333333333333333333333333
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TIME 1 2 3 4 5 6 7 8 9 11 12 13 14 15 16 17	$\begin{array}{c} \text{BBL} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.2E+03} \\ \textbf{6.2E+03} \\ \textbf{6.2E+03} \\ \textbf{6.1E+03} \\ $	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{c} \text{REA} & \text{TH} \\ \text{BE+05} & 1 \\ 9\text{E+05} & 1 \\ 0\text{E+05} & 1 \\ 1\text{E+05} & 1 \\ 1\text{E+05} & 1 \\ 2\text{E+05} & 1 \\ 3\text{E+05} & 1 \\ 3\text{E+05} & 1 \\ 5\text{E+05} & 1 \\ 5\text{E+05} & 1 \\ 9\text{E+05} & 1 \\ 9\text{E+05} & 1 \\ 9\text{E+05} & 1 \\ 0\text{E+05} & 1 \\ 1\text{E+05} & 1$	$ \begin{array}{c} \text{ICKNESS} \\ \textbf{.5E-01} \\ \textbf{.5E-01} \\ \textbf{.5E-01} \\ \textbf{.4E-01} \\ \textbf{.3E-01} \\ \textbf{.3E-01} \\ \textbf{.3E-01} \\ \textbf{.3E-01} \\ \textbf{.3E-01} \\ \textbf{.2E-01} \\ \textbf{.2E-01}$	W DISP 70 3.3E+00 70 3.4E+00 70 3.4E+00 70 3.3E+00 70 3.2E+00 70 3.1E+00 70 3.1E+00 70 3.1E+00 70 3.0E+00 70 2.9E+00 70 2.9E+00 70 2.8E+00 70 2.8E+00 70 2.7E+00 70 2.6E+00 70 2.6E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1 9.8E-01 1 9.5E-01 1 9.2E-01 1 8.9E-01 1 8.4E-01 1 8.4E-01 1 8.1E-01 1 7.6E-01 1 7.3E-01 1 7.3E-01 1 6.9E-01 1 6.9E-01 1 6.8E-01 1	M∕A I .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .2E+03 1 .2E+03 1 .2E+03 2 .2E+03 2 .2E+03 2 .2E+03 2 .1E+03 2 .1E+03 2 .1E+03 2 .1E+03 2	J 1 1 222333333333333333
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TIME 1 234567891123456789112314567891123457891123457891123457891123457891123457891123457891123457891123457891123457891123457891123457891123457891123457891123457891123457891123457891123457891000000000000000000000000000000000000	$\begin{array}{c} \text{BBL} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.2E+03} \\ \textbf{6.2E+03} \\ \textbf{6.2E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.2E+03} \\ \textbf{6.3E+03} \\ $	SPCR A 0.91 6. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 7. 0.91 8. 0.91 8. 0.91 8. 0.91 8. 0.91 8.	$\begin{array}{c} \text{REA} & \text{TH} \\ \text{BE+05} & 1 \\ 9\text{E+05} & 1 \\ 1\text{E+05} & 1 \\ 1\text{E+05} & 1 \\ 1\text{E+05} & 1 \\ 2\text{E+05} & 1 \\ 3\text{E+05} & 1 \\ 3\text{E+05} & 1 \\ 3\text{E+05} & 1 \\ 6\text{E+05} & 1 \\ 9\text{E+05} & 1 \\ 9\text{E+05} & 1 \\ 9\text{E+05} & 1 \\ 1\text{E+05} & 1$	$ \begin{array}{c} \text{ICKNESS} \\ \textbf{.5E-01} \\ \textbf{.5E-01} \\ \textbf{.5E-01} \\ \textbf{.4E-01} \\ \textbf{.4E-01} \\ \textbf{.4E-01} \\ \textbf{.4E-01} \\ \textbf{.4E-01} \\ \textbf{.4E-01} \\ \textbf{.3E-01} \\ \textbf{.3E-01} \\ \textbf{.3E-01} \\ \textbf{.3E-01} \\ \textbf{.3E-01} \\ \textbf{.2E-01} \\ \textbf{.2E-01}$	W DISP 70 3.3E+00 70 3.4E+00 70 3.4E+00 70 3.3E+00 70 3.2E+00 70 3.2E+00 70 3.1E+00 70 3.1E+00 70 3.0E+00 70 2.9E+00 70 2.9E+00 70 2.8E+00 70 2.8E+00 70 2.6E+00 70 2.5E+00 70 2.5E+00 70 2.5E+00	ERATE 0.0E+001 1.0E+001 1.0E+001 9.8E-011 9.3E-011 9.2E-011 8.9E-011 8.6E-011 8.4E-011 7.4E-011 7.4E-011 7.3E-011 6.9E-011 6.8E-011 6.5E-011	M∕A I .4E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .2E+03 1 .2E+03 1 .2E+03 2 .2E+03 2 .2E+03 2 .2E+03 2 .2E+03 2 .1E+03 2	J = = 3222333333333333333333333333333333
TIME 12345678911234567891123145678912314567891231456789123145678921231456789212314567892000000000000000000000000000000000000	$\begin{array}{c} \text{BBL} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.2E+03} \\ \textbf{6.2E+03} \\ \textbf{6.2E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.0E+03} \\ \textbf{6.0E+03} \\ \textbf{6.0E+03} \\ \textbf{6.0E+03} \\ \textbf{6.0E+03} \\ \textbf{6.0E+03} \end{array}$	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	$\begin{array}{c} \text{REA} & \text{TH} \\ \text{BE+05} & 1 \\ 9\text{E+05} & 1 \\ 0\text{E+05} & 1 \\ 1\text{E+05} & 1 \\ 1\text{E+05} & 1 \\ 2\text{E+05} & 1 \\ 3\text{E+05} & 1 \\ 3\text{E+05} & 1 \\ 3\text{E+05} & 1 \\ 3\text{E+05} & 1 \\ 9\text{E+05} & 1 \\ 9\text{E+05} & 1 \\ 1\text{E+05} & 1 \\ 1\text{E+05} & 1 \\ 2\text{E+05} & 1 \\ 3\text{E+05} & 1$	$ \begin{array}{c} \text{ICKNESS} \\ \textbf{.5E-01} \\ \textbf{.5E-01} \\ \textbf{.5E-01} \\ \textbf{.4E-01} \\ \textbf{.4E-01} \\ \textbf{.4E-01} \\ \textbf{.4E-01} \\ \textbf{.4E-01} \\ \textbf{.4E-01} \\ \textbf{.3E-01} \\ \textbf{.3E-01} \\ \textbf{.3E-01} \\ \textbf{.3E-01} \\ \textbf{.3E-01} \\ \textbf{.2E-01} \\ \textbf{.2E-01}$	W DISP 70 3.3E+00 70 3.4E+00 70 3.3E+00 70 3.3E+00 70 3.3E+00 70 3.3E+00 70 3.1E+00 70 3.1E+00 70 3.1E+00 70 3.1E+00 70 3.9E+00 70 2.9E+00 70 2.8E+00 70 2.6E+00 70 2.6E+00 70 2.5E+00 70 2.5E+00 70 2.5E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1 9.8E-01 1 9.3E-01 1 9.2E-01 1 8.9E-01 1 8.6E-01 1 8.6E-01 1 8.1E-01 1 7.6E-01 1 7.3E-01 1 7.3E-01 1 7.3E-01 1 6.8E-01 1 6.8E-01 1 6.5E-01 1 6.3E-01 1	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	J =
TIME 12345678912334567891234567891234567891234567891234567891224	$\begin{array}{c} \text{BBL} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.2E+03} \\ \textbf{6.2E+03} \\ \textbf{6.2E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.0E+03} \\ \textbf{6.0E+03} \\ \textbf{6.0E+03} \\ \textbf{6.0E+03} \\ \textbf{6.0E+03} \end{array}$	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$ \begin{array}{c} \text{ICKNESS} \\ \textbf{.5E-01} \\ \textbf{.5E-01} \\ \textbf{.5E-01} \\ \textbf{.4E-01} \\ \textbf{.3E-01} \\ \textbf{.3E-01} \\ \textbf{.3E-01} \\ \textbf{.3E-01} \\ \textbf{.3E-01} \\ \textbf{.2E-01} \\ \textbf{.2E-01}$	W DISP 70 3.3E+00 70 3.4E+00 70 3.4E+00 70 3.3E+00 70 3.3E+00 70 3.3E+00 70 3.1E+00 70 3.1E+00 70 3.1E+00 70 3.9E+00 70 2.9E+00 70 2.9E+00 70 2.8E+00 70 2.6E+00 70 2.5E+00 70 2.5E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1 9.8E-01 1 9.5E-01 1 9.2E-01 1 8.9E-01 1 8.9E-01 1 8.4E-01 1 7.9E-01 1 7.6E-01 1 7.3E-01 1 7.3E-01 1 6.9E-01 1 6.8E-01 1 6.5E-01 1 6.5E-01 1 6.3E-01	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	J
TIMO 12345678912345678911234567891223	$\begin{array}{c} \text{BBL} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.2E+03} \\ \textbf{6.2E+03} \\ \textbf{6.2E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.0E+03} \\ $	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	REA TH 8E+05 1 9E+05 1 1E+05 1 1E+05 1 2E+05 1 3E+05 1 3E+05 1 3E+05 1 5E+05 1 5E+05 1 7E+05 1 8E+05 1 9E+05 1 1E+05 1 3E+05 1 3E+05 1 3E+05 1 3E+05 1 3E+05 1 1E+05 1 3E+05 1E+05 1 3E+05 1E+05 1	$ \begin{array}{c} \text{ICKNESS} \\ \textbf{.5E-01} \\ \textbf{.5E-01} \\ \textbf{.5E-01} \\ \textbf{.4E-01} \\ \textbf{.4E-01} \\ \textbf{.4E-01} \\ \textbf{.4E-01} \\ \textbf{.4E-01} \\ \textbf{.4E-01} \\ \textbf{.3E-01} \\ \textbf{.3E-01} \\ \textbf{.3E-01} \\ \textbf{.3E-01} \\ \textbf{.3E-01} \\ \textbf{.2E-01} \\ \textbf{.4E-01} \\ \textbf{.4E-01} \\ \textbf{.4E-01} \end{array} $	W DISP 70 3.3E+00 70 3.4E+00 70 3.4E+00 70 3.3E+00 70 3.2E+00 70 3.1E+00 70 3.1E+00 70 3.1E+00 70 3.1E+00 70 3.9E+00 70 2.9E+00 70 2.9E+00 70 2.6E+00 70 2.6E+00 70 2.5E+00 70 2.5E+00 70 2.5E+00 70 2.5E+00 70 2.4E+00 70 2.4E+00	ERATE 0.0E+001 1.0E+001 1.0E+001 9.8E-011 9.3E-011 9.2E-011 8.9E-011 8.6E-011 8.4E-011 7.9E-011 7.4E-011 7.3E-011 6.8E-011 6.8E-011 6.3E-011	M/A I .4E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .3E+03 1 .2E+03 1 .2E+03 1 .2E+03 2 .2E+03 2 .2E+03 2 .2E+03 2 .1E+03 2	J =
TI012345678912345678912345678912345678912345678912345678912222	$ \begin{array}{c} \text{BBL} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.4E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.3E+03} \\ \textbf{6.2E+03} \\ \textbf{6.2E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.1E+03} \\ \textbf{6.0E+03} \\ \textbf$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{c} \text{REA} & \text{TH} \\ \text{BE+05} & 1 \\ 9\text{E+05} & 1 \\ 1\text{E+05} & 1 \\ 1\text{E+05} & 1 \\ 1\text{E+05} & 1 \\ 2\text{E+05} & 1 \\ 3\text{E+05} & 1 \\ 3\text{E+05} & 1 \\ 5\text{E+05} & 1 \\ 5\text{E+05} & 1 \\ 9\text{E+05} & 1 \\ 9\text{E+05} & 1 \\ 9\text{E+05} & 1 \\ 1\text{E+05} & 1 \\ 2\text{E+05} & 1 \\ 3\text{E+05} & 1$	ICKNESS .5E-01 .5E-01 .4E-01 .4E-01 .4E-01 .4E-01 .4E-01 .3E-01 .3E-01 .3E-01 .3E-01 .3E-01 .2E-01 .2E-01 .2E-01 .2E-01 .2E-01 .2E-01 .2E-01 .2E-01 .1E-01 .1E-01	W DISP 70 3.3E+00 70 3.4E+00 70 3.4E+00 70 3.4E+00 70 3.2E+00 70 3.2E+00 70 3.1E+00 70 3.1E+00 70 3.1E+00 70 2.9E+00 70 2.9E+00 70 2.9E+00 70 2.8E+00 70 2.6E+00 70 2.5E+00 70 2.5E+00 70 2.5E+00 70 2.5E+00 70 2.4E+00 70 2.4E+00 70 2.4E+00	ERATE 0.0E+00 1 1.0E+00 1 1.0E+00 1 9.8E-01 1 9.5E-01 1 9.2E-01 1 8.9E-01 1 8.9E-01 1 8.4E-01 1 7.9E-01 1 7.6E-01 1 7.3E-01 1 7.3E-01 1 6.8E-01 1 6.8E-01 1 6.5E-01	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	J L L 2222333333333333333333333333333333

25	5.9E+03	0.91	8.5E+05	1.1E-01	70 2.3E+00	5.8E-01	1.0E+03	2	4
26	5.9E+03	0.91	8.6E+05	1.12-01	70 2.2E+00	5.7E-01	9.95+02	2	4
27	5.9E+03	0.91	8.7E+05	1.1E-01	70 2.2E+00	5.3E-01	9.8E+02	2	4
29	5.9E+03	0.91	8.7E+05	1.1E-01	70 2.2E+00	5.4E-01	9.7E+02	2	4
30	5.8E+03	0.91	8.8E+05	1.1E-01	70 2.1E+00	5.3E-01	9.6E+02	2	4
31	5.8E+03	0.91	8.9E+05	1.0E-01	70 2.1E+00	5.2E-01	9.5E+02	2	4
32	5.8E+03	0.91	8.9E+05	1.0E-01	70 2.0E+00	5.0E-01	9.4E+02	2	4
34	5.8E+03	0.91	9.0E+05	1.0E-01	70 2.0E+00	4.9E-01	9.3E+02	3	4
35	5.8E+03	0.91	9.1E+05	1.0E-01	70 2.0E+00	4.8E-01	9.2E+02	3	4
36	5.7E+03	0.91	9.1E+05	1.0E-01	70 1.9E+00	4.7E-01	9.1E+02	3	4
37	5.7E+03	0.91	9.2E+05	9.9E- 0 2	70 1.9E+00	4.6E-01	9.0E+02	3	4
39	5.7E+03	0.91	9.3E+05	9.8E-02	70 L.9E+00	4.5E-01	8.9E+02	3	4
40	5.7E+03	0.91	9.3E+05	9.7E-02	70 1.8E+00	4.4E-01	8.8E+02	3	4
41	5.7E+03	0.91	9.4E+05	9.6E- 02	70 1.8E+00	4.3E-01	8.7E+02	3	4
42	5.6E+03	9.91	9.4E+05	9.5E-02	70 1.8E+00	4.2E-01	8.7E+02	3	4
44	5.6E+03	0.91	9.5E+05	9.4E-02	70 1.7E+00	4.IE-01	8.6E+02	3	4
45	5.6E+03	0.91	9.6E+05	9.3 E-02	70 1.7E+00	4.1E-01	8.5E+02	3	4
46	5.6E+ 0 3	0.91	9.6E+05	9.2E-02	70 1.7E+00	4.9E-01	8.4E+02	3	4
47	5.6E+ 03	0.91	9.7E+05	9.2 E-02	70 1.6E+00	3.9E-01	8.3E+02	3	4
49	5.6E+03	0.91	9.7E+05	9.1 E-02	70 1.6E+00	3.8 E-0 1	8.3E+02	3	4
50	5.5E+03	0.91	9.8E+05	9.0E-02	70 1.6E+00	3.7 E-0 1	8.2E+02	3	4
5ι	5.5E+03	0.91	9.8E+05	8.9E-02	70 1.6E+00	3.7E-01	8.1E+02	3	4
62	5.4E+03	0.91	1.0E+06	8.3E- 0 2	70 1.4E+00	3.1E-01	7.6E+02	3	4
72	5.3 E+03	0.91	1.1E+06	7.8E-02	70 1.2E+00	2.7 E-0 1	7.1E+02	3	4
82	5.2E+03	0.91	1.1E+06	7.4E-02	70 1.1E+00	2.4E-01	6.8E+02	3	4
92	5.1E+03	0.91	1.1E+06	7.0E-02	70 9.4E-01	2.1E-01	6.4E+02	3	5
102	5.0E+ 0 3	0.91	1.2E+06	6.7E- 02	70 8.4E-01	1.9E-01	6.1E+02	3	5
112	4.9E+03	0.91	1.2E+06	6.4E-02	70 7.6E-01	1.7E-01	5.9E+02	3	5
122	4.8E+03	0.91	1.2E+06	6.2E-02	70 6.9E-01	1.6E-01	5.6E+02	4	5
132	4.7E+03	0.91	1.3E+06	5.9E-02	70 6.3E-01	1.5E-01	5.4E+02	4	5
142	4.7E+03	0.91	1.3E+06	5.7E-02	70 5.7E-01	1.4E-01	5.2E+02	4	5
152	4.6E+03	0.91	1.3E+06	5.5E-02	70 5.3E-01	1.3E-01	5.1E+02	4	5
162	4.5E+03	0.91	1.3E+06	5.4E-02	70 4.8E-01	1.2E-01	4.9E+02	4	5
172	4.5E+03	0.92	1.4E+06	5.2E-02	70 4.5E-01	1.1E-01	4.7E+02	4	5
182	4.4E+03	0.92	1.4E+06	5.0E-02	70 4.1E-01	1.0E-01	4.6E+02	4	2
192	4.4E+03	0.92	1.4E+06	4.91-02	70 3.8E-01	9.7E-02	4.5E+02	4	5
202	-1.3E+03	0.92	1.46+06	4.8E-02	70 3.66-01	9.08-02	4.4E+02	4	5
212	4.32+03	9.92	1.32+06	4.6E-02	70 3.3E-01	8.3E-02	4.38.+02	4	5
222	4.2E+03	0.92	1.05+00	9.0E-02	70 3.1E-01	7.98-92	4.21+02	4	3
232	4.2E+03	0.92	1.35+06	4.4E-92	70 2.9E-01	7.3E-02	4.1E+02	4	5

.

output in Table 17 is essentially a condensed, self-contained, version of the calculated results in Table 16.

Table 18 presents the results of the calculations of the input parameters for the Mackay evaporation equation

$$\frac{dF}{d\Theta} = \frac{v_{\ell}}{RT} \exp \left[\frac{\Delta H v}{R} \left(\frac{1}{T_{b}} - \frac{1}{T_{1}}\right)\right]$$

. .

which is described in detail in Mackay (1982). The constraints required as input to the Mackay model are calculated, if requested, using the TBP data which are input to the ocean-ice oil-weathering code.

Page 75 represents the beginning of the results of a one-plate batch distillation of Prudhoe Bay crude oil. The results of this distillation are data for fraction distilled vs. temperature as presented on page 81. A linear correlation of these data plus values for bulk oil density, bulk molar volume, and mean Trouton's Rule constant are all combined to give the final Mackay evaporation model equation (all on page 81).

COMPUTER INSTALLATION/ACCESS

Currently the ocean-ice oil-weathering code resides on a VAX 8650 computer at SAIC in San Diego, CA and has been delivered to the NOAA OCSEAP office in Anchorage. Due to frequent changes in operating commands and software upgrades, it is not practical to set up open access to the model. Interested parties can call SAIC to obtain username, password, and code execution information.

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Table 18.--Illustration of Output From Ocean-Ice Oil-Weathering Code: Mackay Parameter Calculations, Beginning of One-Plate Batch Distillation Results Using TBP Data as Input.

SIMULATED ONE-PLATE BATCH DISTILLATION:

F	TEMP(F)	Y SUM
0.000E+00	2.918E+02	1.000E+00

I	MOLES I	VP(I)	Y(I)
1	2.749E+94	8.107E+00	4.128E-01
2	3.148E+04	4.589E+00	2.685E-01
3	3.907E+04	2.378E+00	1.727E-01
4	3.668E+04	1.202E+00	8.197E-02
5	3.433E+04	5.857E-01	3.736E-02
6	2.923E+04	2.710E-01	1.472E-02
7	3.304E+04	1.189E-01	7.300E-03
8	3.414E+04	4.918E-02	3.120E-03
9	3.340E+04	1.937E-02	1.202E-03
10	1.741E+04	6.130E-03	1.983E-04
11	3.576E+04	1.363E-03	9.054E-05
12	3.412E+04	2.932E-04	1.859E-05
13	2.745E+04	5.957E-05	3.039E-06
14	3.042E+04	9.128E-06	5.160E-07

	F	TEMP(F)	Y SUM
2	.334E-92	3. 988E+92	t . 000E+00
I	Moles I	VP(I)	Y(I)
1	1.734E+04	9.879E+00	3.39 0E-0 1
2	2.418E+04	5.681E+00	2.687E-01
3	3.398E+04	3.002E+00	L.995E-01
4	3.414E+04	1.552E+00	1.037E-01
5	3.313E+94	7.762E-01	5.030E-02
6	2.874E+04	3.794E-01	2.082E-02
7	3.279E+04	1.689E-01	1.078E-02
8	3.403E+04	7.201E-02	4.793E-03
9	3.335E+04	2.940E-02	1.918E-03
10	1.740E+04	1.014E-02	3.449E-04
Î.	3.575E+04	2.381E-03	1.665E-04
12	3.412E+04	5.414E-04	3.614E-05
13	2.745E+04	1.166E-04	6.264E-06
14	3.042E+04	1.919E-05	1.142E-06

F 4.734E-02		3	TEMP(F) .295E+02	Y SUM 1.000E+00
I	MOLES	ĩ	VP(I)	Y(I)
1	9.992E+€	8	1.240E+01	2.559E-01

.....

2 3 4 5 6 7 8 9 1 1 1 1 1 1 1 1	1.793E+04 2.807E+04 3.087E+04 3.147E+04 3.241E+04 3.385E+04 3.328E+04 1.738E+04 3.575E+04 3.412E+04 2.745E+04 2.645E+04	7.262E+00 3.921E+00 2.080E+00 1.071E+00 5.287E-01 2.490E-01 1.111E-01 4.730E-02 1.740E-02 4.511E-03 1.093E-03 2.517E-04	2.554E-01 2.272E-01 1.325E-02 3.060E-02 1.666E-02 7.769E-03 3.250E-04 3.329E-04 7.698E-05 1.427E-05
7	F. 226E- 92	TEMP(F) 3.538E+02 1	Y SUM .000E+00
I	MOLES I	VP(I)	Y(I)
L 2345678901112314	5.011E+03 1.058E+04 2.139E+04 2.662E+04 2.910E+04 2.694E+04 3.35E+04 3.35E+04 3.315E+04 3.573E+04 3.411E+04 2.745E+04 3.042E+04	1.597E+01 9.536E+00 5.272E+00 1.526E+00 7.816E-01 3.831E-01 1.787E-01 7.964E-02 3.089E-02 9.123E-03 2.370E-03 5.878E-04 1.148E-04	1.750E-01 2.206E-01 1.672E-01 9.706E-02 4.603E-02 2.663E-02 1.311E-02 1.311E-03 7.127E-03 1.172E-03 7.127E-04 1.768E-04 3.528E-05 7.632E-06
9	F . 848E-02	TEMP(F) 3.807E+02 1	y Sum .0992+99
I	Moles i	VP(I)	Y(I)
1234567899 111234	2.442E+03 5.586E+03 1.439E+04 2.125E+04 2.573E+04 2.573E+04 3.076E+04 3.02E+04 3.290E+04 1.731E+04 3.570E+04 3.410E+04 2.745E+04 3.042E+04	2.079E+01 1.266E+01 7.173E+00 4.016E+00 2.200E+00 1.169E+00 5.966E=01 2.911E=01 1.359E=01 5.573E=02 1.818E=02 5.275E=03 1.412E=03 3.025E=04	1.179E-01 1.643E-01 2.398E-01 1.983E-01 1.315E-01 6.856E-02 4.263E-02 2.233E-02 1.039E-02 2.240E-03 1.507E-03 4.179E-04 9.005E-05 2.138E-05

F	TEMP(F)	Y SUM
1.261E-01	4.117E+02	1.000E+00

1	MOLES I	VP(L)	Y(I)
I 123456789011234	MOLES [8.554E+02 2.646E+03 8.259E+03 1.520E+04 2.127E+04 2.273E+04 2.273E+04 3.211E+04 3.216E+04 3.246E+04 3.562E+04 3.408E+04 2.744E+04 2.744E+04	VP(1) 2.759E+01 1.710E+01 9.900E+00 3.252E+00 1.795E+00 9.540E-01 4.873E-01 2.389E-01 1.039E-01 3.660E-02 1.235E-02 3.588E-03 8.4945-04	Y(1) 5.848E-02 1.126E-01 2.042E-01 2.165E-01 1.713E-01 1.011E-01 6.879E-02 3.877E-02 1.922E-02 4.429E-03 3.231E-03 1.043E-04 6.294E-04
	F . 536E- 0 1 4	TEMP(F) 6.437E+02 1	Y SUM .000E+00
I	MOLES I	VP(I)	Y(I)
1234567890111234	6.865E+01 1.131E+03 4.014E+03 9.233E+03 1.579E+04 1.917E+04 2.630E+04 3.165E+04 3.165E+04 3.165E+04 3.165E+04 3.403E+04 3.403E+04 3.041E+04	$\begin{array}{c} 3.680 \pm +01\\ 2.341 \pm +01\\ 1.396 \pm +01\\ 8.271 \pm +09\\ 4.827 \pm +09\\ 2.764 \pm +09\\ 1.528 \pm +09\\ 8.162 \pm -01\\ 4.197 \pm -01\\ 1.934 \pm -01\\ 7.364 \pm -02\\ 2.687 \pm -02\\ 2.687 \pm -03\\ 2.392 \pm -03\\ 2.392 \pm -03\\ \end{array}$	6.706E-03 7.031E-02 1.487E-01 2.032E-01 2.024E-01 1.407E-01 1.075E-01 6.621E-02 3.527E-02 8.734E-03 6.934E-03 2.427E-03 6.669E-04 1.931E-04
1	F . 874E-01 4	TEMP(F) 5.794E+02 1	Y SUM .000E+00
I	MOLES I	VP(I)	Y(I)
12345678901112314	0.000E+00 1.853E+02 2.003E+03 4.648E+03 9.969E+03 1.452E+04 2.261E+04 2.261E+04 3.020E+04 1.663E+04 3.514E+04 3.514E+04 3.391E+04 3.040E+04	4.794E+01 3.112E+01 1.899E+01 1.155E+01 6.931E+00 4.099E+00 2.347E+00 1.303E+00 1.303E+01 3.388E-01 1.383E-01 5.412E-02 2.041E-02 6.125E-03	$\begin{array}{c} 0.000 \\ \hline 0.000 \\ \hline 1.648 \\ \hline 0.088 \\ \hline 0.088 \\ \hline 0.01 \\ \hline $
	F	TEMP(F)	Y SUM

2	.213 E-0 1	5.145E+02 1	
I	MOLES	I VP(I)	Y(I)
122	0.000E+00 0.000E+00	6.194E+01 4.100E+01	0.000E+00 0.000E+00
4	2.2062+0	3 1.595E+01	1.089E-01
5	5.207E+0 9.468E+0	3 5.995E+00	1.586 E-01 1.758 E-0 1
7 8	1.749E+04 2.416E+04	4 3.545E+00 4 2.039E+00	1.9202-01 1.5262-01
9 10	2.784E+04	1.136E+00 5.778E-01	9.791E-02 2.855E-02
11	3.453E+0	4 2.518E-01	2.6925-02
13	2.731E+0	4.260E-02	3.603E-03
14	3.037 2+9 4	• 1.482E-92	1.39 45-03
•	F	TEMP(F)	y sum
2	. 377 2-4 1	3.3405+42 I	. • • • • • • • • • • • • • • • • • • •
I	MOLES	T VP(I)	Y(I)
1 2	0.000E+00	7.918E+01 5.340E+01	0.000E+00 0.000E+00
3	0.000E+00	3.407E+01	0.000E+00 5.4225-02
5	2.436E+0	3 1.374E+01	1.131E-01
°7	3.072E+0	5.252E+00	1.477E-01 2.070E-01
89	1.894E+04 2.421E+04	3.123E+00 1.801E+00	1.998 5-01 1.472 5-01
10	1.4822+04	9.564E-01	4.789E-02
12	3.316E+04	1.970E-01	2.207E-02
13	2.714E+04 3.030E+04	3.202E-02	7.802E-03 3.277E-03
	F	TEMD (F)	V STIM
2	. 967E-01	5.878E+02 1	.000E+00
I	MOLES	(VP(I)	Y(I)
1	0.000E+00	1.001E+02	0.000E+00
3	0.000E+0	4.476E+01	0.000E+00
4	9.394 E+0 9.130 E+0	2.920E+01 2 1.891E+01	1.019 E-0 3 6.429 E-02
6	2.359E+0	3 1.219E+01	1.069E-01
8	1.276E+0	4.681E+00	2.2192-01
9 10	1.910E+04	2.786 2+00	1.977E-01 7.443E-02
11	3.134E+0	7.532E-01	8.7702-02
12	2.678E+04	• 3.3475-01 • 1.6305-01	4.245E-02 1.621E-02
14	3.0132+04	6.601E-02	7.391 E-0 3

3	F	TEMP(F)	y sum
	.386E-01 6	.266E+ 02 [. 000e+00
ı	MOLES I	VP(I)	Y(I)
12345678	0.000E+00	1.257E+02	0.000E+00
	0.000E+00	8.782E+01	0.000E+00
	0.000E+00	5.836E+01	0.000E+00
	0.000E+00	3.890E+01	0.000E+00
	5.004E+01	2.579E+01	5.327E-03
	9.216E+02	1.707E+01	6.492E-01
	2.921E+03	1.098E+01	1.324E-01
	6.901E+03	6.925E+00	1.973E-01
9	1.284E+04	4.246E+00	2.250E-01
10	1.035E+04	2.433E+00	1.039E-01
11	2.787E+04	1.254E+00	1.443E-01
12	3.039E+04	6.230E-01	7.816E-02
13	2.604E+04	3.031E-01	3.258E-02
14	2.977E+04	1.317E-01	1.618E-02
3	F	TEMP(F)	y sum
	.839 E-01 6	.670E+02 1	.000e+00
I	Moles I	VP(I)	Y(I)
123456789011234	0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 4.814E+01 1.140E+03 3.129E+03 6.733E+03 6.931E+03 2.241E+04 2.714E+04 2.458E+04 2.900E+04	1.567E+02 1.113E+02 7.540E+01 5.132E+01 3.480E+01 2.361E+01 1.538E+01 1.010E+01 3.776E+00 2.042E+00 1.066E+00 5.470E-01 2.538E-01	0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 5.278E-03 8.248E-02 1.467E-01 2.006E-01 1.215E-01 2.125E-01 1.343E-01 6.244E-02 3.417E-02
4	F	TEMP(F)	y sum
	.328E-01 7	1.083E+02 1	. 000e+00
I	MOLES (VP(I)	Y(I)
123456789011 112	0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 3.032E+01 1.135E+03 3.036E+03 3.617E+04 2.192E+04	1.933E+02 1.395E+02 9.629E+01 6.686E+01 4.632E+01 3.219E+01 2.176E+01 1.447E+01 9.367E+00 5.732E+00 3.240E+00 1.770E+00	0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.501E-03 8.868E-02 1.519E-01 1.100E-01 2.058E-01

Table 18.--Mackay Parameter Calculations (Continued): End of One-Plate Batch Distillation, Heat of Vaporization and Trouton's Rule Calculations.

> 13 2.192E+94 9.541E-01 1.110E-01 2.742E+04 4.705E-01 14 6.843z-02 TEMP(F) Y SUM 4.853E-01 7.524E+02 1.000E+00 MOLES I VP(I) 1 Y(I) 0.000E+00 2.380E+02 0.000E+00 1 1.745E+02 0.000E+00 9.000E+00 2 0.000E+00 1.227E+02 0.000E+00 3 0.000E+00 8.688E+01 0.000E+00 4 5 0.000E+00 6.147E+01 0.000E+00 4.374E+01 0.000E+00 U. UHOE+00 6 7 0.000E+00 3.029E+01 0.000E+00 0.000E+00 8 0.000E+00 2.066E+01 1.372E+01 1.0138+03 9 8.594E-02 10 1.631E+03 8.654E+00 8.730E-02 7.922E+03 5.107E+00 2.503E-01 1.1 1.483E+04 2.672E-01 2.913E+00 12 1.758E+04 1.646E+00 1.790E-01 13 2.446E+04 8.604E-01 14 1.302E-01 TEMP(F) Y SUM 5.4132-01 8.052E+02 1.000E+00 MOLES I VP(I) YO I 0.000E+00 2.995E+02 0.000E+00 0.000E+00 0.000E+00 2.235E+02 2 3 0.000E+00 1.603E+02 0.000E+00 0.000E+00 1.161E+02 0.000E+00 4 5 8.406E+01 0.000E+00 0.000E+00 0.000E+00 0.000E+00 6.140E+01 6 7 0.000E+00 4.365E+01 0.000E+00 3.062E+01 8 0.000E+00 0.000E+00 0.000E+00 0.000E+00 2.091E+01 0 10 4.561E+02 1.364E+01 4.612E-02 3.467E+03 8.433E+00 2.1686-01 11 5.038E+00 7.0132+03 2.620E-01 12 13 1.094E+04 2.995E+00 2.429E-01 1.8896+94 1.666E+00 2.322E-01 14 DELTAH DELTAH/TB 1.976E+01 1.293E+04 1 1.324E+04 2.040E+01 2 2.086E+01 1.448E+04 3 1.564E+04 2.117E+01 4 1.678E+04 2.141E+01 5 1.791E+04 6 2.160E+01 7 1.904E+04 2.179E+01 2.019E+04 2.197E+01 8 2.098E+04 9 2.176E+01

WHERE: Deltah is the enthalpy of vaporization in btu/lbmole Deltah/TB is the troutons rule constant in btu/lbmole*dec r Table 18.--Mackay Parameter Calculations (Continued): Distillation Curve Correlation, Bulk Oil Properties, Final Mackay Evaporation Equation.

LEAST SQUARES OF B.P. VS. FRACTION EVAPORATED:

SLOPE: 9.690E+02 DEC R/FRACTION EVAPORATED INITIAL B.P.: 2.912E+02 DEC F CORRELATION COEFFICIENT: 9.991E-01

BULK OIL DENSITY: 8.820E-01 GRAMS/CC BULK MOLAR VOLUME OF OIL: 2.940E+02 CC/MOLE MEAN TROUTONS RULE CONSTANT: 2.119E+01 BTU/LBMOLE*DEC R

AFTER SIMPLIFICATION AND COMBINING TERMS, THE MACKAY EVAPORATION MODEL BECOMES:

DELTA-F = DELTA-THETA * EXP(6.400E+00 - 2.324E-02 (7.502E+02 + 9.690E+02(F))

OR

DELTA-F = DELTA-THETA * EXP(-1.103E+01 - 2.251E+01(F))

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APPENDIX

CODE LISTING FOR OCEAN-ICE OIL-WEATHERING MODEL

.

100	С	+++++ OILICE.FOR +++++ INCLUDE 'VARI FOR'
300	C	
400	č	THIS IS THE OPEN-OCEAN OIL-WEATHERING CODE AND
500	č	THE OIL PHASE IS CONSIDERED WELL-STIRRED ALL THE
600	С	TIME.
700	C	
800	Ç	THIS CODE ALSO ALLOWS FOR WEATHERING IN THE PRESENCE OF
900	Ç	SEA ICE.
1000	C	ANOTHER OPTION AVAILABLE IN THIS CODE TO THE ONION ATION
1200	č	ANUTHER UPTION AVAILABLE IN THIS COUL IS THE CALCULATION
1300	č	MODEL
1400	č	
1500	č	AUGUST, 1986
1600	Ċ	
1700	С	GET YOUR OUTPUT FROM OILICE.OUT/FILE:FORTRAN
1800	С	THE PLOT FILE IS OILICE.PLT
1900	Ċ	THE TYPE FILE IS OILICE.TYP/FILE:FORTRAN
2000	C	THE MACKAY CONSTANTS GO INTO MACKAY.DAT
2100	C	
2200		DIMENSION PMP(30) DATA (ANAMEL(1,1) 1-1 S)/(DDUDU) 105 DAY 19 ALV 14584 /
2300		1 ' '/
2500		
2600		1.' '/
2700		DATA (ANAMEL(3, J), J=1.5)/'WILMI'. 'NGTON'.'. CAL'.'IFORN'
2800		1,'IA '/
2900		DATA (ANAMEL(4,J),J=1,5)/'MURBA','N, AB','U DHA','BI '
3000		1,' '/
3100		DATA (ANAMEL(5,J), J=1,5)/'LAKE ', 'CHICO', 'T, LO', 'UISIA'
3200		
3400		UATA (ANAMEL(0,J),J=T,S)/'LIGHT',' DIES','EL CU','T
3500		NATA APIRI /27 35 4 19 4 49 5 54 7 38 9/
3600		DATA ITEML/9.7.94.99999 221 1/
3700		DATA ISAMPL/71011.72025.71052.99999.54062.2/
3800		DATA NCTS/15, 16, 13, 16, 16, 11/
3900	С	, , ,
4000	С	FOR CRUDE OIL THE RESIDUUM CUT IS ASSIGNED A NORMAL
4100	ç	BOILING POINT OF .
4200	С	
4300		UATA (IBL(1,J),J=1,30)/150.,190.,235.,280.,325.,370.
4500		T, 415., 400., 505., 554., 009., 052., /12., /04., 050., 1540./ Data (TRI(2)) 1-1 20)/110 145 100 235 280 325
4600		1 370 415 460 505 554 609 662 712 764 850
4700		2.4•0./
4800		DATA (TBL(3,J), J=1,20)/195.,235.,280.,325.,370.,415.
4900		1,460.,505.,554.,609.,662.,712.,850.,7+0./
5000		DATA (TBL(4,J),J=1,20)/110.,145.,190.,235.,280.,325.
5100		1,370.,415.,460.,505.,554.,609.,662.,712.,764.,850.
5200		
5300		UAIA (IBL(0,J),J=1,20)/110.,145.,190.,235.,280.,325.
3400 5500		1,3/0,,413,,460,,303,,334,,609,,662,,/12,,764,,850. 2,440 /
5600		2,740./ NATA (TRI/6 1) 1-1 11)/313 349 366 306 416 439 461
5700		1 479 501 518 538 /
5800		DATA (APII (1.1), J=1.30)/72 7 64 2 56 7 51 6 47 6 45 2
5900		1,41,5,37,8,34,8,30,6,29,1,26,2,24,.22,5,11,4,15+0./
6000		DATA (APIL(2, J), J=1, 20)/89.2, 77.2, 65., 59.5, 55.4, 50.8

1,46.5,43.,39.6,37.,32.8,31.3,28.7,26.6,25.,11.6,4+0./ DATA (APIL(3,J),J=1,20)/68.6,58.7,53.,48.1,43.2,38.8 6100 6200 6300 1,35.4,32.3,26.8,24.5,22.3,20.3,8.9,7+0. 6400 DATA (APIL(4, J), J=1,20)/96.7,86.2,70.6,62.3,55.7,51.6 6500 1,48.5,45.6,43.,40.,35.8,34.,30.,28.4,26.6,16.7,4+0./ DATA (APIL(5, J), J=1, 20)/92.4,81.,68.9,62.1,57.2,52.5 1,48.8,45.2,41.7,38.2,34.4,33.2,30.6,28.9,26.1,18.1,4+0./ 6600 6700 DATA (APIL(6, J), J=1, 11)/49.6, 47.3, 46., 44., 38.6, 38.8, 37.2 6800 6900 7000 7100 DATA (VOLL(2,J), J=1,20)/2.4,2.5,5.9,6.1,5.1,5.2,4.9 1,5.1,5.2,5.,3.3,5.2,7.,4.2,4.2,25.6,4+0./ DATA (VOLL(3,J), J=1,20)/2.3,2.4,2.4,2.5,2.8,3.6,4.4 7200 7300 7400 1,5.3,4.7,6.3,4.1,5.5,53.3,7*0./ 7500 DATA (VOLL(4, J), J=1,20)/1.7,2.9,4.9,6.,6.8,6.5,5.7 1,5.6,6.,4.9,5.7,5.6,6.5,6.,5.6,19.3,4*0./ 7600 7700 7800 DATA (VOLL(5, J), J=1,20)/7.5,8.2,9.7,11.,9.1,8.3,7.2 1,7.2,7.4,6.9,3.5,3.,1.6,1.4,1.9,2.,4+0./ DATA (VOLL(6,J),J=1,11)/4.78,9.57,9.09,9.57,9.57,9.57 1,9.57,9.57,9.57,9.57,9.57/ 7900 8000 8100 С 8200 C1L, C2L, AND C4L ARE THE MOUSSE FORMATION CONSTANTS. C1L IS THE VISCOSITY CONSTANT. 8300 С С 8400 8500 C C2L IS THE INVERSE OF THE MAXIMUM WATER IN OIL WEIGHT 8600 С FRACTION. C4L IS THE WATER INCORPORATION RATE. 8700 C 8800 DATA C1L/0.62,0.62,0.63,0.64,0.65,0.65/ 8900 DATA C2L/1.42,3.33,1.43,5.,-1.,-1./ 9000 DATA C4L/0.001,0.001,0.01,0.001,0.,0./ 9100 С 9200 С FOR THE DISPERSION PROCESS, KA IS THE CONSTANT IN THE С SEA SURFACE DISPERSION EQUATION, KB IS THE CONSTANT IN THE DROPLET FRACTION EQUATION. STENL(6) IS THE LIBRARY 9300 9400 С OIL-WATER SURFACE TENSION IN DYNES/CM. 9500 С С 9600 DATA KA, KB, STENL/0.108, 50., 30., 30., 30., 30., 30., 30., 30./ DATA VISZL/35., 35., 195., 15., 13.5, 11.5/ 9700 9800 9900 DATA MK3L/9000.,9000.,9000.,9000.,9000.,3000./ DATA MK4L/10.5,7.4,15.3,10.5,2.,2./ 10000 10100 OPEN(UNIT=32, file='OILICE.OUT', status='new') 10200 OPEN(UNIT=34, file='OILICE.PLT', status='new') OPEN(UNIT=35, file='OILICE.TYP', status='new') 10300 10400 10500 10U=32 10600 IPU=34 10700 ITY=35 10800 С 10900 С FILL IN SOME LIBRARY IDENTIFICATIONS. 11000 С 10 11100 TYPE 20 11200 20 FORMAT(1X, 'ENTER THE NUMBER OF TBP CUTS TO BE CHARACTERIZED 11300 1 ON 12) 11400 TYPE 30 11500 30 FORMAT(1X,'IF YOU HAVE NO INPUT DATA JUST ENTER 99') 11600 TYPE 40 11700 40 FORMAT(1X, 'A 99 ENTRY WILL USE A LIBRARY EXAMPLE') 11800 ICODE=1 11900 ACCEPT 50, NCUTS 12000 50 FORMAT(12)

1

12100		LSWTCH=NCUTS
12200	С	
12300	С	LSWTCH=99 IS USED TO INDICATE THAT A LIBRARY CRUDE WAS
12400	С	CHOSEN.
12500	С	
12600		IF(NCUTS.NE.99) GO TO 120
12700	С	
12800	Ċ	USING A LIBRARY CRUDE.
12900	Č	
13000		IFLE=2
13100		TYPE 60
13200	60	FORMAT(1X, 'CHOOSE & CRUDE ACCORDING TO: ')
13300	••	
1.3400		TYPE 70 T (ANAMEL(T, 1), $l=1, 5$)
13500	70	FORMAT(1) 1 545)
13600	80	
13700		
13800	00	
13000	30	
14000		
14100		
14200		ISAMF=ISAMFL(IC)
14300		
14300		
14400		
14500		ANAME(J)=ANAMEL(IC,J)
14000	100	
14/00		17PE 110, (ANAME(J),J=1,5)
14800	110	FORMAI(7,1X, YOU CHOSE: ', 5A5)
14900	-	GO TO 250
15000	C	
15100	C	USER IS ENTERING THE CRUDE DATA OR READING HIS OWN FILE
15200	C	
15300	120	TYPE 130
15400	130	FORMAT(1X,'IS THE CRUDE ON A FILE ?')
15500		IFLE=1
15600		ACCEPT 140, ANS
15700	140	FORMAT(A1)
15800		IF(ANS.EQ.'N') GO TO 170
15900	_	TYPE 150
16000	150	FORMAT(1X,'WHAT IS THE FILE NAME?')
16050		ACCEPT 151, FNAME
16075	151	FORMAT(A10)
16100		OPEN(UNIT=36, file=FNAME,STATUS='OLD')
16200		IFLE=2
16300		READ (36,550) (ANAME(J),J=1,5)
16400		READ (36,560) ITEM, ISAMP, NCUTS
16500		READ (36,570) APIB
16600		DO 160 J=1,NCUTS
16700		READ (36,580) TB(J),API(J),VOL(J)
16800	160	CONTINUE
16900		GO TO 330
17000	С	
17100	170	TYPE 180
17200	180	FORMAT(1X, 'ENTER THE NAME OF THE CRUDE')
17300		ACCEPT 190, (ANAME(I), I=1,5)
17400	190	FORMAT(10A5)
17500		TYPE 200
17600	200	FORMAT(1X, 'ENTER AN IDENTIFICATION NUMBER FOR
17700		1 THIS CRUDE ON I5')
17888		ACCEPT 210 ITEM

17900 210 FORMAT(15) 18000 TYPE 220 18100 FORMAT(1X, 'ENTER A SAMPLE NUMBER ON 15') 220 18200 ACCEPT 210, ISAMP 18300 **TYPE 230** 18400 230 FORMAT(1X, 'ENTER THE BULK API GRAVITY') 18500 ACCEPT 280, APIB 18600 **TYPE 240** FORMAT(/,1X,'YOU MUST ENTER THE TRUE BOILING POINT 1 CUT DATA STARTING',/,1X,'WITH THE MOST VOLATILE CUT 18700 240 18800 18900 2 AND GOING TO THE BOTTOM OF THE BARREL',/) С 19000 19100 С CALCULATE THE BULK DENSITY OF THE CRUDE AT 60/60. 19200 C 19300 250 DCRUDE=141.5/(APIB+131.5) DCRUDE=0.983+DCRUDE 19400 19500 С 19600 С TRANSFER CRUDE INPUT DATA TO THE VARIABLES USED IN 19700 С THE CALCULATIONS. 19800 С DO 320 I=1,NCUTS 19900 GO TO (260,310), ICODE 20000 20100 260 TYPE 270, I 20200 С 20300 С ENTER THE CRUDE CUT DATA. 20400 C FORMAT(1X, 'ENTER THE BOILING POINT AT 1 ATM IN DEG F 20500 270 20600 1 FOR CUT', 13) ACCEPT 280, TB(I) 20700 20800 280 FORMAT(F10.0) 20900 TYPE 290, I FORMAT(1X, 'ENTER API GRAVITY FOR CUT', 13) 21000 290 ACCEPT 280, API(I) 21100 TYPE 300, 1 21200 FORMAT(1X, 'ENTER VOLUME PER CENT FOR CUT'. I3) 21300 300 ACCEPT 280, VOL(I) 21400 21500 GO TO 320 21600 С TRANSFER CRUDE CUT INPUT DATA FROM THE LIBRARY. 21700 С 21800 С 21900 310 TB(I) = TBL(IC, I)API(I)=APIL(IC,I) VOL(I)=VOLL(IC,I) 22000 22100 22200 320 CONTINUE 22300 С С DISPLAY THE CUTS BACK TO THE USER. 22400 22500 С 330 22600 **TYPE 340** FORMAT(/,1X,'CUT',5X,'TB',10X,'API',8X,'VOL') 22700 340 22800 DO 360 I=1, NCUTS TYPE 350, I, TB(I), API(I), VOL(I) 22900 23000 350 FORMAT(1X, 12, 5X, F5.1, 7X, F4.1, 6X, F5.1) 23100 CONTINUE 360 23200 **TYPE 370** 23300 370 FORMAT(1X, 'DO YOU WANT TO CHANGE ANY?') ACCEPT 390, ANS 23400 380 23500 390 FORMAT(A1) 23600 IF (ANS EQ . 'N') GO TO 470 23700 С ALLOW THE INPUT TO BE CHANGED. 23800 С

С **TYPE 400** FORMAT(1X, 'ENTER THE CUT NUMBER TO BE CHANGED ON 12') ACCEPT 50. N **TYPE 410** FORMAT(1X, 'ENTER 1 TO CHANGE TB, 2 FOR API, 3 FOR VOL%') ACCEPT 420, IC FORMAT(I1) TYPE 430 FORMAT(1X,'ENTER THE CHANGED DATA') GO TO (440,450,460), IC ACCEPT 280, TB(N) GO TO 330 ACCEPT 280, API(N) GO TO 330 ACCEPT 280, VOL(N) GO TO 330 DO 480 I=2,NCUTS IM1=I-1IF(TB(I).LT.TB(IM1)) GO TO 490 CONTINUÉ GO TO 510 TYPE 500, I, IM1 FORMAT(/, 1X, 'THE BOILING POINT OF CUT ', I2 1,' IS LESS THAN CUT ', I2, /, 1X, 'AND THIS ORDER IS NOT 2 ACCEPTABLE, SO START OVER', /) GO TO 10 С ALWAYS RENORMALIZE THE INPUT VOLUMES TO 100%. С С VTOTAL=0. DO 520 I=1,NCUTS VTOTAL=VTOTAL+VOL(I) CONTINUE DO 530 I=1,NCUTS VOL(I)=100. +VOL(I)/VTOTAL CONTINUE С С IF YOU READ IT IN, DO NOT RESAVE IT С IF(IFLE.EQ.2) GO TO 590 TYPE 540 FORMAT(1X, 'THIS CRUDE WILL NOW BE WRITTEN TO A FILE. WHAT 1 WOULD YOU LIKE TO CALL IT?') ACCEPT 541, FNAME FORMAT(A19) OPEN(UNIT=38, file=FNAME, STATUS='NEW') OPEN(UNIT=38,TTT0=FNAME,STATUS= WRITE (38,550) (ANAME(J),J=1,5) FORMAT(5A5) WRITE (38,560) ITEM,ISAMP,NCUTS FORMAT(3I5) WRITE (38,570) APIB FORMAT(1X,F6.1) DO 590 (=1 NCUTS DO 590 J=1,NCUTS WRITE (38,580) TB(J), API(J), VOL(J) FORMAT(3(1X,1PE10.3)) CONTINUE С С NOW CHARACTERIZE THE PARENT OIL С

29700		CALL DOCHAR
29800	С	
29900	C	CALCULATE THE INITIAL MASS. MOLES. DENSITY FOR EACH CUT
30000	č	
30100	-	BBL=1000.
30200		BM=0.159+BBL
30300		TMOLES=0.
30400		DO 600 I=1 NCUTS
30500		AMASS=1582 ASPGR(I) ABBL AVOL(I)
30600		
30700		
10800		
30000		PHO(I) = 100 ESTHOLES(I) / (PM-VO) (I)
31000	600	
31000	000	
31100		
31200		
31300	610	WINDLE=WINGLE+MW(I) *MOLES(I)/IMOLES
31400	010	CONTINUE
31500	c	TTPE 620
31600	620	FORMAT(1X, DO YOU WANT THE MACKAY CONSTANTS?)
31700		ACCEPT 390, ANS
31800		IF(ANS.EQ.'N') GO TO 650
31900		TYPE 630
32000	630	FORMAT(1X,'AT WHAT TEMPERATURE, DEG F?')
32100		ACCEPT 280, TE
32200		TE=TE+459.
32300		CALL VPIF(TE,NC1)
32400		OPEN(UNIT=40,file='MACKAY.DAT',STATUS='NEW')
32500		TYPE 640
32600	640	FORMAT(/,1X,'PLEASE WAIT')
32700	С	
32800	С	SUBROUTINE MACK CALCULATES THE PARAMETERS NEEDED FOR INPUT
32900	С	INTO THE EVAPORATION MODEL DEVELOPED BY DR. MACKAY
33000	С	THIS DATA IS PUT INTO A FILE CALLED MACKAY.DAT
33100	Ċ	
33200		CALL MACK
33300	650	CONTINUE
33400	c	
33500	č	N7SWI#0 INDICATES THAT NO PREVIOUS WEATHERING HAS TAKEN
33600	č	PLACE SO A NEW INITIAL OIL THICKNESS IS NEEDED
33700	č	NZSWIMI INDICATES THAT DEFVICUS WEATHERING HAS TAKEN
11800	č	DIACE SO THE DEEVIOUS THICKNESS CAN BE CAPPIED OVER
33000	č	PERCE SO THE FREETOOS THTORNESS ON DE OARTED OVER
34000	•	N7SWI ma
34100	c	NLGWI-0
34200	č	NID-4 INDICATES ICE DOOL WEATHEDING HAS NOT TAKEN DLACE
34300	č	NIF-0 INDICATES ICE POOL WEATHERING HAS NOT TAKEN PLACE
34300	č	RIP=1 INDICATES ICE FOUL WEATHERING HAS TAKEN FLACE
34400	č	NOT-A INDIATES THAT DOMEN TOE FIFTO WEATHERING HAS NOT
34500	č	NDI=U INVIGATES THAT DRUKEN IGE FIELD WEATHENING HAS NUT
34700	č	TAREN FLADE Not-1 indicates that droken for firid weathering the
34/00	č	NOI=1 INVIGALES IMAL BRUKEN IGE FIELD WEATHERINT HAS
34868	C C	TAKEN PLAUE
34900	C	
22000		NIF=0
35100		NU I =0
35200	C	
35300	Ç	NG COUNTS THE NUMBER OF CUTS THAT HAVE BEEN WEATHERED AWAY
35400	С	
35500		NG =0
35600	С	

NQUIT=0 MEANS SLICK HAS NOT DECREASED TO 10% OF ORIGINAL MOLES 35700 С 35800 С NQUIT=1 MEANS SLICK HAS DECREASED TO 10% OF ORIGINAL MOLES 35900 С 36000 NQUIT=0 36100 **TYPE 660** FORMAT(1X, 'DO YOU WANT TO WEATHER THIS OIL?') 660 36200 36300 ACCEPT 390, ANS IF(ANS.EQ.'N') GO TO 4550 36400 36500 **TYPE 670** 36600 670 FORMAT(1X, 'WHAT IS THE SPILL SIZE IN BARRELS?') ACCEPT 280, BBL 36700 36800 С 36900 С CALCULATE AND SAVE INITIAL MASSES FOR OVERALL MASS BALANCE С 37000 37100 8M=.159+88L 37200 MOLSAV=0. TMASAV=0. 37300 37400 DO 680 I=1,NCUTS 37500 MASSAV(I)=1582.+SPGR(I)+BBL+VOL(I) 37600 MLSAV(I)=MASSAV(I)/MW(I) MOLSAV-MOLSAV+WLSAV(I) 37700 37800 TMASAV=TMASAV+MASSAV(I) 37900 680 CONTINUE 38000 С С DELMAS IS THE MASS OF CUTS THAT ARE DELETED BECAUSE THEY EVAPORATE TOO QUICKLY 38100 С 38200 38300 С 38400 DELMAS=0. 38500 С 38600 С THE IS THE TOTAL MASS EVAPORATED 38700 С TMD IS THE TOTAL MASS DISPERSED С 38800 38900 TME=0. 39000 TMD=0. 39100 С 39200 С FE IS THE FRACTION (BASED ON MASS) EVAPORATED 39300 С 39400 FE=0. С 39500 ${\sf MOUSWI=0}$ INDICATES THAT MOUSSE FORMATION HAS NOT BEEN STARTED ${\sf MOUSWI=1}$ INDICATES THAT MOUSSE FORMATION HAS STARTED SUCH THAT 39600 С С 39700 39800 С NEW MOUSSE CONSTANTS MUST MATCH THE EXISTING CONDITIONS С 39900 40000 MOUSWI=0 С 40100 40200 С HOUMOU IS THE NUMBER OF HOURS THAT MOUSSE FORMATION HAS BEEN 40300 С IN EFFECT 40400 С 40500 HOUMOU=0 40600 **TYPE 690** 40700 690 FORMAT(1X, 'WILL THE WEATHERING SCENARIO INCLUDE SEA ICE?') ACCEPT 390,ANS IF (ANS.EQ.'N') GO TO 3060 40800 40900 41000 TYPE 700 41100 700 FORMAT(1X, 'WHEN THE OIL REACHES THE OIL SURFACE, ') 41200 TYPE 710 41300 710 FORMAT(1X, 'WILL IT WEATHER IN POOLS ON TOP OF THE ICE?') 41400 ACCEPT 390, ANS 41500 IF(ANS.EQ.'N') GO TO 1660 41600 **TYPE 720**

41700	720	FORMAT(1X,'AT WHAT TEMPERATURE, DEG F?')
41800		ACCEPT 280.XSAVE
41900		SPRFAC=1
42000		NIP=1
42100		NCC1-NC1
42200		$TK_{=}(YSAVF_{=}32)/1$ 8+273
42300		
42400		
42500	^	A3AVE-A3AVET+33.
42300		AUDRAUTINE NEXT AN AUX ATES THE MADOD DECOUDE OF FACH AUT
42600	C .	SUBROUTINE VPIF CALCULATES THE VAPOR PRESSURE OF EACH COT
42700	Ç	AT A SPECIFIED TEMPERATURE
42800	С	
42900		CALL VPIF(XSAVE, NCC1)
43000		TYPE 730
43100	730	FORMAT(1X,'FOR HOW MANY HOURS?')
43200		ACCEPT 280, X2
43300	С	
43488	ř	NUTD IS THE NUMBER OF HOURS OF ICE DOOL WEATHERING
43500	ž	WHIP IS THE NUMBER OF HOURS OF ICE FOOL WEATHERING
43500	C	
43500		NHIP=X2
43700		TYPE 740
43800	740	FORMAT(1X,'HOW DEEP WILL THE POOLS BE IN CM? TRY 2')
43900		ACCEPT 280,Z
44000		NZSWI=1
44100		Z=Z/100
44288	С	
44300	č	SET C21 SINCE MOUSSE CANNOT BE FORMED
44400	č	
44500	U	
44500	•	C2=-1.
44000	C .	
44700	C	SET STEN TO 1. TO AVOID DIVIDE BY ZERO PROBLEMS LATER
44800	С	
44900	750	STEN=1.0
45000	760	TYPE 770
45100	770	FORMAT(1X, 'ENTER THE MASS-TRANSFER COEFFICIENT CODE: 1
45200		1. 2. OR 3 WHERE: ')
45300		TYPE 780
45400	780	FORMAT(1) '1=USER SPECIFIED OVER-ALL MASS-TRANSFER COFF
45500	/00	FIGURENTIN
45500		
45000	700	TODAT (AV 10.00005) ATION MASS TRANSFED COFFEIGIENT BY
45/00	/90	FORMAI (12, 2=CORRELATION MASS-TRANSFER COEFFICIENT BT
45800		1 MACKAY & MAISUGU')
45900		TYPE 800
46000	800	FORMAT(1X,'3=INDIVIDUAL-PHASE MASS-TRANSFER COEFFICIENTS')
46100		ACCEPT 420, KMTC
46200	С	
46300	С	NOW ENTER THE WIND SPEED IN KNOTS AND CONVERT TO METER/SEC
46400	C	AND METER/HOUR.
46500	č	
46600	•	TYDE 810
46700	910	FORMATING THE WIND OBEED IN PNOTS!)
46900	010	TORMATITA, ENTER THE WIND SPEED IN KNUTS /
+0000	•	ALLEPI 200, WINDS
46900	C .	
47000	C	NEVER LET THE WIND SPEED DROP BELOW 2 KNOTS. A ZERO WIND
47100	С	SPEED DESTROYS THE MASS-TRANSFER CALCULATION AND WILL
47200	С	YIELD A ZERO MASS-TRANSFER COEFFICIENT.
47300	С	
47400		IF(WINDS.LT.2.) WINDS=2.
47500		WINDMS=0.514+WINDS
47600		WINDMH=1853 WINDS

47780 C NOW CALCULATE THE INITIAL GRAM MOLES FOR EACH COMPONENT TO 47800 GET THE INTEGRATION STARTED. 48000 C 48100 820 5800 C 48100 820 5800 C 48100 AMASS-TS2.*SPCR[1]*BBL*VOL(1) 48500 MOLES[1]=AMASS/MW(1) 48500 MOLES[1]=MOLES+MOLES(1) 48500 C 49500 C 49500 C 49500 C 49600 C 49700 D840 49800 C 49800 C 49800 C 49800 C 49800 <			
<pre>*/200 C NOW CALCULATE THE INTERATION STARTED. */200 C GET THE INTEGATION STARTED. *200 C UNCLESSON UNUTURS UNUTURS UNUTURS UNUTURESSON UNUTURS UNCLESSON UNUTURS UNUTURATED AUCONDING TO UNACYAY AND WATSUGU, 1973, CAN. J. CHE, V51, P434-439. UNAUTION UNLESSON UNUTURS UNUTURATED UNUTURS, PA34-439. UNUTURESSON UNUTURESSON UNUTURSUMENTAL DATA SUCH AUXING UNUTURESSON UNUTURESSON UNUTUR UN</pre>	47700	c	
1000 Out_Internation_StateD. 1000 Bue_153+BBL 1000 D000 1000 Bue_153+BBL 1000 MASS=1582.*SPOR[]+BBL+VOL(I) 1000 MASS=1582.*SPOR[]+BBL+VOL(I) 1000 MOLES[]+MALSS/NW(1) 1000 MOLES=TMOLES+MOLES(I) 1000 MOLES=TMOLES+MOLES(I) 1000 MOLES=TMOLES+MOLES(I) 1000 RHO(I)=100.*MOLES(I)/(BM*VOL(I)) 1000 CONTINUE 1000 CONTINUE 1000 COLLENTMOLE+MU(I)*MOLES(I)/TMOLES 1000 WTMOLE=0. 1000 WTMOLE=0. 1000 WTMOLE=0. 1000 WTMOLE=WTMOLE+MU(I)*MOLES(I)/TMOLES 1000 WTMOLE=WTMOLE+MU(I)*MOLES(I)/TMOLES 1000 WTMOLE=WTMOLE+MU(I)*MOLES(I)/TMOLES 10000 WTMOLE-WTMOLE+MU(I)*MOLES(I)/TMOLES 10000 See See 10000 See See 10000 See See 10000 See See 100000 AREA=00. 10000000 AREA=00.	47800	C	NOW CALCULATE THE INITIAL GRAM MOLES FOR EACH COMPONENT TO GET THE INTEGRATION STARTED
48:36 62:0 BW-0.159-8BL 48:260 TMOLES=0. 48:360 DO 83:0 1-1.NCUTS 48:460 MARSS-1582.*SPCR[1)*BBL*VOL(1) 48:560 MOLES(1)-MARSS/WW(1) 48:560 MOLES:TMOLES*MOLES(1) 48:560 TMOLES=TMOLES*MOLES(1) 48:560 C 49:06 C 8:01 RHO(1)=100.*MOLES(1)/(BM*VOL(1)) 49:02 C 49:03 C 49:04 C 49:05 C 49:06 C 49:07 DO 840 1=1, NCUTS 49:080 C 49:090 DO 840 1=1, NCUTS 49:090 WTMOLE=0. 50:00 Set SPREAD=0. 50:00 Set SPREAD=0. 50:00 C	48000	č	SET THE INTEGRATION STARTED.
48200 TMOLES=0. 48300 DO 830 I=1,NCUTS 48400 AMASS=1582.*SPGR(1)+BBL*VOL(1) 48500 MOLES(I)-AMASS/SW(I) 48500 TMOLES=TMOLES(I) 48600 C 8400 C 49000 C 49100 CALCULATE THE MEAN MOLECULAR WEIGHT OF THE CRUDE 49500 C 49500 C 49500 C 49500 C ALCULATE THE MEAN MOLECULAR WEIGHT OF THE CRUDE = '.1PE10.3) 50600 WTMOLE=MTMOLE+MW(I)*MOLES(I)/TMOLES 49500 C 50100 S60 50100 S60 50100 S60 50100 S60 50100 C 50100 C 50100	48100	820	8M=0.159+88L
<pre>48300 D0 830 1=1,NCUTS 48400 AMASS-1582.*SPCR(1)*BBL*VOL(1) 48500 MOLES(1)=MOLES(1) 48500 TMOLES=TMOLES+MOLES(1) 48500 C RHO IS THE DENSITY IN GM MOLES/CUBIC METER. 49000 C RHO IS THE DENSITY IN GM MOLES/CUBIC METER. 49000 C CALCULATE THE MEAN MOLECULAR WEIGHT OF THE CRUDE 49100 C CALCULATE THE MEAN MOLECULAR WEIGHT OF THE CRUDE 49100 C CALCULATE THE MEAN MOLECULAR WEIGHT OF THE CRUDE 49100 C CALCULATE THE MEAN MOLECULAR WEIGHT OF THE CRUDE 49100 C CALCULATE THE MEAN MOLECULAR WEIGHT OF THE CRUDE = ',1PE10.3) 49100 C CALCULATE THE MEAN MOLECULAR WEIGHT OF THE CRUDE = ',1PE10.3) 49100 C SET SPREADING TO ZERO. 50100 850 FORMAT(/,1X,'MEAN MOLECULAR WEIGHT OF THE CRUDE = ',1PE10.3) 50200 C SET SPREADING TO ZERO. 50400 C SET SPREADING TO ZERO. 50400 C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50400 C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50400 C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50400 C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50400 C C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50400 C C CALCULATE THE SLICK WEATHERS. Z=THICKNESS IN METERS. 51000 B70 VOLUM=0. 51100 D0 880 I=1,NCUTS 51200 C CALCULATE THE INITIAL AREA AND DIAMETER. 51300 GC CALCULATE THE INITIAL AREA AND DIAMETER. 51300 C CALCULATE THE INITIAL AREA AND DIAMETER. 51400 C CALCULATE THE INITIAL AREA AND DIAMETER. 51500 C ALCULATE THE INITIAL AREA AND DIAMETER. 51600 C 11. A USER-SPECIFIED OVER-ALL MASS-TRANSFER COEFFICIENT 52000 C 1. A USER-SPECIFIED OVER-ALL MASS-TRANSFER COEFFICIENT 52000 C 3. INDIVIDUAL OIL- AND AIR-PHASE MASS-TRANSFER COEFFICIENT 52000 C 3. INDIVIDUAL OIL- AND AIR-PHASE MASS-TRANSFER COEFFICIENT 52000 C 3. INDIVIDUAL OIL- AND AIR-PHASE MASS-TRANSFER COEFFICIENT 52000 C 3. INDIVIDUAL</pre>	48200		TMOLES=0.
AMASS=1582.*5PCK(1)*0BL*VOL(1) 48500 MOLSS(1)=MOLES(1) 48500 MOLSS(1)=MOLES(1) 48500 C RHO IS THE DENSITY IN GM MOLES/CUBIC METER. 49000 C RHO(1)=100.*MOLES(1)/(BM*VOL(1)) 49200 S30 CONTINUE 49300 C CALCULATE THE MEAN MOLECULAR WEIGHT OF THE CRUDE 49300 C CALCULATE THE MEAN MOLECULAR WEIGHT OF THE CRUDE 49300 C CALCULATE THE MEAN MOLES(1)/TMOLES 49600 WTMOLE=0. 49700 D0 840 I=1,NCUTS 49800 WTMOLE=WTMOLE+MW(1)*MOLES(1)/TMOLES 49700 D0 840 I=1,NCUTS 49800 WTMOLE=WTMOLE+MW(1)*MOLES(1)/TMOLES 50900 C SET SPREADING TO ZERO. 50300 C SET SPREADING TO ZERO. 50300 C C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50300 C SET SPREADING TO ZERO. 50300 C C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50300 C AS THE SLICK WEATHERS. Z=THICKNESS IN METERS. 50300 C C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50300 C C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50300 C C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50300 C C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50300 C AS THE SLICK WEATHERS. Z=THICKNESS IN METERS. 50300 C C CALCULATE THE INITIAL AREA AND DIAMETER. 51300 B30 CONTINUE 51400 C C CALCULATE THE INITIAL AREA AND DIAMETER. 51500 C ALCULATE THE INITIAL AREA AND DIAMETER. 51500 C THE MASS=TRANSFER COEFFICIENT CAN BE CALCULATED ACCORDING TO 52200 C 1. A USER-SPECIFIED OVER-ALL MASS=TRANSFER COEFFICIENT 52300 C 2. THE MASS=TRANSFER COEFFICIENT CORRELATION ACCORDING TO 52400 C 3. INDIVIDUAL OIL- AND AIR-PHASE MASS=TRANSFER COEFFICIENT 52400 C 3. INDIVIDUAL OIL- AND AIR-P	48300		DO 830 I=1,NCUTS
<pre>WOLES(1)=AMARSS/WW(1) #8860 MOLES(1)=MOLES(1) #8760 TMOLES=TWOLES+WOLES(1) #8860 C #8860 C #8860 C #8960 C #9760 RHO(I)=100.+MOLES(I)/(BM+VOL(I)) #9260 830 CONTINUE #9360 C #9460 C #9460 C #9460 C GALCULATE THE MEAN MOLECULAR WEIGHT OF THE CRUDE #9560 WTMOLE=0. #9760 DO 840 I=1,NCUTS #9860 WTIOLE=WW(I)+MOLES(I)/TMOLES #9860 WTIOLE=WTMOLE+WW(I)+MOLES(I)/TMOLES #9860 WTIOLE=WTMOLE+WW(I)+MOLES(I)/TMOLES #9860 WTIOLE=WTMOLE+WW(I)+MOLES(I)/TMOLES #9860 WTIOLE=WTMOLE=WW(I)+MOLES(I)/TMOLES #9860 WTITE (IOU,850) WTMOLE #9860 B50 FORMAT(/,1X,'MEAN MOLECULAR WEIGHT OF THE CRUDE = ',1PE10.3) #9860 S000 B50 FORMAT(/,1X,'MEAN MOLECULAR WEIGHT OF THE CRUDE = ',1PE10.3) #9860 C #9860 C #9860 C #9860 C GALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED #9860 C #9860</pre>	48400		AMASS=1582.+SPGR(I)+BBL+VOL(I)
1001ES=TMOLES=MOLES(I) 48700 TMOLES=TMOLES(I) 48800 C 48900 C 49000 RHO(I)=100.*MOLES(I)/(BM*VOL(I)) 49200 C 49000 C 49100 CONTINUE 49300 C 49400 C 59400 C 59400 C 59400 C 59400 C 59400 C </th <th>40500</th> <th></th> <th>MOLES(1)=AMASS/MW(1) MOLES(1)=AMASS/WW(1)</th>	40500		MOLES(1)=AMASS/MW(1) MOLES(1)=AMASS/WW(1)
<pre>48888 C RHO IS THE DENSITY IN GM MOLES/CUBIC METER. 48908 C RHO IS THE DENSITY IN GM MOLES/CUBIC METER. 49008 C RHO(I)=100.*MOLES(I)/(BM*VOL(I)) 49108 C C CALCULATE THE MEAN MOLECULAR WEIGHT OF THE CRUDE 49508 C WTMOLE=#. 49508 C WTMOLE=#. 49508 C O TINUE 49508 C O TINUE=#TMOLEYHW(I)*MOLES(I)/TMOLES 49508 C O TINUE 50008 B40 CONTINUE 50000 WRITE(IOU,850) WTMOLE 50000 C SET SPREADING TO ZERO. 50500 C SET SPREADING TO ZERO. 50500 C C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50508 C AS THE SLICK WEATHERS. Z=THICKNESS IN METERS. 50500 C C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50508 C AS THE SLICK WEATHERS. Z=THICKNESS IN METERS. 50500 C C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50508 C AS THE SLICK WEATHERS. Z=THICKNESS IN METERS. 50500 C C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50509 C C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50509 C C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50500 C C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50500 C C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50500 C C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50500 C C CALCULATE AN AREA AND DIAMETER. 51000 B70 VOLUM=0. 51100 VOLUM=0. 51100 C C CALCULATE THE INITIAL AREA AND DIAMETER. 51500 C C CALCULATE THE INITIAL AREA AND DIAMETER. 51500 C ILA=SQRT(AREA/0.785) 51900 C I. A USER-SPECIFICIENT CAN BE CALCULATED ACCORDING TO 52100 C I. A USER-SPECIFICIENT CAN BE CALCULATED ACCORDING TO 52100 C I. A USER-SPECIFICIENT CON BE CALCULATED ACCORDING TO 52100 C I. A USER-SPECIFICIENT CORFLATION ACCORDING TO 52100 C I. A USER-SPECIFICIENT CON BE CALCULATED ACCORDING TO 52100 C I. A USER-SPECIFICIENT CORFLATION ACCORDING TO 52100 C I. A USER-SPECIFICIENT CON THE MASS-TRANSFER COEFFICIENT 52100 C I. A USER-SPECIFICIENT CON BE CALCULATED ACCORDING TO 52500 C I. AND ASSED ON SOME REAL ENVIRONMENTAL DATA SUCH 52500 C AS THAT OF LISS AND SLATER. SCALE THE AIR-PHASE 53100 C TEMP IS R+T AND USED TO CHANGE THE UNITS ON THE MASS- 53600 C TEMP IS R+T AND USE</pre>	48700		TMOLES=TMOLES+MOLES(I)
<pre>48900 C 9000 C 9100 RHO(1)=100.*MOLES(I)/(BM*VOL(I)) 49200 S30 CONTINUE 49300 C 49300 B40 I=1.NCUTS 49300 B40 CONTINUE 50300 B40 CONTINUE 50300 C 50300 C 50300</pre>	48800	С	
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49100 RHO([]=100.*MOLES(I]/(BM*VOL(I)) 49200 830 CONTINUE 49200 C CALCULATE THE MEAN MOLECULAR WEIGHT OF THE CRUDE 49500 C CALCULATE THE MEAN MOLECULAR WEIGHT OF THE CRUDE 49500 C WTMOLE=0. 49500 D0 840 I=1,NCUTS 49500 WTMOLE=WTMOLE+WM(I)*MOLES(I)/TMOLES 50500 B40 CONTINUE 50500 B50 FORMAT(/,1X,'MEAN MOLECULAR WEIGHT OF THE CRUDE = ',1PE10.3) 50500 C SET SPREADING TO ZERO. 50500 C SET SPREAD=0. 50500 C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50500 C AS THE SLICK WEATHERS. Z=THICKNESS IN METERS. 50500 C AS THE SLICK WEATHERS. Z=THICKNESS IN METERS. 50600 C AS THE SLICK WEATHERS. Z=THICKNESS IN METERS. 50700 C CALCULATE THE INITIAL AREA AND DIAMETER. 51100 DO B80 I=1,NCUTS 51200 C CALCULATE THE INITIAL AREA AND DIAMETER. 51300 C CALCULATE THE INITIAL AREA AND DIAMETER. 51600 C C	49000	С	
<pre>49200 830 CONTINUE 49300 C 49300 C 49300 C 49500 WTMOLE=0. 90 840 I=1.NCUTS 49700 D0 840 I=1.NCUTS 49700 WTMOLE+HW(I)*MOLES(I)/TMOLES 49700 WTMOLE+HW(I)*MOLES(I)/TMOLES 49700 WTMOLE+HW(I)*MOLES(I)/TMOLES 50100 B50 FORMAT(/,1X,'MEAN MOLECULAR WEIGHT OF THE CRUDE = ',1PE10.3) 50200 C 50300 C SET SPREADING TO ZERO. 50500 C SET SPREAD=0. 50500 C C 50500 C C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50500 C AS THE SLICK WEATHERS. Z=THICKNESS IN METERS. 50900 C VOLUM=0. 51000 B70 VOLUM=0. 51000 B70 VOLUM=0. 51100 D0 880 I=1.NCUTS 51200 C CALCULATE THE INITIAL AREA AND DIAMETER. 51600 C C CALCULATE THE INITIAL AREA AND DIAMETER. 51600 C C CALCULATE THE INITIAL AREA AND DIAMETER. 51600 C C C CALCULATE THE INITIAL AREA AND DIAMETER. 51600 C C C C CALCULATE THE INITIAL AREA AND DIAMETER. 51600 C C C C C C C C C C C C C C C C C C</pre>	49100		RHO(I)=100.+MOLES(I)/(BM+VOL(I))
<pre>State C CALCULATE THE MEAN MOLECULAR WEIGHT OF THE CRUDE 49500 C 49500 WTMOLE=0. D0 840 I=1.NCUTS 49600 WTMOLE=WTMOLE+WTW(I)+MOLES(I)/TMOLES 49900 840 CONTINUE 50000 WRITE (IOU.850) WTMOLE 50000 C SET SPREADING TO ZERO. 50300 C SET SPREADING TO ZERO. 50400 C C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50700 C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50800 C SET SPREAD=0. 50700 C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50800 C SET SPREAD=0. 50900 C C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50700 C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50800 C SET SPREAD=0. 50900 C C CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED 50900 C C CALCULATE THE INITIAL AREA AND DIAMETER. 50900 C SET SPREAD=0. 51000 B80 I=1,NCUTS 51200 C CALCULATE THE INITIAL AREA AND DIAMETER. 51500 C CALCULATE THE INITIAL AREA AND DIAMETER. 51600 C C 1. A USER-SPECIFICIENT CAN BE CALCULATED ACCORDING TO 52100 C 2. THE MASS-TRANSFER COEFFICIENT CORRELATION ACCORDING 52500 C 3. INDIVIDUAL OIL- AND AIR-PHASE MASS-TRANSFER COEFFICIENT 52600 C 3. INDIVIDUAL OIL- AND AIR-PHASE MASS-TRANSFER COEFFICIENT 52600 C 3. INDIVIDUAL OIL- AND AIR-PHASE MASS-TRANSFER COEFFICIENT 52600 C 3. INDIVIDUAL OIL- AND AIR-PHASE MASS-TRANSFER COEFFICIENT 52600 C 3. INDIVIDUAL OIL- AND AIR-PHASE MASS-TRANSFER COEFFICIENT 52600 C 3. INDIVIDUAL OIL- AND AIR-PHASE MASS-TRANSFER COEFFICIENT 52600 C G GRARAT OF LISS AND SLATER. SCALE THE AIR-PHASE 53100 C G GRARAT, 1977, MONTHLY WEATHER REVIEW, V105, P315-920. 53500 C TEMP IS R+T AND USED TO CHANGE THE UNITS ON THE MASS- 53600 C TEMP IS R+T AND USED TO CHANGE THE UNITS ON THE MASS- 53600 C TEMP IS R+T AND USED TO CHANGE THE UNITS ON THE MASS- 53600 C TEMP IS R+T AND USED TO CHANG</pre>	49200	830	CONTINUE
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49700D0 840 I=1.NCUTS49800WTMOLE=WTMOLE+WW(I)*MOLES(I)/TMOLES499008405010085050200FORMAT(/,1X,'MEAN MOLECULAR WEIGHT OF THE CRUDE = ',1PE10.3)50200SET SPREADING TO ZERO.50300C5050086050700C51700AS THE SLICK WEATHERS.51200C<	49600		WTMOLE=0.
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49900 B40 CONTINUE 50000 WRITE (IOU,850) WTMOLE 50100 B50 50100 B50 50100 C 50100 SET SPREADING TO ZERO. 50100 C 50100 C 50100 SET SPREAD=0. 50100 C 51100 D0 51200 VOLUM=0. 51300 C 51300 C 51400 C 51500 C 51600 C 51700 AREA=VOLUM/Z 51800 C 521800 C 1 A USER-SPECIF	49800		WTMOLE=WTMOLE+MW(I)+MOLES(I)/TMOLES
SolodNRTLE (100,030) WINDLESolodSon Mart(/,1x,'MEAN MOLECULAR WEIGHT OF THE CRUDE = ',1PE10.3)SolodSET SPREADING TO ZERO.SolodSET SPREAD=0.SolodSPREAD=0.SolodCCCALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATEDSolodSolodSolodAS THE SLICK WEATHERS.Z=THICKNESS IN METERS.SolodCSolodAS THE SLICK WEATHERS.Z=THICKNESS IN METERS.SolodCSolodAS THE SLICK WEATHERS.Z=THICKNESS IN METERS.SolodCSolodCSolodCSolodCSolodCSolodCSolodCSolodCSolodCSolodCSolodCSolodCSolodCSolodCSolodCSolodCSolodCSolodCSolodCCCCCCCSolodCSolodCSolodCSolodCSolodCSolodCSolodCSolodCSolodCSolodCSolodCSolodCSolodCSolodCSolodCSolodCSol	49900	840	CONTINUE WRITE (IOU REA) WINCIE
Solo Solo Solo Format(y, i.k. maak motecolar weight of the cross of the crose cross of the cross of the cross of the cross of the	50100	850	THE (100,000) WHINDLE FORMATION THE CRUDE - ' 10510 3)
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50400C50500860SPREAD=0.50600CC50700CC50800CAS THE SLICK WEATHERS.50900C51000870VOLUM=0.51100DO 880 I=1,NCUTS51200VOLUM=VOLUM+MOLES(I)/RHO(I)5130088051400C51400C51500C6000C51600C51700AREA=VOLUM/Z51800DIA=SQRT(AREA/0.785)51900C52200C52200C1A USER-SPECIFIED OVER-ALL MASS-TRANSFER COEFFICIENT52300C52400C25200C1A USER-SPECIFIED OVER-ALL MASS-TRANSFER COEFFICIENT52400C25200C31NDIVIDUAL OIL- AND AIR-PHASE MASS-TRANSFER COEFFICIENT52400C32700C52800C31INDIVIDUAL OIL- AND AIR-PHASE MASS-TRANSFER COEFFI-52900C3100C52800C3100C53000C53000C53000C53000C53000C53000C53000C53600C53600C53600C53600C53600C53600C53600C53600C <t< th=""><th>50300</th><th>č</th><th>SET SPREADING TO ZERO.</th></t<>	50300	č	SET SPREADING TO ZERO.
50500860SPREAD=0.50600CC50700CC50800CAS THE SLICK WEATHERS. Z=THICKNESS IN METERS.50900C51000870VOLUM=0.51100D0 880I=1,NCUTS51200VOLUM=VOLUM+MOLES(I)/RHO(I)51300880CONTINUE51400C51400C51600CCCALCULATE THE INITIAL AREA AND DIAMETER.51600CS1700AREA=VOLUM/Z51800DIA=SQRT(AREA/0.785)51900C52200C1.A USER-SPECIFIED OVER-ALL MASS-TRANSFER COEFFICIENT52400C22400C23600C52600C32600C33600C<	50400	С	
Sobeo 50700CCalculate an area in same way it will be calculated 5080050800As the slick weathers.Z=thickness in meters.50900DBT051000870VOLUM=0. DO 880 I=1.NCUTS51100DO 880 I=1.NCUTS VOLUM=VOLUM+MOLES(I)/RHO(I)5130088051400C51500CCalculate the initial area and diameter.51600C51700Area-volum/Z DIA=SQRT(AREA/0.785)51900C52200C1.A USER-SPECIFIED OVER-ALL MASS-TRANSFER COEFFICIENT S2400C2.22300C22400C2400C252002.1.A USER-SPECIFIED OVER-ALL MASS-TRANSFER COEFFICIENT S24002300C2400C352003.1NDIVIDUAL OIL-25200C3.INDIVIDUAL OIL-25200C3.INDIVIDUAL OIL-2400C3.INDIVIDUAL OIL-32800C3.INDIVIDUAL OIL-32800C3.INDIVIDUAL OIL-33100C33100C33200C33400C33400C33400C33600TEMP IS R*T AND USED TO CHANGE THE UNITS ON THE MASS-33600TEMP IS R*T AND USED TO CHANGE THE UNITS ON THE MASS-33600TEMP IS R*T AND USED TO CHANGE THE UNITS ON THE MASS- <th>50500</th> <th>860</th> <th>SPREAD=0.</th>	50500	860	SPREAD=0.
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51100D0 880 I=1,NCUTS VOLUM=VOLUM+MOLES(I)/RH0(I)5130088051400C51500CCALCULATE THE INITIAL AREA AND DIAMETER.51600C51700AREA=VOLUM/Z DIA=SQRT(AREA/0.785)51900C52000C53000C53000C53000C53000C53000C53000C53000C53600C53600C53600C53600C53600C53600<	51000	870	VOLUM-0.
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51300880CONTINUE51400C51500C51500C51600C51700AREA=VOLUM/Z51800DIA=SQRT(AREA/0.785)51900C52000C52100C52200C52200C52200C52400C52400C52400C52400C52400C52400C52400C52400C52400C52400C52400C52400C52400C52500C52600C52600C52700C52800C52800C53800C53100C53100C53100C53100C53400C5	51200		VOLUM=VOLUM+MOLES(I)/RHO(I)
51700CCALCULATE THE INITIAL AREA AND DIAMETER.51500C51600C51700AREA=VOLUM/Z51800DIA=SQRT(AREA/0.785)51900C52000C52100C52200C52200C52200C52400C52400C52400C52400C52400C52400C52400C52400C52400C52400C52600C52600C52700C52800C52800C52800C52800C52800C52800C5380	51300	880	CONTINUE
S1600CCS1600CS1700AREA=VOLUM/ZS1800DIA=SQRT(AREA/0.785)S1900CS2000CS2100CS2100CS22001. A USER-SPECIFIED OVER-ALL MASS-TRANSFER COEFFICIENTS2300CS2400CS2400CS2400CS2400CS2400CS2400CS2400CS2400CS2400CS2400CS2400CS2500CS2500CS2500CS2700CS2800C <th>51500</th> <th>č</th> <th>CALCULATE THE INITIAL AREA AND DIAMETER</th>	51500	č	CALCULATE THE INITIAL AREA AND DIAMETER
51700AREA=VOLUM/Z51800DIA=SQRT(AREA/0.785)51900C52000C52100C52100C522001. A USER-SPECIFIED OVER-ALL MASS-TRANSFER COEFFICIENT52300C52400C52400C52500C53500C53500C53500C53500C53500C53600C53600C53600C53600C53600C53600C53600C53600C53600C53600C53600C53600C53600C53600C53600C	51600	č	CALCOLATE THE INTITAL ANEA AND DIAMETER.
51800DIA=SQRT(AREA/0.785)51900C52000C52100C52100C52200C52200C52300C52400C52400C52500C52500C52500C52600C52700C52800C52800C52800C52800C52800C52800C52800C52800C52800C52800C52800C53800C <t< th=""><th>51700</th><th>•</th><th>AREA=VOLUM/Z</th></t<>	51700	•	AREA=VOLUM/Z
51900C52000C52100C52100C52200C52200C52300C52400C52400C52500C52500C52500C52600C52700C52800C52800C52800C52800C52800C52800C52800C52800C52800C52800C52800C52800C52800C53800C </th <th>51800</th> <th></th> <th>DIA=SQRT(AREA/0.785)</th>	51800		DIA=SQRT(AREA/0.785)
S2000CTHE MASS-TRANSFER COEFFICIENT CAN BE CALCULATED ACCORDING TO52100C52200C52300C52400C52500C52600C52500C52500C52500C52500C52500C52500C52500C53500C53500C53500C53500C53600	51900	ç	
52100C522001.52200C52300C52400C52500C52500C52500C52500C52500C52500C52500C52500C52500C52500C52500C52500C52500C52600C52800C52800C52900C52900C53000C53100C53200C53200C53300C53300C53500C53500C53500C53500C53500C53600C<	52100	C	THE MASS-TRANSFER COEFFICIENT CAN BE CALCULATED ACCORDING TO:
52300C52400C52400C52500C52500C52500C52500C52500C52500C52500C52500C52500C52500C52500C52800C52800C52900C52900C53000C53100C53200C53100C53200C53100C53200C53500C53500C53500C53500C53500C53500C53600C </th <th>52200</th> <th>č</th> <th>1 A USER-SPECIFIED OVER-ALL MASS-TRANSFER COFFEICIENT</th>	52200	č	1 A USER-SPECIFIED OVER-ALL MASS-TRANSFER COFFEICIENT
52400C2.THE MASS-TRANSFER COEFFICIENT CORRELATION ACCORDING52500CTO MACKAY AND MATSUGU, 1973, CAN. J. CHE, V51,52600CP434-439.52700CC52800C3.52900CC52900CC53000CAS THAT OF LISS AND SLATER. SCALE THE AIR-PHASE53100CVALUE WITH RESPECT TO WIND SPEED ACCORDING TO53200CGARRATT, 1977, MONTHLY WEATHER REVIEW, V105,53300CP915-920.53400CTEMP IS R*T AND USED TO CHANGE THE UNITS ON THE MASS-53600CTEMP SEER COEFFICIENT	52300	č	The sound of contract who that the object of the
52500CTO MACKAY AND MATSUGU, 1973, CAN. J. CHE, V51,52600CP434-439.52700CS52800C3. INDIVIDUAL OIL- AND AIR-PHASE MASS-TRANSFER COEFFI-52900CC53000CAS THAT OF LISS AND SLATER. SCALE THE AIR-PHASE53100CVALUE WITH RESPECT TO WIND SPEED ACCORDING TO53200CGARRATT, 1977, MONTHLY WEATHER REVIEW, V105,53300CP915-920.53400CTEMP IS R+T AND USED TO CHANGE THE UNITS ON THE MASS-53600CTRANSFER COEFFICIENT	52400	Ċ	2. THE MASS-TRANSFER COEFFICIENT CORRELATION ACCORDING
52600CP434-439.52700C52800C52800C52900C52900CCCIENTS BASED ON SOME REAL ENVIRONMENTAL DATA SUCH53000CAS THAT OF LISS AND SLATER. SCALE THE AIR-PHASE53100CVALUE WITH RESPECT TO WIND SPEED ACCORDING TO53200CGARRATT, 1977, MONTHLY WEATHER REVIEW, V105,53300C53400C53500CTEMP IS R+T AND USED TO CHANGE THE UNITS ON THE MASS-53600C	52500	Ç	TO MACKAY AND MATSUGU, 1973, CAN. J. CHE, V51,
52700C52800C52800C52900C52900C53000CCAS THAT OF LISS AND SLATER. SCALE THE AIR-PHASE53100CCVALUE WITH RESPECT TO WIND SPEED ACCORDING TO53200CCGARRATT, 1977, MONTHLY WEATHER REVIEW, V105,53300C53400C53500CTEMP IS R+T AND USED TO CHANGE THE UNITS ON THE MASS-53600CTRANSFER COEFFICIENT	52600	C	P434-439.
52900 C CIENTS BASED ON SOME REAL ENVIRONMENTAL DATA SUCH 53000 C AS THAT OF LISS AND SLATER. SCALE THE AIR-PHASE 53100 C VALUE WITH RESPECT TO WIND SPEED ACCORDING TO 53200 C GARRATT, 1977, MONTHLY WEATHER REVIEW, V105, 53300 C P915-920. 53500 C TEMP IS R+T AND USED TO CHANGE THE UNITS ON THE MASS- 53600 C TRANSFER COEFFICIENT	52800	č	THRIVIRIAL OUL AND ATP-PHASE MASS_TRANSFER COFFEL
53000 C AS THAT OF LISS AND SLATER. SCALE THE AIR-PHASE 53100 C VALUE WITH RESPECT TO WIND SPEED ACCORDING TO 53200 C GARRATT, 1977, MONTHLY WEATHER REVIEW, V105, 53300 C P915-920. 53400 C TEMP IS R+T AND USED TO CHANGE THE UNITS ON THE MASS- 53600 C TRANSFER COFFFICIENT	52900	č	CIENTS BASED ON SOME REAL ENVIRONMENTAL DATA SUCH
53100CVALUE WITH RESPECT TO WIND SPEED ACCORDING TO53200CGARRATT, 1977, MONTHLY WEATHER REVIEW, V105,53300CP915-920.53400CTEMP IS R+T AND USED TO CHANGE THE UNITS ON THE MASS-53600CTEMPSEER COEFFICIENT	53000	č	AS THAT OF LISS AND SLATER. SCALE THE AIR-PHASE
53200 C GARRATT, 1977, MONTHLY WEATHER REVIEW, V105, 53300 C P915-920. 53400 C C 53500 C TEMP IS R+T AND USED TO CHANGE THE UNITS ON THE MASS- 53600 C TRANSFER COEFFICIENT	53100	С	VALUE WITH RESPECT TO WIND SPEED ACCORDING TO
53300 C P915-920. 53400 C 53500 C TEMP IS R+T AND USED TO CHANGE THE UNITS ON THE MASS- 53600 C TRANSFER COFFEICIENT	53200	C	GARRATT, 1977, MONTHLY WEATHER REVIEW, V105,
53500 C TEMP IS R+T AND USED TO CHANGE THE UNITS ON THE MASS- 53600 C TRANSFER COFFEICIENT	53300	C	P915-920.
53600 C TRANSFER COFFICIENT	53500	č	TEMP IS RAT AND USED TO CHANCE THE UNITS ON THE MASS-
	53600	č	TRANSFER COEFFICIENT.

53700	C	
53800	890	TEMP=(8.2E-05)+TK
53900		GO TO (900,950,1040), KMTC
54000	С	
54100	С	USER SPECIFIED OVER-ALL MASS-TRANSFER COEFFICIENT.
54200	Č	
54300	900	TYPE 910
54400	910	FORMAT(1X, 'ENTER THE OVER-ALL MASS-TRANSFER COEFFICIENT
54500	•••	
54600		
54700		
54900	020	WATELING, 220) Cornating to the cornecting of other to cornect
54000	920	WEITE (101 ATA TOR WEATHERING OF OIL IN FOOLS ON ICE)
54900		
22000	920	FORMAT(/, OVER-ALL MASS-TRANSFER COEFFICIENT WAS USER
55100	-	1-SPECIFIED AT ', TPETO.3, 'CM/HR BY INPUT CODE 1')
55200	C	
55300	C	CONVERT CM/HR TO GM-MOLES/(HR)(ATM)(M++2) SINCE VAPOR
55400	С	PRESSURE IS THE DRIVING FORCE FOR MASS TRANSFER.
55500	C	
55600		UMTC-UMTC/TEMP/100.
55700		DO 940 I=1,NC1
55800		MTC(I)=UMTC
55900	940	CONTINUE
56000		GO TO 1120
56100	С	
56200	č	USE THE MACKAY AND MATSUGU MASS-TRANSFER COEFFICIENT.
56300	č	
56400	950	TERM1=0.015+WINDMH++0.78
56500	Ċ.	
56600	č	THE SLICK DOES NOT SPREAD SO RASE THE DIAMETER DEPENDENCE
56700	č	ON 1999 METERS AND DIVIDE THE PESULT BY 9 7
56900	ž	on root meters and divide the result by 0.7
56000	060	
50900	300	1 ERM2=0.05
57000		VIL THOLEDED THE COMMENT NUMBER FOR OWNEND
57100		KH INCLUDES THE SCHWIDT NUMBER FOR COMENE.
57200	070	
5/300	970	
57400		WRITE(IOU, 980)
57500	980	FORMAT(1H1, WEATHERING OF OIL IN POOLS ON TOP OF ICE')
57600		WRITE (IOU,990) KMTC
57700	990	FORMAT(/,1X,'OVER-ALL MASS-TRANSFER COEFFICIENTS BY INPUT
57800		1 CODE', I2)
57900		WRITE (IOU,1000) KH
58000	1000	FORMAT(/,1X,'OVER-ALL MASS-TRANSFER COEFFICIENT FOR CUMENE =
58100		1,1PE10.3,' M/HR',/)
58200		WRITE (IOU, 1010)
58300	1010	FORMAT(3X, 'CUT', 12X, 'M/HR', 7X, 'GM-MOLES/(HR)(ATM)(M++2)')
58400		DO 1030 I=1.NC1
58500	С	
58600	Ċ	THE MASS-TRANSFER COEFFICIENT IS CORRECTED FOR THE
58700	Č	DIFFUSIVITY OF COMPONENT I IN AIR. THE SORT IS USED
58800	č	(I.F. LISS AND SLATER) BUT THE 1/3 POWER COULD ALSO
58988	č	BE USED (I E THE SCHMIDT NIMPER)
50000	č	SE OSES (I.C. THE SOMMENT NOMBER).
50100	•	MTCA(1)-KHAQ 03-SOPT((MW(1)+20)/MW(1))
50200	c	mich(1)-Kuse.32s34ki((MM(1)+23.)/MM(1))
55200	č	NTO(1) TO THE OVER ALL MASS TOALSEED ADERTATENT STUDED
23300		MIC(1) IS THE UVER-ALL MASS-TRANSFER COEFFICIENT DIVIDED
39400	U O	DT R+1. R=02.00L-00 (AIM)(M++3)/(G-MOLE)(DEG K)
29266	C	
		MICLENMICALIN/TEMP

WRITE (IOU,1020) I,MTCA(I),MTC(I)
FORMAT(2X,I3,2(10X,1PE10.3)) 59700 59800 1020 CONTINUE 59900 1030 60000 GO TO 1120 60100 С 60200 С USER SPECIFIED INDIVIDUAL-PHASE MASS-TRANSFER COEFFICIENTS. 60300 C 60400 С 60500 1040 TYPE 1050 FORMAT(1X, 'ENTER THE OIL-PHASE MASS-TRANSFER COEFFICIENT 60600 1050 60700 1 IN CM/HR, TRY 10') 60800 ACCEPT 280, KOIL 60900 **TYPE 1060** FORMAT(1X, 'ENTER THE AIR-PHASE MASS-TRANSFER COEFFICIENT 1060 61000 1 IN CM/HR, TRY 1000') 61100 ACCEPT 280. KAIR 61200 61300 TYPE 1070 1070 FORMAT(1X, 'ENTER THE MOLECULAR WEIGHT OF THE COMPOUND 61400 61500 1 FOR K-AIR ABOVE, TRY 200') 61600 ACCEPT 280, DATAMW 61700 C SCALE K-AIR ACCORDING TO WIND SPEED (GARRATT, 1977), 61800 С 61900 С SO THAT AS THE WIND SPEED GOES UP THE MASS TRANSFER 62000 С GOES UP, I.E., THE CONDUCTANCE INCREASES. 62100 С 62200 KAIR=KAIR+(1.+0.089+WINDMS) 62300 RKAIR=1./KAIR 62400 C 62500 С CALCULATE R+T IN ATM+CM++3/GM-MOLE 62600 С 62700 RT=82.06+TK 62800 HTERM=WTMOLE/(DCRUDE+RT) 62900 WRITE (IOU, 990) KMTC 63000 С 63100 С WRITE THE USERS INPUT, WIND SPEED, AND HENRYS LAW С 63200 TERM TO THE OUTPUT. С 63300 WRITE (IOU,1080) KAIR,KOIL,DATAMW FORMAT(/,1X,'K-AIR = ',1PE10.3,', AND K-OIL = ',1PE10.3 63400 63500 1080 63600 1, ' CM/HR, BASED ON A MOLECULAR WEIGHT OF ', 1PE10.3) WRITE (IOU, 1090) WINDMS 1090 FORMAT(1X, 'WIND SPEED = ', 1PE10.3, ' M/S') 63700 63800 WRITE (IOU, 1100) HTERM FORMAT(1X, 'THE HENRYS LAW CONVERSION TERM FOR OIL = ' 1,1PE10.3, ' 1/ATM') 63900 64000 1100 64100 64200 WRITE (IOU, 1010) 64300 С 64400 С CALCULATE THE OVER-ALL MASS-TRANSFER COEFFICIENT BASED 64500 ON GAS-PHASE CONCENTRATIONS FOR EACH CUT. С 64600 С DO 1110 I=1,NC1 64700 HLAW(I)=HTERM+VP(I) 64800 64900 MTCA(I)=RKAIR+HLÀW(I)/KOIL 65000 С 65100 С NOW TAKE THE INVERSE TO OBTAIN CM/HR AND THEN MULTIPLY 65200 Ċ BY 0.01 TO GET M/HR. 65300 C 65400 MTCA(I)=0.01/MTCA(I) 65500 С 65500 С CORRECT FOR MOLECULAR WEIGHT ACCORDING TO LISS & SLATER,

1974, NATURE, V247, P181-184. 100 С 200 С 300 MTCA(I)=MTCA(I)*SQRT(DATAMW/MW(I)) 400 MTC(I)=MTCA(I)/TEMP 500 С AND WRITE THE OVER-ALL MASS-TRANSFER COEFFICIENT 600 С 700 С IN M/HR AND MOLE/HR+ATM+M+M. 800 С 900 WRITE (IOU, 1020) I, MTCA(I), MTC(I) 1000 1110 CONTINUE 1100 1120 SPGRB=141.5/(APIB+131.5) 1200 MASS=0.1582+BBL+SPGRB WRITE (IOU, 1130) BBL, MASS FORMAT(/,1X,'FOR THIS SPILL OF ', 1PE10.3,' BARRELS, THE 1300 1400 1130 1 MASS IS ', 1PE10.3, ' METRIC TONNES') 1500 1600 VOLUMB=VOLUM/0.159 WRITE (IOU, 1140) VOLUM, VOLUMB 1140 FORMAT(/,1X,'VOLUME FROM SUMMING THE CUTS = ',1PE8.1,' M++3 1700 1800 TORMAT(/,TX, 'VCLUME FROM SUMMING THE COTS = ',TPE8.1, Mar 1, OR ', 1PE10.3, ' BARRELS') GO TO (1170,1150,1170), KMTC WRITE (IOU,1160) WINDS,WINDMH FORMAT(/,1X,'WIND SPEED = ',1PE10.3, ' KNOTS, OR ',1PE10.3 1, ' M/HR') 1900 2000 2100 1150 2200 1160 2300 1170 WRITE (IOU,1180) DIA,AREA 1180 FORMAT(/,1X,'INITIAL SLICK DIAMETER = ',1PE10.3,' M, OR AREA 1 = ',1PE10.3,' M**2') WRITE (IOU,1190) 1190 FORMAT(/,1X,'THIS SLICK DOES NOT SPREAD FOR THIS CALCULATION') 2400 2500 2600 2700 2800 2900 С CALCULATE THE KINEMATIC VISCOSITY OF THE CRUDE AT 122 DEG F AND THE ENTERED ENVIRONMENTAL TEMPERATURE. 3000 С 3100 С 3200 С USE THE VISCOSITY MIXING RULE OF (MOLE FRACTION) + (LOG), 3300 SEE PAGE 460 OF REID, PRAUSNITZ & SHERWOOD IN С 3400 THE BOOK 'THE PROPERTIES OF GASES AND LIQUIDS' C 3500 C 3600 1200 VISMIX=0. 3700 DO 1210 I=1, NCUTS VISMIX=VISMIX+MOLES(I)+VLOGK(I)/TMOLES 3800 3900 1210 CONTINUE 4000 VISMIX=EXP(VISMIX) WRITE (IOU, 1220) VISMIX FORMAT(/,1X,'KINEMATIC VISCOSITY OF THE BULK CRUDE FROM 1 THE CUTS = ',1PE8.1,' CENTISTOKES AT 122 DEG F') 4100 4200 1220 4300 VISMIX=0. 4400 4500 С SCALE THE VISCOSITY WITH TEMPERATURE ACCORDING TO 4600 С 4700 С ANDRADE. 4800 С 4900 XSAVE=XSAVE+459. 5000 EXPT=EXP(1923.*(1./XSAVE-0.001721)) 5100 DO 1230 I=1.NCUTS VIS(I)=VISK(I)+EXPT 5200 5300 VLOG(I)=ALOG(VIS(I) 5400 VISMIX=VISMIX+MOLES(I)+VLOG(I)/TMOLES 5500 1230 CONTINUE 5600 XPRINT=32 VISMIX=EXP(VISMIX) 5700 5800 WRITE (IOU, 1240) VISMIX, XPRINT, EXPT 1240 FORMAT(/,1X,'KINEMATIC VISCOSITY OF THE BULK CRUDE FROM THE 1 CUTS = ',1PE8.1,' AT T = ',0PF5.1,' DEG F, SCALE 5900 6000

6100		2 FACTOR = ',1PE8.1)
6200	Ç	
6300	Ç	IMPORTANT NOTE: THE VISCOSITY PREDICTION OF THE WHOLE
6400	C	CRUDE FROM CUT INFORMATION IS NOT GOOD AT ALL. SO THE
6500	C	VISCOSITY INFOMATION CALCULATED ABOVE IS NOT USED IN
6700		MIN VERSION OF THE CODE, BUT IT COULD BE IF A GOOD
6900		MIXING RULE IS EVER DELEMMINED.
6000	č	WEATHERED OPIDE IS CALCULATED ACCORDING TO MACKAY
7030	č	WEATHERED GRODE IS CALCOLATED ACCORDING TO MACKAT.
7100	č	NOW LOAD THE VISCOSITY INFORMATION IN THE FORM
7200	č	OF THREE CONSTANTS:
7.300	č	1. THE VISCOSITY IN CP AT 25 DEG C
7400	č	2. THE ANDRADE-VISCOSITY-SCALING CONSTANT
7500	č	WITH RESPECT TO TEMPERATURE. SEE GOLD &
7600	č	OGLE, 1969, CHEM, ENG., JULY 14, P121-123
7700	Ċ	3. THE VISCOSITY AS AN EXPONENTIAL FUNCTION OF
7800	С	THE FRACTION OF OIL WEATHERED
79 00	С	
8000		IF(LSWTCH.EQ.99) GO TO 1260
8100		TYPE 1250
8200	1250	FORMAT(1X,'SINCE A LIBRARY CRUDE WAS NOT USED
8300		1,',/,1X,'ENTER THE FOLLOWING THREE VISCOSITY CONSTANTS')
8400		GO TO 1280
8500	1260	TYPE 1270
8600	1270	FORMAT(1X, 'DO YOU WANT TO ENTER NEW VISCOSITY CONSTANTS?')
8700		ACCEPT 390, ANS
8800		IF(ANS.EQ. 'N') GO TO 1320
8900	1280	TYPE 1290
9000	1290	FORMAT(1X, 1. ENTER THE BULK CRUDE VISCUSTIT
9100		A A ZO DEG U, CENTIPUISE, TRY 35.)
9200		AUCEF 1 200, V132 Type 13aa
9,000	1 300	FORMAT(1Y '2 ENTER THE VISCOSITY TEMPERATURE SCALING
9500	1000	1 CONSTANT (ANDRADE) TRY 9000 ')
9600		ACCEPT 280 MK3
9700		TYPE 1310
9800	1310	FORMAT(1X.'3. ENTER THE VISCOSITY-FRACTION-OIL
9900		1-WEATHERED CONSTANT, TRY 10.5')
10000		ACCEPT 280, MK4
10100		GO TO 1330
10200	С	
10300	С	USE THE LIBRARY VISCOSITY DATA
10400	С	
10500	1320	VISZ=VISZL(IC)
10600		MK3=MK3L([C)
10700	-	MK4=MK4L(IC)
10800	C	
10900	C	INSERT VISCOSITY CALCULATION ACCORDING TO MASS
111000		FRACTION EVAPORATED. THIS IS THE VISCOSITE
11200	č	MUDIFICATION RELATIVE TO CUTVPT
11300	1110	VELEAD-VISTOFYD(MK3+(1 /TK-0 003387))
11400	1330	WRITE (INH 1340) VICT MK3 MK4 VCIEAN
11500	1340	FORMAT(/ 12 'VISCOSITY ACCORDING TO MASS EVAPORATED.
11600	.040	1 VIS25C =' 1PF9.2.' ANDRADE =' 1PF9.2
11700		2.'. FRACT WEATHERED ='. $1PE9.2'$. VSLEAD ='. $1PE9.2$
11800		3.' CP')
11900		C2P=1./C2
12000		WRITE (IOU, 1500) C1, C2P, C4

NEO=NCUTS FRACTS=0. С С SPECIFY NO DISPERSION С 1350 WRITE (IOU, 1360) FRACTS 1360 FORMAT(/,1X,'THE FRACTIONAL SLICK AREA SUBJECT TO 1 DISPERSION IS ',1PEB.1,' PER HOUR') С С PRINT EVERY XP TIME INCREMENT (HOURS). Ċ X1 IS THE STARTING TIME = 0 С X2 IS THE NUMBER OF HOURS FOR WEATHERING TO OCCUR. C XP=1. X1=0 MOLS(NCUTS+1)=AREA С С PRINT AN OUTPUT FILE FOR 80 COLUMN OUTPUT, THIS IS С THE OILICE. TYP FILE. C WRITE(ITY, 1380) 1380 FORMAT(1X, 'WEATHEPING OF OIL IN POOLS ON TOP OF ICE') 1380 FORMAT(1X, 'WEATHEFING OF OIL IN POOLS ON TOP OF ICE') WRITE (ITY,1390) (ANAME(J),J=1,5) 1390 FORMAT(/,1X,'OIL: ',5A5) WRITE (ITY,1400) XPRINT.WINDS 1400 FORMAT(1X,'TEMPERATURE= ',F5.1,' DEG F, WIND SPEED= ' 1,F5.1,' KNOTS') WRITE (ITY,1410) BBL 1410 FORMAT(1X,'SPILL SIZE= ',1PE10.3,' BARRELS') WRITE (ITY,1420) KMTC 1420 FORMAT(1X,'MASS-TRANSFER COEFFICIENT CODE=',I3) WRITE (ITY,1430) 1430 FORMAT(/,1X,'FOR THE OUTPUT THAT FOLLOWS, MOLES 1=GRAM MOLES') 1#GRAM MOLES') WRITE (ITY, 1440) 1440 FORMAT(1X, 'GMS=GRAMS, VP=VAPOR PRESSURE IN ATMOSPHERES') WRITE (ITY, 1450) WRITE (ITY,1450)
1450 FORMAT(1X,'BP=BOILING POINT IN DEG F, API=GRAVITY')
WRITE (ITY,1460)
1460 FORMAT(1X,'MW=MOLECULAR WEIGHT')
WRITE (ITY,1470)
1470 FORMAT(/,2X,'CUT',3X,'MOLES',6X,'GMS',8X,'VP',8X,'BP'
1,7X,'API',5X,'MW')
D0 1490 I=1,NCUTS
CMS=M0LES()>AMV(I) GMS=MOLES(I) + MW(I) IMW=MW(I) WRITE (ÎTY.1480) I.MOLES(I),GMS,VP(I),TB(I),API(I),IMW FORMAT(3X,I2,5(1X,1PE9.2),1X,I3) CONTINUE WRITE (ITY, 1500) C1, C2P, C4
 1500 FORMAT(/, 1X, 'MOUSSE CONSTANTS: MOONEY=', 1PE9.2 1, ', MAX H20=', 0PF5.2, ', WIND++2=', 1PE9.2) WRITE (ITY, 1510) KA, KB, STEN
 1510 FORMAT(1X, 'DISPERSION CONSTANTS: KA=', 1PE9.2 1, ', KB=', 1PE9.2, ', S-TENSION=', 1PE9.2) WRITE (ITY, 1520) VISZ,MK3,MK4 FORMAT(1X, 'VIS CONSTANTS: VIS25C=', 1PE9.2 1,', ANDRADE =', 1PE9.2,', FRACT =', 1PE9.2) WRITE (ITY, 1530) 1530 FORMAT(/,1X,'FOR THE OUTPUT THAT FOLLOWS, TIME-HOURS')

18100 WRITE (ITY, 1540) 18200 1540 FORMAT(1X, 'BBL=BARRELS, SPGR=SPECIFIC GRAVITY, AREA=M+M') WRITE (ITY, 1550) FORMAT(1X, 'THICKNESS=CM, W=PERCENT WATER IN OIL (18300 18400 1550 18500 1MOUSSE)' 1MOUSSE)') WRITE (ITY,1560) FORMAT(1X,'DISP=DISPERSION RATE IN GMS/M+M/HR') WRITE (ITY,1570) FORMAT(1X,'ERATE=EVAPORTION RATE IN GMS/M+M/HR') WRITE (ITY,1580) FORMAT(1X,'M/A=MASS PER M+M OF OIL IN THE SLICK') WRITE (ITY,1590) FORMAT(1X,'I=FIRST CUT WITH GREATER THAN 1% (MASS) PERMATNING') 18600 18700 1560 18800 18900 1570 19000 19100 1580 19200 19300 1590 1 REMAINING') 19400 WRITE (ITY, 1600) 1600 FORMAT(1X, 'J=FIRST CUT WITH GREATER THAN 50% (MASS) 19500 19600 19700 1 REMAINING') WRITE (ITY, 1610) FORMAT(1X, 'DISPERSION WAS TURNED OFF') WRITE (ITY, 1620) FORMAT(1X, 'SPREADING WAS TURNED OFF') 19800 19900 1610 20000 20100 1620 20200 1630 TCODE=KMTC 20300 **TYPE 1640** 20400 1640 FORMAT(/,1X, 'PLEASE WAIT') 20500 С 20600 С SUBROUTINE BRKG4 DOES THE INTEGRATION 20700 C 20800 CALL BRKG4(MOLS, X1, X2, XP, NEQ, NDEL) 20900 С 21000 С ND IS THE NUMBER OF CUTS THAT WEATHERED COMPLETELY AWAY 21100 С ND=0 21200 21300 DO 1650 I=1,NEQ 21400 IF (YM(I).NE.0.) GO TO 1650 21500 ND=ND+1 21600 1650 CONTINUE 21700 С 21800 С NDEL IS THE NUMBER OF CUTS THAT WERE DELETED BECAUSE THEY С 21900 EVAPORATE TO QUICKLY 22000 С 22100 NEW=NDEL+ND 22200 IF(NQUIT.EQ.1) GO TO 4460 22300 1660 TYPE 1670 22400 1670 FORMAT(1X, 'WILL THE OIL NOW WEATHER IN THE BROKEN ICE FIELD?') 22500 ACCEPT 390, ANS 22600 IF(NIP.EQ.0) GO TO 1710 22700 TV=0. 22800 С 22900 С NOW CALCULATE NEW VALUES FOR VOLUME PERCENT FOR EACH CUT AND SHIFT THE ARRAYS FOR VOLUME PERCENT, BOILING POINT, AND API TO ELIMINATE CUTS THAT ARE GONE 23000 С 23100 С 23200 С 23300 DO 1680 I=1, NEQ-ND 23400 TV=TV+(YM(ND+I)*YMSAVE(ND+I)/SPGR(NEW+I)) 23500 VOL(I)=YM(ND+I)+MOLES(NEW+I)+MW(NEW+I)/(SPGR(NEW+I) 1 * (BBL * 1582.)) 23600 TB(I)=TB(NEW+I) API(I)=API(NEW+I) 23700 23800 23900 1680 CONTINUE 24000 BBL=TV/158200.
24100 NCUTS=NCUTS-(ND+NDEL) NEO=NCUTS 24200 24300 С 24400 С ALWAYS RENORMALIZE THE INPUT VOLUMES TO 100%. Ĉ 24500 VTOTAL=0. 24600 24700 DO 1690 I=1,NCUTS 24800 VTOTAL=VTOTAL+VOL(I) CONTINUE 24900 1690 25000 DO 1700 I=1,NCUTS VOL(I)=100.+VOL(I)/VTOTAL 25100 25200 1700 CONTINUE 25300 I S=0 25400 APISWI=1 25500 CALL DOCHAR 1710 IF(ANS.EQ.'N') GO TO 3060 25600 25700 NG=NG+NEW NBI=125800 25900 **TYPE 1720** FORMAT(1X, 'FOR HOW MANY HOURS?') 1720 26000 26100 ACCEPT 280.X2 26200 С NHBI IS THE NUMBER OF HOURS OF BROKEN ICE FIELD WEATHERING 26300 С 26400 C 26500 NHBI=X2 TYPE 1730 26600 1730 FORMAT(1X, 'AT WHAT TEMPERATURE, DEG F?') 26700 26800 ACCEPT 280,XSAVE 26900 **TYPE 1740** FORMAT(1X, 'ENTER THE FRACTION OF ICE COVER, I.E. 0.7') 27000 1740 27100 ACCEPT 280, FRACIC TK=(XSAVE-32.)/1.8+273. 27200 27300 XPRINT=XSAVE 27400 XSAVE=XSAVE+459 27500 NCC1=NC1 CALL VPIF(XSAVE,NCC1) TEMP=(8.2E-05)+TK 27600 27700 FACMOU=1 27800 27900 C THE FUNCTIONAL DEPENDENCE OF MOUSSE FORMATION RATE WITH 28000 С FRACTION OF ICE COVER IS NOT KNOWN. FOR NOW THE VARIABLE FACMOU WILL BE THE FACTOR WHICH WILL DETERMINE THE С 28100 28200 С AMOUNT OF INCREASE OF FORMATION RATE. IF MOUSSE 28300 С CONSTANTS ARE NOT INPUT BY THE USER, FACMOU-10 С 28400 С 28500 IF(LSWTCH.EQ.99) GO TO 1770 28600 TYPE 1750 28700 28800 1750 FORMAT(1X, 'SINCE YOU DID NOT USE A LIBRARY CRUDE, ') 28900 TYPE 1760 29000 1760 FORMAT(1X, YOU MUST ENTER THE FOLLOWING FOUR MOUSSE 29100 1 FORMATION CONSTANTS') 29200 GO TO 1790 TYPE 1780 29300 1770 29400 1780 FORMAT(1X. DO YOU WANT TO ENTER NEW MOUSSE FORMATION CONS 29500 1TANTS? ACCEPT 390, ANS IF(ANS.EQ.'N') GO TO 1860 29600 29700 29800 С 29900 С TO SPECIFY NO MOUSSE. ENTER C2 = 0 С 30000

30100 1790 **TYPE 1800** 30200 1800 FORMAT(1X,'1. ENTER THE MAXIMUM WEIGHT FRACTION WATER 30300 1 IN OIL') ACCEPT 280, C2 30400 30500 IF(C2.GT.0.) GO TO 1820 30600 C 30700 С SET C2=-1. IF A MOUSSE CANNOT BE FORMED AND LOOP OUT. 30800 С C2=-1 30900 TYPE 1810 31000 1810 FORMAT(/,1X,'SINCE A 0% WATER CONTENT WAS SPECIFIED 31100 1, THE REMAINING THREE MOUSSE', /, 1X, 'CONSTANTS ARE NOT 31200 31300 2 NEEDED' 31400 GO TO 1870 C2=1./C2 TYPE 1830 31500 1820 31600 FORMAT(1X, '2. ENTER THE MOUSSE-VISCOSITY CONSTANT 1830 31700 31800 1. TRY 0.65') 31900 ACCEPT 280, C1 32000 **TYPE 1840** FORMAT(1X,'3. ENTER THE WATER INCORPORATION RATE CONSTANT 32100 1840 32200 1. TRY 0.001') ACCEPT 280, C4 32300 32400 TYPE 1850 32500 1850 FORMAT(1X,'4. ENTER THE BROKEN ICE FIELD MULTIPLIER FOR MOUSSE 1 FORMATION') 32600 ACCEPT 280, FACMOU 32700 32800 GO TO 1870 32900 1860 C1=C1L(IC) 33000 C2=C2L(IC)C4=C4L(IC) 33100 33200 FACMOU=10. 33300 1870 CONTINUE 33400 C4=C4+FACMOU 33500 IF(LSWTCH.EQ.99) GO TO 1900 33600 TYPE 1880 FORMAT(/,1X,'YOU MUST ALSO ENTER AN OIL-WATER SURFACE 1 TENSION (DYNES/CM') 33700 1880 33800 TYPE 1890 33900 FORMAT(1X, 'FOR DISPERSION, TRY 30.') 34000 1890 34100 GO TO 1930 1900 **TYPE 1910** 34200 34300 FORMAT(1X, 'DO YOU WANT TO ENTER A NEW OIL-WATER SURFACE 1910 1 TENSION (DYNES/CM)?') 34400 34500 ACCEPT 390, ANS IF(ANS.EQ.'N') GO TO 1940 34600 TYPE 1920 34700 FORMAT(1X, 'TRY 30.') 34800 1920 34900 1930 ACCEPT 280, STEN 35000 GO TO 1950 STEN=STENL(IC) 35100 1940 35200 С 35300 С START THE MASS-TRANSFER COEFFICIENT SPECIFICATION. 35400 C 35500 1950 **TYPE 1960** FORMAT(1X, 'ENTER THE MASS-TRANSFER COEFFICIENT CODE: 1 35600 1960 1, 2, OR 3 WHERE: ') 35700 TYPE 1970 35800 35900 FORMAT(1X, '1=USER SPECIFIED OVER-ALL MASS-TRANSFER COEF 1970 36000 1FICIENT')

36100 **TYPE 1980** 1980 FORMAT(1X, '2=CORRELATION MASS-TRANSFER COEFFICIENT BY 36200 36300 1 MACKAY & MATSUGU') 36400 **TYPE 1990** 36500 1990 FORMAT(1X, '3=INDIVIDUAL-PHASE MASS-TRANSFER COEFFICIENTS') ACCEPT 420, KMTC 36600 36700 С 36800 С NOW ENTER THE WIND SPEED IN KNOTS AND CONVERT TO METER/SEC С 36900 AND METER/HOUR. 37000 С 37100 TYPE 2000 2000 FORMAT(1X, 'ENTER THE WIND SPEED IN KNOTS') 37200 ACCEPT 280, WINDS 37300 37400 С 37500 NEVER LET THE WIND SPEED DROP BELOW 2 KNOTS. A ZERO WIND С SPEED DESTROYS THE MASS-TRANSFER CALCULATION AND WILL 37600 С YIELD A ZERO MASS-TRANSFER COEFFICIENT. 37700 С 37800 С 37900 IF(WINDS.LT.2.) WINDS=2. 38000 WINDMS=0.514+WINDS 38100 WINDMH=1853.+WINDS С 38200 38300 С NOW CALCULATE THE INITIAL GRAM MOLES FOR EACH COMPONENT TO С GET THE INTEGRATION STARTED. 38400 38500 С 38600 2010 BM=0.159+88L 38700 TMOLES=0. DO 2020 I=1,NCUTS 38800 38900 AMASS=1582. • SPGR(I) • BBL • VOL(I) 39000 MOLES(I)=AMASS/MW(I) 39100 MOLS(I) - MOLES(I) TMOLES-TMOLES+MOLES(I) 39200 39300 С RHO IS THE DENSITY IN GM MOLES/CUBIC METER. 39400 С 39500 С 39600 RHO(I)=100.*MOLES(I)/(BM*VOL(I)) 39700 2020 CONTINUE 39800 С 39900 С CALCULATE THE MEAN MOLECULAR WEIGHT OF THE CRUDE 40000 С 40100 WTMOLE=0. 40200 DO 2030 I=1.NCUTS 40300 WTMOLE=WTMOLE+MW(I)+MOLES(I)/TMOLES 40400 2030 CONTINUE WRITE (IOU,2040) WTMOLE FORMAT(/,1X,'MEAN MOLECULAR WEIGHT OF THE CRUDE = ',1PE10.3) 40500 2040 40600 40700 С 40800 С SPECIFY SLICK SPREADING. 40900 C 41000 2050 SPREAD=0. 41100 TYPE 2060 41200 2060 FORMAT(1X, 'DO YOU WANT THE SLICK TO SPREAD?') ACCEPT 390, ANS IF(ANS.EQ.'N') GO TO 2070 41300 41400 41500 SPREAD=1 41600 GO TO 2100 С 41700 41800 С CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED С AS THE SLICK WEATHERS. Z=THICKNESS IN METERS. 41900 С 42000

IF (NZSWI.EQ.1) GO TO 2090 42100 2070 TYPE 2080 42299 FORMAT(1X, 'SINCE THE SLICK DOES NOT SPREAD, ENTER 42300 2080 42400 1 A STARTING THICKNESS IN CM') 42500 ACCEPT 280. Z 42600 2090 Z=Z/100. 42700 GO TO 2110 42800 С THE SLICK ALWAYS STARTS AT 2-CM THICKNESS. 42900 С 43000 C 43100 2100 IF (NZSWI.NE.0) GO TO 2110 43200 Z=0.02 VOLUM-0. 2110 43300 43400 DO 2120 I=1, NCUTS VOLUM=VOLUM+MOLES(I)/RHO(I) 43500 43600 2120 CONTINUE 43700 NZSWI=1 43800 С CALCULATE THE INITIAL AREA AND DIAMETER. 43900 С 44000 С 44100 AREA=VOLUM/Z DIA=SQRT(AREA/0.785) 44200 44300 C THE FUNCTIONAL DEPENDENCE OF SPREADING WITH FRACTION OF ICE 44499 С 44500 С COVER IS NOT KNOWN. FOR NOW, A LINEAR DEPENDENCE IS ASSUMMED 44600 С 44700 SPRFAC=1.-FRACIC 44800 С THE MASS-TRANSFER COEFFICIENT CAN BE CALCULATED ACCORDING TO: 44900 С 45000 С A USER-SPECIFIED OVER-ALL MASS-TRANSFER COEFFICIENT. 45100 С 1. С 45200 45300 С 2. THE MASS-TRANSFER COEFFICIENT CORRELATION ACCORDING С TO MACKAY AND MATSUGU, 1973, CAN. J. CHE, V51, 45400 С 45500 P434-439. 45600 С С INDIVIDUAL OIL- AND AIR-PHASE MASS-TRANSFER COEFFI-45700 3. 45800 С CIENTS BASED ON SOME REAL ENVIRONMENTAL DATA SUCH Ċ AS THAT OF LISS AND SLATER. SCALE THE AIR-PHASE 45900 46000 С VALUE WITH RESPECT TO WIND SPEED ACCORDING TO 46100 С GARRATT, 1977, MONTHLY WEATHER REVIEW, V105, 46200 С P915-920. 46300 С 46400 С TEMP IS R+T AND USED TO CHANGE THE UNITS ON THE MASS-46500 С TRANSFER COEFFICIENT. 46600 С 2130 46700 TEMP=(8.2E-05)+TK 46800 GO TO (2140,2180,2290), KMTC 46900 С 47000 С USER SPECIFIED OVER-ALL MASS-TRANSFER COEFFICIENT. 47100 С TYPE 2150 47200 2140 47300 FORMAT(1X, 'ENTER THE OVER-ALL MASS-TRANSFER COEFFICIENT 2150 47400 1, CM/HR, TRY 10') 47500 ACCEPT 280, UMTC WRITE (IOU, 2160) UMTC 2160 FORMAT(1H1, 'OVER-ALL MASS-TRANSFER COEFFICIENT WAS USER 47600 47700 47800 1-SPECIFIED AT ', 1PE10.3, ' CM/HR BY INPUT CODE 1') 47900 С 48000 С CONVERT CM/HR TO GM-MOLES/(HR)(ATM)(M++2) SINCE VAPOR

48100 PRESSURE IS THE DRIVING FORCE FOR MASS TRANSFER. C 48200 С 48300 UMTC-UMTC/TEMP/100. 48400 DO 2170 I=1,NC1 48500 MTC(I)=UMTC 2170 48600 CONTINUE 48700 GO TO 2370 48800 С 48900 С USE THE MACKAY AND MATSUGU MASS-TRANSFER COEFFICIENT. 49000 С 49100 2180 TERM1=0.015+WINDMH++0.78 49200 IF(SPREAD.EQ.0.) GO TO 2190 49300 TERM2=DIA++(-0.11) 49400 GO TO 2200 С 49500 IF THE SLICK DOES NOT SPREAD BASE THE DIAMETER DEPENDENCE 49600 С С 49700 ON 1000 METERS AND DIVIDE THE RESULT BY 0.7 49800 С 2190 TERM2=0.65 49900 50000 C С KH INCLUDES THE SCHMIDT NUMBER FOR CUMENE. 50100 50200 C 50300 2200 KH=TERM1+TERM2 50400 WRITE(IOU, 2210) FORMAT (1H1, 'WEATHERING DATA FOR OIL IN A BROKEN ICE FIELD') 50500 2210 50600 IF(NIP.NE.1) GO TO 2230 WRITE(IOU, 2220)NHIP 50700 50800 2220 FORMAT(1X, 'AFTER ICE POOL WEATHERING FOR ', 1PE9.3, ' HOURS') WRITE (IOU, 2240) KMTC FORMAT(/,1X,'OVER-ALL MASS-TRANSFER COEFFICIENTS BY INPUT 50900 2230 51000 2240 1 CODE', 12) WRITE (IOU, 2250) KH FORMAT(/,1X,'OVER-ALL MASS-TRANSFER COEFFICIENT FOR CUMENE = ' 1,1PE10.3,' M/HR',/) 51100 51200 51300 2250 51400 WRITE (IOU, 2260) 51500 51600 2260 FORMAT(3X,'CUT',12X,'M/HR',7X,'GM-MOLES/(HR)(ATM)(M**2)') DO 2280 I=1,NC1 51700 51800 С 51900 THE MASS-TRANSFER COEFFICIENT IS CORRECTED FOR THE C 52000 С DIFFUSIVITY OF COMPONENT I IN AIR. THE SQRT IS USED (I.E. LISS AND SLATER), BUT THE 1/3 POWER COULD ALSO 52100 С 52200 С BE USED (I.E. THE SCHMIDT NUMBER). 52300 С 52400 MTCA(I)=KH+0.93+SQRT((MW(I)+29.)/MW(I)) 52500 С MTC(I) IS THE OVER-ALL MASS-TRANSFER COEFFICIENT DIVIDED 52600 С BY R+T. R=82.06E-06 (ATM) (M++3)/(G-MOLE) (DEG K) 52700 С Ċ 52800 MTC(I)=MTCA(I)/TEMP 52900 WRITE (IOU, 2270) I, MTCA(I), MTC(I) FORMAT(2X, I3, 2(10X, 1PE10.3)) 53000 53100 2270 53200 2280 CONTINUE 53300 GO TO 2370 С 53400 53500 С USER SPECIFIED INDIVIDUAL-PHASE MASS-TRANSFER С COEFFICIENTS. 53600 53700 C 2290 TYPE 2300 53800 53900 2300 FORMAT(1X, 'ENTER THE OIL-PHASE MASS-TRANSFER COEFFICIENT 54000 1 IN CM/HR, TRY 10')

54100		ACCEPT 280, KOIL
54200		TYPE 2310
54300	2310	FORMAT(1X, 'ENTER THE AIR-PHASE MASS-TRANSFER COEFFICIENT
54400		1 IN CM/HR, TRY 1000')
54500		ACCEPT 280, KAIR
54600		TYPE 2320
54700	2320	FORMAT(1X,'ENTER THE MOLECULAR WEIGHT OF THE COMPOUND
54800		1 FOR K-AIR ABOVE, TRY 200')
54900		ACCEPT 280, DATAMW
55000	С	
55100	С	SCALE K-AIR ACCORDING TO WIND SPEED (GARRATT, 1977),
55200	С	SO THAT AS THE WIND SPEED GOES UP THE MASS TRANSFER
55300	С	GOES UP, I.E., THE CONDUCTANCE INCREASES.
55400	С	
55500		KAIR=KAIR+(1.+0.089+WINDMS)
55600		RKAIR-1./KAIR
55700	С	
55800	С	CALCULATE R+T IN ATM+CM++3/GM-MOLE
55900	С	·
56000		RT=82.06+TK
56100		HTERM=WTMOLE/(DCRUDE+RT)
56200		WRITE (IOU, 2240) KMTC
56300	С	
56400	С	WRITE THE USERS INPUT, WIND SPEED, AND HENRYS LAW
56500	С	TERM TO THE OUTPUT.
56600	С	
56700		WRITE (IOU.2330) KAIR.KOIL.DATAMW
56800	2330	FORMAT(/.1X.'K-AIR = '.1PE10.3.'. AND K-OIL = '.1PE10.3
56900		1. CM/HR. BASED ON A MOLECULAR WEIGHT OF '. 1PE10.3)
57000		WRITE (IOU. 2340) WINDMS
57100	2340	FORMAT(1X, 'WIND SPEED = '. 1PE10.3.' W/S')
57200		WRITE (10U.2350) HTERM
57300	2350	FORMAT(1X, THE HENRYS LAW CONVERSION TERM FOR OIL = '
57400		1.1PE10.3. 1/ATN')
57500		WRITE (100.2260)
57600	с	
57700	č	CALCULATE THE OVER-ALL MASS-TRANSFER COEFFICIENT BASED
57800	č	ON GAS-PHASE CONCENTRATIONS FOR EACH CUT.
57900	č	
58000	-	DQ 2360 I=1.NC1
58100		HLAW(I)=HTFRM+VP(I)
58200		MTCA(I)=RKAIR+HLAW(I)/KOIL
58300	С	
58400	č	NOW TAKE THE INVERSE TO OBTAIN CM/HR AND THEN MULTIPLY
58500	č	BY 0.01 TO GET M/HR.
58600	č	
58700	-	MTCA(I)=0.01/MTCA(I)
58800	С	
58900	č	CORRECT FOR MOLECULAR WEIGHT ACCORDING TO LISS & SLATER.
59000	č	1974. NATURE, V247. P181-184.
59100	č	
59200	-	MTCA(I)=MTCA(I)+SORT(DATAMW/WW(I))
59300		MTC(I)=MTCA(I)/TEMP
59400	С	
59500	Ċ	AND WRITE THE OVER-ALL MASS-TRANSFER COEFFICIENT
59600	Ċ	IN M/HR AND MOLE/HR+ATM+M+M.
59700	С	,,
59800	-	WRITE (IOU.2270) I.MTCA(I).MTC(I)
59900	2360	CONTINUE
60000	2370	SPGRB=141.5/(APIB+131.5)

60100		MASS=0.1582+88L+SPGRB
60200		WRITE (100.2380) BBL.MASS
60300	2380	FORMAT (1X 'FOR THIS SPILL OF ' 1PE10.3.' BARRELS. THE
60400		1 MASS IS ' 1PE10.3.' METRIC TONNES')
60500		
60600		WRITE (IOU 239A) VOLUM VOLUMB
69799	2390	FORMATI / 12 YOU WE FROM SUMMING THE CUTS = ' 1PER 1 ' Maa3
60800		1. OR ' 1PF10 3 ' BARRELS')
60900		GO TO (2420 2400 2420) KNTC
61000	2400	WRITE (IOU 2410) WINDS WINDMH
61100	2410	FORMAT (12 WIND SPEED = ' 1PE10 3 ' KNOTS OR ' 1PE10 3
61200		$1 \cdot M/HP()$
61300	2420	WRITE (104 2439) DIA AREA
61400	2430	FORMATI / 14 INITIAL SUCK DIAMETER - ' 19510 3 ' M OR AREA
61500	2400	1 = 1 105 10 1 1 1 1 2 2 1 0 0 1 4 2 1 0 0 1 4 2 1 0 0 1 4 2 1 0 0 0 1 4 2 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
61600		I = (1 + 1) + 1 + 1 = 2
61700		WRITE (INI 24A)
61800	2440	TODAT / 14 THIS SILCE DOES NOT SPREAD FOR THIS CALCULATION!)
61000	2440	FORMAT(7, 1X, THIS SELER DUES NOT SPREAD FOR THIS CALCULATION)
62000	ž	CALCULATE THE KINEMATIC VISCOSITY OF THE COUDE AT 122
62100	č	CALCULATE THE KINEMATIC VISCOSTIT OF THE GROUE AT 122
62200	č	USE THE VISCOSITY MIVING PULE OF (MOLE FRATURE.
62200		USE THE VISCOSITI MIXING ROLE OF (MOLE FRACTION)*(LOG),
62300		SEE PAGE 400 OF REID, PRAUSNIZ & SHERWOOD IN
02400		THE BOOK THE PROPERTIES OF GASES AND LIQUIDS
62500	C .	
62600	2450	VISMIX-0.
62700		
62800		VISMIX=VISMIX+MOLES(1)+VLOGK(1)/TMOLES
62900	2460	CONTINUE
63000		VISMIX=EXP(VISMIX)
63100		WRITE (IOU, 2470) VISMIX
63200	2470	FORMAT(/,1X, KINEMATIC VISCOSITY OF THE BULK CRUDE FROM
63300		1 THE CUTS = ', TPEB.1,' CENTISTOKES AT 122 DEG F')
63400	-	VISMIX=0.
63500	C	
63600	C	SCALE THE VISCOSITY WITH TEMPERATURE ACCORDING TO
63700	Ç	ANDRADE.
63800	С	
63900		EXPT=EXP(1923.*(1./XSAVE-0.001721))
64000		DO 2480 I=1,NCUTS
64100		VIS(I)=VISK(I)+EXPT
64200		VLOG(I)=ALOG(VIS(I))
64300		VISMIX=VISMIX+MOLES(I)+VLOG(I)/TMOLES
64400	2480	CONTINUE
64500		VISMIX=EXP(VISMIX)
64600		WRITE (IOU,2490) VISMIX,XPRINT,EXPT
64700	2490	FORMAT(/,1X, 'KINEMATIC VISCOSITY OF THE BULK CRUDE FROM THE
64800		1 CUTS = ',1PE8.1,' AT T = ',0PF5.1,' DEG F, SCALE
64900		2 FACTOR = (, 1PE8.1)
65 000	С	· ,
65100	С	IMPORTANT NOTE: THE VISCOSITY PREDICTION OF THE WHOLE
65200	С	CRUDE FROM CUT INFORMATION IS NOT GOOD AT ALL. SO THE
65300	С	VISCOSITY INFOMATION CALCULATED ABOVE IS NOT USED IN
65400	С	THIS VERSION OF THE CODE. BUT IT COULD BE IF A GOOD
65500	Č	MIXING RULE IS EVER DETERMINED.

100	С	THEREFORE, FOR THE TIME BEING, THE VISCOSITY OF THE WHOLE
200	С	WEATHERED CRUDE IS CALCULATED ACCORDING TO MACKAY.
300	č	
400	ž	NOW LOAD THE VICCOCITY INFORMATION IN THE FORM
400		NOW LOAD THE VISCOSITY INFORMATION IN THE FORM
200	C	OF THREE CONSTANTS:
600	C	1. THE VISCOSITY IN CP AT 25 DEG C
700	C	2. THE ANDRADE-VISCOSITY-SCALING CONSTANT
800	С	WITH RESPECT TO TEMPERATURE. SEE GOLD 🛦
900	č	OGLE 1969 CHEM ENG JULY 14 P121-123
1000	č	THE VISCOSITY AS AN EXPONENTIAL FUNCTION OF
1000	ž	J. THE VISCOSITI AS AN EXCHENTIAL FUNCTION OF
1100	L L	THE FRACTION OF OIL WEATHERED
1200	C	
1300		IF(LSWTCH.EQ.99) GO TO 2510
1400		TYPE 2500
1500	2500	FORMAT(1X,'SINCE A LIBRARY CRUDE WAS NOT USED
1600		1 ' / 1X 'ENTER THE FOLLOWING THREE VISCOSITY CONSTANTS')
1700		
1700		
1800	2510	17PE 2520
1900	2520	FORMAT(1X,'DO YOU WANT TO ENTER NEW VISCOSITY CONSTANTS?')
2000		ACCEPT 390, ANS
2100		IF(ANS.EQ.'N') GO TO 2570
2200	2530	TYPE 2540
2300	2540	FORMAT(1) 11 ENTER THE BULK OPUDE VISCOSITY
2300	2040	A AT 25 DEC O CENTROLE TRY 35 ()
2400		A 25 DEG C, CENTIFOISE, TRT 55.)
2500		ACCEPT 280, VISZ
2600		TYPE 2550
2700	2550	FORMAT(1X,'2. ENTER THE VISCOSITY TEMPERATURE SCALING
2800		1 CONSTANT (ANDRADE), TRY 9000.')
2900		ACCEPT 280 NK3
3000		Type 2564
3000		
3100	2200	FORMAT(TX, S. ENTER THE VISCOSITT-FRACTION-OIL
3200		1-WEATHERED CONSTANT, TRY 10.5')
3300		ACCEPT 280, MK4
3400		GO TO 2580
3500	С	
3600	č	USE THE LIBRARY VISCOSITY DATA
3700	č	
3700	0.6 7.0	
2000	23/0	VISZ=VISZE(IC)
3900		MK3=MK3L(IC)
4000		MK4=MK4L(IC)
4100	С	
4200	С	INSERT VISCOSITY CALCULATION ACCORDING TO MASS
4300	Ċ	FRACTION EVAPORATED THIS IS THE VISCOSITY
4400	č	MODIFICATION PELATIVE TO CUTVES
4500	ž	WODIFICATION RELATIVE TO COTVET
7000	0.000	
4600	2580	VSLEAD=VISZ+EXP(MK3+(1./TK-0.003357))
4700		WRITE (IOU,2590) VISZ,MK3,MK4,VSLEAD
4800	2590	FORMAT(/,1X,'VISCOSITY ACCORDING TO MASS EVAPORATED:
4900		1 VIS25C ='.1PE9.2.'. ANDRADE ='.1PE9.2
5000		2 ' FRACT WEATHERED =' 1959 2' VSI FAD =' 1959 2
5100		1 · (CP ·)
5200		
5200		
2200		WRITE (100,2850) C1,C2P,C4
5400		NEQ=NCUTS
5500	С	
5600	С	SET UP THE DISPERSION PROCESS CONSTANTS.
5700	ć	CALCHLATE THE FRACTION OF THE SEA SUBFACE SUBJECT TO
5800	č	DISCEPTION OF THE SEA SOUTHER SUBJECT TO
5000	ž	
2900	C	
6000	С	THE FUNCTIONAL DEPENDENCE OF DISPERSION RATE WITH FRACTION

OF ICE COVER IS NOT KNOWN. FOR NOW, THE VARIABLE FACDIS WILL BE USED TO INCREASE THE DISPERSION RATE. ITS DEFAULT VALUE 6100 С 6200 С 6300 С WILL BE 10. 6400 С 6500 FACDIS=10. 6600 **TYPE 2600** FORMAT(1X, 'DO YOU WANT THE WEATHERING TO OCCUR WITH 6700 2600 1 DISPERSION?') 6800 ACCEPT 390, ANS 6900 7000 FRACTS=0. IF(ANS.EQ. 'N') GO TO 2670 7100 7200 IF (LSWTCH.NE.99) GO TO 2620 TYPÈ 2610 7300 FORMAT(1X, 'DO YOU WANT TO ENTER NEW DISPERSION 7400 2610 7500 1 CONSTANTS?') 7600 ACCEPT 390, ANS 7700 IF(ANS.EQ.'N') GO TO 2660 TYPE 2630 7800 2620 7900 2630 FORMAT(1X, 'ENTER THE WIND SPEED CONSTANT, TRY 0.1') ACCEPT 280, KA 8000 8100 **TYPE 2640** 8200 2640 FORMAT(1X, 'ENTER THE CRITICAL DROPLET SIZE CONSTANT 8300 1, TRY 50') 8400 ACCEPT 280. KB 8500 **TYPE 2650** FORMAT(1X, 'ENTER THE BROKEN ICE FIELD DISPERSION MULTIPLIER') 8600 2650 8700 ACCEPT 280, FACDIS 8800 2660 FRACTS=KA+(1.+WINDMS)++2 8900 CONTINUE 2670 9000 FRACTS=FRACTS+FACDIS WRITE (IOU, 2680) FRACTS FORMAT(/,1X,'THE FRACTIONAL SLICK AREA SUBJECT TO 1 DISPERSION IS ',1PEB.1,' PER HOUR') 9100 9200 2680 9300 IF(ANS.EQ. 'N') GO TO 2700 9400 WRITE (IOU, 2690) KA, KB, STEN FORMAT(1X, 'THE DISPERSION PARAMETERS USED: KA = ' 1, 1PE9.2, ', KB = ', 1PE9.2, ', SURFACE TENSION = ', 1PE9.2 9500 9600 2690 9700 2, DYNES/CM') 9800 9900 С PRINT EVERY XP TIME INCREMENT (HOURS). 10000 С 10100 С X1 IS THE STARTING TIME = 0. 10200 С X2 IS THE NUMBER OF HOURS FOR WEATHERING TO OCCUR. 10300 С 10400 2700 XP=1. 10500 X1=0. 10600 MOLS(NCUTS+1)=AREA 10700 С 10800 С PRINT AN OUTPUT FILE FOR 80 COLUMN OUTPUT, THIS IS 10900 С THE CUTVP2.TYP FILE. 11000 С 11100 WRITE(ITY, 2710) 11200 2710 FORMAT(1H1, 'WEATHERING OF OIL IN A BROKEN ICE FIELD') IF(NIP.NE.1) GO TO 2730 11300 WRITE(ITY, 2720) NHIP FORMAT(1X, 'AFTER ICE POOL WEATHERING FOR ', 1PE9.3, ' HOURS') 11400 11500 2720 WRITE (ITY,2740) (ANAME(J),J=1,5) FORMAT(/,1X,'OIL: ',5A5) WRITE (ITY,2750) XPRINT,WINDS FORMAT(1X,'TEMPERATURE= ',F5.1,' DEG F, WIND SPEED= ' 11600 2730 11700 2740 11800 11900 2750 1, F5.1, ' KNOTS') 12000

```
WRITE (ITY,2760) BBL
FORMAT(1X,'SPILL SIZE= ',1PE10.3,' BARRELS')
WRITE (ITY,2770) KMTC
12100
12200
          2760
12300
          2770
                   FORMAT(1X, 'MASS-TRANSFER COEFFICIENT CODE=', I3)
12400
                 WRITE (ITY, 2780)
FORMAT(/, 1X, 'FOR THE OUTPUT THAT FOLLOWS, MOLES
12500
12600
          2780
12700
                 1=GRAM MOLES')
                 WRITE (ITY,2790)
FORMAT(1X,'GMS=GRAMS, VP=VAPOR PRESSURE IN ATMOSPHERES')
WRITE (ITY,2800)
FORMAT(1X,'BP=BOILING POINT IN DEG F, API=GRAVITY')
12800
12900
          2790
13000
          2800
13100
                  WRITE (ITÝ,2810)
Format(1X,'MW-MOLECULAR WEIGHT')
13200
13300
          2810
13400
                   WRITE (ITY, 2820)
          2820 FORMAT(/.2x,'CUT'.3X,'MOLES',6X,'GMS'.8X,'VP'.8X,'BP'
1,7X,'API'.5X.'MW')
DO 2840 I=1,NCUTS
13500
13600
13700
                   GMS=MOLES(I) • MW(I)
13800
                   IMW=MW(I)
13900
14000
                   WRITE (ITY, 2830) I.MOLES(I), GMS, VP(I), TB(I), API(I), IMW
                  FORMAT(3X,12,5(1X,1PE9.2),1X,13)
14100
          2830
14200
          2840
                  CONTINUE
                 WRITE (ITY,2850) C1,C2P,C4
FORMAT(/,1X,'MOUSSE CONSTANTS: MOONEY=',1PE9.2
14300
14400
          2850
                 1, ', MAX H20=',0PF5.2,', WIND++2=',1PE9.2)
14500
                  WRITE(ITY, 2860) FACMOU
14600
                  FORMAT(20X, 'K4=', 1PE9.3)
WRITE (ITY, 2870) KA, KB, STEN
14700
          2860
14800
14900
                  FORMAT(1X, 'DISPERSION CONSTANTS: KA=', 1PE9.2
          2870
                  ,', KB=', 1PE9.2,', S-TENSION=', 1PE9.2)
WRITE(ITY, 2880)FACDIS
                 1,'
15000
15100
15200
          2880 FORMAT(24X, 'KC=', 1PE9.3)
                  WRITE(ITY, 2890) FRACIC
15300
                 FORMAT(1X, 'FRACTION OF ICE COVER=', 1PE9.3)
WRITE (ITY,2900) VISZ,MK3,MK4
FORMAT(1X, 'VIS CONSTANTS: VIS25C=',1PE9.2
15400
          2890
15500
15600
          2900
                      , ANDRADE =', 1PE9.2,', FRACT =', 1PE9.2)
15700
                 1,'
                 WRITE (ITY,2910)
FORMAT(/,1X,'FOR THE OUTPUT THAT FOLLOWS, TIME=HOURS')
15800
15900
          2910
                   WRITE (ITY, 2920)
16000
16100
          2920
                  FORMAT(1X, 'BBL=BARRELS, SPGR=SPECIFIC GRAVITY, AREA=M+M')
                 WRITE (ITY,2930)
Format(1x,'THICKNESS=CM, W=PERCENT WATER IN OIL (
16200
16300
          2930
16400
                 1MOUSSE)')
                 WRITE (ITY,2940)
FORMAT(1X,'DISP=DISPERSION RATE IN GMS/M+M/HR')
WRITE (ITY,2950)
16500
16600
          2940
16700
                  FORMAT(1X, 'ERATE=EVAPORTION RATE IN GMS/M+M/HR')
16800
          2950
          WRITE (ITY, 2960)
2960 FORMAT(1X, 'M/A=MASS PER M+M OF OIL IN THE SLICK')
WRITE (ITY, 2970)
2970 FORMAT(1X, 'I=FIRST CUT WITH GREATER THAN 1% (MASS)
16900
17000
17100
17200
17300
                 1 REMAINING')
          WRITE (ITY, 2980)
2980 FORMAT(1X, 'J=FIRST CUT WITH GREATER THAN 50% (MASS)
17400
17500
                 1 REMAINING')
17600
                   IF(FRACTS.NE.0.) GO TO 3000
17700
                  WRÌTE (ITY,2990)
Format(1X,'DISPERSION WAS TURNED OFF')
17800
17900
          2990
18000
          3000 IF(SPREAD.NE.0.) GO TO 3020
```

18100		WRITE (ITY, 3010)
18200	3010	FORMAT(1X, 'SPREADING WAS TURNED OFF')
18300	3020	TCODE=KMTC
18400		TYPE 3030
18500	3030	FORMAT(/.1X.'PLEASE WAIT')
18600		CALL BRKG4(MOLS.X1.X2.XP. NEQ.NDEL)
18700		IF (C3.EQ1.) GO TO 3040
18800	С	
18900	č	CHECK TO SEE IF MOUSSE HAS BEEN MADE IF IT HAS, SAVE THE
19000	č	RATE CONSTANT SO THAT FURTHER WEATHERING CAN TAKE THIS INTO
19100	č	ACCOUNT
19200	č	
19300	Ŭ	
19499		
19500	1040	
19500	2040	
10700		
10900		$\begin{array}{c} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 $
10000		IF (TW(I).NE.0.) GU IU 3030
19900	7050	
20000	2020	
20100		
20200		IF (NQUIT.EQ.1) GO TO 4460
20300	3060	TYPE 3070
20400	3070	FORMAT(1X, WILL OPEN OCEAN WEATHERING NOW OCCUR?')
20500		ACCEPT 390, ANS
20600		IF(NBI.EQ.0) GO TO 3110
20700		TV=0.
20800		DO 3080 I=1,NEQ-ND
20900		TV=TV+(YM(ND+I)*YMSAVE(ND+I)/SPGR(NEW+I))
21 000		VOL(I)=YM(ND+I)+MOLES(NEW+I)+MW(NEW+I)/(SPGR(NEW+I)
21100		1 + (BBL + 1582.))
21200		TB(I)=TB(NEW+I)
21300		APÌ(Í)=APÌ(NEW+I)
21400	3080	CONTINUE
21500		BBL=TV/158200.
21600		NCUTS=NCUTS-(ND+NDEL)
21700		NEQ=NCUTS
21800	С	
21900	Ċ	ALWAYS RENORMALIZE THE INPUT VOLUMES TO 100%.
22000	Č	
22100		VTOTAL=0.
22200		DO 3090 I=1.NCUTS
22300		VTOTAL=VTOTAL+VOL(I)
22400	3090	CONTINUE
22500		DO 3100 I=1. NCUTS
22600		
22700	3100	CONTINUE
22800		
22900		APISWI-1
23000		
23100	3110	
23200	5110	
23300		TE(ANS EO 'N') CO TO AA68
23300		NC-NCINEW
23400		NU-NUTNER TVDE 1498
23300	1100	
23000	5120	FURMAILIX, FUR HUW MANT HUURSY')
23/00		AUULMI 200,X2
23888		
23900	3130	FURMAI(IX, 'AT WHAT TEMPERATURE, DEG F?')
· / A (A (A (A (A		

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24100
               XPRINT=XSAVE
24200
               XSAVE=XSAVE+459.
24300
               NCC1=NC1
24400
               CALL VPIF(XSAVE, NCC1)
               TK=(XSAVE-491.)/1.8+273.
IF(LSWTCH.EQ.99) GO TO 3160
24500
24600
24700
               TYPE 3140
24800
         3140 FORMAT(1X, 'SINCE YOU DID NOT USE A LIBRARY CRUDE, ')
24900
               TYPE 3150
25000
         3150 FORMAT(1X, 'YOU MUST ENTER THE FOLLOWING THREE MOUSSE
25100
              1 FORMATION CONSTANTS')
25200
               GO TO 3180
               TYPE 3170
25300
         3160
25400
         3170
               FORMAT(1X, 'DO YOU WANT TO ENTER NEW MOUSSE FORMATION CONS
25500
              1TANTS?')
               ACCEPT 390.
25600
                            ANS
25700
               IF(ANS.EQ. 'N') GO TO 3240
25800
         С
25900
        C
                 TO SPECIFY NO MOUSSE, ENTER C2 = 0
26000
         C
26100
         3180 TYPE 3190
26200
         3190
              FORMAT(1X,'1. ENTER THE MAXIMUM WEIGHT FRACTION WATER
26300
              1 IN OIL')
26400
               ACCEPT 280, C2
26500
               IF(C2.GT.0.) GO TO 3210
26600
         С
26700
        С
                  SET C2=-1. IF A MOUSSE CANNOT BE FORMED AND LOOP OUT.
        С
26800
26900
               C2 = -1.
               TYPE 3200
27000
27100
         3200
              FORMAT(/,1X,'SINCE A 0% WATER CONTENT WAS SPECIFIED
27200
              1, THE REMAINING TWO MOUSSE',/,1X, 'CONSTANTS ARE NOT
27300
              2 NEEDED'
               GO TO 3250
27400
27500
         3210
               C2=1./C2
TYPE 3220
27600
27700
         3220
              FORMAT(1X, '2. ENTER THE MOUSSE-VISCOSITY CONSTANT
              1, TRY 0.65')
27800
27900
               ACCEPT 280, C1
28000
               TYPE 3230
28100
         3230 FORMAT(1X.'3. ENTER THE WATER INCORPORATION RATE CONSTANT
28200
              1, TRY 0.001')
28300
               ACCEPT 280, C4
28400
               GO TO 3250
28500
         3240
              C1=C1L(IC)
               C2=C2L(IC)
28600
               C4=C4L(IC)
IF(LSWTCH.EQ.99) GO TO 3280
28700
28800
        3250
               TYPE 3260
28900
        3260 FORMAT(/,1X,'YOU MUST ALSO ENTER AN OIL-WATER SURFACE
1 TENSION (DYNES/CM')
29000
29100
29200
               TYPE 3270
29300
         3270 FORMAT(1X, 'FOR DISPERSION, TRY 30.')
29400
               GO TO 3310
29500
               TYPE 3290
         3280
               FORMAT(1X, 'DO YOU WANT TO ENTER A NEW OIL-WATER SURFACE
29600
         3290
              1 TENSION (DYNES/CM)?')
29700
               ACCEPT 390, ANS
IF(ANS.EQ.'N') GO TO 3320
29800
29900
30000
               TYPE 3300
```

FORMAT(1X,'TRY 30.') 30100 3300 30200 ACCEPT 280, STEN 3310 30300 GO TO 3330 30400 3320 STEN=STENL(IC) 30500 30600 START THE MASS-TRANSFER COEFFICIENT SPECIFICATION. С 30700 30800 3330 **TYPE 3340** FORMAT(1X, 'ENTER THE MASS-TRANSFER COEFFICIENT CODE: 1 30900 3340 1, 2, OR 3 WHERE: ') 31000 TYPE 3350 31100 31200 FORMAT(1X, '1=USER SPECIFIED OVER-ALL MASS-TRANSFER COEF 3350 IFICIENT') 31300 31400 TYPE 3360 FORMAT(1X, '2=CORRELATION MASS-TRANSFER COEFFICIENT BY 31500 3360 31600 1 MACKAY & MATSUGU') 31700 TYPE 3370 31800 3370 FORMAT(1X,'3=INDIVIDUAL-PHASE MASS-TRANSFER COEFFICIENTS') 31900 ACCEPT 420, KMTC 32000 C 32100 NOW ENTER THE WIND SPEED IN KNOTS AND CONVERT TO METER/SEC C 32200 AND METER/HOUR. С 32300 С 32400 **TYPE 3380** 32500 3380 FORMAT(1X, 'ENTER THE WIND SPEED IN KNOTS') 32600 ACCEPT 280. WINDS 32700 С A ZERO WIND NEVER LET THE WIND SPEED DROP BELOW 2 KNOTS. 32800 С SPEED DESTROYS THE MASS-TRANSFER CALCULATION AND WILL 32900 С YIELD & ZERO MASS-TRANSFER COEFFICIENT. 33000 С 33100 С IF(WINDS.LT.2.) WINDS=2. 33200 33300 WINDMS=0.514+WINDS WINDMH=1853. +WINDS 33400 33500 C NOW CALCULATE THE INITIAL GRAM MOLES FOR EACH COMPONENT TO 33600 С 33700 GET THE INTEGRATION STARTED. С 33800 C 33900 3390 BM=0.159+BBL 34000 TMOLES=0. 34100 DO 3400 I=1.NCUTS AMASS=1582.*SPGR(I)*BBL*VOL(I) 34200 34300 MOLES(I)=AMASS/MW(I) MOLS(I)-MOLES(I) 34400 34500 TMOLES=TMOLES+MOLES(I) 34600 С 34700 RHO IS THE DENSITY IN GM MOLES/CUBIC METER. C 34800 С 34900 RHO(I)=100. +MOLES(I)/(BM+VOL(I)) 35000 3400 CONTINUE 35100 C CALCULATE THE MEAN MOLECULAR WEIGHT OF THE CRUDE 35200 С 35300 C 35400 WTMOLE=0. 35500 DO 3410 I=1,NCUTS WTMOLE=WTMOLE+MW(I)+MOLES(I)/TMOLES 35600 35700 3410 CONTINUE WRITE (IOU,3420) WTMOLE FORMAT(/,1X,'MEAN MOLECULAR WEIGHT OF THE CRUDE = ',1PE10.3) 35800 35900 3420 36000 С

36100	С	SPECIFY SLICK SPREADING.
36200	С	
36300	3430	SPREAD=0.
36400		TYPE 3440
36500	3440	FORMAT(1X,'DO YOU WANT THE SLICK TO SPREAD?')
36600		ACCEPT 390, ANS
36700		IF(ANS.EQ.'N') GO TO 3450
36800		SPREAD=1
36900		GO TO 3480
37000	С	
37100	Ċ	CALCULATE AN AREA IN SAME WAY IT WILL BE CALCULATED
37200	Ċ	AS THE SLICK WEATHERS. Z=THICKNESS IN METERS.
37300	č	
37400	3450	IF (NZSWI.EQ.1) GO TO 3470
37500		TYPE 3460
37600	3460	FORMAT(1X, 'SINCE THE SLICK DOES NOT SPREAD, ENTER
37700	0.00	1 A STARTING THICKNESS IN CM')
37800		ACCEPT 280. 7
37900	3470	7=7/100
38000	• • • •	GO TO 3490
38100	C	
38200	č	THE SLICK ALWAYS STARTS AT 2-CM THICKNESS
38300	č	THE SELON ALMAND STAND AT 2-OM THIORAEDS.
38400	TARA	1. (N75WI NE 0) CO TO 3490
19500	3400	7-0 02
19600	3400	
38700	5430	
19900		
19000	1600	
10000	2200	CONTINUE
39000	č	CALCHRATE THE INITIAL AREA AND DIAMETER
39:00	č	CALCULATE THE INITIAL AREA AND DIAMETER.
30300	C	
39300		AREA=VOLUM/2
39400	<u>^</u>	01A=SQR1(AREA/0.763)
39300		THE MASS TRANSFER COFFEELLENT CAN BE CALCULATED ACCORDING TO.
39000	č	THE MASS-TRANSFER COEFFICIENT CAN BE CALCULATED ACCORDING TO:
39/00	č	1 A USED SDECISIED OVER ALL MASS TRANSFED COFFEICIENT
39000		1. A USER-SPECIFIED OVER-ALL MASS-TRANSFER COEFFICIENT.
10000	č	2 THE MASS_TRANSFER COFFEELSTENT CORPENATION ACCORDING
40100	č	2. THE MASS-TRANSFER COEFFICIENT CORRELATION ACCORDING
40200	č	TO MACKAT AND MAISUGU, 1973, CAN. J. CHE, VOI,
40100		F+3 - +33.
40400		T THETATELATE ATT AND ATE BLACE MARE TRANSFER COLEST
70700		J. INDIVIDUAL UIL- AND ALK-PHASE MASS-IKANSFER GUEFFI-
40500		CIENTS DASED UN SOME REAL ENVIRONMENTAL DATA SUCH
70000		AS THAT OF LISS AND SLATER. SUALE THE AIR-PHASE
+0700		VALUE WITH RESPECT TO WIND SPEED ACCORDING TO
+0000		GARRATI, 1977, MUNIFILT WEATHER REVIEW, VIUD,
+0900	U A	P915-920.
41000	C O	TEND TO DUT AND HEED TO CHANGE THE HINTE ON THE MARC
41100	C	TEMP IS NOT AND USED TO CHANGE THE UNITS ON THE MASS-
41200	C	TRANSFER GUEFFICIENT.
41300	U Terr	
41400	3210	$\frac{1}{2} \left[\frac{1}{2} \left[\frac{1}{2} - \frac{1}{2} \right] + \left[\frac{1}{2} \right] \right]$
41500	~	GU IU (3520,3560,3710), KMIC
+1000	C	
41/00	C	USER SPECIFIED OVER-ALL MASS-TRANSFER COEFFICIENT.
41800	C	
41900	3520	ITPE 3530
42000	3530	FORMAT(1X, 'ENTER THE OVER-ALL MASS-TRANSFER COEFFICIENT

1. CM/HR. TRY 10') 42100 ACCEPT 280, UMTC WRITE (IOU, 3540) UMTC FORMAT(1H1, 'OVER-ALL MASS-TRANSFER COEFFICIENT WAS USER 42200 42300 42400 3540 42500 1-SPECIFIED AT ', 1PE10.3, ' CM/HR BY INPUT CODE 1') 42600 С CONVERT CM/HR TO GM-MOLES/(HR)(ATM)(M++2) SINCE VAPOR 42700 С PRESSURE IS THE DRIVING FORCE FOR MASS TRANSFER. С 42800 42900 С 43000 UMTC=UMTC/TEMP/100. 43100 DO 3550 I=1,NC1 MTC(I)=UMTC 43200 43300 3550 CONTINUE 43400 GO TO 3790 43500 C 43600 С USE THE MACKAY AND MATSUGU MASS-TRANSFER COEFFICIENT. 43700 C 43800 3560 TERM1=0.015+WINDMH++0.78 IF(SPREAD.EQ.0.) GO TO 3570 43900 44000 TERM2=DIA++(-0.11) 44100 GO TO 3580 44200 С IF THE SLICK DOES NOT SPREAD BASE THE DIAMETER DEPENDENCE 44300 C ON 1000 METERS AND DIVIDE THE RESULT BY 0.7 44400 С 44500 C 3570 44600 TERM2=0.65 44700 С KH INCLUDES THE SCHMIDT NUMBER FOR CUMENE. 44800 C 44900 45000 3580 KH=TERM1+TERM2 45100 WRITE(IOU, 3590) FORMAT(1H1, 'WEATHERING DATA FOR OIL ON THE OPEN OCEAN') 45200 3590 IF(NIP.NE.1.AND.NBI.NE.1) GO TO 3650 45300 WRÌTE(100,3600) 45400 FORMAT(1X,'AFTER:') IF(NIP.NE.1) GO TO 3620 WRITE(IOU,3610) NHIP 45500 3600 45600 45700 45800 3610 FORMAT(9X, 'ICE POOL WEATHERING FOR ', 1PE9.3, ' HOURS') CONTINUE 45900 3620 46000 IF(NBI.NE.1) GO TO 3640 46100 WRITE(IOU, 3630) NHBI FORMAT(9X, 'BROKEN ICE FIELD WEATHERING FOR ', 1PE9.3, ' HOURS') 46200 3630 46300 3640 CONTINÚE WRITE (IOU, 3660) KMTC FORMAT(/, 1X, 'OVER-ALL MASS-TRANSFER COEFFICIENTS BY INPUT 3650 46400 46500 3660 1 CODE', I2) WRITE (IOU, 3670) KH FORMAT(/, 1X, 'OVER-ALL MASS-TRANSFER COEFFICIENT FOR CUMENE = ' 46600 46700 46800 3670 46900 WRITE (IOU, 3680) FORMAT(3X,'CUT',12X,'M/HR',7X,'GM-MOLES/(HR)(ATM)(M*+2)') DO 3700 I=1,NC1 47000 47100 3680 47200 47300 С 47400 C THE MASS-TRANSFER COEFFICIENT IS CORRECTED FOR THE 47500 DIFFUSIVITY OF COMPONENT I IN AIR. С THE SORT IS USED (I.E. LISS AND SLATER), BUT THE 1/3 POWER COULD ALSO 47600 С BE USED (I.E. THE SCHMIDT NUMBER). 47700 С 47800 С 47900 MTCA(I)=KH+0.93+SQRT((MW(I)+29.)/MW(I)) 48000 С

MTC(I) IS THE OVER-ALL MASS-TRANSFER COEFFICIENT DIVIDED 48100 С 48200 C BY R+T. R=82.06E-06 (ATM)(M++3)/(G-MOLE)(DEG K) 48300 C MTC(I)=MTCA(I)/TEMP 48400 WRITE (IOU, 3690) I, MTCA(I), MTC(I) FORMAT(2X, I3, 2(10X, 1PE10.3)) 48500 48600 3690 48700 3700 CONTINUE 48800 GO TO 3790 48900 С 49888 C USER SPECIFIED INDIVIDUAL-PHASE MASS-TRANSFER 49100 С COEFFICIENTS. 49200 C 49300 3710 TYPE 3720 49400 FORMAT(1X, 'ENTER THE OIL-PHASE MASS-TRANSFER COEFFICIENT 3720 49500 1 IN CM/HR, TRY 10') 49600 ACCEPT 280, KOIL TYPE 3730 49700 49800 3730 FORMAT(1X, 'ENTER THE AIR-PHASE MASS-TRANSFER COEFFICIENT 1 IN CM/HR, TRY 1000') 49900 ACCEPT 280, KAIR TYPE 3740 50000 50100 50200 3740 FORMAT(1X.'ENTER THE MOLECULAR WEIGHT OF THE COMPOUND 50300 1 FOR K-AIR ABOVE, TRY 200') 50400 ACCEPT 280. DATAMW 50500 С 50600 С SCALE K-AIR ACCORDING TO WIND SPEED (GARRATT, 1977). SO THAT AS THE WIND SPEED GOES UP THE MASS TRANSFER 50700 С 50800 С GOES UP, I.E., THE CONDUCTANCE INCREASES. 50900 С 51000 KAIR=KAIR*(1.+0.089*WINDMS) 51100 RKAIR=1./KAIR С 51200 51300 С CALCULATE R+T IN ATM+CM++3/GM-HOLE 51400 С 51500 RT=82.06+TK HTERM=WTMOLE/(DCRUDE+RT) 51600 51700 WRITE (100,3660) KMTC 51800 С 51900 С WRITE THE USERS INPUT, WIND SPEED, AND HENRYS LAW 52000 TERM TO THE OUTPUT. C 52100 C WRITE (IOU,3750) KAIR,KOIL,DATAMW FORMAT(/,1X,'K-AIR = ',1PE10.3,', AND K-OIL = ',1PE10.3 1,' CM/HR, BASED ON A MOLECULAR WEIGHT OF ',1PE10.3) 52200 52300 3750 52400 WRITE (IOU, 3760) WINDMS FORMAT(1X, 'WIND SPEED = ', 1PE10.3, ' M/S') WRITE (IOU, 3770) HTERM FORMAT(1X, 'THE HENRYS LAW CONVERSION TERM FOR OIL = ' 1, 1PE10.3, ' 1/ATM') 52500 52600 3760 52700 52800 3770 52900 WRITE (IOU. 3680) 53000 53100 C 53200 С CALCULATE THE OVER-ALL MASS-TRANSFER COEFFICIENT BASED 53300 С ON GAS-PHASE CONCENTRATIONS FOR EACH CUT. 53400 C 53500 DO 3780 I=1,NC1 53600 HLAW(I)=HTERM+VP(I) 53700 MTCA(I)=RKAIR+HLAW(I)/KOIL 53800 С 53900 С NOW TAKE THE INVERSE TO OBTAIN CM/HR AND THEN MULTIPLY 54000 С BY 0.01 TO GET M/HR.

54100 С 54200 MTCA(I)=0.01/MTCA(I)54300 С CORRECT FOR MOLECULAR WEIGHT ACCORDING TO LISS & SLATER, 54400 С 54500 С 1974, NATURE, V247, P181-184. 54600 С MTCA(I)=MTCA(I)+SQRT(DATAMW/MW(I)) 54700 54800 MTC(I)=MTCA(I)/TEMP 54900 С 55000 С AND WRITE THE OVER-ALL MASS-TRANSFER COEFFICIENT С 55100 IN M/HR AND MOLE/HR+ATM+M+M. 55200 С 55300 WRITE (IOU, 3690) I, MTCA(I), MTC(I) 55400 3780 CONTINÚE 55500 SPGRB=141.5/(APIB+131.5) 3790 55600 MASS=0.1582+BBL+SPGRB WRITE (IOU, 3800) BBL, MASS FORMAT(/,1X,'FOR THIS SPILL OF ',1PE10.3,' BARRELS, THE 1 MASS IS ',1PE10.3,' METRIC TONNES') 55700 55800 3800 55900 56000 VOLUMB=VOLUM/0.159 VOLUMB=VOLUM/0.159 WRITE (IOU,3810) VOLUM,VOLUMB FORMAT(/,1X,'VOLUME FROM SUMMING THE CUTS = ',1PE8.1,' M**3 1, OR ',1PE10.3,' BARRELS') GO TO (3840,3820,3840), KMTC WRITE (IOU,3830) WINDS,WINDMH FORMAT(/,1X,'WIND SPEED = ',1PE10.3,' KNOTS, OR ',1PE10.3 1,' M/HR') WRITE (IOU, 1850) DIA 4551 56100 3810 56200 56300 56400 56500 3820 56600 3830 56700 3840 WRITE (IOU, 3850) DIA, AREA
3850 FORMAT(/,1X,'INITIAL SLICK DIAMETER = ',1PE10.3,' M, OR AREA
1 = ',1PE10.3,' M**2') 56800 56900 57000 IF(SPREAD.GT.0.) GO TO 3870 57100 WRITE (IOU, 3860) FORMAT(/, 1X, 'THIS SLICK DOES NOT SPREAD FOR THIS CALCULATION') 57200 3860 57300 57400 C CALCULATE THE KINEMATIC VISCOSITY OF THE CRUDE AT 122 57500 С DEG F AND THE ENTERED ENVIRONMENTAL TEMPERATURE. 57600 С USE THE VISCOSITY MIXING RULE OF (MOLE FRACTION) + (LOG), 57700 С 57800 С SEE PAGE 460 OF REID, PRAUSNITZ & SHERWOOD IN THE BOOK 'THE PROPERTIES OF GASES AND LIQUIDS' 57900 С 58000 C 58100 3870 VISMIX=0. DO 3880 I=1, NCUTS 58200 VISMIX=VISMIX+MOLES(I)+VLOGK(I)/TMOLES 58300 58400 3880 CONTINUE 58500 VISMIX=EXP(VISMIX) WRITE (IOU, 3890) VISMIX FORMAT(/,1X,'KINEMATIC VISCOSITY OF THE BULK CRUDE FROM 1 THE CUTS = ',1PE8.1,' CENTISTOKES AT 122 DEG F') 58600 58700 3890 58800 58900 VISMIX=0. 59000 C 59100 С SCALE THE VISCOSITY WITH TEMPERATURE ACCORDING TO 59200 С ANDRADE . 59300 C EXPT=EXP(1923.*(1./XSAVE-0.001721)) 59400 59500 DO 3900 I=1,NCUTS 59600 VIS(I)=VISK(I)+EXPT 59700 VLOG(Í)=ALOG(VIS(I)) VISMIX=VISMIX+MOLES(I)+VLOG(I)/TMOLES 59800 CONTINUE 59900 3900 60000 VISMIX=EXP(VISMIX)

60100		WRITE (IOU,3910) VISMIX,XPRINT,EXPT
60200	3910	FORMAT(/,1X, 'KINEMATIC VISCOSITY OF THE BULK CRUDE FROM THE
60300		1 CUTS = '.1PEB.1.' AT T = '.0PF5.1.' DEG F. SCALE
60400		2 FACTOR = (.1PE8.1)
60500	С	
60600	č	IMPORTANT NOTE: THE VISCOSITY PREDICTION OF THE WHOLE
60700	č	CRUDE FROM CUT INFORMATION IS NOT GOOD AT ALL SO THE
60800	č	VISCOSITY INFOMATION CALCULATED ABOVE IS NOT USED IN
60000	č	THIS VERSION OF THE CORE BUT IT COULD BE LEACOOD
61000	č	MINING BULE IS EVED DETENDING
61100	ž	THEREFORE FOR THE TIME DETNO. THE VISCORITY OF THE WHOLE
61000		HEREFORE, FOR THE TIME BEING, THE VISCOSITI OF THE WHOLE
01200	Š	WEATHERED CRODE IS CALCULATED ACCORDING TO MACKAY.
01300	Č	
01400	C	NOW LOAD THE VISCOSITY INFORMATION IN THE FORM
61500	C	OF THREE CONSTANTS:
61600	C	1. THE VISCOSITY IN CP AT 25 DEG C
61700	C	2. THE ANDRADE-VISCOSITY-SCALING CONSTANT
61800	С	WITH RESPECT TO TEMPERATURE, SEE GOLD &
61900	С	OGLE, 1969, CHEM. ENG., JULY 14, P121—123
62 000	С	3. THE VISCOSITY AS AN EXPONENTIAL FUNCTION OF
62100	С	THE FRACTION OF OIL WEATHERED
62200	С	
62300		IF(LSWTCH.EQ.99) GO TO 3930
62400		TYPE 3920
62500	3920	FORMAT(1X, SINCE A LIBRARY CRUDE WAS NOT USED
62600		1. '. /. 1X. 'ENTER THE FOLLOWING THREE VISCOSITY CONSTANTS')
62700		GO TO 3950
62800	3930	TYPE 3940
62900	3940	FORMAT(1X, 'DO YOU WANT TO ENTER NEW VISCOSITY CONSTANTS?')
63000		ACCEPT 390 ANS
63100		IF(ANS.EQ.'N') GO TO 3990
63200	3950	TYPE 3960
63300	3960	FORMAT(1X, '1. ENTER THE BULK CRUDE VISCOSITY
63400		1 AT 25 DEG C. CENTIPOISE, TRY 35. ')
63500		ACCEPT 280 VISZ
63600		TYPE 3970
63700	3970	FORMAT(1) '2 ENTER THE VISCOSITY TEMPERATURE SCALING
63800		1 CONSTANT (ANDRADE) TRY 9000 ()
63900		ACCEPT 280 MK3
64000		TYPE 3080
64100	3980	FORMAT(1) '3 ENTER THE VISCOSITY_EPACTION_OIL
64200	0300	LWEATHEDED CONSTANT TRY 16 51)
64300		ACCEDT 28A NKA
64400		$\begin{array}{c} \begin{array}{c} \begin{array}{c} \begin{array}{c} \end{array} \\ \end{array} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \end{array} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \end{array} \\ \end{array} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \end{array} \\ \end{array} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \end{array} \\ \end{array} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \end{array} \\ \end{array} \\ \end{array} \\ \end{array} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \end{array} \\ \end{array} $
64500	<u>^</u>	60 10 4000
64500		USE THE LIDDARY MICOOCITY DATA
64700		USE THE LIBRART VISCOSITE DATA
04/00	Jane C	
64000	2330	VI32=VI32L(IL)
04900		MRJEMRJL(IC)
00000	~	MK4=MK4L(1C)
00100	C	
65200	C	INSERT VISCOSITY CALCULATION ACCORDING TO MASS
65300	Ç	FRACTION EVAPORATED. THIS IS THE VISCOSITY
65400	C	MODIFICATION RELATIVE TO CUTVP1
655 00	С	

100	4000	VSLEAD=VISZ*EXP(MK3*(1./TK-0.003357))
200		WRITE (IOU, 4010) VISZ, MK3, MK4, VSLEAD
300	4010	FORMAT(/,1X,'VISCOSITY ACCORDING TO MASS EVAPORATED:
400		1 VIS25C =', 1PE9.2, ', ANDRADE =', 1PE9.2
500		2,', FRACT WEATHERED =', 1PE9.2', VSLEAD =', 1PE9.2
600		3,'CP')
700		C2P=1./C2
800		WRITE (IOU. 4300) C1. C2P. C4
900		NEQ=NCUTS
1000	С	
1100	č	SET UP THE DISPERSION PROCESS CONSTANTS
1200	č	CALCULATE THE FRACTION OF THE SEA SUBJECT TO
1300	č	DISPERSIONS / HOUP
1400	ř	
1500	U	TVD5 4000
1600	4020	FORMAT(4V PDO YOU WANT THE WEATHERING TO OCCUR WITH
1700	4020	TORMAT(17, DO TOO WANT THE WEATHERING TO OCCOR WITH
1900		ACCEPT TOO AND
1000		ALLEPI JUD, AND
1900		FRACIS#0.
2000		IF (ANS.EQ. 'N') GO TO 4080
2100		IF(LSWTCH.NE.99) GO TO 4040
2200		TYPE 4030
2300	4030	FORMAT(1X, DO YOU WANT TO ENTER NEW DISPERSION
2400		1 CONSTANTS?')
250 0		ACCEPT 390, ANS
2600		IF(ANS.EQ.'N') GO TO 4070
2700	4040	TYPE 4050
2800	4050	FORMAT(1X, 'ENTER THE WIND SPEED CONSTANT, TRY 0.1')
29 00		ACCEPT 280, KA
3000		TYPE 4060
3100	4060	FORMAT(1X.'ENTER THE CRITICAL DROPLET SIZE CONSTANT
3200		1. TRY 50')
3300		ACCEPT 280, KB
3400	4070	FRACTS=KA+(1 +WINDMS)++2
3500	4080	WRITE (IOU 4090) FRACTS
3600	4090	FORMAT(/ 1% 'THE FRACTIONAL SLICK AREA SUBJECT TO
3700		1 DISPERSION IS ' 1PER 1 ' PER HOUR')
1800		I E (ANS EQ 'N') CO TO 4110
3000		WPITE (INH A100) KA KR STEN
4000	4100	COPMATINE THE DISCEPTION DADAMETERS USED. VA - '
4100	+100	$\frac{1}{1000} = \frac{1}{1000} = 1$
4100		1, 1FE3.2, , ND = , 1FE3.2, , SURFACE IENSION = , 1FE3.2
4200	<u>^</u>	2, DINES/CM)
4300	č	PRINT EVERY MR TIME INCREMENT (HOURS)
4400		PRINT EVERT XP TIME INGREMENT (HOURS).
4500	6	XT IS THE STARTING TIME # 0.
4000	C	X2 IS THE NUMBER OF HOURS FOR WEATHERING TO OCCUR.
4/00	C	
4800	4110	XP=1.
4900		X1=0.
5000		MOLS(NCUTS+1)=AREA
5100	C	
5200	С	PRINT AN OUTPUT FILE FOR 80 COLUMN OUTPUT, THIS IS
5300	С	THE CUTVP2.TYP FILE.
5400	С	
5500		WRITE(ITY,4120)
5600	4120	FORMAT(1H1, 'OPEN OCEAN WEATHERING')
5700		IF(NIP.NE.1.AND.NBI.NE.1) GO TO 4180
5800		WRÌTE(ITY,4130)
5900	4130	FORMAT(1X, 'AFTÉR:')
6000		IF(NIP.NE.1) GO TO 4150

WRITE(ITY, 4140) NHIP FORMAT(9X, 'ICE POOL WEATHERING FOR ', 1PE9.3, ' HOURS') CONTINUE IF(NBI.NE.1) GO TO 4170 WRITE(ITY,4160) NHBI FORMAT(9X,'BROKEN ICE FIELD WEATHERING FOR ',1PE9.3,' HOURS') CONTINUE WRITE (ITY,4190) (ANAME(J),J=1,5) FORMAT(/,1X,'OIL: ',5A5) WRITE (ITY,4200) XPRINT,WINDS FORMAT(1X,'TEMPERATURE= ',F5.1,' DEG F, WIND SPEED= ' KNOTS') 1,F5.1, WRITE (ITY,4210) BBL FORMAT(1X,'SPILL SIZE= ',1PE10.3,' BARRELS') WRITE (ITY,4220) KMTC FORMAT(1X,'MASS-TRANSFER COEFFICIENT CODE=',I3) WRITE (ITY,4230) FORMAT(/,1X,'FOR THE OUTPUT THAT FOLLOWS, MOLES 1=GRAM MOLES') WRITE (ITY,4240) 1=GRAM MOLES') WRITE (ITY,4240) FORMAT(1X,'GMS=GRAMS, VP=VAPOR PRESSURE IN ATMOSPHERES') WRITE (ITY,4250) FORMAT(1X,'BP=BOILING POINT IN DEG F, API=GRAVITY') WRITE (ITY,4260) FORMAT(1X,'MW=MOLECULAR WEIGHT') WRITE (ITY,4270) WRITE (ITY, 4270) FORMAT(/,2X,'CUT',3X,'MOLES',6X,'GMS',8X,'VP',8X,'BP' 1,7X,'API',5X,'MW') DO 4290 I=1.NCUTS GMS=MOLES(I) + MW(I) IMW=MW(I) WRITE (ITY,4280) I,MOLES(I),GMS,VP(I),TB(I),API(I),IMW FORMAT(3X,I2,5(1X,1PE9.2),1X,I3) CONTINUE WRITE (ITY,4300) C1,C2P,C4 FORMAT(/,1X,'MOUSSE CONSTANTS: MOONEY=',1PE9.2 1.', MAX H20=',0PF5.2,', WIND++2=',1PE9.2) WRITE (ITY,4310) KA,KB,STEN FORMAT(1X,'DISPERSION CONSTANTS: KA=',1PE9.2 PORMAT(1X, DISPERSION CONSTANTS, NA-, 12 1, ', KB=', 1PE9.2, ', S-TENSION=', 1PE9.2) WRITE (ITY, 4320) VISZ, MK3, MK4 FORMAT(1X, 'VIS CONSTANTS: VIS25C=', 1PE9.2 1.1 1, ', ANDRADE =', 1PE9.2, ', FRACT =', 1PE9.2) WRITE (ITY,4330) FORMAT(/,1X,'FOR THE OUTPUT THAT FOLLOWS, TIME=HOURS') WRITE (ITY,4340) FORMAT(1X,'BBL=BARRELS, SPGR=SPECIFIC GRAVITY, AREA=M+M') WRITE (ITY,4350) FORMAT(1X,'THICKNESS=CM, W=PERCENT WATER IN OIL (1MOUSSE) ') WRITE (ITY,4360) FORMAT(1X,'DISP=DISPERSION RATE IN GMS/M+M/HR') WRITE (ITY, 4370) FORMAT(1X, 'ERATE=EVAPORTION RATE IN GMS/M+M/HR') WRITE (ITY, 4380) FORMAT(1X, 'M/A=MASS PER M+M OF OIL IN THE SLICK') WRITE (ITY, 4390) FORMAT(1X, 'I=FIR 'I=FIRST CUT WITH GREATER THAN 1% (MASS) 1 REMAINING') WRITE (ITY, 4400)

12100	4400	FORMAT(1Y 'JEFTRST CUT WITH OPFATER THAN 50% (MASS)
12000	++00	
12200		r REMAINING /
12300		IF(FRACTS.NE.0.) GO TO 4420
12400		WRITE (ITY,4410)
12500	4410	FORMAT(1X, DISPERSION WAS TURNED OFF')
12600	4420	LE (SPREAD NE 0) GO TO 4440
12000	4420	
12/00		WRITE (117,4430)
12800	4430	FORMAT(1X,'SPREADING WAS TURNED OFF')
12900	4440	TCODE=KMTC
13000		TYPE 4450
13100	4450	COPMAT(/ 19 'DIFASE WAIT')
13100	++50	$r_{\rm other}$
13200		CALL_BRKG4(MOLS,X1,X2,XP,NEQ,NDEL)
13300	4460	CONTINUE
13400		WRITE(IOU, 4470)
1 3500	4470	FORMAT (/ / 14 PARAMANA FINAL OVERALL MASS BALANCE FOR DADENT
13300	4470	A ATT A A A A A A A A A A A A A A A A A
13600		1 OIL ++++++++++*)
13700		CHECK=TMASS+TME+TMD+DELMAS
13800		DO 4480 I=1.NG
1 3000		FMF(1) = 0
1.1.000		
4000	4400	CONTINUE
14100		DO 4490 I-1,NEQ
14200		FMF(I+NG)=YM1(I)/MASSAV(I+NG)
14300	4400	CONTINUE
14300	++30	
14400		WRITE(100,4500)
14500	4500	FORMAT(/,1X,'FINAL MASS FRACTIONS OF CUTS:')
14600		WRITE (IOU.4510) (FMF(I).I=1.NEO+NG)
14700	4510	FORMAT(11(1) 10F10 3))
44800	4010	
14000		
14900		WRITE(IOU, 4520)FR
15000	4520	FORMAT(1X, 'FRACTION (BASED ON MASS) REMAINING= '.1PE10.3)
15100		WRITE (IOU 4538) THASS THO THE DELMAS CHECK
15100	4870	TOULT (100, 1000) (MASS, 100, 100, 000, 000, 000, 000, 000, 0
15200	40.00	FORMAT (1X, MASS REMAINING= , TPE9.3, 1X, MASS DISPERSED= , TPE9.3,
15300		11X,'MASS_EVAPORATED= ',1PE9.3,1X,'MASS_DELETED= '
15400		2.1PE9.3.1X.'TOTAL= '.1PE9.3)
15500		WRITE(IOU ASAG) THASAV
15000	4840	
12000	4040	FORMAT(1X, ORIGINAL MASS= , IPE9.3)
15700	4550	END
100		PEALAA MW MOLS KA KR MOLES MTO MWILK KA MK MWI KII MKA
200		A MARTINE AL MARTA VILLATI VILLATI MARTINE AND AN AND AN AND AN
200		1, MKJL, MK4L, MICA, KH, KOIL, KAIR, MASS, MKJ, MOLSAV, MLSAV, MASSAV
300		2, NHIP, NHBI
350		CHARACTER+5 ANAMEL.ANAME
375		CHARACTER: 10 ENAME
400		(1) = (1 + 1) + (1 + 1)
400		COMMON / LISI/ BL(0, 30), APIL(0, 30), ANAMEL(0, 5)
200		T, DESC(30,5), VOL(30), APIBL(6), ANAME(5)
600		2,C1L(6),C2L(6),C4L(6),STENL(6),VISZL(6).MK3L(6)
700		3. MK4L(6). TB(30)
800		4 API(3a) SPCP(3a) AW(3a) MOLES(3a) PUO(3a) ATO(3a) ATO(3a)
000		+, H I (30), SGR (30), WU(30), WULES (30), RHU(30), WIC (30), WIC (30)
900		5, HLAW(30), VLOGK(30), VLOG(30), VP(30), VISK(30), VIS(30), YM(30)
1000		6,GONE(30),T10(30),MLSAV(30),MASSAV(30)
1100		7, UOP(30), CI(30), OSPGR(30), OAPI(30), OUOP(30)
1200		8 TC(30) VC(30) PC(30) HVAP1(30) A(30) P(30)
1 100		
1300		9, HVAP2(30), CNOW(30), DELH(30), DELHIB(30), EM(30)
1400		1,MWU(30),VPI(30),VFRAC(100),WYI(30),TBNN(100),K0(30),MK(30)
1500		2, TMPVP(30), TMPDS(30), YM1(30), MOLS(30)
1600		3.K(30) YSAVE(30) YMSAVE(30) YF(30)
1700		A FRACTE DISCERT TERMS COPEND VE WINDE OF CO OT CA MAA MAA
100		T, TRACIS, DISTER, 2, IERM2, STREAU, RS, WINDS, CI, CZ, CS, C4, KIT, MK4
1000		J, AMISWI, AMIB, KH, KUIL, KAIR, MASS, MKJ, MW1, TC1, VC1, PC1, CNUM1, VIS1
1900		6, VSLEAD, STEN, DCRUDE, BM, TMOLES, WTMOLE, MOLSAV, TME, TMD, FE, HOUMOU
2000		7. THASAV CISAVE NHIP NHBI THASS DELMAS SPREAD TE
2100		$(\mathbf{M}) = (\mathbf{M}) + ($
2100		COMMON / LIST2/ NUTS(0), ITEML(0), ISAMPL(0), NU(30)
2200		1,NS(30),NEQ1,NEQ2,NEQ3,IOU,IPU,ITY,NC1,NCUTS,KMTC,MOUSWI

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SUBROUTINE DOCHAR
       INCLUDE 'VARI.FOR'
00000
         THIS SUBROUTINE CHARACTERIZES THE CUTS. IF THE LAST CUT IS
RESIDUUM DO NOT CHARACTERIZE IT BUT USE A VAPOR
PRESSURE OF 0. AND A MOLECULAR WEIGHT OF 600.
10
       MW(NCUTS)=600.
       VP(NCUTS)=0.
C
C
C
C
         NV=1 MEANS NO RESIDUUM CUT PRESENT.
         NV=2 MEANS A RESIDUUM IS PRESENT.
č
       NV=1
       NC1=NCUTS
       DO 90 I=1,NCUTS
SPGR(I)=141.5/(API(I)+131.5)
       SPGR(I)=0.983+SPGR(I)
C
C
         IF APISWI=1 (PREVIOUS WEATHERING HAS OCCURED), CALCULATE
Ċ
         A NEW BULK API GRAVITY
       DCRUDE=0.
       DO 20 J=1,NCUTS
       DCRUDE=((VOL(J)+SPGR(J))/100)+DCRUDE
20
       CONTINUÈ
       APIB=(141.5/DCRUDE)-131.5
       TBN=TB(I)
С
Ċ
         CALCULATE U.O.P. K-FACTOR AND CORRELATION INDEX
       UOP(I)=((TB(I)+459.)**.33333)/SPGR(I)
       CI(I) = (473.7 + SPGR(I)) - 456.8 + (49339)(((TB(I) - 32.)/1.8) + 273.))
       APIN=API(I)
С
         THE RESIDUUM CUT IS IDENTIFIED BY A NORMAL BOILING
C
C
C
         POINT OF 850. LOOP AROUND THE NV=2 SWITCH IF A
         RESIDUUM IS PRESENT. NC1 IS THE NUMBER OF PSEUDO COMPONENTS
č
         WITH FINITE VAPOR PRESSURES.
       IF(TBN.LT.850.) GO TO 30
       NV=2
       NC1=NCUTS-1
30
       CALL CHAR(APIN, TBN, AN, BN, NSN, NV)
C
C
         THE CHARACTERIZATION SUBROUTINE RETURNS THE LOGIO OF THE
c
c
         KINEMATIC VISCOSITY (CENTISTOKES) AT 122 DEG F.
       VISK(I)=10.**VIS1
       VLOGK(1)=ALOG(VISK(1))
       GO TO (40,90), NV
C
С
         STORE THE CUT INFORMATION FOR A NON-RESIDUUM CUT.
С
40
       NS(I)=NSN
       A(Ì)=AN
B(I)=BN
       MW(I) = MW1
       TC(I)=TC1
TC(I)=TC(I)+459.
```

```
VC(I)=VC1
PC(I)=PC1
        CNUM(I)=CNUM1
С
С
           FIND THE TEMPERATURE AT WHICH THE VAPOR PRESSURE IS 10 MMHG
Ċ
           BY USING NEWTON-RAPHSON WITH TB AS THE FIRST GUESS.
С
        NC(I)=0
        YTEN=ALOG10(0.01315/PC(I))
        X=(TB(I)+459.)/TC(I)
EX=EXP(-20.*(X-B(I))**2)
50
        Y=-A(I)+(1.-X)/X-EX
        YOBJ=Y-YTEN
        VP(I)=PC(I)+10.++Y
TEST=ABS(VP(I)-0.01315)
        IF(TEST.LT.0.001315) GO TO 80
NC(I)=NC(I)+1
IF(NC(I).GT.20) GO TO 60
DY=A(I)/(X*X)+40.*(X-B(I))*EX
        BI=YOBJ-DY+X
        X=-BI/DY
        GO TO 50
С
Č
          UNSUCCESSFUL EXIT FROM NEWTON-RAPHSON
С
      TYPE 70, I,X,Y
FORMAT(1X,'T10 FAILURE FOR',I4,' AT T = ',1PE10.3,' WHERE
1 LOG10(P) = ',1PE10.3)
60
70
        GO TO 460
С
С
          SUCCESSFUL EXIT FROM NEWTON-RAPHSON
С
80
        T10(I) = X + TC(I)
С
č
          CALCULATE THE HEAT OF VAPORIZATION AT 10 MMHG WITH THE
CLAPEYRON EQUATION AND USE WATSONS METHOD FOR THE
VAPOR PRESSURE BELOW 10 MMHG. SEE GAMSON AND WATSON,
С
С
          1944, NATIONAL PETROLEUM NEWS, R-258 TO R-264.
С
        TR2=T10(I)/TC(I)
        EX=92.12*(TR2-B(I))*EXP(-20.*(TR2-B(I))*2)
        HVAP=1.987+T10(I)+T10(I)+(2.303+A(I)/(TR2+TR2)+EX)/TC(I)
       HVAP1(I)=HVAP/MW(I)
HVAPZ(I)=HVAP/(1.-TR2)++0.38
90
        CONTINUÉ
С
Ç
          END OF TRUE-BOILING-POINT CUTS CHARACTERIZATION
C
        WRITE (IOU, 100) (ANAME(I), I=1,5)
        FORMAT (1H1, 'SUMMARY OF TBP CUTS CHARACTERIZATION FOR: '
100
       1,545)
        IF(NIP.NE.1.AND.NBI.NE.1) GO TO 150
       WRITE(IOU,110)
FORMAT(1X,'AFTER:')
IF(NIP.NE.1) GO TO 130
110
        WRITE(IOU, 120) NHIP
        FORMAT(8X, 'ICE POOL WEATHERING FOR ', 1PE9.3, ' HOURS')
120
130
        CONTINUE
        IF(NBI.NE.1) GO TO 150
        WRITE(IOU, 140) NHBI
```

```
140
         FORMAT(8X, 'BROKEN ICE FIELD WEATHERING FOR ', 1PE9.3.' HOURS')
        CONTINUE
150
        WRITE (IOU, 160)
Format(/, 1x, 'Code version is cutica of may 84')
160
        WRITE (IOU, 170) ITEM, ISAMP
        FORMAT(1X, 'ITEM ', 15, ', SAMPLE ', 15)
170
180
        CONTINUE
       WRITE (IOU, 190)
FORMAT(/,8x,'TB',7x,'API',6x,'SPGR',7x,'VOL',8x,'MW',8x
1,'TC',8x,'PC',8x,'VC',8x,'A',9x,'B',8x,'T10',7x,'VIS'
2,4x,'NC NS')
190
        DO 210 I=1, NCUTS
       WRITE (IOU, 200) I, TB(I), API(I), SPGR(I), VOL(I), MW(I), TC(I)
1, PC(I), VC(I), A(I), B(I), T10(I), VISK(I), NC(I), NS(I)
200
        FORMAT(1X, 12, 12(1X, 1PE9.2), 2(1X, 12))
        CONTINUE
210
        WRITE(IOU,220)
Format(//,7X,'UOP K',4X,'CORRELATION INDEX')
220
        DO 240 I=1, NCUTS
        WRITE(IOU,230) I,UOP(I),CI(I),(DESC(I,J), J=1,5)
FORMAT(1X,I2,1X,1PE9.2,7X,1PE9.2,7X,5A5)
230
240
        CONTINUE
        WRITE (IOU,250) APIB
FORMAT(//,1X,'BULK API GRAVITY = ',F5.1)
WRITE (IOU,260)
250
        FORMAT(//.1X,'TB = NORMAL BOILING TEMPERATURE, DEG F')
WRITE (IOU.270)
FORMAT(1X,'API = API GRAVITY')
WRITE (IOU.280)
FORMAT(1X,'VOL = VOLUME PER CENT OF TOTAL CRUDE')
260
270
280
        WRITE (IOU, 290)
FORMAT(1X, 'MW = MOLECULAR WEIGHT')
290
        WRITE (IOU, 300)
FORMAT(1X,'TC = CRITICAL TEMPERATURE, DEG RANKINE')
300
        WRITE (IOU, 310)
FORMAT(1X, 'PC = CRITICAL PRESSURE, ATMOSPHERES')
310
        WRITE (IOU, 320)
FORMAT(1X, 'VC = CRITICAL VOLUME, CC/MOLE')
WRITE (IOU, 330)
FORMAT(1X, 'A AND B ARE PARAMETERS IN THE VAPOR PRESSURE
320
330
       1 EQUATION')
        WRITE (IOU, 340)
FORMAT(1X, 'T10 IS THE TEMPERATURE IN DEG R WHERE THE VAPOR
340
       1 PRESSURE IS 10 MM HG')
        WRITE (IOU, 350)
FORMAT(1X, 'VIS IS THE KINEMATIC VISCOSITY IN CENTISTOKES
350
       1 AT 122 DEG F')
        WRITE(IOU, 360)
360
        FORMAT(1X, 'UOP K IS THE U.O.P. K CHARACTERIZATION FACTOR')
        WRITE(100,370)
        FORMAT(1X, 'CORRELATION INDEX IS DEFINED IN (COLEMAN, 1978)')
370
        WRITE (IOU, 380)
FORMAT(1X, 'NC = ERROR CODE, SHOULD BE LESS THAN 20')
WRITE (IOU, 390)
380
        FORMAT(1X, 'NS = ERROR CODE, SHOULD BE EQUAL TO 1')
390
        WRITE (IOU, 400) NCUTS
FORMAT(1X, 'IGNORE THE ERROR CODES FOR COMPONENT NUMBER ', 12
400
       1, ' IF IT IS A RESIDUUM')
        WRITE (IPU, 420) ITEM, ISAMP
410
420
        FORMAT(215)
```

430	WRITE (IPU.430) (ANAME(I),I=1,5) FORMAT(5A5)
C C C	THE CUTVP2.PLT PLOT FILE IS WRITTEN AS: 1. ITEM AND SAMPLE NUMBER ON 215
C	2. THE CRUDE NAME ON 5A5 3. NCUTS ON 15
C	4. BOILING POINT IN DEG F OF EACH CUT ON 10(1X,1PE10.3).
č	5. TEMPERATURE IN DEG F OF EVAPORATION, XPRINT WIND SPEED IN KNOTS, WINDS
č	SURFACE TENSION IN DYNES/CM, STEN
č	C1, C2, AND C4 IN THE MOUSSE EQUATION, KMTC, MASS TRANSFER COFFICIENT CODE (FLOATED)
C C	ALL ON 10(1X, 1PE10.3). 6. NUMBER OF CUTS+1 ON IS
C C	7. TIME, MASS OF CUTS, AREA ON 10(1X,1PE10.3) 8. Total Mass Fraction Remaining in the oil
	SLICK FOR EACH TIME STEP PRINTED ON 10(1X,1PE10.3)
00000	ITEMS 6 AND 7 ABOVE ARE WRITTEN FOR EACH TIME STEP WITH THE FIRST TIME STEP BEING ZERO. WHEN THE VERY LAST TIME STEP IS WRITTEN THEN ITEM 8 IS WRITTEN.
	THE NUMBER OF LINES WRITTEN ON THE CUTVP2.PLT PLOT FILE REFERS TO THE NUMBER OF 'TIMES' WRITTEN THROUGH ITEMS 6 AND 7 ABOVE.
140	WRITE (IPU,440) NCUTS FORMAT(I5)
150 160	WRITE (IPU,450) (TB(I),I=1,NCUTS) FORMAT(10(1X,1PE10.3)) CONTINUE
	RETURN END

100		SUBROUTINE CHAR(API1,TB1,A1,B1,NS1,NV)
200		INCLUDE 'VARI.FOR'
300		DIMENSION T(2,6),C(2,6),P(4),V(2,6)
400		DATA ((C(I,j), j=1,6), I=1,2)/6.241E+01,-4.595E-02,-2.836E-01
500		1,3.256E-03,4.578E-04,5.279E-04
6 00		2,4.268E+02,-1.007,-7.449,1.38E-02,1.047E-03,2.621E-02/
700		DATA ((T(I,J),J=1,6),I=1,2)/4.055E+02,1.337,-2.662,-2.169E-03
800		1,-4.943E-04,1.454E-02
900		2,412.2,1.276,-2.865,-2.888E-03,-3.707E-04,2.888E-02/
1000		DATA P/1.237E-02.0.2516.4.039E-024.024E-02/
1100		DATA ((V(I,J),J=1,6),I=1,2)/ -0.4488,-9.344E-04,0.01583
1200		1,-5.219E-05,5.268E-06,1.536E-04
1300	_	2,-0.6019,1.793E-03,-3.159E-03,-5.1E-06,9.067E-07,3.522E-05/
1400	C	
1500	C	THIS SUBROUTINE CHARACTERIZES A CUT OF CRUDE OIL WITH RESPECT
1600	С	TO VAPOR PRESSURE. THE INPUT REQUIRED IS API GRAVITY AND THE
1700	С	BOILING POINT AT 1 ATMOSPHERE. THE OUTPUT IS A SWITCH NS
1800	C	WHERE NS1-1 MEANS THE VAPOR PRESSURE EQUATION CAN BE USED DOWN T
1900	С	10MM HG AND NS-2 MEANS THE CLAPEYRON EQUATION SHOULD BE USED.
2000	С	
2100	С	THE VAPOR PRESSURE EQUATION IS:
2200	С	
2300	С	LOG10(PR) = -A*(1TR)/TR - EXP(-20*(TR-B)**2)
2400	С	
25 00	С	WHERE PR = REDUCED PRESSURE, TR = REDUCED TEMPERATURE AND
2600	С	A AND B ARE RETURNED BY THIS SUBROUTINE.
2700	С	
28 00	С	API = GRAVITY, TB = BOILING POINT AT 1 ATMOSPHERE IN DEG F.
29 00	С	CALCULATE CRITICAL TEMPERATURE AND MOLECULAR WEIGHT.
3000	С	
3100		API2=API1+API1
3200		TB2=TB1+TB1
3300		CROSS=API1+TB1
3400		I=1
3500		IF(API1.GT.35.) I=2
3600		VIS1=V(I,1)+V(I,2)+TB1+V(I,3)+API1+V(I,4)+CROSS+V(I,5)+TB2
3700		1+V(I,6)*API2
3800		GO TO (10,30), NV
3900	10	I=1
4000		IF(TB1.GT.500.) I=2
4100		MW1=C(I,1)+C(I,2)+TB1+C(I,3)+API1+C(I,4)+CROSS+C(I,5)+TB2
4200		1+C(I,6) • API2
4300		TC1=T(I,1)+T(I,2)+TB1+T(I,3)+API1+T(I,4)+CROSS+T(I,5)+TB2
4400		1+T(I,6)+API2
450 0		TCK=(TC1+459.)/1.8
4600	С	
4700	С	CALCULATE THE VISCOSITY OF THE CUT.
4800	С	
4900		I=1
5000		IF(API1.GT.35.) I=2
5100		VIS1=V(I,1)+V(I,2)+TB1+V(I,3)+API1+V(I,4)+CROSS+V(I,5)+TB2
52 00		1+V(I,6)+API2
5300	C	
5400	С	CALCULATE THE CARBON NUMBER
5500	С	
5600		CNUM1=(MW1-2.)/14.
5700		X-ALOG10(CNUM1)
5800	С	
5900	С	CALCULATE B FOR THE VAPOR PRESSURE EQUATION
6000	С	

6100		BPRIME=P(1)+X+(P(2)+X+(P(3)+X+P(4)))
6200		B1=BPRIME-0.02
6300	С	
6400	Ċ	CALCULATE THE CRITICAL VOLUME, CC/GMOLE
6500	Ċ	
6600		VW=1.88+2.44+CNUM1
6700		VC1=VW/0.044
6800	С	
6900	Č	CALCULATE THE CRITICAL PRESSURE IN ATMOSPHERES
7000	Č	
7100	-	PCP=20.8+TCK/(VC1-8.)
7200		PC1=PCP+10.
7300		TR=(TB1+459.)/(TC1+459.)
7400		PR=1./PC1
7500		NS1=1
7600		IF(TR.LE.B1) GO TO 20
7700		A1 = (ALOG10(PR) + EXP(-20. + (TR-B1) + 2)) + TR/(TR-1.)
7800		GO TO 30
7900	20	NS1=2
8000	30	RETURN
8100	~ •	FND
		

¥

```
SUBROUTINE MACK
       REAL+4 KAY, KAY0, MID, MOLEFT, MDH, MVO, L0, LH
INCLUDE 'VARI.FOR'
       DIMENSION KAY(30), KAY0(30)
THIS SUBROUTINE CALCULATES THE INPUT PARAMETERS FOR THE
          MACKAY EVAPORATION MODEL
          THE MACKAY EVAPORATION EQUATION IS:
                 DF = DTHETA + H
         WHERE DF IS THE CHANGE IN THE VOLUME FRACTION EVAPORATED
         IN ONE TIME INCREMENT, H IS THE HENRY'S LAW COEFFICIENT, AND DTHETA IS THE INCREASE IN THE "EVAPORATIVE EXPOSURE", WHICH
          IS DEFINED AS:
               DTHETA = K+A+DT/V
         WHERE A IS THE SLICK AREA, DT IS THE TIME INCREMENT, V IS
THE SLICK VOLUME AT THE BEGINNING OF THE TIME INCREMENT,
AND K IS THE MASS TRANSFER COEFFICIENT.
          FIRST DETERMINE WHICH CUTS EVAPORATE. FOR NOW USE CUTS WHICH
          HAVE VAPOR PRESSURES GREATER THEN 1X10E-07 AT
          ENVIRONMENTAL TEMPERATURE.
С
       MAC=40
       CUTOFF=1.0E-07
       ICNT=0
10
       ICNT=ICNT+1
       IF (VP(ICNT).GT.CUTOFF) GO TO 10
ICNT=ICNT-1
С
č
          CALCULATE HEAT OF VAPORIZATION USING RESULTS OF
С
          FALLON AND WATSON
Ĉ
       DO 20 I=1. ICNT
       API2=API(I)+API(I)
       TB2=TB(I) + TB(I)
       CROSS=ÀPÍ(I) + TB(I)
       DELH(I) = 232.2 - (0.2441 + TB(I)) - (0.6937 + API(I))
      1-(3.583E-04+CROSS)+(1.024E-04+TB2)+(1.037E-04+API2)
       DELH(I)=DELH(I)+MW(Ì)
       DELHTB(I)=DELH(I)/(TB(I)+459.)
20
       CONTINUE
C
C
          CALCULATE MEAN (DELTAH/TB) FOR "TROUTON'S RULE"
Ċ
       SDH=0
       DO 30 I=1, ICNT
       SDH=SDH+DELHTB(I)
30
       CONTINUE
       MDH=SDH/ICNT
С
С
          CALCULATE MOLAR VOLUME OF OIL
С
       MVO=WTMOLE/DCRUDE
С
          NOW PERFORM A SIMPLE (ZERO PLATE) BATCH
C
```

DISTILLATION IN ORDER TO FIND THE BUBBLE POINT VERSUS C C VOLUME FRACTION DISTILLED CURVE. THE INTEGRATION IS CARRIED OUT USING A FIRST ORDER RUNGA-KUTTA NUMERICAL 0000000000 INTEGRATION SCHEME (SEE GREENSPAN, 1971). TVOL IS THE TOTAL VOLUME OF THE BATCH (INITIALLY) IN METERS CUBED. VOLU IS THE REMAINING VOLUME OF THE BATCH. EM(I) IS THE NUMBER OF GRAM-MOLES REMAINING IN EACH CUT. MOLEFT IS THE TOTAL NUMBER OF MOLES LEFT. LØ IS THE TOTAL INITIAL NUMBER OF MOLES IN THE BATCH. WRITE(MAC, 40) 40 *****') 1 +++ WRITE(MAC.50) FORMAT(/,2X, THE MACKAY EVAPORATION MODEL IS DESCRIBED IN') 50 WRITE(MAC,60) FORMAT(2X,'(MACKAY,1982)') 60 WRITE(MAC, 70) FORMAT(2X, 'THE FOLLOWING ARE THE RESULTS OF A CALCULATION OF THE') 70 WRITE($\dot{M}AC.80$) (ANAME(I), I=1,5) Format(2x,'INPUT PARAMETERS FOR THE MACKAY MODEL FOR ',5A5) 80 TT=TE-459. WRITE(MAC,90) TT FORMAT(2X,'AT ',1PE9.3,' DEGREES F') WRITE(MAC,100) 90 FORMAT(//, 2X, 'SIMULATED ONE-PLATE BATCH DISTILLATION: ') 100 TVOL=BM VOLU-BM DO 110 I=1,NCUTS EM(I)=MOLES(I) 110 CONTINUE J=1L0=TMOLES С LH AND RH ARE THE ENDPOINTS FOR THE INTERVAL HALVING TRIAL AND С Č C ERROR THAT IS USED TO CALCULATE THE BUBBLE POINT OF THE REMAINING LIQUID. С LH=TB(1)+459. RH=T8(NC1)+459. 120 CONTINUE MOLEFT=0 DO 130 I=1,NCUTS MOLEFT=MOLEFT+EM(1) 130 CONTINUE С С BEGIN TRIAL AND ERROR TO GET BUBBLE POINT C DO 160 L=1,20 YTOT=0. MID=(RH+LH)/2. С С THE SUBROUTINE VPIF RETURNS THE VAPOR PRESSURE OF THE С NON-RESIDUUM CUTS IN ATMOSPHERES AT THE TEMPERATURE ç MID. MID IS THE CENTER OF THE INTERVAL OF INTERVAL HALVING. С CALL VPIF(MID, NC1) С С WYI(I) IS THE THE MOLE FRACTION OF EACH CUT

```
IN THE VAPOR PHASE. YTOT IS THE TOTAL MOLE FRACTION OF CUTS.
C
С
       DO 140 I=1,NC1
       WYI(I)=(VP(I) + EM(I)/MOLEFT)
       YTOŤ=ÝTOT+ŴYÍ(I)
       CONTINUE
140
       IF(YTOT.GT.1.) GO TO 150
       LH-MID
       GO TO 160
       CONTINUE
150
       RH=MID
       CONTINUE
160
C
          VFRAC IS THE VOLUME FRACTION DISTILLED. TBNN(J) IS THE BUBBLE POINT OF THE CURRENT FRACTION.
C
C
С
       VFRAC(J)=1.-(VOLU/TVOL)
       TBNN())=MID-459.
       WRITE(MAC, 170)
FORMAT(///.8X,'F',7X,'TEMP(F)',5X,'Y SUM')
WRITE(MAC, 180) VFRAC(J),TBNN(J),YTOT
170
       FORMAT(2X,3(1X,1PE10.3))
WRITE (MAC,190)
FORMAT(//4X,'I',3X,'MOLES I',5X,'VP(I)',5X,'Y(I)',/)
D0 210 I=1.NC1
180
190
       WRITE(MAC, 200) I, EM(I), VP(I), WYI(I)
200
       FORMAT(2X, 12, 3(1X, 1PE10.3))
       CONTINUE
210
С
C
          IF ALL OF THE LAST CUT WITH VAPOR PRESSURE (AT ENVIRONMENTAL
          TEMPERATURE) GREATER THAN 1X10E-7 IS GONE THEN STOP INTEGRATION.
С
С
       IF (EM(ICNT).EQ.0.) GO TO 310
       TMK=0.
С
          KØ AND MK ARE INTERMEDIATE VALUES FOR THE RUNGA KUTTA.
С
С
       DO 230 I=1,NC1
       KAYO(I) = -(0.05 + L0) + (VP(I) + EM(I)/MOLEFT)
       MK(I) = EM(I) + KAYO(I)
С
С
          ZERO MK IF IT GOES NEGATIVE.
C
       IF (MK(I).GT.0.) GO TO 220
       MK(Ì)=Ò.
220
       CONTINUE
       TMK=TMK+MK(I)
230
       CONTINUE
       IF(TMK.EQ.0.) GO TO 310
IF (NC1.EQ.NCUTS) GO TO 240
TMK-TMK+EM(NCUTS)
240
       CONTINUE
С
č
          RESET ENDPOINTS FOR SECOND HALF OF INTEGRATION.
С
       RH=MID+100.
       LH=MID-100.
       DO 270 L=1,20
       YTOT=0.
       MID=(RH+LH)/2.
```

	CALL VPIF(MID,NC1)
	DO 250 I=1,NC1
	YTOT=YTOT+(VP(I)+MK(I)/TMK)
250	
	IF (TIUI.GI.I.) GU IU 200
	LN=M1U CO TO 278
260	CONTINUE
200	RH-MID
270	CONTINUE
	VOLU=0.
	DO 290 I=1.NC1
	KAY(I) = -(0.05 + L0) + (VP(I) + MK(I) / TMK)
	EM(I) = EM(I) + 0.5 + (KAYO(I) + KAY(I))
С	
С	ZERO EM IF IT GOES NEGATIVE
С	
	IF(EM(I).GT.0.) GO TO 280
	EM(I)=0.
280	CONTINUE
Ç	
C	CALCULATE THE REMAINING VOLUME. RHO IS THE DENSITY IN
C	GRAM MOLES PER METER CUBED.
C	
204	CONTINUE
290	LE(NC1 ED NCHTS) CO TO 300
	VOLUEVOLU+MOLES(NCUTS)/RHO(NCUTS)
300	CONTINUE
Ċ	
Č	RESET THE ENDPOINTS AND RETURN FOR ANOTHER "TIME" STEP
С	
	LH=TBNN(J)+459.
	RH=LH+100.
	J=J+1
	GO TO 120
310	CONTINUE
C C	NOW LEAST COULARES THE TRNN VG. VERAC DATA
	NUW LEAST SQUARES THE IDAN VS. VPRAC DATA.
C	S7-8
	5X-0 5Y=0
	5×2=0
	SXY=0
	SY2=0
	DO 320 I=1,J
	SX=SX+VFRAC(I)
	SY=SY+TBNN(I)
	SX2=SX2+VFRAC(I)+VFRAC(I)
	SY2=SY2+TBNN(I)+TBNN(I)
100	SXT=SXT+IBNN(I)+VFRAC(I)
320	
	BNUM SXY-(SXASY/.)
	BDEN=SX2-(SX+SX/J)
	BEE=BNUM/BDEN
	AA=YMM-BEE+XM
С	
С	CALCULATE CORRELATION COEFFICIENT

```
С
           FAC1=(SX2-SX+SX/J)
          FAC2=(SY2-SY+SY/J)
RDEN=(FAC1+FAC2)++0.5
           R=BNUM/RDEN
С
С
              PRINT OUT MACKAY PARAMETERS
С
         WRITE (MAC,330)
FORMAT (/,6X,'DELTAH'.
14X,'DELTAH/TB')
330
          DO 350 I=1, ICNT
          WRITE (MAC,340) I,DELH(I),DELHTB(I)
Format(1x,12,5(1x,1PE10.3))
340
350
          CONTINUE
          WRITE (MAC, 360)
FORMAT(//,2X, 'WHERE:')
WRITE (MAC, 370)
FORMAT (2X, 'DELTAH IS THE ENTHALPY OF VAPORIZATION IN BTU/LBMOLE')
360
370
          WRITE (MAC, 380)
Format(2X, 'Deltah/TB is the troutons rule constant in btu/lbmole
380
         1+DEG R')
          CONTINUÉ
390
          WRITE (MAC, 400)
FORMAT(//,2X,'LEAST SQUARES OF B.P. VS. FRACTION EVAPORATED:')
WRITE (MAC, 410)BEE
400
          WRITE (MAC, 410)BEE
FORMAT(/,5X,'SLOPE: ',1PE10.3,' DEG R/FRACTION EVAPORATED')
WRITE (MAC, 420) AA
FORMAT(5X,'INITIAL B.P.: ',1PE10.3,' DEG F')
WRITE (MAC, 430) R
FORMAT(5X, 'CORRELATION COEFFICIENT: ',1PE10.3)
WRITE (MAC, 440) DCRUDE
FORMAT (/,2X,'BULK OIL DENSITY: ',1PE10.3,' GRAMS/CC')
WRITE (MAC, 450) NYO
410
420
430
440
          WRITE (MAC,450) MVO
FORMAT(2X,'BULK MOLAR VOLUME OF OIL: ',1PE10.3,' CC/MOLE')
WRITE (MAC,460) MDH
FORMAT(2X,'MEAN TROUTONS RULE CONSTANT: ',1PE10.3,' BTU/LBMOLE
450
460
         1+DEG R')
          WRITE (MAC,470)
Format(//,2x,'After simplification and combining terms, the '
470
         1)
          WRITE (MAC,480)
FORMAT(2X,'MACKAY EVAPORATION MODEL BECOMES:')
AAA=MV0+0.01219/(((XPRINT-32.)/1.8)+273.)
480
           AAA=ALOG(AAA)
           888=MDH/1.987
           CCC=BBB/(XPRINT+459.)
           888=888+AAA
           DDD=AA+459.
         WRITE (MAC.490)B8B.CCC.DDD.BEE
FORMAT(/,10X,'DELTA-F = DELTA-THETA + EXP(',1PE10.3
1,'-',1PE10.3,' (',1PE10.3,' + ',1PE10.3,'(F)))')
490
           EEE=CCC+DDD
           FFF=888-EEE
           GGG=CCC+BEE
          WRITE (MAC, 500)
FORMAT(/, 15X, 'OR')
500
         WRITE(MAC,510)FFF,GGG
FORMAT(/,10X,'DELTA-F = DELTA-THETA + EXP( ',1PE10.3,' - ',1PE10.3
1,'(F))')
510
           CONTINUE
520
           RETURN
           END
```

SUBROUTINE BRKG4(Y, X1, X2, XP, NEQ, NDEL) INCLUDE 'VARI.FOR' REAL+4 K1,K2,K3,K4 DIMENSION Y(30), YARG(30), K2(30), K1(30), K3(30), K4(30) С С RUNGA-KUTTA 4-TH ORDER NUMERICAL INTEGRATION FOR SIMULTANEOUS 00000 DIFFERENTIAL EQUATIONS, SEE C.R. WYLIE, PAGES 108-117 OR D. GREENSPAN, PAGES 113-115. THIS SUBROUTINE DOES THE PRINTING, THE INITIAL AND FINAL VALUES ARE ALWAYS PRINTED. PRINT THE RESULTS EVERY XP INCREMENT č IN X. С Ĉ THE USER MUST WRITE SUBROUTINE FXYZ WHICH CALCULATES THE K1, K2, K3, AND K4 VECTORS AS A FUNCTION OF X AND THE CURRENT Y VECTOR. INTEGRATION FOLLOWS THE REFERENCES AND С Ċ С WAS TESTED ON PROBLEM 5, PAGE 116 IN WYLIE. Č C THE FIRST NOUTS POSITIONS IN THE Y VECTOR ARE THE MOLES OF THE COMPONENTS, POSITION NCUTS+1 IS THE AREA OF THE SLICK. POSITION NCUTS+2 IS THE MASS LOST FROM THE SLICK Ċ C ¢ BY DISPERSION ALONE. POSITION NCUTS+3 IS THE MASS LOST č FROM THE SLICK BY EVAPORATION ALONE. Ċ č LINE KEEPS TRACK OF HOW MANY LINES ARE WRITTEN TO THE С PLOT FILE. NEQ1 IS THE NUMBER OF COMPONENTS+1. NS IS A ROUTING SWITCH TO CHANGE THE PRINT INTERVAL. IN AN INPUT ROUTING SWITCH TO DELETE RAPIDLY CHANGING č IN IS С COMPONENTS. GONE(LINE) IS THE MASS FRACTION REMAINING AT TIME STEP LINE. INT IS A SWITCH TO INDICATE WHEN THE Ċ С INTEGRATION HAS STARTED; INT=1, NOT STARTED; INT=2, STARTED. ITYP IS A HEADER PRINT SWITCH FOR THE č Ĉ 80-COLUMN FILE. INT=1 ITYP=1 LINE=0 NEQ1=NEQ+1 NEQ2=NEQ+2 NEQ3=NEQ+3 NSS=1 TN=1 IKEEP=1 GONE(1)=1. DISPER=0. С С TOTAL IS THE INITIAL NUMBER OF MOLES. С TSAVE IS THE INITIAL MASS. С TOTAL=0. TSAVE=0. DO 10 I=1.NEQ ¢ С CALCULATE AND SAVE THE INITIAL CONDITIONS. ċ YSAVE(I)=Y(I) YMSAVE(I)=Y(I)*MW(I)MWU(I) = MW(I)TSAVE-TSAVE+YMSAVE(I) TOTAL=TOTAL+Y(I)

134

```
10
       CONTINUE
С
С
          SAVE THE INITIAL AREA.
С
       YMSAVE(NEQ1)=Y(NEQ1)
С
С
          INITIALIZE THE MASS LOST BY DISPERSION ALONE AND
С
          EVAPORATION ALONE.
С
       Y(NEQ2)=0.
       Y(NEQ3)=0.
с
с
          NDEL IS THE NUMBER OF COMPONENTS DELETED BECAUSE THEY
С
          EVAPORATE TOO FAST. NEAST IS THE CURRENT ARRAY LOCATION
          OF THE FASTEST MOVING COMPONENT.
Ċ
С
       NDEL=0
       NFAST=0
       X=X1
С
С
          INITIALIZE THE PRINT SWITCH TO FORCE A PRINT AND
          SUBSEQUENT CALCULATIONS THE FIRST TIME THROUGH.
С
C
       X₩=-1.
       WRITE (IOU, 20)
FORMAT(/, 1X, 'COUNT THE CUTS IN THE FOLLOWING OUTPUT FROM LEFT
20
      1 TO RIGHT',/)
       WRITE (IOU,30)
FORMAT(1X,'THE INITIAL GRAM MOLES IN THE SLICK ARE:')
WRITE (IOU,40) (Y(I),I=1,NEQ)
FORMAT(11(1X,1PE10.3))
WRITE (IOU,50)
FORMAT(/,1X,'THE INITIAL MASSES (GRAMS) IN THE SLICK ARE
30
40
50
      1:
      WRITE (IOU,40) (YMSAVE(I), I=1,NEQ)
WRITE (IOU,60) TSAVE
FORMAT(1X,'THE TOTAL MASS FROM THESE CUTS IS '
1,1PE10.3,' GRAMS')
60
       WRITE (IOU,70)
FORMAT(/)
70
С
          CALCULATE DY/DX AND SET THE STEP SIZE TO APPROXIMATE
С
          A 5% CHANGE IN THE MOST RAPIDLY CHANGING Y. WHEN THIS
¢
С
          Y DECREASES BY A FACTOR OF 20, RESET THE STEP SIZE
          ACCORDING TO THE NEXT Y.
C
C
          SOME Y'S WILL CHANGE SO FAST THAT THEY WILL BE GONE
С
          IN A FEW MINUTES. THESE ARE DELETED BEFORE INTEGRATION
С
          STARTS AND NOTED ON THE PRINTED RESULTS.
С
С
          INITIALIZE OR INCREMENT NEAST.
Ĉ
80
       NFAST=NFAST+1
90
       CALL FXYZ(X,Y,K1,NEQ)
С
С
          THE TIME UNIT IS HOUR.
С
          SET THE STEP SIZE TO H=0.05+Y/(DY/DX).
С
       H=0.05+Y(NFAST)/K1(NFAST)
       YOLD=Y(NFAST)
       H=ABS(H)
```

```
H_{2}=H_{2}.
       GO TO (100,170), IN
¢
          IF THERE IS A RAPIDLY MOVING COMPONENT AT THE BEGINNING ITS STEP SIZE WILL BE VERY SMALL, DO NOT LET THE
Č
C
          STEP SIZE BE LESS THAN 0.05 HOUR.
С
С
100
       IF(H.GT.0.05) GO TO 130
С
С
          Y(NFAST) CHANGES TOO FAST TO CALCULATE. DELETE IT AND MOVE
č
          EVERYBODY ONE SPACE TO THE LEFT.
Ċ
          WHEN YOU MOVE THE AREA BE SURE TO SUBTRACT THE CONTRIBUTION
          OF THE CUT JUST DELETED.
С
       ISTART=1
       NFAST=1
       NDEL=NDEL+1
С
Ċ
          DECREASE THE NUMBER OF COMPONENTS BY 1
Č
C
          DELMAS IS THE TOTAL MASS OF DELETED CUTS
       DELMAS=DELMAS+(Y(NDEL) + MW(NDEL))
       NEQ=NEQ-1
       NEQ1=NEQ+1
       NEQ2=NEQ+2
       NEQ3=NEQ+3
       NEQ4=NEQ+4
       AD=Y(1)/RHO(1)/Z
DO 110 I=1,NEQ
С
          SHIFT THE ARRAYS.
С
С
       I1 = I + 1
       Y(I)=Y(I1)
       VP(I)=VP(I1)
MTC(I)=MTC(I1)
       YSAVE(I)=YŠAVE(I1)
       VLOG(I)=VLOG(I1)
       RHO(I)=RHO(I1)
MWU(I)=MWU(I1)
       YMSÁVE(I)=ÝMSÁVE(I1)
110
       CONTINUE
С
С
          BE SURE AND DO THE LAST THREE POSITIONS WHEN SHIFTING
С
       Y(NEQ1)=Y(NEQ2)-AD
Y(NEQ2)=Y(NEQ3)
Y(NEQ3)=Y(NEQ4)
       WRITE (IOÙ, 120) NDEL
FORMAT(1X, 'CUT', 12,
      FORMAT(1X, 'CUT ', 12, ' GOES AWAY IN MINUTES, THEREFORE IT WAS 1 DELETED AND THE CUTS RENUMBERED',/)
120
       WRITE (ITY, 120) NDEL
GO TO 90
       IN=2
130
       GO TO (140,160) ITYP
       ITYP=2
140
       WRITE (ITY, 150)
       FORMAT(/, 1X, 'TIME', 2X, 'BBL', 3X, 'SPGR', 2X, 'AREA', 2X
150
```

```
1, 'THICKNESS W', 2X, 'DISP', 4X, 'ERATE', 4X, 'M/A
                                                                   I J.)
С
č
          THE COMPONENTS THAT MOVE TOO FAST TO CONSIDER (AT TIME
          ZERO) HAVE BEEN DELETED AND THE ARRAYS SHIFTED.
С
160
       NEQ1=NEQ+1
       NEQ2=NEQ+2
       NEQ3=NEQ+3
С
Ĉ
          NEVER LET THE STEP SIZE BE GREATER THAN 0.5
С
170
        IF(H.GT.0.5) H=0.5
       WRITE (IOU, 180) H,NFAST
FORMAT(/,2X,'STEP SIZE OF ',1PE10.3,' IS BASED ON CUT ',I3,/)
180
С
С
          CHECK THE PRINT SWITCH.
Ċ
190
        IF(X.LT.XW) GO TO 400
C
C
          INCREMENT THE PRINT SWITCH AND CALCULATE INTERMEDIATE
С
          RESULTS NOT CARRIED WITH THE INTEGRATION.
Ċ
        XW=X+XP
        YTOT=0.
        TMASS=0.
       DO 200 I=1,NEQ
        YF(I)=Y(I)/YSAVE(I)
        YTOT=YTOT+Y(I)
        YM(I)=Y(I)+MWU(I)
        YMI(I) = YM(I)
        TMASS=TMASS+YM(I)
        YM(I)=YM(I)/YMSAVE(I)
200
        CONTINUE
        YM1(NEQ1)=Y(NEQ1)
С
С
          CALCULATE THE MEAN MOLECULAR WEIGHT OF THE SLICK.
С
        WMEANS=0.
       DO 210 I=1,NEQ
        WMEANS=WMEANS+MWU(I) +Y(I)/YTOT
210
        CONTINUE
        LINE=LINE+1
      WRITE (IOU,220) X,LINE
FORMAT(2X,'TIME = ',1PE8.1,' HOURS, MASS FRACTION OF EACH
1 CUT REMAINING:',65X,I3)
WRITE (IOU,230) (YM(I),I=1.NEQ)
FORMAT(14(1X,1PE8.1))
CHECK=TMASS+Y(NEQ2)+Y(NEQ3)
WRITE (IOU 240) THES Y(NEQ2) Y(NEQ3)
220
230
       WRITE (IOU, 240) TMÁSS, Y(NEQ2), Y(NEQ3), CHECK
FORMAT(2X, 'MASS REMAINING = ', 1PE10.3, ', MASS DISPERSED
240
      1 = ',1PE10.3,', MASS EVAPORATED = ',1PE10.3,
2, SUM = ',1PE10.3)
        WRITE (IPU, 250) NEQ1
       FORMAT(I5)
WRITE (IPU,260) X,(YM1(I),I=1,NEQ1)
FORMAT(10(1X,1PE10.3))
250
260
С
Ĉ
          WHEN THE FRACTION REMAINING OF COMPONENT I GETS LOW,
С
          SET ITS VAPOR PRESSURE AND MOLES EQUAL TO ZERO.
С
```
DO 270 I-ISTART, NEQ IF(YF(I).GT.1.0E-08) GO TO 270 IKEEP=I+1 VP(I)=0. Y(1)=0. 270 CONTINUE ISTART=IKEEP NFAST=IKEEP GONE(LINE)=TMASS/TSAVE ZP=Z+100. WRITE (IOU,280) GONE(LINE), Y(NEQ1), ZP, WMEANS FORMAT(2X, 'FRACTION (BASED ON MASS) REMAINING IN THE SLICK 1=',1PE8.1,', AREA=',1PE8.1,' M++2, THICKNESS=' 280 2,1PE8.1,' CM, MOLE WT=',0PF5.1) С C WIO IS THE MOUSSE CALCULATION. 0000000 FIRST CHECK TO SEE IF MOUSSE HAS ALREADY BEEN FORMED. IF IT HAS, CALCULATE XMOU, WHICH IS A FAKE TIME. THIS WILL MATCH THE MOUSSE AND VISCOSITY DATA TO THE PREVIOUS CONDITIONS IF NOT. PROCEED IN THE NORMAL MANNER Ċ IF (MOUSWI.NE.1) GO TO 290 C3NEW=C4+WINDS+WINDS XMOU=X+(HOUMOU+C3SAVE)/C3NEW CALL WIO(XMOU, W, VTERM) GO TO 300 290 CALL WIO(X,W,VTERM) С VISCP1 IS THE VISCOSITY OF THE PARENT OIL WITH NO WATER Ċ С INCORPORATED. VISCPI IS IN CENTIPOISE, FEVAP IS THE FRACTION OF OIL EVAPORATED. NOTE THAT FEVAP IS NOT 00000000000 1 - (FRACTION REMAINING) BECAUSE DISPERSION LOSSES WOULD BE INCLUDED. THE FRACTION EVAPORATED MUST CORRECT FOR THE LOSS DUE TO DISPERSION. ***************** WE MIGHT WANT TO CHANGE TO A BETTER FEVAP CALCULATION LATER. č **************** Ċ 300 FEVAP=(1.-GONE(LINE))/YM(NEQ)+FE VISCP1=VSLEAD+EXP(MK4+FEVAP) С C VTERM IS THE VISCOSITY MULTIPLIER FROM THE MOUSSE č CALCULATION. С VISCP=VISCP1+VTERM С С CALCULATE THE BULK SPGR. С BSPGR=0. DO 310 I=ISTART, NEQ BSPGR=BSPGR+SPGR(I) +Y(I)/YTOT 310 CONTINUE VISQT=SQRT(VISCP/10.)

```
С
Ċ
          CALCULATE THE DISPERSION FACTOR.
С
        FB=1./(1.+KB+VISQT+Z+STEN/0.024)
        DISPER=FRACTS+FB
      WRITE (IOU, 320) W, VISCP, DISPER
FORMAT(2X, 'WEIGHT FRACTION WATER IN OIL = ', 1PEB.1.', VIS
1COSITY = ', 1PEB.1, ' CENTIPOISE, DISPERSION TERM = '
320
       2,1PE8.1,' WEIGHT FRACTION/HR')
        CVOLUM=Y(NEQ1)+Z
        TBBL=CVOLUM/0.159
        CVOLUM=(1.0E+06)+CVOLUM
        CSPGR=TMASS/CVOLUM
        WAREA=(1.0E+06)+Z+CSPGR
        WDISP=WAREA+DISPER
        IF(INT.EQ.1) ERATE=0.
ERATE=ERATE/Y(NEQ1)
      WRITE (IOU, 330) WAREA, CSPGR, TBBL, WDISP, ERATE
FORMAT(2X, 'MASS/AREA=', 1PE8.1, 'GMS/M+M, SPGR='
1,1PE8.1,', TOTAL VOLUME=', 1PE8.1, 'BBL, DISPERSION='
2,1PE8.1,'GMS/M+M/HR, EVAP RATE=',1PE8.1,'GMS/M+M/HR')
330
С
          PRINT AN OUTPUT FILE FOR 80 COLUMN OUTPUT.
С
С
        DO 340 J=1,NEQ
        JCUT=J
        IF(YM(J).GT.0.5) GO TO 350
340
        CONTINUE
350
        DO 360 I=1,NEQ
        ICUT=I
        IF(YM(I).GT.0.01) GO TO 370
360
        CONTINUE
        IX=X
370
        IW=W+100.
        WRITE (ITY, 380) IX, TBBL, CSPGR, Y(NEQ1), ZP, IW, WDISP
       1, ERATE, WAREA, ICUT, JCUT
380
       FORMAT(1X, I3, 1PE8.1, 0PF5.2, 2(1PE8.1), 1X, I3
       1,3(1PE8.1),I2,I3)
        WRITE (IOU, 70)
С
С
           INCREASE XP TO 10 HOURS AFTER 50 HOURS OF WEATHERING.
С
        GO TO (390,400), NSS
390
        IF(X.LT.50.) GO TO 400
        NSS=2
        XP=10.
С
           TAKE A STEP IN TIME
С
С
400
        XARG=X
        DO 410 I=1,NEQ3
        YARG(I)=Y(I)
410
        CONTÍNÚE
С
C
C
           INT IS A SWITCH TO INDICATE THAT THE INTEGRATION WAS
           INITIATED.
Ċ
        INT=2
        CALL FXYZ (XARG, YARG, K1, NEQ)
        XARG=X+H2
```

```
DO 420 I=1.NEQ3
        YARG(I)=Y(I)+H*K1(I)/2.
420
        CONTINUE
С
С
          SAVE THE EVAPORATION RATE FROM THE FIRST TIME
č
c
          THE DERIVATIVES ARE CALCULATED.
        ERATE=K1(NEQ3)
        CALL FXYZ(XARG, YARG, K2, NEQ)
        DO 430 I=1,NEQ3
        YARG(I)=Y(I)+H*K2(I)/2.
430
        CONTINUE
        CALL FXYZ(XARG, YARG, K3, NEQ)
        XARG=X+H
        DO 440 I=1,NEQ3
        YARG(I)=Y(I)+H*K3(I)
440
        CONTÌNÚE
        CALL FXYZ(XARG, YARG, K4, NEQ)
       DO 450 I=1,NEQ3
        Y(I)=Y(I)+H*(K1(I)+2.*(K2(I)+K3(I))+K4(I))/6.
450
       CONTINUE
С
          IF 10 PER CENT BY MOLES OR LESS OF THE SLICK IS LEFT, STOP
0000
          THE CALCULATION BECAUSE STRANGE THINGS HAPPEN CLOSE TO
          ZERO OIL.
       REMAIN=0.
       DO 460 I=1,NEQ
REMAIN-REMAIN+Y(I)
460
        CONTINUE
        TEST=REMAIN/MOLSAV
        IF(TEST.GT.0.1) GO TO 510
       NOUIT=1
        TYPE 470
470
        FORMAT(1X, 'THE SLICK HAS DECREASED TO 10% OF THE ORIGINAL MOLES.')
        TYPE 480
       FORMAT(1X,'THE INTEGRATION WILL BE STOPPED HERE.')
WRITE (IOU,490)
FORMAT(/,1X,'THE SLICK (MOLES) HAS DECREASED TO 10%
OR LESS, THEREFORE THE CALCULATION WAS STOPPED.')
480
490
      1 OR LESS,
       WRITE (ITY, 500)
FORMAT(/,1X,'SLICK DECREASED TO 10% MASS **STOP**')
500
       GO TO 550
С
С
          RECALCULATE THE OVER-ALL MASS-TRANSFER COEFFICIENTS OUTSIDE
000000000000
          THE DERIVATIVE SUBROUTINE. THE DIAMETER DEPENDENCE IS VERY
          SLOW. TERM2 IS THE OLD DIA++(-0.11). SO DIVIDE THE OLD
          COEFFICIENT BY TERM2 AND MULTIPLY IN THE NEW ONE.
          WHEN YOU CHANGE THE WIND SPEED WITH RESPECT TO TIME, CHANGE THE MASS-TRANSFER COEFFICIENT HERE. DIVIDE
          OUT THE OLD WIND TERM AND MULTIPLY IN THE NEW ONE.
          ALSO, IF THE TEMPERATURE CHANGES, RECALCULATE THE VAPOR PRESSURE HERE. THIS APPLIES ONLY TO MACKAY
          AND MATSUGU.
С
       GO TO (540,520,540), KMTC
DIA=SQRT(Y(NEQ1)/0.785)
TNEW=DIA++(-0.11)
510
520
       ADJUST=TNEW/TERM2
```

```
DO 530 I=1,NEQ
       MTC(I)=MTC(I) + ADJUST
       CONTINUE
530
        TERM2=TNEW
С
č
          CHECK TO SEE IF THE INTEGRATION IS COMPLETED.
С
540
       IF(X.GE.X2) GO TO 550
       X=XARG
С
          CHECK TO SEE IS THE FIRST NON-ZERO MOLES HAS FALLEN TO
0.01 OF ITS STARTING VALUE. IF IT HAS, RECALCULATE THE
STEP SIZE ON THE NEXT NON-ZERO COMPONENT. NOTE THAT
С
00000
          A COMPONENT IS NOT ZEROED UNTIL ITS MOLE NUMBER HAS
          FALLEN TO LESS THAN 1.0E-08.
       TEST=ABS(Y(NFAST)/YOLD)
       IF(TEST.LT.0.01) GO TO 80
       GO TO 190
550
       NSTART=NDEL+1
       WRITE (IOU, 560) NSTART
Format(/,1x,'The cut numbering begins with',13,' based on
560
      1 THE ORIGINAL CUT NUMBERS',/)
        LINE=LINE+1
      WRITE (IOU, 570) X, LINE
FORMAT(1X, 'THE FINAL MASS FRACTIONS FOR THE SLICK AT '
1, 1988.1, 'HOURS ARE: ', 65X, I3)
570
       HOUMOU=X
        TMASS=0.
       DO 580 I=1,NEQ
YM(I)=Y(I)+MWU(I)
       TMASS=TMASS+YM(I)
        YM1(I)=YM(I)
        YM(Ì)=YM(Ì)/YMSAVE(I)
580
       CONTINUE
        YM1(NEQ1)=Y(NEQ1)
       GONE(LINE)=TMASS/TSAVE
       WRITE (IOU,40) (YM(I),I=1,NEQ)
WRITE (IPU,250) NEQ1
WRITE (IPU,260) X,(YM1(I),I=1,NEQ1)
WRITE (IPU,260) (GONE(I),I=1,LINE)
        ZP=Z+100.
       WRITE (IOU, 280) GONE(LINE), Y(NEQ1), ZP, WMEANS
       CHECK=TMASS+Y(NEQ2)+Y(NEQ3)
       WRITE (IOU, 240) TMÁSS, Y(NEQ2), Y(NEQ3), CHECK
       TME=TME+Y(NEQ3)
TMD=TMD+Y(NEQ2)
        FE=(Y(NEQ3)/TMASAV)+FE
       590
               •••••••**
      1....
       RETURN
        END
```

0000	SUBROUTINE VPIF(TEES,N) INCLUDE 'VARI.FOR'										
	THIS SUBROUTINE CALCULATES THE VAPOR PRESSURE OF THE CUTS AT A SPECIFIED TEMPERATURE, TEES. IT USES A SIMPSONS RULE INTEGRATION WITH 21 POINTS										
C	YI(X)=((1X)**0.38)/(X*X) DO 30 I=1,N TEE=TEES IF (TEE.LT.T10(I)) GO TO 10 TEE=TEE/TC(I) EX=EXP(-20*(TEE-B(I))**2) Y=-A(I)*(1TEE)/TEE-EX VP(I)=PC(I)*10.**Y										
10	GO TO 30 CONTINUE TR1=TEE/TC(I) TR2=T10(I)/TC(I) DH=(TR2-TR1)/20. RESULT=YI(TR1) TR=TR1 DO 20 L=1,10 TR=TR+DH RESULT=RESULT+4.*YI(TR) TR=TR+DH										
20	RESULT=RESULT+2.•YI(TR) CONTINUE TR=TR+DH RESULT=RESULT+4.•YI(TR) TR=TR+DH RESULT=DH+(RESULT+YI(TR))/3. P1=-4.33-HVAPZ(I)+RESULT/(1.987•TC(I)) VP(I)=FYP(P1)										
30	CONTINUE RETURN END										

```
SUBROUTINE FXYZ(XARG, MOLES1, KK, NEQ)
       REAL+4 MOLES1,KK
       INCLUDE 'VARI.FOR
       DIMENSION KK(30), MOLES1(30)
000000000
          THE VECTOR BEING INTEGRATED RESIDES IN MOLESI(I).
          POSITIONS I-1 THROUGH I-NEQ ARE THE PSEUDO COMPONENTS,
          POSITION NEQ1=NEQ+1 IS THE AREA.
POSITION NEQ2=NEQ+2 IS THE MASS LOST BY DISPERSION ALONE.
POSITION NEQ3=NEQ+3 IS THE MASS LOST BY EVAPORATION ALONE.
       SUM=0.
DO 10 I=1,NEQ
       SUM=SUM+MOLES1(I)
       CONTINUE
10
       DO 20 I=1.NEQ
C
C
          CALCULATE THE MOLE DERIVATIVES.
č
       TMPVP(I)=MTC(I)*MOLES1(NEQ1)*VP(I)*MOLES1(I)/SUM
TMPDS(I)=DISPER*MOLES1(I)
       KK(I)=TMPVP(I)+TMPDS(I)
KK(I)=-KK(I)
20
       CONTÍNUE
       VOLLU=0.
       DO 30 I=1,NEQ
       VOLLU=VOLLU+MOLES1(I)/RHO(I)
       CONTINUE
30
c
c
          CALCULATE THE AREA DERIVATIVE.
С
       Z=VOLLU/MOLES1(NEQ1)
       KK(NEQ1)=(5.4E+05)*(Z**1.33)*MOLES1(NEQ1)**0.33
KK(NEQ1)=SPREAD*KK(NEQ1)*SPRFAC
CCCC
          CALCULATE THE MASS LOST FROM THE SLICK DUE TO
          EVAPORATION ALONE AND THEN DISPERSION ALONE.
       KK(NEQ2)=0.
       KK (NEQ3)=0.
       DO 40 I=1,NEQ
       KK(NEQ3)=KK(NEQ3)+TMPVP(I)*MWU(I)
KK(NEQ2)=KK(NEQ2)+TMPDS(I)*MWU(I)
40
       CONTINUÉ
       RETURN
        END
```

SUBROUTINE WIO(TIME, W, VTERM) INCLUDE 'VARI . FOR' WFUNC(W)=(1.0-C2+W)+EXP(-2.5+W/(1.0-C1+W)) VIS(W)=EXP(2.5+W/(1.0-C1+W)) DATA WSAVE,C4SAVE/-1.,-1./ С THIS IS THE WATER-IN-OIL (MOUSSE) ROUTINE. W IS THE FRACTIONAL WATER CONTENT IN THE OIL. WINDS IS THE WIND SPEED IN KNOTS. TIME IS IN HOURS. C1 IS A VISCOSITY CONSTANT = 0.65 C2 IS AN OIL-COALESCING CONSTANT AND IS OIL DEPENDENT, AND IS THE INVERSE OF THE MAXIMUM WEIGHT FRACTION WATER IN OIL. C3 IS A WATER INCORPORATION RATE (1./HR). USUALLY 0.01+U+U THE PREDICTION EQUATION FOR W IS IMPLICIT AND IS SOLVED BY TRIAL AND ERROR. REFERENCE: CHAPTER 4 BY MACKAY IN OIL SPILL PROCESSES AND MODELS. DECEMBER, 1981 IERR IS THE ERROR CODE. IERR=1 IS A NORMAL EXIT, IERR=2 IS A PROBLEM IN THE TRIAL-AND-ERROR ROUTINE, IERR=3 IS A STEADY-STATE MOUSSE EXIT. IF THE OIL DOES NOT FORM MOUSSE, C2 WAS SET TO -1. Ċ IF(C2.GT.0.) GO TO 10 С NO MOUSSE FOR THIS OIL, SET TERMS AND RETURN. С С W=0. VTERM=1. GO TO 90 IERR=1 10 С Ĉ CHECK TO SEE IF THE WIND OR INCORPORATION RATE CONSTANT С CHANGED. С IF (WINDS.EQ.WSAVE.AND.C4.EQ.C4SAVE) GO TO 20 WSAVE=WINDS C4SAVE=C4 U2=WINDS+WINDS C3=C4+U2 20 EX=C3+TIME IF(EX.GT.20.) GO TO 80 TEST=EXP(-EX) С С BRACKET THE TIME WITH TWO VALUES OF W. С W=0 . WMAX=1./C2 WSTEP=WMAX/10. W=W+WSTEP 30 TRY=WFUNC(W) IF(TRY.LT.TEST) GO TO 40

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DEVELOPMENT OF A PREDICTIVE MODEL FOR THE WEATHERING OF OIL IN THE PRESENCE OF SEA ICE

by

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ABSTRACT

The objective of this program has been to develop a predictive model that describes the qualitative and quantitative weathering of spilled oil and refined petroleum products in the presence of first-year and multi-year ice. To achieve this objective and verify model predictions, cold-room and field experiments were performed to provide suitable data for describing time-series changes in the physical and chemical properties of oil spilled in the presence of first-year and multi-year ice in various configurations. For modeling purposes, fresh and weathered crude oil were characterized as distillable cut fractions (i.e., pseudocomponents). In addition, specific mechanisms for enhancing the transport of spilled oil components to the benthic environment were recognized during this program, and additional studies were completed to investigate these potentially significant dispersion/dissolution processes. Results from these studies and the development of the computer model provide a significant contribution toward OCSEAP's goal of developing predictive capabilities for defining the magnitude of the impacts from OCS oil and gas activities to exposed Arctic and sub-Arctic biota.

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1. INTRODUCTION

Beginning in 1979, Science Applications Inc., now Science Applications International Corporation (SAIC), undertook the development of a computerdriven model for simulating the weathering behavior of crude oil and refined petroleum products released in open ocean environments (Payne et al., 1984a). The weathering model included algorithms describing evaporation, dissolution, water-in-oil emulsification, spreading of oil on the sea surface, and predicted percent oil remaining in a slick as a function of open ocean weathering condi-The model algorithms are based on physical properties data and the tions. physical/chemical partitioning behavior of oil driven by dynamic equilibria and mass transfer coefficients. Model verification was completed by outdoor subarctic wave tank studies in which quantitative data on evaporation, dissolution, water-in-oil emulsification, microbial degradation, and adsorption onto suspended particulate material were obtained and compared with the modelpredicted values for the first three processes. As a logical extension of that SAIC undertook a modeling and experimental program to evaluate speciprogram, fic changes in the physical and chemical properties of oil due to weathering in arctic environments in the presence of first-year and multi-year sea ice.

This report contains the results of the oil-in-ice studies and describes the model development or modifications to the existing Open Ocean Oil-Weathering Model Code that enable predictions to be made for oil weathering behavior in the presence of first-year and multi-year ice. The following section (2) is an Executive Summary which includes conclusions and implications from these studies that are relevant for OCSEAP's purpose of analyzing OCS oil and gas development in the Arctic.

Background information is presented in Section 3 describing the structure and characteristics of first-year and multi-year ice and their interactions with oil. Much of this existing information on the behavior of oil in ice is based on observations from spills under simulated blowout conditions (e.g., DOME, 1981; Nelson and Allen, 1981). Although results from such cited studies are relevant to discussions of oil-in-ice behavior (and possible spill

cleanup methods), no previous attempts have been made to measure specific mass transfer rates and the changes in physical and chemical properties of oil due to weathering processes as are required for predictive modeling.

Section 4 contains information on controlled coldroom wavetank experithat were undertaken to quantify changes in the physical and chemical ments properties of oil spilled in the presence of simulated first-year and multi year ice. The experiments were designed to generate data necessary for predicting rates of oil dispersion, dissolution, evaporation, and water-in-oil emulsification in arctic environments where sea ice is an important, if not controlling, factor in oil weathering. Descriptions are presented of not only frazil and slush ice formation under turbulent conditions, but also how columnar ice growth in less turbulent regimes will ultimately affect the qualitative and quantitative behavior of whole crude oil released into "first-year" and "multi-year" ice systems. The construction and utilization of the experimental flow-through wave tank and the cold room at the NOAA Kasitsna Bay laboratory are also discussed. Specifically, the ability to simulate not only the structure and behavior of first-year and multi-year ice, but also the interactions of spilled oil with sea ice in the scaled-down wave tank (i.e., relative to natural spill conditions) was a major concern for the wave tank studies. Consequently, a limited field data collection and observation program was undertaken in the Chukchi Sea in February/March 1984 to provide additional information on real and simulated "first-year" ice properties and also on possible scaling problems. In this effort, first-year ice samples were colthe Chukchi Sea to compare crystal structure and salinity lected in characteristics of the field ice with those of simulated "first-year" wave tank Conductivity (salinity) and temperature measurements were obtained for ice. the first-year ice and subsurface water in the field and compared with equivalent values from the wave tank studies. The results of these and other "scaling" field studies are presented in Section 4.

Section 5 contains information on a more extensive field effort that was undertaken in the Chukchi Sea in February/March 1985. Based on information in the open literature as well as the results of the wave tank studies in Section 4, this field effort was designed to investigate the possible transport

of dissolved hydrocarbon compounds from an oil spill in open, re- freezing lead systems to benthic environments beneath surface ice fields. Descriptions of the laboratory and field efforts as well as the experimental results and their possible environmental relevance are presented in this section.

Section 6 presents a discussion of the endproduct numerical model that has been generated to predict additional weathering behavior of oil in the presence of first-year and multi-year sea ice. Analytical data and qualitative (descriptive) information derived from both the Kasitsna Bay wave tank experiments and the Chukchi Sea field programs were taken into account and incorporated into the on-going development of NOAA's Oil Weathering Model. In addition to the wave tank and field efforts, controlled diffusion experiments were performed in the laboratory to measure component-specific dissolution rates from an oil slick into a well-stirred water column at ambient (cold water) conditions. The results were used to generate partition coefficients for individual true boiling point distillate oil cuts. These results are also presented in Section 6, and they were taken into account for the oil-in-ice model.

By virtue of this building process, the oil-in-ice model is similar to, and compatible with, the previously developed open-ocean oil-weathering model (CUTVP2). Both models are based on a pseudo-component characterization of the parent crude oil or refined product, and they calculate a material balance after specified periods of exposure. Additional modifications to the oil weathering code were made during the execution of this program to allow predictions regarding changes in physical properties (e.g., rheological) of the oil using a "fractioned weathered" parameter (as defined by Dr. Donald Mackay of the University of Toronto). The algorithms required for developing the new oil-in-first-year and oil-in-multi-year ice model code are described in this section.

In addition to the discussion of the model, Section 6 also includes a brief description of an application of the model to a real-world spill-of-opportunity. On 21 January 1984 the M/V Cepheus went aground on the west side of Knik Arm almost due west of Carin Point near Anchorage, AK. Approximately 200,000 gallons of JP-5 fuel were released into the water. SAIC collected and

performed appropriate analyses of oil samples from the <u>Cepheus</u>. These analytical results were then introduced into the code for the model, and the output was provided to NOAA HAZMAT in support of their spill response effort.

Section 7 describes the relevant Quality Assurance/Quality Control (QA/QC) procedures employed and the results obtained during the completion of this program. It includes a description of instrument calibration frequency, the levels of precision and accuracy obtained as reflected in replicate analyses, spike and recovery determinations, method and system blanks, and results from analyses of interim reference materials supplied by the NOAA/NMF QA lab in Seattle. Limits of detection and methods used to define them are also presented.

Section 8 contains the Bibliography for all cited references, and Appendices A & B present FORTRAN code descriptions for component specific dissolution from oil slicks and dispersed oil droplets, respectively.

A User's Guide for the oil-in-ice model is provided as a separate document. This guide includes information on topics such as model access, model prompts and model output, and contains a complete listing of the NOAA/ SAIC Oil Ice-Weathering Code. 2. EXECUTIVE SUMMARY--CONCLUSIONS AND IMPLICATIONS RELEVANT TO OCSEAP'S ANALYSIS OF OUTER CONTINENTAL SHELF OIL AND GAS DEVELOPMENT IN THE ARCTIC

The ultimate objective of this research effort was the development of a computer model that predicts the chemical and physical weathering behavior of oil released in the presence of first-year and multi-year sea ice. Several different oil-ice configurations have been incorporated into the model, includoil released on top of or under first-year or multi-year ice; 2) oil ing: 1) released in melting first-year or multi-year ice; and 3) oil weathering in the The third option represents the code from the previous NOAA absence of ice. sponsored open-ocean oil weathering model. In addition, bounding calculations have been performed to estimate dissolved component-specific concentrations resulting from oil released in first-year or multi-year ice lead systems that are subject to refreezing and thawing events. Additional model development completed during this program included the encoding of algorithms to use data from the NOAA oil weathering model for generating bulk physical properties of oil based on the Mackay "fraction weathered" formulation. The model uses a pseudocomponent approach based on distillate cut fractions to characterize and generate physical properties for the spilled product under environmental conditions specified by the model user. Therefore, the model can consider any specified whole crude oil or refined petroleum product (e.g., fuel oil, gasoline, aircraft fuel, Bunker C, etc.).

Data were collected during both wave tank experiments and field sampling programs in the Chukchi Sea to assist in the development and verification of the oil-in-ice weathering model. Data obtained from both wave tank experiments and field observations yielded comparable results when the inherent scaling differences between these two regimes are considered. For example, the similarities in sea ice behavior and properties between wave tank and field studies included the mechanisms for ice growth and decay sequences of ice types (i.e., frazil, grease, and columnar ice), ice crystal structures, general ice morphology (e.g., smooth first-year ice versus ridge and keel systems in pack and/or multi-year ice), and vertical salinity profiles in the ice and water column layers. These similarities between the wave tank and field observations suggest that data derived from the wave tank studies for oil-ice interactions
are relevant to anticipated oil-ice interactions in field situations. Output from the model was used in support of a spill response effort by NOAA HAZMAT for a spill-of-opportunity when the <u>M/V Cepheus</u> went aground near Anchorage, AK and released approximately 200,000 gallons of JP-5 fuel oil into ice-covered waters. Results from the model output helped to predict rates of oil loss in the ice covered waters. However, time series samples of the spilled product could not be obtained because of the extremely dynamic nature of the ice and the transient behavior of the easily dispersed and volatile fuel oil. Thus, <u>field</u> verification of model predictions from an oil spill in ice-covered waters still awaits a future opportunity.

The oil-in-ice wave tank studies provided several findings that are important for predicting the weathering behavior of oil in the presence of first-year and/or multi-year sea ice. The significant findings are summarized in the following paragraphs.

One of the most important aspects of the oil-in-ice experiments was the role of ice morphology in controlling the rate and extent of stable waterin-oil emulsion formation. Melting first-year ice produced substantial amounts of slush ice and a water-in-oil emulsion of Prudhoe Bay crude oil containing to 60% water was formed within four hours of the onset of wave agitation in up this slush ice field. In contrast, rotting multi-year ice appeared to have a much lower tendency to produce a slush ice matrix during melting, and formation of the stable water-in-oil emulsions occurred over a relatively longer period of time. Therefore, data from the wave tank experiments suggest that the presence of a slush ice matrix and wave-generated turbulence promote the formation of stable water-in-oil emulsions. Emulsification presumably is the result of subjecting oil to microscale turbulence from the wave-induced grinding between slush ice crystals. Rapid formation of stable water-in-oil emulsions is important to potential spill cleanup and containment approaches, and for in situ burning from considerations of the lowered combustability of water-in-oil emulsions. Furthermore, it was observed that these water-in-oil emulsions had a density (specific gravity) which was intermediate between slush ice and seawater, and that they tended to reside just below the surface of the slush ice

fields. Therefore, under actual spill conditions, emulsified oil in the presence of relatively thick slush ice (e.g., 10 cm) may be extremely difficult to locate or observe from helicopters or fixed-wind aircraft.

Wave-turbulence induced compression and pumping of oil onto the surface of pancake ice was also observed in the wave tank experiments. This surfaced oil can become trapped by ridges of frozen slush ice that form around the edges of the pancake ice surfaces. At the same time, wave turbulence in the broken ice fields simulated in the cold-room wave tanks was responsible for rapid and appreciable increases in concentrations of dispersed oil droplets in the water column due to enhanced dispersion. This resulted in significant increases of dissolved-component concentrations; however, in the presence of slush ice, this dispersion (and concomitant dissolution) quickly became selflimiting with the rapid onset of stable water-in-oil emulsions that were characterized by high in situ oil viscosities.

It is expected that the long-term dispersion behavior of oil under similar sea ice conditions in the field would be dependent on the nature and composition of the oil. For example, if a refined oil product was released into seawater in the presence of slush ice and minor levels of turbulence, then dispersion of the refined product might continue for longer periods of time than would be expected for a crude oil. Refined products (as opposed to crude oils) generally do not contain surface active compounds that are important for stabilizing water-in-oil emulsions. Thus, small scale turbulence generated by the grinding of ice crystals could actually enhance the dispersion of refined oil products. In turn, this could lead to elevated water column levels of dispersed oil droplets and also dissolved compounds (e.g., more water-soluble aromatic compounds) due to high surface to volume ratios inherent to small oil droplets.

The importance of modeling a well-stirred versus a diffusion controlled oil slab (pool) has been considered from a theoretical standpoint throughout the development of the existing NOAA oil weathering models. Wave tank experiments completed during this program have now demonstrated that the diffusion controlled mechanism must be incorporated into future predictions of

rates of evaporation from emulsified slicks and from thicker pools of oil stranded on floating ice surfaces. Diffusion controlled evaporation of lower molecular weight components from oil pools was verified for the first time during the oil on ice weathering experiments. Significant differences in the retention of lower molecular weight components occured as a function of depth in the oil pool. In wave tank experiments involving interactions between oil and slush ice, water-in-oil emulsification occurred before significant evaporative losses of lower molecular weight components could occur. This situation different from that encountered during open ocean oil weathering scenarios is where evaporative losses of lower molecular weight components from surface oil not only relatively rapid but also important to the subsequent behavior of are the oil. Thus, once a stable emulsion has formed in the presence of first-year and agitation, delayed evaporative losses of lower molecular weight compoice nents would be expected because evaporation from these emulsions is a diffusion controlled process. Under such conditions, modeling the evaporation and dissolution behavior of components from the water-in-oil emulsion would require a combination of well-stirred and diffusion controlled algorithms.

Evaporation of lower molecular components from oil confined within channels in sea ice was also observed during wave tank experiments. brine Migration of oil in brine channels is severely retarded due to high viscosities of oils that are maintained at low (<0°C) temperatures. Furthermore, temperature gradients can exist within thick ice systems between the upper ice surface that is at or near the ambient temperature of the overlying air and the lower ice surface that is usually at thermal equilibrium with the underlying sea-Therefore, migration rates for oil in brine channels may also vary as a water. function of depth in the ice field. Nevertheless, dissolved gases can still be released from the oil, which results in a selective partitioning of lower molecular weight components while the oil is still trapped in the brine channels. However, this phenomenon is probably not important for modeling oil weathering in the presence of sea ice because selective component evaporation would only affect the upper-most portions of oil in the brine channels. The actual release of the majority of the volatile gases from the trapped oil would be retarded until the bulk oil reached the surface of the ice or water.

In addition to these studies of direct interactions between oil and sea ice, a mechanism for transporting dissolved hydrocarbons to bottom waters in the presence of sea ice was investigated in this program. During the initial stages of sea ice formation (i.e., frazil, grease and/or columnar ice growth), brine is extruded from the ice to the adjacent seawater, which results in a localized increase in the salinity (and, thus, density) of this water. In the absence of turbulent mixing and dilution, the higher density water can sink as a relatively discrete mass in a process known as brine cabling. Hydrocarbons from a surface oil spill that dissolve in the water mass (e.g., watersoluble, lower molecular weight aromatic compounds) can be transported along with the salt toward the bottom by such processes with minimal dilution. Preliminary field studies performed during February/March 1984 in the Chukchi Sea, and experimental wave tank studies, suggested a transport mechanism for dissolved oil compounds. An experimental spill with a combined aromatic compound cocktail was performed in an open but refreezing lead system near Pt. Franklin in the Chukchi Sea in February/March 1985. Subsequent analyses of water samples collected from beneath the surface ice yielded measurable concentrations of both benzene and toluene at selected sampling sites and depths. Furthermore, the actual distributions of these concentrations could be explained by a brine cabling scenario that was compatible with accompanying near bottom current and hydrographic measurements (i.e., salinity, temperature and density). Therefore, results of this field effort demonstrated the transport of dissolved hydrocarbon compounds to bottom waters by brine cabling. This process has important implications for potential spills from drilling activities during periods of ice-growth or from accidential oil or refined product releases from tankers or barges in open lead systems.

3. BACKGROUND INFORMATION AND RELEVANCE TO OCSEAP'S NEEDS

3.1 FORMATION CHARACTERISTICS OF ICE IN SEAWATER

Formation of ice in seawater requires in situ temperatures below the freezing point of the water. However, the physical conditions of the water at the time of the freezing will determine the nature of the ice formed. Depending on these conditions, one or more of the following initial ice types can result: 1) frazil ice, 2) slush ice and 3) columnar ice (Martin, 1979). Although each type of ice has unique characteristics, all three are characterized by having high surface salinities due to the exclusion of sea salts during the freezing process.

In general, the first type of sea ice formed is frazil ice. It is generated directly from supercooled seawater that is subjected to turbulence (e.g., from wind and/or wave action) at a sufficient level that direct, smooth surface ice freezing at the air-sea interface does not occur. Studies of the morphology of frazil crystals formed in saline solutions indicate that their shapes can include either two-dimensional circular discs (Martin, 1981a) or three-dimensional configurations with thin fingers and plates protruding in directions other than the main crystal axis (Hanley and Tsang, 1984). Individual saline frazil crystals are approximately 1×10^{-3} meters in diameter and 1-10 x 10^{-6} meters in thickness (Martin and Kauffman, 1981). They are also surrounded by brine films that are generated in the freezing process. Due to this salt rejection, the brine immediately surrounding the crystal has a higher salinity than that of the surrounding water. This results in a lower freezing point for the water around the crystal, and imparts an inherent resistance to continued growth of the crystal (Hanley and Tsang, 1984). Under appropriate conditions, frazil crystals may be generated throughout a water column. Once formed, they will rise to the surface since their densities are less than that of the ambient seawater.

Martin (1981a) summarizes four situations that can produce the formation of frazil ice crystals in seawater. First, cold winds blowing across regions of open water (e.g., polynyas adjacent to shorelines or leads further

out to sea) can result in frazil formation. If the open water has sufficient fetch, Langmuir circulation patterns can "herd" frazil ice into streaks parallel to the direction of the wind and/or cause the frazil to accumulate against some downwind, solid object (e.g., the edge of a lead or a shoreline). Second, seawater adjacent to the face of an ice shelf or iceberg can generate frazil crystals by either direct cooling of the water or upward movement of a cold, deep seawater mass (parcel) to a depth where pressure effects (i.e., freezing point depression) result in the water being cooled below its freezing point. Third, frazil crystals may form between water masses of different salinities (e.g., when a layer of fresh melt water at its freezing point lies over a layer of seawater at its freezing point). And, fourth, slow drainage of cold dense brine from sea ice can lead to the formation of frazil ice layers beneath the ice.

Regardless of the mechanism responsible for the initiation of frazil formation, frazil crystals frequently accumulate in masses at the air-water interface or under-ice surface. This can be due to either the inherent buoyancy of the crystals themselves (i.e., they rise to surfaces) or wind and current advection phenomena. Such accumulations of frazil crystals are known as grease (or slush) ice. Armstrong et al. (1966) define grease ice as "a later stage of freezing than frazil ice, where the spicules and plates of ice have coagulated to form a thick soupy layer on the surface of the water". Under the influence of wave or wind agitation, the original structure of the source frazil crystals may be degraded in a grease ice field by turbulent grinding action. Martin (1981b) notes that grease ice consists of approximately 3 parts ice to 7 parts seawater (by mass). In particular, grease ice accumulations are known to occur against the downwind edges of leads that are perpendicular to the direction of the wind (see Figure 3-1; Bauer and Martin, 1983) and in convergence zones of Langmuir circulation patterns that are parallel to the direction of the wind (Pollard, 1977). Areas of frazil and grease ice formation as described in the preceding several paragraphs are common in marginal seas such as the Bering and Chukchi Seas (Martin and Kauffman, 1981) and the Weddell Sea (Gill, 1973). Grease ice formation was observed in open leads off Point Barrow, Alaska during the field efforts in this NOAA program.



Figure 3-1.--Schematic Overview Depicting the Growth and Downwind Accumulation of Grease Ice in an Open Lead. The dead zone denotes area where ice thickness dampens wave turbulence and internal circulation within ice. (Adapted from Bauer and Martin, 1983.)

The second type of ice that can be formed in seawater is slush ice. Martin (1979) states that it is generated in surface waters when blowing snow accompanies wind. If the ambient air and water temperatures are sufficiently low, the snow will persist in the water to form a mixture of snow crystals and seawater. From a practical standpoint, however, it is difficult to distinguish snow/seawater slush from accumulations of frazil crystals (i.e., grease ice) in surface waters. Therefore, for the purposes of this report the terms slush ice and grease ice will be used interchangeably for a common ice type.

Columnar ice consists of long, individual crystals or platelets that have a vertical orientation. Figure 3-2 shows a portion of an ice fragment containing columnar ice that was collected from ice fields in the Chukchi Sea during this program. The common vertical planar orientation of the ice crystals is illustrated in the figure. Columnar ice growth may continue up to depths of approximately 1-2 meters during the ice growing season (Martin, 1979; Martin, 1984, personal communication). In typical ice cores the lower 10-40 mm of columnar ice is called the skeletal layer. This layer charactristically is highly porous and fragile, which will facilitate the adsorption or incorporation of any oil that might be released or driven beneath the ice layer (Martin, 1979).

A physical requirement for the formation of columnar ice is the existence of calm or quiescent conditions in the water column. Thus, agitation of the water due to wave or wind action must be sufficiently small to allow for the orderly, non-random vertical growth of columnar ice crystals. Such conditions may result from either an absence of both wave and wind action or an induced "damping" of these turbulent forces by an overlying layer of a more viscous material such as grease or slush ice (or oil as described later in this study).

3.2 CHARACTERISTICS OF FIRST-YEAR ICE

By definition, first-year ice has existed only for the current growth season. It may comprise any or all of the ice types described in Section 3.1 (i.e., congealed frazil ice and/or grease ice, slush ice, or columnar ice).



Figure 3-2.--Columnar Ice in the Chukchi Sea.

First-year ice usually grows to a thickness of approximately 1-2 meters, with a predominantly columnar ice crystal structure beneath a near-surface layer of congealed frazil or grease ice (Martin, 1979).

The salinity of sea ice varies with the age and degree of exposure to changing thermal regimes (Weeks and Weller, 1984). As mentioned previously, one feature common to the formation of all first-year ice forms is the occurrence of high salt concentrations on the surface due to rejection of sea salts during the freezing process. The resulting frozen surface brine can crystallize into small (20-50 mm) salt "flowers" with salinities ranging from 45-95 ppt (Martin, 1979). Salt "flowers" have been observed in field samples of ice from the Beaufort Sea (Martin, 1979) and the Chukchi Sea (this study, see Section 4.3), and they were also generated in the artificial "first-year" ice growth wave tank experiments summarized in this report (Sections 4.2.1 and 4.4.1). The high surface ice salinities due to brine rejection determine not only subsequent surface properties of the ice but also contribute to the formation and propagation of brine channels through the ice. As noted in Martin (1979), brine channels form between crystal facies of the ice with channel diameters up to 10 mm. Smaller feeder channels run diagonally between platelet boundaries. Development of brine channels in first-year ice can occur throughout the growth season, although the size and spatial frequency of the channels increases as the ice warms. The most extensive development of brine channels occurs in the spring when air and ice temperatures increase toward the freezing point. The presence of brine channels represents an important mechanism for the vertical migration of oil spilled underneath first-year ice, and was investigated during the wave tank studies described in Section 4.2.2.

Melting of first-year ice may occur in the following sequence: 1) ice warm-up and brine drainage; 2) formation of surface melt ponds with increasing levels of solar radiation; and 3) decomposition into slush and broken ice (Martin, 1979). As the surface layers of the ice are heated, the highly saline surface ice melts and forms liquid brine pools. Brine drainage channels are then formed in the surface ice layers with interior temperatures greater than

-4°C. These brine channels eventually extend throughout the depth of the ice floe, and represent a major mechanism for the vertical (downward) flux of salt and the upward flux of entrapped oil if present (see Section 4.2.2).

In the months of June and July in the Arctic, sufficient solar radiation is available to melt the surface saline layer of first-year ice. As the pond water absorbs more heat, this ice melt tends to form large ponds that gradually expand both horizontally and vertically in the ice. This tendency toward radial expansion may also be enhanced if oil lenses are present in the ice. Once an oil lens is liberated from the ice, the oil floats to the surface of the melt pond. Thermal convection from the heating of this dark surface oil promotes even more rapid melting of the surrounding ice, with an accompanying expansion of the original pond size (Martin, 1979; NORCOR, 1975). Melting of ice that has been advected to the marginal ice zone is also promoted by interaction with warmer water, and melting of ice along the northern coastal zone in the Beaufort Sea can be promoted by river overflow in the late spring and early summer.

3.3 CHARACTERISTICS OF MULTI-YEAR ICE

Multi-year ice describes ice that has survived for more than one growth season. Since this ice may have been subjected to several partial thaw and refreeze cycles, the brine rejection process will have had multiple opportunities to be expressed (Weeks and Weller, 1984). Therefore, multi-year ice may be characterized by lower salinities, as well as lower abundances of internal brine channels than in first-year ice.

Multi-year ice occurs primarily in offshore regions that are not stabilized by attachment to shorelines (see Section 3.4). Ice in offshore regions normally is in constant motion, resulting in repeated breaking and reworking of the ice and the formation of surface and bottom ridge systems and rubble fields surrounded by refrozen first-year ice leads. Therefore, multi-year ice is usually characterized by much greater bottom relief than first-year ice (Kovacs, 1977; Ackley et al., 1974). Due to this greater bottom relief, multi-year ice is more likely than first-year ice to "feel" water

currents moving beneath the ice. This will lead to a greater tendency for multi-year ice to be set in motion by currents, with an accompanying increased tendency for fracturing and breakup resulting in the formation of offshore open leads. First-year ice then forms when newly opened water leads in the multi-year ice field refreeze. Therefore, multi-year ice fields normally consist of a combination of multi-year and first-year ice. Since offshore open water leads can occur in multi-year ice fields (as described here), the phenomenon of brine cabling (see Section 3.5.2) is relevant to multi-year ice fields as well as first-year ice fields. The higher bottom relief of multi-year ice can also influence the character of the water currents beneath the ice by causing increased eddy turbulence due to bottom ice roughness. This can enhance the general mixing properties of the water, which will become important in explaining hydrocarbon distributions observed in the field brine cabling study in Section 5.3. Independent of the brine cabling phenomenon, the higher relief on the underside of multi-year ice can also be important for direct entrapment of oil released or driven beneath ice surfaces (see Section 3.5.1.3).

3.4 NATURAL ICE FORMATIONS IN ALASKAN ARCTIC MARINE REGIONS AND THEIR RELATION TO BOTTOM MORPHOLOGY

Relative to the shoreline on the northern coast of Alaska, three zones of ice cover occur: (1) the fast ice zone; (2) the pack ice zone; and (3) the area of intersection between the two zones (Reimnitz et al., 1978). A schematic representation of these zones is presented in Figure 3-3. Figure 3-4 illustrates the formation sequence for ice types that can occur in these different zones.

For the most part, the fast ice zone includes floating and bottom-fast ice that has formed near the shore each year, although it may also include occasional multi-year ice floes and/or remnants of grounded ridges. Fast ice is subject to movement and deformation by winds during the first few months of its formation. Eventually, however, it becomes immobilized and is usually protected by the shore on one side and grounded fast ice ridges on the other. The fast ice zone normally tends to be relatively flat and undeformed since the initial movement and deformation phases occur for only a relatively short time during its formation.



Figure 3-3.--Seasonal Development of Ice Zonation in Relation to Bottom Morphology. (Adapted by Tau Rho Alpha, from Reimnitz et al., 1977.)



Figure 3-4.--Sea-ice Terminology in Genetic Sequence (Weeks, 1978).

The zone of seasonal pack ice is further offshore from the fast ice, and can contain a substantial portion of multi-year ice. Since the seasonal pack ice is not directly attached to the shore, winds and water currents tend to keep it in almost constant motion. Cracks frequently open in pack ice to form leads that quickly freeze over with thin layers of first-year ice. The latter phenomenon is one reason that pack ice normally comprises some mixture of first-year and multi-year ice (see Section 3.3). It is also possible to have additional growth of columnar ice (i.e., first-year ice) below multi-year ice structures (depending on their thickness). In any event, some of the leads that open in pack ice will be closed by movements of the ice, which breaks and piles up both old and new ice to form ridges and rubble fields. The result is an ice field characterized by a relatively high degree of structural relief.

The area where the moving pack ice meets the stationary shore-fast ice is a highly active shear zone. A great amount of ice deformation takes place in this area, which is characterized by heavy ice ridging and highly irregular ice features. Water depths are often in the range of 10-30 meters. Since many of the ice ridge keels can be deeper than this, this active shear zone is often characterized by bands of grounded ice ridges. These grounded sea-ice formations formed as a result of "ice heaping" are known as "stamukhi" (Zubov, 1945). Reimnitz et al., (1978) refer to this area of ice ridges and hummocks seaward of the fast-ice zone as the "stamukhi zone" (see Figure 3-3).

A fourth zone of very dynamic ice activity that also has great importance for considerations of oil-ice interactions is the marginal ice zone (MIZ). The MIZ includes the boundary region between ice and open water, and the affected regions on each side of the boundary. The location of the MIZ can vary seasonally and spatially relative to shorelines. However, a common characteristic of all MIZ areas is the complex and rapidly changing interplay between the atmosphere, the ice and the ocean on a variety of temporal and spatial scales. Processes that affect conditions in the MIZ include ocean fronts and eddies, changes in the roughness of both the ice and associated open water surfaces, and wind and atmospheric circulation patterns driven by local surface temperature gradients. Further, ocean convection or circulation

patterns are influenced by sea ice formation (brine generation) and ice break-up and melting (fresh-water generation at the surface) as controlled by varying temperature conditions and the effects of waves and ocean swells.

3.5 INTERACTIONS OF OIL AND ICE

The behavior and fate of oil spilled in regions of ice covered seawater will depend upon factors including not only the type of oil or distillate product released but also where it is released (i.e., under the ice or in open leads) and the state of the ice growth at the time of the spill. In general, interactions between oil and sea ice can be divided into two types of processes: 1) those that "capture" oil and 2) those that "transport" oil. "Capture" processes will include 1) entrainment of oil by grease or slush ice and by rafted or ridged first-year and multi-year ice, 2) interactions of oil with smooth, unbroken first-year ice and 3) interactions between ocean waves, oil and ice floes at the edge of the ice. "Transport" processes will include 1) interactions of oil with Langmuir circulation patterns in near-shore polynyas (consistent open water regions along the lee-sides of shorelines such as the area south of St. Lawrence Island and parts of the Chukchi Sea) or more transient offshore leads where grease ice occurs, 2) general advection of oil by large-scale ice movements and 3) specific advection of oil associated with ice bands that form at the ice edge. More detailed background information regarding these "capture" and "transport" processes will be presented in Sections 3.5.1 and 3.5.2, respectively.

3.5.1 <u>"Capture" or Incorporation Processes Contributing to Oil-Sea Ice</u> Interactions

Mechanisms for the incorporation of oil into a sea ice cover will vary with both the morphology of the ice and the season. Oil may be incorporated into new ice forming in leads, it may seep upwards to the ice surface through cracks or unconsolidated ridges in the ice cover, or it may be frozen into existing ice by new ice growth.

3.5.1.1 Oil Release in a Grease Ice Field

Martin and Kauffman (1981) described the general movement patterns of ice in the initial formation stages of grease or slush ice fields under the influence of waves that propagate into an ice slurry (see Figure 3-1). Surface waves can "herd" the grease ice against a solid object (e.g., the edge of a lead) where the radiation stress from the wave action will create a thickness increase in the ice wedge with distance into the ice layer. Grease ice is an excellent wave absorber because it has a nonlinear viscosity that increases as the ice concentration increases and the shear rate decreases. As a result, the wedge of grease ice will divide into separate regions approximating liquid and solid behavior, and these regions will be separated by an abrupt transition zone termed the "dead zone". Ahead of the dead zone, the waves propagate as heavily damped water waves; behind the dead zone, they propagate as elastic waves. If oil is spilled in the wave field just in front of a grease ice wedge, most of the oil will end up on the surface of the ice beyond the dead zone, with some oil droplets circulating in the grease ice field ahead of the The exact distribution of oil intrapped in the grease ice and on dead zone. the ice surface will be largely controlled by the oil's inhearent density (and degree of weathering or water-in-oil emulsification). Oils with densities higher than the grease ice (0.917 g/ml) may be subject to greater encapsulation (Payne et al., 1984b and Wilson and Mackay 1986). Similar oil distributions would be expected in grease ice accumulations that arise due to Langmuir circulation patterns. Therefore, if oil were spilled in a polynya or open lead where grease ice was forming, then some of the oil would be expected to accumulate in local dead zones and/or Langmuir convergence zones, and a smaller fraction would be dispersed into oil droplets by breaking waves and would circulate around both grease ice and Langmuir rotors.

Once grease ice begins to solidify, ice "pancakes" are observed to form in the grease ice field. Martin (1981b) demonstrated that crude oil released beneath grease ice pancakes in a wave field appeared in cracks around the pancakes. The oscillating motion of the pancakes then drove the oil laterally through the cracks and pumped some of it onto the ice floes. However, the grease ice did retard the rise of the oil to the ice surface and its lateral

spreading within the cracks. Therefore, in the case of oil spilled beneath a wind-agitated field of pancake ice, one would expect that a certain fraction of the oil would be "pumped" onto the surface of the ice, while the remainder would be bound up in or below the grease ice/pancake ice system.

3.5.1.2 Oil Released on Top of a Solid Ice Field

If oil were released onto the surface of solidified ice (first-year or multi-year) by either direct spills or working its way up through forming ice, the spreading properties of the oil would become important to its eventual fate and composition. Snow cover or ice ridges would confine the oil and thus limit the extent of its spreading. In contrast, strong winds and/or horizontal seepage would tend to increase areal spreading (NORCOR, 1975). The weathering of oil on the ice surface during winter would be relatively slow due to cold temperatures, reduced solar radiation, and diffusion-controlled restriction of component evaporation resulting from limited surface area, greater oil layer thickness and the lack of turbulent mixing. However, during the spring thaw, melt pools would form rapidly on oil-covered ice surfaces due to increased absorption of solar radiation (Martin, 1979). The subsequent thinning of the oil slick would accelerate weathering processes. Martin (1979) concluded that oil spread on the surface of ice would eventually be released into surface waters after the oil either melted through the ice or flowed off its edges.

3.5.1.3 Oil Released Underneath a Solid Ice Field

Consideration of the spreading properties of oil will also be important for estimating the fate and composition of oil released under a solid ice field. Factors affecting this spreading will include the density and viscosity of the oil, the degree of under-ice roughness, the in situ water current velocities and the "porosity" of the ice (e.g., brine channels and skeletal layers of columnar ice). All effect the capacity of the ice to contain subsurface releases of oil.

Bottom Ice Roughness and Oil Containment Potential

If new ice forms in calm conditions, the underside of the ice is usually relatively flat and smooth. Depending on a balance between surface tension, viscosity and density, oil can then spread beneath this ice to some equilibrium thickness. Values for equilibrium slick thicknesses have been reported to range from approximately 5-12 mm for refined oils with densities in the range of crude oils (Cox et al., 1980). Minimum stable drop thicknesses for crude oil under ice have been reported to be appromimately 5-10 mm (Lewis, 1976). Using these values for slick thicknesses and assuming a completely smooth surface, Thomas (1984) has estimated that approximately 8000 m³ of oil can spread beneath each km² of ice in the absence of currents or ice motion.

However, the underside of sea ice is generally not perfectly smooth. Therefore, each km^2 of sea ice will actually be able to contain more oil than the above estimate. Furthermore, under-ice roughness will vary between fast ice, pack ice and ice in the stamukhi zone.

The nearshore areas of fast ice normally tend to be relatively flat and undeformed. The under-ice roughness in these areas is determined primarily by spatial variations in snow cover that cause differences in sub-surface ice growth rates. Barnes et al. (1979) reported that snow cover on surface ice accumulates in drifts parallel to the prevailing wind direction, and that these drifts are fairly stable throughout the ice season. The drifts in turn insulate the ice from the much colder overlying ambient air, causing reduced ice growth beneath the drifts. Therefore, the underside of the surface ice takes on an undulating appearance. As the ice continues to grow through the winter, these subsurface undulations become more pronounced.

An impulse radar system has been used to map the under-ice relief of fast ice zones at various places in Prudhoe Bay in the early spring (Kovacs, 1977, 1979; Kovacs et al., 1981). From the resulting contour maps, these

authors estimated that the volume of under-ice voids lying above the mean ice draft (i.e., the oil containment potential) was $10,000-35,000 \text{ m}^3 \text{km}^{-2}$ for areas of undeformed fast ice. For areas of slightly deformed ice, the void volume estimate was as high as $60,000 \text{ m}^3 \text{km}^{-2}$.

In the pack ice zone, the degree of under-ice roughness increases since the ice is in constant motion and subject to repeated breaking and reworking processes. This region contains not only first-year ice floes and pressure ridges but also variable amounts of multi-year ice and refrozen leads. Under multi-year ice, there is a very substantial increase in void volume that could contain oil. Kovacs (1977) profiled the underside of a multi-year ice floe and estimated that 293,000 m³km⁻² of void space existed above the mean draft of approximately 4.3 meters. Other investigators (Ackley et al., 1974) have also reported greater relief under multi-year ice than under first-year ice.

Under-ice Currents and Oil Spreading

Under-ice currents can contribute to the spread of oil beneath sea ice. Until it is completely encapsulated by new ice growth, oil can be moved beneath ice by differential currents of sufficient magnitude until either solid objects are encountered or the currents cease.

Relationships between differential current speed, bottom roughness, and the movement of oil under ice have been evaluated in Cox et al. (1980). These investigators concluded that the threshold differential current velocity required for moving oil beneath an absolutely smooth ice surface was approximately 3-7 cm/sec. For an ice roughnesses of 1 and 10 mm, the threshold velocities were 12-16 cm/sec and 22-25 cm/sec, respectively. For current speeds above these threshold velocities, oil would be moved at some fraction of the current speed. Oil trapped upstream of large obstructions could also be "flushed out" at current velocities in the range of 15-25 cm/sec. In general terms, Cox et al. (1980) concluded that oil spilled beneath an ice cover would not be transported by currents until the relative current velocities were in the range of 15-25 cm/sec. At velocities less than this critical value, a

typical ice field would have substantial oil spill containment capacity. Under-ice currents can range from 2 to 5 cm/sec in parts of the multi-year Beaufort ice pack (Kawalik and Untersteiner, 1978), and Aagaard (1981) reported similar current speeds 10 m below the ice on the Beaufort inner-shelf in 30 to 40 meter depths north of Prudhoe Bay. It should be noted that these measurements were not in the region of the Beaufort Sea extension of the Alaskan Coastal current where Aagaard (1981) has reported average under-ice currents ranging from 25-30 cm/sec. Matthews (1981) used sub-surface and bottom drifters to estimate currents in a wide variety of areas in the central Beaufort shelf. He reported under-ice currents in the range of 7 to 10 cm/sec and near-bottom currents of 0.5 to 2 cm/sec. Near bottom currents (1 meter above the sediment) were measured at 1 to 4 cm/sec under floating shore-fast ice at depths of 20 m in the Beaufort Sea northeast of Pt. Barrow and at 20 to 30 m in the Chukchi Sea near Pt. Franklin as part of this program (see Table 5-7, Section 5.3).

It should be emphasized that the preceeding velocity estimates must be considered as current speeds <u>relative</u> to an under-ice surface. If the ice field is also in motion, then the critical values for current speeds would have to be adjusted to arrive at velocities relative to the under-ice surface.

Effects of Ice Growth, Structural Characteristics and Brine Channels on Oil Retention Under Sea Ice

Oil released into water beneath sea ice will rise through the water column and be trapped on the underside of the ice. If this oil becomes associated with the porous skeletal layer of columnar ice during periods of active ice growth, it will remain essentially static until the ice begins to warm (Martin, 1979). During periods of ice growth, an ice lip will also form as horizontal platelets around subsurface pools of trapped oil (Martin, 1979). Depending on the seasonal conditions, an ice sheet could then continue to grow under the oil and eventually completely trap the oil.

As noted in Section 3.2, first-year ice in particular is characterized by the presence of brine channels that have their origin in the initial

freezing process. The importance of these brine channels to the migration of subsurface or encapsulated oil becomes especially important during warming periods. As the ice begins to warm, brine pools maintained as "salt flowers" on the ice surface over winter as well as brine trapped between the columnar ice crystals begins to drain down through the ice. By the time the air and ice temperature approach freezing point values, the brine channels normally extend throughout the ice. Once the channels connect the surface and bottom of the ice, dense brines drain through the ice and escape from the under ice surface. Oil that was initially trapped under or in the ice may then begin to appear on the upper ice surface due to density-mediated migration of the oil up through the open brine channel pathways. Oil that surfaces through these channels will float in surface melt ponds. If such ponds do not exist, they soon form as the oil darkens the surface of the ice and further enhances absorption of solar radiation.

3.5.2 <u>"Transport" Processes Contributing to Oil-Sea Ice Interactions</u>

Once oil becomes associated with ice by any of the processes discussed in Section 3.5.1, it has the potential to be physically transported to areas substantially removed from the initial point of release. Some of these transport processes can be of substantial magnitude, as evidenced by rates of movement for ice of up to 130 km/day along the Chukchi Sea coast following an ice breakout through the Bering Strait (Lewbel, 1984). More detailed information on potential spatial transport of oil by ice can be found in numerous publications such as Martin and Bauer (1981), Martin (1981b), Pease (1981), and Lewbel and Gallaway (1984).

Other less direct mechanisms may also contribute to the spatial transport of dissolved oil components. For example, the previously mentioned expulsion of sea salts from ice during the initial freezing process may play a role in hydrocarbon transport. In addition to the expulsion of brine to ice surfaces, the freezing process also rejects salts to the water below the ice. As discussed in Kozo (1983) and Schumacher et al. (1983), this can produce water parcels that have higher salinities (and thus densities) than the surrounding water. These water masses can sink in the surrounding water column

by a process known as brine cabling. If dissolved oil compounds or neutral density oil droplets become incorporated into these denser saline water parcels (i.e., in conjunction with the salts, that are excluded from the ice crystal lattice during the freezing process), then this brine cabling mechanism provides a possible route for the transport of either dissolved or dispersed oil components to benthic environments. This concept of transport of oil compounds by brine cabling was evaluated in both wave tank and field studies for this program, and the results are presented in Sections 5.2 and 5.3, respectively.

3.6 COMPUTER MODELING OF OIL WEATHERING IN THE PRESENCE OF SEA ICE

Previous studies by Payne et al. (1984a) have measured and modeled the physical and chemical properties of oil during weathering in an open-ocean environment. However, oil weathering in the presence of sea ice will be highly dependent on the oil/ice configuration. Modeling oil weathering processes under sea ice will be different in virtually all respects from oil weathering on the open ocean, primarily because oil released under sea ice will not be subjected to a similar weathering environment. Nevertheless, any approach to modeling the oil/ice system must be compatible with existing open-ocean weathering models (i.e., Payne et al., 1984a) because the oil eventually is exposed to the same weathering processes when the oil migrates to the ice/air interface or the ice finally breaks up. In addition, if oil is released in broken ice, or if escaping gas from a subsurface blowout causes a bubble or crack in relatively thin ice (DOME, 1981), then this oil would also be subject to a combination of open-ocean and oil-in-ice weathering processes. In either case the ice can refreeze and prevent further short-term evaporative losses (depending on the season and weather conditions). Eventual break-up of the ice with the spring/summer thaw ultimately will release the oil, possibly at appreciable distances from the initial point of oil release. When this occurs, evaporation, dissolution, dispersion, spreading, water-in-oil emulsification, and other weathering processes considered in the open-ocean model will again The currently used True Boiling Point (TBP) or pseudobecome important. component oil-characterization for open-ocean weathering processes has been incorporated into SAIC's model for oil-ice interactions, and this approach is, by design, entirely compatible with the open-ocean oil-weathering model (Section 6.4).

In modeling oil under ice with the oil still in contact with water, the mass transfer processes considered are dispersion and dissolution. Dispersion will not be an important weathering mechanism when under-ice turbulence levels are low and under-ice currents are sufficiently small such that the oil will remain stationary against the ice (DOME, 1981). Thus, in most oil releases below land-fast first-year ice, the only mass transfer process expected to be of importance is dissolution. Dispersion may become important, however, in the shear zone, in moving pack ice, or in areas with stronger tidal currents. Furthermore, dispersion will certainly become an important process when the ice breaks up and wave-induced turbulence in the broken ice field pumps oil onto the ice surface and into the water column.

4. COLD ROOM/WAVE TANK STUDIES

Laboratory studies were completed during this program to measure rates of oil weathering in the presence of simulated first-year and multi-year sea ice. Experiments were conducted using natural seawater in a flow-through wave tank system constructed in a specially designed cold room at the NOAA-Kasitsna Bay Laboratory (Figures 4-1A and 4-1B). Artificially generated sea ice was produced to simulate actual arctic or sub-arctic ice conditions (as described in Martin, 1981).

During the first-year sea ice experiments, fresh Prudhoe Bay crude oil was added below the grease- and columnar-ice layer to simulate a subsurface release. Results from these studies are described in detail in the Final Report for RU640 (Payne et al., 1984b). The multi-year ice experiments involved repeated simulated freeze/thaw cycles, ridge construction and several oil/ice scenarios. The physical and chemical weathering behavior of the oil was evaluated through time series measurements of the oil during freezing and thawing conditions.

4.1 DESCRIPTION OF THE COLD ROOM AND WAVE TANK SYSTEM

A flow-through seawater wave tank constructed in the cold room of the Kasitsna bay Laboratory is illustrated schematically in Figures 4-2A and 4-2B. Seawater for the wave tank was pumped through PVC pipe from a depth of 3 meters below lower low tide in Kasitsna Bay. The PVC pipes were flushed for a minimum of two weeks prior to the initiation of the tank tests to reduce potentials for background (phthalate) contamination. Seawater blanks were also collected and analyzed prior to each of the tank experiments. Several under ice differential current regimes were generated by varying the seawater flow rate into and out of the tank. During the first-year ice experiments, seawater was introduced into the tank at a flow rate of 1 liter/minute (equivalent to a current speed of 0.003 cm/sec), while the flow rate was ~3 liters/minute (0.01 cm/sec) during the multi-year ice experiments. These seawater flow rates result in one tank volume turnover (~1870 1) every 1.25 days in the oil in fist-year ice and every



Figure 4-1A.--Outside View of the Compressor Room and Cold Room Used for Oil/Ice Studies at Kasitsna Bay.



Figure 4-1B.--Wave Tank System and Five Blower Evaporator Unit Inside the Cold Room at Kasitsna Bay. The paddle wheel system at the far end of the tank was later replaced by the hinged system described in the text and shown schematically in Figure 4-2A.





Figure 4-2A.--Ice/Wave Tank Dimensions (not to scale).



Figure 4-2B.--General Layout of the Flow-Through Cold Room System.

10 hours in the oil in multi-year ice experiments, respectively. In both instances, the differential under-ice currents were intended to simulate advective removal of dissolved components and dispersed oil droplets. Higher flow velocities would of course have been desirable to simulate a wider variety of differential currents as would be expected under landfast and pack ice. However, flow rates were restricted by the cooling capacity of the evaporator unit and 5 horse-power compressor used to refrigerate the cold room and lower the ambient water temperature from $+4^{\circ}C$ (as encountered outside at Kasitsna Bay during the winter months) to approximately $-1.7^{\circ}C$ for ice growth inside the wave tank. If higher water flow velocities had been used, then the desired ice regimes could not have been generated.

4.2 SIMULATED FIRST-YEAR ICE TANK STUDIES

4.2.1 Generation of First-Year Ice

A profile of the desired ice/oil configuration for a simulated subsurface oil discharge under first year ice, shown schematically in Figure 4-3, consists of an upper 5 cm layer of frazil/frozen grease ice above a 4 cm layer of columnar ice. Oil would be added beneath the columnar ice, and then additional ice formation would be initiated to entrap the oil within the ice block.

The ice thicknesses were constrained both by the refrigeration capabilities and flow-through seawater systems. The maximum ice growth of the tank system can be calculated using the differential form of the equation of Anderson (1961):

$$(2D + 0.051) WD = 2.8 \times 10^{-5} (T_w - T_a) Wt$$
 (1)

where D is the initial ice thickness in meters,



Figure 4-3.--Diagram of Desired Ice-Oil Configuration.

WD is the ice growth in time interval Wt,

T is the water temperature assumed at freezing point
-1.7°C),

 T_{a} is the air temperature (-30°C),

and Wt is the time interval in hours.

For an initial ice thickness of 10cm, ice growth over a one hour period is WD - 3.2 mm, which equals the growth of ice necessary to cool seawater at the flow rate of 2.4 liters/minutes. Minimum water flow rates in the tank are 1 liter/ minute, thus oil could only be spilled in depths less than 10 cm (Martin, 1984; personal communication during site visit at Kasitsna Bay).

During initial ice formation, the incoming seawater was supercooled to -1.8°C in the presence of wave turbulence. Wave turbulence then was reduced allowing the formation of frazil ice crystals on the water surface. Frazil ice growth occurred within 1 to 2 minutes after the wave generator was turned off, with a 3-5 knot wind and a room temperature of -30°C. Wave turbulence was reinitiated to drive the frazil ice crystals into the water column and encourage the formation of grease ice and slush ice. Frazil ice crystals were observed throughout the water column, and grease ice accumulated to a depth of approximately 4 cm before the paddle system was turned off three hours later. Vertical temperature profiles during all ice experiments were monitored with a thermister array. Figure 4-4 shows the time-series temperature profiles of air, ice, and seawater in the wave tank during growth of grease ice. A chronology of the ice formation and oil spill events is presented in Table 4-1.

Within three hours of the initial frazil ice formation, a 5 cm layer of grease ice covered 80% of the tank surface. A 4 cm layer of columnar ice was then grown over the next 20-21 hours below the grease ice layer prior to initiating the subsurface oil spill (see Table 4-1). Additional columnar ice growth was allowed to occur below the spilled oil to simulate oil-in-ice encapsulation as illustrated in Figure 4-3. Figures 4-5 and 4-6 show an ice core with the frozen grease ice on the surface and the columnar ice immediately beneath it. This core was obtained during initial ice growth stages and, as



Figure 4-4.--Temperature/Depth Profiles Obtained During Oil/Ice Interaction Experiment. (See also Table 4-1 for a time-series chronology of events in the cold-room experiments.)



Figure 4-4.--(Continued)



Figure 4-4.--(Continued)



Figure 4-4.--(Continued)

Date/Time Flow Rate Significant Event Description (1/min) 2/7 2340 Initiation of cool down -Grease ice over 2/3 of the tank 2/8 0130 -0220 2" thick -41 0315 Wave generation terminated .. 0330 2.4 Grease ice 3" thick-surface skin formed 46 0600 1.1 Abundance of salt flowers 66 1300 First appearance of columnar ice $3^{"}$ grease ice + 1/2 " columnar ice 66 1500 1.1 11 3" grease ice + 1" columnar ice 1830 .84 3" grease ice + 2" columnar ice 2/9 0100 .88 5 liter spill of PB crude complete 0500 -... .80 3" grease ice + 2 1/2 " columnar ice-even with oil pools 1100 11 3" grease ice + 3 1/2" columnar ice-oil encapsulation complete 1900 .94 3" grease ice + 4 1/2 " columnar ice 2/10 0900 .88 3" grease ice + 5 1/4 " columnar ice-initial brine channeling 1630 -3" grease ice 5 3/4 " columnar ice 2/11 2100 .76 Initiation of thaw 1200 2/13 .68 $3^{"}$ grease ice + 6 1/4 " columnar ice-pools of brine 1800 2/14 0430 First oil surfacing -0630 .67 3" grease ice + 6 3/4 " columnar ice-maximum ice thickness 2/15 1930 .62 Open leads introduced .64 Ice 5 1/2 " thick-90% columnar 2315 2/16 0130 10% of the oil has surfaced .67 14 1000 Oil removed for distillation -2/18 1730 1.7 Break-up (wave action initiated) 2/20 1200 1.8 4" grease ice 2/22 1100 1.8 Ice free

Table 4-1.--Chronology of Times and Dates of Significant Events Occurring During the Oil/Ice Wave Tank Experiment.


Figure 4-5.--Side view of Ice Core Obtained from Wave Tank System Illustrating the Discontinuity Between the Frozen Grease Ice (top) and the Columnar Ice (bottom). Most of the 3-5 inches of grease ice which was on top of the columnar ice was lost during sampling.



Figure 4-6.--Same Ice Sample as Described in Figure 4-5 with Backlighting to Better Illustrate the Crystal Structure of the Columnar Ice.

such, the columnar ice was only 10 cm thick at the time of sampling. Most of the 5 to 6 cm layer of grease ice originally present on the top of the core was lost during extrusion of the core. The abrupt transition apparent between the grease ice and columnar ice is also characteristic of cores from first-year ice collected in the field (Martin, 1979).

Salinity data collected during the ice formation experiments are summarized in Table 4-2.

Characteristics of the structural morphology (e.g., crystal orientation) and salinity measurements for ice formed in the wave tank were similar to those observed in actual field samples of ice in the Chukchi Sea (see Section 4.3.1 for comparisons).

4.2.2 <u>Oil/Ice Interactions</u>

When the ice layer in the tank consisted of 5-6 cm of surface grease ice and 4 to 6 cm of columnar ice, 5 liters of fresh Prudhoe Bay crude oil were introduced below the ice layer through a Teflon tube. Following addition of oil to the tank, oil droplets congealed immediately underneath the ice and some oil pooling was observed in under-ice depressions generated by placing styrofoam blocks on the upper ice surface to simulate snow drifts. Figure 4-7 shows one such pool of oil adjacent to the underwater thermister array, and also illustrates the formation of millimeter to 2 cm diameter oil droplets under the ice layer.

An under ice depression was intentionally formed near one of the vertical view ports to permit observations of the accumulation of the oil in this under-ice cavity. Within 23 hours the spilled oil was completely encapsulated by a 5 mm (minimum) layer of columnar ice. An additional 12 cm of columnar ice was then generated beneath the oil lens, and the spill remained entrapped within the columnar ice until a thaw cycle was initiated.

	Salinity (°/) of samples at													
Sample type	Pre- freeze-up	Initial ice formation (1/30/84 2100)	Solid ice (1/31/84 1230)	Maximum ice thickness (2/2/84 2200)	Thaw initiation (2/3/84 1100)	8 hours into thaw (2/3/84 1900	36 hours after breakup) (2/6/84 2100)							
Seawater	34.1	37.1		31.1			30.4							
Grease ice		29.2					10.5							
Surface brine			85.0	76.4	0.5	12.0	47.0 (residing inside pancake ice)							
Ice at: surface			27.7	17.5		5.8	10.5							
2" depth				13.3		5.5								
4" depth				12.5		9.5								
6" depth				14.2										

Table 4-2.--Salinities of Various Ice Types and Brines Obtained During the Oil/Sea Ice Interaction Experiment.



Figure 4-7.--Oil Pooling in Under-Ice Depressions Just After the Spill.

Approximately four days after the spilled oil was entrapped in the lower ice layer, a thaw cycle was initiated. Water column measurements of dissolved and dispersed hydrocarbons were completed over this period to insure that the system (which was constantly being exposed to fresh seawater flow) had returned to near "background" levels before initiation of the thaw. Just before initiation of the thaw cycle a significant temperature gradient was observed in the frozen grease ice and columnar ice (Figure 4-8), which at this point had reached a total thickness of 15-17 cm. Within 48 hours of initiation of the thaw cycle, the temperature gradient in the ice began to break down, which resulted in both melting of the surface grease ice and formation of standing pools of brine on top of the ice along with brine channel drainage.



Figure 4-8.--Temperature/Depth Profiles Obtained During Oil/Ice Interaction Experiment. (See also Table 4-1 for time-series chronology of events in the cold-room experiments.)



Figure 4.8.--(Continued)

A 71 cm diameter test floe was cut in the center of the ice to facilitate brine channel drainage and oil migration in a floating ice patch. This test floe was left in place, but its buoyancy was not restrained by the surrounding fast-ice layers which were held in place by the tank walls. With this circular test floe, time-series brine channel drainage and oil migration could be measured on ice behaving under natural buoyancy conditions. The remaining ice in the tank which was fast against the tank walls was also used for monitoring oil migration. However, slight changes in the water level due to partial blockage of the drainage pipe may have affected the migration rates in the fast ice, although this was not a factor in the central test floe.

A pool of oil trapped adjacent to the vertical viewport allowed observation of oil migration during initial formation of brine channels. Figure 4-9 shows the initiation of this brine channel migration, with a pocket of dissolved gases (methane, ethane, propane, and butane) leading the oil phase. Figure 4-10 shows the brine channels as outlined on the glass window and additional migration of the oil with time. While this migration was subject to "wall effects", the elapsed time for the oil to reach the surface was approximately the same as that observed for the floating ice floe. Chromatographic measurements of oil samples, obtained by penetrating the brine channel from above with a syringe, showed that some evaporation and loss of low molecular weight compounds occurred before the oil reached the ice surface.

Such losses would be diffusion controlled, however, and would not affect the bulk of the oil still residing in the trapped pool beneath the ice surface. Approximately four hours after the test floe had been cut out of the fast ice surface the first oil surfaced through the circular test floe.

Estimates of oil flow rates through the brine channels were derived from the amount of surface oil measured (area x thickness) on the test floe over time. In addition, time series photographs were used to document the changes and arrive at the volume and rate estimates listed in Table 4-3. The data in Table 4-3 were used to evaluate the brine channel migration predictions

Area (cm ²)	Thickness (cm)	Volume (mls)	Average Rate (mls/hr)
9.1	.05	.45	.11
1.4	.30	.87	.09
52.8	.22	11.9	.71
279	.46	129	5.2
269	.83	224	6.2
1260	.30	378	4.3
	Area (cm ²) 9.1 1.4 52.8 279 269 1260	Area (cm ²) Thickness (cm) 9.1 .05 1.4 .30 52.8 .22 279 .46 269 .83 1260 .30	Area (cm²)Thickness (cm)Volume (mls)9.1.05.451.4.30.8752.8.2211.9279.46129269.832241260.30378

Table 4-3.--Experimentally Determined Oil Migration Rates.

by Cox et al. (1980). The expression, given by Cox et al. (1980), for the minimum brine channel diameter that will allow oil migration (d_i) is:

$$d_{i} = \frac{4\sigma_{ow}}{\delta} \cdot \frac{\cos \alpha}{(L_{w} - L_{o})g}$$
(2)

where, for the experimental spill, σ_{ow} is the oil/water interfacial tension (24.2 g/sec²), α is angle of contact (0), ω is the under ice oil lens thickness (2.5 cm), L_w is the water density (1.03 g/cm³), L_o is the oil density (.92 g/cm³), δ is the slick thickness and g is the gravitational constant (980 cm/sec²). Using these values to solve for d_i indicates a minimum brine channel diameter of 3.6 mm, which seems reasonable in light of observations made in the wave tank and published brine channel diameters from oil spill studies completed in the field (Martin, 1979).

The rise rate velocity is given by:

$$\mu_{z} = \frac{(L_{w} - L_{o})g \, \delta d^{2}}{32 \, L\mu}$$
(3)



Figure 4-9.--Initial Migration of Encapsulated Oil as Viewed Through Vertical Viewport. Note gas bubbles above migrating oil surface due to the slow release of volatile components during the brine channel migration. Photograph was taken at 1900 hours, 2/10/84.



Figure 4-10.--Continued Brine Channel Migration as Observed Through Vertical Viewport at 2245 Hours, 2/10/84. The location of brine channel drainage from the surface is illustrated by outlining the brine pools with Magic Marker.

where L_w , L_o , g, and δ are as before, d is the brine channel diameter (.36 cm), L is the ice thickness (5.7 cm), and μ is the oil viscosity (5.5 g cm⁻¹ sec⁻¹). Solving for μ_z , a rise rate of .35 mm/sec was determined. This value is lower by a factor of two than the rise rate of 0.7 mm/sec determined experimentally by Martin (1979). However, slight changes in in situ oil viscosity (while still in the ice) or even a slight (1.4 fold) difference in brine channel diameter could result in a factor of two change in μ_z .

Finally, the volume flow rate to the surface can be expressed by:

$$V = \frac{\Pi d^2}{4} \mu_z N' A \tag{4}$$

where d is as before, μ_{z} is the rise rate velocity (.035 cm/sec), N' is the number of brine channels per area $(.01/cm^2)$ and A is the area of the spill (209 cm^2). Solving for V, with the experimentally determined data, indicates that the volume of oil deposited on the surface as a function of time should be approximately 27 mls/hr. This value is somewhat high when compared to the experimentally determined values presented in Table 4-3. However, other factors which may need to be taken into consideratin to explain the differences between calculated and observed flow rates include: 1) the depth of the oil pool in the ice, 2) the rate of temperature increase (totally controlled by laboratory conditions), 3) the fact that the laboratory ice was relatively thin (< 10 cm), 4) the fact that the oil lens was initially trapped in columnar ice 4 cm below a 5 cm thick canopy of refrozen grease ice, 5) uncertainties in the number of brine channels/unit area in the laboratory and field studies and 6) the influence of the oil after it has surfaced with additional ice ablation and Obviously, additional refinement of the modeling of oil migration in melting. brine channels appears warranted; however, to our knowledge this is the first comparison of measured data with predictions based on Cox's approach.

Approximately 6 hours after the first brine channel oil migration was noted in the circular test floe, the oil had pooled in approximately five areas; the largest oil pool was approximately 1 cm in diameter. Approximately 24 hours later, several oil pools, the largest of which was estimated to be 5 cm long, were noted in the test floe. With increased absorption of infrared energy these pools then led to enhanced oil spreading and ice melting as reflected in the temperature profiles shown in Figure 4-11. Approximately 3 days later an estimated 90% of the oil was present on the ice/water surface. Gas chromatographic analysis of this surface oil pool illustrated that lower boiling distillate cuts up through TBP cut 7 (BP 282-304°F; Payne et al., 1984a) had been removed by evaporative weathering (see Figure 4-20; Section 4.2.4).

Three days after the thaw was initiated (Table 4-1), the ice was quite rotten and was manually broken up into 60-80 cm diameter floes. The paddle system was then later turned back on to generate 6-8 cm waves to examine the effects of light turbulence on oil weathering behavior in the presence of grease ice and test ice floes. The micro-scale turbulence introduced by the grinding of the ice floes against one another, and the grinding action of the frazil ice and grease ice crystals between the major floes, significantly enhanced the formation of a stable water-in-oil emulsion. The 4-6 cm wave oscilliations in the grease ice also led to a pumping action, as described by Lee et al. (1974), causing the oil to collect on the ice floes and around the Subsurface observations and water sampling (see Section 4.2.3) rims. illustrated that elevated levels of dispersed oil in the water column also resulted from this small scale turbulence which causes oil droplets to Dispersion quickly became self-limiting, however, due to the rapid disperse. (within 4 hours) formation of a water-in-oil emulsion (mousse) and drastic increases in oil viscosity.

A further observation was that the water-in-oil emulsion formed in the tank was not neutrally buoyant and, in fact, had a density (0.982 g/ml) such that most of the larger emulsified oil patches resided immediately below the grease ice on the water surface. The larger mousse balls were approximately 5 to 8 cm in diameter. With continued agitation and eventual melting of the



Figure 4-11.--Temperature/Depth Profiles Obtained During Oil/Ice Interaction Experiment. (See also Table 4-1 for a time-series chronology of events in the cold-room experiments.)



Figure 4-11.--(Continued)

grease ice (Table 4-1), the emulsified water-in-oil mixture eventually surfaced in the open water between the ice floes. Similar observations have been reported by Wilson and Mackay (1986). In their experiments rotating-shaker generated water-in-oil emulsions and Sudan Red dyed white oil (Bayol 35; SG 0.790) plus tetrachloroethylene (SG 1.615) mixtures were incorporated into agitated fresh-water grease ice contained in 3500 ml graduated beakers. These waterin-oil emulsions and the oil/chlorinated solvent mixtures had densities ranging from 0.92 to 0.98 g/ml). The reported density of the fresh water grease ice was 0.917 g/ml. Thus, when Wilson and Mackay poured an artificially generated water-in-oil emulsion (with a density of 0.946 g/ml) into the beaker with the grease ice and stirred it, an estimated 80 to 90% of the oil was In the Kurdistan incident where No. 6 fuel oil was spilled in incorporated. ice covered waters in Cabot Strait, the measured oil density was again greater than the grease ice density and only slightly less dense than the water (C-Core, 1975). As a result, it was reported that the oil often resided beneath the grease ice, and as much as 50% of the oil was estimated to be entrained in the brash ice to a depth of 1 meter.

Tables 4-4 through 4-6 present rheological properties data for the emulsified oil generated in the cold room/wave tank experiments completed at Kasitsna Bay. The oil/water interfacial surface tension in the emulsified oil did not change throughout the duration of the experiment but remained at approximately 25-26 dynes per centimeter. Like-wise, the oil/air interfacial surface tension did not change during the emulsification process. Comparisons between changes in the rheological properties of mousse generated under open ocean/ice-free conditions (Payne, et al. 1984a) and those in mousse in the presence of artificial first-year ice can be made by examining the data in Tables 4-4 through 4-6 and Figure 4-12. A smooth decrease in oil/water interfacial surface tension from 27 to 13 dynes per centimeter was observed during open ocean oil weathering processes, with the oil/air interfacial surface tension showing values very similar to those observed in the ice tank system. Thus, in the presence of ice a stable water-in-oil emulsion was generated even without the change in oil/water interfacial surface tension noted under open-ocean weathering conditions.

Table 4-4.--Interfacial Tension (Oil/Water) and Surface Tension (Oil/Air) Obtained at Various Times During the Oil/Sea Ice Interaction Experiment.

Sample State ^a	Oil/Water Interfacial Tension (dynes/cm)	Oil/Air Surface Tension (dynes/cm)
Fresh crude (pre-spill)	26.2	33.4
Oil approaching the ice surface through brine channels (oil temp. @ 1.8°C - ambient measurement)	24.2	36.8
Pooled oil after surfacing	23.4	34.7
Mousse - 4 hrs after break-up	25.8	35.9
Mousse - 12 hrs after break-up	27.3	35.2
Mousse - 4 days after break-up	26.7	36.7

^aExcept where noted. all measurements were obtained after sample equilibration at room temperature.

Table 4-5.--Water Content (% by weight) in Oil Weathered in the Presence of Sea Ice.

Sample Description	Sampling T	ime and Date	Water Content ^a (%)				
Fresh Prudhoe Bay Crude	Pre	-Spill	<.01				
Oil Encapsulated by Ice	0600	2/16/84	4.3				
Freshly Exposed Oil	1100	2/16/84	7.4				
Mousse - 4 hrs after break-up	1600	2/18/84	64				
Mousse - 11 hrs after break-up	2230	2/18/84	65				
Mousse - 3 days after break-up	1330	2/21/84	64				
Mousse - 4 days after break-up	2200	2/22/84	66				

^aWater content determined by Karl Fischer titration or ASTM 1796.

Table 4-6.--Oil Viscosities at Various Times and Temperatures Obtained During the Oil/Sea Ice Interaction Experiment.

Sample State	Oil Temperature (^O C) ^a	Viscosity (centipoise)
Fresh Crude (pre-spill)	20.0	50
Oil approaching the ice surface through brine channels	1.0	550
Oil on ice surface (~10% remaining in the ice)	2.1	500
Weathering oil - 11 hrs after break-up	-2.0	25,000
Weathering oil - 11 hrs after break-up	38	1,100
Mousse - 36 hrs after break-up	-2.5	30,000
Mousse - 36 hrs after break-up	38	1,200
Mousse - 4 days after break-up	1.0	30,000
Mousse - 4 days after break-up	38	1,400

^aExcept for 38^oC cases, viscosities were taken at experimental ambient temperatures.



Figure 4-12.--Comparison of Oil Weathering Rheological Properties Between Open Ocean and with Sea Ice Present. (A) interfacial tension, (B) water incorporation, and (C) viscosity.

For comparison, water content in the mousse reached 64% within 4 hours after ice break-up and initiation of wave turbulence (Table 4-5), whereas water build-up in a stable water-in-oil emulsion did not occur in open-ocean test tank studies for 12 days, and then only in a smooth increasing pattern (see Figure 4-12).

Large increases in viscosity were measured in the water-in-oil emulsion generated in the wave tank systems (Table 4-6). Fresh oil, as it surfaced through the brine channels had a viscosity of 550 centipoise at 1°C, whereas mousse formed four hours after the onset of turbulence exhibited a viscosity of 25,000 cp at -2°C. When this sample was warmed in the laboratory to 38°C for more standard (100°F) viscosity testing, a value of 1,100 centiporse was obtained. For comparison, the viscosities of mousse formed in open ocean oil weathering experiments approach 1,100 centipoise (at 38°C) only after 3-4 days of weathering under subarctic conditions (Payne et al., 1984a). Maximum oil viscosities approached 30,000 centipoise at ambient (-2.5°C) temperatures and 1,400 centipoise at 38°C after 4 days during the oil-in-ice experiments.

4.2.3 Compound Specific Partitioning and Whole Oil Droplet Dispersion

Aliquots of fresh Prudhoe Bay crude oil and samples of weathered oil and water from the wave tank were collected before spill initiation and at regular intervals during the experiment, respectively, for subsequent chemical analyses. The aliphatic and aromatic fractions of each of these samples as well as true boiling point (TBP) distillate cuts, were characterized for chemical and rheological properties by methods described in Payne et al. (1984a).

Concentrations of specific dissolved aromatic hydrocarbons in the water column are presented in Tables 4-7A and 4-7B for post-spill and post-ice break-up cycles, respectively. Time series profiles of dissolved aromatic hydrocarbon concentrations, shown in Figure 4-13 illustrate the slight increase in dissolved hydrocarbon concentrations in the water column immediately after subsurface oil release with a decrease in hydrocarbon concentrations after oil encapsulation in the ice during Day 3 to Day 4. With the initiation of wave

Table 4-7A.--Time Series Dissolved Hydrocarbon Concentrations (μ g/liter) in the Presence of Sea Ice Before and During Encapsulization. Note: Open leads refers to the presence of several small open water leads resulting from cutting a 71-cm-diameter test floe in the center of the tank. Temperature regimes during the experiment can be seen in Figures 4-4, 4-8, and 4-11.

		FORT SPILL TIME											Open Loads			
Compound	rovat	Prespill	2 Hours	4 Hours	6 Hours	9 Bours	13 Bours	17 Bours	28 Hours	36 Hours	2 Days	3 Deys	4 Days	5 Daya	7 Deys	9 Days
Ethylbenzene m,p-sylene o-sylene Isopropylbenzene N-propylbenzene Cbenzene Cbenzene Cbenzene Cbenzene Cbenzene Cbenzene Cbenzene Tetramethylbenzene Naphthalene 2-methylnaphthalene 1.1-biphenyl 2.6-dimethylnaphthalene Cnaphthalene Cnaphthalene 2.3.5-trimethylnaphthalene	854 856 891 921 950 960 960 978 978 992 1020 1107 1180 1290 1307 1375 1399 1414 1433 1448 1556	24 246 246 246 246 246 246 246 246 246 2	.635 2.53 1.11 .0594 .0753 .294 .0985 .130 .358 .214 .0972 .235 .103 .0952 ND .0630 ND .0383 ND .0255	.690 2.79 1.22 .0661 .0814 .321 .0978 .154 .397 .238 .107 .289 .129 .129 .122 ND .0852 ND .0549 ND .0549	.799 3.40 1.50 .0757 .0944 .382 .116 .176 .502 .213 .146 .368 .230 .158 ND .11 ND .0747 ND .0414	1.29 4.41 1.97 .145 .524 .163 .226 .603 .365 .135 .502 .281 .209 .0246 ND .0313 .0809 ND ND	.455 2.00 .868 .0504 .0618 .233 .0706 .108 .291 .163 .101 .245 .107 .104 ND .0668 ND .0254 ND .0254	.907 3.32 1.46 .0874 .108 .393 .121 .121 .121 .266 .127 .360 .214 .0204 .0204 .0232 .0532 ND .0326 .0413	.482 2.83 1.07 .0694 .0830 .340 .102 .163 .436 .178 .0865 .329 .195 .148 ND ND ND	.926 3.45 1.54 .0941 .127 .446 .146 .205 .567 .240 .150 .520 .348 .254 .0416 .103 .0464 .0690 ND .0595 .0475	.126 .850 .341 .0253 .0284 .111 .0318 .0497 .131 .114 ND .0868 .0611 .0476 ND ND ND	.0583 .453 .185 ND .0736 .0226 .0270 .0891 .0585 .0252 .0578 .0405 .0384 ND ND ND ND	.0308 .362 .147 .0227 ND .0557 ND .0258 .0685 .0575 ND .0376 .0265 .0376 .0265 .0376 .0265 .0376 ND .0218 ND ND ND	.0890 .751 .291 ND .119 .0346 .0511 .154 .144 ND .0832 .0554 .0323 .0468 ND ND	.695 2.76 1.22 .0784 .106 .405 .139 .180 .519 .318 ND .410 .0336 .0336 .0551 .145 ND .0576	3.01 10.9 5.12 .261 .463 1.63 .553 .647 2.02 1.13 .201 1.15 1.08 .669 MD .869 .114 .257 ND ND .142
Phenanthrene	1773	ND	ND	.0334	ND	.0532	.0249	ND	ND	.06 86	ND	.0283	ND	ND	.150	ND
Total Resolved Compounds	-	2.77	8.60	9.42	26.8	34.0	6.25	15.7	13.6	18.5	4.92	4.71	3.69	3 .99	12.6	66.0
Unresolved Compounds	-	0	8.27	7.92	19.8	14.0	6.89	6.83	4.50	14.0	0	0	0	0	12.5	20.7

"ND indicates "not detected".

Table 4-7B.--Time Series Dissolved Hydrocarbon Concentrations (μ g/liter) in the Presence of Sea Ice After Ice Breakup and Initiation of Wave Turbulence. Wave action was initiated at 0 minutes on day 9 post spill (see also Figure 4-13).

	900 78 (D	POST BREAK-UP TIME											
CONDOCINO	NOVAL	15 min	1 hr	2 hrs	4 hrs	8 hrs	12 hrs	24 hrs	48 hrs	3 days	4 days	5 days	6 days
Ethylbenzene m, p-xylene o-xylene Isopropylbenzene N-propylbenzene C ₃ -benzene C ₃ -benzene C ₄ -benzene C ₄ -benzene Tetramethylbenzene 2-methylnaphthalene 1,1-biphenyl 2,6-dimethylnaphthalene C ₂ -naphthalene C ₂ -naphthalene C ₂ -naphthalene C ₂ -naphthalene	854 866 891 921 950 960 966 978 992 1020 1107 1290 1307 1375 1399 1414 1433 1448 1458	13.6 47.4 22.9 1.63 2.48 9.27 3.38 4.11 11.9 6.84 2.18 8.19 6.24 .857 1.33 1.34 .391 .420	15.2 54.4 27.8 2.28 3.32 12.3 4.42 5.63 16.4 9.88 2.14 12.4 9.87 1.41 1.97 1.89 .530 .513 736	17.5 62.9 32.5 2.47 4.25 15.8 5.92 7.46 21.6 13.8 2.40 19.8 15.6 2.24 3.16 2.92 .807 1.11	26.7 98.3 52.0 4.00 7.38 25.7 9.74 12.1 34.5 21.7 2.18 27.8 21.9 3.32 4.50 4.00 1.17 1.50	- 58.6 34.3 3.23 5.89 21.7 8.50 10.8 32.4 21.6 1.80 36.4 29.5 4.68 6.06 5.35 1.69 2.12	12.0 47.2 27.9 2.62 4.86 17.8 7.09 8.87 27.1 17.9 1.17 34.4 27.9 4.48 6.35 5.00 1.48 2.14	3.45 15.8 10.1 1.04 2.14 8.11 3.38 4.27 13.8 9.55 .340 27.3 22.5 3.54 5.50 4.83 1.25 1.57	1.61 9.80 5.87 .745 1.71 6.49 2.82 3.47 11.8 8.20 .133 33.2 25.1 4.06 6.49 5.66 1.60 1.96	.476 4.27 2.54 .378 .907 3.34 1.55 1.82 6.46 4.73 ND 28.2 21.5 3.64 5.67 4.98 1.43 1.77	.104 1.36 .956 .104 .292 1.26 .601 .819 2.67 2.10 ND 18.7 14.8 2.66 4.25 3.38 .881 1.42	ND ^a .262 .209 ND ND .385 .204 .255 .918 .749 ND 9.14 7.43 1.48 2.07 1.50 .363 .619	ND .108 ND ND .173 ND .124 .475 .534 ND 6.67 5.59 1.23 1.70 1.39 .366 .591
Dibenzothiophene Phenanthrene	1746 1773	.228	.280 .232	.350 .340	.534 .508	.679 .686	.759 .650	.595	.896 .951	.870 .860	.769	.296 .333	.350
Total Resolved Compounds	-	306.0	363.0	441.0	632.0	502.0	444.0	246.0	222.0	160.0	88.0	39.0	26.9
Unresolved Compounds	-	104.0	148.0	136.0	213.0	249.0	197.0	115.0	78.6	49.6	22.3	0	0

^aND indicates "not detected".



Figure 4-13.--Time Series Dissolved Hydrocarbon Concentrations with Sea Ice Present. (A) o-xylene and 1,3,5-trimethylbenzene; (B) naphthalene and 1,1'-biphenyl; and (C) total resolved compounds and UCM.



Note: the 71 cm circular test floe for brine channel oil migration studies was installed on day five and additional leads were cut in the ice canopy on day 7 (see Table 4-1). Some dispersion of oil droplets resulting in enhanced dissolution inadvertently occurred during these activities.

Figure 4-13.--(Continued)

turbulence after ice break-up on Day 9, however, an approximate 50-fold increase in dissolved hydrocarbon concentrations was observed for the compounds ortho-xylene, trimethylbenzene, naphthalene, and 1,1-biphenyl. The total resolved components and unresolved complex mixtures, as determined by FID-GC analyses, increased by factors of 700 and 300, respectively, after wave turbulence was introduced. The immediate spike in the total resolved component concentrations, due to the initiation of wave turbulence, was followed by a gradual decline (over 6 days) in water column concentrations due to the combined effects of subsurface advection and evaporative loss from the water surface.

Flame ionization detector gas chromatograms are presented in Figure 4-14 for methylene chloride extracts of: (a) a pre-spill seawater blank; (b) a water sample collected 9 hours after the subsurface release; and (c) a water sample collected five days after the initiation of the spill but before ice break-up. The chromatogram in Figure 4-14B for the 9 hour sample shows the presence of dissolved lower molecular weight aromatic hydrocarbons in the alkyl-substituted benzene through alkyl-substituted naphthalene range. After oil encapsulation and continued under-ice water column flushing of one tank-volume every 1.25 days (simulating 0.006 cm/sec subsurface currents), the water column was significantly cleaner after 5 days, as shown in the chromatogram in Figure 4-14C. AT higher under ice currents in the field, this process would obviously occur over a shorter time frame.

The thaw cycle in the tank system was initiated after the water column concentrations of dissolved aromatic hydrocarbons had returned to near prespill levels (see Figure 4-13). Immediately after ice break-up and initiation of wave turbulence, water column samples were again collected. Figure 4-15 presents the FID/GC profiles of the dissolved aromatic hydrocarbons in the water column with sea ice present: chromatogram A corresponds to a sample collected 8 hours after initial break-up, chromatogram B is from a water column sample collected 4 days after ice break-up, and chromatogram C shows the hydrocarbon components present in a sample collected after 6 days. Many of the lower molecular weight components were lost within six days due to evaporation and advective removal of the water from the wave tank system.



Figure 4-14.--FID-GC Chromatographic Profiles Depicting Hydrocarbons Dissolved in the Water Column with Sea Ice Present. (A) prespill; (B) 9 hours post spill; and (C) 5 days post spill (before ice breakup).



Figure 4-15.--FID-GC Chromatographic Profiles Depicting Hydrocarbons Dissolved in the Water Column with Sea Ice Present. (A) 8 hours; (B) 4 days; and (C) 6 days after ice breakup.

Water samples collected throughout the post spill and post break-up phases were also filtered for analyses of dispersed oil fractions, as described in Payne et. al. (1984a). Time series concentrations of dispersed oil concentrations in the tank are presented in Table 4-8. Concentrations of total resolved and unresolved complex mixture (UCM) aliphatic hydrocarbons (representing the dispersed oil phase) remained low (generally less than 10 μ g/liter) throughout the post-spill period, with only relatively small changes from the pre-spill to the post-spill levels. In contrast, levels of dispersed total resolved and UCM hydrocarbons increased by two to three orders of magnitude following the break-up of the ice and onset of 4-6 cm wave turbulence. Maximum resolved and unresolved concentrations were measured 12 hours after ice breakup, although levels subsequently decreased to approximate pre-spill conditions at six days after break-up. Time series concentrations of total resolved and unresolved components in the dispersed oil phase are shown in Figures 4-16A and 4-16B, respectively. These data indicate that very little of the oil is dispersed into the water column during encapsulation by the ice, which occurred approximately 24 hours after the spill.

Detectable levels of some of the medium molecular weight alkanes (from nC_{12} to nC_{20}) were apparent 13 to 17 hours after the spill. This weak pulse of dispersed oil suggests a delayed mixing of oil micelles down to the depth of the sampling port, approximately 50 cm below the bottom of the ice layer. By 24 hours after the spill, all of the oil had been encapsulated by the ice; however, the concentration of the total resolved components continued to increase up to 36 hours post-spill. Beyond 36 hours, concentrations of individual alkanes and the UCM dropped to pre-spill levels. Chromatograms of the dispersed oil extracts are shown in Figure 4-17. The presence of some of the intermediate molecular weight alkanes, as well as a small UCM "hump", are apparent in the chromatogram of the 13 hour sample (Figure 4-17B) relative to the clean baseline and general absence of a series of n-alkane peaks for the chromatograms of pre-spill and 24 hour filter extract samples.

Compound	POST SPILL TIME									POST BREAK-UP TIME (9 DAYS +)							
	Prespill	4 hrs	6 hrs	13 hrs	17 hrs	36 hrs	2 days	9 days	1 hr	4 hrs	8 hrs	12 hrs	24 hrs	2 days	4 days	6 days	
N-C9	ND ^a	ND	ND	ND	ND	ND	ND	ND	.336	.427	.929	1.54	ND	ND	ND	ND	
N-C10	ND	ND	ND	ND	ND	ND	ND	ND	2.03	3.89	6.11	7.92	1.95	2.11	.226	ND	
N-C12	ND	ND	ND	.00686	.00875	ND	ND	ND	12.2	18.4	25.0	29.9	15.9	15.6	2.15	ND	
N-C14	ND	ND	ND	.0108	.0280	ND	ND	ND	17.2	22.1	30.0	36.7	23.5	23.1	3.83	ND	
N-C ₁₇	ND	ND	ND	.0580	.0233	ND	ND	ND	12.6	15.6	21.9	24.7	17.5	17.8	3.67	.265	
Pristane	ND	ND	ND	.00971	.0122	ND	ND	ND	6.87	8.11	10.9	11.9	8.80	8.93	2.48	.451	
N-C18	ND	ND	ND	.0860	.0540	.0268	ND	ND	11.3	13.7	19.0	21.6	15,1	15.8	3.45	.232	
Phytane	ND	ND	ND	. 01 97	.0293	ND	ND	ND	6.63	7.56	9.99	10.7	8,40	7.95	2.47	.0330	
N-C ₂₀	ND	ND	ND	.00935	.0131	ND	ND	ND	8.03	10.1	15.6	15.5	12.7	11.1	3.35	.0419	
Total Resolved	1.23	1.14	2.25	4.75	4.21	6.76	2.09	2.84	310	402	507	592	403	3.87	93.0	3.21	
υα <mark>ν</mark> Β	0	0	0	3.81	5.41	0	0	0	1050	1480	1990	2120	1860	1510	309	0	

Table 4-8.--Time Series Dispersed Oil Concentrations ($\mu g/liter$) in the Presence of Sea Ice. Turbulence was initiated 9 days after the spill.

a - ND indicates "not detected"

b - 'Unresolved complex mixture'



Figure 4-16.--Time Series Water Column Concentration of (A) Total Resolved Dispersed Oil Compounds, and (B) Unresolved Dispersed Oil Compounds.



⁽A) prespill, (B) 13 hours, and (C) 24 hours post spill.

Following the break-up of ice in the tank, concentrations of most of individual n-alkanes increased with time up to 12 hours. Concentration the subsequently decreased over the next six days to approximate pre-break-up levels with the formation of high viscosity water-in-oil emulsions which inhibited further dispersion. The presence of lower molecular weight n-alkanes $(nC_0 \text{ through } nC_{14})$ was not detectable in the water column after six days. A series of peaks corresponding to the intermediate and higher molecular weight n-alkanes are apparent in the chromatogram of the filter extracts of the one hour and four day post-break-up samples (Figures 4-18A and B, respectively). Most, if not all of the lower molecular weight n-alkanes below nC_{10} (TBP Cut 7) are not as prominent in either the one hour or four day samples, suggesting a rapid loss due to evaporation and dissolution. The significantly reduced number of resolved intermediate and higher molecular weight compounds in the filter extract from the six day sample reflects the nearly complete inhibition of dispersed oil droplets in the water due to the formation of the high viscosity, water-in-oil emulsion (see Tables 4-5 and 4-6 and Figure 4-12).

4.2.4 Oil Phase Chemistry

Oil samples were also obtained from ice cores during the thawing cycle and analyzed by FID/GC. Chromatograms of the oil both immediately after it was released from ice encapsulation and after it had been exposed at the water surface for 3 hours are shown in Figure 4-19. Qualitatively, the chromatographic profiles appear identical, indicating little, if any, evaporative loss. However, other chromatograms obtained from oil in the brine channels showed some evaporative losses of lower molecular weight alkanes in the methane through heptane range. Due to the extremely high viscosity (550 centipoise) of oil at the ice temperatures during brine channel migration, the evaporative behavior is believed to be diffusion-controlled, producing a gradient of more highly evaporated oil nearer to the surface. Thus, in the bulk oil sample shown in Figure 4-19C, there appears to be little evaporative loss.



Figure 4-18.--FID-GC Chromatograms of 0.45- μ m Glass Fiber Filter Extracts Depicting Dispersed Oil in the Water Column After Ice Breakup: (A) 1 hour, (B) 4 days, and (C) 6 days after breakup.



Figure 4-19.--FID-GC Chromatograms of Oil Weathering in the Presence of Sea Ice: (A) fresh Prudhoe bay crude oil; (B) encapsulated oil; and (C) bulk oil exposed for 3 hours.

In other cases, however, there was evidence of loss of lower molecular weight components from the oil even as it was migrating through the brine channels. Figure 4-9 (in Section 4.2.2) illustrated the presence of a gas pocket above the upwardly migrating oil. In several other ice floes, it was possible to sample the oil before it had migrated through the brine channel and reached the surface. Oil was removed with a syringe tip from a depth of approximately 5 cm below the ice/air interface through a brine channel having a diameter of approximately 3 millimeters. Figure 4-20 presents chromatograms obtained on: (A) encapsulated oil, (B) an oil sample obtained from the brine channel below the ice/air interface, and (C) a sample from a 5 mm deep oil pool which had migrated through a brine channel and flowed over the ice surface. Even at a depth of approximately 5 cm into the brine channel, some evaporative loss of lower molecular weight components below nC_0 had occurred. After this oil surfaced and had been exposed at the surface for 48 hours, the thicker whole oil mass showed loss of compounds below nC_{10} and nC_{11} (Figure 4-20C). This is equivalent to evaporative loss of most if not nearly all lower boiling components contained in TBP distillate cuts up through cut 7 (BP 282-304°F; 1984a). Payne, et al. With the oil in a thicker pool on the ice surface, diffusion-controlled evaporation is believed to predominate simulataneous weathering processes.

The possibility of diffusion-controlled evaporative weathering has been considered during earlier oil weathering investigations (Payne et al., 1981, 1984a). This process was investigated during these cold room wave tank experiments. An overflow of oil, which occurred during a temporary blockage of the seawater drain line, spread to varying thicknesses on the ice surface allowing the investigation of the diffusion controlled process. The oil spread out in a wedge from the point of origin to a final film thickness of less than 1 mm on the ice surface. This entire oil mass was then exposed to a 5 knot wind at an ambient average temperatue of -20°C. After 12 hours of exposure, samples of the less than 1 mm thick oil on the ice were obtained by carefully scraping the ice surface, melting the shavings, and then extracting the water for petroleum hydrocarbon measurements. Depth profiles in the thicker portion



Figure 4-20.--FID-GC Chromatograms of Wave/Ice Tank Oil Samples: (A) fully encapsulated by ice, (B) during upward brine channel migration, and (C) exposed on the ice surface for 48 hours.

of the wedged shape oil were also obtained to investigate differential evaporation with depth into the sample. Figure 4-21 presents the gas chromatograms obtained on the samples. As the chromatogram in Figure 4-21A illustrates, compounds with molecular weights less than nC_{14} (B.P. ~480°F) were completely removed within the 12 hour period from the 1 mm thick film. An oil sample obtained with a 2 mm thick film showed loss of compounds only below nC12; B.P. ~420°F (Figure 4-21B). The oil samples at deeper intervals of 4 and 5 mm yielded the chromatograms shown in Figure 4-21C and 4-21D, respectively. In these samples, only components with boiling points below 300-350°F are missing. Clearly, the differential residence time of the lower molecular weight components at depth in the film is established. Thus, in thicker oil pools stranded on ice surfaces, evaporation of the complete mass of oil will be diffusion controlled. The differences in evaporation rates due to different film thicknesses must be considered in the weathering model algorithms. The approach to modeling evaporation from a diffusion controlled slab was presented in the Open Ocean Oil Weathering Final Report (Payne et al., 1984a). A modeling approach of the analogous dissolution from a diffusion controlled slab is described in Section 6.0 of this report. To our knowledge, however, these are the first data that actually demonstrate the diffusion controlled process and verify its importance in accurately modeling oil weathering behavior.

There currently is only a mathematical model which describes the diffusive transport of specific molecular species through a stagnant slab of oil with evaporation at the oil-air interface. This model is not useable for an entire (whole) crude because of two reasons: First the diffusivities of pseudocomponents (used to described whole oil) have never been measured, and second, the actual diffusion-evaporation process results in a moving boundary that has never been incorporated into a model that describes concentration as a function of position. The primary reason for concluding that a diffusion-controlled weathering phenomenon was observed in the experiments described here is that the oil was not uniform in concentration as a function of depth. Therefore, species were transporting due to diffusion to the oil-air interface (no complete mixing).


Figure 4-21.--FID-GC Chromatograms of Oil Stranded on the Ice Surface with Oil Thickness of (A) 1 mm, (B) 2 mm, (C) 4 mm, and (D) 5 mm. These samples had been exposed to evaporative weathering under a 5-knot wind at -20°C for approximately 12 hours.

The time-series changes in hydrocarbon composition with the formation of stable water-in-oil emulsions were monitored by collecting and analyzing (FID-GC) bulk oil samples from the oil/water emulsion. Some evaporative weathering of the emulsion had occurred, although most of the lower molecular components were still present in this mixture (Figure 4-22). Comparisons between the aliphatic concentrations in fresh oil, encapsulated oil, exposed oil, and mousse are shown in Table 4-9. Relative to concentrations in fresh oil, significant losses of n-alkanes below nC_{12} were observed in exposed and emulsified oil, and losses of nC_8 through nC_{10} were particularly apparent in the mousse samples. During open ocean oil weathering with Prudhoe Bay Crude oil, comparable stable water-in-oil emulsion formation was not observed until evaporative weathering resulted in much greater losses of the lower molecular weight components (Payne et al., 1984a).

Whole Prudhoe Bay crude oil contains 36% non-distilled residuum which partially comprises surfactants that are important for formation of stable water-in-oil emulsions. Surfactant materials such as asphaltenes, higher molecular weight waxes (n-alkanes), and metalloporphyrin compounds serve to stablize whole water-in-oil emulsions and coat water droplets (Payne and Phillips, 1985). This prevents water/water droplet coalescence and phase separation (for additional data on the chemical and physical properties of fresh and artificially weathered Prudhoe Bay crude please refer to Payne et al; 1984a).

With the rapid onset of mousse formation due to the micro-scale turbulence of grinding grease ice and the ice floes, experiments were undertaken to attempt to quantify the percent asphaltenes and waxes in this emulsified mass. As noted earlier, stable water-in-oil emulsion formation was not observed in the outdoor (ice free) wave tank experiments until significant evaporation and/or generation of surface active materials, by a combination of photochemical and microbial degradation processes, had occurred.



Figure 4-22.--FID-GC Chromatograms of Emulsified Oil Weathering in the Presence of Sea Ice: (A) oil exposed for 32 hours, (B) oil exposed for 57 hours, and (C) subsurface mousse obtained two days after ice breakup.

Oil sample description								
Fresh	Encanculated	Exposed	Exposed	Mousse2 days				
riesh	Dicapsulaced	52 10015	57 110013	aitei bieakup				
3,670	2,590	432	228	ND ^b				
5,160	4,520	3,570	2,520	426				
5,680	5,500	3,760	3,640	1,540				
4,520	4,520	3,550	3,840	2,270				
4,960	4,950	4,140	4,760	3,280				
4,490	3,820	3,670	4,460	3,350				
3,630	3,210	3,210	3,820	3,060				
1,790	1,630	1,660	2,140	1,650				
2,960	2,610	2,620	2,980	2,490				
1,540	1,490	1,470	1,530	1,410				
2,240	2,130	2,160	2,220	1,950				
1,800	1,420	1,690	1,140	1,400				
144,000	127,000	112,000	184,000	70,900				
412,000	297,000	309,000	240,000	309,000				
	Fresh 3,670 5,160 5,680 4,520 4,960 4,490 3,630 1,790 2,960 1,540 2,240 1,800 144,000 412,000	Fresh Encapsulated 3,670 2,590 5,160 4,520 5,680 5,500 4,520 4,520 4,960 4,950 4,490 3,820 3,630 3,210 1,790 1,630 2,960 2,610 1,540 1,490 2,240 2,130 1,800 1,420 144,000 127,000 412,000 297,000	011 sample descrip Exposed Fresh Encapsulated 32 hours 3,670 2,590 432 5,160 4,520 3,570 5,680 5,500 3,760 4,520 4,520 3,550 4,960 4,950 4,140 4,490 3,820 3,670 3,630 3,210 3,210 1,790 1,630 1,660 2,960 2,610 2,620 1,540 1,490 1,470 2,240 2,130 2,160 1,800 1,420 1,690 144,000 127,000 112,000 412,000 297,000 309,000	Exposed Exposed Exposed 3,670 2,590 432 228 5,160 4,520 3,570 2,520 5,680 5,500 3,760 3,640 4,520 4,520 3,550 3,840 4,960 4,950 4,140 4,760 4,490 3,820 3,670 4,460 3,630 3,210 3,210 3,820 1,790 1,630 1,660 2,140 2,960 2,610 2,620 2,980 1,540 1,490 1,470 1,530 2,240 2,130 2,160 2,220 1,800 1,420 1,690 1,140 144,000 127,000 112,000 184,000 412,000 297,000 309,000 240,000				

Table 4-9.--Aliphatic Hydrocarbon Concentrations ($\mu g/g$) in Crude Oil as it Weathers in the Presence of Sea ice.

^a Concentrations corrected for water content.

^b Not detected.

A sample of the stable mousse from the wave tank ice chamber was removed and subjected to deasphaltization and dewaxing using the procedures of Bridie et al. (1980). Essentially, dewaxing was completed by dissolving the mousse into a six-fold dilution of methylethylketone:dichloromethane (1:1) at a temperature of -10° to -20° C. On standing for approximately 3 hours the waxes precipitate and can be filtered from the whole crude oil. Asphalts are removed by taking the dewaxed oil and completing a 30-fold dilution in n-pentane at the -10° to -20°C temperature. With this procedure, the percent wax in the weathered mousse from the wave tank was determined to be 4.6% and the asphalts were 7.4% (by weight). In fresh Prudhoe Bay crude oil the wax and asphalt content were measured at 3.9 and 3.7%, respectively. Thus, with evaporative losses of the lower molecular weight components, the relative percent of wax and asphalt in the mousse (compared with the fresh oil) is observed to increase. However, this increase is not believed to be large enough to account for the observed mousse stability, and the rapid onset of a stable emulsion instead be attributed to the water temperature $(-1.7^{\circ}C)$ and the must micro-scale turbulence introduced by the grinding action of the grease ice crystals.

4.3 CHUKCHI SEA FIELD OBSERVATIONS AND COMPARISONS WITH FIRST-YEAR ICE DURING TANK EXPERIMENTS

During February and March, 1984, the Oil Weathering Program was expanded to include a limited survey of ice structure and behavior in the Chukchi Sea. Helicopter overflights and observations of ice floe behavior and ice growth in open cracks and leads, as well as ice coring for ice salinity determinations and conductivity, temperature, depth (CTD) casts in the Chukchi sea, were performed. The purpose of the field observations and measurements was to facilitate comparisons of ice structure and temperature/salinity profiles observed in the wave tank experiments with actual conditions in first year ice fields. Results from these activities are described in this section.

Three station transects (B, C and D) west of Point Barrow were occupied during this field program (Figure 4-23). The sea ice encountered in the Chukchi Sea was characterized as a mixture of first-year and multi-year ice with fractured ice blocks (rubble fields) and numerous ice ridges (Figures 4-24 and 4-25). In addition, salt flowers similar to those formed in the wave tank at Kasitsna Bay were observed on the ice surface in the Chukchi Sea, and these are also characteristic of the rejection/exudation of brine in newly formed ice (Martin, 1979). Extremely sporadic (intermittent) multi-year ice ridges were characterized (as best as possible) by smoothed surface relief of elevated ridges (>3 m), excessive snow accumulation compared to adjacent floes and pans, and extremely low salinities (-3-5 ppt) where ice samples could be collected. In general, it was not easy to differentiate between first and multi-year ice in the study area, and the characterization was qualitative at best.

During the field observations in March 1984, the ambient air temperature was -38°C. Under these conditions, grease ice and frazil ice formation was observed in numerous open lead systems, along with accumulations of grease ice in both the dead zone and against the ice floes. The presence of the grease ice attenuated the small wind-induced chop within the open leads, and the ice formation sequence was similar to that observed during the previous first-year ice wave tank experiments at Kasitsna Bay (Section 4.2). In addition to the grease ice, hundreds of ice chunks ranging from 15 to 20 cm in thickness were piled up along the leads. These ice chunks were believed to represent one to two days of ice growth, which occurred after the lead first opened. The chunks were then pushed onto the adjacent ice when the lead closed due to differential motion of adjacent pans.

Several ice cores were collected near the open lead system near Station D2 to compare the crystal structure with that of the ice formed in the Kasitsna Bay wave tank. A columnar ice fragment from first year ice growth is shown in Figure 3-2 (Section 3.1). The parallel alignment of the vertically oriented ice crystals is similar to the structure of the columnar ice grown in





Figure 4-24.--Rubble Field of Fractured Ice Observed in the Chukchi Sea During February 1984.



Figure 4-25.--Ice Ridge Adjacent to Large Smooth Pan Studied During Ice Measurements in the Chukchi Sea in February/March 1984.

the wave tank (Figures 4-5 and 4-6 in Section 4.2.1). In the field, however, columnar ice may form to depths from 1 to 2 meters during the growing season (Martin, personal communication).

At many of the station locations CTD casts were taken for tracing subsurface water masses. In addition, ice samples were collected for salinity determinations for comparison with ice surface salinity measurements during the wave tank experiments. Table 4-10 presents salinity data obtained from ice samples collected near Point Barrow in the Chukchi Sea. Ice salinities ranged from 3.5 °/oo in a columnar ice sample to 45 °/oo in a thin brine-coated surface ice sample from a new lead. Water samples associated with the ice cores had salinities of approximately 29 °/oo whereas a sample of surface brine had a salinity of 62° /oo. These salinities were similar to the corresponding measurements obtained from ice, seawater, and surface brine samples collected during wave tank experiments (see Table 4-2).

Sea water salinity and temperature measurements were made at a series of stations from approximately 5 km to 50 km offshore (see Figure 4-23 for Salinity data from CTD casts along a transect off Station locations). Wainwright are plotted in Figure 4-26. The profiles suggest that relatively high salinity waters $(>33^{\circ}/oo)$ are generated from the brine produced during nearshore ice formation. During periods of ice growth in the Chukchi Sea, particularly in nearshore polynyas, salt extruded during frazil ice and grease ice formation may be responsible for localized increases in sea water salinities (Bauer and Martin, 1983; Kozo, 1983). The denser and more saline waters that accompany ice formation subsequently sink to the bottom and result in the near-bottom increases in sea water salinity shown in Figure 4-27. The denser bottom waters eventually may be transported by gravity flow in an offshore direction and accumulate in topographic basins or valleys. A similar brine transport mechanism has been suggested previously by McPhee (1980).

Table 4-10.--Salinities of Various Ice Types Obtained During Chukchi Sea Ice Investigations.

Field Site i ^a	Depth or Description	Salinity (0/00)
C-1	10"	11.5
•	12*	7.5
C-2	10*	16.1
•	18"	15.0
•	Water	28.7
C-3	Surface Brine	61.9
	3*	14.3
•	12*	15.4
C-4	24*	12.5
C-5	Water	29.1
C-6	2*	21.5
	24*	8.0
C-6*	12"	8.3
	36"	12.5
C_7	6*	11.0
	8.	8.3
•	12"	9.0
•	24*	10.2
n -2	Querflow 1 ^C	18.0
	Overflow 2	17.5
n_ 3	Columnar Ice - 10"	3.5
D-3	Surface Ice	21.0
New Londo	Thin New Ice	45.3
	Thick New Ice	14.1
	Columnar Ice	4.7

^aSite # designated by field study according to Lon Hachmeister ^bNot an official field site ^COverflow ice samples obtained at two different locations at site D-2



Figure 4-26.--Salinity Section off Wainwright, Alaska from March 1984.



Figure 4-27.--Temperature and Conductivity Profile from Near Station B2, 15 km Offshore. (See Figure 4-23 for station locations.)

4.4 LABORATORY SIMULATED MULTI-YEAR ICE TANK STUDIES

4.4.1 Generation of Multi-Year Ice

The experimental studies designed to investigate and verify the modeled behavior of oil spilled in or under first-year and/or multi-year ice required careful control of a wide variety of environmental parameters. These include the following: cooling and heating temperature conditions (including infrared radiation) to control ice growth and decay; the structure (macro and micro) of the simulated first- and multi-year sea ice; the rates of under ice currents to remove extruded brine generated during ice growth and dispersed oil droplets and dissolved aromatic components resulting from a spill; and the energy regime necessary to generate wave turbulence, which is crucial to both realistic initial formation of frazil and grease ice crystals and the subsequent deterioration of first- and multi-year ice floes/pans during melting and break-up. In the following section, the results of wave tank studies with oil in "pseudo multi-year" ice are considered.

A slightly modified or "pseudo multi-year" ice growth approach was utilized to simulate multi-year ice that has undergone more extensive brine channel drainage. A methodology was designed wherein simulated first-year ice was grown to a depth of 10 to 18 cm (including columnar ice) and then subjected to a partial thaw to induce brine channel drainage. The solid ice sheet was then mechanically broken into 50 cm by 75 cm blocks and subjected to additional wave turbulence for periods of up to 2-4 hrs, which allowed for further removal of salt brine from ice surfaces. With continued wave turbulence, the air temperature was intentionally reduced to -30°C to allow refreezing, with ridging and rubble field formation occurring during ice growth in the new This process was repeated several times, creating a small scale leads. simulation of the broken rubble fields, ice ridges, and multi-year floes that were observed in the Chukchi Sea (Section 4.3). Ice and seawater samples were collected for salinity determinations and for comparisons with field observations. The following section describes the processes and events and the data collected during the pseudo multi-year ice experiment. Table 4-11

presents a chronology of the times and dates of significant events that occurred during this experiment. Table 4-12 presents values for salinities of simulated first-year and multi-year ice, brine and seawater measured during the experiment as described in the following sections and outlined in Table 4-11.

The cold room and wave tank were basically configured as described in Section 4.1 for oil/first-year ice experiments, with the exception that a heat exchanger was installed on the tank discharge and incoming seawater lines so that flow-through seawater conditions could be maintained at higher flow rates without excessive strain on the cooling system and/or undesirable heating of the seawater in the wave tank. A nominal flow of 2.5 to 3 liters/min of -0.5 to -0.8°C seawater was supplied to the tank to simulate desired under-ice currents of 0.01 cm/sec. This flow rate resulted in one tank volume turnover (1870 liters) approximately every ten hours.

Following an initial cooling of the seawater temperature to -1.8°C, frazil platelets ranging from 1 to 5 mm across and 0.1 mm thick formed uniformly throughout the tank to a depth of 1 m. After an additional 1.5 hrs, slush ice had accumulated over the entire tank surface. Three and one-half hours after the first frazil ice was noted, the slush ice was approximately 10 cm thick over most of the tank, and three 20 cm diameter pieces of pancake ice formed near the dead zone at the quiet end of the tank. Wave generation was terminated at that time, and the surface ice was allowed to congeal and freeze in place.

Later, the entire ice surface was completely frozen, with the exception of several brine pools (several mm deep) with salinities of 56 $^{\circ}$ /oo (Table 4-12). These pools eventually evaporated and were replaced by salt flowers there and elsewhere in the tank. Approximately 24 hours after the first appearance of frazil ice, the solid slush ice surface was 14 cm at the vertical viewing window, and the first growth of columnar ice was noted. The air, ice, and water temperature profile was similar to that shown in Figure 4-4 for first-year ice.

Date	Time	Flow Rate (l/min)	Significant Event Description
3/15	1720	-	Initiation of cool down
.11	2250	3.2	Frazil ice throughout tank
3/16	0020	2.8	Grease ice 3" thick
11	0225	2.4	Wave generation terminated
H	1915	3.5	Appearance of salt flowers
PR .	2300	3.2	First appearance of columnar ice
3/17	1315	3.0	4" grease ice + 1 1/2" columnar ice
99	2230	2.8	Initiation of thaw
3/18	0930	-	4" grease ice + 2" columnar ice - brine pools
	2000	-	Initial brine channel formation
3/19	1410	-	Wave turbulence initiated - ridge system established
	1440	-	Turbulence terminated - cool down initiated
3/21	1100	2.5	Open leads and pressure ridge formed
н	1720	-	Open leads refrozen 1/4 to 1/2"
3/22	1440	2.4	700 ml PB Crude Oil Spill
3/23	0240	3.0	1/2" columnar ice under oil
	1440	2.5	l 1/2 - 2" columnar ice under oil
3/24	0030	2.5	Initiation of thaw
3/25	1215	2.6	Initiation of turbulence
3/26	0210	-	Brine channel oil migration
H	1500	-	Emulsification of oil - degradation of multi-year ice

Table 4-11.--Chronology of Times and Dates of Significant Events Occurring During the Oil/Multi-Year Ice Wave Tank Experiments.

Sampling Time			
Date	Time	Sampling Description	Salinity (%)
3/15/85	2200	Tank Seawater	30.9
	2250	Frazil Ice	21.9
3/16/85	0040	Grease Ice	17.7
11	1030	Top 1 cm Ice Surface	56.0
3/17/85	1600	Tank Seawater	30.5
	11	Top 1 cm Ice Surface	59.3
11	2300	Salt Flowers	100.0
3/18/85	1045	Tank Seawater	30.2
1	n	Pooled Surface Brine	57.5
	1930	Columnar Ice Under Ridge	10.1
3/19/85	2200	Tank Seawater	29.1
n	n	Grease Ice from Open Lead	24.4
3/20/85	1200	Surface of Refrozen Lead Ice	60.3
3/21/85	1300	Tank Seawater	30.4
11	n	Ridge Frozen into Lead	4.3
11	11	Columnar Ice from Ridge System	1.8
3/22/85	2030	Tank Seawater 6 hrs Post Spill	31.6
3/23/85	0240	Tank Seawater 12 hrs Post Spill	31.1
	1440	Tank Seawater 24 hrs Post Spill	31.0
3/25/85	1100	Tank Seawater 3 days Post Spill	30.3
	"	Columnar Ice from Ridge System	8.5
"	1630	Tank Seawater 4 hrs Post Break-up	31.0
3/26/85	0100	Tank Seawater 12 hrs Post Break-up	29.2
3/28/85	1200	Tank Seawater 3 days Post Break-up	29.7
11	11	Multi-Year Ice	8.9

Table 4-12.--Salinities During an Oil Spill in Multi-Year Ice Chamber Experiment.

Twenty-four hours of additional columnar ice growth was allowed until a 5 cm layer had accumulated beneath 10 cm of frozen slush ice at the vertical window. At that time, the cold room was allowed to stand open overnight at -5 to -2°C to initiate the first "Spring" thaw (Table 4-11). Later, a quartz infrared heater was installed 1 m above the tank and the ice was illuminated for several hours while the room temperature was maintained at -5 to -10°C to initiate brine channel formation and drainage.

A 15 cm by 45 cm chunk of ice was physically cut from the center of the tank and two similar sized pieces were pryed from the tank walls to create a 45 cm wide "lead" across the entire width of the tank. The remaining slush/ columnar ice in front of the paddle was loosened. Two large blocks of ice, which had been removed from the surface, were forced by hand under the leading edge of the remaining fast ice in the tank to form a ridge system at that end of the tank.

A subsequent freeze and ice breakup cycle was performed to build up simulated "multi-year" ice ridge keel system. In so doing, surface- and the under-ice relief was generated with blocks of older ice which had now undergone two and one-half freeze/thaw cycles providing appropriate ice conditions for the oil release experiment. The surface ice relief exceeded 20 cm where ridging occurred, and the under-ice relief encompassed a range of 8-35 cm. The newly opened lead system was refrozen to a depth of 4-6 cm in preparation for Most of the ridge surfaces and keels were fairly smoothed the spill event. over due to the various freeze/thaw cycles. The new ice in the lead was 4 cm thick and no longer plastic. Salt flowers were abundant in the newly refrozen lead, but did not occur elsewhere because the remainder of the ice field had undergone numerous freeze/thaw cycles and surface rinses which lowered salinities considerably (Table 4-12). A 0.3 meter wide lead, approximately one meter long, was cut from side-to-side at the paddle end of the wave tank, and a large chunk of refrozen grease ice was left in the center of the intended experimental lead.

4.4.2 <u>Oil/Multi-Year Ice Interactions</u>

A measured volume of 750 mls of fresh Prudhoe Bay crude oil was added to the experimental lead using a funnel and Teflon tubing to prevent inadvertent spillage onto adjacent ice surfaces. Oil was released at a depth of approximately 2.5 cm below the water surface in the open lead, and little of the oil was injected underneath the ice surface. The oil spread to form pools in small patches, approximately 4-5 cm in diameter on the quesant, open water in the lead system, and the total volume introduced was measured by difference. After the initial addition, no oil was visible on the under-ice surface and, likewise, no oil was observed on the under-ice ridges. The seawater temperature was -1.7° C at the time of the spill, and the cold room temperature was maintained at -3 to -8° C.

Water samples were obtained by pumping 20 liter volumes through a small hole drilled in the ridge system between the nearshore rubble field and end of the tank ridge zone through a 293 mm diameter glass fiber filter in a Millipore stainless steel filter unit. This procedures allowed differentiation of dispersed and dissolved aromatic hydrocarbon components in the water column. Water samples were collected at 0, 1, 3, 6, 10, 12, 24, 48 and 72 hours following the initial spill event. After three days a break-up event was initiated and additional water samples were collected at 1, 4, 8, 12, and 24 hours and then again at 3 days and 5 days post-break-up. As in the oil/firstyear ice experiments, oil samples were collected at various intervals to measure rheological properties, including oil/air and oil/water interfacial surface tension, oil viscosity, and percent water uptake due to water-in-oil emulsification.

Approximately 50 minutes after the spill, the paddle was turned on in very short bursts to simulate the pumping action of a closing lead system. With the first 3-4 cm wave, the oil was observed to wash onto the ice surface adjacent to the lead where it was trapped in the 3-5 cm ice rubble, chips of columnar ice, and around the base of small (5-8 cm) ridges in the upper ice surface, such that an estimated 3-5% of the oil was prevented from returning to

the lead. As the paddle went through a complete revolution and seawater was also deposited on the upper ice surface, oil was observed to spread out in a colored sheen on top of the ice floe adjacent to the paddle. Where standing water was present, the oil flowed evenly over the ice. With a complete paddle revolution, oil was also observed to wash over the nearshore ice in the fast ice zone and pool in areas adjacent to the vertical window and in ridge and rubble ice structures approximately 50 cm from the open lead. At this time, additional oil droplets were noted impinging on the under-ice surface of the ridge systems adjacent to the vertical window. Oil that was not trapped in surface ice depressions flushed slowly backwards towards the open lead system. The horizontal extent of the oil flowing over the ice was limited to the 50 cm closest to the lead opening by the presence of a 5-10 cm ridge system of blocks which prevented further spreading. The ice edge adjacent to the paddle was then positioned to trap the oil in the lead system and prevent it from running back to the paddle area and behind it. As a result of the several "ice push" incidents, there was a considerable amount of oil forced up onto the near lead refrozen ice. Most of this pooled in areas up to approximately 3 mm thick.

On the underside of the smooth ice and ridge keels adjacent to the experimental lead, several very small oil drops could be observed on the ridge side closest to the paddle turbulence. These impinged as small droplets ranging in size from barely visible to up to 2 millimeters. The average size of most droplets was about 1 millimeter in diameter or slightly smaller. In an effort to drive a slightly larger quantity of oil under the ice ridge system the paddle turbulence was again initiated and pulses approaching 1/2 cycle were used. These pulses caused a considerable volume of oil to be washed over the ice surface, and a small volume of the oil (estimated 5-10%) was observed to disperse under the ice surface and impinge on the under-ice ridge system. Considerable amounts of the oil were washed on the upper ice surface nearly to the first ridge system 50 cm from the experimental lead. However, considerable amounts of oil still drained back into the open lead system.

Approximately 1-1/2 hours after the initiation of the spill, most of the oil, which had been in the swash zone on the fast ice immediately next to the lead had been washed off and returned to the oil pool in the open lead. There was still approximately 200 or 250 mls of oil stranded on the ice surface, which was not subject to drainage into the lead system, and these pools were allowed to remain to monitor evaporation weathering. Approximately 2 hours after the initiation of the spill, the compressor unit was turned back on to initiate a partial re-freeze. An estimated 90% of the open lead was covered by a thin film of oil.

During collection of the 3 hour water sample, the oil in the refrozen lead system was on a thin layer of freshly growing ice, estimated by penetration with a syringe to be about 1 or 2 millimeters thick. Under these conditions with limited direct water contact, the potential for addition dissolution of hydrocarbons was clearly minimized. Oil covered 80-90% of the experimental lead system, and in areas where oil did not coat the lead system, ice formed to a depth of approximately 1-3 millimeters. Freezing under the oil, was allowed to continue for at least another three hour period. At that time, ice thicknesses directly under the oil and in the open areas adjacent to the oil were examined to see if the oil imparted some differential rate of ice growth in this system. As suggested by Ross, et al. (1977), Walker (1975) and Wilson and Mackay (1986), any difference, if noted, was not significant under the calm test conditions examined in this experiment.

Six hours after initiation of the spill, most of the thicker oil in the lead system had been undergrown by 3-7 millimeters of <u>columnar</u> ice. The oil itself set up as a viscous film which pooled on the ice surface, and the oil thickness was measured to be 1 to 3 mm thick. Deeper pools of oil were observed on the stranded ice floe of grease and columnar ice intentionally frozen in the center of the lead. Elsewhere, oil which had been stranded in pools on the fast ice adjacent to the vertical window and ridge system appeared unchanged, although it had weathered by evaporation over the 6-hour period since all turbulence had been terminated.

In certain areas, stranded oil pooled to an estimated depth of 1 to 2 and chips of broken ice, which had been generated during the breakout mm. events and deposited in the "swash zone", had collected oil coatings over 90% of their surface. Larger 8 to 10 cm pieces of ice were unstained although they were coated with oil around the base. Several pools of oil formed higher on the fast-ice surface, on the lee side of several ridge systems. These pools which had been driven onto the ice surface during the wave turbulence approached 1 cm in thickness in several places. The washing effect of waves caused oil on the smoother areas to be removed almost completely with each wave During water flooding the oil tended to float off the ice into the open pulse. lead system and was only later caught by the capillary systems of the ice after water had drained through. Surprisingly, the stranded oil was very fluid to the touch despite the -23°C temperature conditions, and it did not exhibit a crust or more viscous surface layer.

Based on observations of oil behavior during the first 12 hours after the spill, it was noted that the oil floating on the water surface behaved very much like slush ice. It was herded by the wind from the refrigeration system into quiet zones against ice floes. Then under varying conditions of light wind, the oil spread out to some uniform thickness (1-5 mm) controlled by the volume spilled, the viscosity of the oil, and the area of the lead system available. Once this spreading occurred, the oil then cooled rapidly and with wave dampening due to the higher oil viscosities at ice formation temperatures, columnar ice growth then occurred beneath it. Modeling such conditions should be possible in that the oil could be considered as a diffusioncontrolled slab with no turbulence or diffusive mixing allowed. The only parameters required to model such a system would be the area of the lead and the volume of the oil spilled.

At this point in the experiment, it was apparent that three separate oil-weathering scenarios could be examined. The first was oil spilled into a refreezing lead system under calm conditions where grease and columnar ice soon formed beneath the oil surface. In this instance, the oil weathers by evaporation only as a diffusion controlled slab, as if it were spilled on top of solid

ice. The second case was oil spilled beneath the ice surface, where it was subject only to dissolution weathering before being encapsulated by additional ice growth (as considered during the oil in first-year ice spill scenarios in Section 4.2 of this report). Finally, although it was not occurring at the time, it was clear that the experiment <u>could</u> be modified by initiating a gradual thaw to evaluate conditions where oil was spilled into a decaying older pack-ice or multi-year ice field in which ice would break-up and decay due to wave turbulence and warming (air and water) conditions.

Very little additional change or activity was noted in the pooled oil after the lead froze over, so to investigate oil weathering behavior during the break up of older pack ice, a break-up event was initiated 3 days after the oil spill. The first paddle surge resulted in a water wash over the oil-covered refrozen lead system. Some of the oil on that lead system immediately started flowing from the edges of the refrozen lead. Oil then was washed from the refrozen lead system onto the swash zone of the fast ice where the thicker portions of oil remained fairly intact. The oil was still amazingly fluid and was observed to flow smoothly over the ice surface, spreading out in bands that were dark brown in color; no colored sheen was observed at the initiation of Greater than 98% of the oil which had been on the refrozen lead was break-up. eventually washed from its surface within five to seven minutes of the start of wave turbulence. All of this oil was observed to flow back and forth with each passing 3-5 cm wave onto the adjacent fast ice front. With continued paddle turbulence, oil droplets were forced beneath the fast ice surface where they impinged on the skeletal layer of the columnar ice under the ice surface. Much of the oil washed off the upper swash zone of the fast ice and into the backwater area immediately adjacent to the vertical windows. Oil floated on the stranded water surface as the seawater filled in and ran among the ridge systems frozen in the blocks of columnar ice associated with the simulated "multi-year" ridge buildup.

After the majority of oil was removed from the refrozen lead, where it was originally released, pockets of oil droplets (up to one cm in diameter) could be observed still frozen in the ice. Evidently these small volumes of

oil were trapped in columnar ice during the downward ice growth phase. The contribution of these trapped oil droplets was estimated to be much less than 1% of the total volume added to the tank.

Within 20 minutes of the onset of surface wave turbulence, the oil which had previously been stranded in the swash zone eventually was washed clear and onto the water surface. There was evidence of small pockets of oil that had frozen into deeper cracks in the swash zone, but these were not yet The entire under-ice surface was coated with millimeter to 5.5 cm affected. diameter oil droplets (Figure 4-28) within one hour of the onset of 4-6 cm wave turbulence. Oil which washed from the lead area accumulated in small pools in the ridge zone and on the under surface of the ice. Some oil migrated up through the columnar ice system. Also present under the ice were chips of grease and columnar ice blocks of 2-8 cm diameter, which broke away from the main stationary ice body and were forced under the fast ice by the action of the wave turbulence. With each passing wave, oil appeared to be forced into and through the under-ice capillary system to the point that it had penetrated the brine channels and the skeletal layer by as much as 3 or 4 millimeters.

Over 90% of the oil released in the tank eventually impinged on the bottom of the ice. It is possible that this behavior could also occur with waves breaking against larger pack- or multi-year ice pans, not just on shorefast ice. That is, larger pans with diameters greater than 10 meters would have sufficient size and momentum associated with them that wave and current turbulence could tend to wash slightly over and under their edges if surface and subsurface relief was not too extensive. Such wind and current induced under ice oiling was noted in the Bouchard #65 spill in Buzzards Bay (Arctec Inc., 1977, and Deslauriers et al., 1979) under pack ice during the Kurdistan spill in Cabot Straight (C-Core, 1975) and in a spill of No. 6 fuel oil in the Gulf of the St. Lawrence River, Canada near Matane, Quebec where the slick was driven by winds across open water only to become intrained within a shoreline field of grease and pancake ice (Wilson and Mackey 1986). Smaller floes on the other hand may tend to ride over waves or swells with less turbulent interaction such that less oil may be trapped beneath then. With



Figure 4-28.--Underwater Photograph of Dispersed Oil Droplets Entrained in the Under-Ice Ridge Keel System Nearest the Newly Opened Lead (Vertical Window) 5 Minutes after the Introduction of Quarter-cycle Paddle Pulsed Turbulence During the Breakup Event.

such turbulence under larger floes, any submerged oil (if present) could be subject to dissolution and not evaporation weathering.

Time-series measurements showed that oil deposited earlier beneath the ice (immediately after the spill) had migrated 3 or 4 millimeters into the columnar ice structure. Later arriving oil was deposited as emulsified droplets with higher viscosities.. With continued thawing these oil droplets then moved through the columnar ice until they reached the angular ridge systems imbedded in the ice earlier during the ridge formation and multiple re-freezing process. At this point, the oil was subject to differential entrapment and migration at different angles into the ridge system where columnar ice directions were no longer vertical. With continued thaw, this material would be released to the water column, although it would be delayed for some time when the migrating oil interacts with columnar ice with a different crystal structure orientation due to freezing of blocks and chunks of ice in a random orientation during multi- year ice ridge formation.

4.4.3 <u>Compound-Specific Partitioning, Whole Oil Droplet Dispersion and Oil</u> <u>Phase Chemistry</u>

Figure 4-29 presents flame ionization detector gas chromatograms obtained on representative oil samples from the surface of the refrozen lead and oil pooled on the multi-year ice floes as a function of time. Figure 4-29A the time zero starting crude oil, which is characterized by even and odd is n-alkanes from nC_7 through nC_{32} along with a wide variety of other resolved components in the KOVAT INDEX range of 700 to 3200. Evaporative losses of compounds below nC10 represented the major weathering process during the 48 hours following the spill (Figure 4-29B). Break-up of the refrozen lead containing most of the oil, then re-injected the partially weathered oil into the water It should be noted that although many of the lower molecular weight column. compounds appear to be lost by evaporation, there were still sufficient concentrations of many mono-cyclic aromatics such as toluene, o,m,p-xylene and ethylbenzene that dissolved hydrocarbon levels in the water column were elevated one hour post-break-up (e.g. see Table 4-13). The final chromatogram shown in Figure 4-29C is of a surface oil sample obtained 4 days post-break-up. At this

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Figure 4-29.--GC-FID Chromatograms Depicting Prudhoe Bay Crude Oil Spilled in Multi-Year Ice: (A) time 0 (prespill), (B) 48 hours post spill (surface of refrozen lead), and (C) 4 days post breakup.

point the oil had weathered considerably; it had undergone moderate water-in-oil emulsification (to be discussed later) and a combination of evaporation <u>and</u> dissolution losses had removed all compounds below nC₁₁.

Figure 4-30 presents FID gas chromatograms for the filtered (dissolved) whole seawater extracts obtained at several time points throughout the Chromatogram 4-30A presents a time zero pre-spill blank, and is experiment. characterized by a few low level compounds intrinsic to the seawater system of Kasitsna Bay plus an internal standard. Chromatogram 4-30B shows those dissolved aromatic hydrocarbons present 3 hours after the spill. At this time, many lower and intermediate molecular weight compounds through the alkylsubstituted naphthalenes are present in the seawater, despite the fact columnar ice was already forming under the oil pooled in the refreezing lead. Several wave pulses immediately after the spill distributed dispersed hydrocarbons beneath the ridge system, but subsequent columnar ice formation effectively separated the surface oil from the water column. The continued tank volume turnover every 10 hours cleansed the water column of these lower molecular weight aromatics, such that concentrations of all contaminants had been reduced significantly 3 days post-spill (Figure 4-30C). Figure 4-30D shows the chromatographic profile of dissolved aromatics measured in the water column one hour post-break-up; at this point the oil had undergone significant diffusioncontrolled evaporation weathering while stranded in above-ice pools in the lead system. Nevertheless, dissolved aromatics were released when oil droplets dispersed into the water column and impinged on the under-ice surface. This significant dissolved aromatic hydrocarbon pulse presumably reflects the increased surface area due to the 6-10 cm wave induced formation of less than 1 micron to 1 millimeter sized oil droplets which coated the entire under-ice surface. Thus, even though many lower molecular weight compounds had been removed by evaporation, significant concentrations remained to allow for an elevated concentration of these aromatics immediately after the break-up event. Finally, chromatogram 4-30E shows the residual higher molecular weight compounds still remaining in the water column five days after the break-up. Notably, the chromatogram is characterized by naphthalene, 1- and 2-methylnaphthalene, and alkyl-substituted naphthalenes and phenanthrenes.



Figure 4-30.--GC-FID Chromatograms of Extracts of Seawater Obtained During the Oil/Multi-Year Ice Interaction Experiment: (A) time 0 (prespill), (B) 3 hours post spill, (C) 3 days post spill, (D) 1 hour post breakup, and (E) 5 days post breakup.

Summary concentration profiles of individual and total aromatic hydrocarbons in the water column are presented in Figure 4-31. Specifically, Figure 4-31A shows the sum of the total resolved and unresolved complex mixture (UCM) compounds in the dissolved fraction versus time during the spill event. The total resolved compounds, and several lower molecular weight aromatics including toluene, o,m,p-xylene, and ethylbenzene (i.e., Figure 4-31B and Figure 4-31D), displayed elevated concentrations in the water column immediately after the spill event. The total resolved plus unresolved complex mixture compounds in the first to second hour after the spill reached concentrations of approximately 40 micrograms per liter. Not surprisingly, the majority of these compounds were lower molecular weight mono- and dicyclic aromatics. Toluene was present at the highest concentration, approaching 12 micrograms per liter within 2 hours of the spill.

Within 3 to 6 hours after the spill event (Figure 4-31) concentrations of these compounds declined rapidly with the onset of columnar ice formation, under the surface oil slick, which effectively decoupled or removed the source of hydrocarbons from the water column. Thus, by 24 hours after the spill, most the lower molecular weight compounds had been removed from the water column of subsurface advection. When the break-up event occurred, the concentrations bv of several lower molecular weight aromatics remaining in the oil (such as the xylenes, C2-benzenes, and 2-methylnaphthalenes) were still high enough in the oil such that concomitant water column concentrations still exceeded the initial concentrations of these compounds in the water column by a factor of 3 The concentrations of dissolved toluene at least equalled the initial 5. to spike levels measured immediately after the spill. The dicyclic, higher molecular naphthalene, 1-methylnaphthalene, weight aromatics. and 2,6-dimethylnaphthalene, with their higher m-values were not present in the water column immediately following the spill event. It was only after the break-up event and the introduction of wave turbulence that concentrations of these compounds reached substantial levels. Table 4-13 presents time-series concentrations of each of the resolved aromatic hydrocarbons in the water column following the spill and break-up events. The data follow the same general pattern exhibited in Figure 4-31; with the formation of columnar ice

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Figure 4-31.--Selected Dissolved Hydrocarbon Concentrations versus Time from an Oil Spill in Multi-Year Ice.



Figure 4-31.--(Continued)

······································	Concentration (ug/1)														
				Time	Post Spill						Τίπ	e Post Brea	(-up	<u> </u>	
Compound	1 hour	3 hours	6 hours	10 hours	12 hours	24 hours	48 hours	3 days	1 hour	4 hours	8 hours	12 hours	24 hours	3 days	5 days
Toluene	12.7	12.3	6.72	6.07	5.50	.839	.228	.654	14.0	9.97	10.3	4.80	1.51	.525	.0577
Ethylbenzene	1.31	1.30	.728	.673	.679	.0974	.0238	.0800	3.13	2.02	2.79	1.35	.651	.232	ND
m6p-Xylene	3.98	4.16	2.26	2.11	2.09	.335	.0687	.278	10.9	7.53	10.6	5.40	1.89	.979	ND
o-xylene	1.90	1.94	1.07	.948	.963	.143	.0250	.102	-	4.08	5.82	3.03	1.09	.529	ND
Isopropylbenzene	.130	.125	.0642	.0656	.0689	ND	ND .	ND	.540	.342	.638	.277	.240	.966	ND
n-propylbenzene	.189	.186	.0950	.981	.102	.0223	ND	.0150	1.04	.613	1.10	.557	.505	.221	ND
C ₃ -benzene	.650	.642	.352	.333	.330	.624	.0145	.0538	3.57	2.35	4.26	2.32	1.83	.842	.0432
C ₂ -benzene	.209	.205	.103	.106	.113	.0232	ND	.0174	1.46	.905	1.69	.977	.939	.415	ND
1,3,5-trimethylbenzene	.284	.286	.157	.146	.151	.0266	ND 1	.0212	1.73	1.16	2.11	1.22	1.19	.451	ND
C ₂ -benzene	.730	.730	.402	.372	.245	.0758	.0259	.0602	5.07	3.43	6.44	3.90	2.96	1.53	.0942
C ₄ -benzene	.438	.442	.260	.227	.244	.0528	.0309	.0493	3.40	2.31	4.41	2.89	3.35	1.13	.0872
Tetramethylbenzene	.128	.137	.0735	.0376	.0585	.0471	ND	ND	.204	.188	.0824	ND	ND	ND	ND .
Naphthalene	.657	.680	.428	.343	.345	.0618	.0191	.0397	7.73	6.00	11.7	10.3	1.09	.520	.472
2-methynaphthalene	.408	.378	.240	.202	.207	1.0467	.0177	.0306	6.76	5,49	11.1	11.8	8.33	6.90	2.58
1-methylnaphthalene	.322	.302	.197	.168	.175	.0373	NO	.0243	5.44	4.40	9.00	9.57	8.41	5.41	1.97
1.1'-biphenvl	.0430	.0199	ND	ND	ND	ND	ND	ND	.909	.690	1.42	1.83	2.01	1.10	.466
2.6-dimethylnaphthalene	.121	.0844	.0467	.0380	.0357	ND	ND	NO	1.61	1.23	2.50	3.00	2.49	2.33	1.07
C ₂ -nachthalene	.139	.0906	.0414	.0352	.0347	ND	NO	ND	1.94	1.65	3.49	4.20	1.55	3.14	1.48
C-naphthalene	.0288	.0181	ND	ND	ND	ND	ND	NO	.436	.334	.685	.871	.718	.650	.311
C-nachthalene	.0231	ND ^a	NO	ND	NO	ND	ND	NO	.385	.378	.809	.678	.600	.469	.383
2.3.5-trimethylnaphthalene	.0278	ND	ND	NO	NO	ND	ND	ND	.322	.245	.468	.623	.700	.548	.345
Dibenzoth iophene	.0206	NO	NO	ND	ND	ND	I ND	ND	.237	.155	.332	.450	.633	.453	.321
Phenanthrene	.0220	ND	ND	ND	ND	ND	ND	ND	.225	.179	.357	.498	.633	.456	.362
Total Resolved Compounds	28.1	26.7	14.9	13.2	13.0	2.70	1.27	Z.11	91.3	65.7	114	92.2	77.0	46.5	16.8
Unresolved Compounds	8.79	7.35	3.02	1.34	5.00	1.7	6.49	3.85	25.4	13.8	47.7	22.1	45.5	28.4	14.5

Table 4-13.--Dissolved Hydrocarbons from an Oil Spill in Multi-Year Ice.

a - "ND" indicates "not detected"

beneath the oil, many of the higher molecular weight compounds were rapidly removed from the water column. Also, concentrations of the lower molecular weight compounds (toluene, ethylbenzene, and xylene) decreased by several orders of magnitude within 3 days. Nevertheless, the concentrations after break-up were still sufficient to reach levels at least equal to those observed in the first hours after the spill. Furthermore, the higher molecular weight compounds, which were not removed by evaporation dispersed and dissolved into the water at concentrations approaching 1 ppb (see Table 4-13).

Wave turbulence is critical for dispersion of whole oil droplets into the water column. Data from dispersed whole oil droplet concentrations in the water column are presented in Table 4-14. Dispersed oil concentrations were only moderate during the first 1 to 3 hours following the spill. The dispersed oil concentrations, as represented by n-alkanes, then decreased rapidly in the water column after columnar ice formation. After break-up and resumption of 6-10 cm wave turbulence, however, concentrations increased by over two orders of magnitude; at 8 hours post-break-up the total dispersed hydrocarbons concentrations were in excess of 800 ppb. After 12 hours, with water-in-oil emulsification, higher oil viscosities, and the impingement of most dispersed oil droplets onto the under-ice surface, the spike in the dispersed hydrocarbon concentrations decreased. However, the large number of dispersed oil droplets trapped on the underside of the ice surface still provided a significant surface area for interphase mass transfer and, therefore, dissolution of lower and intermediate molecular weight compounds.

Table 4-15 presents the chemical and physical characteristics of the oil spilled in the pseudo "multi-year" ice. The interfacial surface tension and viscosity were not effected as drastically as during the oil in first-year ice experiments (Section 4.2). This is primarily due to differences in the ice behavior during the breakup event. Specifically, the multi-year ice floe was degraded by melting in the warmer (-1.0 to -1.5°C) water and wave radiation (ablation) interactions, as discussed in Pease (1981) and Martin et al. (1983). The first-year ice, on the other hand, was observed to breakup into slush ice with the onset of 6-10 wave turbulence during the spring thaw. Thus, the high

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	Concentration (ug/1)						
Time	Resolved Compounds	Unresolved Compounds	Total Hydrocarbons				
1 hour Post Spill	19.4	18.7	38.1				
3 hours ""	22.4	18.4	40.8				
6 hours ""	17.6	7.82	25.4				
10 hours " "	3.74	4.32	8.06				
12 hours " "	5.88	7.41	13.3				
24 hours ""	1.99	5.87	7.86				
1 hour Post Break-up	2.73	11.7	14.4				
4 hours "	3.60	9.29	12.9				
8 hours "	220.	589.	809.				
12 hours "	3.89	13.2	17.1				
24 hours "	4.47	14.9	19.4				

Table 4-14.--Dispersed Oil Concentrations from an Oil Spill in Multi-Year Ice.

Table 4-15.--Chemical and Physical Characteristics of Oil Spilled in Multi-Year Ice.

	Hydrocarbon	Concentration (mg/g)	Surface Tensio	on (dynes/cm)	Viscosity 0 38 ⁰ C	Water Content (% by weight)	
Time	Total Resolved	Unresolved Compounds	0il/Water	0il/Air	(centipoise)		
Stanting Coudo	110	220	24 6	21 0	20	02	
1/2 be Deet Soill	119	229	24.0 a	51.0	30	.03	
1/2 nr Post Spill	98.2	182	-	-	-	.99	
3 hrs Post Spill	67.6	161	-	-	-	-	
12 hrs Post Spill	91.8	206	-	-	-	-	
24 hrs Post Spill	77.1	238	-	-	-	-	
9 hrs Post Break-up	20.8	55.2	-	-	-	13.6	
24 hrs Post Break-up	28.8	134	-	-	-	-	
3 days Post Break-up	19.3	88.5	-	-	-	-	
6 days Post Break-up	14.9	98.4	17.4	35.3	2000	28.1	
					.L		

 $^{\rm a}$ – limited sample volumes precluded measurements

concentrations of slush ice observed during first-year ice decay created localized microscale turbulence under the influence of the surface waves, and this important for the generation of stable water-in-oil emulsions. was In the multi-year ice case, the ice structure appeared to be ablated and worn down more slowly. Thus, a gradual thaw of the ice, rather than physical break-up into grease ice, occurred. As such, localized turbulence was much lower than in the oil/first-year ice study, which resulted in the delayed viscosity increase to 2,000 centipoise (measured on an aliquot in the lab at 38° C) (6 days post breakup) and the minimal water incorporation. The water content in the emulsified crude was 13.6% 9 hours after the break-up event. During oil/first-year ice studies, the water content was 60% just 4 hours after the initiation of wave turbulence. The grinding of slush ice resulted in the increased microscale turbulence responsible for rapid emulsification. Six days after the final break-up event in the multi-year ice study, water content in the oil was still only 28% by weight while the viscosity was similar to that in the first-year ice experiment (i.e., 2,000 centipoise at 38°C). In contrast, water content for Prudhoe Bay crude oil weathering in the presence of firstyear ice was 64% at the same time. Open-ocean wave tank simulations of waterin-oil emulsification with Prudhoe Bay crude oil are somewhat dependent on the formation of surface active agents to stabilize the emulsion and prevent water/ water droplet coalescence. Thus, it was only after a longer period of 6-9 days that similar water content and viscosities were observed in sub-arctic open ocean simulations (Payne et al., 1984a).

4.5 SIMILARITIES AND DIFFERENCES IN WAVE TANK SIMULATIONS OF OIL WEATHERING BEHAVIOR IN FIRST- AND MULTI-YEAR ICE

The similarities and differences between oil weathering behavior in first- and pseudo-multi-year ice are considered in the following discussion. First of all, the importance of molecular weight in compound specific aromatic hydrocarbon dissolution, in oil weathering with both first- and multi- year ice, cannot be overemphasized. There was an initial concentration spike of 40 μ g/l of lower molecular weight components (toluene, o-, m-, and p-xylene, ethylbenzene and C₃-benzenes) immediately after the oil release in the multi-year ice experiment; however, after freezeup occurred (columnar ice formed
under the oil), water column concentrations returned to near background levels within a 24 hour period. Following columnar ice formation the surface slick weathered by evaporation only. After break-up, there were still sufficent lower molecular weight aromatic hydrocarbon concentrations in the slick to at least equal the earlier concentration spike in the water column. Nevertheless, columnar ice growth under oil in calm conditions is extremely important because it decouples oil from the water column. However, this probably will be a factor only under very calm conditions in the field.

In the oil/first-year ice experiments, the initial concentration spike of dissolved aromatics in the water column (before encapsulation in the ice) was also about 40 μ g/l. These concentrations declined over a 24 hour period, except that the seawater-exchange flow rate was three times slower (1 liter/ minute). This slower water flow rate and the greater volume of oil released (5,000 ml vs 750 ml) suggest that aromatic hydrocarbon dissolution was approximately 18 times slower in the oil under first-year ice release. However, the slick was contained in larger, thicker pools on the under-ice surface before encapsulation. Thus, the surface area for interphase mass transfer was greatly reduced. In both experiments the seawater temperature was measured at -1.7 to 1.8°C.

With ice break-up and wave turbulence in both studies, significantly higher dissolved concentrations were again observed, and much higher concentrations of dissolved components <u>on a per ml of oil spilled basis</u> were measured in the multi-year ice case. Specifically, the maximum total dissolved (resolved plus UCM) components three to four hours after break-up were 0.23 and 0.20 (in units of total dissolved aromatics in μ g/liter of seawater per ml of oil spilled) for the oil in multi-year and first-year ice cases, respectively. However, the seawater flow rate was three times higher in the multi-year ice case, which suggests that the relative oil droplet surface area to volume ratios were approximately three times higher when turbulence was introduced in the multi-year ice break-up event. That is, to reach and maintain a similar dissolved aromatic hydrocarbon concentration on a per gram of oil-spilled basis, when different volumes were spilled and different seawater flushing rates were encountered, significantly different surface to volume ratios must have been generated. In the first-year ice study, 6.6 times more oil was released at one-third the flushing (seawater turnover) rate, and yet, the total dissolved concentration was only 5.8 times higher on break-up. Thus, there may have been a three fold higher surface area to volume ratio for interphase mass transfer in the multi-year ice case after break-up. Again, in the multi-year ice study there was little droplet dispersion without wave pumping. Then, with just 30 minutes of 6-10 cm wave turbulence, over 80% of the oil was trapped under the fast ice as <1 μ m to 1 cm droplets. Alternatively, the very rapid onset of a stable water-in-oil emulsion and the concomitant increase in oil viscosity in the first-year ice study may have slowed or prevented dispersion of smaller oil droplets into the water column.

The coldroom wave tank experiments also suggested that oil may be forced by waves under fast (or stationary) ice to a greater degree than first-Wave-induced pumping can force oil both directions, on top of vear pancakes. and beneath smaller, floating ice pans. In fast ice (and presumably larger multi-year floes with stabilizing ridges, etc.) the waves interacting with the ice will also cause the oil to be distributed on top of and underneath the floe (depending on freeboard). That oil which ends up under the floe tends to stay there (as demonstrated in the wave tank with both first- and multi-year ice). It is trapped in under-ice depressions, ridges, and even in the skeletal layer of columnar ice (if present). Oil will tend to remain in place even in the presence of ice/water differential current velocities of up to 15 to 25 cm/sec (Cox et al., 1980). The oil deposited on the upper surface of larger multiyear floes, on the other hand, is subject to repeated washings. Some of the oil (e.g., approximately 10-20%) was washed further back onto the surface layers of ridges, cracks, and rubble (8-12 cm above the water surface), but the majority of the oil, which was initially deposited on the ice "beach face", did not stay there. Small waves (6-10 cm high), which are equivalent to localized wind chop, quickly rinsed the oil back into the water (i.e., the oil did not stick to the smooth multi-year ice surface). Within hours, approximately 90% of the oil ended up in the open water or was deposited on the under side of the ice. This was particularly true if the ice "beach face" sloped down at the ice

water interface. If there was an abrupt verticle face and a surface depression on the ice behind the edge then some oil was splashed up onto the ice, but only if the freeboard was not greater than 10 to 15 cm. If it was, then the oil went under or around the floe. First year pancakes in the wave tank, on the other hand, tended to be smaller and, as such, had less inertia and more bouyancy. Thus, they tended to float higher in the waves, and small waves did not wash oil off. Instead, the smaller pans tended to get pushed along, with oil contained within their rims, by the wind and waves in a less turbulent manner.

Obviously, the laboratory scale by virtue of the tank size and water depth cannot duplicate field conditions. In actual arctic environments higher freeboards would inhibit ice surface contamination, and the oil would be more likely to be confined to dispersion around and under the floes. Nevertheless, in actual oil spills in the presence of active sea ice (e.g. the Bouchard #65 oil spill in Buzzard's Bay, MA in January 1977) as much as 29% of the oil was estimated to ultimately reside in deep oil pools in rafted ice (Baxter et al., The ultimate fate of the oil (on or under the ice) will be controlled 1978). by the stochastic nature of the spill event and environmental conditions. The experiments discribed herein were not intended to simulate all possible spill scenarios; but rather to examine the chemical and physical changes that occurred to the oil and its distribution (on the ice and in the water as dissolved and dispersed entities) under conditions that could be controlled and carefully monitored.

Once the break-up of multi-year ice in the coldroom wavetank was initiated with full-cycle paddle turbulence, the landfast and multi-year ice tended to break up into larger pieces which were not ground into slush ice. Instead, after breaking off of the "fast ice shelf", the pseudo-multi-year ice floes and ridges were subject to <u>in situ</u> melting similar to the decay described for first-year ice bands in the marginal ice zone (Pease, 1981). Presumably, the multi-year ice floe's resistance to degradation into slush ice in the wave tank reflects the lower salinities resulting from previous brine drainage during earlier freeze/thaw cycles and ridge formation. This behavior (i.e.,

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lack of grinding into slush) may have implications for inhibited water-in-oil emulsification during the release of oil trapped in multi-year ice ridges. When oil was finally released from under the multi-year ice ridges in the wavetank system, it did not form a stable water-in-oil emulsion as quickly as the oil released in first-year ice because of the absence of slush-ice induced micro-scale turbulance. This was demonstrated by slower increases in both oil viscosity and final water content in the water-in-oil emulsion.

Also, during the melting/break-up phase of the multi-year ice wavetank experiments, the oil on upper ice surfaces tended to readily wash off the melting ice. Pooled oil on the ice surface remained remarkably fluid despite the cold ice/room temperature. As described in Payne et al. (1984a), viscosity increases in oil due to evaporation alone are not sufficient to affect oil behavior when stranded as pools on ice surfaces. Mixing and water-in-oil emulsification with melt water from ice or snow (or seawater from wave swash and overflooding) would be required to permanently increase spilled oil viscosity while still stranded on upper ice surfaces. Some of the oil did become trapped (frozen during the initial spill event) in cracks on the ice-floe surface or in the capillary channels of broken chips of rafted columnar ice on the upper ice surface; this trapped oil resisted washing and remained longer on initial wave washing. Nevertheless, with continued wave turbulence and washing, trapped oil was also released in a matter of hours as the ice gradually melted.

During the execution of the oil-in-ice experiments we also endeavored to examine the effect that spilled oil had on ice behavior itself. It can speed up melting when trapped within the ice, but if the oil remains on the ice surface, it will only initially enhance melting by lowering the albedo of the ice. Then, one of two things can happen. First, if the pan is small and mobile and subject to wave washing and erosion, the oil quickly will be washed off the ice. Or, if the ambient temperature drops after melting in a localized spot, then the oil can float on the melt-water and be partially refrozen in place. However, during a subsequent thaw event, this oil can be washed off the ice and end up under the ice or in the open water. 5.

INVESTIGATIONS OF LEAD REFREEZING, BRINE INJECTION AND DISSOLUTION OF AROMATICS INTO SINKING BRINE

5.1 INTRODUCTION

An important concern for marine pollution research is the potential transport of spilled oil or dissolved hydrocarbon components to benthic environments and prolonged exposure of benthic organisms to the more toxic fractions of oil. However, experience from laboratory and field studies conducted under temperate (ice-free) open-ocean conditions indicates that soluble aromatic hydrocarbons do not reach deep bottom waters or ocean sediments in concentrations that might produce long-term impacts (McAuliffe et al., 1975; Payne et al., 1980a and b; Boehm and Fiest, 1982, McAuliffe et al., 1980; and Gearing et al., 1979). Although hydrocarbons can spread onto and disperse into near-surface water, oil droplets are usually less dense than sea water and return to the surface. Likewise, dissolved compounds are usually confined to the upper mixed layer (generally above the thermocline or pycnocline, if As such, they are subject to gradual evaporative removal from the present). Field measurements at several major open ocean oil spills (the water column. IXTOC I blowout in the Bay of Campeche, Gulf of Mexico being the most notable) have indicated few significant increases in hydrocarbon levels in sediments or bottom-dwelling organisms, even after many months of continuous oil input to the water column (National Academy Press, 1985). There generally appears to be very limited effect from open water oil spills to the benthos, except in the narrow band of shallow coastal waters and in regions of direct vertical mixing of oil with nearshore sediments (e.g., Amoco Cadiz spill; Gundlach et al., 1983).

Hydrocarbons released in or under ice in arctic waters can be rapidly incorporated into the ice cover, which implies little opportunity for dissolution, advection, or transport of hydrocarbons to the bottom. Weeks and Weller (1984) stated that "ice (would) assist in confining the oil to a relatively small area... under the ice and in the absence of high ice/water relative currents the oil will stay in place."

However, the ice formation processes that occur during arctic winter conditions in the nearshore regions of the Beaufort and Chukchi Seas provide a previously undescribed mechanism for the potential transport of oil components to bottom water environments. During periods of ice growth, particularly in nearshore leads and polynyas in the Chukchi Sea, salt is exuded into surface waters during frazil and slush ice formation (Bauer and Martin, 1983; Kozo, 1983). CTD measurements in the Chukchi Sea indicate that the exuded brine sinks (due to its higher density) and flows by gravity to the bottom where it can spread laterally and form a highly stable bottom boundary layer that can be 1-2 m thick (Hachmeister and Vinelli, 1985). A salinity cross section (Figure 5-1) obtained from CTD data collected in February 1984 along transect B-1 to B-7 (shown in Figure 4-23 in Section 4.3.1) illustrates the presence of a higher density bottom layer.

Brine formation and sinking can occur in both multi-year and firstyear ice areas when open-water leads form (due to ice movement, wind stress, or subsurface currents) and air and water temperatures are suitable for active ice formation (Bauer and Martin, 1983; Kozo, 1983; Martin and Kauffman, 1981; McPhee, 1980). In many areas in the arctic, frazil and grease ice growth can occur during extended periods of the year. For example, satellite imagery shows frequent polynyas and leads in this area, which implies that sea ice formation (if rapid enough) in these open waters may result in continued production of high-salinity waters beyond the initial fall freezeup period (Bauer and Martin, 1983). If an open lead is in shallow water, the extent of the lead and rate of freezing do not have to be as great to produce bottom water with a comparably elevated salinity because dilution of the water mass will be reduced. Aagaard (as cited by McPhee, 1980) reported high salinity bottom waters off Cape Lisburne in the Chukchi Sea, which could have originated from brine exclusion processes during ice formation. Brine layers also have been observed as pools in depressions in shallow and nearshore lagoons in the Beaufort Sea. These layers at times remain through winter and into summer months when the highest seasonal biological production occurs. For example, in Prudhoe Bay in the summers of 1984, 1985, and 1986 a bottom layer with salinities up to 70



Figure 5-1.--Salinity Profile from Station Transect Line in Northeast Chukchi Sea (see Figure 4-23) During February 1984.

⁰/oo remained from the winter season into mid-August before being flushed from the area by intense summer storm events (Hachmeister et al., 1986).

If crude oil or refined petroleum (distillate) products were spilled in an open lead during ice growth and brine formation, the more water soluble lower molecular weight aromatic hydrocarbons (McAuliffe, 1966 and 1969; Mackay and Shiu, 1976; Sutton and Calder, 1974, 1975a, 1975b; Clark and MacLeod, 1977; Payne et al., 1984a; and Payne and McNabb, 1984) could be readily incorporated into the sinking brine, where they could then behave as conservative species (similar to sale) and be advected to the bottom with the denser water. Some dilution would be expected due to entrainment of surrounding water during the sinking process; however, this would be minimized in shallower nearshore waters. Once present in the bottom waters, these dissolved aromatics would not be subject to rapid release to the surface and removal by evaporation processes.

Implicit in the hypothesis that soluble aromatics will be transported with sinking brine is that the dissolved components will behave as conservative variables. Conservative behavior is expected based on the fact that virtually all molecular and atomic species (with the exception of helium and hydrogen) have similar diffusion constants (usually around 10^{-5} cm²/sec) in aqueous environments (Reid et al., 1977; Lymen et al., 1982).

This mechanism for the potential transport of hydrocarbons by a dense (brine excluded) water mass was investigated during three areas of study included in the oil in multi-year ice program. Theoretical calculations of potential aromatic hydrocarbon dissolution and transport were completed based on measured oil/seawater partition coefficients and calculated rates of brine generation during frazil/slush ice formation. This topic is discussed in Section 6.9 of this report. Simulated brine generation and sinking experiments were then completed in a laboratory test-tank (Section 5.2 below). Finally, a chemical and physical oceanographic field program was completed in the Chukchi Sea near Pt. Franklin in which an aromatic hydrocarbon mixture was released into a refreezing near-shore lead. Water samples subsequently were collected

from beneath the ice and analyzed chemically to monitor transport of dissolved hydrocarbons in the bottom waters (Section 5.3).

5.2 LABORATORY STUDIES OF BOTTOM WATER GENERATION PHENOMENA

5.2.1 Background

To demonstrate the phenomenon of surface brine formation, sinking and gravity induced flow along the bottom, a series of laboratory experiments were conducted to model two sets of environmental conditions typically encountered in arctic coastal waters during the winter. The first experiment modeled the fall freeze-up; the initial conditions include a vertically mixed (typical of late Fall conditions in shallow water) water column with no ice present at the start of the freeze-up process. The second experiment modeled the deep winter, with 10/10ths ice coverage and a newly opened lead located approximately 15 km This lead remains open for several days in the model and then offshore. closes, thus terminating the rapid freezing process and the generation of brine. Data collected during the laboratory experiment included photographs of the phenomenon, water samples collected from the experimental tank, and in situ measurements of the water's conductivity and temperature. Photographic data provided information on depth and "offshore" position of the brine layer and upper convective layer. In addition, information on the velocity field was obtained by using vertical dye lines as a tracer element. Analysis of water sample data produced information on vertical density profiles and water movement from the nearshore to offshore regions.

5.2.2 <u>Scaling Parameters</u>

The laboratory experiments were intended simply as a demonstration that the phenomena described in Section 5.1 can occur. A secondary goal was to evaluate the entrainment (dilution) of the brine and estimate water velocities induced by the freeze-up process. In the field, the region to be modeled consists of the coastal boundary from the shoreline to approximately 50 km offshore. In the laboratory experiment, it was desirable to keep tank-end and

side-wall boundary effects to a minimum. Therefore a scale model as large as can be accommodated is preferred. For this experiment side-wall effects were limited to within 1-2 cm of the wall; therefore, in our two-dimensional experimental 50-cm-wide tank, only 4-8 percent of the water column was affected by the wall boundary layers. Previous experiments, with a moving salt intrusion forming a slowly advancing front, were used to guide the selection of the proper tank dimensions. Therefore, 5.7 m of an available 15 m test tank were used for the experiment, modeling the 50-km wide slope by 5 m in the tank (Figure 5-2). Turbulence was not modeled in the tank, and initial conditions of vertical stratification were assumed to be typical of late-fall early-winter shallow-water conditions (i.e., non-stratified). These factors were not considered to be critical for the demonstration of the phenomena.

To insure proper scaling of laboratory results to the field case, the Richardson number given by

$$R_{i} = g_{\rho_{o}}^{\Delta p} \frac{h \cos \theta}{u^{2}}$$
(1)

must be preserved in the laboratory model. We begin the scaling analysis by first defining nondimensional variables (primed):

$x = t_{X}x^{\prime}$	horizontal distance	น = ใน'	horizontal velocity
z = ^l z ^z '	vertical distance	$\Delta \rho = \ell_{\Delta \rho} \Delta \rho'$	density differences
$t = l_t t'$	time	$\cos\theta = t_{\cos\theta}\cos^{1}\theta$	slope

For the purpose of this modeling effort we were partially constrained by the dimensions of the tank (which was designed for horizontal intrusion studies), and our desire to limit the vertical to horizontal exaggeration to no more than 100:1. Therefore we assumed that

$$\frac{l_x \mod e1}{l_x \operatorname{field}} = \frac{1}{10,000}, \quad \frac{l_z \mod e1}{l_z \operatorname{field}} = \frac{1}{100}, \quad \frac{l_{\cos \theta \mod e1}}{l_{\cos \theta \operatorname{field}}} = 1 \tag{2}$$



Figure 5-2.--SAIC/Northwest Experimental Tow Tank with Slope and Brine Delivery Channels Installed.

Richardson number scaling requires that

$$\frac{\frac{R_{i \text{ model}}}{R_{i \text{ field}}}}{R_{i \text{ field}}} = \frac{\frac{\ell_{\Delta \rho_{m}}}{\ell_{m}}}{\frac{\ell_{z}}{\ell_{z}}} \frac{\ell_{\cos \theta_{m}}}{\ell_{cos \theta_{f}}} \frac{\ell_{u_{f}}^{2}}{\ell_{u_{m}}^{2}} = 1$$
(3)

Substituting,

$$\frac{\ell^2}{\ell^2} \frac{u_m}{u_f} = \frac{1}{100} \frac{\ell_{\Delta \rho_m}}{\ell_{\Delta \rho_f}}$$
(4)

If we model the stratification effects as

$$\frac{\ell_{\Delta\rho_{\rm m}}}{\ell_{\Delta\rho_{\rm f}}} = 10$$
⁽⁵⁾

then velocities scale as

$$\frac{u_{m}^{2}}{u_{f}^{2}} = \frac{1}{10} \text{ and } \frac{u_{m}}{u_{f}} = \frac{1}{3.16} = 0.316$$
(6)

From the definition of velocity

$$\left(\frac{U}{x/t}\right)_{model} - \left(\frac{U}{x/t}\right)_{field,}$$
(7)

which yields a temporal scaling law

$$\frac{\ell_{t_{m}}}{\ell_{t_{f}}} = \frac{\ell_{u_{f}}}{\ell_{u_{m}}} \frac{\ell_{x_{m}}}{\ell_{x_{f}}} = 3.16 \times \frac{1}{10,000} = 3.16 \times 10^{-4}$$
(8)

$$\frac{k_{x_{m}}}{k_{x_{f}}} = \frac{5 \text{ m}}{50,000 \text{ m}} = \frac{1}{10,000}$$
(9)
$$\frac{k_{z_{m}}}{k_{z_{f}}} = \frac{0.5 \text{ m}}{50 \text{ m}} = \frac{1}{100}$$
(10)
$$\frac{k_{\Delta\rho_{m}}}{k_{\Delta\rho_{f}}} = \frac{0.005 \text{ gm/cc}}{0.0005 \text{ gm/cc}} = 10$$
(11)
$$\frac{k_{u_{m}}}{k_{u_{f}}} = \frac{1}{10} \frac{k_{\Delta\rho_{m}}}{k_{\Delta\rho_{f}}} = 0.316$$
(12)
$$\frac{k_{t_{m}}}{k_{t_{f}}} = \frac{k_{u_{f}}}{k_{u_{m}}} \frac{k_{x_{m}}}{k_{x_{f}}} = 3.16 \times 10^{-4}$$
(13)

Table 5-1 gives examples of corresponding basic unit scaling parameters for the modeling program.

Table 5-1Scaling	Parameters	for Tow	Tank Model	Studies.
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Parameter	Field Scale	Model Scale	
x	1 km	10 cm	
Z	1 m	1 cm	
Δρ	0.0005 gm/cc	0.005 gm/cc	
u	1 cm/sec	0.32 cm/sec	
t	l day	27.3 sec	

To calculate the amount of brine produced during the fall freeze-up process, we started with the assumption that 2.2 gm of salt are released per square cm for each 1 meter of ice formed (assuming 32 ppt seawater and 0 ppt ice; Martin, 1985; personal communication). If we assume -20°C temperature during freeze-up and allow ~0.65 m of ice to form over 20 days we will produce 2 m^3 of 40 °/oo brine per square meter of ocean (Martin, 1985; personal communication). In the laboratory this will scale to 2 cc of 40 °/oo brine introduced into each square centimeter of surface over a period of ~10 minutes.

For the winter lead experiment, model scaling is slightly different. We assumed that a midwinter lead opens to a uniform width of 500 m under conditions of -30°C and 10-knot along-axis winds. To simplify the modeling effort, this lead is assumed to remain open for a total of four days and then close. We also assumed that ice is being formed at a uniform rate such that 24 cm of ice results over the 96 hour period. Also, newly formed ice is assumed to be advected along the axis of the lead out of the study section. This will, in turn, produce a 0.72 m layer of 40 $^{\circ}$ /oo brine over each square meter of the lead which will be modeled by 0.72 cm in the laboratory. Approximately 50 cc of 40 $^{\circ}$ /oo brine will then be added per model day (27 sec) to the 5 x 50 cm model lead. Again, it is important to recognize that we were only attempting to demonstrate the phenomena of brine cabeling in shallow, near-shore waters.

5.2.3 Experiments

Laboratory experiments were conducted to model brine formation during two conditions: (1) fall freeze-up when considerable open water is present and (2) refreezing of a newly opened lead. These two cases will be called the open-water freeze-up and lead refreezing experiments, respectively.

5.2.3.1 General Description

Initial stratification conditions in the modeled nearshore waters were intended to be both horizontally and vertically homogeneous in temperature, salinity and density, thus simulating the conditions which occur during rapid

surface cooling and vertical convection but prior to the actual formation of Freezing was assumed to occur uniformly throughout the nearshore region ice. as modeled by the uniform input of brine over the entire water surface. In order to achieve a spatially uniform addition of dense brine to the surface while preventing the brine from immediately sinking to the bottom, the brine was initially heated to a temperature where its density is less than the ambient density of the underlying water. The decreased density of the upper brine layer is sustained only by its elevated temperature and as surface cooling occurs, the brine layer gradually achieves a density greater than that of the fluid below it and sinking occurs. Dilution of the brine temperature and salinity begins during its addition to the surface of the tank through mixing salt finger formation, and heat loss to the air. These effects resulted in surface water dilution such that surface waters rapidly achieved an excess density of ~0.004-0.006 gm/cc over ambient water. This range encompasses the 0.005 gm/cc desired for the start of the brine-formation simulations (see Section 5.2.2). PVC tubing suspended near the water surface down the entire length of the tank comprised a brine delivery system that proved to be quite efficient in depositing the brine into a 1.0-1.5 cm thick layer with very little initial mixing. The experiment start time was defined as the time that the first warm water began to spread along the water surface.

5.2.3.2 Open-Water Freeze-up Simulation

Two open-water simulations were conducted during the series of experiments. The first was intended to study the formation of the upper-ocean thermohaline convective layer and the vertical transport of brine into the water column. The second was intended to study the bottom boundary-layer flow and horizontal velocity profile induced by the dense brine flow. Table 5-2 gives the initial conditions present for each of the two open-water freeze-up experiments.

Experiment	Total Depth (cm)	S ocean (ppt)	S brine (ppt)	T ocean (°C)	T brine (°C)	ρ ocean (20°C) (σt)	ρ brine (20°C) (σt)	ho brine at T (σ t) ⁱ	
Run I	52.8	34.5	40.9	20.5	57.0	23.5	28.1	15.5	-
Run II	51.7	31.3	40.0	20.0	62.5	22.0	27.5	14.5	

Table 5-2.--Open-Water Freeze-up Initial Conditions (Laboratory Model).

Tests were conducted in a 7.5 m section of a 15 m stratified tow tank. A 10% slope, 5 m long, was constructed at one end of the tank which terminated in a flat plane 2 m long (Figure 5-2). At the start of the experiment, brine at 40.9 $^{\circ}$ /oo and 54.0°C was added to the entire surface of the experimental section over a 2.5-min period, through fill channels suspended at the water surface as shown in Figure 5-3.

Measurements taken during the experiment included conductivity, temperature and depth (CTD) profiles, water samples, and visual recordings. The visual records consisted of 35 mm slides and VCR videotapes. Both rhodamine and fluorescein dyes were used to aid in the collection of visual records. Verbal observations were recorded on VCR audio tracks and handheld magnetic tape recorders.

A subsequent open water freeze-up simulation was performed under similar conditions (Table 5-2). Pre- and post-experimental measurements were made of the temperature, salinity and density fields as in the previous experiment. Time-lapse photographs of initially vertical dye lines were made to deduce vertical profiles of the horizontal velocity field.



Figure 5-3.--Fill Channels While Dyed Brine is Put into Surface of Water.

5.2.3.3 Lead Freeze-up Simulation

A single lead freeze-up experiment was conducted. For this experiment a 5 x 50 cm "lead" was constructed at the location of the 15 cm depth (1.5 m from the modeled coastline). This lead was intended to be two-dimensional and to simulate a 500 meter wide opening of the ice at the shear zone during office winds. The initial conditions for this experiment are given in Table 5-3.

Experiment	Total Depth (cm)	S ocean (⁰ /00)	S brine (⁰ /oo)	T ocean (°C)	T brine (°C)	ρ ocean (20°C) (σt)	ρ brine (20°C) (σt)	
Run III	51.5	31.7	38.2	20.3	20.1	21.5	26.5	

Table 5-3.--Lead Freeze-up Initial Conditions (Laboratory Model).

For this experiment a 5 x 50 cm box was floated at the water surface to contain the added brine (Figure 5-4). At the start of the experiment, brine was added uniformly across the lead at a rate of 100 cc/min. For the first minute, brine marked with fluorescein dye was added to the tank. For the next 30 seconds, brine marked with rhodamine dye was added at the same rate. For the final minute, fluorescein-marked brine was again added. Horizontal velocity profiles were determined from time-lapse photographs of initially vertical dye lines.

5.2.4 Results

Experimental results for the two sets of environmental conditions are discussed below in separate sections. Results for both of the open-water freeze-up experiments are given together because the environmental parameters were very similar.



Figure 5-4.--Experimental 5 x 50 cm Lead Model with Brine Fill Channel in Place.

5.2.4.1 Open-Water Freeze-up Results

Figures 5-5A and 5-5B show the initial temperature, salinity and density profiles in the experimental section of the tank for the two open-water freeze-up experiments. Note that the conductivity cell displays anomalous behavior near the water surface and readings for the first 1-2 cm should be ignored. There is also a slight cooling effect observed near the tank surface which may lower the surface temperature by as much as a degree prior to the beginning of the experiment. This surface cooling is relied upon later during the experiment to rapidly cool the heated surface brine to a temperature where its density is greater than the underlying water density. Figures 5-6A and 5-6B show the temperature, salinity and density profiles in the tank 5.5 min (BW2) and 5.0 min (BW12) after the warm brine has been added to the surface water in each experiment. Both casts were taken at the end of the slope at a distance 5 m from the modeled coastline. Note that, in the cast of BW2, mixing of the heated brine occurred down to a depth of 20 cm, whereas in the case of BW12 mixing has occurred down to a depth of 40 cm and a distinct bottom layer with salinities greater than 35° /oo was observed. This layer of brine is confined to the lower 2 cm of the water column (Figure 5-7).

A third cast was taken at 50 min (BW4) and 49 min (BW13) into each experiment. Data from these profiles are shown in Figures 5-8A and 5-8B. Note that considerably more heat and salt are retained in the upper layers of the water column in BW4 than in BW13. However, in both cases, the bottom brine layer developed very similarly with respect to its thickness and the increased salinity and density relative to the ambient water. The minimal temperature deviation between the two experiments indicated similar mixing processes.

A final CTD cast (BW5) was taken 127 minutes into Run I (Figure 5-9). A bottom layer of approximately 10 cm thickness had developed in the tank at this time. This layer was observed as a region of increased dye concentration at the time of the cast.



Figure 5-5.--Initial (Time = 0) Temperature, Salinity and Density Profiles for Laboratory-Scale Open-Water Freeze-up Experiments: (A) No. 1, and (B) No. 2. (Casts BW1 and BW9 at base of slope, 5 m from modeled coastline.)



Figure 5-6.--Temperature, Salinity and Density Profiles Taken During Laboratory-Scale Open-Water Freeze-up Experiments: (A) No. 1 at 5.5 minutes, and (B) No. 2 at 5.0 minutes. (Casts BW2 and BW12 at base of slope, 5 m from the modeled coastline.)



Figure 5-7.--Dyed Brine Mixed to Approximately 20 cm Depth.



Figure 5-8.--Temperature, Salinity and Density Profiles Taken During the Laboratory-Scale Open-Water Freeze-up Experiments: (A) No. 1 at 50 minutes, and (B) No. 2 at 49 minutes. (Casts BW4 and BW13 at base of slope, 5 m from modeled coastline.)



Figure 5-9.--Temperature, Salinity and Density Profiles Taken 127 Minutes into Laboratory-Scale Open-Water Freeze-up Simulation No. 1. (Casts BW5 at base of slope 5 m from the modeled coastline.)

The velocity data show similar down slope speeds for each of the openwater freeze-up experiments. Measurements of the advancing bottom brine layer give the same value (0.53 cm/sec) for fronts near the 5 m mark at 16 minutes and near the 2 m mark at 5 minutes into the experiments. Figures 5-10A and 5-10B show velocity profiles at the 2 m mark for the two experiments at 5 minutes. Although the shape of the profiles varies considerably, the maximum bottom layer speed is approximately 0.53 cm/sec in both profiles. This maximum value is consistent with the observed speed for the advance of the bottom boundary layer front given above. Figure 5-10C shows the velocity profile at the 3 m mark, 19 minutes into Run No 2. By this time an off-slope flow is seen in the upper 6 cm of the water column. Down-slope flow in the bottom boundary layer, however, remains nearly 0.53 cm/sec.

Time series temperature and salinity measurements of the bottom brine layer front at the 5.0 m mark are shown in Figure 5-11. There is a rapid increase in temperature observed as the front passes. Assuming the measured frontal speed of 0.53 cm/sec, water would have traveled from as far as 2.38 m up the slope to the site of the CTD probe during the 7.5 min recording period. Given the average speed of the front, the water forming the leading edge began its descent down the slope about 5 minutes into the experiment. This is consistent with observations which indicated that an upper-layer flow toward the coastline was present at 3.5 minutes into the experiment and the upper convective layer had mixed to 10 cm at the 2.0 m mark and to 15 cm (i.e., to the bottom) at the 1.5 m mark by 4.5 minutes into the experiment. Presumably this denser fluid, now at the bottom in the region between the coastline and 1.5 m offshore, would begin to flow down the slope. A bottom brine layer was clearly visible at 7.8 minutes between the 1.5 and 2.0 m marks, as was an upper-layeronshore/lower-layer-offshore flow field.

Dilution or entrainment of ambient water into the falling brine can be calculated by knowledge of the initial brine concentration, the ambient salinity of the water, and the final salinity at the bottom brine layer. For a



Figure 5-10.--Velocity Profiles from Laboratory-Scale Open-Water Freeze-up Experiments: (A) No. 1 at 2.0 m from the modeled coastline at 5 minutes; (B) No. 2 at 2.0 m from the modeled coastline at 5 minutes; and (C) No. 2 at 3.0 m from the modeled coastline at 19 minutes.



Figure 5-11.--Temperature, Salinity and Density Time Series in Advancing Bottom Brine Layer as it Arrived at the 5.0-m Mark in Laboratory-Scale Experiment 1.

particular milliliter volume of brine introduced at the surface, the minimum dilution can be expressed in terms of the maximum observed salinity as

$$(S_{\text{brine}})^{(1 \text{ ml})} + (S_{\text{ambient}})^{(x \text{ ml})} - (S_{\text{btm layer max}})^{(x+1 \text{ ml})}$$
(14)

Table 5-4 gives computed values for the minimum dilution for several bottom samples taken during the two open water freeze-up experiments.

S brine (⁰ /oo)	S ambient (⁰ /oo)	S btm max ([°] /oo)	Minimum Dilution (x+1)/x	Elapsed Time (min)
40.9	34.5	35.2	9.1	84
40.0	31.3	33.8	3.5	22
40.0	31.3	33.3	4.4	57
	S brine ([°] /oo) 40.9 40.0 40.0	S S brine ambient ([°] /00) ([°] /00) 40.9 34.5 40.0 31.3 40.0 31.3	S S S brine ambient btm max (°/oo) (°/oo) (°/oo) 40.9 34.5 35.2 40.0 31.3 33.8 40.0 31.3 33.3	SSSSMinimum Dilutionbrine (°/oo)ambient (°/oo)btm max (°/oo) $(x+1)/x$ 40.934.535.29.140.031.333.83.540.031.333.34.4

Table 5-4.--Calculated Brine-Dilution Ratios for Open-Water Experiments.

Although elapsed time is shown in this table, time should not be inferred as the dominant variable in determination of the dilution factor. To put these factors in perspective, if 1.0 cm of 40.9 $^{\circ}$ /oo brine were added to the surface of 34.5 $^{\circ}$ /oo brine and uniformly mixed to a depth of 7.5 cm, 35.25 $^{\circ}$ /oo brine would result (see Run I case in Table 5-4 for comparison). Water samples collected at 2.5 cm (35.5 $^{\circ}$ /oo), 5.0 cm (35.3 $^{\circ}$ /oo), and 7.5 cm (34.8 $^{\circ}$ /oo) depths at 65 minutes after the start of Run I show an average salinity of 35.2 $^{\circ}$ /oo for the upper 7.5 cm. Water below that upper 7.5 cm layer remains at the pre-run value of 34.8 $^{\circ}$ /oo to a depth of 50 cm, where an increase to 35.2 $^{\circ}$ /oo is observed for the bottom 2.5 cm of water (Run I).

5.2.4.2 Lead Freeze-up Results

Figure 5-12A shows the initial temperature, salinity and density profiles (BW6) for the lead freeze-up experiment. Some difficulty was encountered during the tank-filling process for this experiment and a density jump was created at the 40 cm depth. This accident provided some interesting observations which will be presented later. As discussed in the previous section, the conductivity cell displays anomalous behavior near the surface and both salinity and density readings for the upper 1-2 cm should be disregarded. Temperature measurements in this region also indicate a 3 cm thick cooler surface layer (~19 C°) due to overnight surface cooling.

Observations of dyed brine discharge from the modeled lead indicated that sinking occurred rapidly (the brine was at ambient temperature) and in a relatively uniform manner across the 5×50 cm lead. Downslope flow began almost immediately and, at 8 minutes into the experiment, a 1 cm bottom boundary layer was fully established at the 2.0 m mark. The leading edge of the front was observed to reach the 3.5 m mark at 12:35 into the experiment, yielding a rate of advance of 0.26 cm/sec. Other observations of the advancing front at the 1.25 m and 2.5 m marks yielded similar velocities of 0.24 and 0.26 cm/sec, respectively, at elapsed times of 1:50 and 6:35 min. The front continued to advance downslope toward the 4.0 m mark where the density step at the -35.0 cm depth was encountered (see Figure 5-12A). The downslope flow slowed considerably and eventually stopped near 4.0 m where it began to "pool" in front of the lens of denser water.

Figure 5-12B shows temperature, salinity and density profiles at the 3.0 m mark, 33 minutes into the experiment, well after the bottom boundary layer front had reached the position of the cast and had begun to "pool". Visual observations indicated that the downslope flow had accumulated dyed fluid to a depth of approximately 5 cm at this position. This observation is





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Figure 5-12.--Temperature, Salinity and Density Profile Taken During the Laboratory-Scale Lead Refreezing Experiments: (A) 0 minutes (initial), at the base of slope 5 m from the modeled coastline, (B) 33 minutes, 3.5 m from the modeled coastline, and (C) 79 minutes, 4.0 m from the modeled coastline.

consistent with data collected in the cast (see Figure 5-12B) which shows an increase in the salinity and density data from the pre-experiment values between the depths of 30 and 37 cm. The maximum salinity observed in this layer was 32 ⁰/oo, which is an increase from the originally measured salinity of 31.6 %/oo at that depth. At an elapsed time of 79:25 a third profile (Figure 5-12C) was taken at the 4.2 m mark over the layer of pooled brine. The forms of the lower portion of the salinity and density profiles are almost exactly the same as those observed at 3.9 m, displayed lower in the water column when adjusted for the difference in water depth of 3.0 cm. With further elapsed time, the pooled brine at 4.0 m slowly spread horizontally along a depth of equilibrium density (approximately 35 cm) in the original density profile (see Figure 5-12A). The mixed brine did not have sufficient density to continue its advance down the slope along the bottom and was starting to spread laterally along the density interface. This process can be likened to an observed Chukchi Sea situation where dense brine, formed in the nearshore region, flows into Barrow Canyon and then northward along the canyon axis until it reaches the layers of dense Atlantic and intermediate water (Figure 5-13) where it spreads laterally into the Beaufort Sea. Dilution of the original brine (38.2 ^o/oo) introduced into the lead was 22:1 (Table 5-5). This is considerably greater than the dilution observed for the open-water cases (Table 5-4) where an average dilution of 6:1 was observed.

Experiment	S brine (⁰ /oo)	S ambient ([°] /oo)	S btm max ([°] /oo)	Minimum Dilution (x+1)/x	Elapsed Time (min)
Run III	38.2	31.7	32.0	21.6	33
Run III	38.2	31.7	32.0	21.6	79

Table 5-5.--Calculated Brine-Dilution Ratios for the Lead Experiment (Laboratory Model).



Figure 5-13.--Density Section Along Axis of Barrow Canyon, Showing Depth of Atlantic Water (shaded). (See Figure 4-23 for Transect D station locations.)

This apparent higher dilution rate is a consequence of water depth at the point of brine introduction. In the "refreezing lead" experiment, the brine was introduced and mixed into 15 cm of water. In the "open-water" case, a considerable portion of brine (i.e. that volume introduced inshore of 150 cm) vertically mixed with less than 15 cm of water and produced less dilution and therefore higher salinities. A simple calculation using the 250 ml of brine (equivalent to 1 cm of height in the 5 x 50 cm lead) at 38.2 °/oo added to the lead and completely mixed with the underlying 15 cm of water at 31.7 °/oo (15:1 dilution) yields water at 32.1 °/oo, which is similar to the observed maximum salinity of 32.0 °/oo pooled at the 4.0 m mark.

Velocity profiles for the lead freeze-up experiment are shown in Figures 5-14A and 5-14B for the 2 m and 3.5 m marks at 7.6 and 12.0 minutes into the experiment. Note that the maximum bottom layer velocity (~0.1 cm/sec) in the fluid behind the front is considerably less than that observed for the advance of the front itself, which was measured at ~0.25 cm/sec. Although temperature and salinity time-series data similar to Figure 5-11 were not taken for this advancing front, it must be assumed that the density of this layer is less than that of the initial front. The majority of the relatively undiluted brine (entering at the lead) proceeded downslope (at 0.25 cm/sec) as a "parcel" of fluid, which was followed by the more dilute and less dense water moving with a slower downslope velocity.

5.2.5 <u>Discussion</u>

The series of experiments conducted to demonstrate the process of dense brine formation in arctic nearshore waters have been extremely informative in illustrating the basic physical phenomena active during fall freeze-up and winter refreezing periods. Important observations relative to the nearshore exchange of water during fall freeze-up can be extrapolated from the laboratory data to field conditions as: (1) the formation of a slow (0.3-0.9 cm/sec) near-surface (≤ 10 m) onshore flow balancing (2) a more rapid (1.5-1.7 cm/sec) offshore flow in a 2 to 5 m thick bottom layer. (These current estimates are consistent with the observed field values described in Section 5.3.3



Figure 5-14.--Velocity Profile Taken During the Laboratory-Scale Lead Refreezing Experiments: (A) 7.6 minutes, 2.0 m from the modeled coastline, and (B) 12.0 minutes, 3.5 m from the modeled coastline.

on Field Studies.) In the case of a nearshore oil spill this general circulation pattern would tend to concentrate (in the absence of wind effects) surface spilled oil products in the nearshore region. If winds are present they would dominate surface oil movement. Onshore winds would tend to compound such behavior, whereas offshore winds might tend to disrupt the pattern. Winds might also tend to herd surface oil to one end of an open lead system. However, wind effects must be modeled as a stochastic process, so further discussion of perturbations caused by surface winds is unwarranted as the laboratory experiments were not designed to include them.

In nearshore areas, dissolved lighter fractions of the oil would be incorporated into the forming brine and be transported with the brine. In deeper waters the brine (and any associated hydrocarbons) would of course be diluted as the brine is exuded and sinks. These laboratory observations indicate that much of the dense brine formation occurs in water depth less than 20 meters (typically within 15 to 20 km of shore) although scaling-up of the experimental laboratory results relative to vertical entrainment of the surface brine must be done very cautiously. Existing field data do support these laboratory observations that brine formation occurs in this region. Aagaard (1984) observed a thin (<2 m) layer of brine (33-36.5 $^{\circ}$ /oo which formed at depths less than 25 m at Pt. Lay. Similar brine layers were observed in his Pt. Franklin and Pt. Barrow salinity sections. Historical data repoted by Garrison (1977) also suggest the near shore formation of dense brine in the Chukchi Sea at depth less than 20 m. The salinity profile shown in Figure 5-1 (from Hachmiester and Vinelli, 1985) also very clearly support the observations from these earlier studies.

A very simplistic model of the freeze-up process for open water is shown in Figure 5-15. Starting with ambient water at $31.6^{\circ}/\circ o$ and allowing (per Section 5.2.2) 0.65 m of ice to form over 20 days, 2 m³ of 40 °/oo brine will be input uniformly across the nearshore surface waters. The resulting salinity field (Figure 5-15B) is obtained if no horizontal mixing is allowed. As observed in the laboratory experiments, the bottom brine shows maximum offshore bottom salinity which is characteristic of the water formed at 5-10 km


Figure 5-15.--Simplistic Model of the Freeze-Up Processes: (A) Initial conditions in 10 km-wide cells, and (B) final conditions in 10 km-wide cells after formation of 65 cm of ice over 20 days assuming no horizontal mixing. (Results in uniform input of 2-m layer of 40% water across 50-km distance.)

offshore (Table 5-4) or 33.3-34.0 °/oo. Given the downslope speeds predicted by the open-water freeze-up experiments, in the absence of other external forces, this brine should reach a 20 km offshore position within 20 days of A 1.5 to 2.0 m bottom layer flowing at 1.5-1.7 cm/sec would remove formation. a volume of water equal to that in the 0-10 km region in approximately the same time (17-25 days), thus implying an onshore flow of surface water of equal magnitude and additional dilution to perhaps 33.5 °/oo. Measurements made in February 1984, (see Figure 5-1) under ambient salinities of 32.1 °/oo and considerably reduced brine formation rates, showed bottom salinities of $33.1^{\circ}/\circ\circ$ in a 2 m thick lower layer. With all other processes remaining the same, this would imply a 70% reduction in the brine-formation rate in the nearshore where the 33.1 ^o/oo water was formed, or additional dilution of the nearshore water as described above through onshore flow, or both. The important fact remains, however, that dilution in both the fall freeze-up and the lead refreezing cases is sufficiently low in the nearshore region to allow for the possibility that significant concentrations of dissolved hydrocarbons from a hypothetical spill might persist in the sinking brine.

5.3 FIELD PROGRAM TO STUDY DISSOLUTION AND TRANSPORT OF SPILLED AROMATIC HYDROCARBON COMPONENTS DURING OPEN LEAD REFREEZING AND BRINE GENERA-TION PROCESSES IN THE CHUKCHI SEA

5.3.1 Objectives of the Field Program

The field program tested the hypothesis that the dissolved fraction of an oil spill in the upper water layer of a refreezing lead could be incorporated into a denser brine mass that is transported to the bottom as the brine sinks under the influence of gravity. Specific objectives of the field experiments were the following:

- 1) demonstrate brine production and its association with the lead system northeast of Pt. Franklin,
- 2) demonstrate incorporation of hydrocarbons (from a 38 liter aromatic "cocktail" spilled into the lead surface waters) by brine produced during the refreezing process, and

3) track any such brine (and accompanying dissolved hydrocarbons) over time and distance by using acoustic transmitting bottom drifters to aid in station/site selection and collecting water samples for measurements of aromatic hydrocarbon concentrations.

5.3.2 Field Methods and Materials

The field program was conducted in early March 1985 at a nearshore location northeast of Pt. Franklin, Alaska (Figures 5-16 and 5-17). Selection of this test site was based on 1) its proximity to logistics support at Barrow, 2) year-to-year persistence of an open-water lead system in shallow water in the area, 3) anticipated low water current velocities in the area, and 4) previoulsy observed brine formation events during freezing in the area (i.e., February/March of 1982 and 1984; Hachmeister and Vinelli, 1985).

Cocktail Deployment -- 10 March 1985

For the field oil-spill experiment, an aromatic hydrocarbon "cocktail" mixture (Table 5-6), not whole crude oil, was used. A total of 38 liters was released on 10 March 1985 in the open water of an extensive lead system northeast of Pt. Franklin, Alaska (see Figures 5-16 and 5-17). The spill occurred at site 10 (71° 1.4'N, 158° 12.1'W, Figure 4-25) in an open refreezing lead that was approximately 30 m wide. Water depth at the spill site was 29 m, which was slightly greater than the desired depth (15-20 m). However, the solid ice on both the north and south sides of the lead provided stable platforms from which the spill was initiated and from which subsequent sampling of near-surface and bottom waters could be performed. CTD measurements were obtained at selected sites and times through holes in the ice cover to monitor relevant water mass properties before and after the spill event.

Conditions at the time of the spill were favorable for the occurrence of brine formation: air temperature was -24°C, and frazil and grease ice were being actively formed. CTD and current meter data collected in the region on 9 March (i.e., the day before the spill) indicated that higher salinity water existing under the lead was sinking and moving in an onshore direction.





Figure 5-17.--Station Locations in the Chukchi Sea, Pt. Franklin Area.

Compound	Amount					
Toluene	18.9	liters	(5.0 gallons)			
Benzene	9.5	liters	(2.5 gallons)			
p-Xylene	3.8	liters	(1.0 gallons)			
o-Xylene	3.8	liters	(1.0 gallons)			
Ethylbenzene		500	grams			
Naphthalene		1,000	grams			
2-Methylnaphthalene		500	grams			
Uranine dye		500	grams			

Table 5.6---Individual Components and Amounts in the Chukchi Sea Aromatic Cocktail Mixture.

Immediately before the cocktail release, a CTD cast was completed, and prespill surface and bottom water samples were obtained with Nansen bottles deployed through a 25 cm diameter hole augered through the ice. An Inter Ocean S4 current meter was deployed directly into the lead at the site approximately 15 minutes before the spill to measure current speed and direction (5 minute vector averages). This meter indicated a bottom current with a speed of 1.5 cm/sec and a heading of $25^{\circ}-35^{\circ}$ (i.e., NNE) at the time of the spill.

At 1405 hrs, the spill mixture (Table 5-6) was released over a 10 minute period into the middle of the lead at a depth of 2-4 cm below the water surface. After release of the mixture, two transponders were deployed into the lead. A 27.0 kHz acoustic seabed drifter was deployed with a drogue flotation collar (to impart neutral density in 33-38 $^{\circ}$ /oo, -1.8°C seawater) to track the bottom water movement, and a 37.0 kHz transponder, with no flotation, was released to mark the deployment site.

The cocktail had approximately 20-25 minutes to mix with the forming slush ice and associated brine. The uranine dye in the mixture very clearly allowed differentiation between the cocktail that was floating on accumulating slush ice and associated pieces of broken ice chunks and that which was actually mixed into the surface waters. Specifically, the cocktail that was spilled or pooled on top of existing or freshly formed ice was still in the oil (toluene) phase, and the uranine dye retained a dark red color. When the cocktail mixed with the water the uranine turned a bright yellow-green.

Five to ten minutes after the release of the cocktail, additional 1-liter near bottom and surface (1 m below the bottom of the ice cover) water samples were obtained with a Niskin bottle through a 25 cm diameter hole augered in a small ice floe approximately 15 m from the release site. (This location (sample) was identified as Station 10.)

Between 20 and 30 minutes after the experimental spill was initiated, became apparent that the lead was closing. At first, it appeared that the it lead was only filling up with excessive slush and grease-ice covered pans, but then observations of the ice in the rubble field on the northern side of the lead clearly indicated that the entire rubble field was moving slowly towards the pan from which the cocktail had been released. Eventually, the rubble field from the other side of the lead pushed grease ice and larger ice chunks in front of it as it approached. Larger chunks (1-2 m) were up-ended and forced against, under and on top of the edge of the southern floe that supported the scientific party and all field equipment. After slightly more than an hour (1512 hrs or 68 min post-spill) the moving rubble field had completely closed the lead, and some of the dye-stained (red, yellow and green) ice had actually been subducted and forced beneath the rubble field and (presumably) under the pan from which the observations were being made. Approximately half of the dye-stained ice ended up ridged against the stationary observation pan, and the rest was ground up or incorporated into or under the rubble field that now occupied the lead where the experimental spill had been initiated an hour earlier. Schematic plan views of the experimental spill site and lead system before and after closing are presented in Figure 5-18.

In designing the experiment, we had hoped to work in a lead system that remained open with active ice formation for 2-3 hours after the spill release. Therefore, as a result of the lead closing, there was some uncertainty as to how much of the hydrocarbon cocktail actually dissolved into the sinking brine at the time. This confounded subsequent attempts to estimate the rate of initial mixing or dilution of the aromatic cocktail.

The S4 current meter was retrieved at 1450 hrs, and the scientific party retreated from the observation pan (Station 10) and occupied an adjacent more stable ice floe (100 m by 200 m) which had been used as a staging area where the helicopter had landed prior to the experiment. This location was approximately 50 meters to the south of the spill site (see Figure 5-18B).



Figure 5-18.--Plan View of the Lead/Ice System on 10 March 1985: (A) 1400 hours and (B) 1500 hours.

While it could not be observed from the original pan at Station 10 or the adjacent floe by the helicopter, there was a large new lead (100 to 150 m wide) opening up approximately 30 m north of the rubble field that resulted from the closure of the initial experimental lead. This new lead (Figure 5-18B plan view) was discovered during the helicopter flight to Station 11, which was 300 to 400 m to the west of the initial spill release point.

After completing a CTD cast and deploying the current meter at Station 11 at 1655 hrs, a directional EFCOM sonar receiver system was used to obtain direction headings on the two transponders that had been released at site 10. The receiver system was assembled by attaching the sonar head to six 1-meter long, 7.5 cm diameter PVC extensions for under-ice depth and directional control. The electrical leads for the sonar head were contained within the PVC tubing, and these were attached to an EFCOM sonar receiver system that was contained in an IglooTM cooler. The cooler was equipped with an automobile battery and heater that maintained the unit at a necessary temperature level such that the liquid crystal frequency display could be used to tune to the 27.0 and 37.0 kHz transponders.

At 1720 hrs the ice pan at Station 10 was still intact, so it was reoccupied (identified as Station 10A) and another sampling hole drilled. Two additional 1-liter water samples (at 26 m bottom and 14 m intermediate depths) were collected with a Nansen bottle. The sonar receiver system was then reassembled and an additional fix on the 37.0 and 27.0 kHz pingers obtained. At 1740 hrs the two deployed transponder units were separated by approximately 15 degrees, but an exact distance separation between the two could not be obtained because the sonar receiver system was located almost directly over the

transponders. Open water to the north of the spill site and safety considerations prevented occupation of additional stations on 10 March. Therefore, we returned to Station 11 to retrieve the S4 current meter at 1835 hrs, and the scientific party returned to base at UIC/NARL.

Water Column Sampling--11 March 1985

The general area of the spill site was surveyed, and Station 12 (see Table 5-7 and Figure 5-17) was occupied immediately to the southeast of a 500 meter wide rubble field and ridge system approximately 2 miles south/southeast of the spill site. CTD and current meter data were collected from 1225-1445 hrs, and a near bottom current was detected with a velocity of 1.1 cm/sec and a direction of 161 degrees True (toward the south/southeast). Surface (just below the ice), and near bottom (0.5-1m above the bottom) water samples were collected for hydrocarbon analyses, and the EFCOM sonar receiver system was assembled to locate the positions of the fixed 37 kHz and seabed drifting 27 kHz transponder units. No sonar signal could be detected from either transponder. Presumably, this was because of the vertical dimensions of the rubble field and ice ridge systems to the northwest of the area (i.e., ridges had elevations in excess of 3 m and estimated keel depths of 15 to 20 m).

At 1520 hrs Station 13 was occupied 1.9 km to the north/northwest of Station 12 (see Figure 5-17). Station 13 was characterized by much smoother ice, and directional readings for the two transponders were successfully obtained. Water samples were again obtained at the surface and bottom depths.

Station 14 was located on smooth ice approximately 300 m southeast of the original spill site. Surface (just below the ice) and bottom water samples were collected, and sonar fixes were obtained for the two transponder units. From the position-fix obtained for the helicopter and triangulation of the sonar readings at Stations 13 and 14, it was apparent that the surface ice had not moved relative to the 37 kHz transponder beneath the spill site. The seabed drifting transponder (27 kHz) had travelled approximately 500 to 1000 m in a direction of 25-30° True from the original release site. Because of

Date	Station number t. Barrow;	Latitude (°N)	Longitude (°W)	depth (m)		Speed	Direction		Depth
(Newth of D	t. Barrow,				CTD	(cm/s)	(° True)	Time	(m)
(NOTTH OF P		, equipment	checks)						
3/8/85	001	71°31.3'	155°22.7'	22	Х	3.2 3.9	275 91	1150-1430 1440-1530	21 21
3/8/85	002	71°28.3'	155°19.5'	20	Х		-		
3/8/85	003	71°24.4'	155°15.1'	18	Х				
3/8/85	004	71°19.3'	155°11.1'		Х				
3/8/85	005	71°33.5'	155°30.3'	120	Х				
(Pre-spill)									
3/9/85	006	70°50.9'	158°16.0'	11	Х				
3/9/85	007	70°58.7'	158°19.0'	21	х	3.0	154	1335-1545	21
3/9/85	008	71° 0.1'	158°19.3'	26	X		-2 .		
3/9/85	009	70°56.9'	158°17.1'	20	X				
Spill event	: 1405-141	15 hours 3/1	.0/85, Station	010					
3/10/85	010	71° 1.4'	158°12.1'	29	x	1.5	35	1455	28
3/10/85	011	71° 1.4'	158°12.4'	28	х	1.6	25	1655-1835	27
3/11/85	012	70°59.8'	158°10.2'	24	X	1.1	161	1225-1445	23
3/11/85	013	71° 1.0'	158°10.7'	27	x				
3/11/85	014	71° 1.4'	158°12.1'	29	x				
3/11/85	015	71° 1.4'	158°12.1'	26					
3/10/85	016a	71° 1.6'	158°12.0'	29	x	3.0	284	1255-1355	27
3/10/85	016b	71° 1.6'	158°12.0'	26		3.1	272	1405-1455	25
3/12/85	0166	71° 1.6'	158°12.0'	26		3.9	265	1505-1545	25
3/12/85	017	71° 1 6'	158°12 0'	26		5.5	205	1505 1545	
3/12/85	018	71° 1 6'	158°12 0'	26					
3/12/85	019	71° 1 6'	158°12 0'	25					
3/12/85	020	71° 1 6'	158°12 0'	25					
3/12/85	021	71° 1.6'	158°12.0'	26					

Table 5-7.--Station Locations and Bottom Current Meter Readings for 1985 Field Program.

extremely thin ice to the north of the original spill site, however, no stations could be occupied in this direction (i.e., where the 27 kHz seabed drifting transponder was detected).

The spill site itself was then reoccupied now designated as (Station 15), and the original experimental lead was observed to be completely covered by a partially frozen rubble field. The broad expanse of open water that had opened to the north of Site 10 just after the spill event (see Figure 5-18B) had begun to refreeze, but neither it or the rubble field over the initial spill site were explored further due to uncertainties regarding their stability. At 1730 hrs (26-27 hours post-spill) two additional water samples (subsurface and bottom) were obtained through a freshly drilled auger hole at Station 15, which was located 7 m from the original spill site.

Water Column Sampling--12 March 1985

Observations during the flight from Barrow to Pt. Franklin indicated that considerable refreezing of the offshore lead system had occurred over the previous 48 hours. Therefore, the original spill site location (Station 10/15) Figure 5-19 presents a schematic plan view of the original was reoccupied. spill location as well as Stations 16 through 21 which were occupied on 12 All of the latter stations were located on the freshly refrozen March 1985. lead that had opened to the north of the original spill site (Figure 5-18B) within one to two hours of the start of the experiment 48 hrs earlier. The ice thickness at these stations was now 12 to 18 cm, and open pools of fresh seawater or cracks in the ice were occasionally encountered in the area. Station 16 was occupied, and the seabed drifting transponder (27 kHz) was located by triangulation using the EFCOM sonar receiver system at Site 16C and auger boring Site X further to the west (see Figure 5-19). The transponder was approximately 500 to 750 m from the original spill release point, and appeared to be trapped in the under-ice ridge system between Stations 16 and 17. The location of the seabed drifting transponder at this time was consistant with bottom current directions that had been measured during the first two hours following the spill. However, the estimated distance from the spill site



Figure 5-19.--Station Area Overview on 11-12 March 1985.

indicated that the transponder may have become trapped in the subsurface ice ridge system in the first 1 to 2 hours after its release. This ridge system was quite extensive, with upper surface relief up to 3-4 m and estimated underice relief of 15 to 23 m. It was possible that portions of this under-ice relief extended all the way to the bottom sediment, although this could not be determined from the surface. At certain locations on the northern slope of the ice ridge system (i.e., near Station 16), the ice was sufficiently thick immediately adjacent to the ridge to support the helicopter and thereby expedite sampling operations.

A series of water samples were obtained near the location of the seabed drifting transponder for an east-west transect of auger holes at Stations 16A, B and C and from Station 17. An ice thickness of 5-6 m prevented boring of a sampling hole immediately over the transponder. Four 1.3 meter long auger bits were connected in the attempt to drill in this area, and open water beneath the ice was never reached. Therefore, Station 17 was located as close as possible to the transponder on a direct line between it and the original spill site (Figure 5-19). Surface and near bottom water samples for hydrocarbon analyses were collected at Stations 17 through 21, which were located on a direct line between the seabed drifting transponder and the spill site. A single CTD cast was taken at site 16A.

During the later sampling events on 12 March, the wire angles on the hydrowire for water sampling casts indicated currents with directions of 268° True at Station 20 and 254° at Station 21. All field sampling efforts concluded with Station 21.

5.3.3 Sample Analyses for Aromatic Hydrocarbons

At the time of collection, all water samples were placed in 580 ml plastic-jacketed screw cap containers to prevent freezing. These containers had been pre-cleaned and rinsed prior to use. Each container was filled completely with seawater to minimize headspace, and while in the field, the

filled containers were stored in Igloo coolers as a further precaution against freezing and sample loss due to container breakage.

Subsets of selected water samples were used for calibration of the CTD data. Upon receipt in the laboratory, all remaining samples were stored at 4°C until analysis for hydrocarbons by GC/MS. Hydrocarbon spiked control samples as well as field and method blanks were analyzed to insure against sample degradation (by either volatilization or microbial activity) and/or contamination during handling and analysis. No evidence of either of these analytical problems was encountered.

For analysis, water samples for hydrocarbon measurements were allowed to come to room temperature before the sample container was opened. The entire sample (580 mls) was transferred to a cleaned and kiln-fired, two-neck, 1000 ml roundbottom flask. To recover hydrocarbons of interest, the flask was fitted for gas purging with an attachment for in-series, back to back Tenax^R traps. Before exposure to a water sample, the Tenax^R traps were first "blanked" with the sample extraction and analysis procedure (see procedure below for GC/MS with Selected Ion Monitoring mode). For a sample, water in the round bottom flask was purged for two hours with Ultra-pure helium gas at a flow rate of 30 mls/min. After this purge cycle, the front and back Tenax^R traps were immediately capped with stainless steel Swage-Lok^R fittings. The entire purging process was conducted in a laminar flow hood to minimize sample contamination from laboratory sources of volatile organic compounds.

The GC/MS analyses of Tenax^R trap samples were conducted within 30 minutes of their removal from the purging apparatus. Both front and back traps were analyzed separately to determine if any sample analyte breakthrough from the front trap had occurred during the gas purging process. For GC/MS analysis, each trap was attached to a Tekmar LSC-2 Liquid Sample Concentrator^R and backflushed while being rapidly heated to 180° C to thermally desorb any trapped volatile aromatic compounds. The compounds were then transferred directly into the inlet of a Finnigan 4021 gas chromatograph, where they were subsequently separated on a 2.8 meter x 2 mm I.D. glass column packed with 1% SP-1000 on

Carbopak 3, 60/80 mesh. Compound identification and quantitation was accomplished in the Selected Ion Monitoring Mode in a Finnigan 4021 quadrupole GC/MS. Absolute amounts of benzene and toluene were determined by comparing specific ion area counts for each compound (78 and 91 m/z, respectively) against 500 pg standard of each. Method detection limits for benzene and toluene were 0.01 ng/1.

5.3.4 Results and Discussion

Field locations for the water samples, CTD measurements and current speed/direction estimates are summarized in Table 5-7 and Figure 5-17. Data from the CTD casts (Table 5-8) and current speed/direction measurements are particularly important in explaining the measured levels of benzene and toluene in bottom and near-surface water samples from selected field locations.

5.3.4.1 Analyses of Seawater Samples for Dissolved Aromatic Hydrocarbons

Table 5-9 presents the results of the "purge and trap" GC/MS analyses of the seawater samples. Benzene and toluene were detected at low part per trillion levels in a number of samples, while other samples had undetectable levels (below the part per quadrillion level). Those samples having undetectable levels for benzene and toluene also serve as additional defacto field/ method blanks. It should be noted that the other higher molecular weight compounds in the original field spike mixture (i.e., Table 5-6) were not detected in any of the water samples. The latter absence presumably derives from a combination of: 1) lower water solubilities for these compounds (see Sections 6.8 and 6.9 for a complete discussion of partitioning behavior and estimated amounts of water-soluble components contained in crude oil in general, and Prudhoe Bay crude in particular), 2) and the fact that not all of the initial spill "cocktail" was effectively introduced into the refreezing lead as originally planned. It is also significant that of these other components, o- and p-xylene were only introduced in limited (3.8 1) amounts, and only 0.5 to 1.0 kg quantities of the other components were in the original mixture (see Table 5-6). Nevertheless, absence of the higher molecular weight

Table 5-8.--CTD Data from Stations 7 to 16 for 1985 Field Program.

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	NS. CAST NISE ID: CATION:	•	7	DATE TIME: 2	3/85/ 9 11:20 OMT	LATITUD	E 70-56 DE 150-14	9. 7N 9. GW	BOTTOM CAST D	DEP TH: EP TH:	21 0.
PRESS 0. 6 2. 0 3. 2 4. 3 5. 4 6. 5 7. 5 8. 6 9. 7 11. 1	TENP -0. 676 -1. 235 -1. 423 -1. 768 -1. 770 -1. 779 -1. 786 -1. 790 -1. 790 -1. 792	5AL 31. 316 32. 133 32. 426 32. 477 32. 575 32. 700 32. 752 32. 779 32. 806 32. 848	810-T 25, 185 25, 841 26, 103 26, 152 26, 231 26, 332 26, 375 26, 375 26, 397 26, 419 26, 483	8-VEL 1441. 0 1439. 6 1437. 6 1437. 7 1437. 9 1437. 9 1438. 0 1438. 0 1438. 1	DYN-DEP 0.000 0.003 0.006 0.010 0.010 0.012 0.014 0.015 0.017 0.017 0.019	PRESS 12. 2 13. 2 14. 2 15. 3 16. 6 17. 7 18. 8 19 9 20. 9	TEHP -1. 796 -1. 801 -1. 803 -1. 805 -1. 807 -1. 801 -1. 820 -1. 822 -1. 820	5AL 32, 933 33, 003 33, 047 33, 129 33, 344 33, 470 33, 477 33, 699	810-T 24. 522 24. 579 26. 601 24. 631 24. 681 24. 685 27. 120 27. 142 27. 143	S-VEL 1438, 2 1438, 3 1438, 4 1438, 4 1438, 5 1438, 9 1439, 3 1439, 3 1439, 3	DYN-DEP 0. 021 0. 023 0. 024 0. 026 0. 027 0. 029 0. 030 0. 031 0. 032
 CR CR LC	DNS. CAST Ruise ID: DCATION:	•••	•	DATE TIME: :	3/85/ 9 23: 0 omt	LATITUE LONGITU	DE 71- JDE 159-1	0. 1N •. 3N	BOTTO CAST [1 DEPTH: DEPTH:	26. Q.
PRESS 3. 1 4. 4 5. 7 7. 0 8. 1 9. 4 10. 7 12. 1 13. 5 14. 6	TEMP -1. 640 -1. 792 -1. 794 -1. 794 -1. 794 -1. 805 -1. 825 -1. 829 -1. 831 -1. 833	5AL 32. 873 32. 948 32. 975 32. 984 33. 021 33. 309 33. 507 33. 563 33. 625 33. 657	810-T 26. 470 26. 534 26. 556 26. 543 26. 593 26. 627 26. 986 27. 050 27. 064 27. 110	S-VEL 1438. 4 1438. 2 1438. 2 1438. 2 1438. 3 1438. 9 1439. 0 1439. 1 1439. 1	DYN-DEP 0.005 0.007 0.011 0.012 0.014 0.014 0.016 0.017 0.018 0.020	PRESS 15. 9 17. 2 18. 2 19. 5 21. 0 22. 3 23. 8 24. 9 24. 9 24. 1	TEMP -1. 836 -1. 836 -	SAL 33. 704 33. 719 33. 728 33. 732 33. 742 33. 742 33. 748 33. 746 33. 756 33. 627	819-T 27.148 27.160 27.167 27.171 27.179 27.192 27.193 26.887	8-VEL 1439, 2 1439, 3 1439, 3 1439, 3 1439, 3 1439, 4 1439, 4 1437, 3	DYN-DEP 0.021 0.022 0.023 0.025 0.025 0.025 0.027 0.026 0.029 0.029 0.029
 CI CI	DNS. CAST Ruise ID: DCATION:	' # :	•	DATE TIME:	3/85/10 0:10 GMT	LATITUD LONGITU	VE 70-5 DE 158-1	6. 7N 7. 1W	BOTTO CAST	n depth: Depth:	20. 0.
PRESS 0.2 1.6 2.9 4.1 5.3 6.3 7.5 8.9 10.4	TEMP -1. 442 -1. 368 -1. 609 -1. 732 -1. 734 -1. 734 -1. 736 -1. 753 -1. 777	SAL 31. 837 31. 744 31. 887 31. 748 31. 748 31. 748 31. 748 31. 748 32. 548 32. 548 32. 836	810-T 25. 428 25. 549 25. 670 25. 722 25. 732 25. 743 25. 802 26. 209 26. 443	S-VEL 1438. 2 1438. 4 1437. 5 1437. 0 1437. 0 1437. 1 1437. 2 1437. 0 1438. 1	DYN-DEP 0.000 0.003 0.006 0.009 0.012 0.014 0.017 0.020 0.022	PRESS 11. 5 13. 1 14. 2 15. 3 16. 5 17. 6 18. 7 19. 8	TEMP -1. 794 -1. 803 -1. 807 -1. 807 -1. 807 -1. 807 -1. 801 -1. 796 -1. 790	EAL 32. 951 33. 084 33. 141 33. 204 33. 248 33. 283 33. 285	810-T 26. 536 26. 646 26. 691 26. 742 26. 793 26. 793 26. 807	8-VEL 1438.4 1438.4 1438.4 1438.4 1438.4 1438.4 1438.4 1438.4	DYN-DEP 0.024 0.026 0.029 0.031 0.031 0.032 0.034 0.035

CONS. CAST : CRUISE ID: LOCATION:	10 DAT TIP	TE 3/85/10 L ME: 23:15 GMT L	ATITUDE 71- 1.4N ONGITUDE 158-12.1W	BOTTOM DEPTH: 29 Cast Depth: 0.
PRESS TEMP Second state 1.5 -1.697 33.0 2.5 -1.773 33.0 4.5 -1.790 33.0 6.1 -1.790 33.0 7.2 -1.796 33.0 9.3 -1.803 33.3 9.5 -1.809 33.0 10.7 -1.820 33.1 12.0 -1.827 33.0 13.1 -1.827 33.0 14.2 -1.931 33.0	AL SIG-T S-1 046 26.627 140 023 26.594 140 229 26.762 140 316 26.832 140 326 26.840 140 332 26.845 140 332 26.845 140 594 27.038 140 743 27.179 140 838 27.256 140 873 27.285 140	VEL DYN-DEP / 38.7 0.002 38.3 0.004 38.5 0.006 38.7 0.008 38.7 0.010 38.7 0.011 38.7 0.011 38.9 0.012 39.0 0.014 39.2 0.015 39.4 0.016 39.4 0.017	PRESS TEMP SAL 15.8 -1.830 33.898 17.1 -1.840 33.897 18.7 -1.830 33.893 20.3 -1.840 33.893 21.4 -1.840 33.997 22.8 -1.840 33.903 24.1 -1.836 33.902 26.3 -1.840 33.901 27.6 -1.836 33.903 28.9 -1.840 33.904	SIQ-T S-VEL DYN-DEP 27. 297 1439. 4 0. 018 27. 305 1439. 5 0. 019 27. 301 1439. 5 0. 020 27. 303 1439. 5 0. 022 27. 304 1439. 5 0. 022 27. 306 1439. 6 0. 023 27. 307 1439. 6 0. 024 27. 307 1439. 6 0. 025 27. 307 1439. 6 0. 025 27. 309 1439. 6 0. 025 27. 309 1439. 6 0. 025 27. 309 1439. 6 0. 025 27. 309 1439. 6 0. 027 27. 309 1439. 7 0. 028
CONS. CAST :: CRUISE 1D: LOCATION:	11 DA TJ	TE 3/85/11 IME: 2:30 GMT	LATITUDE 71- 1.4N LONGITUDE 158-11.6W	BOTTON DEPTH: 28 Cast Depth: 0.
PRESS TEMP 1 2.6 -1.933 33 4.1 -1.603 33 5.2 -1.803 33 6.6 -1.803 33 7.9 -1.607 33 9.3 -1.812 33 10.8 -1.833 33 12.2 -1.634 33 13.7 -1.634 33 14.9 -1.836 33 15.9 -1.638 33	SAL SIG-T S- 284 26.807 14 163 26.725 14 218 26.753 14 219 26.753 14 245 26.775 14 247 26.819 14 443 26.936 14 751 27.186 14 773 27.204 14 873 27.273 14 875 27.285 14	-VEL DYN-DEP 138, 4 0.003 138, 4 0.005 138, 5 0.007 138, 5 0.008 138, 6 0.010 138, 8 0.012 139, 2 0.013 139, 2 0.014 139, 4 0.016 139, 4 0.017 139, 4 0.017	PRESS TEMP SAL 17.0 -1.836 33.871 18.2 -1.838 33.878 19.2 -1.838 33.877 20.3 -1.838 33.877 21.4 -1.838 33.801 22.5 -1.838 33.800 23.6 -1.838 33.800 24.7 -1.838 33.801 26.7 -1.840 33.801 26.7 -1.840 33.801 26.7 -1.838 33.802	SIG-T S-VEL DYN-DEP 27.283 1439.4 0 018 27.289 1439.5 0 019 27.289 1439.5 0 020 27.299 1439.5 0 021 27.291 1439.5 0 022 27.291 1439.5 0 023 27.291 1439.5 0 024 27.291 1439.6 0 024 27.292 1439.6 0 025 27.295 1439.6 0 026 27.292 1439.6 0 026 27.292 1439.6 0 026
CONS. CAST 0: Cruise ID: Location:	12 D/ Ti	ATE 3/85/11 Ime: 20: 0 GMT	LATITUDE 70-59. ON LONGITUDE 150-10. 20	BOTTON DEPTH: 24. CAST DEPTH: 0
PRESS TEMP 2.3 -1.703 32 3.6 -1.757 32 4.8 -1.757 32 5.8 -1.762 32 6.9 -1.768 32 9.6 -1.773 32 9.6 -1.768 32 10.7 -1.786 32 11.7 -1.805 33 12.6 -1.822 33	SAL SIQ-T S- .387 26.077 14 .410 26.097 14 .440 26.138 14 .545 26.207 14 .612 26.261 14 .646 26.321 14 .927 26.517 14 .648 26.431 14	-VEL DYN-DEP 437.7 0.004 437.5 0.007 437.6 0.009 437.7 0.011 437.8 0.013 437.9 0.016 438.2 0.018 438.4 0.019 438.9 0.021 439.1 0.022	PRESS TEMP SAL 14.0 -1.831 33.734 15.2 -1.831 33.751 16.3 -1.831 33.765 17.5 -1.827 33.767 18.6 -1.827 33.767 19.6 -1.827 33.767 20.8 -1.825 33.770 21.8 -1.825 33.774 22.8 -1.825 33.774 24.0 -1.807 33.764	SIQ-T S-VEL DYN-DEP 27.174 1439.2 0 023 27.184 1439.3 0 024 27.197 1439.3 0 025 27.197 1439.3 0 025 27.200 1439.4 0 027 27.202 1439.4 0 028 27.201 1439.4 0 029 27.199 1439.4 0 030 27.204 1439.4 0 031 27.199 1439.3 0 031

CONS. CAST CRUISE ID: LOCATION:	. 13	DATE 3/05/12 TIME: 0:20 GMT	LATITUDE 71- 1.0N LONGITUDE 150-10.70	SOTTOM DEPTH: 27. CAST DEPTH: 0.
PRESS TEMP 3.6 -1.639 4.7 -1.777 6.0 -1.783 7.1 -1.786 8.4 -1.786 9.4 -1.801 10.9 -1.816 12.1 -1.827 13.1 -1.829 14.4 -1.829	SAL SIG-T 32 748 26.348 32 870 24.470 32 902 26.496 32 902 26.545 33 187 26.545 33 187 26.728 33 187 26.728 33 624 27.083 33 646 27.117 33 646 27.134 33.703 27.147	S-VEL DYN-DEP 1438. 6 0.006 1438. 1 0.000 1438. 2 0.011 1438. 4 0.013 1438. 5 0.015 1439. 1 0.016 1439. 1 0.016 1439. 2 0.019 1439. 2 0.020	PRESS TEMP SAL 15.8 -1.831 33.715 17.1 -1.831 33.724 18.4 -1.827 33.726 19.6 -1.831 33.726 20.6 -1.831 33.742 22.1 -1.827 33.739 23.3 -1.827 33.741 24.4 -1.827 33.740 25.6 -1.827 33.741 26.6 -1.825 33.741	BIG-T S-VEL DYN-DEP 27. 157 1439. 2 0. 021 27. 164 1439. 3 0. 022 27. 164 1439. 3 0. 023 27. 175 1439. 3 0. 023 27. 179 1439. 3 0. 024 27. 176 1439. 4 0. 027 27. 176 1439. 4 0. 021 27. 176 1439. 4 0. 021 27. 176 1439. 4 0. 030 27. 176 1439. 5 0. 031
CONS. CAST CRUISE ID: LOCATION:	. 14	DATE 3/85/12 TIME: 3: 0 GMT	LATITUDE 71- 1.4N LONGITUDE 158-12.1W	SOTTOM DEPTH: 29 CAST DEPTH: 0.
PRESS TEMP 2.5 -1.792 4.0 -1.803 5.0 -1.803 7.6 -1.803 7.6 -1.805 8.7 -1.805 8.7 -1.809 9.6 -1.818 11.0 -1.827 12.1 -1.829 13.3 -1.831 14.6 -1.833	SAL SI9-T 33, 33° 26, 851 33, 244 26, 790 33, 251 26, 790 33, 251 26, 790 33, 251 26, 790 33, 251 26, 790 33, 251 26, 790 33, 451 26, 824 33, 451 26, 824 33, 451 26, 742 33, 769 27, 200 33, 769 27, 200 33, 796 27, 224 33, 799 27, 225	S-VEL DYN-DEP 1438.7 0.003 1438.5 0.005 1438.6 0.006 1438.6 0.009 1438.6 0.007 1438.6 0.011 1439.1 0.012 1439.2 0.013 1439.3 0.014 1439.3 0.015 1439.3 0.016	PRESS TEMP SAL 15.0 -1.631 33.011 17.1 -1.631 33.011 17.1 -1.631 33.024 18.5 -1.031 33.024 19.5 -1.031 33.024 19.5 -1.031 33.024 19.5 -1.034 33.024 21.2 -1.034 33.024 22.5 -1.034 33.044 22.5 -1.040 33.072 23.0 -1.040 33.072 25.3 -1.040 33.072 26.7 -1.040 33.075 28.0 -1.040 33.0902 29.0 -1.040 33.0907	SIG-T S-VEL DYN-DEI 27.235 1439.4 0 01 27.247 1439.4 0 01 27.250 1439.4 0 01 27.250 1439.5 0 02 27.270 1439.5 0 02 27.275 1439.5 0 02 27.285 1439.5 0 02 27.295 1439.6 0 02 27.295 1439.6 0 02 27.309 1439.6 0 02 27.314 1439.7 0 02
CONS. CAST Cruise ID: Location:	•: 14	DATE 3/85/12 TIME: 17: 0 GMT	LATITUDE 71- 1. 6N LONGITUDE 158-12. ON	BOTTOM DEPTH: 29 CAST DEPTH: 0
PRESS TEMP 3. 1 -1. 742 4. 2 -1. 757 5. 5 -1. 757 7. 0 -1. 760 8. 7 -1. 766 10 4 -1. 794 11. 7 -1. 809 13. 0 -1. 914 14 5 -1. 822 16 0 -1. 827	SAL SI9-T 32.479 26.153 32.475 26.150 32.490 26.162 32.521 26.167 32.714 26.344 33.182 26.724 33.297 26.817 33.509 26.909 33.670 27.120 33.710 27.133	S-VEL DYN-DEP 1437.7 0.006 1437.6 0.008 1437.7 0.010 1437.7 0.013 1438.0 0.016 1438.5 0.019 1438.7 0.020 1439.0 0.022 1439.2 0.023 1439.2 0.023	PRESS TEMP SAL 17.3 -1.829 33.721 18.7 -1.831 33.728 20.0 -1.831 33.732 21.4 -1.629 33.731 22.6 -1.827 33.751 24.0 -1.825 33.753 25.3 -1.625 33.757 26.6 -1.827 33.779 28.1 -1.827 33.761 27.2 -1.827 33.761 27.2 -1.827 33.606	SIG-T S-VEL DYN-DEI 27.161 1439.3 0 02 27.167 1439.3 0 02 27.170 1439.3 0 02 27.170 1439.3 0 02 27.170 1439.4 0 03 27.186 1439.4 0 03 27.187 1439.4 0 03 27.197 1439.5 0 03 27.191 1439.5 0 03 27.208 1439.5 0 03 27.210 1439.5 0 03 27.232 1439.5 0 03

		a		CTD				
Stat: No.	ion Depth(m)	Sampling Depth(m)	Sample <u>Co</u> Depth	ncentrati Benzene	lons (ng/l) Toluene	Temp (°C)	Salinity (°/00)	σ _t
10	29	3	Subsurface	NA	NA	-1.77	33.02	26.63
		28	Bottom	NA	NA	-1.84	33.90	27.31
10A	28	14	Subsurface	.5	ND	-1.83	33.28	26.81
		27	Bottom	.3	ND	-1.84	33.88	27.30
12	24	2	Subsurface	6.9	2.8	-1.70	32.39	26.08
		23	Bottom	76	13	-1.82	33.77	27.20
13	27	4	Subsurface	.6	.04	-1.64	32.75	26.37
		26	Bottom	2.1	. 2	-1.82	33.74	27.18
14	29	2	Subsurface	.2	ND	-1.79	33.34	26.85
		28	Bottom	ND	ND	-1.84	33.91	27.31
15	26	2	Subsurface	1.6	. 2	NA	NA	NA
		25	Bottom	. 9	.02	NA	NA	NA
16A	29	2	Subsurface	16	.5	-1.74	32.48	26.15
		28	Bottom	1.9	. 2	-1.83	33.80	27.22
16B	26	2	Subsurface	1.1	ND	NA	NA	NA
		25	Bottom	1.7	.06	NA	NA	NA
16C	26	2	Subsurface	13	ND	NA	NA	NA
		25	Bottom	1.8	ND	NA	NA	NA
17	26	2	Subsurface	2.4	.1	NA	NA	NA
		25	Bottom	.4	. 02	NA	NA	NA
18	26	1	Subsurface	.7	ND	NA	NA	NA
		25	Bottom	1.0	.07	NA	NA	NA
19	25	1	Subsurface	. 5	.09	NA	NA	NA
		24	Bottom	1.9	. 2	NA	NA	NA
20	25	1	Subsurface	.4	.03	NA	NA	NA
		24	Bottom	1.0	. 2	NA	NA	NA
21	26	1	Subsurface	. 2	ND	NA	NA	NA
		25	Bottom	15	5.5	NA	NA	NA

Table 5-9.--Concentration of Aromatic Spike Components in Chukchi Sea Seawater Samples and CTD Information.

^a Bottom sampling depth nominally 0.5-1.0 m above the bottom.

b No detectable amounts of ethylbenzene, o,m-xylenes, naphthalene or 2-methylnaphthalene were found in any samples.

ND Not detected at method detection limit of 0.01 ng/l.

NA Not available.

compounds in the water samples indicates that sample contamination due to handling in the field was not a problem.

Comparison of the measured concentrations for the detectable hydrocarbons (i.e., benzene and toluene) and the salinity data allow for a rational hypothesis to be developed for the hydrocarbon distributions observed in the field (Table 5-9). For example, the highest benzene and toluene concentrations were measured in bottom water samples associated with the largest salinity/ density gradients in the water column (e.g., Station 12; Figure 5-20A and Table 5-8). This situation was in contrast to the low or undetectable hydrocarbon levels at stations with little or no density stratification (e.g., Station 14; Figure 5-20B and Table 5-8). Furthermore, benzene and toluene concentrations generally were higher in bottom water compared to surface water (e.g., Stations 12, 13, 16b, 18, 19, 20, and 21). Exceptions to these trends can be explained when ice formation sequences, extensive ridge structures and current measurement data are considered.

Seawater samples collected three hours after the spill at Station 10A contained low (<1 ng/l) but detectable concentrations of benzene and nondetectable (<0.01 ng/l) concentrations of toluene. Based on S4 current meter data collected at the time of the spill, this site was upcurrent from the spill site. Therefore, minimal transport/mixing of water that had been in direct contact with the original surface spill could be expected. The measurable benzene concentrations may simply represent background contamination due to the close (7-10 m) proximity to the spill site.

Bottom water samples collected at Site 12 (23 hours post-spill) contained the highest concentrations of aromatic hydrocarbons of any location examined. These concentrations for benzene and toluene were 76 and 13 ng/l, respectively. The surface water sample (1 m below the ice canopy) at Site 12 contained concentrations of benzene and toluene of 7 and 3 ng/l, respectively. These concentrations likely reflect limited vertical mixing of deeper water toward the surface due to the presence of the extensive ridge/keel system immediately northwest of Station 12. The ice keel associated with this ridge



Figure 5-20.--CTD Data from the 1985 Field Program for (A) Station 12 and (B) Station 14.

could promote turbulence around the keel, and thus mix the benzene-enriched bottom water into near surface under-ice waters. Station 12 was 3.2 km southeast of the spill site. Bottom current measurements taken at this site (Table 5-7) indicated a southeasterly flow of bottom water with a velocity of 1.1 cm/sec. Although this current direction could explain the presence of hydrocarbons derived from the initial spill site, the magnitude of the current velocity should have been slightly higher (ca.3.8 cm/sec) to transport the hydrocarbons to Site 12 by the time of sampling. It is possible, however, that higher current speeds with a southeasterly direction could have occurred while the leads north of Station 10 were open during the 24 hour period between the initial spill and the sample collections at Site 12.

Such southeasterly transport of 33.7 ^o/oo salinity bottom water at 3.0 cm/sec was in fact, measured the day before the experimental spill at Station 7 on 9 March 1985, when active ice formation was occurring in extensive offshore open-leads in the vicinity of Station 8, which was located on a 50 m diameter stable pan in those leads to the north of Stations 7 and 9 (see Figure 5-17 and Table 5-8). Also, the rather uniform salinity values (up to 32.9 ^o/oo at the surface and 33.7 ^o/oo at the bottom) at Station 8 suggested the formation and active sinking of brine at that site compared to surface and bottom salinities at Sites 7 and 9 (Table 5-8).

At Station 13, higher concentrations of both benzene and toluene were measured in the bottom water sample (2.1 ng/l and 0.2 ng/l, respectively) as compared to the near-surface sample (0.6 ng/l and 0.04 ng/l, respectively). However, the concentrations of benzene and toluene in the bottom water sample at Station 13 were substantially less than those in the bottom water at Station 12. Because Station 13 was in a region with a relatively smooth surface ice cover about 1.6 km southeast of the initial spill release point, the data suggest that the majority of the dissolved aromatic hydrocarbon plume had been transported past or adjacent to this site by the time the station was occupied (i.e., approximately 26 hours after the spill). That is, the spill released at Site 10 served as a short-term point source (versus a longer term "continuous" source) to the water column due to the initial lead closure shortly after the

spill event. Thus, hydrocarbons reaching the bottom at Station 10 could advect along a line from the release site toward Station 12 and largely miss Station 13.

Benzene and toluene were not detected in the bottom water at Station 14. However, CTD data (Figure 5-20B and Table 5-8) from the area around Stations 14 and 15 suggest that the water column was only weakly stratified (i.e., the surface water salinity of 33.34°/oo was similar to the bottom water salinity of 33.91°/oo). Under weakly stratified conditions, the aromatic hydrocarbons that were dissolved in the water (e.g., benzene) could have been mixed vertically and diluted (below detection limits) more effectively than at stations with more pronounced water column stratification (e.g., Station 12).

Benzene and toluene were both present at concentrations of <2 ng/l in water samples from Station 15 (26-27 hrs post-spill). The concentrations at this site were slightly higher in the surface versus the bottom sample. However, the possibility of accidental sample contamination at this site cannot be discounted completely, even though a new auger hole was drilled in the ice for sampling. Alternatively, cold-room wave-tank studies (Sections 4.4.2 and 4.4.3) have demonstrated that with only minor wave turbulence, dispersed oil droplets can impinge on under-ice surfaces adjacent to leads where the hydrocarbons have been introduced. Entrapment of hydrocarbons on the under-ice surface adjacent to the experimental spill site due to turbulence accompanying the initial lead closure could easily explain the detectable benzene and toluene concentrations in the near surface waters at Site 15.

Stations 16 A, B, and C were on a transect that ran parallel to but 30 m north of a ridge system approximately 500-700 m north-northeast of the spill site (see Figure 5-19). Samples from these three stations contained low concentrations (≤ 0.5 ng/l) of toluene, but variable concentrations (i.e, up to 16 ng/l) of benzene. At Station 16B the benzene and toluene concentrations in the bottom water were 2 ng/l and 0.06 ng/l, respectively, whereas surface water concentrations of benzene were 1 ng/l and toluene concentrations were below detection. However, at Stations 16A and C, the surface water concentrations of

benzene were elevated compared to those in the bottom water. A possible explanation for this variation in concentrations at Station 16 could be the existence of turbulent flow on the downcurrent (northern) side of the ridge system. Such turbulent flow could have mixed benzene-enriched bottom water into the near-surface zone. Alternatively, micro-scale ridge/keel melting could have introduced fresher, lower-density water near the bottom of the water column, and thereby induced an upward mixing of bottom water toward the surface.

Bottom water between Stations 17 and 21 (Figure 5-19) contained relatively uniform concentrations of benzene and toluene. However, the concentrations in the bottom water samples were relatively higher at those stations closest to the original spill site. Surface water concentrations at these stations were uniformly low, except Station 17 immediately adjacent to the northern-most ridge system where the 27 kHz bottom drifting transponder was eventually located. Again, it is conceivable that the nearby 4-6 m ice keel structure produced an irregular flow pattern that resulted in mixing of bottom water toward the surface at Site 17. This could account for the higher aromatic concentrations in the surface water (2 ng/l benzene, 0.1 ng/l toluene) vs the bottom water at that station.

There appeared to be a strong correlation between the relative bottom vs surface water concentrations of dissolved aromatics and the degree of stratification (i.e., vertical density gradient) in the water column. Where the water column was weakly stratified, aromatic hydrocarbon concentrations in both surface and bottom water samples were generally low or undetectable (Tables 5-8 and 5-9 and Figure 5-20). Slightly higher aromatic concentrations were noted in surface waters near ice ridge systems, which could have induced irregular and turbulent flows in the subsurface waters near the ice ridge keels. These results from the field experiment agree with processes observed in smaller scale laboratory studies of brine generation and associated nearbottom flows (Section 5.2) as well as model predictions on the rates and magnitude of aromatic hydrocarbon dissolution into surface brine generated during frazil and grease ice growth (Section 6.9).

5.3.4.2 <u>Transport Scenario for Dissolved Hydrocarbons from the Initial Spill</u> <u>Mixture</u>

Salinity sections (Figures 5-21 and 5-22) derived from CTD and current measurements completed on 9 and 11 March (Tables 5-7 and 5-8) suggest an onshore (i.e., generally southeasterly) flow of brine along the bottom during the initial 48 hours following the spill event. Between 9 and 11 March, the inshore salinity increased from 32.8 to 33.3°/oo. A calculation estimating the total volume of water inshore of a location at 15 km (approximately 20 m water depth) indicates that an onshore current velocity of 3 cm/sec in the lower 10 m of the water column and an accompanying offshore current velocity of 3 cm/sec in the upper 10 m of the water column could yield the observed change in Onshore (southeasterly) bottom water velocities of 1-3 cm/sec were salinity. observed on 9 and 11 March (Table 5-7) and an average current velocity in this range could transport benzene and toluene in a brine generated bottom layer from Station 10 to Station 12 in a period of 24-28 hours as observed. An apparent anomaly, however, is the net under-ice movement of the 27 kHz seabed drifting transponder to the north-northeast and measured benzene and toluene levels at Stations 16 through 21.

These findings can be explained if the rearrangement of the ice canopy and experimental lead system are considered in context with the timing of the cocktail release. At the time of the spill, a 1.5 cm/sec near-bottom current to the north-northeast was measured immediately beneath the experimental lead (Station 10, Figure 5-18 and Table 5-7).

This current could transport dissolved hydrocarbons in the brine and the 27 kHz bottom drifting transponder toward the north- northeast during the first 1-2 hours after the spill. With the closing of the exprimental lead and the opening of the broad (several 100 meter) expanse of open water to the north of the experimental site, however, a different flow pattern (more closely approximating that observed on 9 and 11 March) might be anticipated. A similar pattern was suggested by the tank experiments in Section 5.2.3.2, Open Water Freeze-up.



Figure 5-21.--Salinity Section on 9 March 1985 and Average Bottom Velocity Vector Taken at Station 7. (See Figure 5-17 for station locations.)



Figure 5-22.--Salinity Section on 11 March 1985 and Average Bottom Velocity Vector Taken at Station 12. (See Figure 5-17 for station locations.)

Figure 5-23 presents idealized vertical cross-sections for flow regimes and ice structures along an approximate northwest-southeast transect line in the study area (also examine Figure 5-17 for station locations). The illustrated current flow patterns are extrapolated from current meter data (Table 5-7), vertical salinity profiles and cross-sections from CTD data for 9-11 March (Table 5-8 and Figures 5-21 and 5-22), and ice movement observations.

As shown in Figure 5-23A, brine appeared to be generated in the experimental lead system at the time of the initial cocktail release (Site 10), while ice fields to the south of this region were continuous. This would tend to generate a weak northerly flow as measured in the field at the initiation of the experiment (shown in Figure 5-23A). After the opening of the larger off-shore lead system to the north of the spill site (Figure 5-23B), water currents under the continuous ice field to the south could have reversed and have a predominantly horizontal component to their flow direction for the next 20-24 hour period following the spill. In contrast, water flow patterns directly under the new offshore lead system to the north would have a greater vertical component during this period due to extensive brine generation and the proximity of a deep ridge keel in this direction (Figure 5-23B). Such currents would serve to further dilute any benzene or toluene introduced into the area initially after the spill, as observed by the low concentrations measured on 12 March 1985 after the freezing in the vicinity of Stations 17 through 21.

Kozo (1983) predicted comparable directional flow regimes using an initial model for arctic mixed layer circulation under a refreezing lead. This model represents idealized circulation under a refreezing lead in the Arctic Ocean and presents mathematical calculations that determine the salt flux to the bottom. The model considers conditions including zero geostrophic current superimposed over the lead circulation system and also geostrophic currents running parallel and perpendicular to the lead system. With a geostrophic current of 2.5 cm/sec perpendicular to the lead axis, a circulation pattern would be established that mimics the distributions of currents and water masses, the temperature and salinity profiles, and the benzene/toluene

Northwest





Figure 5-23.--Vertical Ice Conditions for (A) 3/10/85, (B) 3/11/85, and (C) 3/12/85.

concentrations that were measured during this study near the lead at Stations 14 and 15. Kozo's model for mixed layer circulation under a refreezing lead in the absence of geostrophic influence predicts a maximum horizontal flow from brine generation in the range of 2 to 5 cm/sec. These current estimates agree with values measured in this program in March 1985.

In summary, at the time of the hydrocarbon spill for this field study, active freezing occurred in the open lead system with an accompanying production of downward advecting brine. The lead was only open for approximately one hour after the spill. At the beginning of this period the measured bottom current (i.e., 5-minute vector average) was northerly (approximately 25 to 35°T) at a speed of 1.5 cm/sec. The seabed drifter (27 kHz) deployed to track bottom water movement was transported to the north-northeast, until it became trapped in the ridge system 0.5 to 1 km north of Station 10 (see Figure 5-23B).

Bottom topography in the immediate vicinity of the spill site was quite uniform. Therefore, current shifts due to the in situ water column density structures or tidal fluctuations would have been primarily responsible for determining flow directions for the bottom brine layer and any associated dissolved aromatic hydrocarbons. Thus, with the subsequent opening of the larger lead to the north of the spill site, the bottom current would have likely shifted to an approximate southerly direction at the immediate spill site due to brine-mediated flow processes illustrated in Figure 5-23B. The latter flow regime would explain the higher concentrations of aromatics observed in the bottom water samples at Sites 12 and 13 within approximately the first 24-26 hours after the spill event.

Such flow reversals due to brine rejection during refreezing of polynyas have also been reported by Schumacher et al. (1983). These authors suggested that ice formation and accompanying brine rejection affected bottom water flow in the vicinity of the polynya south of St. Lawrence Island. Eleven flow reversals were detected in the regional circulation patterns that could be explained by combinations of brine rejection processes and offshore wind stress. Scaling of a simplified equation of motion yielded results suggesting

density induced quasi-geostrophic flow resulting from brine rejection that was an important element for the circulation patterns. During the study, approximately 5 m of ice formed in the polynya. The estimated increases in water salinities in the northern Bering Sea shelf polynas suggest that this process is comparable in effect, but opposite in phase, to that of runoff. Therefore, brine rejection is an important part of the seasonal salt budget in these waters.

In the case of the present study in the Chukchi Sea, the offshore development of open leads and concomitant brine rejection provide conditions required to generate the observed (1-3 cm/sec) onshore flow patterns of higher salinity bottom water. Under these conditions, the dissolved aromatic hydrocarbons (benzene and toluene) detected in bottom waters are clearly consistent with the source of those water masses from formation of brine in the refreezing lead at the experimental spill site and the measured bottom-water flows. The observation of (only) benzene and toluene transport to the bottom does not exclude the possibility of the transport of other compounds, including other aromatics, and (to a lesser extent) paraffins and naphthas, to the bottom. While benzene and toluene do have water/oil partition coefficients that are larger than other compounds present in crude oil, finite partition coefficients will result in transport of other less soluble components. Only benzene and toluene were detected in the field experiments; however, other parameters that must be specified include the quantity of each compound in the spill itself. In the case of the Chukchi Sea field experiments, these quantities were extremely small compared to the carrier solvent, toluene, and benzene (Table 5-6). From ice chamber wave tank experiments presented in Sections 4.2.3 and 4.4.3, it is clearly evident that there are numerous other water-soluble, lower-molecular weight aromatic hydrocarbons which partition from Prudhoe Bay crude oil into the water colume (see also Sections 6.8 and 6.9). Once present as truly dissolved species in solutions of brine generated during ice growth, these other compounds would be subject to the same transport mechanisms demonstrated in the Chukchi Sea field experiment for benzene and toluene.

The low velocities (1 to 5 cm/sec) associated with both the sinking brine and the horizontal advection of this brine away from the lead system in the lower layers of the water column may result in the motion of the brine being driven by localized currents or tidal movements. Nevertheless, with time, a mean down-slope, offshore movement of brine is expected (especially after closure or complete refreezing of the offshore leads).

The extreme difficulty of field sampling due to weather and the dynamic nature of the ice fields (and experimental lead) in this study limited the synopticity of sampling. Additional water samples and current measurements could have provided further information for tracking the cocktail plume, estimating dilution rates, and evaluating the longer term fate of the soluble hydrocarbons. Nevertheless, dissolution and transport of aromatic hydrocarbons from the surface to the bottom of the water column (and up to 3 km from the spill site) are demonstrated by the results of the field program. The low flow period encountered during this study may not be typical of all conditions in the area. In fact, given the limited size of the spill (38 liters) and location (further offshore and in deeper water than desired), the benzene and toluene components may not have been recoverable under higher flow conditions.

Nevertheless, the observations of aromatic hydrocarbon dissolution suggest a mechanism by which a spill of crude oil or refined products in a refreezing lead system could result in elevated concentrations of aromatics in bottom waters. Once incorporated into a bottom brine layer, these aromatic compounds would persist depending on rates of mixing and dilution. Potential problems with extrapolating results from this experiment to an actual oil spill would involve consideration of the type and volume of oil (or petroleum product) spilled, the degree of weathering of the oil prior to mixing with brine, the duration of the ice (brine) formation process, and the degree of water column density stratification and depth.

6. OCEAN-ICE OIL-WEATHERING MODEL DEVELOPMENT

6.1 INTRODUCTION

The objectives for a mathematical model of oil weathering in the presence of first and multi-year sea ice are to temporally predict both the mass of oil remaining in the slick and the chemical composition and physical properties of the oil slick. These two objectives require that oil composition be described in terms of both specific components and lumped-component categories, "pseudocompounds". Pseudocomponent classification has been widely used in or the petroleum industry to describe crude oil because of the inherent interest in bulk. oil characteristics and accounting for total mass. Α specific-component description is of interest in describing spilled oil as a changing source of foreign chemicals to an aquatic ecosystem, but the complexity of oil composition makes it impractical to keep track of bulk oil mass in terms of individual components.

The Ocean-Ice Oil-Weathering Model presented in this report has been developed over the last thirty-six months. The basis for this model is the Open-Ocean Oil-Weathering code that was developed between 1979 and 1984. During this time, additional stand-alone models have been derived and used to guide experimental and development work. Some of these, as well as the openocean code itself, are described in detail in Payne et al. (1984a). Others will be presented here.

The most developed models are mass transport models which describe evaporation and dissolution processes. These two processes describe molecular transport, in contrast to the dispersion/oil-weathering process which describes the transport of discrete oil drops into the water column due to wind/wave action and other physical processes.

These models incorporate the concepts of interfacial mass transfer, the considerations of both mechanically well-stirred and stagnant oil phases, the effects of slick spreading, and the boundary conditions imposed on the oil by the environment. In addition, these models include descriptive predictions

of specific compound concentrations in the air and water column in contact with a slick or other spilled oil phase.

Both portions of the model require distinct and independent mathematical formulations. In order to predict the mass of oil remaining in a slick as a function of time, a method of characterizing the bulk oil with respect to the various transport processes that alter and dissipate oil must be utilized. The total oil mass cannot be characterized by its individual components because of both their large number and complexity and the limitations of analysis. To compensate for these limitations, the pseudo-component approach "cuts" oil into a number of fractions, assigning appropriate physical properties to each.

In attempting to predict the mass of oil remaining in a slick, the two most important mass transport processes to consider are evaporation and dispersion. Of these two, evaporation appears to have the greater influence, certainly over short time scales, making vapor pressure an especially important oil characteristic. Adequate description of the dissolution process, on the other hand, requires water solubility information. The pseudo-component approach to describe these processes is to cut the oil into a number of fractions based on properties of distillation fractions (Payne et al., 1984a).

The pseudo-component approach, employed in virtually all previous efforts to model oil weathering, is singularly useful for providing a total material balance versus time for spilled oil (especially for slicks). However, this approach does not predict the time-dependent material balance for specific chemical components. In order to obtain component-specific information, component-specific physical properties (e.g., solubilities, vapor pressures and other phase partitioning parameters) must be used. No other functional component-specific models have been developed to date. Ironically, most of the data generated when an actual oil spill has occurred have been component- specific concentrations across phase boundaries, and virtually no pseudo- component concentration data have been reported.

Although evaporation and dispersion are the oil-weathering processes of greatest importance during the initial stages of a spill, other longer-term
weathering processes also destroy and produce compounds that are important to any component-specific model. In the case of photo- or autoxidation, a compound may chemically react to become an aldehyde, ketone, alcohol or acid, all of which are more soluble in water than the precursor hydrocarbon compounds. Similarly, metabolites of microbial degradation have physical properties markedly different from their corresponding parent compounds. These secondary or long-term processes are typically more complex than the evaporation and dispersion processes, thus increasing the complexity of the mathematical descriptions.

In discussing the segments of the model which follow, three basic aspects have been considered for each oil weathering process:

- (1) physical properties (of bulk oil and specific components)
- (2) mass balance equations (for specific components and pseudo- components)
- (3) environmental parameters (which the oil encounters upon being spilled)

Physical properties include the thermodynamic and transport characteristics required to describe a particular process. In the cases of evaporation and dissolution, <u>thermodynamic</u> properties are the vapor pressures, Henry's Law coefficients, oil/water partition coefficients, and mixing rules, while the <u>transport</u> properties include diffusivities, viscosities and, again, mixing rules.

6.2 MODEL APPROACH

In considering the most useful approach for modeling oil-weathering in the presence of sea ice, a "scenario" approach was selected to provide clarity to the user with maximum flexibility. In this approach, the user is given the freedom to choose a series of environmental conditions and physical locations for the oil to weather. Then, since sea and ice conditions change (for a real or conceptualized situation), they can be changed by the user also. In other words, the user can alter environmental and physical parameters in order to create a "scenario" that best fits the situation for the desired weathering

prediction. Flexibility has been provided in the following manner. Using the open-ocean oil-weathering code as a basis, the model has been compartmentalized into four basic oil-ice configurations: oil in pools on top of ice, oil trapped under (and encapsulated in) a growing ice field, oil on the ocean surface in a broken-ice field, and oil on the open-ocean (no ice). Each of these configurations is offered to the user chronologically but none is required. When a configuration is chosen, the specific environmental parameters required to predict weathering in that configuration are then requested from the user. After this information is supplied the oil is <u>re-characterized</u> so that the user can track the progress of the various pseudo-components and learn about the physical processes that occur during oil weathering. After re- characterization, the user is then offered the next oil-ice configuration. In this way, the user has a large amount of freedom to subject the oil to specific (user-defined) weathering conditions.

In order to introduce users to the operation of the model, a standalone users manual has been prepared as a separate volume.

6.3 PHYSICAL PROCESSES CONSIDERED

Predicting the quantity of oil in the slick as a function of time requires that a total mass balance approach be used. It is not possible to write a total material balance for crude oil by using component-specific information. If one tries to use component specific information, it soon becomes apparent that all the components in crude oil will never be identified, thus precluding an accounting of the total mass of the oil. No predictive equations have ever been successfully developed based on specific components for the purpose of predictions a total mass balance for oil.

The question then is raised as to how one uses bulk properties of the oil to make specific predictions? The petroleum industry refers to these bulk properties of oil as "characterization parameters". The characterization of an oil must be done with respect to a specific prediction (process design or mathematical model) as the objective. For example, when the prediction is a process that involves vapor-liquid transport, the characteristic parameters are

vapor pressures or partial pressures. When the prediction is the performance of a catalytic reformer where naphthas are converted to aromatics, the characteristics required on the catalytic reformer feedstock are combined contents of paraffins-olefins-naphthas-aromatics, referred to as PONA. Kinetic equations use PONA values as starting concentrations along with kinetic constants to predict the product from the catalytic reforming process. Both of these examples illustrate a pseudo-component model, sometimes referred to as a "lumped" model.

In predicting the mass of oil remaining in an oil slick as a function of time as evaporation proceeds, the oil must be characterized with respect to vapor pressure. An overall mass balance utilizes the vapor pressure and environmental parameters to predict loss of oil and, therefore, mass of oil remaining in the slick. The following discussion considers: 1) the procedure for characterizing crude oils with respect to pseudo-component vapor pressures; and 2) the pertinent equations for describing the overall mass balance as they apply to the oil weathering model.

6.4 PSEUDO-COMPONENT CHARACTERIZATION OF CRUDE OIL

The standard inspections on a crude oil include distillation, density of the distillate cuts, and viscosity of the distillate cuts. Virtually no component-specific data can be obtained which will allow adequate prediction of the bulk properties of the oil. The standard distillation data come from either a true boiling point (TBP) distillation or an ASTM (American Society for Test and Materials) D-86 distillation; both are usually carried out at one atmosphere total pressure. Each of these distillations can also be carried out at 40 mm Hg total pressure to obtain information on the less volatile fractions of the oil.

Either distillation is conducted in a manner such that the distillate fractions are collected separately (i.e., the fraction distilling at 50 to 75°C is physically separated from the fraction distilling at 75 to 100°C). The total number of fractions collected is usually five to seven, but can be as many as 20. Characteristic data for the distillate fractions include the temperatures at the beginning and end of each fraction (or "cut"), sometimes in the

form of a continuous curve of temperature vs percent distilled. The API (American Petroleum Institute) gravity and, occasionally, the viscosity of each cut are then measured.

Given the boiling point (1 atm) and API gravity of each cut (or pseudo-component), the vapor pressure of the cut can be calculated as a function of temperature. First, the molecular weight and critical temperature of the cut are calculated according to the following correlation (Fallon and Watson, 1944):

$$Y = c_1 + c_2 x_1 + c_3 x_2 + c_4 x_1 x_2 + c_5 x_1^2 + c_6 x_2^2$$
(1)

where X_1 is the boiling point (°F) at one atmosphere, X_2 is the API gravity, and the constants C_1 to C_6 have the values indicated in Table 6-1. Similarly, the critical temperature can be calculated from the same equation form using the indicated constant values in Table 6-1.

Next the equivalent paraffin carbon number if calculated according to (Gamson and Watson, 1944):

$$N_{\rm C} = (MW - 2)/14$$
 (2)

The critical volume is then calculated according to:

$$V_{c} = (1.88 + 2.44N_{c})/0.044$$
 (3)

and the critical pressure is calculated from:

$$P_{c} = \frac{20.8T}{(V_{c} - 8)} + P_{c}'$$
(4)

where $P_c' = 10$ to correct the critical pressure correlation from a strictly paraffinic mixture to a naphtha-aromatic-paraffin mixture. Next a parameter (b) is calculated according to

$$b = b' - 0.02$$
 (5)

PROPERTY	c,	¢2	c3	C ₄	¢5	с ₆
Molecular weight t ≤ 500°F b	6.241E+01	- 4 . 595E -02	-2.836E-01	3,256E-03	4.578E-04	5.279E-1M
Holecular weight t > 500 b	4 . 268E +02	-1.007	-7.491	1.380E-02	1.047E-03	2.621E-02
Critical temperature $t_b \leq 500$	4.055E+02	1.337	-2.662	-2.169E-03	-4.943E-04	1.454E-02
Critical temperature t > 500	4.122E+02	1.276	-2.865	-2.888E-03	-3.707E-04	2.288E-02
b'	1.237E-02	2.516E-01	4.039E-02	-4.024E-02		
Kinematic vis, cs @ 122"F API ≤ 35	- 4.4 88E-01	-9.344E-04) . 583E-02	-5.219E-05	5.2688-06	1 . 536E - ()4
Kinematic vis, cs @ 122"F API > 35	-6.019E-01	1.79 3 E-03	-3.159E-03	-5.1E-06	9.067 E-07	3.522E-05

Table 6-1.--Correlation Equation Constants for the Characterization of Narrow Boiling Petroleum Fractions (see text for equation form).

where

$$b' = c_1 + c_2 N_c + c_3 N_c^2 + c_4 N_c^3$$
(6)

and the values of the constants C_1 to C_4 are indicated in Table 6-1.

A final parameter designated as A is then calculated according to:

$$A = \frac{T_{rb}}{T_{rb}^{-1}} \log_{10}(P_{rb}) + \exp\left[-20(T_{rb}^{-b})^2\right]$$
(7)

where T_{rb} and P_{rb} are the reduced temperature and reduced pressure at the normal boiling point.

The vapor pressure equation which can be used down to 10 mm Hg is:

$$\log_{10} P_{r} = \frac{-A(1-T_{r})}{T_{r}} - \exp\left[-20(T_{r}-b)^{2}\right]$$
(8)

where A, b, T_c and P_c were determined from the normal boiling point and API gravity of the cut. The temperature at which the vapor pressure is 10 mm Hg can be obtained by the root-finding algorithm of Newton-Raphson.

Below 10 mm Hg, the vapor pressure is calculated according to the Clausius-Clapeyron equation as follows (Gamson and Watson, 1944):

$$\ln \frac{P_2}{P_1} = \frac{\lambda_0}{RT_c} \qquad \int \frac{T_r (1-T_r)^{0.38}}{T_r T_1 T_r^2} dT_r$$
(9)

and is based on the law which states the ratio of the heat of vaporization, λ , to $(1 - T_r)^{0.38}$ is a constant at any temperature. The latent heat of vaporization is calculated from the slope of the natural log of the vapor pressure equation with respect to temperature at the temperature where the vapor pressure is 10 mm Hg. Thus, in the above equation, P_2 is the 10 mm Hg vapor pressure at the temperature, T_r , previously determined.

A sample calculation for the characterization of Prudhoe Bay crude oil is presented in Tables 6-2 and 6-3. Table 6-2 presents the standard inspections (Coleman, 1978; PPC, 1973) for the crude and provides the starting point for the characterization calculations. Note that the distillation in Table 6-2 was conducted at 40 mm Hg for cuts 11 to 15. Thus, these cut temperatures must be corrected to one atmosphere (API, 1976). Table 6-3 presents the computer generated output along with the corrected cut temperatures.

6.5 PSEUDO-COMPONENT EVAPORATION MODEL ON THE OCEAN SURFACE

The evaporation model that predicts the oil remaining in a slick is derived from the physical properties of the oil cuts and a total material balance. From the previous discussion a number of pseudo-components are defined. For each pseudo-component the vapor pressure, molecular weight and initial quantity are known, and a material balance can be written to include each:

$$\frac{dM_i}{dt} = -K_i \text{ Ax } P_i^* \text{ for } i = 1,2,\dots \text{ Total number}$$
(10)
of components

where it is assumed that the oil slick is well stirred and a pseudo-Raoult's law applies as the mixing rule. In this rate equation, M_i is the number of moles of pseudo-component i in the oil slick, P_i * is the vapor pressure at the prevailing environmental temperature, A is the area of the slick, K_i is an overall mass-transfer coefficient based on partial pressure driving forces, and x_i is the mole fraction of pseudo-component i in the slick. The differential equations are all coupled through the mole fraction term where the total number of moles appears in the denominator.

The over-all mass-transfer coefficient can be calculated using two different methods. One method is the approach of Mackay and Matsugu (1976).

$$K = 0.0292 \ U^{0.78} \ x^{-0.11} \ sc^{-0.67} \tag{11}$$

where U is the wind velocity in m/hr, X is the slick diameter (assumes circular slick), and Sc is the Schmidt number (2.7). This expression is a correlation

Table 6-2.--Standard Inspections for Prudhoe Bay Crude Oil (Coleman et al., 1978).

Prudhae Bay field Sadlerachit, Triassic 8,890 - 9,008 feet

Alaske North Slape

GENERAL CHARACTERISTICS

Gravity, specifie, 0.893	Gravity. * API, 27,0	Pour point, * F.,		
Viscouty, Sayholt Universal as	77" F, 111 sec; 100" F, 64 sec	Color, brownish black Nitragen, percent, 0.230		

DISTILLATION, BUREAU OF MINES ROUTINE METHOD

			87×08 1 F	hulallistunin ist. Firm	741 mm He					
Frantina	Citt	l'ereent	Sum Interul	NI EF . 60 NO F	()*1 60* F	c i	i Hefmetise tridet, n. 61 20" 1"	"perific dispersion	N U Vier 100* P	Cinud trat.
i 2 3 4 5 6 7 8 7 8 9	122 167 212 257 302 347 399 437 482 527	2.1 2.6 3.5 3.6 3.7 3.5 4.3 4.8 5.0	2.1 4.7 8.2 11.8 15.5 19.0 23.3 28.1 33.1	0.693 .723 .752 .773 .790 .801 .818 .836 .851	72.7 64.2 56.7 51.6 47.6 45.2 41.5 37.8 34.8	23 27 30 31 30 33 36 38	1.38591 1.40312 1.41722 1.43082 1.43922 1.44626 1.45528 1.45528 1.4565	127.9 139.0 141.9 147.0 149.6 152.1 154.7 157.0 160.5		
11 12 13 14 15 Residuum	392 437 482 527 572	2.8 6.5 6.8 6.0 7.4 36.3	35.9 42.4 49.2 55.2 62.6 98.9	1 0.873 .881 .977 .910 .919 .990	30.6 29.1 26.2 24.0 22.5 11.4	45 45 45 49 52 53	1.48218 1.48650 1.49477	161.5 168.6 169.4	40 45 58 93 176	10 30 50 70 90

Carbon reaidus, Contection - Ri iiduum	11.6 purent; crude 4.7 APPROXIMATE	percent. SUMMARY	Residuom: Sulfur, perc Nitrogen, p	eni, - erc on i, -	-		
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Total resolute and peoplities		19.0	i 0.72	54.2			
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Gen mi		. 18.4	. 860	33.1			
Nun, menus luberentine distillate		11.0	. 887 911	28.0-23.9	58-109		
Vedue inbreature dutiliate		8.1	1.911922	23.9-22.0	108-208		
Automa lubrication dustillate		1.8	. 922 924	22.0-21.6	Abeve 200		
Rendunm		36.3	. 990	11.4			
Destillation loss		1.1		i i			

SUMMARY OF TBP CUTS CHARACTERIZATION FOR: PRUDHOE BAY, ALASKA

CODE VERSION IS CUTICA OF MAY 84. ITEM 9, SAMPLE 71011

	TB	API	SPCR	VOL.	MW	TC	PC	VC	Α	B	T10	VIS	NC	NS
1	1.50E+02	7.27E+01	6.81E-01	2.12E+00	8.35E+01	9.14E+02	3.95E+01	3.66E+02	3.17E+00	1.90E-01	4.47£+02	3.88E-01	3	1
2	1.90E+02	6.42E+01	7.11E+01	2.63E+00	9.39E+01	9.63E+02	3.79E+01	4.07E+02	3.24E+00	2.03E-01	4.788+02	4.48E-01	3	1
3	2.35E+02	5.67E+01	7.39E-01	3.54E+00	1.06E+02	1.02E+03	3.64E+01	4.54£+02	3.31E+00	2.15E-01	5.13E+02	5.44E-01	3	1
4	2.80E+02	5.16E+01	7.60E-01	3.64E+00	1.198+02	1.07E+03	3.48E+04	5.07E+02	3.41E+00	2.27E-01	5.49E+02	6.73E-01	3	1
5	3.25E+02	4.76E+01	7.77E-01	3.74E+00	1.348+02	1.128+03	3.32E+01	5.65E+02	3.52E+ 00	2.39E-01	5.86E+02	8.46E-01	3	1
6	3.70E+02	4.52E+01	7.87E-01	3.54E+00	1.51E+02	1.16£+03	3.16E+01	6.32E+02	3.67E+00	2.50E-01	6.23E+02	1.07E+00	3	1
7	4.15E+02	4.15E+01	8.04E-01	4.35E+00	1.678+02	1.21E+03	3.03E+01	6.98E+02	3.80E+00	2.59E-01	6.60E+02	1.38E+00	3	1
8	4.60E+02	3.78E+01	8.22E-01	4.85E+00	1.85E+02	1.26E+03	2.91E+01	7.67E+02	3.94E+00	2.67E-01	6.98E+02	1.81E+00	3	- 1
9	5.05E+02	3.48E+01	8.36E-01	5.06E+00	2.00E+02	1.31E+03	2.84E+01	8.28E+02	4.06E+00	2.74E-01	7.36E+02	1.75E+00	3	1
10	5.54E+02	3.06E+01	8.58E-01	2.83E+00	2.21E+02	1.35E+03	2.74E+01	9.09E+02	4.228+00	2.82E-01	7.77E+02	2.48E+00	3	1
11	6.098+02	2.91E+01	8.66E-01	6.57E+00	2.52E+02	1.40E+03	2.58£+01	1.03E+03	4.498+00	2.92E-01	8.26E+02	4.00E+00	3	1
12	6.62E+02	2.62E+01	8.82E-01	6.88E+09	2.81E+02	1.45E+03	2.47E+01	1.15E+03	4.731.+00	2.99E-01	8.73E+02	7.18E+00	3	1
13	7.12E+02	2.40E+01	8.94E-01	6.07E+00	3.13E+02	1.491+03	2.36E+01	1.27E+03	5.00E+00	3.06E-01	9.19E+02	1.36E+01	- 3	1
14	7.64E+02	2.25E+01	9.03E-01	7.48E+00	3.51E+02	1.53E+03	2.25E+01	1.43E+03	5.35E+00	3.13E-01	9.68E+02	2.81E+01	3	Ĩ.
15	8.50E+02	1.14E+01	9.73E-01	8.67E+01	6.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+60	1.81E+02	0	

	UOP K	CORRELATION INDEX
1	1.24E+01	1.16E+01
2	1.228+01	1.66E+01
3	1.20E+01	2.12E+01
4	1.196+01	2.32E+01
5	1.19E+01	2.43E+01
6	1.19E+01	2.32E+01
7	1.198+01	2.56E+01
Å	1.186+01	2.90E+01
9	1.18E+01	3.15E+01
ė.	1.17E+01	3.73E+01
Ĩ	1.18E+01	3.66E+ 0 1
2	1.18E+01	4.02E+01
3	1.14E+01	4.27E+01
4	1.18E+01	4.36E+01
5	1.12E+01	7.21E+01

BULK API CRAVITY = 28.9

TH = NORMAL BOILING TEMPERATURE, DEC F API = API CRAVITY VOL = VOLDME PER CENT OF TOTAL CRUDE MW = MOLECULAR WEIGHT TC = CRITICAL TEMPERATURE, DEC HANKINE PC = CRITICAL PRESSURE, ATMOSPHERES VC = CRITICAL PRESSURE, IN THE VAPOR PRESSURE FOUATION TIO IS THE TEMPERATURE IN DEC & WHERE THE VAPOR PRESSURE IS 10 MM HC VIS IS THE TEMPERATURE IN DEC & WHERE THE VAPOR PRESSURE IS 10 MM HC VIS IS THE KINEMATIC VISCOSITY IN CENTISTORES AT 122 DEC F UOP & IS THE U.O.P. & CHARACTERIZATION FACTOR CORRELATION INDEX IS DEFINED IN (COLEMAN, 1978) HC = ERROR CODE, SHOULD BE LESS THAN 20 HS = FRROM CODE, SHOULD BE LESS THAN 20 HS = FRROM CODE, SHOULD BE FOUAL TO I ICHORE THE ERROR CODES FOR CONFORMENT NUMBER IS IF IT IS A RESIDUUM

MEAN MOLECULAR WEIGHT OF THE CRUDE = 2.593E+02

and is the proper mass transfer coefficient to multiply by the partial pressure to obtain the rate. Here K is specific to a particular cut i through the Schmidt number.

Implicit in the rate equation for the i-th pseudo-component is the assumption that the partial pressure in the bulk atmosphere is zero. The mass transfer coefficient above takes into account (through the X term) an averaging effect whereby the evaporation rate on the downwind portion of the slick is lower than the upwind portion due to the fact that P_i becomes finite in the air immediately over the oil slick in the down-wind direction.

Another approach to calculating overall mass transfer coefficients is that of Treybal (1955) and Liss (1974):

$$\frac{1}{k} = \frac{1}{k_g} + \frac{\mu}{k_g}$$
(12)

where k is the individual gas-phase mass-transfer coefficient, K is the individual liquid-phase mass-transfer coefficient and H* is the Henry's law coefficient which is defined by:

$$P_{i} = H * X_{i}$$
(13)

The units on k_g for a <u>partial pressure</u> driving force are typically moles/(m² hr atm), the units on k_g for a <u>mole fraction</u> driving force are moles/(m² hr), and the units on H* are atm. The individual mass transfer coefficients, K and k_g , must then be obtained from actual data in a manner similar to that used to deduce K.

The other bulk property of interest for the oil slick is its viscosity. When oil is spilled on the ocean surface, the viscosity is low enough so that mixing into the water column occurs, and the well-mixed oil-phase assumption is valid. However, as evaporation occurs the bulk viscosity increases because the low-viscosity fractions are removed. The viscosity "blending" relationship used to predict the bulk viscosity as a function of composition is:

$$\frac{\mu}{\mu_0} = \exp(K_4 F) \tag{14}$$

where μ_0 is the viscosity of the unweathered oil at 25°C, F is the fraction weathered (i.e., how much has evaporated and dissolved), and K₄ is an oil- dependent constant (Tebeau, et al., 1982).

The bulk viscosity predicted from equation (14) is scaled with respect to temperature according to the Andrade equation (Gold, 1969) which is

$$\ln \frac{\mu_1}{\mu_0} = B \frac{1}{\Gamma_1} - 0.00335 \tag{15}$$

where μ_0 is the viscosity of the bulk oil at 25°C, and B is an oil-dependent constant. None of the above viscosity equations take into account water-in-oil emulsion (mousse) formation (Mackay, 1980).

The area for mass transfer in equation (10) is calculated from the rate at which the oil spreads on the water surface. Considerable research has been devoted to the spreading of oil on calm water surfaces; however, many of the resulting models are still relatively elementary. The model of Elliott (1986) was evaluated for these considerations. The major assumption of this spreading model is "oil was modelled as a distribution of droplets whose individual buoyancies depended on droplet size.....". The major conceptual problem with this assumption is the connection between the oil slick itself and the oil droplets in the water column. This concept was not discussed. In order to integrate the defining partial differential equation (page 121 of reference) a source of oil droplets must be available. Instead, the model is "carried out" by injecting "mathematically" 1000 droplets and calculating the spa-This model is not plausible because it assumes the oil slick tial positions. exists as droplets and spreads as droplets. There is no discussion presented on how much of an oil slick exists as droplets and how much exists as oil on the surface.

The type of data needed for a spreading model such as Elliott's to be mechanistically plausible is the <u>rate</u> of production of oil droplets (from the

slick), their size distribution, and the rate of return to (or loss from) the slick. The Mackay et al. (1980) spreading model was selected for our purposes because this model is based on observations.

Using arguments based on observations the area of the slick is calculated according to the differential equation

$$\frac{dA}{dt} = K_2 K_3 Z^{1.33} A^{0.33}$$
(16)

where A is the slick area, Z is the thickness, K_3 is a constant, and K_2 is the factor by which spreading is inhibited in a broken-ice field. This equation, without K_2 , is sometimes referred to as the thick-slick area (Mackay, et al., 1980). Other spreading equations, such as those based on gravity-surface tension theories have been found to be inadequate on the open sea surface and would be of even less use in predicting spreading in the presence of ice. predicting spreading in the presence of ice.

The prediction of water-in-oil emulsification (mousse) is important in oil-weathering material balances because of the viscosity change due to the incorporation of water into oil. Descriptions of water-in-oil emulsification formation are based on three equations from Mackay, et al. (1980) and a fourth which describes the increase in mousse formation rate due to broken-ice (see Section 4.2.2).

$$(1-K_2W) \exp\left[\frac{-2.5W}{1-K_1W}\right] = \exp\left(-K_3K_4T\right)$$
(17a)

where W is the weight fraction water in the oil-water mixture, K_1 is a constant in a viscosity equation (Mooney, 1951), K_2 is a coalescing-tendency constant, K_3 is a lumped water-incorporation rate constant and K_4 is the broken-ice field multiplier. The viscosity equation from Mooney (1951) is:

$$\mu = \mu_0 \exp\left[\frac{-2.5W}{1-K_1W}\right]$$
(17b)

where μ_0 is the parent oil viscosity and K₁ is usually around 0.62 to 0.65 and apparently does not change much with respect to different types of oils. The

constant K_2 above must satisfy the relation $K_2W < 1$ in order for the water incorporation rate term (right-hand side of equation 17a) to be >0. Thus, K_2 is the inverse of the maximum weight fraction of water in the mixture. K_3 is the water incorporation rate constant and is a function of the wind speed.

The dispersion (oil into water) weathering process is described by two equations (Mackay et al., 1980). These equation are:

$$F = K_{a}K_{c}(V + 1)^{2}$$

$$F_{B} = (1 + K_{b}u^{1/2}\delta X)^{-1}$$
(17c)
(17d)

where F is the fraction of oil on the sea surface subject to dispersions per second, V is the wind speed in m/sec and K_a is a constant. F_B is the fraction of droplets of oil below a critical size which do not return to the slick, K_b is a constant, μ is the oil viscosity in centipoise, X is the slick thickness in meters, δ is the oil/water interfacial surface tension in dynes/cm, and K_c is the factor by which dispersion is increased in a broken-ice field due to enhanced lead matrix pumping. The mass fraction that leaves the slick as dispersed droplets is F_b/F ; this fraction applies to <u>each cut of oil</u> simultaneously.

6.6 OIL-ICE CONFIGURATIONS

The interaction of oil with first and multi-year ice in the Arctic environment can be described with varying degrees of complexity. A very detailed description would include discussions of a variety of ice types (grease, frazil, etc.) and formations (brine channels, leads, etc.), the dependence of ice growth (or melt) on environmental conditions, and many other considerations. A more general description of oil-ice interactions, however, would seek to discuss only the most important variables and conditions that affect oil-ice behavior phenomena. In developing a computer model to predict such interactions, a more generalized approach must (at first) be undertaken for many reasons. First, in constructing and testing a model, the processes that will be dominant should be added first. After these processes are adequately described, other more minor effects can be added. Second, many of the more detailed effects (such as brine channel migration, variation of ice type, etc.) are stochastic in nature and thus difficult to predict. Third, a generalized model can be used more effectively to identify further required experimental efforts and to utilize the results of those efforts.

Because of the above, and in order to make the most use of the existing open-ocean oil-weathering model, the ocean-ice oil-weathering code has been developed so that generalized oil-ice configurations are considered. The configurations chosen are currently considered to be the major logical sets of conditions that determine oil-weathering. With time, and a continued improvement in our understanding of the Arctic, more configurations can be added and existing configurations can be improved. Below is a discussion of the three existing oil-ice configurations, preceded by a discussion of why a fourth one was not included in the computer code except as a separate stand-alone model to predict pseudo-component loss due to dissolution alone. As will be noted, this mechanism effects such a small percentage of the overall oil mass, that it is not factored into mass balance calculations embodied in the main oil weathering code.

6.6.1 Under-Ice Weathering

When oil is spilled under sea ice, most of the weathering processes that occur in the open-ocean are not operative. Evaporation is prevented by the ice cover, dispersion and mousse formation are inhibited by the lack of strong turbulence, and the oil does not spread significantly under ice. While it is known that spreading of oil under ice does occur and is current dependent, the macroscopic configuration of the oil will not have an effect on its weathering. In addition, the dissolution of aromatic hydrocarbons into the water column is slow enough (as evidenced by Sections 4.2.3 of this report), that the oil will be encapsulated before a significant amount of oil can dissolve. Furthermore, even if all of the 1-2% of the oil that is soluble were to dissolve, this would not impact the API gravities and volume percents of the TBP cuts that are utilized as input to each section of the oil-weathering code. Thus, since oil under ice is limited to a very small weathering effect, it has not been included as an oil-ice configuration in the ocean-ice oil-weathering model at this time.

6.6.2 Oil in Pools on Top of Ice

In spring when the temperature rises, the encapsulated oil travels to the ice surface through brine channels or because the ice above melts away. Evaporation begins when the oil is exposed to the atmosphere. For the cases when oil is released over a long period of time, the evaporation must be modeled by considering incremental releases of oil on the ice surface. This technical approach was used to model the continuous release of oil on ocean surface where discrete "patches" of oil are identified (B.E. Kirstein, 1984). Varying amounts of water will be present in the on-ice pools, but spreading, mousse formation, and dispersion will certainly be much less important than in the open-ocean or later as the ice breaks up (see Broken Ice Field). Thus, for this section of the ocean-ice model, evaporation is the only mass-transfer The user is prompted for the environmental temperature process considered. (the ice temperature), the number of hours for weathering to occur, and other parameters relating to evaporation. The model then performs the integration required to "weather" the oil and re-characterizes the oil in the same manner described in Section 6.4. This allows each pseudo-component of the oil to be tracked through the course of the weathering scenario, enables the user to monitor the bulk properties of the oil, and provides intermediate results that can be compared with real data from field experiments (pseudo-components lost as determined by TBP distillation or simulated by FID-GC analyses).

The results of the intermediate characterization of the oil are subsequently used as input for any weathering specified later in the weathering scenario (such as broken ice and ultimately, open ocean conditions).

6.6.3 Broken-Ice Field

After further ice melting takes place, the oil can reach the ocean surface and weather in the broken-ice field. Because the oil is in contact with water it is important to consider the spreading, mousse formation, and dispersion processes. The effect of varying ice cover on the rates of these processes, however, is not well known. For this reason the code has been

written such that constants that describe the dependence of these processes on ice cover are required model input.

Data from the wave tank experiments at Kasitsna Bay (See Section 4) indicate that the mousse formation rate (K_3) in broken ice is increased by about an order of magnitude. It must be emphasized that this observation cannot be scaled easily to natural sea-ice conditions because very little is quantitatively known about this process. Dispersion without sea ice is still a research topic. Therefore, field observations with similar situations is A value of 10 is used in the mousse equations to take the highly desirable. previously mentioned increase into account. This value can be changed by the user as more data are collected. For example, in wave tank experiments examining oil weathering behavior in "pseudo multi-year ice" where slush ice and grinding ice flows were not present, mousse formation rates appeared intermediate between open ocean and broken floe/slush ice conditions.

The data for oil droplet dispersion are even less indicative of an ice cover dependence. However, a constant (K_c) of 10 has been chosen to describe the increase of (initial) dispersion in broken ice. As emulsified oil viscosity increases limiting continued dispersion, the constant can once again be changed as the data-base increases.

For the oil spreading rate a linear dependence with ice cover has been assumed; thus a 50% ice cover will decrease the spreading rate (area) 50% and a 75% ice cover will decrease the spreading rate (area) 75%, etc. The assumption of a linear spreading function for ice cover may not be true since theoretical predictions are not possible. As data becomes available, possibly from the State of Alaska Tier II work, a more realistic algorithm or correlation can be used.

6.6.4 Open Ocean

When all of the ice has melted, the oil undergoes open-ocean weathering. Thus all of the weathering processes are in effect as described in the open-ocean oil-weathering users manual (Payne et al., 1984a).

Figure 6-1 presents an abbreviated flow chart of the calculation performed in the Ocean-Ice oil-weathering code. The majority of the coding calculates the required physical properties and kinetic constants. The actual integration routine is relatively small.

Tables 6-4 through 6-6 present examples of abbreviated numerical output (80-column) for the weathering of Prudhoe Bay crude. The cut information which numbers 1-15 presents the physical properties of the cuts: molecular weight, vapor pressures, density and boiling point. The kinetic parameters are contained in the mass-transfer coefficient code (2 in this case), wind speed and temperature. The integrated material balance presents the volume remaining in the slick, the density, area, thickness, weight % water-in-oil, evaporation rate, mass per unit area and compositional information. Note that the user has chosen three different weathering compartments (pools on ice, Table 6-4; then oil in broken ice, Table 6-5; then open ocean conditions, Table 6-6) and output is presented for each compartment with an oil characterization at the beginning of each. A more detailed output was also generated but it is quite lengthy; an example of this output is presented in the User's Manual which is a stand-alone companion document to this report.

In summary the open-ocean oil-weathering code considers the following processes:

- evaporation
- dispersion
- spreading
- physical property changes
- mousse formation

The Ocean-Ice oil-weathering code User's Manual (a separate document) presents detailed input-output information along with a code listing. It is imperative that the user understands the common terms used to describe oil in the environment. Thus, the User's Manual and the code itself were written to aid the user in gaining the necessary knowledge. All that is required to use the code is the User's Manual and an installed copy of the computer code.



Figure 6-1.--Ocean-Ice Oil Weathering Model Flow Chart.

Table 6-4.--Illustration of 80-Column Output from Ocean-Ice Oil-Weathering Code; Prudhoe Bay Crude Oil; Weathering of Oil in Pools on Top of Ice at 32°F.

WEATHERING OF OIL IN POOLS ON TOP OF ICE OIL: PRUDHOE BAY, ALASKA 32.0 DEC F, WIND SPEED= 1.000E+04 BARRELS TEMPERATURE= 10.0 KNOTS SPILL SIZE= MASS-TRANSFER COEFFICIENT CODE= FOR THE OUTPUT THAT FOLLOWS, MOLES=GRAM MOLES CMS=CRAMS, VP=VAPOR PRESSURE IN ATMOSPHERES BP=BOILING POINT IN DEC F, API=CRAVITY MW=MOLECULAR WEIGHT CMS CUT MOLES VP BP API MW 2.74E+05 2.29E+07 4.09E-02 1.50E+02 7.27E+01 83 3.13E+05 2.96E+07 t.35E-02 1.90E+02 6.42E+01 93 3.91E+05 4.14E+07 3.25E-03 3 2.35E+02 5.67E+01 105 3.67E+05 4.37E+07 7.05E-04 2.80E+02 5.16E+01 119 3.25E+02 5 3.43E+05 4.60E+07 1.40E-04 4.76E+01 133 2.92E+05 4.41E+07 2.44E-05 3.70E+02 4.52E+01 6 150 3.30E+05 5.53E+07 3.98E-06 4.15E+02 4.15E+01 167 7 3.41E+05 6.31E+07 5.86E-07 4.60E+02 8 3.78E+01 184 8.22E-08 3.34E+05 6.69E+07 5.05E+02 a 3.48E+01 200 1.74E+05 3.84E+07 8.24E-09 5.54E+02 3.06E+01 220 10 3.58E+05 9.01E+07 4.12E-10 6.09E+02 2.91E+01 251 11 3.41E+05 6.62E+02 9.59E+07 2.02E-11 12 2.62E+01 281 8.59E+07 7.12E+02 2.75E+05 8.60E-13 13 2.40E+01 312 1.96E-14 3.04E+05 1.07E+08 7.64E+02 2.25E+01 351 14 9.42E+05 5.65E+08 0.00E+00 8.50E+02 15 1.14E+01 600 MOUSSE CONSTANTS: MOONEY= 0.00E+00, MAX H20=-1.00, WIND**2= 0.00E+00 DISPERSION CONSTANTS: KA= 1.08E-01, KB= 3.00E+01, S-TENSION= 1.00E+00 VIS CONSTANTS: VIS25C= 3.50E+01, ANDRADE = 9.00E+03, FRACT = 1.05E+01 FOR THE OUTPUT THAT FOLLOWS, TIME=HOURS BBL=BARRELS, SPCR=SPECIFIC GRAVITY, AREA=M*M THICKNESS=CM, W=PERCENT WATER IN OIL (MOUSSE) DISPEDISPERSION RATE IN CMS/M*M/HR ERATE=EVAPORTION RATE IN CMS/M*M/HR M/A=MASS PER M*M OF OIL IN THE SLICK I=FIRST CUT WITH CREATER THAN 1% (MASS) REMAINING J=FIRST CUT WITH CREATER THAN 50% (MASS) REMAINING DISPERSION WAS TURNED OFF SPREADING WAS TURNED OFF ME BBL SPGR AREA THICKNESS 0 1.0E+04 0.88 7.9E+04 2.0E+00 W DISP TIME BBL ERATE M/A T J 0 0.0E+00 0.0E+00 1.8E+04 1 1 1 9.8E+03 0.88 7.9E+04 2.0E+00 0 0.0E+00 1.7E+02 1.7E+04 1 1 2 9.7E+03 0.88 7.9E+04 1.9E+00 3 9.7E+03 0.88 7.9E+04 1.9E+00 0 0.0E+00 1.3E+02 1.7E+04 1 0 0.0E+00 9.5E+01 1.7E+04 1 2 2 9.6E+03 0.88 7.9E+04 1.9E+00 0 0.0E+00 7.5E+01 1.7E+04 1 3 4 5 9.6E+03 0.89 7.9E+04 1.9E+00 6 9.5E+03 0.89 7.9E+04 1.9E+00 0 0.0E+00 6.2E+01 1.7E+04 1 0 0.0E+00 5.2E+01 1.7E+04 1 3 3 9.5E+03 0.89 7.9E+04 1.9E+00 0 0.0E+00 4.5E+01 1.7E+04 7 1 3 8 9.4E+03 0.89 7.9E+04 1.9E+00 0 0.0E+00 4.0E+01 1.7E+04 2 3 9 9.4E+03 0.89 7.9E+04 1.9E+00 0 0.0E+00 3.6E+01 1.7E+04 2 3 10 9.4E+03 0.89 7.9E+04 1.9E+00 0 0.0E+00 3.3E+01 1.7E+04 2 3 11 9.4E+03 0.89 7.9E+04 1.9E+00 0 0.0E+00 3.0E+01 2 3 1.7E+04 12 9.4E+03 0.89 7.9E+04 1.9E+00 0 0.0E+00 2.8E+01 1.7E+04 2 з 13 9.3E+03 0.89 7.9E+04 1.9E+00 0 0.0E+00 2.6E+01 1.7E+04 2 3 2 9.3E+03 0.89 7.9E+04 1.9E+00 0.0E+00 2.4E+01 1.7E+04 3 14 0 15 9.3E+03 0.89 7.9E+04 1.9E+00 0.0E+00 2.2E+01 1.7E+04 2 3 ø 0 0.0E+00 2.1E+01 1.7E+04 0 0.0E+00 2.0E+01 1.7E+04 16 9.3E+03 0.89 7.9E+04 1.9E+00 2 4 17 9.3E+03 0.89 7.9E+04 1.9E+00 2 4 18 9.3E+03 0.89 7.9E+04 1.9E+00 0.0E+00 1.9E+01 1.6E+04 Ø 2 4 19 9.2E+03 0.89 7.9E+04 1.8E+00 20 9.2E+03 0.89 7.9E+04 1.8E+00 0 0.0E+00 1.8E+01 1.6E+04 2 0 0.0E+00 1.7E+01 1.6E+04 2 4 21 9.2E+03 0.89 7.9E+04 1.8E+00 22 9.2E+03 0.89 7.9E+04 1.8E+00 0 0.0E+00 1.6E+01 1.6E+04 2 4 0 0.0E+00 1.6E+01 1.6E+04 2 23 9.2E+03 0.89 7.9E+04 1.8E+00 0 0.0E+00 1.5E+01 1.6E+04 2 4

Table 6-5.--Illustration of 80-Column Output; Prudhoe Bay Crude Oil; Broken Ice Field Weathering at 32°F Following Weathering in Pools on Top of Ice.

WEATHERING OF OIL IN A BROKEN ICE FIELD AFTER ICE POOL WEATHERING FOR 2.400E+01 HOURS OIL: PRUDHOE BAY, ALASKA 32.0 DEG F, WIND 9.195E+03 BARRELS TEMPERATURE= WIND SPEED= 12.0 KNOTS SPILL SIZE= MASS-TRANSFER COEFFICIENT CODE= FOR THE OUTPUT THAT FOLLOWS, MOLES=CRAM MOLES CMS=CRAMS, VP=VAPOR PRESSURE IN ATMOSPHERES BP=BOILING POINT IN DEC F. API=CRAVITY MW=MOLECULAR WEIGHT API 7.27E+01 CUT MOLES VP BP MW CMS 1.87E-01 1.57E+01 5.99E-02 1.50E+02 83 1 6.42E+01 3.11E+03 2.92E+05 2.06E-02 1.90E+02 93 2 1.31E+05 2.35E+02 1.38E+07 5.42E-03 5.67E+01 105 3 2.90E+05 3.46E+07 1.24E-03 2.80E+02 5.16E+01 4 119 3.25E+92 5 3.28E+05 4.39E+07 2.59E-04 4.76E+01 133 4.37E+07 2.90E+05 3.70E+02 4.81E-05 4.52E+01 150 6 7 3.30E+05 5.52E+07 8.33E-06 4.15E+02 4.15E+01 167 3.41E+05 4.60E+02 6.31E+07 1.31E-06 3.78E+01 184 R 3.34E+05 6.69E+07 5.05E+02 3.48E+01 200 9 1.95E-07 2.12E-08 1.74E+05 3.84E+07 3.06E+01 220 10 5.54E+02 9.01E+07 1.17E-09 6.09E+02 3.58E+05 2.91E+01 251 11 9.59E+07 12 3.41E+05 6.39E-11 6.62E+02 2.62E+01 281 8.59E+07 2.75E+05 7.12E+02 2.40E+01 312 13 3.03E-12 3.04E+05 1.07E+08 7.87E-14 7.64E+02 2.25E+01 351 14 9.42E+05 5.65E+08 0.00E+00 8.50E+02 15 1.14E+01 600 MOUSSE CONSTANTS: MOONEY= 6.20E-01, MAX H20= 0.70, WIND**2= 1.00E-02 K4=1.000E+01 DISPERSION CONSTANTS: KA= 1.08E-01, KB= 5.00E+01, S-TENSION= 3.00E+01 KC=1.000E+01 FRACTION OF ICE COVER=6.600E-01 VIS CONSTANTS: VIS25C= 3.50E+01, ANDRADE = 9.00E+03, FRACT = 1.05E+01 FOR THE OUTPUT THAT FOLLOWS, TIME=HOURS BBL=BARRELS, SPCR=SPECIFIC GRAVITY, AREA=M*M THICKNESS=CM, W=PERCENT WATER IN OIL (MOUSSE) DISP=DISPERSION RATE IN CMS/M*M/HR ERATE=EVAPORTION RATE IN GMS/M*M/HR M/A=MASS PER M*M OF OIL IN THE SLICK I=FIRST CUT WITH GREATER THAN 1% (MASS) REMAINING J=FIRST CUT WITH CREATER THAN 50% (MASS) REMAINING CUT 1 GOES AWAY IN MINUTES, THEREFORE IT WAS DELETED AND THE CUTS RENUMBERED TIME BBL SPGR AREA THICKNESS W DISP ERATE M/A I J 0 9.2E+03 0.89 7.9E+04 1.8E+00 0 7.6E+01 0.0E+00 1.6E+04 1 1 1 9.1E+03 0.89 1.1E+05 1.3E+00 29 7.3E+01 2.5E+01 1.2E+04 1 1 48 4.4E+01 2.3E+01 9.5E+03 1 2 9.0E+03 0.89 1.4E+05 1.1E+00 2 60 2.8E+01 2.1E+01 8.2E+03 1 66 1.9E+01 1.9E+01 7.3E+03 1 3 9.0E+03 0.89 1.6E+05 9.2E-01 2 1.7E+05 8.2E-01 8.9E+03 0.89 66 2 5 8.9E+03 0.89 1.9E+05 7.4E-01 69 1.5E+01 1.7E+01 6.7E+03 1 3 6 8.8E+03 0.89 2.0E+05 6.9E-01 7 8.8E+03 0.89 2.2E+05 6.4E-01 70 1.3E+01 1.5E+01 6.1E+03 1 70 1.3E+01 1.3E+01 5.7E+03 2 3 3 2.3E+05 5.9E-01 8 8.7E+03 0.90 70 1.2E+01 1.2E+01 5.3E+03 2 3 8.7E+03 0.90 2.5E+05 5.6E-01 70 1.2E+01 1.1E+01 5.0E+03 2 3 10 8.6E+03 0.90 2.6E+05 5.3E-01 70 1.2E+01 9.6E+00 4.8E+03 2 3 70 1.1E+01 8.7E+00 4.5E+03 2 11 8.6E+03 0.90 2.7E+05 5.1E-01 3 12 8.5E+03 0.90 2.8E+05 4.8E-01 70 1.1E+01 7.9E+00 4.3E+03 4 13 8.5E+03 0.90 2.9E+05 4.6E-01 70 1.1E+01 7.3E+00 4.2E+03 2 4 70 1.1E+01 6.8E+00 4.0E+03 2 70 1.0E+01 6.3E+00 3.9E+03 2 14 8.5E+03 0.90 3.0E+05 4.5E-01 16 8.4E+03 0.90 3.1E+05 4.3E-01 4 4 17 8.4E+03 0.90 3.2E+05 4.2E-01 70 1.0E+01 5.9E+00 3.8E+03 2 4

18	8.3E+03 0.90	3.3E+05	4.1E-01	70	9.8E+00	5.5E+00	3.6E+03	3	4
19	8.3E+03 0.90	3.4E+05	3.9E-01	70	9.6E+00	5.2E+00	3.5E+03	3	4
20	8.3E+03 0.90	3.4E+05	3.8E-01	70	9.4E+00	4.9E+00	3.4E+03	ä	4
21	8.2E+03 0.90	3.5E+05	3.7E-01	70	9.2E+00	4.6E+00	3.3E+03	ä	4
22	8.2E+03 0.90	3.6E+05	3.6E-01	70	9.0E+00	4.3E+00	3.3E+03	3	4
23	8.1E+03 0.90	3.7E+95	3.5E-01	70	8.8E+00	4.1E+00	3.2E+03	3	4
24	8.1E+03 0.90	3.7E+05	3.5E-01	70	8.6E+00	3.9E+00	3.1E+03	3	4
25	6.1E+03 0.90	3.8E+05	3.4E-01	70	8.4E+00	3.7E+00	3.0E+03	3	4
26	8.0E+03 0.90	3.9E+05	3.3E-01	70	8.2E+00	3.5E+00	3.0E+03	3	4
27	8.0E+03 0.90	3.9E+05	3.2E-01	70	8.0E+00	3.3E+00	2.9E+03	3	4
28	8.0E+03 0.90	4.0E+05	3.2E-01	70	7.8E+00	3.1E+00	2.9E+03	3	4
29	7.9E+03 0.90	4.1E+05	3.1E-01	70	7.6E+00	2.9E+00	2.8E+03	3	4
31	7.9E+03 0.90	4.1E+05	3.0E-01	70	7.4E+00	2.8E+00	2.7E+03	3	4
32	7.9E+03 0.90	4.2E+05	3.0E-01	70	7.3E+00	2.6E+00	2.7E+03	3	4
33	7.8E+03 0.90	4.3E+05	2.9E-01	70	7.1E+00	2.5E+00	2.6E+03	3	4
34	7.8E+03 0.90	4.4E+05	2.8E-01	70	6.9E+00	2.4E+00	2.6E+03	3	5
35	7.7E+03 0.90	4.4E+05	2.8E-01	70	6.8E+00	2.3E+00	2.5E+03	3	5
37	7.7E+03 0.90	4.5E+05	2.7E-01	70	6.6E+00	2.2E+00	2.5E+03	3	5
38	7.7E+03 0.90	4.5E+05	2.7E-01	70	6.5E+00	2.1E+00	2.4E+03	3	5
39	7.7E+03 0.90	4.6E+05	2.7E-01	70	6.3E+00	2.0E+00	2.4E+03	3	5
40	7.6E+03 0.90	4.6E+05	2.6E-01	70	6.2E+00	1.9E+00	2.4E+03	3	5
41	7.6E+03 0.90	4.7E+05	2.6E-01	70	6.1E+00	1.8E+00	2.3E+03	3	5
42	7.6E+03 0.90	4.7E+05	2.5E-01	70	6.0E+00	1.8E+00	2.3E+03	3	5
43	7.5E+03 0.90	4.8E+05	2.5E-01	70	5.8E+00	1.7E+00	2.3E+03	3	5
44	7.5E+03 0.90	4.8E+05	2.5E-01	70	5.7E+ 00	1.7E+00	2.2E+03	3	5
45	7.5E+03 0.90	4.9E+05	2.4E-01	70	5.6E+00	1.6E+00	2.2E+03	3	5
46	7.5E+03 0.90	4.9E+05	2.4E-01	70	5.5E+00	1.6E+00	2.2E+03	4	5
47	7.4E+03 0.90	5.0E+05	2.4E-01	70	5.4E+00	1.5E+00	2.1E+ 0 3	4	5
48	7.4E+03 0.90	5.0E+05	2.3E-01	70	5.3E+ 00	1.5E+00	2.1E+03	4	5
49	7.4E+03 0.90	5.1E+05	2.3E-01	70	5.2E+00	1.4E+00	2.1E+03	4	5
50	7.4E+03 0.90	5.1E+05	2.3E-01	70	5.1E+00	1.4E+00	2.1E+03	4	5
5 t	7.3E+03 0.90	5.2E+05	2.3E-01	70	5.0E+00	1.4E+00	2.0E+03	4	5
61	7.1E+03 0.90	5.6E+05	2.0E-01	70	4.2E+00	1.1E+00	1.8E+03	4	5
71	6.9E+03 0.90	5.9E+05	1.8E-01	70	3.5E+00	8.4E-01	1.7E+03	4	5
81	6.7E+03 0.91	6.3E+05	1.7E-01	70	3.0E+00	6.8E-01.	1.5E+03	4	5
91	6.6E+03 0.91	6.6E+05	1.6E-01	70	2.6E+00	5.6E-01	1.4E+03	4	6

Table 6-6.--80-Column Output; Prudhoe Bay Crude Oil; Open-Ocean Weathering Following Weathering in Pools on Top of Ice and Broken Ice Field Weathering.

OPEN OCEAN WEATHERING AFTER: ICE POOL WEATHERING FOR 2.400E+01 HOURS BROKEN ICE FIELD WEATHERING FOR 1.000E+02 HOURS OIL: PRUDHOE BAY, ALASKA TEMPERATURE: 40.0 DEC F, WIND SPEED: 20.0 KNOTS SPILL SIZE: 6.428E+03 BARRELS MASS-TRANSFER COEFFICIENT CODE= FOR THE OUTPUT THAT FOLLOWS, MOLES=CRAM MOLES CMS=CRAMS, VP=VAPOR PRESSURE IN ATMOSPHERES BP=BOILING POINT IN DEC F, API=CRAVITY MW=MOLECULAR WEIGHT MOLES CMS VP BP API CUT MW 1.77E-03 4.40E-02 5.25E+00 2.80E+02 5.16E+01 119 1 1.40E+06 3.25E+02 9 1.04E+04 3.84E-04 4.76E+01 133 3 1.26E+05 1.90E+07 7.40E-05 3.70E+02 4.52E+01 150 4.15E+01 167 1.33E-05 4.15E+02 2.33E+05 3.90E+07 4 4.84E+07 5 2.62E+05 2.18E-06 4.60E+02 3.78E+01 184 2.60E+05 5.21E+07 3.40E-07 5.05E+02 3.48E+01 200 6 1.36E+05 3.00E+07 3.86E-08 5.54E+02 3.06E+01 220 7 6.09E+02 2.79E+05 7.03E+07 2.29E-09 2.91E+01 251 8 7.49E+07 2.62E+01 281 6.62E+02 Q. 2.66E+05 1.33E-10 2.14E+05 6.70E+07 6.76E-12 7.12E+02 2.40E+01 312 10 7.64E+02 2.37E+05 8.34E+07 1.91E-13 2.25E+01 351 11 4.41E+08 0.00E+00 8.50E+02 7.35E+05 1.14E+01 600 12 MOUSSE CONSTANTS: MOONEY= 6.20E-01, MAX H20= 0.70, WIND**2= 1.00E-03 DISPERSION CONSTANTS: KA= 1.08E-01, KB= 5.00E+01, S-TENSION= 3.00E+01 VIS CONSTANTS: VIS25C= 3.50E+01, ANDRADE = 9.00E+03, FRACT = 1.05E+01 FOR THE OUTPUT THAT FOLLOWS, TIME=HOURS BBL=BARRELS, SPCR=SPECIFIC CRAVITY, AREA=M*M THICKNESS=CM, W=PERCENT WATER IN OIL (MOUSSE) DISP=DISPERSION RATE IN CMS/M*M/HR ERATE=EVAPORTION RATE IN CMS/M*M/HR JEAN AND THE MAN OF OIL IN THE SLICK I=FIRST CUT WITH CREATER THAN 1% (MASS) REMAINING J=FIRST CUT WITH CREATER THAN 50% (MASS) REMAINING BBL SPGR TIME AREA THICKNESS - **W** DESP EBATE M/A 1 0 6.4E+03 0.91 6.8E+05 1.5E-01 70 3.5E+00 0.0E+00 1.4E+03 1 1 1 6.4E+03 0.91 6.9E+05 1.5E-01 2 6.4E+03 0.91 7.0E+05 1.5E-01 3 6.4E+03 0.91 7.1E+05 1.4E-01 70 3.4E+00 1.0E+00 1.3E+03 1 1 70 3.4E+00 1.0E+00 1.3E+03 1 2 70 3.3E+00 9.8E-01 1.3E+03 1 $\bar{\mathbf{2}}$ 70 3.2E+00 9.5E-01 1.3E+03 1 2 4 6.3E+03 0.91 7.1E+05 1.4E-01 2 5 6.3E+03-0.91 7.2E+05 (.4E-01 70 3.2E+00 9.2E-01 1.3E+03 1 6 6.3E+03 0.91 7.3E+05 1.4E-01 70 3.1E+00 8.9E-01 1.2E+03 1 3 7 6.3E+03 0.91 7.4E+05 1.4E-01 70 3.1E+00 8.6E-01 1.2E+03 1 3 8 6.2E+03 0.91 7.5E+05 1.3E-01 70 3.0E+00 8.4E-01 1.2E+03 3 2 **70** 2.9E+00 8.1E-01 1.2E+03 2 **70** 2.9E+00 7.9E-01 1.2E+03 2 **70** 2.8E+00 7.6E-01 1.2E+03 2 9 6.2E+03 0.91 7.5E+05 1.3E-01 3 11 6.2E+03 0.91 7.6E+05 1.3E-01 12 6.2E+03 0.91 7.7E+05 1.3E-01 3 3 13 6.1E+03 0.91 7.8E+05 1.3E-01 14 6.1E+03 0.91 7.9E+05 1.2E-01 15 6.1E+03 0.91 7.9E+05 1.2E-01 70 2.8E+00 7.4E-01 1.1E+03 2 3 70 2.7E+00 7.3E-01 1.1E+03 70 2.7E+00 7.1E-01 1.1E+03 3 2 3 16 6.1E+03 0.91 8.0E+05 1.2E-01 70 2.6E+00 6.9E-01 1.1E+03 2 3 2.6E+00 6.8E-01 1.1E+03 17 6.1E+03 0.91 8.1E+05 1.2E-01 70 2 3 18 6.0E+03 0.91 8.1E+05 1.2E-01 70 2.5E+00 6.6E-01 1.1E+03 2 3 19 6.0E+03 0.91 8.2E+05 1.2E-01 70 2.5E+00 6.5E-01 1.1E+03 2 3 70 2.5E+00 6.3E-01 20 6.0E+03 0.91 8.3E+05 1.2E-01 1.1E+03 2 3 21 6.0E+03 0.91 8.3E+05 1.1E-01 70 2.4E+00 6.2E-01 1.0E+03 2 3 70 2.4E+00 6.1E-01 1.0E+03 2 70 2.3E+00 6.0E-01 1.0E+03 2 22 6.0E+03 0.91 8.4E+05 1.1E-01 23 6.0E+03 0.91 8.4E+05 1.1E-01 3 3

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25	5.96+03	0.91	8.5E+05	1.1E-01	70	2.36+00	5.8E-01	1.0E+03	2	4
20	3.4E+03	0.91	8.0E+00	1.1E-01	70	2.21+00	5.7E-01	9.96+02	2	4
27	5.9E+03	0.91	0.75+00	1.1E-01	70	2.21+00	3.3E-01	9.8E+02	2	4
29	5.9E+03	0.91	8. (E+93	1.1E-01	70	2.22+00	5.4E-01	9.7E+02	2	4
30	5.8E+03	0.91	8.85+05	1.1E-01	70	2.1E+00	5.3E-01	9.6E+02	2	4
31	5.8E+03	0.91	8.96+05	1.0E-01	70	2.1E+00	5.2E-01	9.5E+02	2	4
32	5.8E+03	0.91	8.95+05	1.0E-01	70	2.00+00	5.0E-01	9.4E+02	2	4
-34	5.8E+03	0.91	9.08+05	1.0E-01	70	2.0E+00	4.96-01	9.3E+02	3	4
35	5.8E+03	0.91	9.1E+05	1.0E-01	70	2.0E+00	4.8E-01	9.2E+02	3	4
36	5.7E+03	0.91	9.1E+05	1.0E-01	70	1.9E+00	4.7E-01	9.1E+02	3	4
37	5.7E+03	0.91	9.2E+05	9.9E-02	70	1.9E+00	4.6E-01	9.0E+02	3	4
39	5.7E+03	0.91	9.3E+05	9.8E-02	70	1.9E+00	4.5E-01	8.9E+ 0 2	3	-4
40	5.7E+03	0.91	9.3E+05	9.7E-02	70	1.8E+00	4.4E-01	8.8E+02	3	4
41	5.7E+03	0.91	9.4E+05	9.6E- 02	70	1.8 E+00	4.3E-01	8.7E+02	3	- 4
42	5.6E+03	0.91	9.4E+05	9.5E- 02	70	1.8E+00	4.2E-01	8.7E+02	3	- 4
44	5.6E+03	0.91	9.5E+05	9.4E-02	70	1.7E+00	4.1E-01	8.6E+02	3	4
45	5.6E+03	0.91	9.6E+05	9.3 E-02	70	1.7E+ 00	4.1E-01	8.5E+02	3	4
46	5.6E+03	0.91	9.6E+05	9.2E- 02	70	1.7E+00	4.0E-01	8.4E+02	3	4
47	5.6E+03	0.91	9.7E+05	9.2 E-02	70	1.6E+ 00	3.9E-01	8.3E+02	3	4
49	5.6E+03	0.91	9.7E+05	9.1 E-02	70	1.6E+ 00	3.8E-01	8.3E+02	3	4
50	5.5E+03	0.91	9.8E+05	9.0E-02	70	1.6E+00	3.7E-01	8.2E+02	3	4
5 t	5.5E+03	0.91	9.8E+05	8.9E-02	70	1.6E+ 99	3.7E-01	8.1E+02	3	4
62	5.4E+03	0.91	1.0E+06	8.3E-02	70	1.4E+00	3.1E-01	7.6E+02	3	4
72	5.3E+03	0,91	1.1E+06	7.8E-02	70	1.2E+00	2.7E-01	7.1E+02	3	4
82	5.2E+03	0.91	1.1E+06	7.4E-02	70	1.1E+00	2.4E-01	6.8E+02	3	4
92	5.1E+03	0.91	1.1E+06	7.0E-02	70	9.4E-01	2.1E-01	6.4E+02	3	5
102	5.0E+03	0.91	1.2E+06	6.7E-02	70	8.4E-01	1.9E-01	6.1E+02	3	5
112	4.9E+03	0.91	1.2E+06	6.4E-02	70	7.6E-01	1.7E-01	5.9E+02	3	5
122	4.8E+03	0.91	1.2E+06	6.2E-02	70	6.9E-01	1.6E-01	5.6E+02	4	5
132	4.7E+03	0.91	1.3E+06	5.9E-02	70	6.3E-01	1.5E-01	5.4E+02	4	5
142	4.7E+03	0.91	1.3E+06	5.7E-02	70	5.7E-01	1.4E-01	5.2E+02	4	5
152	4.6E+03	0.91	1.3E+06	5.5E-02	70	5.3E-01	1.3E-01	5.1E+02	4	5
162	4.5E+03	0.91	1.3E+06	5.4E-02	70	4.8E-01	1.2E-01	4.9E+02	4	5
172	4.5E+03	0.92	1.4E+06	5.2E-02	70	4.3E-01	1.1E-01	4.7E+02	4	5
182	4.4E+03	0.92	1.4E+06	5.0E-02	70	4.1E-01	1.0E-01	4.6E+02	4	5
192	4.4E+03	0.92	1.4E+06	4.9E-02	70	3.8E-01	9.7E-02	4.5E+02	4	5
202	4.3E+03	0.92	1.4E+06	4.8E-02	70	3.6E-01	9.0E-02	4.4E+02	4	5
212	4.3E+03	0.92	1.5E+06	4.6E-02	70	3.3E-01	8.5E-02	4.3E+02	4	5
222	4.2E+03	0.92	1.5E+06	4.5E-02	70	3.1E-01	7.9E-02	4.2E+02	4	5
232	4.2E+03	0.92	1.5E+06	4.4E-02	70	2.9E-01	7.3E-02	4.1E+02	4	5

6.7 DISCUSSION OF DISTILLATION DATA NEEDED FOR THE MACKAY EVAPORATION MODEL

6.7.1 <u>Requirements for Compatibility with the Existing NOAA/SAIC Oil</u> <u>Weathering Code</u>

The evaporation calculation used in the oil-weathering model developed by Mackay (1982) which is utilized by many of the existing oil-weathering models, requires as input the slope and intercept of a distillation curve. For most petroleum products (including crude oil), distillation curves (liquid boiling point vs volume fraction distilled) are linear over the range of boiling temperatures of the components that will weather under environmental conditions. Thus, if such data are available, the method of least squares can be used to find the slope and intercept (initial boiling point) of the distillation curve over this range.

There are many different distillation methods and conditions, some standardized and some not. For instance, one could use an ASTM D-86 distillation or a true boiling point (TBP) distillation. These are only two of a number of standardized methods for distilling oil. However, neither of these methods is appropriate since they do not directly simulate environmental oilweathering. In both of these methods the vapor leaving the boiling liquid condenses and revaporizes (refluxes) before leaving the apparatus. This countercurrent flow of material produces greater separation of components than in a simple no-reflux distillation. Since no reflux occurs in the evaporation of oil in the environment, the required distillation should also involve no reflux. Further, the input data for the Mackay model should be from a batch distillation since an environmental spill will generally involve a finite amount of material. Thus, a simple, batch, no-reflux distillation is required.

A simple batch distillation is not routinely performed on petroleum, however. Thus, in order to use the Mackay model, this distillation must be performed in the lab or the curve must be calculated from physical data. The second approach will be developed here.

The mathematical description of a simple, batch distillation is as follows. If v is the vapor removal rate of the distillation in moles per time, then a material balance over L moles of the bulk oil is:

$$dL/dt = -v \tag{18}$$

Then, if m_i is the number of moles of the i-th component in the oil, and y_i is the mole fraction of the i-th component in the vapor, a material balance over the i-th component is:

$$dm_{i}/dt - y_{i}v$$
(19)

However, dt = -(1/v)dL from above, so substitute for dt in Equation (19) to obtain:

$$-v (dm_i/dL) = -y_i v$$
 (20)

or

$$dm_i/dL = y_i$$
 for i=1,2,3,...,n (21)

where n is the number of components.

Equation (21) must be integrated for each component with the following constraints and initial conditions. Since the material is always at its bubble point, the sum of the vapor pressures (p_i) os the components should be 1.0 atmosphere. If Dalton's Law is assumed, then

$$y_{i} - p_{i}/P_{T}$$
(22)

where P_{T} = total pressure = 1.0 atm. Thus,

$$\sum_{i=1}^{n} y_i = 1 \tag{23}$$

Next, assume Raoult's Law:

$$\mathbf{P}_{i} = \mathbf{x}_{i} \mathbf{P}_{i} \tag{24}$$

where x_i is the mole fraction of the i-th component in the liquid phase and P_i is the pure component vapor pressure of component i. Combining equations (22), (23), and (24) gives

$$\sum_{T} \frac{x_{T} P_{T}}{P_{T}} = 1$$
(25)

The final constraint is:

$$\sum_{i=1}^{n} \sum_{j=1}^{n} (26)$$

where

$$x_{i} = \frac{m_{i}}{\sum_{i=1}^{m} m_{i}}$$
(27)

A number of different numerical integration methods could be used for this problem. The method chosen here is a simple Runga-Kutta integration (Greenspan, 1971). The integration proceeds as follows:

- 1. Specify m_1, m_2, \ldots, m_n at start of integration step.
- 2. Calculate bubble point temperature using interval-halving trial and error. This also yields $y_1, y_2, y_3, \ldots, y_n$.
- 3. Take an integration step and use y_1, y_2, \ldots, y_n to calculate new m_1, m_2, \ldots, m_n .

These three steps are repeated until the desired fraction of the oil has been distilled.

The existing NOAA open-ocean oil-weathering model calculates all of the parameters required to perform the integration (distillation) described above. Instead of using each individual compound of the oil (which is impossible), the oil is broken up into "cuts" according to a TBP distillation so that many compounds of similar volatility are considered together as one "pseudo-component". The TBP data for many different petroleum products are readily available. These data are input to the model, which then calculates the number of moles, the specific gravity, the molecular weight, and the vapor pressure versus temperature for each cut. At the end of each integration step above, the following values are calculated:

- 1. Boiling point of remaining liquid (*K)
- 2. Total volume fraction distilled $\sum_{i=1}^{m} \frac{m_{i}(MW)_{i}}{(SPGR)_{i}} + initial volume$ where (SPGR)_i specific gravity of cut i

(MW), - molecular weight of cut i in grams per mole

These values of volume fraction distilled versus boiling point are then input to a least squares linear curve fitting routine to calculate the "best" initial boiling point (intercept) and boiling curve gradient (slope). These values can then be used as direct input to the Mackay evaporation model.

6.7.2 Calculation of the Input Parameters for the Mackay Evaporation Model

The oil-weathering model developed by Mackay (1982) employs an analytical expression in which the vapor pressure of the oil is expressed as a function of the fraction evaporated. Thus, the oil as a whole is assigned one vapor pressure. Other physical data, such as enthalpy of vaporization, molar volume and boiling point curve are either measured for each oil or measured and "averaged" for many oils to give bulk physical properties.

The NOAA evaporation model, however, uses a pseudo-component approach and focuses much more on the calculation of oil physical properties than the Mackay model. This is important since some physical parameters such as heat of vaporization and molecular weight can vary widely over the range of TBP cuts for any one oil. Furthermore, other parameters such as mean molecular weight vary significantly from oil to oil, and this is particularly important for refined petroleum products, such as light diesel or gasoline. For this reason, it is more appropriate and accurate to assign values for these physical properties to a range of cuts rather than to assign a single value to the bulk oil.

The ability of the NOAA model to calculate many physical properties for a range of pseudo-components (distillate cuts) enables it to calculate the bulk oil constants and input parameters that are required by the Mackay evaporation model. No further input is required for these calculations and the model itself is not affected in any way. The following is a discussion of the Mackay

evaporation model and the procedure for calculating the input constants for Mackay's equation using the NOAA model.

The Mackay evaporation calculation (Mackay, 1983) is:

$$\Delta F = \Delta \Theta \cdot H \tag{28}$$

where

F - Volume fraction evaporated
H - Henry's law constant (dimensionless)
Θ - Evaporative exposure, a dimensionless parameter defined by:

$$\Theta = K A t/V$$
(29)

where

K = Mass transfer coefficient (m/sec)
A = Area of slick (m²)
t = Time (seconds)
V = Initial slick volume (m³)

Thus

$$\Delta \Theta = KA\Delta t/V \tag{30}$$

K, A, V, and t are all "bulk" properties. Therefore, the NOAA model will not improve upon the value of θ .

The Henry's law constant is calculated as follows:

$$H = \frac{Concentration in gas phase}{Concentration in liquid phase} = \frac{\frac{n_g}{V_g}}{\frac{n_g}{I_g}} = \frac{\frac{P_g}{RT}}{\frac{1}{V_g}} = \frac{\frac{P_gV_g}{RT}}{RT}$$
(31)

where

P is the vapor pressure of the evaporated oil (pascals)
V is the molar volume of the oil
$$(m^3/mole)$$

R is the gas constant (8.314 Pa $m^3/mole^{-0}K$)
T is the temperature (*Kelvin)

P can be calculated further using the Clausius-Clapeyron equation and boiling point data. It should be noted, however, that this equation is not strictly applicable to mixtures (Denbigh, 1971). At atmospheric pressure, though, the error introduced by using this equation is probably small in comparison to the overall errors associated with other necessary assumptions of the model. The Clausius-Clapeyron equation is:

$$\ln(P_{1}/P_{2}) = \frac{\Delta H}{R} \left[\frac{1}{T_{2}} - \frac{1}{T_{1}} \right]$$
(32)

where ΔH is the enthalpy of vaporization of the material. Let $P_2 = 1$ atm, then $T_2 = T_b$, the boiling point of the liquid. The result is:

$$P_{1} = \exp \frac{\Delta H}{R} \left[\frac{1}{T_{b}} - \frac{1}{T_{1}} \right]$$
(33)

and

$$\Delta F = \Delta \Theta \frac{V_{g}}{RT} \exp \frac{\Delta H}{R} \left[\frac{1}{T_{b}} - \frac{1}{T_{1}} \right]$$
(34)

At this point, use an average value for V_{g} and Trouton's rule ($\Delta H_{v} = 88 T_{b}$) for an average value of ΔH_{v} to obtain:

$$P_1 = \exp -\frac{88T_b}{R} \left[\frac{1}{T_b} - \frac{1}{T_1} \right]$$
(35)

and

$$\Delta F = \Delta \Theta \exp\left[6.3 - 10.6 \frac{T_b}{T}\right]$$
(36)

Further, the Mackay model uses a "boiling point curve" (B.P. vs fraction evaporated) to determine the prevailing boiling point: $T_b = initial BP + (F)$ (boiling point curve gradient).

The NOAA model is capable of calculating values of V_{ℓ} and ΔH_{V} and of calculating the initial boiling point and boiling point curve gradient. The details of these calculations are below:

 V_{g} : The molar volume of the oil is the mean molecular weight of the oil in grams per mole divided by the density in grams per m³, both of which are calculated by the NOAA model.

 V_q = mean molecular weight/density

 ΔH_V : ΔH_V for petroleum fractions has been correlated with API gravity and boiling point (Fallon and Watson, 1944), both of which are input to the NOAA model. This correlation is:

> $\Delta H_{V} = 232.2 - .2441(TB) - .6937(API)$ - 3.58 x 10⁻⁴(TB)(API) + 1.024 x 10⁻⁴(TBP)² + (1.037 x 10⁻⁴)(API)(API)

where

ΔH_V is in BTU/lb TB is the cut boiling point in °F API is the API gravity

TBP (Boiling Point Curve):

For most petroleum products (including crude oil), the boiling point vs fraction distilled curve is linear over the range of compounds that evaporate under normal environmental conditions. The distillation curve required for input to the Mackay model is a simple, batch distillation, and can be calculated using the physical properties calculated by the NOAA model. The details of that calculation are presented in the previous section. Once the distillation curve (volume fraction vs boiling point) is calculated, it is fit to a straight line by the method of least squares:

 T_{h} - initial boiling point + (gradient) (fraction evaporated)

Following calculations of V_{ℓ} , ΔH_V , and the linear boiling point curve, the Mackay evaporation equation can be constructed as follows:

 ΔH_V for each cut is divided by the molecular weight of the cut (to convert to Joules/mole) and by the boiling point of the cut in order to find a "Trouton's rule" constant. The "Trouton's rule" constants (one per cut) are then averaged. This average constant (TR) is then used in place of the classical value of 88 J/°K mole. The evaporation equation then becomes:

$$\Delta F = \Delta \Theta - \frac{V_{\varrho}}{RT} \exp\left[\frac{TR}{R} - 1 - \frac{T_{b}}{T}\right]$$
(37)

where

 $T_{b} = \text{Initial boiling point} + (\text{TBP gradient})(F) \quad (\text{in } ^{\kappa}K)$ $T = \text{Environmental temperature } (^{\kappa}K)$ $R = \text{Gas constant } (8.314 \text{ Pa} \cdot \text{m}^{3} \text{mole} \cdot ^{\kappa}K)$ $V_{g} = \text{Molar volume of the oil } (\text{m}^{3}/\text{mole})$ $TR = \text{Average Trouton's rule constant } (\text{Joules}/^{\kappa}K \cdot \text{mole})$

These calculations are performed by the ocean-ice oil-weathering code as an add-on calculation. The output from these calculations are the input parameters for the Mackay Evaporation Model. These values are calculated using existing literature data and do not require experimental work for most oils.

6.8 COMPONENT-SPECIFIC DIFFUSION THROUGH AN OIL "SLAB" AND DISSOLUTION IN-TO THE WATER COLUMN IN THE ABSENCE OF EVAPORATION

When oil is released under sea ice the primary weathering process is thought to be the dissolution of soluable hydrocarbons into the water column. The oil is not exposed to the atmosphere and the water currents are relatively weak (see Section 3.5). Thus evaporation, dispersion, mousse formation, and spreading do not occur to any large extent. It becomes important then to predict the rate at which individual components will transfer from the oil phase to the water phase. The mathematics to describe such mass-transfer will depend heavily on whether the oil phase can be considered "well mixed" or whether it behaves like a "slab". The following presents derivations for both of these situations. The solutions of the equations below, along with the experimental data presented in Sections 4.2 and 4.4, can be used to determine which state the oil is likely to be in in the environment and to determine which resistances to mass-transfer are dominant for dissolution.

The dissolution of specific components from an oil slick into the water column is described mathematically in much the same way as evaporation. The pertinent physical property required to describe dissolution is the liquid-liquid partition coefficient which is the analogy of Henry's Law for evaporation.

Unfortunately there is no characterization process for dissolution that can be applied to the bulk oil in the same manner that distillation is used to characterize the oil with respect to evaporation. There have been two attempts to classify the oil into pseudo-components with respect to solubility, one by Yang and Wang (1977) which was not carried through to the quantitative stage, and another by Mackay (1980) where only two major "cuts" were recognized. Since dissolution apparently accounts for a relatively small mass loss from the slick, an independent component-specific approach to dissolution is presented here.

The physical property data required are liquid-liquid partition coefficients, referred to in the content of this work as M-values. It must be

emphasized that pure component solubility data alone are not useful in obtaining M-values, because these types of data only yield information about the chemical potential of the species in the aqueous phase. What is required along with pure component solubility data is the chemical potential of the species in the oil phase. Henry's Law data coupled with solubility and vapor pressure data will provide M-values through calculation, while liquid-liquid equilibrium experiments measure the M-values directly.

6.8.1 "Slab" Case

For the case of a species dissolving from an oil "slab" into the water column, consider a water column which is well-stirred (i.e., of uniform concentration) and in contact with a stagnant oil slick of thickness \mathbf{i} . The diffusion of a compound in the oil is described by:

$$\frac{\partial C_0}{\partial t} = D_0 \frac{\partial^2 C_0}{\partial \chi^2} \qquad o\langle x \langle x, t \rangle 0 \qquad (38)$$

where C_0 is the oil concentration of the species of interest, t is the time, X is the distance from the oil/water interface, and D_0 is the diffusivity of the species in the oil. The water column concentration is zero at t = 0 so that

$$C_{u}(X) = 0$$
 at t=0 (39)

where C_{ij} is the water column concentration.

For this derivation mass transfer does not occur across the x-l boundary, so

$$\frac{dC_0}{dX} = 0 \qquad \text{at } x = \ell, t > 0 \qquad (40)$$

At the oil-water interface the mass fluxes from the oil and into the water must be equal, which yields

$$A\delta \frac{dC_{w}}{dt} = AD_{o} \frac{dC_{o}}{dX} \quad at x = 0, t > 0$$
(41)

where A is the interfacial area, and δ is the water-phase thickness. Thus $A\delta$ is the volume of water. This equation is rewritten as

$$\frac{dC_{w}}{dt} = \frac{D_{o}}{\delta} \frac{dC_{o}}{dX} \qquad \text{at } x = 0, t > 0 \qquad (42)$$

The component flux from the oil is written as

$$AD_{0} \frac{dC_{0}}{dx} = AK_{0}(C_{0} - C_{0}^{*}) \quad at \ x = 0, \ t > 0$$
(43)

where C_{λ} is a hypothetical oil-phase concentration that is in equilibrium with the water-phase concentration, and K_0 is an over-all mass-transfer coefficient based on oil-phase concentrations. The above equation is analogous to a heat transfer equation for the flux of energy across a film resistance. However, mass transfer requires that some form of a potential be used to write the driving force rather than observable concentrations. It is not correct to write the driving force for mass transfer as the concentration difference between the two phases. The reason for this is apparent when a simple system such as pure benzene and water is considered. At equilibrium the concentration of benzene in the water is on the order of 1700 ppm. Thus, the benzene concentration difference between the two phases is not zero, yet mass transfer, does not occur. Therefore, in order to write a driving force for mass transfer the concentration in one of the phases must be related to the other phase on a thermodynamic basis. Once this relationship is defined, the mass transfer problem looks like a heat transfer problem where the temperature is the potential for heat transfer. Thus, in the preceding expression C_{0}^{*} is an oil-phase concentration (hypothetical) in equilibrium with the bulk water-phase concentration C. As a result of this problem definition an oil-water partition coefficient is required. The oil-water partition coefficient is defined as follows:

$$m = \frac{C_0}{C_w} \qquad \text{at equilibrium} \qquad (44)$$

At this point do not relate C_0 and C_w above to those same symbols appearing in the previous equations. Because of the way the previous equations

are written, it is convenient to keep C_0 in them as it appears now. This means C_w must change. The recipe for doing this is embodied in the mass transfer resistance equation ($C_0 - C_0^*$) term. Here C_0^* is that hypothetical concentration in water in equilibrium with the concentration in the oil. Therefore the oil-phase concentration must change according to

$$C_{w} = \frac{C_{o}}{m}^{*}$$
(45)

And C_{w} must be replaced with $\frac{C_{0}}{m}$ in equation (42) above to yield

$$\frac{dC_{0}^{*}}{dt} = \frac{D_{0}}{m\delta} \frac{dC_{0}}{dx} \quad \text{at } x = 0, t > 0$$
(46)

Concelling the area in the component flux equation yields

$$\frac{dC_{0}}{dx} + \frac{K_{0}}{D_{0}} (C_{0} - C_{0}^{*}) = 0$$
(47)

Finally, the initial concentration in the oil is C_{o}^{o} .

The set of differential equations and boundary conditions above can be solved analytically using the technique of Laplace transforms which is described in Carslaw and Jaeger (1967). The analytical solution for the water-phase concentration is

$$\frac{C_{w}}{C_{o}^{o}} = \frac{\ell}{m\ell+\delta} - \frac{2\ell H^{2}}{\delta} \sum_{j=1}^{\infty} \frac{\exp(-\alpha_{j}^{2}T)}{P_{n}}$$
(48)

and for the oil-phase concentration

$$\frac{C_{o}}{C_{o}^{o}} = \frac{m\ell}{m\ell+\delta} + 2H^{2}\sum_{j=1}^{\infty} \frac{\alpha_{j}\cos\left[\alpha_{j}\left(1-\frac{x}{\ell}\right)\right]\exp\left(-\alpha_{j}^{2}\tau\right)}{\sin\alpha_{j}P_{\alpha_{j}}}$$
(49)

where a_j is the j-th positive root of

Tan
$$\alpha_{j} = \frac{H\alpha_{j}}{\alpha_{j}^{2} - K H}$$
 (50)
 $H = lh$
 $h = \frac{K_{0}}{D_{0}}$
 $K' = \frac{ml}{\delta}$
 $T = \frac{D_{0}t}{l^{2}}$
 $\tau = time$

and

$$P(\alpha_{j}) = \alpha_{j}^{4} + \alpha_{j}^{2} (H^{2} + H - 2K'H) + K'H^{2}(1 + k')$$
⁽⁵¹⁾

These equations provide useful information in that the effect of the parameters of the problem can readily be determined. For example, note that the parameter K' is a ratio of the capacitance of each phase for the component of interest, and that the partition coefficient M multiplies the water phase thickness δ to yield an equivalent water-phase thickness.

6.8.2 Well-Mixed Oil Phase Case

For the case of a "well-stirred" oil-phase in contact with a "well-stirred" water-phase, the concentration of the compound of interest is <u>not</u> a function of distance in either phase (i.e., both phases are uniform).

The flux equation for this case is

$$A \mathfrak{L} \frac{dC_0}{dt} = -AK_0(C_0 - C_0^*)$$
(52)
From the "slab" case

$$C_0^* = mC_W \tag{53}$$

Thus, cancelling the area from both sides, substituting for C_0^* , and rearranging gives

$$\frac{dC_o}{dt} = -\frac{K_o}{\ell} (C_o - mC_w)$$
(54)

However, a mass balance for the system gives

$$C_{W}A\delta + C_{O}A\ell = C_{O}^{O}A\ell$$
 (55)

so

$$C_{W} = \frac{\ell}{\delta} \left(C_{0}^{0} - C_{0} \right)$$
(56)

substituting into the flux equation gives

$$\frac{dC_o}{dt} = -\frac{K_o}{\ell} \quad C_o - \frac{m\ell}{\delta} \quad (C_o^o - C_o)$$
(57)

or

$$\frac{dC_{o}}{dt} = -\frac{K_{o}C_{o}}{k} + \frac{K_{o}m}{\delta}C_{o}^{o} - \frac{K_{o}m}{\delta}C_{o}$$
(58)
$$\frac{dC_{o}}{\delta} = -\frac{K_{o}C_{o}}{k} + \frac{K_{o}m}{\delta}C_{o}^{o} = -\frac{K_{o}m}{\delta}C_{o}$$
(59)

$$\frac{dC_{o}}{dt} = -K_{o} \quad C_{o} \quad \frac{m\ell+\delta}{\ell\delta} - C_{o}^{o} \quad \frac{m}{\delta}$$

This differential equation, along with boundary conditions specified in the previous section are solved to give

$$\frac{C_{o}}{C_{o}^{0}} = C_{2} + (1 - C_{2}) \exp(-C_{1}K_{o}t)$$
(60)

and

$$\frac{C_{w}}{C_{o}^{0}} = C_{3} \quad 1 - \exp(-C_{1}K_{o}t)$$
(61)

where

$$C_{1} = \frac{m\ell+\delta}{\ell\delta}$$
$$C_{2} = \frac{m\ell}{m\ell+\delta}$$
$$C_{3} = \frac{\ell}{m\ell+\delta}$$

In order to make the analytical solutions for component-specific dissolution usable they have been programmed in FORTRAN to allow easy investigations of the results. The details of this particular code, input-output information, and a code listing are presented in Appendix A of this report: Code Description for Component-Specific Dissolution from slicks.

6.8.3 <u>Stirred Chamber Experiments Conducted to Measure Component-Specific</u> Dissolution - La Jolla, California

Mass transfer and diffusivity coefficients were determined for seven aromatic compounds with regard solely to their dissolution from Prudhoe Bay crude oil into seawater. Using a specially constructed chamber, designed to eliminate whole oil droplet dispersion and compound evaporation, the rates and amounts of compound dissolution were determined experimentally. To obtain mass transfer and diffusivity coefficients, theoretically predicted values were adjusted until they matched the experimental values. These data will ultimately be required for predicting the component specific dissolution of aromatics into seawater as a result of a below-ice oil-release incident. While such information may not be required for mass balance considerations, it is important for assessing potential biological impacts.

An air tight, cylindrical chamber was constructed, primarily of glass, with the dimensions shown in Figure 6-2. The chamber was equipped with a water sampling port 5.1 cm from the bottom, a water replacement port 15 cm from the top, an oil sampling port located on the glass cover plate, and an oil addition port with a glass tube positioned to deliver the oil within a few millimeters of the cover plate. The glass cover plate was seated on a viton lip and clamped in place to form an airtight seal. The entire chamber was housed on a steel



Figure 6-2.--Stirred Chamber for Mass Transfer and Diffusivity Determinations.

plate containing four leveling screws. Water column mixing was accomplished by placing a submergible circulating pump (Little Giant Model 1) in the chamber; water column mixing was further enhanced by a series of one inch stainless steel baffles, which were positioned vertically around the circumference inside the chamber, but not into the oil.

The experiment was initiated by the addition of 1000 ml (a 1.47 cm thick slab) of Prudhoe Bay crude oil over a period of ten minutes. This was

accomplished by gravity feeding the oil into a funnel - attached to a glass entry tube, which extended upwards to within a few millimeters of the glass cover plate. A tube extending from the water sampling port was positioned such that concurrent with the addition of the oil, a similar volume of water was forced out of the tank. In this manner, the oil was layered uniformly and smoothly on top of the seawater, with minimal oil dispersion and no air introduced into the chamber. As soon as the entire 1000 ml of oil had been added, the funnel and tube were disconnected and the port was stoppered.

Water samples (200 ml) were obtained according to the following schedule: prespill, 10 minutes, four hours, eight hours, 12 hours, 24 hours, two days, three days, four days, five days, seven days, nine days, 11 days, 13 days, 15 days, and 17 days after the spill. As the 200 ml sample was drawn off, fresh replacement seawater was simultaneously added via the constant head arrangement. A stopcock, positioned between the funnel and then entry tube, was closed (except during sampling) to prevent any backflushing. In order to minimize evaporation of the more volatile dissolved compounds, all water samples were extracted and analyzed immediately after collection.

Triplicate oil samples were collected, though a Teflon sampling port located on the cover plate, at the initiation and termination of the experiment.

All water samples were filtered (to remove any discreet oil droplets) then extracted three times with 50 mls of CH_2Cl_2 . The effect of the filtration step on the concentration of dissolved compounds in the water was investigated by splitting one sample into two equal portions - one aliquot was filtered while the other remained unfiltered - and no differences were noted in final concentrations. Solvent reduction was accomplished by using standard Kaderna-Danish evaporation techniques as described elsewhere (Payne et al., 1984a). Before instrumental analysis (capillary column FID-GC) all samples were spiked with d_{10} -phenanthrene as an internal standard.

Triplicate oil samples were first weighed (~ 50 mg) and then taken up in approximately one ml of hexane. The oil was fractionated into its aliphatic and aromatic constituents by SiO_2 liquid chromatography and analyzed by capillary FID gas chromatography.

Compound identification was accomplished by analyzing one representative water sample extract with a Finnegan 4000 quadrupole GC/MS. Quantification of the selected compounds was achieved by generating a response factor on the FID-GC for each of the seven compounds, from an aromatic standard containing those compounds.

M-values were calculated by dividing each compounds oil phase concentration by its water phase concentration at equilibrium. M-values of the components of interest are presented in Table 6-7. Using curve-fitting techniques, values for mass transfer coefficients were found to range from 2.5 x 10^{-4} cm/sec to 4.0 x 10^{-4} cm/sec and diffusivities were found to be no less than 1.0 x 10^{-6} cm/sec. Ultimately these values will be used for estimating dissolved phase aromatic concentrations in oil weathering simulations as described in Section 6.9.2.4.

Table 6-7.--M-Values Determined from the Stirred Chamber Experiment.

Compound Name	M-Value ^a
ethylbenzene	3300
m & p-xylene	3600
o-xylene	5900
1,3,5-trimethylbenzene	19000
naphthalene	7800
2-methylnaphthalene	46400
1-methylnaphthalene	35800

a - the M-value is defined as the compound concentration in oil divided by the compound concentration in water at equilibrium.

6.9 DISSOLUTION OF HYDROCARBONS AND TRANSPORT TO BOTTOM WATERS

This section investigates the effect of freezing ocean conditions on the potential transport of dissolved oil to sensitive areas of the marine environment (see also Section 5). As a very simplistic summary, when the surface water freezes, ice is formed that is lower in salinity than the water from which it is formed. The "excess" salt water is denser than the surrounding water and will sink creating a downward vertical current. This has been considered a potential mechanism for the transport of pollutants to bottom waters in the Arctic environment.

With regard to an oil spill in freezing Arctic conditions, it is believed that the spill of oil into an open lead would present the "worst case scenario" for haline transport of dissolved oil since the freezing (ice formation) rates for an open lead have been shown by numerous investigators to be considerably higher than freezing rates in open water (Foster 1972, Schaus and Galt 1973). A high freezing rate would induce rapid transport of surface material to bottom waters. An analysis of potential pollutant transportation rates based on measurements taken in Arctic leads in included in Section 6.9.3.

To assess an "upper bound" effect of an oil slick on dissolved species transport, calculations have been made to estimate the amount of material that will dissolve out of the slick into the surrounding water. The material that does dissolve is generally considered as having an oil/water partition coefficient that is less than about 150,000. This implies that when an equal amount of water and oil is contacted, the water phase concentration of the compound of interest will be 1/150,000 of that in the oil. When dilution is further taken into account as specified in an environment situation, the water-phase concentration is always considerably less. Calculations in Section 6.9.2 indicate that very little oil is dissolved directly from the slick as it effects the slick mass balance; however, using the flow estimates in Section 6.9.3, the amount of dissolved material reaching the bottom waters could be in the range of 0.2 to 3 ppm. These numbers are strictly upper bound estimates and were calculated by specifying environmental parameters from a list of

observed parameters in such a manner that the calculated concentration would be a maximum. No effort was made to also determine an average because of the paucity of published data. This also implies that the maximum values reported here could be higher due to the fact that the extremes in nature have not necessarily been observed.

The primary source of transport of oil species to the bottom waters would be through the dispersion of fine drops into the water column. The transport of small dispersed oil droplets would occur due to the downward current exceeding the droplet's Stokes rising velocity. A five micron diameter oil droplet will rise at 1.5 cm/hour (0.0004 cm/sec) while a salt-rejection plume velocity can be much greater than this. However, it must be noted that dispersed oil has always been studied with the objective of a material balance of the oil slick, not with the objective of the droplet size leaving the slick. Nevertheless, at the present, dissolution from either the slick or oil droplets is all that can be postulated to provide an estimate of "oil" transported to the bottom. As discussed in Section 6.9.2, the small droplet size (1-50 μ m) allows for greater dissolution of oil species than that obtained from the slick directly.

6.9.1 A Discussion of the "Solubility" of Petroleum

One of the fundamental mass transfer processes that occurs when crude or refined petroleum is spilled on water is dissolution. This process, which results in oil components being dissolved (on a molecular scale) into the water phase, has also been called solubilization, incorporation, and accommodation.

When an overall mass balance is derived for oil spilled on water, the total mass dissolved (resulting from the dissolution of many different components) into the water is small compared to the original oil mass. It is important to be able to quantify this mass balance, however, since biological impact will, in part, be determined by this result. There is some confusion and misunderstanding in the literature about what is important and/or required to quantify dissolution and some misuse of terminology.

The following discussion is designed to point out the important aspects of the mass transfer of petroleum components into water, particularly the resulting concentration (at equilibrium) of those components in the two phases (water and oil). The main point to be made is that crude oil (or refined petroleum) is a very complex, continuum of components that behaves differently than single components alone.

In order to illustrate the proper use of the term "solubility" and then illustrate how it does not apply to oil, consider the definition. The solubility of a compound in water is the concentration obtained at equilibrium when a finite amount of the pure compound is (still) present. In applying this definition to benzene or sugar, the compound is added to (and dissolved in) water until no more will go into solution. When no more goes into solution, the pure compound phase is visible. The reason this definition of solubility does not apply to oil is that oil is not a pure compound. Some of the compounds in oil are soluble and at the other extreme some are essentially (for practical purposes) insoluble. Thus, for compounds present in oil that are soluble, a liquid-liquid equilibrium exists for the component because it distributes between both phases and a ratio of the concentrations in each phase at equilibrium is the important parameter to measure. It is this ratio that is usually constant over concentration ranges near zero, and it is this ratio that is required to determine how much "oil" will distribute (not dissolve) into water. This distribution concept is illustrated below.

First consider the following system: 1 ml of benzene is layered on top of 10 ml of water in a closed system so that evaporation is prevented. The system is allowed to come to equilibrium. At equilibrium, the concentration of benzene in the water phase is found to be 1700 parts per million (ppm). This concentration is what is normally called the <u>solubility</u> of benzene in water. The important concept is that the relative volumes of the two phases (benzene and water) do not affect the concentration of benzene in the water. In other words, if 1 ml of benzene was equilibrated with 1000 ml of water, the resulting concentration of benzene in the water would again be 1700 ppm. However, the above cannot be said of petroleum, or for any other mixture of compounds. To illustrate this, consider a second system: 1 ml of crude oil (which contains

benzene) is equilibrated with 10 ml of water in a closed system. The numbers will vary from oil to oil, but for a typical set of conditions, the concentration of benzene in the oil and water phases at equilibrium will be 1000 mg/l and 1 mg/l, respectively. Next, consider another system in which 1 ml of crude oil is equilibrated (closed system) with 1000 ml of water. In this case, the oil and water phase concentrations of benzene are 505 mg/l and 0.505 mg/l, respectively. The crucial point is that, unlike with pure benzene, the concentration of benzene in the water phase is not independent of the relative volumes of the two phases. The quantity that is independent of these volumes is the ratio of the concentrations of benzene in the two phases. This ratio is called the partition coefficient and is defined for each component of the system as:

partition coefficient = $\frac{\text{concentration in oil}}{\text{concentration in water}} = \frac{1000}{1} = \frac{505}{.505} = 1000$

Each component in each oil will have a different partition coefficient. For this reason, it is difficult to define the "solubility" of a mixture (such as crude oil) since the concentration of the components of the mixture in the water will depend on the volumes of the two phases and their initial concentration in the mixture.

Most authors have ignored this fact and have measured what they call solubility with a particular volume ratio of water and oil and in some cases the solubility varies three or four orders of magnitude. For example, Boehm and Quinn, 1974, measured "oil solubility" by equilibrating 4 mg of oil with 1.0 liter of water (volume ratio = 200,000) while Mackay and Shiu, 1976, used 10 ml of oil and 100 ml of water (volume ratio = 10). These authors tested different oils so their results cannot be compared. However, the point is that both authors report their results as the "solubility of crude oils" without any indication of the experimental conditions (i.e., volume ratios). Using the results of a derivation presented later in this report, it can be shown that a four order of magnitude difference in volume ratio can produce a one-to-two order of magnitude difference in measured concentration for the more soluble petroleum compounds.

In addition to the difficulty in defining a solubility for mixtures, it must be realized that an equilibrium experiment does not reproduce the dynamics of dissolution in the environment. Since the ocean is turbulent, "clean" water is usually (except possibly in a bay or lagoon) flowing past the oil. Thus, the partitioning behavior described above can deplete the oil of the components that have small partition coefficients and thus distribute these components to the water phase in appreciable quantities (see definition of partition coefficient above). To illustrate this, consider the system described above in which 1 ml of oil is equilibrated with 1000 ml of water. The resulting benzene concentrations are 505 mg/l in the oil and 0.505 mg/l in the water. Now imagine removing the water phase and bringing 1000 ml of fresh water into contact with the remaining oil. After equilibration, the oil and water phase concentrations of benzene are 253 mg/l and 0.253 mg/l, respectively. Thus, the benzene concentration in the oil has been reduced from 1000 mg/l (originally) to 253 mg/l. With further equilibrations, the benzene would eventually be removed completely from the oil phase.

It becomes apparent, then, that the desired data, at least from a biological impact point of view, are the <u>total mass fraction</u> of components that will dissolve in a chosen period of time under the dynamic conditions described above in which "clean" water is flowing past the oil. A published value for this is about three percent (Murray, et al., 1984). However, this number is expected to vary from oil to oil and especially for refined products such as gasoline, which is known to contain large amounts of individually-soluble aromatic components. The following sections discuss a number of mathematical models and experimental methods that have been used to obtain or predict the necessary data to quantify dissolution.

6.9.2 <u>Experimental Method for Measurement of Total Soluble Fraction of Pe-</u> troleum

When water is brought into contact with petroleum in a closed system and allowed to equilibrate, mass transfer from the oil phase to the aqueous phase takes place. A chemical analysis of the resulting aqueous phase reveals that many compounds are present. Repeated equilibrations of the oil phase with clean water will eventually remove all of these individual components from the

oil. The following discussion presents the theory and experimental protocol for measuring the "total soluble fraction" of a crude or refined petroleum. Results from such experiments follow these discussions.

6.9.2.1 Theory

Consider the Equilibration of a Volume of Oil with a Volume of Water

V_-volume of water V_-volume of oil X-original mass of the component of interest M_-mass of component of interest in oil after equilibration M_-mass of component of interest in water after equilibration

Now define the volume ratio and partition coefficient:

$$r = volume ratio = V_V / V_A$$

 $m = \begin{bmatrix} concentration of component in oil \\ concentration of component in water \end{bmatrix} = \frac{M_o}{V_o} \frac{V_w}{M_w}$ at equilibrium

As mass is conserved, write:

 $X = M_0 + M_w$ (62)

Now substitute in the above definitions and solve for the concentration of the component in the water $(M_{\downarrow}/V_{\downarrow})$, which is directly observable.

$$\mathbf{M}_{\mathbf{W}} = -\mathbf{X} - \mathbf{M}_{\mathbf{O}} \tag{63}$$

$$= X - \frac{mV_0 M w}{V_w}$$
(64)

$$= x - \frac{mM_{W}}{r}$$
(65)

$$rM_{w} = rX - mM_{w}$$
(66)

$$M_{W} = \frac{rX}{(r+m)}$$
(67)

$$\frac{M_{W}}{V_{W}} = \frac{rX}{V_{W}(r+m)} = \frac{X}{V_{O}(r+m)}$$
(68)

or inverting, write

$$\frac{V_w}{M_w} = \frac{V_o(r+m)}{X}$$
(69)

Thus, since r and V_o are known and (V_w/M_w) is the reciprocal of the concentration of the component of interest in the water phase (which can be measured), a series of equilibrations of fresh oil with water at varying volume ratios (r) will yield a plot $(V_w/M_w$ vs r) with slope V_o/X and intercept $(V_om)/X$. An examination of the equation above indicates that a significant difference in the measured concentration (M_w/V_w) will only be "seen" when r is on the order of m or bigger. Since typical oil-water partition coefficients for aromatic hydrocarbons are in the range of $10^3 \cdot 10^5$, the series of equilibrations must include volume ratios in this range and larger if possible.

6.9.2.2 Experimental

In order to verify the above theory and measure the "total soluble fraction" of fresh Prudhoe Bay crude oil, the following experimental protocol was followed. A Hamilton S-1500 1.5 liter super-syringe, fitted with a luerlock adaptor, was filled with approximately 1300 ml of seawater. All air bubbles were expelled from the syringe and then a known volume of fresh Prudhoe Bay crude oil was introduced to the syringe chamber through the luer-lock fitting using a smaller syringe of appropriate volume. The large syringe was tipped such that the displaced seawater could flow out of the luer-lock fitting as the oil was added. A luer-lock valve was then attached to the large syringe to close the system from the room air. The syringe was then agitated (by hand) continuously for 20 minutes and then allowed to sit for an additional 40 minutes with occasional agitation.

Next, the luer-lock valve was replaced by a 0.45 micron filter and luer-lock needle. The syringe was then inverted and configured as in Figure 6-3. A 1.0 liter round bottom flask containing 100 ml of fresh hexane was placed under the syringe so that the syringe needle was immersed in the hexane. This was done so that the seawater, after filtration, would not be exposed to the room air, thus preventing evaporation of volatile compounds.

The back-pressure created by the 0.45 micron filter was too large for one person to filter the sea water so the platform arrangement in Figure 6-3 Extra supporting rods (plungers) were added to the syringe was constructed. and attached to a wooden platform. Lead bricks (~60 lbs) were then placed on the platform to supply the necessary force to filter the aqueous phase. Approximately 1.0 liter of seawater was filtered; the remaining water and oil discarded. The seawater/hexane mixture was then put into a separatory funnel and shaken. After settling, the hexane phase was removed, and the aqueous phase was extracted twice with 100 ml of methylene chloride. The hexane and methylene chloride fractions were then combined and concentrated to approximately 1 ml and analyzed by GC-FID. An analytical standard mixture of typical aromatic hydrocarbons was utilized to calibrate the chromatograph.

The above procedure was repeated for varying volume ratios, e.g., r = 10, 10^2 , 10^3 , 10^4 , 10^5 . Concentration versus r data were then prepared for each peak in the resulting chromatograms and m (partition coefficient) and X (original mass) were calculated. The following section presents these results.

6.9.2.3 Results

Fresh Prudhoe Bay crude oil was utilized to perform the experiment described above. Table 6-8 is a summary of the oil and seawater volumes utilized



Figure 6-3.--Experimental System Used to Measure Total Soluble Fraction of Prudhoe Bay Crude Oil.

Equilibration Sample No.	Oil Volume (V _o)	Sea Water Volume (V _W)	Volume Ratio (r=V _w /V _o)
1	1µ2	1.281	6 1.28 x 10
2	10 µ2	1.321	1.32×10^{5}
3	100 µ <i>1</i>	1.291	4 1.29 x 10
4	1 m <i>1</i>	1.301	1.30×10^3
5	10 m 1	1.31 1	1.31×10^{2}

Table 6-8.--Volumes and Volume Ratios for Experiment to Measure Total Soluble Fraction of Prudhoe Bay Crude Oil.

Table 6-9.--Results of Partitioning Experiments, Compound of Interest: 2-Methyl Naphthalene.

Equilibrium Sample No.	Concentration of 2-Methyl-Naphthalene	Volume Ratio (r)
1	0.39µg/1	6 1.28 x 10
2	3.53µg/1	5 1.32 x 10
3	7.6 µg/l	4 1.29 x 10
4	10.9 µg/1	1.30×10^{3}
5	25.4 μg/l	1.31×10^2

in five separate equilibrations. As shown, the volume ratio for these samples varied from 1.31 x 10^2 to 1.28 x 10^6 .

Table 6-9 presents the results of the experiment for one compound, 2-methyl naphthalene. When the data in Table 6-9 (1/concentration vs r) are linearized, the following are the results:

$$1/C_{w} = (1.95 \times 10^{-6})r + 6.61 \times 10^{-2}$$

correlation coefficient = 0.9995

Thus, from the theory presented above,

slope
$$= V_0/X = 1.95 \times 10^{-6}$$

intercept =
$$(mV_0)/X = 6.61 \times 10^{-2}$$

When these equations are solved for the X/V_o (original oil concentration) and m (partition coefficient), we find:

$$X/V_{o} = 0.51 \text{ g/1}$$

m = 33,900

These values of X/V_{O} and m are in the range of literature values. This analysis can be performed on the other peaks in the GC trace with similar results.

In order to apply the above theory to determine the total soluble fraction in (Prudhoe Bay) crude oil the chromatographic data from each component (that distributes appreciably) is linearized so that values for X/V_o and m are found. Table 6-10 presents these data for all the observed components. As shown in the table, the total concentration of distributing components is

Retention Time	Partition Coefficient (m)	Oil-Phase Concentration (x/V ₀)(g/ <u>1</u>)
3.14	3700	1.36
5.11	3700	0.31
5.37	4000	0.84
6.11	6400	0.57
7.24	5900	0.037
8.37	8800	0.064
8.69	10000	0.23
9.38	17000	0.15
9.93	41000	0.69
11.10	31000	0.33
13.75	59000	0.15
17.97	21000	0.38
22.58	34000	0.51
23.25	52000	0.37
27.51	148000	0.22

Table 6-10.--Partition Coefficients and Total Oil-Phase Concentrations for Observed Oil Components.

Total = 6.21 g/1

Table 6-11.--Groupings of Individual Oil Components into "Pseudocomponents."

	Oil-Phase		
 m	Concentration		
3700 3700 4000	$\begin{array}{c}1.36\\0.31\\0.84\end{array}$	"Cut" 1	m = 3800 C = 2.51g/j
6400 5900 8800 10000 17000 21000	0.57 0.037 0.064 0.23 0.15 0.38	"Cut" 2	m = 12000 C = 1.43 g/j
41000 31000 59000 34000 52000 148000	0.69 0.33 0.15 0.51 0.37 0.22	"Cut" 3 "Cut" 4	m = 51000 C = 2.31 g/ j $m = \infty$ C = 873.8 g/
		(remaining	oil) control g/

6.21 g/l. This value does not, however, include benzene, which is the only low molecular weight aromatic that cannot be measured with the capillary column used for the analysis. Quantitation of benzene could be achieved with another column. Since the purpose of the experiment was to develop a technique for measuring total soluble fraction (and not exact quantitative results), this second column analysis was not performed. Using the density of Prudhoe bay crude oil (880 g/l) the total weight fraction of these soluble components is (6.21/880)(100) = 0.71% (excluding benzene) which is in line with estimates from the literature.

6.9.2.4 Use of Experimental Data for Predictions of Water Column Concentrations

The experimental data presented above (concentration and partition coefficient) are important because they indicate how much of the distributing components are present in the oil and how large the driving force for dissolution is. They do not, however, represent the complete set of data required to assess water column concentrations in dynamic systems, such as in the open ocean or under ice. The remaining data needed are mass transfer coefficients (K_i) , which indicate, in a loose sense, how fast components can travel across the oil/water boundary, and diffusivities (D_i) , which indicate the speed at which components diffuse through the oil phase.

Once these data are known, mathematical models can be written to predict the flux of distributing components into the water column as a function of time. Then, if the flowrate of water past the slick is known, the final water column concentration can be calculated. For example, in the case of oil in an open ice lead, this flowrate can be approximated as discussed in the following sections by the rate at which brine is formed and flows down into the water column.

SAIC and others have measured mass transfer coefficients and diffusivities of oil components. One such experiment is described in Section

6.8.3 of this report. In this experiment, oil was spilled on a tank of seawater and covered so that evaporation was prevented. Time series water column concentrations were then measured and the data fit to a model to "back out" mass transfer coefficients and diffusivities. Mass transfer coefficients ranged from 0.9 to 2.25 cm/hr, and diffusivities were found to be no less than 1.0×10^{-6} cm²/sec. Cohen (Cohen, et al., 1980) reports mass transfer coefficients cients of about 1.0 cm/hr. Liquid phase diffusivities are typically in the range of 10^{-5} to 10^{-6} cm²/sec. Thus the experimental data agree well with the literature.

The set of required kinetic and thermodynamic data is thus complete. The discussions that follow present the simple models that predict the flux of components from oil as a function of time, and then actual predictions utilizing the experimental data for Prudhoe Bay crude oil.

6.9.2.5 Dissolution from a Well-Stirred Oil Slick into a "Clean" Water Column

Consider a slick of oil with volume V and area A in contact with a "clean" (semi-infinite) water column. A differential mass balance on a distributing component of the oil is:

$$\mathbf{v} - \frac{d\mathbf{C}_{o}}{dt} = \mathbf{\lambda} \mathbf{K}_{\mathbf{w}} (\mathbf{C}_{\mathbf{w}}^{*} - \mathbf{C}_{\mathbf{w}})$$
(70)

where

 $C_o = oil-phase$ concentration $K_w = wate r-phase$ mass transfer coefficient $C_w = water-phase$ concentration and C_{W} is the hypothetical water-phase concentration that would be in equilibrium with the oil-phase concentration. Or,

$$\mathbf{m} = \mathbf{C}_{\mathbf{o}} / \mathbf{C} \mathbf{*}_{\mathbf{W}} \tag{71}$$

where **m** is the partition coefficient. We now assume that the water phase concentration is zero ($C_w=0$) since in general "clean" water will be flowing past the slick. Substitution of (71) into (70) gives

$$\frac{dC_{0}}{dt} = \frac{A}{V} \frac{K_{V}}{m} C_{0}$$
(72)

The appropriate boundary condition is:

$$C_{0} = C_{0}$$
 at $t = 0$ (73)

The solution to (72) and (73) is:

$$\frac{C_{o}}{C_{o}^{o}} = \exp\left[-\frac{A}{V} \frac{K_{v}}{R}t\right]$$
(74)

An implicit assumption for this model is that the oil-phase is wellstirred. This assumption eliminates the need for consideration of the diffusion of oil components through the oil. This assumption will be evaluated later when the experimental data are used as input to this model. Equation (74) does show, however, that the required data (as discussed above) are the mass transfer coefficients (K_w) , partition coefficients (m), and initial oil-phase concentrations $(C_o o)$, as well as geometrical factors (A, V).

6.9.2.6 Dissolution of Prudhoe Bay Crude Oil Components from a Slick

The model developed above enables us to predict the dissolution of Prudhoe Bay crude oil from a slick using the experimental data above. One approach would be to apply Equation (74) to <u>every distributing component</u> using the data from Table 6-10. This would be tedious, though, and would obscure the point that will be made. The approach taken here will be to "<u>cut</u>" the oil up into four parts which we will call pseudocomponents. The pseudocomponents will be comprised of individual components that have similar partition coefficients and thus similar driving forces for mass transfer (into the water column). Table 6-11 shows how these pseudocomponents have been chosen. Each pseudocomponent is assigned a partition coefficient which is the weighted average (by concentration) of the partition coefficients of the individual components.

A typical value for mass transfer coefficient, 1.0 cm/hr, will be used. A/V is just the inverse of the slick thickness. A typical slick thickness of 1 cm will be used, i.e. $A/V = 1 \text{ cm}^{-1}$. With these data and those from Table 6-11, Equation (74) predicts the following half-lifes for the pseudocomponents in the oil:

Pseudocomponent	<u>Half-life (1 cm slick)</u>	<u>Half-life (1 mm slick)</u>
1	110 days	11.0 days
2	0.95 yrs	34.5 days
3	4.0 yrs	146 days
4	~∞	~∞

These results indicate that dissolution from a well-stirred oil slick will <u>not</u> result in significant water-phase concentrations of distributing components.

Now return to the discussion above about the mechanical state of the oil. If the oil-phase was modeled as a stagnant slick rather than wellstirred, the diffusivity of the pseudocomponent would have to have been considered. However, if this were done, the half-lives calculated above would be even longer because of the <u>added</u> resistance to mass transfer within the oil- phase. Thus, the simple "well-stirred" model is sufficient for the purpose here, that being to illustrate the <u>very slow</u> rate of dissolution from slicks.

Another possible mechanism for transport of oil components to the water phase is dissolution from small oil droplets that have been dispersed (mechanically or chemically) into the water column. The following sections explore this mechanism.

6.9.2.7 Dissolution from Oil Droplets into an Infinite Water Column

Consider a spherical oil droplet of radius a in an infinite wellstirred water column (r>a). Let the diffusivity of an oil component be D. The concentration of the component in the droplet is C_0 , initially C_0^0 . The water column concentration is C_w . The diffusion equation for the component in the oil is

$$\frac{dC_{o}}{dt} = D \left[\frac{\partial^{2} C_{o}}{\partial r^{2}} + \frac{2}{r} \frac{\partial C_{o}}{\partial r} \right]$$
(75)

At the oil/water interface, the diffusive flux must equal the flux of component across the interface:

$$- AD \frac{\partial C_0}{\partial r} = AK_w(C_w^* - C_w) \quad (at r = a)$$
(76)

where

such that
$$m = C_0/C_w^*$$
 (77)

The appropriate initial condition is:

$$C_{o} = C_{o}^{o} \qquad (t = 0) \tag{78}$$

The system of Equations (75), (76), and (78) can be solved by the method of Laplace Transforms. Carslaw and Jaeger (1959) present the solution:

$$\frac{c_{o}}{c_{o}^{o}} = \frac{2h}{r} \sum_{n=1}^{\infty} \frac{(a_{n}^{\alpha})^{2} + (1-ah)^{2}}{\alpha_{n}^{2} \alpha_{n}^{2} \alpha_{n}^{2} \alpha_{n}^{2} + ah(ah-1)} \sin(\alpha_{n}r) \sin(\alpha_{n}a) e^{-D\alpha_{n}^{2}} t (79)$$

where
$$h = k_w / Dm$$
 (80)

and αn are roots of:

$$(a\alpha_n) \cos(a\alpha_n) = (1-ah)\sin(a\alpha_n)$$
 for $n = 1, 2, 3, ...$ (81)

Thus, Equations (79-81) comprise a model for the prediction of dissolution from oil droplets.

6.9.2.8 Dissolution of Prudhoe Bay Crude Oil Components from Droplets

The model above (Eqs. 79-81) has been programmed on the SAIC computer so that predictions can be plotted. A code listing of this model is presented in Appendix B of this report: Code Description for Component-Specific Dissolution from Droplets. The data presented below utilize the same experimental data as before with the addition of a value for the oil phase diffusivity, D, of 1×10^{-5} cm²/sec (a typical value found in the literature). Once again, the pseudocomponent approach will be taken.

Figures 6-4A through 6-4C present plots of the average dimensionless concentration of the pseudocomponents in the oil phase as a function of time for three different droplet radii. These average concentrations are obtained by integrating Equation (79) over the range 0<r<a and dividing by the volume of the drop (4/3 πa^3).

As shown in the plots, the half-lives for the three pseudocomponents are very sensitive to drop radius. For drops of radius 10^{-1} cm, the half-life of Cut 1 is about 3-4 days. This value drops to a few hours for drops of radius 10^{-3} cm. The reason for this decrease in half-life is the increased amount of surface area of the drops in proportion to their volume. It becomes very important then to predict the drop size or size distribution in order to make accurate estimates of the flux of soluable oil components into water.

The results presented in Figures 6-4A, B and C agree well with an approximate equation for dissolution half-lives given by Mackay, 1983.

6.9.2.9 Summary and Implications for Oil/Ice Systems

The preceding sections have illustrated two important facts concerning oil dissolution:

1) Petroleum is a complex mixture of components whose dissolution behavior cannot be described simply by a single measurement of



Figure 6-4.--Predicted Diffusion and Dissolution from a Droplet into an Infinite Medium for Droplet Radii of (A) 0.1 cm, (B) 0.01 cm, and (C) 0.001 cm.

"solubility." Such a description requires both kinetic and thermodyanmic data. Methods of measuring these data and mathematical models to predict dissolution using them are given.

 Oil dissolution from an oil slick is a very slow process. Dissolution from very small oil droplets is much faster, chiefly because of the increased surface area per volume in small droplets.

The first implication of these facts is the need for research into the mechanism(s) that produce very small oil drops (5-50 microns). This droplet size has a been observed frequently by many investigators but the details of the process that creates them is not known (Shaw 1973; Gordon , et al. 1973). In some oil-water-electrolyte systems, spontaneous oil-in-water emulsions form in the absence of turbulence. Presumably, this "natural" process would be accelerated by ocean turbulence. Whatever the mechanism is, however, more information is needed before accurate prediction of droplet-size distribution can be made.

Secondly, the results above indicate that unless oil droplets are broken up or formed from sub-surface turbulance for under ice release (pipeline rupture or blow out) very little dissolution will occur from oil spilled under ice. Typically, slicks under ice are on the order of centimeters thick (very small surface area per volume) and are subject to small levels of turbulence. Thus, the time scale for dissolution from these large pools will be very large in comparison to the time scale for encapsulation of the oil into the ice. If smaller oil droplets are distributed, as observed in wave tank simulations (Sections 4.2 and 4.4) or in simulated blowouts under first year ice in the field (DOME, 1981) then dissolution would be significantly enhanced. In the following section, model-predicted water column concentrations of total dissolved species as observed measurements are presented for a subsurface oil spill under growing first year ice.

It is more difficult to make such statements about the later stages of oil/ice weathering, i.e., in the spring when the ice thaws. During this period

(after release), the oil begins to spread (increase surface area) and the hydrodynamic conditions are more turbulent. In addition, the oil comes into contact with the atmosphere so evaporation competes with dissolution. In general, the components that dissolve are also very volatile in an evaporation sense. For these reasons, the prediction of the oil droplet size distribution as a function of hydrodynamic conditions and percent ice cover becomes important. As noted in Section 4.2, grinding slush ice can enhance smaller oil droplet dispersion.

The dissolution of oil in open leads during freezeup is similar to that during thaw. The mass transfer from the parent slick will be slow, but if small droplets are being produced that transfer would be increased.

6.9.3 Determination of Ice Production and Salt Rejection Rates in Open Leads

The following model for ice production and salt rejection rates is primarily based on the model of Bauer and Martin (1983). Other similar models are also available (Schaus and Galt, 1973; Foster, 1972). The model used here has been simplified and modified to obtain order-of-magnitude estimates of brine flow rates.

The ice production rate is a function of the heat fluxed through the open lead. The model presented is only applicable for open water. Salinity plumes occur under all freezing ice but at much lower rates of ice production and salinity rejection. Bauer and Martin (1983) estimated coverage times for leads of various size, wind speeds and air temperatures ranging from three hours for a 50 m fetch at -40°C with wind speeds of 10 m/s to 200 hours for a 500m fetch at -10°C and 90 m/s winds. Twenty-four hours for coverage seems to be a reasonable average time for a small fetch (250 m) with mild winds (20 m/s) and temperatures -20°C. The calculated heat flux values are therefore reasonable for times of hours to a few days.

The total heat fluxed is Q* where

$$Q^* = Q_H + Q_E \quad (W/m_2)$$

and

 $Q_{H} = \text{sensible heat flux}$ $= (0.485 k_{n} + 1.9 W_{2})(T_{W} - T_{A})$ $k_{n} = 8.0 + 0.35 (T_{W} - T_{A})$ $W_{2} = \text{wind speed at 2 m (m/s)}$ $T_{A} = \text{air temperature (°C)}$ $T_{W} = \text{water temperature (°C)}$ $Q_{E} = \text{latent heat flux}$ $= (0.76k_{n} + 2.95 W_{2})(e_{SW} - e_{a})$ $e_{a} = \text{atmospheric va por pressure (mbars)}$ $e_{SW} = \text{saturated water vapor pressure (mbars)}$

Q* often includes values for radiant heat flux which is gene rally small compared to $Q_{\rm H}$ and $Q_{\rm E}$ and close to zero in cloudy weather or with very thin ice cover (10⁻⁶ cm). For this model, radiant heat flux is assumed to be zero.

The ice production rate is then (from Bauer and Martin, 1983)

$$I (kg/m^{2} hr) = \frac{3.6 Q^{*}}{(L - C_{p} T_{W})}$$
(82)

The temperature of the sea water at freezing can be obtained from tables of freezing temperature versus salinity (the freezing temperature of 31 $^{\circ}$ /oo water is -1.73°C). A formula for this relationship is given by (Zubov, 1943)

$$T_{F}(^{\circ}C) = -0.054 \ S(^{\circ}/00)$$
 (83)

Salinity rejection rates are based on ice production, where the amount of ice formed gives a direct indication of the salt rejection. There is considerable disagreement in the literature as to the amount of salt retained in newly-formed ice. Bauer and Martin (1983) assume that no salt is retained; Foster (1972) assumes the ice has a salinity 30 °/oo less than sea water (4 °/oo in ice for 34 °/oo water); and Schaus and Galt (1973) assume 8 °/oo. Zubov (1943) relates observed values of 5-10 °/oo for an air temperature of -16°C to -40°C with the maximum observed salinities at 25 °/oo (also at ~-40°C). Ice salinity is a function of air temperature, age and speed of formation with salinity decreasing with age of the ice (see for example, Tables 4-2, 4-10 and 4-12 for sea ice salinities measured in this program). Foster (1969) also observed experimental ice salinities of 25 °/oo to 30 °/oo.

For this model, it is conservatively assumed that newly-formed ice contains 10 $^{\circ}$ /oo so that the <u>salt rejection rate</u> becomes

$$\overline{S} (kg/m^2 hr) = \frac{3.6 Q^2}{(L - C_p T_W)} \frac{S}{(1000 - S)} \frac{(S - 10)}{S}$$
(84)

Using Equations (82) and (83) and values for L and C_p , Equation (84) becomes

$$\frac{1}{S} (kg/m^2 hr) = \frac{3.6 Q^{\circ} (S - 10)}{(335 + 0.114S) (1000 - S)}$$

or

$$\frac{1}{S (kg/m^2 s)} = \frac{0.001 q^4 (S - 10)}{(335 + 0.114S) (1000 - S)}$$
(85)

6.9.3.1 Salinity Plumes and Salt Flux

Table 6-12 gives a summary of salinity values for the top and bottom of plumes associated with open leads (Payne 1985). The average value observed at the surface is 32.9 ^o/oo and at the bottom is 33.8 ^o/oo giving a difference of 0.9 ^o/oo. Salinity profiles observed by various authors show a wide variation in surface values and bottom values; the numbers considered here are used to obtain rough estimates only. A difference of 0.9 ^o/oo may, in fact, be higher than other observed values (Foster, 1972) for open leads, but this would yield conservative results for estimating flow rates.

The salt fluxed from the surface may be determined using the equation

where

Salt Fluxed $(kg/m^3) = \Delta S \rho_{SW}$ $\rho_{SW} = density of sea water$ $<math>\simeq 1.023 \text{ gm/cm}^3 \text{ at } 0^{\circ}\text{C}$

For the data from Table 6-12, this value is approximately

Salt Fluxed $(kg/m^3) = [0.9gm/1000gmSW][1.023gmSW/cm^3][kg/1000gm][100cm/m]^3 = 0.92 kg/m^3$

6.9.3.2 Volumetric Flow Rates

A volumetric flow rate may now be determined from the previous calculations and assumed values.

Vol Flow (m^3 / s) = Salt Rejection Rate $(kg/m^2 s)$ per unit surface area Salt Fluxed (kg/m^3)

Site	Depth	<u>s</u> o	<u>S</u> B	DS
10	30m	33.1 ppt	33.9 ppt	0.8 ppt
11	28m	33.2 ppt	33.9 ppt	0.7 ppt
12	24m	32.4 ppt	33.8 ppt	1.4 ppt
13	27m	32.8 ppt	33.7 ppt	0.9 ppt
14	29m	33.3 ppt	33.9 ppt	0.6 ppt
16	29m	32.5 ppt	33.8 ppt	1.3 ppt

 $S_0 = at surface measurement$

 $S_B = at bottom measurement$

Table 6-13.--Heat Flux Values from Bauer and Martin (1983) with Corresponding Rejection Rates Based on a Salinity of 32.9 $^{\circ}/_{\circ\circ}$ and Volumetric Flow Rates.

Air Temp	Water Temp	Wind Speed	Heat Flux	Salt Reject Rate	Vol. Flow Rate*
(°C)	(°C)	(m/s)	(W/m ²)	(kg/m ² s)	(m ³ /s)
-10°	-2°	10	290	2.0 E-5	2.2 E-5
		30	700	4.9 E-5	5.3 E-5
		90	1850	1.3 E-4	1.4 E-4
-20°	-2°	10	600	4.2 E-5	4.6 E-4
		30	1350	9.4 E-5	1.0 E-4
		90	8500	2.4 E-4	2.7 E-4
-30°	-2°	10	940	6.6 E-5	7.1 E-5
		30	2000	1.4 E-4	1.5 E-4
		90	5200	3.6 E-4	3.9 E-4
-40°	-2°	10	1330	9.3 E-5	1.0 E-4
		30	2700	1.9 E-4	2.1 E-4
		90	6900	4.8 E-4	5.2 E-4

* per unit surface area

A summary of heat flux values from Bauer and Martin and salt rejection rates calculated from the assumed initial salinity of 32.9 $^{\circ}$ /oo is given in Table 6-13. Volumetric flow rates were also calculated using the salt fluxed value of 0.92 kg/m³. This gives a range of flow rates that might be used to transport dissolved species to the bottom water layers. A change in initial salinity to 35 $^{\circ}$ /oo with no change in Δ s will lower the volumetric flow rates by one order of magnitude while using the increased salinity and decreasing Δ s by one half will halve the flow rates so that within reasonable estimation ranges, changes in salinity values have only small affects on the results.

6.9.4 Dissolved Oil Concentration Transported to Bottom Waters

The results of the last two sections can now be used to estimate the maximum dissolved oil concentration in water under forming ice. The dissolution rate of oil from a slick is considered to be the sum of the dissolution rates of pseudocomponents (these dissolution or solubility pseudocomponents are not strickly the same as those used when considering volatility). From Section 6.9.2 the concentration of individual pseudocomponents in the oil phase is:

$$C_{o} = C_{o}^{o} \exp \left[-\frac{A}{V} \frac{K w}{m} T\right]$$
(86)

The environmental temperature is used implicitly in the dissolution calculations through the temperature dependence of the partition coefficient, m. This temperature dependence is "weak", and as a result, the water temperature due to thermal coupling, is always used to specify the environmental oil temperature, even though the air temperature may be different.

The mass y of each pseudocomponent is (assuming the volume is roughly constant)

$$\mathbf{y} = \mathbf{C}_{\mathbf{o}}^{\mathbf{o}} \quad \mathbf{v} \quad \exp\left[-\frac{\mathbf{A}}{\mathbf{v}} \quad \frac{\mathbf{K} \mathbf{y}}{\mathbf{m}} \mathbf{T}\right]$$
(87)

Differentiating Equation (87) yields an equation for the rate of loss of mass (-dy/dt)

$$\left(-\frac{d v}{d t}\right) = -c_{0}^{\circ} v \frac{\lambda}{v} \frac{K v}{m} \exp \left[-\frac{\lambda}{v} \frac{K v}{m} T\right]$$
(88)

Simplifying and dividing by A gives the rate of loss of mass per unit area.

$$\frac{dy}{dt} = C_{0}^{0} \frac{Kw}{m} \exp \left[-\frac{A}{V} \frac{Kw}{m}T\right]$$
(89)

At T = 0, when the dissolution rate is at its maximum

$$\frac{d v}{dt} = \frac{C_0^{\circ} K w}{m}$$
(90)

This result indicates that the <u>initial</u> rate of loss of mass is independent of the thickness of the slick. This appears to be a contradictory to the results of Section 6.9.2 in which it was found that increased surface area per volume increases mass transfer rates from slicks. It is only for the special case of $\tau = 0$ that the rates are identical. At later times, mass transfer is enhanced for thinner slicks (larger A/V).

For the first dissolution-pseudocomponent, the mass concentration is about 0.3 percent, the "m-value" (partition coefficient) is 3800, and the bulk oil density is approximately .88 gm/cc. Thus, the rate of loss of mass of pseudocomponent 1 (per meter squared area) is:

$$\frac{dy}{dt} = \frac{(0.003) (.88 \text{ gm/cc}) (1 \text{ cm/hr}) 10^4 \text{ cm/m}^2}{3800} = 0.007 \text{ g/hr/m}^2} = 0.17 \text{ g/day/m}^2$$

The (water) flow rate per square meter due to a salinity plume is approximately 1 x 10-4 m³/sec or 8.64 m³/day or approximately 8.64 x 10^6 g/day.

Therefore an upper bound estimate of the dissolved oil concentration of pseudocomponent one in the water due to dissolution from a slick is approximately:

$$\frac{0.17 \text{ g/day/m}^2}{8.6 \times 10^6 \text{ g/day/m}^2} = 0.02 \text{ ppm}$$

For pseudocomponents two and three the dissolved concentrations are 0.003 and 0.0015 ppm, respectively, giving a total dissolved concentration of 0.025 ppm. It must be emphasized that these calculations are based on the pseudocomponents as defined in Table 6-10. These are not the same pseudocomponents that are used in evaporation calculations. Thus, these dissolution pseudocomponents are to be used only in the scenario described. Further, these calculations illustrate how the dissolution (or partition coefficient) is used in the prediction. Because all compounds have a finite partition coefficient, they can be transported, albeit the transport could be quite small.

As mentioned in Section 6.9.2, however, dispersion of small oil droplets can significantly increase the dissolution rates of the pseudocomponents. A 600-fold increase in droplet dispersion rate and concomitant increase in dissolved components was measured in the cold-room test tank immediately after the introduction of 4-6 cm wave turbulence (Section 4.2.2). This was primarily due to small-scale turbulence in the undulating ice field. Thus, in order to calculate an estimated rate of mass loss from a slick that has undergone dispersion, the following particle size distribution will be used.

droplet diameter	<pre>% of total mass of dispersed oil</pre>
10 µm	30%
100 µm	50%
1 mm	20%

The above droplets sizes were chosen so that the results of Section 6.9.2 (Figures 6-4A, B and C) can be utilized to calculate initial mass loss rates from droplets, and thus water phase concentrations. For these calculations, the initial slope of the plots is used to calculate the <u>initial</u> rate of loss of mass from the oil droplets.

Two hypothetical situations will be considered: a 2 cm thick slick with 10% dispersion and a 1 mm thick slick with 10% dispersion. Tables 6-14 and 6-15 present the results. The total mass loss rates in Tables 6-14 and 6-15, when divided by the calculated volumetric flow rates (Section 6.9.3), give total estimated water column dissolved concentrations of 3.1 and 0.18 ppm, respectively.

It should be noted that the above calculations do not consider evaporation and they represent an upper bound calculation. The water that flows past the oil at the initial moment of the spill will eventually mix with less concentrated water and thus be diluted.

The calculations above do <u>not</u> consider, however, the dissolution of benzene. Thus, the results presented here could possibly be low by a factor proportional to the the concentration of benzene in crude oils (or refined products) relative to the other water soluble compounds which were measured.

The results presented in this section illustrate and reinforce those of Section 6.9.2. The rates of dissolution of oil components into the water column are strongly dependent on the surface area to volume ratio. When small droplet dispersion occurs before significant evaporation takes place, dissolution of hydrocarbons becomes an important process. This importance is not due to a large impact on the mass balance of the slick itself, but rather because of the possible transfer of oil components to localized water bodies or flows, such as brine drainage from a lead.

6.10 THE M/V CEPHEUS SPILL - SAIC MODELLING AND ANALYTICAL SUPPORT TO NOAA RESPONSE

6.10.1 Background of the Spill Event

The M/V Cepheus grounded at approximately 0640 hours (1-21-84) on the shallow point on the western side of Knik Arm almost due west of Carin Pt. An estimated 200,000 gal (~4800 bbls) of JP-5 (Jet A) aircraft fuel had been lost during both the grounding incident and movement of the ship to the dock. NOAA

Source		pseudoo	component	
	1	2	3	Total
Parent slick	.17	.028	0.012	0.21
10mm	15.8	2.1	1.9	19.8
100mm	5.3	0.40	0.33	6.0
1mm	0.2	0.014	0.01	0.22
			Total	26.21

Table 6-14.--Initial Mass Loss Rates $(g/day/m^2)$ for 2-cm Slick and 10% Dispersion.

Table 6-15.--Initial Mass Loss Rates $(g/day/m^2)$ for 1-mm Slick and 10% Dispersion.

Source		pseudoc	omponent	
	1	2	<u>3</u>	Total
Parent slick	.17	0.028	0.012	0.21
10mm	0.79	0.11	0.10	1.0
100mm	0.27	0.020	0.017	0.31
1mm	0.01	0.0007	0.0005	0.011
			Total	1.51
trajectory estimates suggested that JP-5 may have been deposited in the mud flats to the north of the grounding site as far as Sixmile Creek (about half way between Carin Pt. and Eagle River). With subsequent tides, the spilled product may have moved to the southwest at least as far as Fire Island. At the time of the grounding, ice coverage was estimated to be ~60-80% and the air temperature was in the -23 to -32°C range.

6.10.2 Observations and Activities Completed During the Site Investigation

SAIC (J. Payne and D. McNabb) visited the spill site, collected samples of both JP-5 and seawater containing the spilled product, and made visual observations of the spill behavior. Visual examination of "Chain of Custody" JP-5 samples collected by the Coast Guard showed the material to be a clear, low-viscosity and low density (0.7 - 0.8 g/ml) fluid, which was quite similar in appearance to intermediate distillate cuts of Prudhoe Bay Crude, distilled into fractions for GC characterization (see, for example, pp 3-28 to 3-40 of Payne et al., 1984a).

At approximately 1600 hours on 1/28/84, pancake ice ranging in size from 1-3 meters (diameter) and ice rafts approaching 10-20 meters (across) were fast against the ship. With the ice cover pressing against the ship, no evidence of any spilled product (JP-5) could be observed from a distance of 5 to 10 meters above the surface. With the outflow of the ebb tide current around 1615 hours, several 10-20 meter wide leads opened adjacent to the hull and JP-5 could be observed bubbling to the surface (Figure 6-5). The fuel appeared as a dull grey film against the opaque olive-green color of the sediment-laden water. No color sheen was observed. With the outgoing tide the oil and broken ice moved parallel to and away from the vessel at an estimated speed of 1-2 The oil was not visible after a distance of 10-20 meters. Very little knots. could be done to contain the spill in the presence of the moving ice. Also, contamination of intertidal mud flats in the Knik Arm and south of Anchorage was of concern, and during the 1-28-84 overflight there was one location south and west of Fire Island where the presence of surface product was suspected. It was extremely difficult, however, to document the extent of this spill from



Figure 6-5.--Sampling JP-5 from the MV <u>Cepheus</u>. With incoming tides the ice was pressed fast to the hull. As the tide ebbed, an open lead approximately 4 m wide was generated and the oil could be observed surfacing as a dull sheen after its release from a below-waterline rupture in the number 2 hold.

helicopter or fixed wing aircraft overflights due, in part, to the fact that Cook Inlet in the Anchorage area was covered at the time by 50-80% ice.

Approximately 3 liters of the JP-5 cargo were obtained from the punctured hold of the <u>Cepheus</u>. The JP-5 cargo analyzed by FID-GC at the Kasitsna Bay Laboratory was characterized by n-alkanes ranging from nC6 through nC16, with the maximum n-alkane concentrations between nC10 and nC11. The chromatographic profile also showed evidence of numerous branched and cyclic aliphatic and alkyl-substituted aromatic components. Table 6-16 illustrates the types of components which could be present in each of the distillate cuts (data from Prudhoe Bay Crude Oil) as re-defined to produce the synthetic JP-5.

A True Boiling Point (TBP) distillation on the bulk samples was performed to allow additional JP-5 characterization. Physical properties data for five distillate cuts of the JP-5 are presented in Table 6-17; FID-GC chromatograms of whole fuel and of the corresponding distillate cuts are shown in Figures 6-6 and 6-7. From comparisons with FID-GC chromatograms of Prudhoe Bay Crude distillate cuts (see Payne et al., 1984a), it is apparent that the JP-5 is generally devoid of many of the higher boiling compounds that comprise the heavier distillate cuts and pot residue of the crude oil.

Partition coefficients or M-values were determined for specific components of the JP-5 by layering 3 ml of the jet fuel on top of 37 ml of seawater, allowing the oil and water phases to equilibrate, and then analyzing the relative concentrations of individual compounds in each phase. The measured M-values for several aromatic compounds present in the JP-5 are shown in Table 6-18. Compounds with lower M-values are more soluble in seawater, and thus have a greater tendency to partition from the oil to the water phase. Chromatograms of extracts of the oil and water phase are shown in Figure 6-8. These chromatograms indicate that a relatively greater proportion of the lower molecular weight compounds partition from the oil into the water phase.

P.B. Crude Cut No.	JP-5 Cut no.	Boiling Point (°F)	n-alkanes in CEPHEUS JP-5 Cargo *,***	Aromatics that <u>may occur</u> within boiling point range**
2	1	186 - 212	c ₆ - c ₇	benzene, toluene
3	2	213 - 257	c ₈ - c ₉	ethyl benzene; o,m,p xylenes cumene, n-propylbenzene
4	3	258 - 302	KOVAT 950 - 1030	p-cumene, mesitylene
5	4	303 - 347	KUVAT 1040 - 1150	butylbenzene, C ₄ benzene
6	5	348 - 392	KOVAT 1150 - 1230	naphthalene, benzothiophene n-hexylbenzene
7	6	393 - 437	KOVAT 1230 - 1380	l-methylnaphthalene, biphenyl,2,6 dimethyl- naphthalene
8	7	438 - 482	KOVAT 1380 - 1490 (?)	naphthalene
9	8	483 - 527	nC ₁₅ - nC ₁₆	trimethylnaphthalene and fluorene

Table 6-16.--Distillate Cut Boiling Point Ranges and the Associated Aliphatic and Aromatic Components of JP-5 from the MV Cepheus Spill.

* boiling point range estimated from data in Payne et al. (1984)

****** aromatics chromatograph within the respective n-alkane Kovat index range

*** Kovat Retenction Index (Kovats, 1958)

Sample Cut		Density	Viscosity	Oil/Air Interfacial	Oil/Water Interfacial
		(g/ml)	(centistokes)	Tension(dynes/cm)	Tension (dynes/cm)
JP-5	Cut 3	.746	.842	43.8	27.3
	Cut 6	.762	.941	37.6	27.7
	Cut 9	.770	1.18	36.7	28.0
	Cut 12	.790	1.65	36.7	30.4
	Cut 15	.826	2.66	3.90	29.1
Pruchoe Bay	Cut 2	.734	.632	41.9	25.7
	Cut 4	.770	.822	35.0	26.6
	Cut 7	.822	1.79	34.0	29.8
	Cut 9	.848	3.21	29.0	31.9
	Bottom	.937	407.	30.3	35.5

Table 6-17.--Physical Properties of JP-5 and Prudhoe Bay Crude Distillate Cuts.



Figure 6-6.--FID-GC Chromatograms of Distillate Cuts of JP-5 Jet Fuel: (A) whole fuel before distillation, (B) cut 3 ($280-293^{\circ}F$), and (C) cut 6 ($313-324^{\circ}F$).



Figure 6-7.--FID-GC Chromatograms of Distillate Cuts of JP-5 Jet Fuel: (A) cut 9 (347-370°F), (B) cut 12 (415-437°F), and (C) cut 15 (482+ °F).

Table 6-18.--M-Values and Concentrations Determined by Partitioning JP-5 Jet Fuel Against Seawater.

	Concen	Concentration (ug/g)			
Compound	0il Phase	Water Phase	M-Value ^a		
Ethylbenzene	378	.113	3350		
m & p-xylene	2660	.549	4850		
o-xylene	4670	.401	11600		
1,3,5-trimethylbenzene	4430	.0701	63200		
C ₃ -benzene	2840	.113	25100		
C ₃ -benzene	17 300	.322	53800		
C ₄ -benzene	4060	. 194	20900		
Tetramethylbenzene	1690	.198	8540		
Naphthalene	3160	.187	16900		
2-methylnaphthalene	6830	.0933	73200		

a - the M-value is defined as the oil phase concentration divided by the water phase concentration at equilibrium.



Figure 6-8.--JP-5 Cargo Obtained from MV <u>Cepheus</u> Grounding. FID-GC profiles of m-value determinations: (A) oil phase, and (B) water phase.

Several weathering simulations were run on JP-4 (already in the Model code) and on a "synthesized" JP-5 fuel (made by combining distillate cuts of fractionated Prudhoe Bay crude oil, as described below, to obtain a real-time estimate of JP-5 weathering behavior). Examination of estimated boiling point ranges for Jet Fuel, as provided in Curl and O'Donnell (1977), suggested that JP-4 may be too volatile for adequate simulation of the behavior of the cargo lost from the <u>M/V Cepheus</u>. Therefore, a "synthetic" jet fuel was generated for model simulation by combining PB crude oil distillation cuts 3 through 9 (boiling point 257° to 527°F) and cuts 2 through 9 (boiling points 212° to 527°F) (data for Prudhoe Bay crude oil are given on page B-43 of Appendix B in Payne et al., 1984a). Gas chromatographic and physical properties analyses demonstrated that the choice of cuts 2 through 9 provided the best match with the cargo lost from the vessel (see Table 6-17).

Oil weathering simulations were run on the SAIC computer system for the simulated JP-5 mixture at temperatures of -20 and 0°F with a 10 knot wind. Data were obtained out to 200 hours and subsequently provided to USCG and NOAA personnel. Model simulations indicated that 60% of the cargo would still present after 10 days at -20°F with a 10 knot wind. This estimate agreed with values predicted by the HAZMAT group for jet fuel evaporation at various temperatures:

HAZMAT DATA

Temperature		Percent Remaining					
	Day 1	Day 2	Day 3	Day 4	Day 5		
10°C (+32°Z)	67	48	36	29	23		
-10°C (+14°F)	81	67	56	48	42		
-20°C (-4°F)	90	81	74	67	61		
-30°C (-22°F)	94	90	85	81	77		

The Oil Weathering Model output at -20°F showed almost no additional mass lost in the 5 to 10 day interval; thus, the overall mass balance of the slick predicted by the two models was similar.

The results of environmental measurements are only valuable insofar as they are accurate and precise. This is particularly true if results of the measurements of chemical levels or properties from this program are to be used for predictive assessments in decision-making processes. Therefore, particular attention toward generating reliable data has been an important consideration during the experimental stages of this program.

The specific QA/QC measures taken during various experiments included the routine analysis of system and method blanks, replicate sampling and analyses, spike and recovery tests for matrices of interest, and instrumental recalibration at prescribed intervals. This section presents the results of the experimental QA/QC data generated during the program as well as pertinent results from our participation in the NOAA Status and Trends interlaboratory intercalibration program in force during the completion of this project.

7.1 WAVE TANK STUDIES

Prior to all of the oil/ice interaction experiments conducted in the cold room at Kasitsna Bay, a number of QA/QC measures were undertaken that primarily addressed seawater extraction efficiency and potential contamination The experimental wave tank used for studies was scrupulously cleaned sources. by 1) physical removal of residual oil remaining from any previous spill experiments, 2) thorough solvent washing, 3) soap and water washing and 4) allowing the system to flush with seawater. A seawater/method blank was analyzed before experimental spill initiation to ensure that all residual sources of contamination had been removed. An example of an FID-GC chromatogram depicting such a wave tank blank is presented in Figure 4-14A. Furthermore, the sample preparation method was investigated for extraction efficiency by conducting two spike and recovery experiments. In the first of these tests, known quantities of aliphatic and aromatic hydrocarbons were spiked directly into clean seawater before sample extraction. Compound recoveries are presented in Table 7-1. Approximately 81% of the aliphatic and aromatic hydrocarbons were recovered in

	Recover	y (%)
S&R Test	Aliphatic	Aromatic
Seawater Extraction	81.0	80.6
Filtration System ^a (Dissolved)	40.7	77.6
Filtration System ^a (Dispersed)	63.4	18.7

Table 7-1.--Kasitsna Bay Spike and Recovery Experiment Results.

^a "Dissolved indicates the seawater filtrate, while "dispersed" refers to the extracted filter pad.

this seawater extraction. In the second test, known amounts of aliphatic and aromatic hydrocarbons were introduced to a seawater sample. The sample was then filtered by the method described in Payne et al. (1984a). The seawater filtrate ("dissolved" oil) as well as the filter pad ("dispersed" oil) were then extracted and analyzed separately. For the sum of the "dissolved" and "dispersed" fractions (Table 7-1), 104% of the aliphatics and 96% of the aromatic hydrocarbons were recovered.

During various wave tank experiments, routine analyses of replicates were conducted for seawater hydrocarbon chemistry, surface oil, dispersed oil, seawater and ice salinities, and surface tension measurements. The results of (primarily) duplicate sample analyses are presented in Tables 7-2 through 7-6. These results give indications of experimental and instrumental precision.

Table 7-2 shows results for individual compound concentrations for duplicate seawater samples from one hour, six hour and 12 hour post-spill samples from a wave tank experiment. Good agreement was observed for each set of duplicates.

	Concentra			ation(ug/l)		
	1 hou	1 hour		6 hours		nours
Compound	Rep 1	Rep 2	Rep 1	Rep 2	Rep 1	Rep 2
Toluene	9.46	15.9	7.87	5.57	5.30	5.70
Ethylbenzene	.961	1.66	. 829	.626	.648	.708
m&p-xylene	2.97	4.99	2.58	1.93	2.00	2.17
o-xylene	1.41	2.38	1.21	.927	.930	.995
Isopropylbenzene	.101	.159	.0702	.0582	.0665	.0712
n-propylbenzene	.138	. 240	.104	.0860	.0985	.105
C ₃ -benzene	.478	.822	.402	. 302	.307	.353
C ₃ -benzene	.148	. 269	.114	.0923	.104	.122
Třimethylbenzene	.209	.358	.177	.137	.145	.157
C ₂ -benzene	. 536	.924	.449	.356	. 381	.406
C ₄ -benzene	. 322	.553	. 293	. 227	.232	.257
Tetramethylbenzene	.104	.152	.0673	.0796	.0511	.0659
Naphthalene	.468	.847	.485	.371	. 327	.363
2-methylnaphthalene	. 302	.514	.275	.205	.196	.218
1,1'-biphenyl	.0511	.0348	ND	ND	ND	ND
2,6-dimethylnaphthalene	.0903	.152	.0531	.0403	.0387	.0431
C ₂ -naphthanlene	.0959	.183	.0478	.0350	.0319	.0374
C_2^2 -naphthalene	.0216	.0360	ND	ND	ND	ND
C ₂ -napphthalene	.0170	.0292	ND	ND	ND	ND
2,3,5-trimethylnaphthalene	.0214	.0341	ND	ND	ND	ND
Dibenzothiophene		.0206	ND	ND	ND	ND
Phenanthrene		.0220	ND	ND	ND	ND
Unresolved Compounds	8.93	8.65	3.19	2.84	4.57	5.43
Total Resolved Compounds	21.3	34.9	16.8	12.9	12.3	13.6

	Hydrocarbon Concentrations (ug/l)				
	Total Resolved		Unresolved Compound		
Sample	Rep 1	Rep 2	Rep 1	Rep 2	
36 hour 1 year residual Stranded 1 year 3 hour 3 day Starting Crude	80.7 6.89 3.07 41.3 33.6 107	91.7 7.90 4.89 31.3 27.4 68.0	191 78.3 38.6 96.6 113 229	155 74.4 59.2 83.2 123 236	

Table 7-3.--Results of Replicate Oil Sample Analyses.

Duplicate oil sample analyses were conducted on starting Prudhoe Bay crude, 3 hour, 36 hour, 3 day post-spill and one year residual oil sample from wave tank experiments. These results for total resolved and unresolved compounds are presented in Table 7-3. As seen, duplicate analyes were in close agreement.

Replicate filter pad (dispersed oil) samples were extracted and analyzed at the six hour and 12 hour sampling points from a wave tank experiment. These results are shown in Table 7-4. For these types of samples precision is relatively poor (as expected) due to the somewhat random nature of the analyte.

Precision estimates for replicate salinity samples are shown in Table 6-6. The values presented are very close and indicate that he measurments are very reproducable.

	Hydrocarbon Concentrations (ug/l)			
	Total Re	solved	Unresolved Compounds	
Sample	Rep 1	Rep 2	Rep 1	Rep 2
6 hours 12 hours	20.8 17.1	14.4 5.88	7.29 23.1	8.35 7.41

Table 7-4.--Results of Replicate Dispersed Oil (Filter Pad) Sample Analyses.

Table 7-5.--Results of Replicate Salinity Measurements.

		Salinity (0/00)			
Sample	Rep 1	Rep 2	Rep 3		
D-2 (field sample)	18.0	17.5	<u> </u>		
Incoming Seawater	30.9	30.1	30.3		
Tank Seawater	30.4	31.0	30.5		
Ice Surface (1cm)	56.0	59.3	-		
6 hr Water	31.6	31.0	-		
12 hr Water	31.1	31.2	-		
24 hr Water	31.0	31.0	-		

Table 7-6.--Results of Replicate Surface Tension Measurements.

Sample	Surface Ten Rep 1	nsion (dynes/cm) Rep 2
Starting Crude	32.0	31.5
4-days	32.6	33.8

Replicate sample measurements for bulk physical properties or oil were not attemped for the most part because of 1) the large volumes of oil required for each parameter and 2) the inaccessability of oil in the seawater-ice system. However, duplicate samples were obtained for surface tension measurements at the 4 day sampling point in one experiment along with the starting crude. Table 7-6 shows that precision was excellent.

Because sample collection, work-up and analyses were conducted consecutively (generally on the same day), QA/QC measures related to sample preservation, transportation and storage were circumvented. However, consistent instrument response and reproducibilities were monitored throughout experiments by (at least) daily recalibration of the FID-GC and salinity meter. FID-GC analyses of routine methylene chloride solvent blanks also served as instrument blanks to ensure that system contamination from previous chromatogram carryover was prevented.

The surface tension meter was initially calibrated according to instructions from the manufacturer. The instrument was then tested for accuracy by comparing measured surface tension values against those reported for two solvents. The following lists these measured values and the corresponding literature values.

		Surface Tension(dynes/cm)		
		Measured	Reported	
50/50	Methanol/Water	33.3	34.5	
	Water	75.3	73.1	

Good agreement between measured and reported values indicates that surface tension determinations were accurate.

7.2 GAS CHROMATOGRAM DATA REDUCTION

Hydrocarbon concentrations for individual resolved peaks in each gas chromatogram were calculated on a DEC-10 System Computer using the formula given in equation 1. This particular example of the program is for analysis of a seawater sample. Operator-controlled modification of the DEC-10 program allows similar data reduction for sediment, tissue, or individual oil (mousse) samples.

ug compound X/L seawater = $(A_x) \times (R.F.) \times$

P.I.V. + 1.	Pre-C.S. Vol.	100	100	1 (1)
	-x	x	xx	(1)
Inj.S.Vol.	Post-C.S.Vol.	%NSL on LC	&DW/FW	liters

where:

A _x	-	the area of peak X as integrated by the gas chromatograph (in arbitrary GC area units)
R.F.	-	the response factor (in units of ug/GC area unit)
P.I.V. + 1	=	the post-injection volume (in ul) from which a l-ul aliquot had been removed for analysis by GC (measured by syringe immediately following sample injection)
Inj.S.Vol.	=	the volume of sample injected into the GC (always 1.0 ul as measured by an HP Automatic Liquid Sampler)
Pre-C.S. Vol. & Post-C.S. Vol.	=	the total solvent volumes before and after an aliquot is removed for gravimetric analysis on a Cahn electrobalance
%NSL on LC	-	the precent of sample non-saponifiable lipid used for SiO_2 column chromatography
\$D₩/F₩	-	the percent dry weight of wet weight in the sediment tissue, or oil sample being analyzed
liters	-	liters of seawater initially extracted (or grams wet weight of oil or sediment).

During analyses of extracts, the Hewlett Packard 5840A gas chromatograph was recalibrated after every 8 to 10 injections, and individual response

factors were calculated for all detected even and odd n-alkanes between nC_8 and nC_{32} . Concentrations of other components (e.g., branched and cyclic aliphatics) that eluted between the major n-alkanes were calculated by linear interpolation of the adjacent n-alkane response factors and the unknown compound peak's KOVAT index. In addition, an aromatic standard was run daily for retention time determinations. By incorporating the post-injection volume (PIV) into the calculation, the amount of hydrocarbons measured in the injected sample was converted to the total hydrocarbon concentration in the sample.

Unresolved complex mixtures (UCM's) were measured in triplicate by planimetry. The planimeter area was converted to the gas chromatograph's standard area units at a given attenuation and then quantified using the average response factors for all n-alkanes occurring within the GC elution range of the UCM (see equation 2).

$$\frac{\text{ug UCM}}{\text{liter}} = \text{Area}_{p} \times (\text{Conv. F}) \times \frac{\text{S. Att.}}{\text{Ref. Att.}} \times (\text{R.F.}_{a-b}) \times [\dots]$$
(2)

where:

Area	 UCM area in arbitrary planimeter units,
Conv. F.	 a factor for converting arbitrary planimeter units to GC area units at a specific GC attentuation,
S. Att. and Ref. Att.	 the GC attenuation at which the sample chromatogram was run and the reference attenuation to determine the conversion factor (Conv. F.), respectively,
R.F. _{a-b}	= the mean response factor for all sequential n-alkanes (with carbon numbers a to b) whose retention times fall within the retention time window of the UCM, and
[]	- the same parameters enclosed in brackets in equation 1.

Confirmation of KOVAT index assignment to n-alkanes was done by computer correlation with n-alkane standard retention times and direct datareduction-operator input.

Assignment of a KOVAT index to each branched or cyclic compound eluting between the n-alkanes was done by interpolation using the unknown compound and adjacent n-alkane retention times. Assignment of KOVAT indices to peaks in the aromatic fraction was made by direct correlation of unknown peaks with retention times from the n-alkane and aromatic standard runs completed prior to sample injection.

7.3 FIELD STUDIES

During the field study conducted in the Chukchi Sea, water column samples were collected with Nansen or Niskin sample bottles for analysis of hydrocarbon cocktail components. All sample containers (Thermos bottles) were scrupulously cleaned with soap and water and then rinsed with copious amounts of distilled water prior to use. Collected water samples were placed in the cleaned bottles and capped with no head space (to prevent compound volatili-Logistical constraints precluded the collection of field replicate zation). All samples were maintained at 4° C during storage. Sample analyses samples. were conducted according to the methods described in Section 5.3.3. All Tenax R traps were baked out and analyzed by Specific Ion Monitoring (SIM) GC/MS prior Therefore, each sample was accompanied by a corresponding to sample purging. GC/MS system blank that ensured no contamination for instrumental analysis. The sample preparation (i.e., purging step) was evaluated as a potential source of contamination by purging one liter of clean seawater prior to an actual sample purging. This sample blank was clean with respect to benzene and toluene. A detection limit of 0.01 ng/liter was established based on the sample volume, response from a 500 pg standard, and a 5 to 1 signal to noise ratio. Compound quantitation was accomplished according to equation 3.

$$Concentration (ng/1) = (AC \times RF)/V_{c}$$
(3)

where:

AC = the SIM area count in the sample

RF = the response factor for benzene and toluene standards in ng (of standard)/specific ion area counts, and

V = sample volume in liters

The specific ions monitored were 78 amu for benzene and 91 amu for toluene.

In addition, a spiked seawater blank was analyzed in order to determine the recovery efficiency of the purging method. One liter of clean seawater was spiked with 100 ng of the actual cocktail, purged, and analyzed by SIM GC/MS according to methods described in Section 5.3.3. Of the 100 ng of cocktail spiked into the blank, 40 ng were recovered (40% method efficiency). This recovery reflects the effects of each compound's solubility properties and Henry's Law coefficients in a seawater matrix.

7.4 INTERLABORATORY INTERCALIBRATION PROGRAMS

While precision is a relatively easy parameter to measure by replicate determinations, accuracy is somewhat more intractable. Spiked sample recovery is valuable as far as determining the efficiency of an extraction procedure for compounds <u>added by the investigator</u>. It does little, however, to determine extraction efficiency of the subject compounds as they are present in an original sample matrix. At this time, there are no Standard Reference Materials (SRM's) to assist in such determinations. Therefore, NOAA has initiated a number of interlaboratory/intercalibration programs wherein the results obtained on real environmental samples (designated as Interim Reference Materials) by a variety of participating laboratories can be compared. Tables 7-7 and 7-8 contain the results from a recent participation effort by SAIC in the NOAA-sponsored Status and Trends Intercalibration Program and compares our data to those of other participating laboratories.

Data in Tables 7-7 and 7-8 reflect variability due to the extraction and analysis of mussel tissue and sediment samples, which are not matrices encountered during oil/multi-year ice experiments. However, they do indicate SAIC's ability to generate reliable aromatic hydrocarbon data and confirm our

sample preparation and instrumental analysis dependability. As indicated in Tables 7-7 and 7-8, SAIC's aromatic hydrocarbon data are seen to fall within reasonable agreement of values reported by the other six participating laboratories.

							• • • • • • • • • • • • • • •	
Compound	NAF Set A	NEC Set B	SEC Set C	BOS Set D	SAI Set E	TAM Set F (MS)	TAM Set G (FID)	
napthalene	2000	1900	2000	1800	1500	2000	1600	
2-methylnaphthalene	7200	7700	8300	6300	6200	7200	12000	
1-methylnaphthalene	6200	5800	7100	5300	5200	7000	9000	
biphenyl	1300	1500	1600	1300	1400	1500	1500	
2.6-dimethylnaphthalene	2500	2700	3200	2700	3200	3300	2800	
acenaphthene	**130	1300	790	230	340	330	97	
fluorene	900	940	1200	1200	1300	1000	1300	
phenanthrene	1200	1200	1500	1300	1500	1300	1200	
anthracene	160	150	200	270	170	180	53	
1-methylphenanthrene	170	350	1000	460	330	290	230	
fluoranthene	860	820	860	930	980	820	560	
pyrene	430	430	**560	870	530	490	650	
benz(a)anthracene	190	1100	250	210	140	260	180	
chrysene	420	340	400	*620	280	350	700	
benzo(e)pyrene	180	180	**160	190	*90	170	910	
benzo(a)pyrene	74	110	280	<25	120	100	82	
perylene	130	56	**200	<30	-	100	100	
dibena[a,h]anthracene	31	25	90	<42	-	84	39	
* n=1								
**n=2	NAF = N	ational	Analvt	ical Fa	cilitv			
	NEC = Northeast Fisheries Center							
	SEC = Southeast Fisheries Center							
	BOS - Battelle Ocean Sciences							
	SAI = Science Applications International							
	TAM = T	exas A&	M Unive	rsitv				

Table 7-7.--Mean Concentrations (n = 3) in ng/g Dry Weight of Aromatic Hydrocarbons Found in Reference Tissue: Mussel II. Table 7-8.--Mean Concentrations (n = 3) in ng/g Dry Weight of Aromatic Hydrocarbons Found in Reference Tissue: Duwamish III.

Compound	NAF Set A	NEC Set B	SEC Set C	BOS Set D	SAI Set E	TAM Set F (MS)	TAM Set G (FID)
napthalene	320	250	330	400	310	370	330
2-methylnaphthalene	160	110	180	210	140	170	150
1-methylnaphthalene	120	80	150	130	88	120	110
biphenyl	39	31	57	48	33	42	48
2,6-dimethylnaphthalene	70	58	76	96	63	72	64
acenaphthene	300	290	420	290	330	320	350
fluorene	310	280	430	460	340	320	360
phenanthrene	2300	2200	3200	3200	2500	2400	2700
anthracene	510	650	730	850	600	590	650
l-methylphenanthrene	220	410	320	330	300	300	310
fluoranthene	3900	3700	5600	5200	4200	4600	4900
pyrene	4100	3900	5800	6600	4800	5500	6000
penz(a)anthracene	1500	1400	2100	2000	1500	2100	2200
chrysene	2600	2100	3600	3500	2500	3000	3000
benzo(e)pyrene	1600	1400	2000	2300	1900	1400	1700
benzo(a)pyrene	1800	1700	2700	2400	1800	1900	2200
perylene	510	460	710	850	580	490	680
dibena(a,h)anthracene	310	310	430	460	430	220	240

* Extraction by NS&T protocol (MacLeod et al., 1985): quantitation by GC/MS
 ** Extraction based on previous NAF procedure (Brown et al., 1980): quantitation by GC/MS

NAF = National Analytical Facility
NEC = Northeast Fisheries Center
SEC = Southeast Fisheries Center
BOS - Battelle Ocean Sciences
SAI = Science Applications International
TAM = Texas A&M University

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APPENDIX A: CODE DESCRIPTION FOR COMPONENT-SPECIFIC DISSOLUTION FROM SLICKS

The following are code listings and sample output from the FORTRAN code DIFFU.FOR. This code was developed in order to both describe and predict component-specific dissolution of oil from slicks in the absence of evaporation and to aid in the experimental measurement of diffusivities of individual compounds in crude oil. Briefly, the user is prompted for appropriate data, oilsuch as water mass-transfer coefficients, oil-water partition coefficients, initial concentration of oil components, and slick thickness and area. The output from the program is time series concentrations of the compound and interest in the water column for both well-mixed and "slab" type slicks.

Details of the derivation of compound-specific dissolution are presented in Section 6.8.1 of this report.

C	******* DIFFU.FOR *********
C	THIS CODE CALCULATES THE WATER COLUMN CONCENTRATION
	AND TOTAL MATFILLA BALANCES FOR
č	COMPONENT SPECIFIC DISSOLUTION FROM AN OLI SLICK IN
č	A WELL STIBBED TANK. EVAPORATION IS NOT ALLOWED.
č	
č	FOR DETAILS, SEE DERIVATION BY R. REDDING, DEC 1983
č	
č	
-	IMPLICIT REAL*8 (A-H.O-Z)
	REAL*8 L.KW.M.KO.KPRIME,LOTERM,LWTERM,INTE,LH
	DIMENSION ALPHA (300), PAJ (300), CWO (50), COO (50), SUM (300), CMPD (5)
	1,HOURS(50),CW(50),COA(50),TMW(50),TMO(50),TM(50),COOA(50)
	2. CEEW (50)
	OPEN(UNII=32, DIALOG= DSKD: DIFFU. 001)
	UPEALUNII-34, DIALOG- DSKD; DIFFU, FLI)
10	FORMAT(2X 'ENTER & COMPOUND ID')
10	ACCEPT 20. (CMPD(1) 1=1.4)
20	FORMAT (4A5)
	TYPE 30
30	FORMAT(2X, 'ENTER THE NUMBER OF INTERVAL HALVES')
	ACCEPT 40, NHALF
40	FORMAT(13)
50	FORMAT(2X, 'ENTER TOTAL NUMBER OF HOURS FOR EXPERIMENT')
	ALLET 10, INVERS
60	FORMAT (2%, 'ENTER THE SLICK THICKNESS IN CM')
00	ACCEPT 70.1
70	FORMAT(F10.0)
••	TYPE 80
80	FORMAT(2X,'ENTER THE WATER DEPTH IN CM')
	ACCEPT 70, DELTA
90	FURMATIZA, ENTER THE OVERALL WATER-THASE MASS TRANSFER
	TYPE 100
100	FORMAT(2X, 'ENTER THE M VALUE (OIL/WATER)-DIMENSIONLESS')
	ACCEPT 70,M
	TYPE 110
110	FORMAT(2X, 'ENTER THE DIFFUSIVITY IN CM*CM/SEC')
	ACCEPT 70, DZ
	TYPE 120
120	FORMATION, ENTER THE NUMBER OF TERMS IN THE SERIES)
120	ACCET 130, NON FORMAT(14)
100	
140	FORMAT(2X, 'ENTER THE INITIAL OIL CONCENTRATION IN MG/L')
	ACCEPT 70,01LC0
	TYPE 150
150	FORMAT(2X, 'ENTER THE SLICK AREA IN CM*CM')
	ACCEPT 70,A
	STALLA-KUZZZ
	LWTERN=L/((M*L)+DELTA)
	C1 = ((L*N) + DELTA)/(L*DELTA)
C	
C	DO INTERVAL HALVING TO FIND THE ROOTS OF THE FUNCTION:
C	
U	GUI (A)=(A#A=KFRIME#BIGH)/(A#BIGH)

```
CCC
        THEN FIND THE POLYNOMIAL (PAJ)
      PI=3.14159265358979323
DO 180 I=1,NUM
      RH=I*PI
      LH=(I-1)*PI
      DO 170 K=1, NHALF
      XM = (LH + RH) / 2.00
      COT=DCOS(XM)/DSIN(XM)
      FX=XM×COT-((XM×XM-KPRIME*BIGH)/BIGH)
IF(FX .LT. 0.D0) CO TO 160
      LH=XM
      GO TO 170
      RH=XM
160
      CONTINUE
170
      ALPHA(I)=XM
      PAJ(I)=ALPHA(I)**4.
      PAJ(I)=PAJ(I)+(ALPHA(I)*ALPHA(I)*(BIGH+(BIGH*BIGH)-(2.*KPRIME
     1*BIGH)))
      PAJ(I)=PAJ(I)+(KPRIME*BICH*BICH*(KPRIME+1.))
C
C
         NOW FIND THE SUM OF NUM TERMS
С
180
      CONTINUE
      SEC=3600.*THOURS
       INTE=SEC/40
      DO 190 J=1,40
      SUM(J)=0
       CONTINUE
190
      HOURS(1)=0.
      CW(1)=0
       DO 220 J=2,40
       B=J
      TIME=B*INTE
      HOURS(J)=TIME/3600.
      DO 210 I=1,NUM
       ARG=ALPHA(I)*ALPHA(I)*DZ*TIME/(L*L)
       IF(ARG.LT.50.) CO TO 200
      EXPON=0.
      GO TO 210
      EXPON=DEXP(-(ARG))
200
      SUM(J) = SUM(J) + EXPON/PAJ(I)
      CONTINUE
210
       CWO(J) = LWTERM + (2.*L*BIGH \times BIGH / DELTA) \times SUM(J)
C
         NOW CALCULATE THE WATER COLUMN CONCENTRATION, INTEGRATED TOTAL MASS OF COMPONENT IN THE OIL AND MATERIAL
С
C
         BALANCE FOR THE SYSTEM
С
С
       COOA(J)=LOTERM*L+(2.*BIGH*BIGH*L*SUM(J))
       CW(J) = CWO(J) * OILCO
       COA(J) = COOA(J) * OI LCO
       TMW(J)=CW(J)*DELTA*A/1000.
       TMO(J) = COA(J) * A \neq 1000.
       TM(J) = TMW(J) + TMO(J)
220
       CONTINUE
С
Ĉ
         WRITE OUTPUT TO FILE: DIFFU.OUT
       100=32
       IPU=34
      230
       WRITE (10U.240) THOURS
       FORMAT (//, 2X, 'TOTAL HOURS: ', 1PE10.3)
240
```

WRITE (100,250)L FORMAT(2X, 'SLICK_THICKNESS: ',1PE10.3.' CM') 256 WRITE (IOU, 260) DELTA FORMAT(2X, 'WATER DEPTH: ', 1PE10.3,' CM') 260 WRITE (100,270)A FORMAT(2X, 'SLICK AREA: '.1PE10.3.' CM*CM') WRITE (100,280)M FORMAT(2X, 'M-VALUE: ',1PE10.3) 270 280 WRITE (IOU,290)KW FORMAT(2X,'KW: '.1PE10.3.' CM/SEC') 290 WRITE (10U,300)KO FORMAT(2X,'KO: '.1PE10.3.' CM/SEC') WRITE (10U,310)DZ FORMAT(2X,'DO: '.1PE10.3.' CM*CM/SEC') 300 310 WRITE (IOU, 320) NHALF FORMAT(2X, 'NUMBER OF INTERVAL HALVES: ', I3) 320 WRITE (IOU, 330)OILCO FORMAT(2X,'INITIAL OIL CONCENTRATION: ', 1PE10.3,' MG/L') WRITE(IOU, 340) 330 FORMAT(///,20X,'***********) WRITE(IOU,350) 340 350 FORMAT(20X, '*OIL SLAB*') WRITE(100,360) FORMAT(26X, '**********') WRITE (10U,370)NUM 360 FORMAT (2.2X, 'RESULTS WITH ', 14, ' TERMS IN THE 370 1 SERIES WRITE (100,380) FORMAT (//, 12X, 'ALPHA', 8X, 'POLYNOMIAL') 380 DO 400 I=1,NUM WRITE (100,390) I.ALPHA(1), PAJ(1) FORMAT(2X, 14, 2(1X, 1PE14.7)) 390 CONTINUE 400 TMASS=01LCO*A*L/1000. WRITE (IOU, 410) TMASS FORMAT(2.2X, 'TOTAL INITIAL MASS: ', 1PE10.3, ' MG') 410 WRITE (IOU, 420) FORMAT(//,7X, 'TIME'.9X,'CW',7X, 'MASS/WATER', 15X, 'MASS/OIL',3X, 'TOTAL MASS') 420 WRITE(IOU,430) FORMAT(6X,'HOURS'.8X,'MG/L',9X,'MG',10X,'MG',10X.'MG') 430 DO 450 I=1,40 WRITE (100,440) HOURS(1).CW(1),TMW(1),TMO(1),TM(1) FORMAT(2X, 5(2X, 1PE10.3)) 440 CONTINUE 430 FINCW=01LCO*LWTERM FINMW=FINCW*DELTA*A/1000. FINMO=OILCO*A*L*LOTERM '1000. WRITE (IOU, 460) FINCW, FINMW, FINMO, TMASS FORMAT(4X, 'EQUILIBRIUM', 1X, 1PE10.3, 3(2X, 1PE10.3)) 460 С Ĉ NOW DO WELL MIXED CASE WRITE(100,470) 470 480 FORMAT(7X, '*OIL WELL-MIXED*') WRITE(10U,490) 490 DO 500 I=1.40 CEEW(I) = OILCO*LWTERM*(1.-DEXP(-C1*KO*HOURS(I)*3600.))CONTINUE 500 **WRITE(IOU, 510)** 510 FORMAT(/.10X, 'TIME (HOURS)', 8X, 'CW (MG/L)') DO 516 I=1,40 WRITE(IOU, 514) HOURS(I), CEEW(I)

514	FORMAT(2X,2(2X,1PE10.3))
516	CONTINUE
С	
C	WRITE TO PLOT FILE: DIFFU.PLT
С	
	WRITE(IPU, 520)(CMPD(I), I=1,4)
520	FORMAT(1X,4A5)
	WRITE(IPU, 530)THOURS, M.KW, DZ, OILCO, FINCW, L
530	FORMAT(7(1X, 1PE10.3))
	DO 550 I=1.40
	WRITE(IPU, 540) HOURS(I)
540	FORMAT(1PE10.3)
550	CONTINUE
	DO 570 I=1,40
	WRITE(IPU, 360) CW(I)
560	FORMAT(1PE10.3)
570	CONTINUE
	DO 576 I=1,40
	WRITE(IPU, 574) CEEW(I)
574	FORMAT(1PE10.3)
576	CONTINUE
	END

TOTAL HOURS: 2.500E+02 SLICK THICKNESS: 1.000E+00 CM WATER DEPTH: 3.900E+01 CM SLICK AREA: 5.000E+02 CM*CM M-VALUE: 4.000E+03 KW: 1.000E-04 CM/SEC KO: 2.500E-08 CM/SEC DO: 1.000E-05 CM*CM/SEC NUMBER OF INTERVAL HALVES: 25 INITIAL OIL CONCENTRATION: 3.000E+02 MC/L

> ***:******* *01L SLAB* ***:*****

RESULTS WITH 25 TERMS IN THE SERIES

	ALPHA	POLYNOMIAL
1	5.0861659E-01	1.2945706E-03
2	3.1424094E+00	9.2537591E+01
3	6.2835857E+00	1.5388602E+03
4	9.4250440E+00	7.8457616E+03
5	1.2566570E+01	2.4857788E+04
6	1.5708123E+01	6.0757300E+04
7	1.8849689E+01	1.2606448E+05
Å.	2.1991262E+01	2.3363734E+05
9	2.5132841E+01	3.9867168E+05
10	2.8274422E+01	6.3870115E+05
11	3.1416006E+01	9.7359720E+05
12	3.4557592E+01	1.4255691E+06
13	3.7699178E+01	2.0191639E+06
14	4.0840766E+01	2.7812666E+06
15	4.3982354E+01	3.7410999E+06
16	4.7123943E+01	4.9302243E+06
17	5.0265532E+01	6.3825381E+06
18	5.3407122E+01	8.1342778E+06
19	5.6548712E+01	1.0224017E+07
20	5.9690302E+01	1.2692668E+07
21	6.2831893E+01	1.5583479E+07
$\overline{22}$	6.5973484E+01	1.8942040E+07
23	6.9115075E+01	2.2816274E+07
24	7.2256666E+01	2.7256445E+07
25	7.5398257E+01	3.2315155E+07

TOTAL INITIAL MASS: 1.500E+02 MG

TIME HOURS	CW MG-1L	MASS/WATER MG	MASS/OIL MG	TOTAL MASS
0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
1.250E+01	8.163E-03	1.392E-01	1.498E+02	1.500E+02
1.875E+01	1.190E-02	2.321E-01	1.498E+02	1.500E+02
2.500E+01	1.543E-02	3.009E-01	1.497E+02	1.500E+02
3.123E+01	1.876E-02	3.657E-01	1.496E+02	1.500E+02
3.750E+01	2.190E-02	4.270E-01	1.496E+02	1.500E+02
4.375E+01	2.486E-02	4.847E-01	1.495E+02	1.500E+02
5.000E+01	2.765E-02	5.392E-01	1.495E+02	1.500E+02
5.625E+01	3.029E-02	5.906E-01	1.494E+02	1.500E+02
6.250E+01	3.277E-02	6.391E-01	1.494C+02	1.500E+02
6.873E+01	3.512E-02	6.849E-01	1.493C+02	1.500E+02

7.500E+01	3.734E-02	7.280E-01	1.493E+02	1.500E+02
8.125E+01	3.942E-02	7.688E-01	1.492E+02	1.500E+02
8.750E+01	4.139E-02	8.072E-01	1.492E+02	1.500E+02
9.373E+01	4.325E-02	8.435E-01	1.492E+02	1.500E+02
1.000E+02	4.501E-02	8.777E-01	1.491E+02	1.500E+02
1.063E+02	4.666E-02	9 099E-01	1.491E+02	1.500E+02
1.125E+02	4.822E-02	9.404E-01	1.491E+02	1.500E+02
1.188E+02	4.970E-02	9.691E-01	1.490E+02	1.500E+02
1.250E+02	5.109E-02	9.962E-01	1.490E+02	1.500E+02
1.313E+02	5.240E-02	1.022E+00	1.490E+02	1.500E+02
1.375E+02	5.364E-02	1.046E+00	1.490E+02	1.500E+02
1.438E+02	5.480E-02	1.069E+00	1.489E+02	1.500E+02
1.500E+02	5.590E-02	1.090E+00	1.489E+02	1.500E+02
1.563E+02	5.694E-02	1.110E+00	1.489E+02	1.500E+02
1.625E+02	5.792E-02	1.129E+00	1.489E+02	1.500E+02
1.688E+02	5.885E-02	1.148E+00	1.489E+02	1.500E+02
1.750E+02	5.972E-02	1.165E+00	1.488E+02	1.500E+02
1.813E+02	6.054E-02	1.181E+00	1.488E+02	1.500E+02
1.875E+02	6.132E-02	1.196E+00	1.488E+02	1.500E+02
1.938E+02	6.205E-02	1.210E+00	1.488E+02	1.500E+02
2.000E+02	6.274E-02	1.223E+00	1.488E+02	1.500E+02
2.063E+02	6.340E-02	1.236E+00	1.488E+02	1.500E+02
2.125E+02	6.401E-02	1.248E+00	1.488E+02	1.500E+02
2.188E+02	6.459E-02	1.260E+00	1.487E+02	1.500E+02
2.250E+02	6.514E-02	1.270E+00	1.487E+02	1.500E+02
2.313E+02	6.566E-02	1.280E+00	1.487E+02	1.500E+02
2.375E+02	6.614E-02	1.290E+00	1.487E+02	1.500E+02
2.438E+02	6.660E-02	1.299E+00	1.487E+02	1.500E+02
2.500E+02	6.704E-02	1.307E+00	1.487E+02	1.500E+02
EQUILIBRIUM	7.428E-02	1.448E+00	1.486E+02	1.500E+02

TIME	(HOURS)
0.000E+00	0.000E+00
1.230E+01	8.169E-03
1.875E+01	1.191E-02
2.500E+01	1.544E-02
3.125E+01	1.877E-02
3.750E+01	2.191E-02
4.375E+01	2.487E-02
5.000E+01	2.767E-02
5.625E+01	3.031E-02
6.250E+01	3.279E-02
6.873E+01	3.514E-02
7.500E+01	3.736E-02
8.125E+01	3.945E-02
8.750E+01	4.142E-02
9.375E+01	4.328E-02
1.000E+02	4.503E-02
1.063E+02	4.669E-02
1.125E+02	4.825E-02
1.188E+02	4.972E-02
1.250E+02	5.111E-02
1.313E+02	5.242E-02
1.375E+02	5.366E-02
1.438E+02	5.482E-02
1.500E+02	5.593E-02
1.563E+02	5.696E-02
1.625E+02	5.794E-02
1.688E+02	5.887E-02
1.750E+02	5.974E-02

C₩	(MG/L)		
		1.813E+02	6.056E-02
		1.875E+02	6.134E-02
		1.938E+02	6.207E-02
		2.000E+02	6.276E+02
		2.063E+02	6.341E-02
		2.125E+02	6.403E-02
		2.188E+02	6.461E-02
		2.250E+02	6.515E-02
		2.313E+02	6.567E-02
		2.375E+02	6.616E-02
		2.438E+02	6.662E-02
		2.500E+02	6.705E-02

APPENDIX B: CODE DESCRIPTION FOR COMPONENT-SPECIFIC DISSOLUTION FROM DROPLETS

The following is a code listing from the FORTRAN code DRPLET.FOR. This code predicts component-specific dissolution of oil in the absence of evaporation from oil droplets.

Details of the derivation of component-specific dissolution are presented in Section 6.9.2.7 of this report.

	IMPLICIT REAL+8 (A-H,O-Y)
	REAL+8 KW,M,LH
	DIMENSION ALPHA(100), POLY(100), ZTIME(101), CURVES(4,101)
	1, CUR(101), ZCURVS(4, 101), ZCUR(101), ZWORDS(20)
	2, ZX(4), ZÝ(4), ZLINE1(30), ZLINE2(30), ZLINE3(30), ZRAY(30)
	OPEN(UNIT=32.DIALOG='CHECK.OUT')
	TYPE 5
5	FORMAT(1X,'ENTER A IN CM')
•	ACCEPT 20.A
	TYPE 10
10	FORMAT(1X 'ENTER DIFFUSIVITY CM++2/SEC')
	ACCEPT 20 DO
20	FORMAT(F10 0)
20	TYPE 21
21	FORMAT(1) 'ENTER KW (M/SEC')
21	ACCEDT 28 KW
	IF(FX.LI.0.D0) GO TO 30
-	
30	
40	CONTINUE
	ALPHA(I)=XM/A
	POLY(I)=A+A+(ALPHA(I)++2.D0)+((A+H-1.D0)++2.D0)
	POLY(I)=POLY(I)/(ALPHA(I)++4.D0)
	POLY(I)=POLY(I)/(A+A+(ALPHA(I)++2.D0)+A+H+(A+H-1.D0))
50	CONTINUE
	DO 200 J=1,101
	T=(J−1)+86400.D0
	SUM1=0.D0
	DO 100 I=1,100
	SUM1=SUM1+DSIN(A+ALPHA(I))+DSIN(A+ALPHA(I))+POLY(I)+
	1DEXP(-T+DO+(ALPHA(I)++2.D0))
100	CONTINUE
	CURVES(L,J)=SUM1+6.D0+H+H/(A+A)
200	CONTINUE

1000	CONTINUE
	DO 2000 I=1,101
	ZTIME(I)=(I-1)+10./100.
2000	CONTINUE
	DO 3000 I=1,4
	DO 2500 J=1,101
_	ZCURVS(I,J)=CURVES(I,J)
2500	CONTINUE
3000	CONTINUE
	CALL COMPRS
	CALL SUMPLA
	CALL AREAZO(0.,0.) CALL YNAME('AVERAGE DIMENSIONLESS CONCENTRATION' 35)
	CALL XNAME ('TIME (DAYS)' 11)
	CALL GRACE(0.0)
	CALL FRAME
	CALL GRAF(0.,1.,10.,0.,0.1.1.)
	CALL BLREC(4.75,.8,3.05,1.0.0.01)
	CALL HEADIN('PREDICTED DIFFUSION AND DISSOLUTION', 35, 1.8, 3)
	CALL HEADIN('FROM A DROPLET INTO AN', 22, 1.8, 3)
	CALL HEADIN('INFINITE MEDIUM', 15, 1.8, 3)
	DO 5000 I=1,4
	DO 4000 $J=1,101$
	ZCUR(J)=ZCURVS(I,J)
4000	CONTINUE
5000	CALL CURVE(ZIIME, ZCUR, 101,0)
2000	
	2X(1)#2]ME(0) 7X(0)_7T145(00)
	ZX(Z)=Z IMC(20) 7Y(3)_7TIWC(35)
	7Y(4) = 7TIME(75)
	7Y(1) = 7CURVS(1 4)
	ZY(2) = ZCURVS(2, 17)
	ZY(3) = ZCURVS(3, 30)
	ZY(4) = ZCURVS(4,55)
	ZMM=1000.
	DO 6000 I=1,4
	ZMM=ZMM+10.
	ENCODE(11,4500,ZWORDS)ZMM
4500	FORMAT('M= ', 1PE8.1)
	$2 \text{TVAL} = 2 \text{T} \left(1 \right)$
6000	CONTINUE
0000	MAYLIN-LINEST(7PAY 100 23)
	FNCODE(20, 7000, 71 INF1)7A
7000	FORMAT('RADIUS=', 1969, 2, ' CM\$')
	ENCODE (20.8000.ZLINE2)ZKW
8000	FORMAT('KW=', 1PE9.2,' CM/SEC\$')
	ENCODE (23,9000, ZLINE3) ZDO
9000	FORMAT('DO=',1PE9.2,'CM+CM/SEC\$')
	CALL LINES(ZLINE1, ZRAY, 1)
	CALL LINES(ZLINE2, ZRAY, 2)
	CALL LINES(ZLINE3, ZRAY, 3)
	UALL BLKEY(ID)
	CALL BLUFF(IU) CALL ISTOPY(7DAY 3 4 0 1)
	CALL LOIURT(ZRAT, J, 4. 3, 1.) CALL ENDDI(A)
	CALL DONEPI
	END