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The Evaporation of Oil Spills

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Abstract

An experimental method has been devised to measure the evaporation of oil products using weight loss from a pan. This method has been used to explore oil evaporation. Approximately 250 runs averaging 1 ½ days each have been conducted. The scope of the experimentation to date has included varying the data collection methods and 12 specific physical studies.

The major finding to date is that oil is not strictly boundary-layer regulated. This has profound implications for most oils including:

1. area of the spill is not important to evaporation prediction in most situations
2. wind speed is not important
3. temperature is the most important environmental consideration
4. evaporation can be predicted for mass loss by an equation of the form:

$$Ev = MT \ln t$$

where: Ev is the mass evaporating per unit time, t
M is the mass
T is the temperature
t is the time

5. evaporation can be predicted even more simply by an equation of the form:

$$Ev = T \ln t$$

where: Ev is the percentage evaporating per unit time, t
T is the temperature
t is the time

6. the constant parameters for the above can be calculated accurately from physical properties.

Introduction

Evaporation is a very important process for most oil spills. In a few days, light crude oils can be reduced by up to 75% of their initial volume and medium crudes up to 40% of their volume. Heavy or residual oils will only lose about 5% of their volume in the first few days following a spill. Most oil spill behaviour models include evaporation as a component of the process and output of the model. Despite the importance of the field, relatively little work has been conducted on the basic physics and chemistry of oil spill evaporation (Fingas, 1995). The particular difficulty with oil evaporation is that oil is a mixture of hundreds of compounds and this mixture varies from source to source and even over time. Much of the work described in the literature focuses on 'calibrating' equations originally developed for water evaporation. Similarly very little empirical data on oil evaporation is published.

Scientific and quantitative work on water evaporation is decades old (Brutsaert, 1982; Jones 1992). The basis for the oil work in the literature is also water evaporation. There are several fundamental differences between the evaporation of a pure liquid such as water and for a multi-component system such as crude oil. First, the evaporation rate for a single liquid such as water is a constant with respect to time. Evaporative loss, by total weight or volume, is logarithmic with time for crude oils and other multi-component fuel mixtures. This is due to the depletion of more volatile components. These are exponentially depleted with time. The second major difference is the effect of atmospheric conditions. Water evaporation is strongly dependent on wind speed and relative humidity. Air can only hold a certain volume of water. The boundary layer above an evaporating water mass governs the rate at which the evaporation occurs. Once this air layer is saturated with water (or any other evaporating component), evaporation ceases. Normal air does not contain a high level of benzene and similar oil components and furthermore, the saturation level of these in air is often well above concentrations that can be achieved from an evaporating slick.

Physics of Evaporation

Evaporation of a liquid can be considered as the movement of molecules from the surface into the vapour phase above it. The layer of air directly above the evaporation surface is known as the boundary layer. The characteristics of this air layer can influence evaporation. In the case of water, the air regulates the evaporation rate. Air is capable of holding a variable amount of water, depending on temperature. This is known as relative humidity. At constant temperature, and constant removal of the water vapour from the boundary layer, the evaporation rate of water is a constant. Under conditions where the boundary layer is not moving (no wind) or has a low turbulence, the air immediately above the water quickly becomes saturated and evaporation slows or ceases. In practice, the actual evaporation of water proceeds at a small fraction of the maximum rate because of the saturation of the boundary layer. The boundary layer physics are then said to regulate the evaporation of water. Water is then 'boundary-layer regulated'. This regulation manifests itself by the variability in evaporation when wind or turbulence is or is not present. When there is little or no turbulence present, the evaporation can slow by several orders-of-magnitude. The diffusion of water molecules is said to be 10^3 times slower than turbulent diffusion (Jones, 1992).

Evaporation can then be viewed as consisting of two fundamental components, basic evaporation itself and regulatory mechanisms. Basic evaporation is that process consisting of the evaporation of the liquid directly into the vapour phase without any regulation other than dictated by the thermodynamic properties of the liquid itself. Regulatory mechanisms are those processes which serve to regulate the final evaporation rate into the environment. For water, the main regulation factor is the boundary layer regulation alluded to above. The boundary layer regulation is by means of the limited rate of diffusion, both molecular and turbulent diffusion, and by saturation dynamics. Molecular diffusion is the movement of molecules through still air. The rate of molecular diffusion for water is about 10^5 slower than that the maximum rate of evaporation would permit (Jones, 1992). The rate for turbulent diffusion, the combination of molecular diffusion and movement with turbulent air, is on the order of 10^2 slower than that for maximum evaporation.

If evaporation of oil were like that of water and were boundary-layer regulated one could write the mass transfer rate as:

$$E \approx K\ C\ T_u\ S \qquad (1)$$

Where: E is the evaporation rate in mass per unit area
K is the mass transfer rate of the evaporating liquid, presumed constant
C is the concentration of the evaporating liquid as a mass per volume (or thickness)
T_u is the turbulence factor, as noted above the turbulent diffusion rate is much greater than the molecular diffusion rate
S is a factor that relates to the saturation of the boundary layer above the evaporating liquid. If the air is already saturated with the compound in question, the evaporation rate is zero. This also relates to the scale length of an evaporating pool. If one views a large pool over which a wind is blowing, there is a high probability that the air is saturated downwind and the specific evaporation rate is lower than for a smaller pool.

Much of the pioneering work for evaporation equation work was performed by Sutton (1934). Sutton proposed the following equation based largely on empirical work:

$$E \;=\; K\ C_s\ U^{7/9}\ d^{1/9}\ Sc^{-r} \qquad (2)$$

Where: E is the mean evaporation rate per unit area
K is the mass transfer coefficient
C_s is the concentration of the evaporation fluid (mass/volume)
U is the wind speed
d is the area of the square or circular pool
Sc is the Schmidt number and
r is the empirical exponent assigned values from 0 to 2/3.

The terms in this equation are analogous to the very generic equation (1) proposed above. The turbulence is expressed by a combination of the wind speed, U, and the Schmidt number, Sc, which relates the diffusivity of a particular gas in air. The coefficient of the wind power is representative of the turbulence level. The value of 0.78 (7/9) as chosen by Sutton represents a turbulent wind whereas a coefficient of 0.5 would represent a wind flow that was more laminar. The Schmidt number is the ratio of kinematic viscosity of a gas (ν) over the molecular diffusivity (D) of that gas in air. It is a dimensionless value and can be thought of as representing the molecular diffusivity of the evaporating substance in air. The scale length is represented by d and has been given an empirical coefficient of 1/9. This represents, for water, a very small increase in evaporation rate with increasing size. The coefficient of the Schmidt number, r, represents the value of the diffusivity of the particular chemical, and historically ranged between 0 and 2/3.

This water evaporation work was subsequently used by those working on oil spills to predict and describe oil and petroleum evaporation. Much of the literature follows the work of Mackay (1973 and 1984). Mackay and Matsugu (1973) corrected the equations to hydrocarbons using the evaporation rate of cumene. It was noted that the difference in constants was related to the enthalpy differences between water and cumene. Data on the evaporation of water and cumene have been used to correlate the gas phase mass transfer coefficient as a function of wind-speed and pool size by the equation,

$$K_m = 0.0292\, U^{0.78}\ X^{-0.11}\, Sc^{-0.67} \qquad (3)$$

Where: K_m is the mass transfer coefficient in units of mass per unit time
U is wind speed, to the power of 0.78
X is the pool diameter or the scale size of evaporating area
Sc is the Schmidt number which is a dimensionless number representing the viscosity ratio of the evaporating material and air to the diffusivity

Stiver and Mackay (1984) subsequently developed this further by adding a second equation:

$$N = KAP/(RT) \qquad (4)$$

Where: N is the evaporative molar flux (mol/s)
K is the mass transfer coefficient under the prevailing wind (ms^{-1})
A is the area (m^2)
P is the vapour pressure of the bulk liquid
R is the gas constant (8.314 $Pa{\cdot}m^3/(mol\text{-}K)$)
T is the environmental temperature (K).

Thus boundary layer regulation is assumed to be the primary regulation for oil and petroleum evaporation. This assumption was never tested by experimentation as revealed by the literature search. The implications of these assumptions are that evaporation rate for a given oil is increased by:

- increasing turbulence
- increasing wind speed
- increasing the surface area of a given mass of oil
- decreasing the scale size of the evaporating area (note the balance between this and the above factor)

These factors can then be verified experimentally to test if oil is boundary-layer regulated or not.

Experimental

Evaporation rate was measured by weight loss using an electronic balance. The balance used was a Mettler PM4000, capable of measurements to 0.01 ±0.02 g. The weight was recorded using a computerized system consisting of a Toshiba 3100, a serial cable to the balance and a modified version of the software program, 'Collect', sold by Labtronics, Richmond, Ontario. The latter consisted of an older version of the program written in Basica which could then be easily modified to incorporate certain features.

The software program normally acquires data at fixed time intervals. Adjustments were made to the program to allow different time multiples for data acquisition. This then allowed minimization of data at times after the initial rapid evaporation period. Intervals of data acquisition could be set at multiples such that each time increment had an equal weight loss increment. For example in one day, using a timing multiplier of 1.1 and an interval of 10 seconds, 75 data points were collected compared to 8640 if a regular time intervals were used. It was important then to use the time increment to yield data sets which were manageable. Experiments were done to measure the effect of the number of data points on data quality. A sequence using the multiplier 1.1 was found to be optimal. For example, using this timing sequence measurements were taken at the following minute intervals, 8.3, 9.1, 10, 11.1, 13.4, etc. After one day, sequences were already at intervals of several hours.

Measurements were typically conducted in the following fashion. A tared petri dish of known dimensions was loaded with a specified amount of oil. Data acquisition was started and continued until the desired time (varying from a few hours for a volatile substance to several days for a less-volatile oil). At the end of the experiment, the weathered oil was saved for chemical analysis for other experiments not related to this project. Vessels were cleaned and rinsed with dichloromethane and a new experiment started.

This method differs significantly from previous measurements which were taken by weighing the pan at fixed intervals. This results in fewer data points and thus less reliable data. The method described here is possible because of the development of computers and balances that can output data and software to couple these. Furthermore, a new type of balance, the Mettler PM4000, provides accuracy to an order magnitude less weight than previous balances with the same maximum loading weight. This is important in accurately measuring the weight loss of heavy oils which evaporate slowly. In fact, often many of the changes observed occur only in the tens of milligrams, which this type of balance measures.

The weight loss dishes were standard glass petri dishes from Corning. A standard 139 cm diameter (ID) dish was most frequently used. Petri dishes of other sizes were used in experiments where the area of evaporation was a variable. All petri dishes were from Corning and were of inside diameters, 44.8, 88.9, 138.6, 143.2, and 162.2 mm.

Oil was directly placed on the glass petri dish unless otherwise noted. Experiments were conducted with oil on water to show that the effect was the same. However, use of water under the oil could result in serious errors if the water became exposed to the air and evaporated.

Measurements were done in one of four locations: inside a fume hood, inside a controlled temperature room, on a counter top and some were performed outside to verify that evaporation data obtained was not unduly influenced by experimental conditions.

Most experiments were conducted in the fume hood, where there was no temperature regulation. Temperatures at this and other locations were measured using a Keithley 871 digital thermometer with a thermocouple supplied by the same firm. Temperatures at the fume hood location were relatively constant at 20°C except during the coldest of winter months. During these times, experiments of a different nature were generally carried out such as those involving variable temperatures using the cold room. Temperatures were taken at the beginning and the end of a given experimental run, and were occasionally measured in the middle of runs to verify that they were not changing rapidly.

Wind velocities were measured using a Taylor vane anemometer (no model number on the unit) and a Tadi, 'Digital Pocket Anemometer'. These velocities were later confirmed using a hot wire anemometer and appropriate data manipulations of the outputs. The anemometer was a TSI - Thermo Systems model 1053b. The power supply in the unit was a TSI model 1051-1, the variable decade a TSI model 1056, the averaging circuit, a TSI model 1047 and the signal linearlizing circuit was a TSI model 1052. The voltage from the averaging circuit was read with a Fluke 1053 voltmeter. The hot wire sensors was angled and was a TSI model 1213-60. The sensor probe resistance at 0°C was 7.21 ohms and was operated at 12 ohms for a recommended operating temperature of 250°C. Data from the hot wire anemometer was collected on a Campbell Scientific CR-10 data logger at a rate of 64 Hz. At this data rate about 8000 data points or about 2 ½ minutes of data could be collected before the CR-10 was over-writing data. These data were subsequently down-loaded to a lap top computer and saved for subsequent analysis.

Evaporation data were collected on the Toshiba 3100 laptop computer and subsequently transferred to other computers for analysis. The 'Collect' program records time and the weight directly. Data was recorded in ASCII format and converted to Excel format by the program of the same name, Microsoft Incorporated, Redmond, Washington. Curve fitting was performed using the software program "Table Curve", Jandel Scientific Corporation. The weight percent and the absolute weight were always fit separately and statistics on these parameters recorded separately. This was done to enable subsequent analysis of dimensionless and absolute evaporation. The program "Table Curve" enables the user to fit hundreds of relationships to a set of data and rank the resulting fit in order of regression coefficient (R^2). In this study, the 'common' functions were generally used. The particular best equation was typically the logarithmic one and the regression coefficient (correlation coefficient squared) generally were over 0.95. Equations without the constant or single-parameters equations were also calculated for correlation work.

Results and Discussion

Table 1 shows the experiments conducted to date and the best equation constant for a single parameter equation.

Eighteen series of experiments, totalling over 250 experiments, lasting over 450 days in total, have already been conducted:

1. Preliminary Series - *Determination of Basic Evaporation Physics* - The purpose of these was to explore the topic. Five runs were conducted which include oil alone, oil-on-water and water alone.
2. Second Series - *Confirmation of the Rate of Evaporation and The Exponential Rate* - The purpose of these was to further detail the behaviour of evaporating oil. Several of the variables were measured to note the effects these would have. The experimental method was continually improved to remove error and noise. Two sub-series of experiments were performed; A. those logged manually, and B. those logged using a computer. Method improvements made during this round included the automatic data logging, rapid method of adding oil to avoid high rate of loss, the selection of glassware types with consistent flat bottoms and the shielding of the experiment to avoid drafts which cause erratic behaviour of the scale when not measuring the effect of wind.

Table 1

Summary Table of Experiments on Evaporation

Series	Date 1993	Prime Purpose	Oil Type	Days Length	Total Time (hr)	Pan (cm²) Area	Initial Loading (g)	Initial (mm) Thickness	End Wt.	% Evap	Temp C	Wind m/s	Variable	Variable Value	R² Best Equation	Best Equation	Single Parameter
1	May 12	preliminary	ASMB	0.5	9	151	8.53	0.67	5.5	36	23.4	0	rate		-		for
	May 22	preliminary	ASMB	0.2	4	151	6.62	0.52	3.9	42	20.3	0	rate		0.969	ln	equation
	May 24	preliminary	ASMB	0.5	8	151	10.1	0.8	3.2	68	20.3	0	rate		0.971	ln	
	May 24	preliminary	ASMB	0.2	4	151	7.21	0.57	4.3	40	18.7	0	rate		0.732	ln	
	June 1	preliminary	ASMB	3	80	151	7.81	0.62	5	36	18.8	0	rate		0.997	ln	
	June 20	preliminary	ASMB	1	27	151	8.05	0.64	4.4	45	21.5	0	rate		0.941	ln	
2	June 21	rate	ASMB	1	15	151	8.18	0.65	5.3	35	21.2	0	rate		0.991	ln	5.35
	June 23	rate	ASMB	1	22	268	16.29	0.72	11	34	21	0	rate		0.978	ln	4.76
	June 24	rate	ASMB	1	23	270	29.49	1.3	20	32	21.8	0	rate		0.97	ln	4.43
	June 25	rate	ASMB	7	182	151	8.04	0.63	4.5	44	22.6	0	rate		0.99	ln	4.95
	July 2	rate	ASMB	1	15	151	20.16	1.59	14	30	22.4	0	rate		0.937	ln	4.05
	July 3	rate	ASMB	2	51	151	22.52	1.78	15	35	21.9	0	rate		0.975	ln	4.36
	July 5	rate	ASMB	2	65	151	27.15	2.14	17	36	24.4	0	rate		0.954	ln	4.26
	July 9	rate	ASMB	1	25	151	34.1	2.69	21	38	23.8	0	rate		0.952	ln	4.45
	July 16	rate	ASMB	4 (5)	73	151	35.98	2.84	24	32	21.7	0	rate		0.96	ln	3.81
	July 20	rate	ASMB	2(8)	36	151	57.67	4.55	39	32	22.8	0	rate		0.963	ln	4.09
	Aug 30	rate	ASMB	1	18	151	115.03	9.08	85	26	20.1	0	rate		0.879	ln	3.07
	Sept 1	rate	ASMB	4	73	151	96.41	7.61	62	36	20.3	0	rate		0.886	ln	3.86
3	Sept 4	rate	ASMB	10	217	151	66	5.21	42	36	20	0	rate		0.937	ln	3.56
	Sept 13	rate	ASMB	4	64	151	19.35	1.53	12	38	22.1	0	rate		0.981	ln	4.66
	Sept 16	rate	ASMB	3	56	151	40.67	3.21	27	34	17.8	0	rate		0.952	ln	3.95
	Sept 18	rate	ASMB	2	47	151	16.87	1.33	11	36	19.2	0	rate		0.987	ln	4.73
	Sept 20	rate	ASMB	1	23	151	7.43	0.59	4.7	36	18.8	0	rate		0.988	ln	5.16
	Sept 21	rate	ASMB	1	25	151	7.92	0.63	5	36	20.1	0	rate		0.985	ln	5.18
	Sept 22	rate	ASMB	3	71	151	24.8	1.96	16	37	23.1	0	rate		0.976	ln	4.49
	Oct 15	rate	ASMB	1	32	151	32.2	2.54	21	35	18.6	0	rate		0.977	ln	4.78
	Oct 16	rate	ASMB	5	89	151	66.82	5.27	42	37	22.9	0	rate		0.98	ln	4.27
	Oct 20	rate	ASMB	4	76	151	18.06	1.43	10	45	20.4	0	rate		0.993	ln	5.7
	Oct 23	rate	ASMB	4	66	151	17.56	1.39	11	40	20.3	0	rate		0.986	ln	5.26
	Oct 26	rate	ASMB	3	88	151	35.44	2.8	22	37	19.1	0	rate		0.962	ln	4.27
4	Oct 29	stirring	ASMB	1	25	151	18.32	1.45	12	33	22.6	0	rate		0.992	ln	4.54
	Oct 30	stirring	ASMB	2	45	151	37.52	2.96	26	32	14.1	0	rate		0.964	ln	3.65
	Nov 1	stirring	ASMB	2	51	151	20.48	1.62	14	32	20.9	0	rate		0.994	ln	4.28
	Nov 3	stirring	ASMB	2	47	151	21.67	1.71	14	34	17.9	0	rate		0.995	ln	4.16
	Nov 5	stirring	ASMB	5	70	151	25.07	1.98	16	35	17.6	0	rate		0.984	ln	4.16
	Nov 8	stirring	ASMB	8	166	151	70.86	5.59	53	26	21.8	0	rate		0.931	ln	3.32
	Nov 16	stirring	ASMB	6.5	150	151	24.82	1.96	15	39	20	0	rate		0.996	ln	5.58
	Nov 22	stirring	ASMB	5	117	151	30.38	2.4	19	36	22.2	0	rate		0.997	ln	4.07
	Nov 27	stirring	ASMB	10	237	151	125.3	9.89	83	34	19.4	0	rate		0.924	ln	3.08
5	Dec 8	Time	ASMB	2	46	151	19.46	1.54	13	35	17	0	constant	0.5 hr	0.998	ln	4.37
	Dec 10	Time	ASMB	2.5	65	151	21.47	1.69	14	34	20.2	0	constant	0.5 hr	0.967	ln	4.28
	Dec 13	Time	ASMB	1	30	151	40.21	3.17	28	30	13.6	0	constant	0.5 hr	0.987	ln	3.85
	Dec 14	Time	ASMB	3	72	151	27.26	2.15	18	36	13.8	0	constant	1 hr	0.994	ln	4.23
	Dec 17	Time	ASMB	2.5	65	151	37.92	2.99	26	32	7.5	0	constant	1 hr	0.996	ln	3.74
	Dec 20	Time	ASMB	2	44	151	33.87	2.67	23	34	21.4	0	constant	1.2	0.987	ln	3.84
	Dec 22	Time	ASMB	2	47	151	37.15	2.93	26	31	21.6	0	constant	1.2	0.989	ln	4.02
6	Dec 24	Oil	Bunker	4	99	151	252.07	17.14	250	1	11.8	0	rate		0.687	ln	0.048
	Dec 28	Oil	Gasoline	1	19	151	73.61	6.68	8.7	88	13.4	0	rate		0.983	ln	10.1
	Dec 29a	Oil	Gasoline	0.5	4	151	20	1.81	1.6	92	9.1	0	rate		0.922	ln	12.1
	Dec 29b	Oil	Gasoline	0.5	2	151	20	1.81	2.3	89	19.5	0	rate		0.889	ln	15.9
	Dec 29c	Oil	Bunker	3	72	151	20.06	1.36	19	6	19.6	0	rate		0.875	ln	0.473
	1994																
	Jan 1	Oil	Prudhoe1	2	49	151	20	1.49	17	15	21.5	0	rate		0.993	ln	1.65
	Jan 3	Oil	Prudhoe2	3	71	151	20	1.49	16	19	21.3	0	rate		0.997	ln	2.17
	Jan 6	Oil	Orimulsion 1	1	26	151	20	1.34	9.2	54	21.2	0	rate		0.95	ln	6.4
	Jan 7	Oil	Orimulsion 2	1	20	151	20	1.34	15	26	12	0	rate		0.951	ln	3.38
	Jan 8	Oil	Brent	2	48	151	40	3.18	27	33	18	0	rate		0.995	ln	3.93
	Jan 10	Oil	Brent	1	27	151	20	1.59	12	38	21.6	0	rate		0.991	ln	4.06
	Jan 11	Oil	Orimulsion	1	25	151	40	2.71	12	69	6	0	rate		0.792	ln	5.07
	Jan 12	Oil	Brent	3	67	151	30	2.38	20	35	19.5	0	rate		0.991	ln	4.03
	Jan 15	Oil	Brent	3	74	151	50	3.97	33	33	18.1	0	rate		0.986	ln	3.97
	Jan 18	Oil	Endicott	2	42	151	50	3.62	46	9	20.1	0	rate		0.972	ln	0.926
	Jan 20a	Oil	Av Gas 80	1	3	151	20	1.91	0	100	5.6	0	rate		0.974	ln	16.8
	Jan 20b	Oil	Av Gas 80	1	2	151	20	1.91	0	100	18	0	rate		0.964	ln	15.4
	Jan 20c	Oil	Issungnak	2	47	151	20	1.56	16	22	19	0	rate		0.947	ln	2.23
	Jan 22	Oil	Terra Nova	2	43	151	20	1.54	17	17	18.8	0	rate		0.971	ln	1.93
	Jan 24	Oil	Heating Oil	4	95	151	20	1.53	12	39	5.6	0	rate		0.852	ln	3

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Series	Date 1993	Prime Purpose	Oil Type	Days Length	Total Time (hr)	Pan (cm^2) Area	Initial Loading (g)	Initial (mm) Thickness	End Wt.	% Evap	Temp C	Wind m/s	Variable	Variable Value	R^2 Best Equation	Best Equation	Single Parameter
	Jan 28a	Oil	Jet 40 Fuel	0.5	6	151	20	1.71	4.2	79	20.8	0	rate		0.915	ln	9.63
	Jan 28b	Oil	Prudhoe Bay	8	190	151	30	2.23	23	24	11.2	0	rate		0.986	ln	2.36
	Feb 5	Oil	Santa Clara	2	48	151	20	1.44	16	18	24.1	0	rate		0.967	ln	2.3
7	Feb7	Area	ASMB	3	50	16	10	7.45	7.1	29	24.2	0	area	16 cm^2	0.969	ln	2.95
	Feb 9	Area	ASMB	1	25	16	5	3.72	3.4	31	23.9	0	area	16 cm^2	0.96	ln	3.67
	Feb 10	Area	ASMB	1	21	16	2.12	1.58	1.6	24	8	0	area	16 cm^2	0.72	ln	2.89
	Feb 11	Area	ASMB	1	25	16	1.06	0.79	0.7	32	24.6	0	area	16 cm^2	0.791	ln	5.23
	Feb 12	Area	ASMB	2	50	62	20	3.84	14	32	22.5	0	area	62 cm^2	0.992	ln	3.52
	Feb 14	Area	ASMB	1	22	62	10	1.92	7.2	28	15.6	0	area	62 cm^2	0.996	ln	3.77
	Feb 15	Area	ASMB	1	26	62	8.2	1.58	5.4	34	25.3	0	area	62 cm^2	0.982	ln	4.35
	Feb 16	Area	ASMB	1	23	62	4.1	0.79	2.7	33	23.8	0	area	62 cm^2	0.994	ln	4.57
	Feb 17	Area	ASMB	1	24	161	20	1.48	14	32	21	0	area	161 cm^2	0.987	ln	3.98
	Feb 18	Area	ASMB	1	23	161	10.7	0.79	7.5	30	25.2	0	area	161 cm^2	0.973	ln	4.07
	Feb 19	Area	ASMB	2	50	161	21.4	1.58	14	35	23.9	0	area	161 cm^2	0.941	ln	3.66
	Feb 21	Area	ASMB	5	83	161	50	3.7	33	33	19.1	0	area	161 cm^2	0.933	ln	3.16
	Feb 26	Area	ASMB	2	50	161	30	2.22	19	36	21	0	area	161 cm^2	0.99	ln	4.7
	Feb 28	Area	ASMB	1	25	161	10	0.74	6.9	32	20	0	area	161 cm^2	0.953	ln	4.06
	Mar 01	Area	ASMB	3	74	206	27.3	1.58	18	35	18	0	area	206 cm^2	0.984	ln	3.63
	Mar 04	Area	ASMB	1	20	206	13.65	0.79	8.7	37	21	0	area	206 cm^2	0.974	ln	5.27
	Mar 05	Area	ASMB	2	51	206	20	1.16	13	33	19.5	0	area	206 cm^2	0.963	ln	3.64
	Mar 07	Area	ASMB	2	44	151	20	1.58	13	34	20.5	0	area	151 cm^2	0.993	ln	4.18
	Mar 09	Area	ASMB	1	26	151	10	0.79	6.5	35	19	0	area	151 cm^2	0.994	ln	4.8
8	Mar 10	Wind	ASMB	1	23	151	20	1.58	13	37	22.9	1.45	wind	1.0 m/s	0.98	ln	5.28
	Mar 11	Wind	ASMB	1	24	151	20	1.58	13	37	22	1.45	wind	1.0 m/s	0.972	ln	5.3
	Mar 12	Wind	ASMB	2	42	151	40	3.16	25	37	21.1	1.45	wind	1.0 m/s	0.99	ln	4.77
	Mar 14	Wind	ASMB	2	46	151	40	3.16	25	38	21.2	1.45	wind	1.0 m/s	0.993	ln	4.77
	Mar 16a	Wind	Water	0.5	3	151	20	1.32	1.9	91	21.8	1.45	wind	1.0 m/s	0.997	lin	0.592
	Mar 16b	Wind	Water	0.5	3	151	20	1.32	1	95	21.8	1.45	wind	1.0 m/s	0.997	lin	0.612
	Mar 16c	Wind	Water	0.5	3	151	40	2.65	18	55	21.8	1.45	wind	1.0 m/s	0.999	lin	0.34
	Mar 16d	Wind	ASMB	1	21	151	20	1.58	13	37	22.1	1.65	wind	1.6 m/s	0.981	ln	5.19
	Mar 17	Wind	ASMB	1	22	151	20	1.58	12	38	21.4	1.65	wind	1.6 m/s	0.949	ln	5.27
	Mar 18	Wind	ASMB	1	23	151	20	1.58	13	37	21.4	1.65	wind	1.6 m/s	0.996	ln	5.15
	Mar 19	Wind	ASMB	2	46	151	40	3.16	25	39	22.7	1.65	wind	1.6 m/s	0.986	ln	4.9
	Mar 21	Wind	ASMB	1	20	151	20	1.58	12	39	22.8	1.65	wind	1.6 m/s	0.977	ln	5.63
	Mar 22a	Wind	Water	0.5	1	151	20	1.32	4.6	77	21.7	1.65	wind	1.6 m/s	0.998	lin	0.512
	Mar 22b	Wind	ASMB	1	17	151	20	1.58	13	37	23.9	1.65	wind	1.6 m/s	0.978	ln	5.47
	Mar 23a	Wind	Water	0.5	3	151	20	1.32	2.7	87	22.2	1.65	wind	1.6 m/s	0.999	lin	0.515
	Mar 23b	Wind	Water	0.5	5	151	40	2.65	3.4	92	23.6	1.65	wind	1.6 m/s	0.989	lin	0.312
	Mar 23c	Wind	ASMB	1	22	151	20	1.58	12	39	24.3	1.65	wind	1.6 m/s	0.981	ln	5.54
	Mar 24a	Wind	Water	0.5	1	151	20	1.32	8.6	57	23.4	1.85	wind	2.1 m/s	0.998	lin	0.7
	Mar 24b	Wind	ASMB	2	44	151	40	3.16	25	37	23	1.85	wind	2.1 m/s	0.991	ln	4.85
	Mar 26	Wind	ASMB	1	6	151	20	1.58	14	32	21.7	1.85	wind	2.1 m/s	0.993	ln	5.78
	Mar 26b	Wind	ASMB	2	39	151	40	3.16	25	38	20.4	1.85	wind	2.1 m/s	0.993	ln	4.99
	Mar 28a	Wind	Water	0.5	2	151	20	1.32	4.5	78	21.8	1.85	wind	2.1 m/s	0.994	lin	0.603
	Mar 28b	Wind	Water	0.5	5	151	40	2.65	2.8	93	22.6	1.85	wind	2.1 m/s	0.998	lin	0.316
	Mar 28c	Wind	ASMB	1	12	151	20	1.58	13	35	22.4	1.85	wind	2.1 m/s	0.993	ln	5.52
	Mar 29	Wind	FCC-heavy	1	32	151	40	2.92	30	26	21.7	1.85	wind	2.1 m/s	0.987	ln	0.557
	Mar 30a	Wind	Gasoline	0.5	1	151	20	1.87	4.5	78	22.6	1.85	wind	2.1 m/s	0.983	ln	18.2
	Mar 30b	Wind	Gasoline	0.5	2	151	40	3.74	9.4	77	22.4	1.85	wind	2.1 m/s	0.975	ln	15.4
	Mar 30c	Wind	FCC-heavy	1	22	151	20	1.46	14	30	22.3	1.85	wind	2.1 m/s	0.996	ln	0.8
	Mar 31	Wind	ASMB	1	21	151	20	1.58	12	39	23.4	3.8	wind	2.5 m/s	0.981	ln	5.82
	April 1a	Wind	Water	0.5	1	151	20	1.32	6.6	67	22.4	3.8	wind	2.5 m/s	0.997	lin	1.02
	April 1b	Wind	Water	0.5	2	151	40	2.65	20	50	22.2	3.8	wind	2.5 m/s	0.999	lin	0.56
	April 1c	Wind	Gasoline	0.5	0	151	20	1.87	5.9	70	22.2	3.8	wind	2.5 m/s	0.984	ln	21.6
	April 1d	Wind	Gasoline	0.5	1	151	40	3.74	14	64	21.9	3.8	wind	2.5 m/s	0.994	ln	16.6
	April 2a	Wind	Water	0.5	3	151	20	1.32	13	38	21.7	0	wind	0	0.999	lin	0.186
	April 2b	Wind	FCC-heavy	2	47	151	40	2.92	23	41	21.4	3.8	wind	2.5 m/s	0.994	ln	0.785

Table 1

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Series	Date 1993	Prime Purpose	Oil Type	Days Length	Total Time (hr)	Pan (cm²) Area	Initial Loading (g)	Initial (mm) Thickness	End Wt.	% Evap	Temp C	Wind m/s	Variable	Variable Value	R^2 Best Equation	Best Equation	Single Parameter
	April 4	Wind	FCC-heavy	2	39	151	20	1.46	9.3	54	22	3.8	wind	2.5 m/s	0.997	ln	1.13
	April 6	Wind	ASMB	2	34	151	20	1.58	12	40	22.5	3.8	wind	2.5 m/s	0.993	ln	5.52
	April 7	Wind	ASMB	1	18	151	40	3.16	26	36	21	3.8	wind	2.5 m/s	0.997	ln	5.21
	April 8a	Wind	Water	0.5	1	151	20	1.32	4.9	75	22	3.8	wind	2.5 m/s	0.986	lin	1.04
	April 8b	Wind	Water	0.5	2	151	40	2.65	12	70	22.9	3.8	wind	2.5 m/s	0.994	lin	0.602
	April 8c	Wind	FCC-heavy	1	19	151	20	1.46	14	31	23	3.8	wind	2.5 m/s	0.992	ln	0.905
	April 9a	Wind	Gasoline	0.5	1	151	20	1.87	4.6	77	22.1	1.65	wind	1.6 m/s	0.996	ln	19.7
	April 9b	Wind	Gasoline	0.5	3	151	40	3.74	6.8	83	22.4	1.65	wind	1.6 m/s	0.983	ln	16.6
	April 9c	Wind	FCC-heavy	2	40	151	40	2.92	27	33	22.3	1.65	wind	1.6 m/s	0.997	ln	0.669
	April 11a	Wind	Gasoline	0.5	1	151	20	1.87	4.8	76	21.8	1.45	wind	1.0 m/s	0.992	ln	19.5
	April 11b	Wind	Gasoline	0.5	2	151	40	3.74	9.2	77	22.1	1.45	wind	1.0 m/s	0.973	ln	16
	April 11c	Wind	FCC heavy	1	21	151	20	1.46	14	31	23.1	1.45	wind	1.0 m/s	0.99	ln	0.887
	April 12	Wind	FCC heavy	2	51	151	40	2.92	25	36	24.2	1.45	wind	1.0 m/s	0.996	ln	0.66
	April 14	Wind	FCC heavy	2	46	151	20	1.46	16	18	24	0	wind	0	0.986	ln	0.308
	April 16a	Wind	Water	0.5	3	151	20	1.32	14	29	23.9	0	wind	0	0.999	lin	0.179
	April 16b	Wind	FCC heavy	4	87	151	40	2.92	33	17	23.9	0	wind	0	0.996	ln	0.216
	April 20a	Wind	Water	0.5	8	151	40	2.65	23	41	25	0	wind	0	0.999	lin	0.088
	April 20b	Wind	Water	1	16	151	40	2.65	11	72	25.1	0	wind	0	0.998	lin	0.0778
	April 21a	Wind	Gasoline	0.5	7	151	20	1.87	4.8	76	22.5	0	wind	0	0.92	ln	8.55
	April 21b	Wind	Gasoline	1	17	151	40	3.74	8.2	80	22.5	0	wind	0	0.944	ln	9.43
	April 22a	Wind	Water	0.5	6	151	20	1.32	7.6	62	23	0	wind	0	0.99	lin	0.178
8	April 22b	Temp	ASMB	1	26	151	20	1.58	14	30	10	0	temp	10°C	0.996	ln	3.87
	April 23	Temp	ASMB	2	47	151	20	1.58	14	30	5	0	temp	5°C	0.987	ln	3.48
	April 25	Temp	ASMB	1	24	151	20	1.58	14	32	15	0	temp	15°C	0.995	ln	4.22
	April 26	Temp	ASMB	1	25	151	20	1.58	13	33	20	0	temp	20°C	0.997	ln	4.28
	April 27	Temp	ASMB	1	24	151	20	1.58	13	34	25	0	temp	25°C	0.998	ln	4.45
	April 28	Temp	ASMB	1	24	151	20	1.58	13	36	30	0	temp	30°C	0.995	ln	4.88
	April 29	Temp	ASMB	1	23	151	20	1.58	13	38	35	0	temp	35°C	0.996	ln	5.13
	April 30	Temp	ASMB	2	48	151	20	1.58	15	24	0	0	temp	0°C	0.984	ln	2.76
	May 2	Temp	ASMB	2	45	151	20	1.58	16	22	-5	0	temp	-5°C	0.894	ln	1.81
	May 4	Temp	ASMB	3	61	151	20	1.58	15	24	-5	0	temp	-5°C	0.938	ln	2.44
	May 6	Temp	ASMB	3	52	151	20	1.58	16	18	-10	0	temp	-10°C	0.826	ln	1.33
	May 13	Temp	ASMB	6	143	151	20	1.58	16	18	-15	0	temp	-15°C	0.673	ln	1.06
	May 28a	Temp	ASMB	0.5	5	151	20	1.58	13	33	40	0	temp	40°C	0.994	ln	5.49
	May 28b	Temp	ASMB	1	21	151	20	1.58	19	4	-15	0	temp	-15°C	0.754	ln	0.536
	May 29	Temp	ASMB	3.5	72	151	20	1.58	17	15	-20	0	temp	-20°C	0.659	ln	0.916
9	May 19	humidity	ASMB	1	17	151	20	1.58	14	32	15	0	humidity	40	0.994	ln	4.36
	May 20a	humidity	Water	0.5	6	151	40	2.65	26	34	15	0	humidity	40	0.999	lin	0.0898
	May 20b	humidity	ASMB	1	22	151	20	1.58	14	31	15	0	humidity	30	0.998	ln	4.04
	May 21	humidity	Water	0.5	14	151	40	2.65	8.9	78	15	0	humidity	30	0.999	lin	0.0959
	May 22	humidity	ASMB	1	29	151	20	1.58	13	33	15	0	humidity	50	0.998	ln	4.36
	May 23	humidity	ASMB	1	21	151	20	1.58	14	31	15	0	humidity	55	0.997	ln	4.29
	May 24a	humidity	Water	0.5	3	151	40	2.65	35	14	15	0	humidity	60	0.997	lin	0.0797
	May 24b	humidity	ASMB	1	15	151	20	1.58	14	30	15	0	humidity	60	0.999	ln	4.24
	May 25a	humidity	Water	0.5	5	151	40	2.65	32	21	15	0	humidity	70	0.999	lin	0.0646
	May 25b	humidity	ASMB	1	18	151	20	1.58	14	31	15	0	humidity	70	0.997	ln	4.31
	May 26a	humidity	Water	0.5	8	151	40	2.65	30	26	15	0	humidity	80	0.994	lin	0.0559
	May 26b	humidity	ASMB	1	15	151	20	1.58	14	30	15	0	humidity	80	0.995	ln	4.25
	May 27a	humidity	Water	0.5	6	151	40	2.65	33	19	15	0	humidity	90	0.999	lin	0.0518
	May 27b	humidity	ASMB	1	17	151	20	1.58	14	31	15	0	humidity	90	0.994	ln	4.2
10	Sept 22a	Pure cmpd.	Benzene	0.5	2	151	20	1.51	3.5	83	23.9	0	rate		0.999	lin	0.689
	Sept 22b	Pure cmpd.	Dodecane	2	45	151	20	1.77	16	18	23.3	0	rate		0.999	lin	0.0068
	Sept 24	Pure cmpd.	Undecane	2	46	151	20	1.79	9.4	53	24.3	0	rate		0.999	lin	0.0193
	Sept 26a	Pure cmpd.	p-Xylene	0.5	7	151	20	1.54	7.3	63	24	0	rate		0.989	lin	0.161
	Sept 26b	Pure cmpd.	Nonane	1	11	151	20	1.83	3.9	80	24	0	rate		0.999	lin	0.117
	Sept 27	Pure cmpd.	Decane	1	19	151	20	1.81	9.3	54	22.3	0	rate		0.998	lin	0.0498
	Sept 28a	Pure cmpd.	Heptane	0.5	3	151	20	1.94	8.3	59	18.5	0	rate		0.999	lin	0.326
	Sept 28b	Pure cmpd.	Octane	0.5	3	151	20	1.88	13	36	20.4	0	rate		0.997	lin	0.221
	Sept 28c	Pure cmpd.	Decahydron	1	18	151	20	1.48	13	36	21	0	rate		0.996	lin	0.0351
	Oct 6	Pure cmpd.	Tridecane	1	23	151	20.36	1.79	20	2	21.1	0	rate		0.986	lin	0.0014
	Oct 8	Pure cmpd.	Hexadecane	7	167	151	20	1.71	20	1	15	0	rate		0.847	lin	8.25E-05

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11	Sept 29a	Pure cmpd. &w.	Heptane	0.5	0	151	20	1.94	3.7	81	16.4	1.45	rate		0.999	lin	2.82
	Sept 29b	Pure cmpd. &w.	Octane	0.5	2	151	20	1.88	4.9	75	18.2	1.45	rate		0.991	lin	1.27
	Sept 29c	Pure cmpd. &w.	Undecane	1	17	151	20.1	1.8	8.6	57	19.8	1.45	rate		0.998	lin	0.0586
	Sept 30a	Pure cmpd. &w.	Nonane	0.5	3	151	20	1.83	2.3	89	20.2	1.45	rate		0.999	lin	0.545
	Sept 30b	Pure cmpd. &w.	Decane	0.5	6	151	20.5	1.86	7	66	21.6	1.45	rate		0.999	lin	0.2
	Sept 30c	Pure cmpd. &w.	Hexadecane	3	63	151	20.3	1.74	20	0	22.3	1.45	rate		-	lin	0
	Oct 7	Pure cmpd. &w.	Tridecane	1	25	151	20	1.75	18	12	26.2	1.45	rate		0.986	lin	0.0078
	Oct 17a	Pure cmpd. &w.	Benzene	0.5	0	151	21	1.58	2.8	87	17.1	1.45	rate		0.993	lin	3.68
	Oct 17b	Pure cmpd. &w.	p-Xylene	0.5	2	151	23.25	1.79	2.3	90	17.2	1.45	rate		0.999	lin	0.756
	Oct 17c	Pure cmpd. &w.	Dodecane	0.5	7	151	20	1.77	18	9	21.3	1.45	rate		0.988	lin	0.0245
	Oct 17d	Pure cmpd. &w.	Decahydronap	0.5	14	151	20	1.48	1.2	94	20.1	1.45	rate		0.997	lin	0.122
12	Oct 3	outdoor	ASMB	0.5	8	151	24.4	1.93	18	27	7	m	rate		0.926	ln	3.9
	Oct 4	outdoor	ASMB	0.5	6	151	25.45	2.01	20	23	8	m	rate		0.821	ln	2.89
	Oct 5	outdoor	ASMB	0.5	5	449	67.95	1.8	50	27	6.5	m	rate		0.834	ln	3.92
13	Oct 15	Doping	WAS - 34.5	2	40	151	20	1.58	20	2	18	0	rate		0.937	square	0.0333
	Oct 18	Doping	Heptane+WAS	0.5	8	151	20	1.58	17	17	17.9	0	rate		0.931	square	0.841
	Oct 18b	Doping	Dodecane+WA	3	64	151	20	1.58	18	9	17.8	0	rate		0.972	square	0.137
	Oct 21	Doping	Nonane+WAS	1	27	151	20	1.58	16	19	20.3	0	rate		0.943	square	0.535
	Oct 22	Doping	Tridecane+WAS	3	77	151	20	1.58	19	7	21	0	rate		0.94	square	0.083
	Oct 26	Doping	Decane+WAS	1.5	34	151	14.93	1.18	12	20	17.9	0	rate		0.974	square	0.481
	Oct 27	Doping	Undecane+WA	3	70	151	20	1.58	16	18	16	0	rate		0.973	square	0.251
14	Oct 30	Dope&wind	Undecane +WA	1.5	41	151	20	1.58	16	21	20	1	rate		0.996	square	0.414
	Nov 1	Dope&wind	Decane +WAS	1	24	151	20	1.58	16	21	22	1	rate		0.924	square	0.597
	Nov 2	Dope&wind	Dodecane+WA	3	76	151	20	1.58	16	22	21	1	rate		0.979	square	0.294
	Nov 5	Dope&wind	Tridecane+WAS	5	125	151	20	1.58	16	18	23.9	1	rate		0.987	square	0.2
	Nov 10	Dope&wind	Nonane+WAS	1	18	151	20	1.58	16	20	21.2	1	rate		0.854	square	0.72
	Nov 11a	Dope&wind	Heptane+WAS	0.5	5	151	20	1.58	17	18	20.1	1	rate		0.746	square	1.22
	Nov 11b	Dope&wind	WAS - 34.5%	3	64	151	20	1.58	19	6	18.5	1	rate		0.923	square	0.0967
15	Nov 14a	component	2-compon	0.5	7	151	20	1.77	3.9	80	17	0	curve		0.999	lin	0.2
	Nov 14b	component	4-compon	0.5	11	151	20	1.72	1.9	91	23.7	0	curve		0.995	square	3.2
	Nov 15a	component	3-compon	0.5	5	151	20	1.74	1.9	91	20	0	curve		0.988	linear	0.353
	Nov 15b	component	6-compon	2	49	151	20	1.7	1.7	92	19	0	curve		0.948	square	1.79
	Nov 17	component	5-compon	1	27	151	20	1.72	1.6	92	21.2	0	curve		0.985	square	2.25
	Dec 10	component	14-compon	1	21	151	20.03	1.7	5.6	72	18.6	0	curve		0.975	square	2.17
	Dec 11	component	13-compon	1	30	151	20.14	1.71	5.9	71	19	0	curve		0.923	square	1.93
	Dec 12	component	12-compon	1	25	151	20.09	1.71	7	65	8	0	curve		0.984	square	1.8
	Dec 13	component	11-compon	4	92	151	20.2	1.72	4	80	9.2	0	curve		0.916	square	1.26
	Dec 17	component	10-compon	2	50	151	20.05	1.7	5.5	72	22.2	0	curve		0.913	square	1.52
	Dec 19	component	9-compon	2	40	151	20.17	1.71	7.4	63	18.6	0	curve		0.954	square	1.44
	Dec 21	component	8-compon	1	29	151	20	1.7	7.9	61	23.4	0	curve		0.956	square	1.66
	Dec 22	component	7-compon	1	25	151	20	1.7	7.2	64	23	0	curve		0.968	square	1.77
16	Dec 23	oil type	Komineft	5	121	151	12.88	1.02	8.8	32	23.3	0	rate		0.995	ln	3.4
	Dec 28	oil type	Federated	6	142	151	20	1.58	12	40	23.1	0	rate		0.982	ln	4.44
	1995																
	Jan 3	oil type	Federated	4	95	151	20	1.58	13	34	15	0	rate		0.985	ln	3.99
	Jan 7	oil type	Federated&	4	96	151	20	1.58	12	38	15	1&	rate		0.988	ln	4.42
	Jan 11	oil type	Avalon	3	70	151	20	1.56	18	9	15	0	rate		0.96	ln	2.08
	Jan 14	oil type	Gulfaks	4	89	151	20	1.61	15	26	15	0	rate		0.983	ln	2.89
	Jan 18	oil type	Brent	3	79	151	20	1.58	13	36	15	0	rate		0.995	ln	4.23
	Jan 21	oil type	Amauligak	5	120	151	20.14	1.5	15	24	15	0	rate		0.952	ln	2.3
17	Jan 26	skinning	Terra Nova-c	4	96	151	20	1.54	15	23	15	0	stirring	some	0.927	ln	2.39
	Jan 30	skinning	Terra Nova-b	6	120	151	20	1.54	15	27	23.2	0	stirring	no agit	0.937	ln	2.75
	Feb 4	skinning	Terra Nova-s	3	72	151	20	1.54	15	25	21.5	0	stirring	stirred	0.954	ln	2.79
	Feb 7	skinning	Statfjord-s	4	93	151	20	1.59	13	36	21.5	0	stirring	stirred	0.986	ln	4.12
	Feb 11	skinning	Statfjord-b	4	99	151	20	1.59	13	33	22.4	0	stirring	no agit	0.978	ln	3.49
	Feb 15	skinning	Statfjord-c	5	118	151	20	1.59	13	33	15	0	stirring	some	0.983	ln	3.65
18	Feb 20	temperature	Gulfaks	4	96	151	20	1.61	15	24	10	0	temperature	10°C	0.959	ln	2.53
	Feb 24	temperature	Gulfaks	8	188	151	20	1.61	15	25	5	0	temperature	5°C	0.975	ln	2.54
	Mar 4	temperature	Gulfaks	6	144	151	20	1.61	15	23	0	0	temperature	0°C	0.977	ln	2.19
	Mar 10	temperature	Gulfaks	3	72	151	20	1.61	15	26	15	0	temperature	15°C	0.984	ln	2.81
	Mar 13	temperature	Gulfaks	3	72	151	20	1.61	15	26	20	0	temperature	20°C	0.997	ln	3
	Mar 16	temperature	Gulfaks	2	48	151	20	1.61	15	26	25	0	temperature	25°C	0.997	ln	3.01
	Mar 18	temperature	Gulfaks	2	46	151	20	1.61	15	27	30	0	temperature	30°C	0.972	ln	3.24
	Mar 20	temperature	Gulfaks	2	42	151	20	1.61	14	29	35	0	temperature	35°C	0.985	ln	3.54

3. Third Series - *Precise Determination of Evaporation Rate* - The purpose was to begin "regular" measurements so that correlatable data could be collected. Eleven experiments of this type were conducted. The data was collected using a new modification to the data collection software that enabled time-interval multiples of non-integers. This resulted in more accurate curve fits after the data was collected.
4. Fourth Series - *Study of Film Formation and Its Experimental Elimination* - The purpose was to check whether a film, which often forms when oil evaporates under quiescent conditions, is a serious effect with certain types of oil and whether a pneumatic stirring device would remove this effect.
5. Fifth Series - *Study of the Variability of Evaporation Physics With Oil Type* - This series was to test that the findings are relevant to many different types of oils. Several differing oil types from gasoline to emulsions were tested.
6. Sixth Series - *Determination of the Evaporation Area and Thickness Effects* - The sixth series was an experiment of area of evaporation. Several different pan sizes were used to measure this effect.
7. Seventh Series - *Determination of the Regulation by Boundary Layer* - This series was a measurement of the effect of wind on the evaporation rate and thus a test of boundary layer regulation. This was done with several oils including Alberta Sweet Mixed Blend (ASMB), Gasoline, FCC Heavy Cycle (a narrow cut refinery intermediate) and water, about which so much is known.
8. Eighth Series - *Determination of the Temperature Effect on ASMB Evaporation* - This series was a test of the temperature effect from -20°C to 40°C.
9. Ninth Series - *Test of the Effect of Relative Humidity on Oil Evaporation Rate* - If oil evaporation were strongly boundary-regulated, evaporation would be affected by the relative humidity. A controlled environmental chamber was used in this study to test the humidity effect.
10. Tenth Series - *Measurement of the Evaporation Rate of Pure Hydrocarbons without Wind* - This series and the next were conducted to measure the rate of evaporation with and without wind. This will determine at what molecular weight, boundary layer regulation is a factor and when it is not.
11. Eleventh Series - *Measurement of the Evaporation Rate of Pure Hydrocarbons with Wind.*
12. Twelfth Series - *Experiment with ASMB Outdoors* - This series was a test of the entire laboratory result. The instrumentation was moved outdoors and 3 experimental runs conducted to test the hypothesis under 'real' conditions.
13. Thirteenth Series - *Experiments on Oils 'Doped' with Pure Hydrocarbons With No Wind* - This series and the next were conducted to measure if the evaporation of pure compounds was affect or changed by the presence of the oil residue (weathered oil).
14. Fourteenth Series - *Experiments on Oils 'Doped' with Pure Hydrocarbons With Wind.*
15. Fifteenth Series - *Determination of the Curve-type with Number of Components Evaporating* - Several synthetic mixtures consisting of 2 to 14 components were evaporated to determine the curve of best fit for each one. This answered the question of why most oils fit the logarithmic curve best and what the mathematical justification for this is.
16. Sixteenth Series - *Further Studies on Variances of Oil Type* - Several different types of oils were evaporated to determine whether there were differences in evaporation

behaviour with these types. All experiments were conducted in a controlled environment except for two.

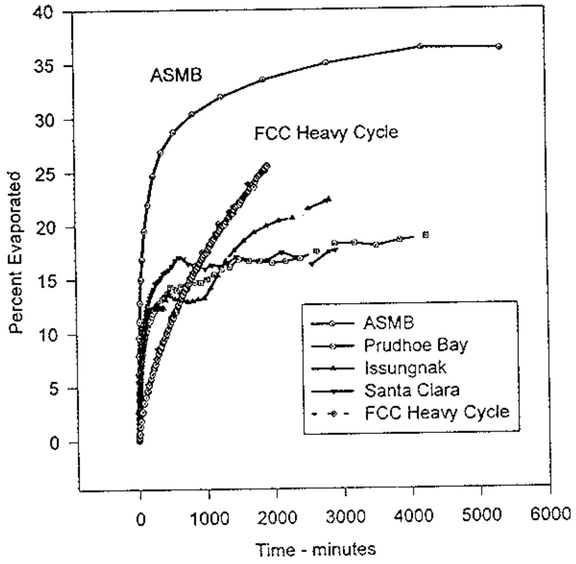
17. Seventeenth Series - *Studies on the Formation of Skin Formation* - Two oils, Terra Nova and Statfjord were tested for skin formation by conducting experiments with and without stirring.

18. Eighteenth Series - *Determination of the Temperature Effect on Gullfaks Evaporation* - This series was a test of the temperature effect from 0°C to 35°C.

The Evaporation Characteristics of Oil

This study shows that most oils evaporate at an exponential or logarithmic rate with respect to time. A few exceptions to this exist, particularly narrow-cut products such as FCC Heavy Cycle which fits a square root curve best. A comparison of the evaporation of several different oils is shown in Figure 1.

Figure 1 Evaporation Curves of Various Oils



The logarithmic shape of the curves is due to the number of components evaporating at one time. A separate study was conducted on the type of curve resulting from differing numbers of components and the curve resulting. This study shows that about 5 components yield a square root and about 12 components yield a logarithmic curve. This shows that the best fit curve is simply a result of the number of components evaporating.

Boundary Layer Regulation

The major concern is whether or not oil is boundary-layer limited. The easiest test is whether or not oil evaporation is affected by winds. Several experimental runs were conducted to examine the relationship between wind velocity and oil evaporation rate. It is important to remember the boundary-regulated water evaporation shows a strong relationship varying as U^x, where x=.5 to .78 depending on the turbulence level of the wind. Figure 2 shows a series of evaporation curves with varying wind velocities (all rich in turbulence) for ASMB (Alberta Sweet Mixed Blend crude oil).

Figure 2 **Evaporation of ASMB with Varying Wind**

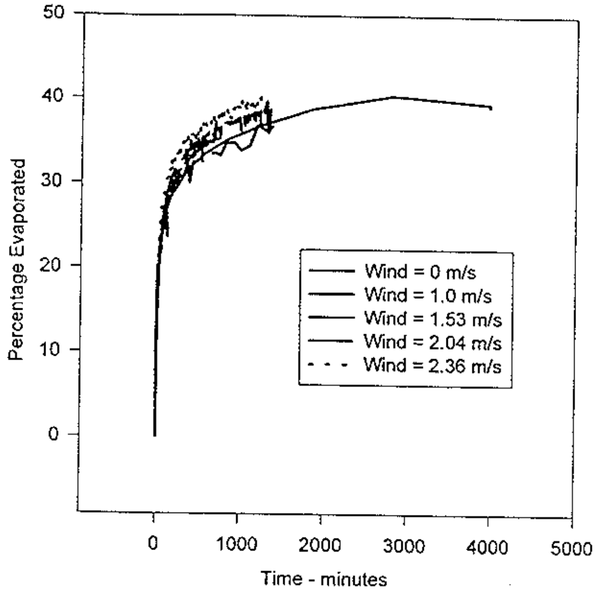
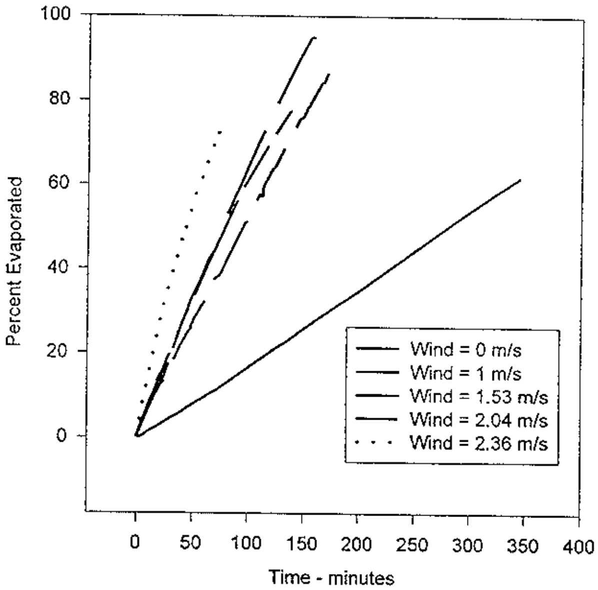


Figure 2 shows that evaporation rate only increases a small amount after the first wind increment. Figure 3 shows the same type of graph with water. The classical relationship with water is seen here, each increase in wind speed results in an increased evaporation rate. This would appear to indicate that oil is not boundary-regulated or is marginally so.

Figure 3 **Evaporation of Water with Varying Wind**



The evaporation rates themselves can be compared with the wind velocities to determine if a relationship exists. Figure 4 shows the correlation between evaporation rates of ASMB, FCC Heavy Cycle, gasoline and water.

Figure 4 **Correlation of Evaporation Rate and Wind Velocity**

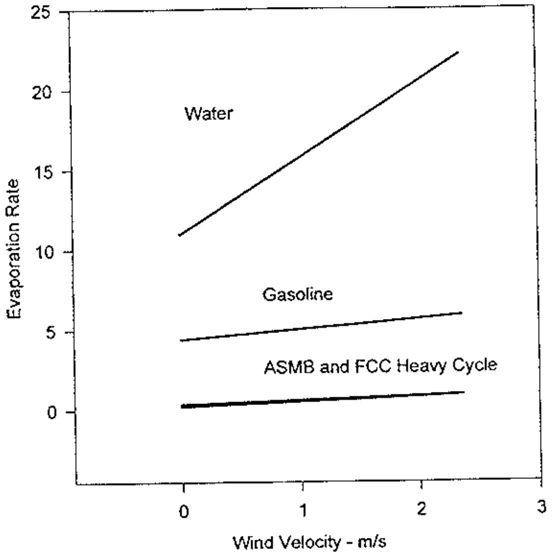
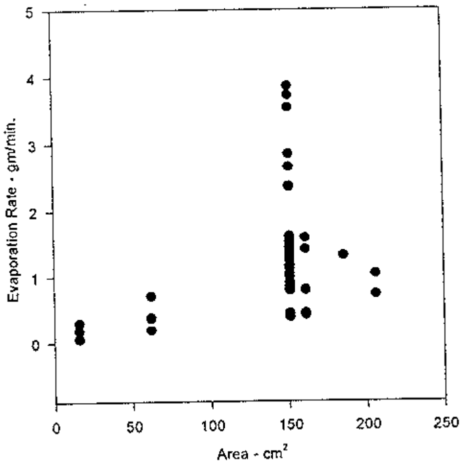


Figure 4 clearly shows that there is little relationship between the evaporation rate for the ASMB and FCC Heavy Cycle and just a very small amount for gasoline - the most volatile petroleum product. Water shows a typical large increase in evaporation rate with increasing wind velocity. It should be noted that the lines were fit by regression and thus any curves would not show.

Another 'classic' indication of boundary-layer regulation is the relationship of evaporation rate to area. If boundary layer regulation exists, evaporation rate should be directly related to the area of the evaporating substance (except, of course, over very long scales where the scale of the evaporating area would actually decrease evaporation rate because of saturation over long wind fetches. This is not relevant to these experiments because the scale size, in order of magnitudes, was not changed during the course of the experiments). Figure 5 shows the relationship between evaporation rates and area for a number of experiments conducted with ASMB.

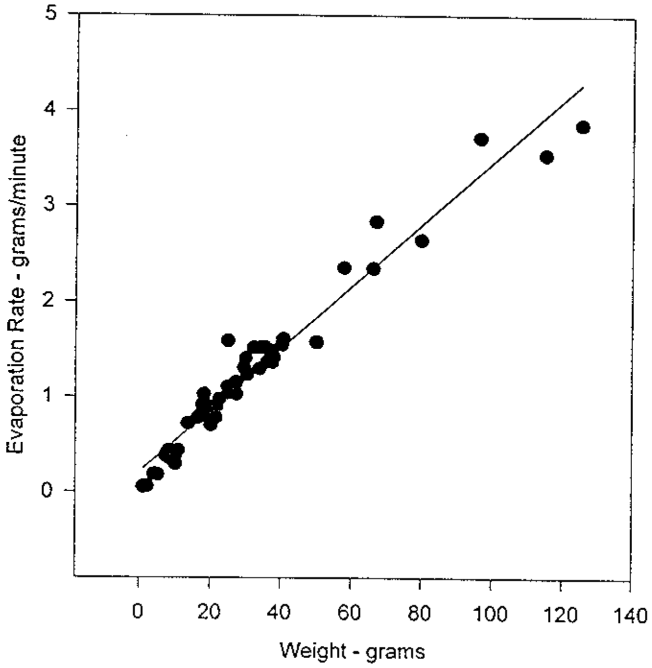
Figure 5 **Scatter Plot of Evaporation Rate and Evaporation Area**



This figure shows that there is little relationship between spill area and evaporation rate. The slight relationship noted may be due to partial boundary-layer regulation or to the fact that increasing areas may have increasing oil volumes, to which there is a strong relationship.

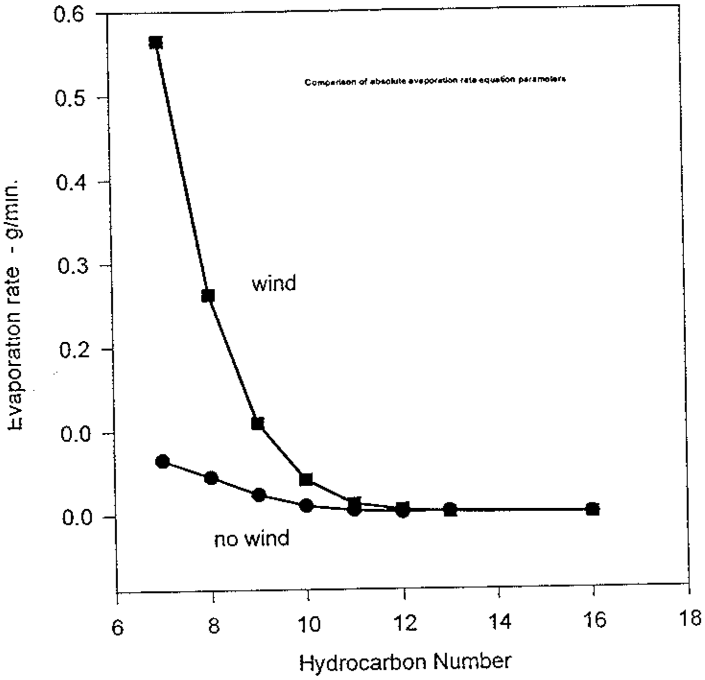
Another indication of boundary layer regulation is the relationship between mass or weight of the material evaporating and evaporation rate. If boundary layer regulation is strictly applied, there is little relationship between the two parameters. Figure 6 shows the relationship between spill mass and evaporation rate for a series of experiments conducted with ASMB. It can be clearly seen that there is strong correlation between spill volume and evaporation rate - indicating that the boundary-layer regulation is either very weak or non-existent.

Figure 6 **Correlation of Evaporation Rate and Weight of Oil**



It thus appears that oil and petroleum product evaporation is weakly boundary-layer regulated or not at all. In any event, the parameters relating to boundary-layer regulation do not necessarily need to be included in evaporation predictions. These include wind velocity, turbulence level, area or thickness. The result will be to simplify the equations for evaporation very significantly. This will have benefit to spill modelers because these parameters are often difficult to determine at the time of a spill. Instead the modeler will only need temperature and mass of spilled material - two relatively easy parameters to obtain. The question now is, why is oil not boundary-regulated. The answer appears to be that most of the components of oil evaporate so slowly that molecular diffusion is sufficient to carry the molecules from the surface. The fact that even gasoline only shows a slight boundary-regulation tendency indicates that most of its components evaporate at rates less than that of molecular diffusion. A separate series of experiments was conducted to determine the boundary-layer regulation of pure components. Results of this experiment are shown in Figure 7. The figure shows that there is no significant boundary-layer regulation above C10, and that the regulation is only important for C7. For most petroleum products and crude oils, there is only a small percentage of mass equivalent below C10 and this explains the lack of boundary regulation.

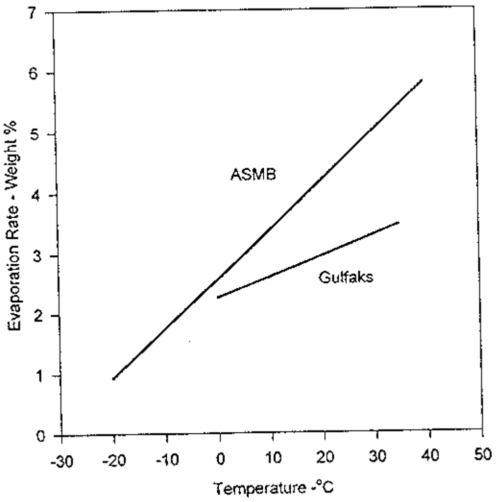
Figure 7 **Evaporation Rate for Pure Compounds**



Temperature

Another factor examined in these studies was the relationship between temperature and evaporation rate. Figure 8 illustrates two such studies and shows that the relationship found between evaporation rate and temperature is linear. Figure 8 also shows that the linear relationships are different for different oils. Work continues on developing a method of correlating these to other readily-available oil data.

Figure 8 **Temperature Correlations**



Equations

Extensive data analysis shows that most oil evaporation data fits a logarithmic curve. Curves were fit for both percentage evaporated and for actual weight lost. Furthermore, single parameter equations, that is without the constant term, were fit for both types of curves. The single-parameter equation term for percentage lost is given in Table 1. The regression coefficient (R^2) is given in Table 1 and was calculated for the two-parameter equation for percentage of weight lost. The single-parameter equations are of the form:

$Ev = P \ln t$

where: Ev is the percentage or weight evaporating per unit time, t
P is the parameter, which is calculated separately if weight or percentage is used
t is the time

The two-parameter equations are of the form:

$Ev = a + P \ln t$

where: Ev is the percentage or weight evaporating per unit time, t
a is a constant term
P is the parameter, which is calculated separately if weight or percentage is used
t is the time

Temperature was found to be the most important environmental variable affecting oil evaporation. Evaporation amount or rate changes linearly with temperature. Equations which include the influence of temperature are of the form:

$Ev = PT \ln t$

where: Ev is the percentage or weight evaporating per unit time, t
P is the parameter, which is calculated separately if weight or percentage is used
T is the temperature
t is the time

Research has also shown that the parameter, P, for the above equations can be estimated from oil distillation data with accuracy similar to that of measurement.

Conclusions

The principal finding to date is that oil is not strictly boundary-layer regulated. This is a result of the fact that oil evaporation, especially after a short initial time period, is slower that the molecular diffusion rate of the evaporated components in air.

This has profound implications for most oils including:

1. area of the spill is not important to evaporation prediction
2. wind speed is not important
3. temperature is the most important environmental consideration
4. evaporation can be predicted for mass loss by an equation of the form:

$Ev = MT \ln t$

where: Ev is the mass evaporating per unit time, t
M is the mass
T is the temperature
t is the time

5. evaporation can be predicted even more simply by an equation of the form:

$$Ev = T \ln t$$

where: Ev is the percentage evaporating per unit time, t
T is the temperature
t is the time

The most important implication is that prediction of evaporation will be much simpler in the future. The input parameters suggested here, temperature and mass of the oil are usually the only parameters known in the event of a spill. Furthermore, one does not even require the mass, because the percentage equation could be used, leaving only temperature as an input parameter.

Research on oil evaporation continues. Future publications will include description of the relationship of oil evaporation equation parameters to distillation data and to temperature. Further empirical data is being gathered and this will ultimately be added to Environment Canada's public data bases.

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