

The Evaporation of Oil Spills: Variation with Temperature and Correlation with Distillation Data

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Abstract

The relationship between oil evaporation and temperature was investigated. It was found that the evaporation rate is linear with temperature change. Although each oil or petroleum product yields a unique relationship for temperature and evaporation rate, these can be predicted using the evaporation rate at 15 °C alone or using distillation data. The slope of the distillation curve at 140 °C correlates well with the slope and intercept of the temperature curve determined empirically. These correlations were used to develop a scheme for the prediction of temperature effects on evaporation rate.

In the second part of the study, the evaporative characteristics of 19 different crude oils and petroleum products were measured. Best-fit equation parameters were determined for both percentage loss by time and absolute weight loss. All oils except for three (diesel fuel, FCC Heavy Cycle and Bunker C light) were found to fit logarithmic curves. The exceptions noted, fit square root curves with time. The equation constants were correlated with oil distillation data and it was found that the equation constants correlated highly with the percentage distilled at 180 °C (r^2 ranged from 0.98 to 0.74). Using this correlation, equations were developed by which the oil evaporation can be predicted from distillation data alone.

The evaporation equations for approximately 60 oils and petroleum products are given.

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. In contrast, 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, 1995a). 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 developed for water evaporation. Furthermore, very little empirical data on oil evaporation has been published.

The present author has undertaken a major study of oil evaporation (Fingas, 1994, 1995a, 1995b). These have shown a number of new findings with respect to oil evaporation. This paper will focus on temperature effects and predicting oil evaporation from experimental data or from distillation data.

The effect of temperature on the evaporation has been a matter of discussion. The most-accepted point of view is that extracted from the Mackay equation (Stiver and

Mackay, 1984):

$$N = kAP/(RT) \quad (1)$$

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 universal gas constant and T is temperature (K).

Most interpretations of this equation are that evaporation rate is related to temperature by $\log T/T$. This interpretation derives from the view that P (vapour pressure) is related to temperature as $\log T$. Work by Lehr (1992, 1994) assumes that this estimation is correct and thus that the equations are highly sensitive to temperature. In fact, Lehr (1992) states that the change of evaporation rate with temperature is greater than linear and may be even as much as T^2 .

Examination of other theoretical material indicates that the relationship of evaporation rate to temperature may in fact be linear. The Clausius-Clapeyron equation, Maxwell's equations and the ideal gas equation show that the volume change and thus the evaporation rate is directly and linearly related to the temperature. This theoretical information will be tested experimentally and the results presented in this paper.

The evaporation rates of oils and petroleum products are largely governed by temperature and time. Equations were derived which correlated the temperature changes to the equations with both, the empirical findings themselves and with distillation data. The experiments to determine these empirical parameters involve experiments lasting several days. Obviously, means to predict these equations would be convenient for users of the data. Furthermore, it is necessary for full understanding of the evaporation process to determine if there are relationships between the evaporation parameters and other properties of oil. This paper will then also present the results of correlations to distillation data, enabling the calculation of evaporation from that data alone.

Experimental

Evaporation rate was measured by weight loss using an electronic balance. The balance was a Mettler PM4000, capable of measurements to 0.01 ± 0.02 g. An open balance was chosen to allow for application of wind to the oil surface. 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' (Labtronics, Richmond, Ontario). The latter consisted of an older version of the program written in Basic which could then be easily modified to incorporate new 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 quantity at times after the initial rapid evaporation period. Intervals of data acquisition could be set at multiples such that each time increment had an approximately 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 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 optimal. 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. At the end of the experiment, the time sequence was re-triggered to add the last data point. Data was usually collected for 5 to 20 data points to

improve the curve fits. This addition of data points on the end of the run counterbalances the many data points at the start of a run and thus the tendency for curve fit to weigh the initial points heavier than those at the end.

Measurements were typically conducted in the following fashion. A tared petri dish of defined size was loaded with a measured amount of oil. The weight loss dishes were standard glass petri dishes from Corning. A standard 139 mm diameter (ID) dish was most frequently used. Petri dishes of other sizes were used in experiments where the area of evaporation was a variable and included those of inside diameters 44.8, 88.9, 143.2, and 162.2 mm. Diameters and other dimensions were measured using a Mitutoyo digital vernier caliper.

Oil was directly placed on the glass petri dish unless otherwise noted. Experiments were initially conducted with oil on water to evaluate the effects of the substrate. However, use of water under the oil resulted in errors if the water became exposed to the air and evaporated. The resulting evaporation curve is then an undetermined composite of oil and water evaporation. Data acquisition was started and continued to the desired endpoint (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. Vessels were cleaned and rinsed with Dichloromethane and a new experiment started.

Temperature experiments were conducted in a constant temperature chamber (room), a Constant Temperature model constructed in 1993. It can maintain temperatures from -40°C to $+60^{\circ}\text{C}$ within $\pm 1^{\circ}\text{C}$. The chamber also controls relative humidity. At relative humidities of 40 to 70%, the unit maintains set humidities within $\pm 2\%$, at other levels this precision decreases. The relative humidity was maintained at 40% when relative humidity was not a parameter of concern. Temperatures were confirmed using a Keithley 871 digital thermometer with a thermocouple supplied by the same firm. Temperatures were taken manually at the beginning and the end of a given experimental run to confirm the functioning of the temperature controller. A data recorder also monitored temperatures in the chamber.

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, Microsoft Incorporated, Redmond, Washington. Curve fitting was performed using the software program "TableCurve", Jandel Scientific Corporation, San Raphael, California. 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. It is important to note that the absolute weight calculation still relates to the weight of the starting substance. If oil were boundary-layer regulated, evaporation rate as a weight loss, would relate to the specific area. The program "TableCurve" 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, although the complete set of equations (several thousand) was also used. The latter consist largely of higher-order polynomials, which are typically used for data interpolation, rather than for determining the physical relationships applicable to a given set of experimental data.

The properties of the oils used in the tests are listed in Table 1 and the experiments conducted are listed in Table 2a and 2b.

Table 1

Properties of the Test Liquids

Name	Description	Density	Viscosity
		g/mL at 15°C	mPa.s at 15°C
Amauligak	A light crude oil from Canada's Beaufort Sea	0.871	14
Arabian Light	A common blend of Saudi Arabian oil exported around the world	0.867	14
Avalon	One of the test crude oils from Newfoundland's Hibernia field	0.871	15
ASMB	Alberta Sweet Mixed Blend - A common crude oil in Canada	0.839	9
Brent	A common British, North Sea oil, sometimes exported to Canada	0.833	6
Bunker C	A heavy residual fuel containing distillation residuals	0.98	48000
Bunker C Light	A variation on Bunker C, a refinery residual product, with some diesel-like diluent	0.969	10000
Diesel	Standard automotive/truck diesel fuel	0.809	2
Endicott	Oil from one of the smaller fields on Alaska's North Slope	0.915	84
Federated	A light, sweet Alberta crude that forms the primary feed of Edmonton's refineries	0.826	5
FCC Heavy	A light refinery intermediate product, the "heavy" refers to the number of times the product is re-cycled	0.908	3
Gasoline	Standard automotive non-leaded gasoline	0.709	0.6
Gulfaks	A common Norwegian oil - sometimes exported to Canada	0.882	13
Issungnak	Oil from the Canadian Beaufort Sea, a very light oil	0.849	4
Komineft	Crude oil from the Russian Komi republic	0.85	14
Prudhoe Bay	Oil from the largest field on Alaska's North slope	0.905	26
Santa Clara	A heavy crude oil from Southern California	0.92	300
Statfjord	A common Norwegian oil - sometimes exported to Canada	0.834	7
Terra Nova	One of the oils from the Hibernia field off Newfoundland	0.864	17

Table 2a

Experiments Conducted to Test the Temperature Effect

Series	Date	Oil Type	Days Length	Total Time (hr)	Pan (cm ²) Area	Initial Weight (g)	Initial (mm) Thickness	End Wt.	% Evap	Temp C	Wind m/s	R ²	Best Equation	Best Equation	Single Parameter
8	April 22b	ASMB	1	26	151	20	1.58	14	30	10	0	0.996	ln		3.87
	April 23	ASMB	2	47	151	20	1.58	14	30	5	0	0.987	ln		3.48
	April 25	ASMB	1	24	151	20	1.58	14	32	15	0	0.995	ln		4.22
	April 26	ASMB	1	25	151	20	1.58	13	33	20	0	0.997	ln		4.28
	April 27	ASMB	1	24	151	20	1.58	13	34	25	0	0.998	ln		4.45
	April 28	ASMB	1	24	151	20	1.58	13	36	30	0	0.995	ln		4.88
	April 29	ASMB	1	23	151	20	1.58	13	38	35	0	0.996	ln		5.13
	April 30	ASMB	2	48	151	20	1.58	15	24	0	0	0.984	ln		2.76
	May 2	ASMB	2	45	151	20	1.58	16	22	-5	0	0.894	ln		1.81
	May 4	ASMB	3	61	151	20	1.58	15	24	-5	0	0.938	ln		2.44
	May 6	ASMB	3	52	151	20	1.58	16	18	-10	0	0.826	ln		1.33
	May 13	ASMB	6	143	151	20	1.58	16	18	-15	0	0.673	ln		1.06
	May 28a	ASMB	0.5	5	151	20	1.58	13	33	40	0	0.994	ln		5.49
	May 28b	ASMB	1	21	151	20	1.58	19	4	-15	0	0.754	ln		0.536
	May 29	ASMB	3.5	72	151	20	1.58	17	15	-20	0	0.659	ln		0.916
18	Feb 20	Gulfaks	4	96	151	20	1.5	15	24	10	0	0.959	ln		2.53
	Feb 24	Gulfaks	8	188	151	20	1.5	15	25	5	0	0.975	ln		2.54
	Mar 4	Gulfaks	6	144	151	20	1.5	15	23	0	0	0.977	ln		2.19
	Mar 10	Gulfaks	3	72	151	20	1.5	15	26	15	0	0.984	ln		2.81
	Mar 13	Gulfaks	3	72	151	20	1.5	15	26	20	0	0.997	ln		3
	Mar 16	Gulfaks	2	48	151	20	1.5	15	26	25	0	0.997	ln		3.01
	Mar 18	Gulfaks	2	46	151	20	1.5	15	27	30	0	0.972	ln		3.24
	Mar 20	Gulfaks	2	42	151	20	1.5	14	29	35	0	0.985	ln		3.54
19	Mar 22	Arabian Lt	5	101	151	20	1.53	14	28	15	0	0.993	ln		3.11
	Mar 26	Bunker C lt	4	88	151	20	1.37	19	3	15	0	0.99	sq. rt.		0.0422
	Mar 30a	Gasoline	0.5	3	151	21.1	1.97	3.1	85	15	0	0.956	ln		16
	Mar 30b	Gasoline	0.5	3	151	20.4	1.91	3.1	85	15	0	0.955	ln		15.8
	Mar 30c	Diesel	4	89	151	20.3	1.66	13	38	15	0	0.991	sq. rt.		0.538
	April 3a	Gasoline	0.5	4	151	20	1.87	5.5	73	-5	0	0.99	ln		12
	April 3b	Gasoline	0.5	3	151	21.6	2.02	6.6	70	-5	0	0.944	ln		12.2
	April 3c	Diesel	3	120	151	20.2	1.65	15	24	-5	0	0.997	sq. rt.		0.276
	April 6	Bunker C lt	3	119	151	20.2	1.38	20	1	-5	0	0.407	sq. rt.		0.003
	April 13	Arabian Lt.	2.5	95	151	20	1.53	16	22	-5	0	0.992	ln		2.37
	April 17	Staffjord	5	117	151	20.05	1.59	18	10	-5	0	0.747	ln		2
	April 22	Brent	5	121	151	20	1.59	14	30	-5	0	0.956	ln		3.08
	April 27	Terra Nova	6	137	151	21.86	1.73	19	11	-5	0	0.818	ln		0.955
	May 3a	Gasoline	0.5	1	151	20.03	1.87	1.1	94	35	0	0.943	ln		21.5
	May 3b	Gasoline	0.5	1	151	20	1.87	1.2	94	35	0	0.954	ln		22.3
	May 3c	Diesel	2	41	151	20	1.64	11	47	35	0	0.984	sq. rt.		0.988
	May 5	Brent	1.5	32	151	20	1.59	12	38	35	0	0.988	ln		5.07
	May 6	Bunker Lt	3	70	151	20	1.37	19	7	35	0	0.999	sq. rt.		0.105
	May 9	Arabian Lt.	3	73	151	20	1.53	14	32	35	0	0.997	ln		3.78
	May 12	Terra Nova	3.5	88	151	20	1.58	14	30	35	0	0.991	ln		3.26
	May 16	Staffjord	2	46	151	20	1.59	12	39	35	0	0.993	ln		4.69
	May 19	Bunker C Lt.	9	216	151	20.02	1.37	20	0	5	0	0.85	sq. rt.		0.0031
	May 28	Arab Light	2	49	151	20	1.53	16	22	5	0	0.998	ln		2.61
	May 30	Staffjord	2.5	66	151	20	1.58	14	29	5	0	0.979	ln		3.3
	June 2a	Gasoline	0.5	4	151	20	1.87	2	90	5	0	0.997	ln		14.8
	June 2b	Gasoline	0.5	2	151	20	1.87	4.3	79	5	0	0.991	ln		15.6
	June 2c	Diesel	3	73	151	20	1.64	15	26	5	0	0.998	sq. rt.		0.389
	June 05	Brent	2.5	63	151	20	1.59	14	32	5	0	0.994	ln		3.67
	June 23c	Gasoline	0.5	2	151	20	1.87	0.9	95	25	0	0.979	ln		16.9
	June 23t	Gasoline	0.5	2	151	20	1.87	0.9	95	25	0	0.978	ln		16.9
	June 23c	Diesel	3	70	151	20	1.64	12	39	25	0	0.99	sq. rt.		0.623
	June 26	Terra Nova	3	50	151	11.7	0.92	8.7	26	25	0	0.99	ln		3
June 28	Bunker C Lt.	12	283	151	20	1.37	18	8	25	0	0.999	sq. rt.		0.061	
July 10	Staffjord	9	220	151	20	1.59	12	39	25	0	0.996	ln		4.1	
July 19	Brent	3	68	151	20	1.59	13	37	25	0	0.991	ln		4.44	
July 22	Arab Light	2	51	151	20	1.53	14	28	25	0	0.997	ln		3.5	

Table 2b

Summary Table of Experiments Involving Different Oils

Series-year-93	Date	Oil Type	Days Length	Total Time (hr)	Fan (cm ²) Area	Inflot Load (g)	Inflot (mm) Thickness	End Wt.	% Evap	Temp C	Wind m/s	R ² Equation	Best Equation	Single Parameter	
2	July 2	ASMB	1	15	151	20.2	1.59	14	30	22.4	0	0.937	ln	4.05	
3	Sept 22	ASMB	3	71	151	24.8	1.96	16	37	23.1	0	0.976	ln	4.49	
4	Nov 1	ASMB	2	51	151	20.5	1.62	14	32	20.9	0	0.994	ln	4.28	
5	Dec 8	ASMB	2	46	151	19.5	1.54	13	35	17	0	0.998	ln	4.37	
	Dec 10	ASMB	2.5	65	151	21.5	1.69	14	34	20.2	0	0.967	ln	4.28	
6	Dec 24	Bunker	4	99	151	252	17.13	250	1	11.8	0	0.687	ln	0.048	
	Dec 29b	Gasoline	0.5	2	151	20	1.81	2.3	89	19.5	0	0.889	ln	15.9	
	Dec 29c	Bunker	3	72	151	20.1	1.37	19	6	19.6	0	0.875	ln	0.473	
7	Jan 1	Prudhoe	2	49	151	20	1.49	17	15	21.5	0	0.993	ln	1.65	
	Jan 3	Prudhoe	3	71	151	20	1.49	16	19	21.3	0	0.997	ln	2.17	
	Jan 10	Brent	1	27	151	20	1.59	12	38	21.6	0	0.991	ln	4.06	
	Jan 12	Brent	3	67	151	30	2.38	20	35	19.5	0	0.991	ln	4.03	
	Jan 15	Brent	3	74	151	50	3.97	33	33	18.1	0	0.986	ln	3.97	
	Jan 18	Endicott	2	42	151	50	3.62	46	9	20.1	0	0.972	ln	0.926	
	Jan 20c	Issungnak	2	47	151	20	1.56	16	22	19	0	0.947	ln	2.23	
	Jan 22	Terra Nova	2	43	151	20	1.54	17	17	18.8	0	0.971	ln	1.93	
	Jan 28b	Prudhoe Bay	8	190	151	30	2.23	23	24	11.2	0	0.986	ln	2.36	
	Feb 5	Santa Clara	2	48	151	20	1.44	16	18	24.1	0	0.967	ln	2.3	
	8	April 14	FCC heavy	2	46	151	20	1.46	16	18	24	0	0.986	sq. rt.	0.31
		April 25	ASMB	1	24	151	20	1.58	14	32	15	0	0.995	ln	4.22
16	Dec 23	Komineff	5	121	151	12.9	1.02	8.8	32	23.3	0	0.995	ln	3.4	
	Jan 3	Federated	4	95	151	20	1.58	13	34	15	0	0.985	ln	3.99	
	Jan 11	Avalon	3	70	151	20	1.56	18	9	15	0	0.96	ln	2.08	
	Jan 14	Gulfaks	4	89	151	20	1.61	15	26	15	0	0.983	ln	2.89	
	Jan 18	Brent	3	79	151	20	1.58	13	36	15	0	0.995	ln	4.23	
	Jan 21	Amauligak	5	120	151	20.1	1.5	15	24	15	0	0.952	ln	2.3	
17	Jan 26	Terra Nova	4	96	151	20	1.54	15	23	15	0	0.927	ln	2.39	
	Feb 15	Stafford	5	118	151	20	1.59	13	33	15	0	0.983	ln	3.65	
18	Mar 10	Gulfaks	3	72	151	20	1.5	15	26	15	0	0.984	ln	2.81	
19	Mar 22	Arabian Lt	5	101	151	20	1.53	14	28	15	0	0.993	ln	3.11	
	Mar 26	Bunker C lt	4	88	151	20	1.37	19	3	15	0	0.99	sq. rt.	0.0422	
	Mar 30a	Gasoline	0.5	3	151	21.1	1.97	3.1	85	15	0	0.956	ln	16	
	Mar 30b	Gasoline	0.5	3	151	20.4	1.91	3.1	85	15	0	0.955	ln	15.8	
	Mar 30c	Diesel	4	89	151	20.3	1.66	13	38	15	0	0.991	sq. rt.	0.538	

Results and Discussion

Figure 1 shows the composite of all evaporation rates versus the temperature. The evaporation rates are the coefficients of the logarithmic equation except for diesel and Bunker C light, where they are the coefficients of the square root equation. Figure 1 shows that the evaporation rates (used here interchangeably with equation parameters) are linear with respect to temperature. This confirms the theoretical approaches discussed in the introduction above. Figure 2 shows an expanded correlation of evaporation rates versus temperature, this expansion is achieved by eliminating the gasoline curve which has very high evaporation rates. The small amount of noise seen in these graphs, is possibly due to error in fitting the logarithmic or square curves. These figures indicate that most of the curves are parallel. This phenomenon is further examined in Figure 3 and Figure 4. These show the evaporation rates, with and without gasoline, with curves fit with linear regression. The curves for the light crudes, ASMB, Brent, Arabian Light, Statfjord and Gullfaks appear to be parallel. The curves for gasoline, Terra Nova crude, diesel, and Bunker C light have different slopes than those for crude oils and may be due to the unique properties of these liquids. Gasoline evaporates at a rapid rate and is composed of only lighter crude components. Terra Nova is a heavier crude with a large wax component. Diesel is a refined cut with medium to heavy components remaining. Bunker C light is a refined residual with a small amount of diesel as a diluent. The evaporation rates of the latter two products are best fit with square root equations rather than logarithmic equations.

Further examination of the temperature behaviour of oil evaporation was conducted by determining the equations by which the evaporation rates, or equation parameters, change with temperature. A series of correlations was performed, between the evaporation rates, by both percentage and weight loss, using a linear equation. The evaporation rates or equation parameters used to perform the correlations are listed in Table 1. Figures 5 to 13 show the correlations for ASMB, Gullfaks, Brent, Arabian Light, gasoline, Terra Nova, Statfjord, diesel and Bunker C light. Each figure shows the rank of the linear equation out of the simple equations available in the TableCurve program used to fit the equations. The regression coefficient (r^2), the standard error of fit and the F statistic are given and then a and b, the equation constants. Figure 14 shows the same plot for the weight loss equation form of ASMB evaporation. These figures show the high correlation of the single-factor equation parameter (evaporation rate) with temperature using a linear equation. Regression coefficients range from a low of 0.90 to a typical 0.98. Table 4 lists the equations obtained performing these correlations. It is noted that the slopes obtained for the various equations, although similar, are different enough to conclude that a unique equation is required for each oil.

The result that unique equations may be needed for each oil is a significant disadvantage to practical end use, and a way to accurately predict evaporation using other readily-available data is necessary. Two means to predict the evaporation were developed. The first data type is to use the value of the slope (fitted with one parameter) at 15°C as a basis for correlation. The assumption here is that the slopes of the temperature parameters are similar, so that they can be used as a predictor. It has already been noted that only light and medium crude oils display similar slopes. However, it will be fruitful to test such a hypothesis. The other observation noted is that the slope of the equation appears to correlate with the magnitude of the evaporation rate at 15°C. The second type of data used to study evaporation are distillation data. Distillation data are

Figure 1

The Variation of Evaporation Rates with Temperature

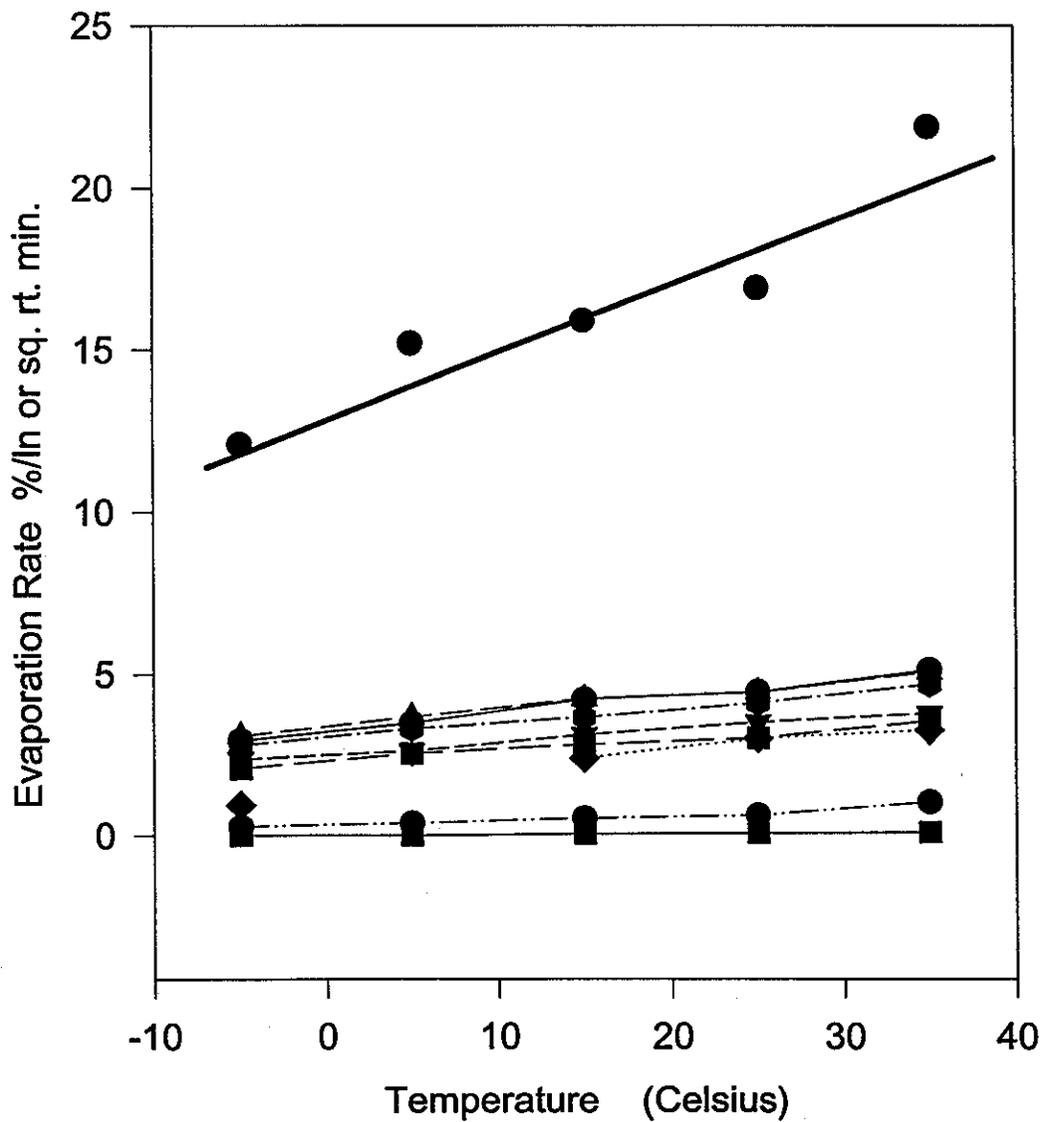
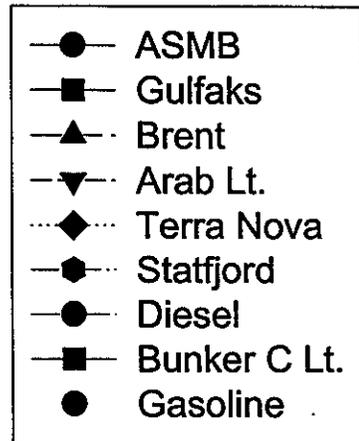


Figure 2

The Variation of Evaporation Rates with Temperature - Without Gasoline

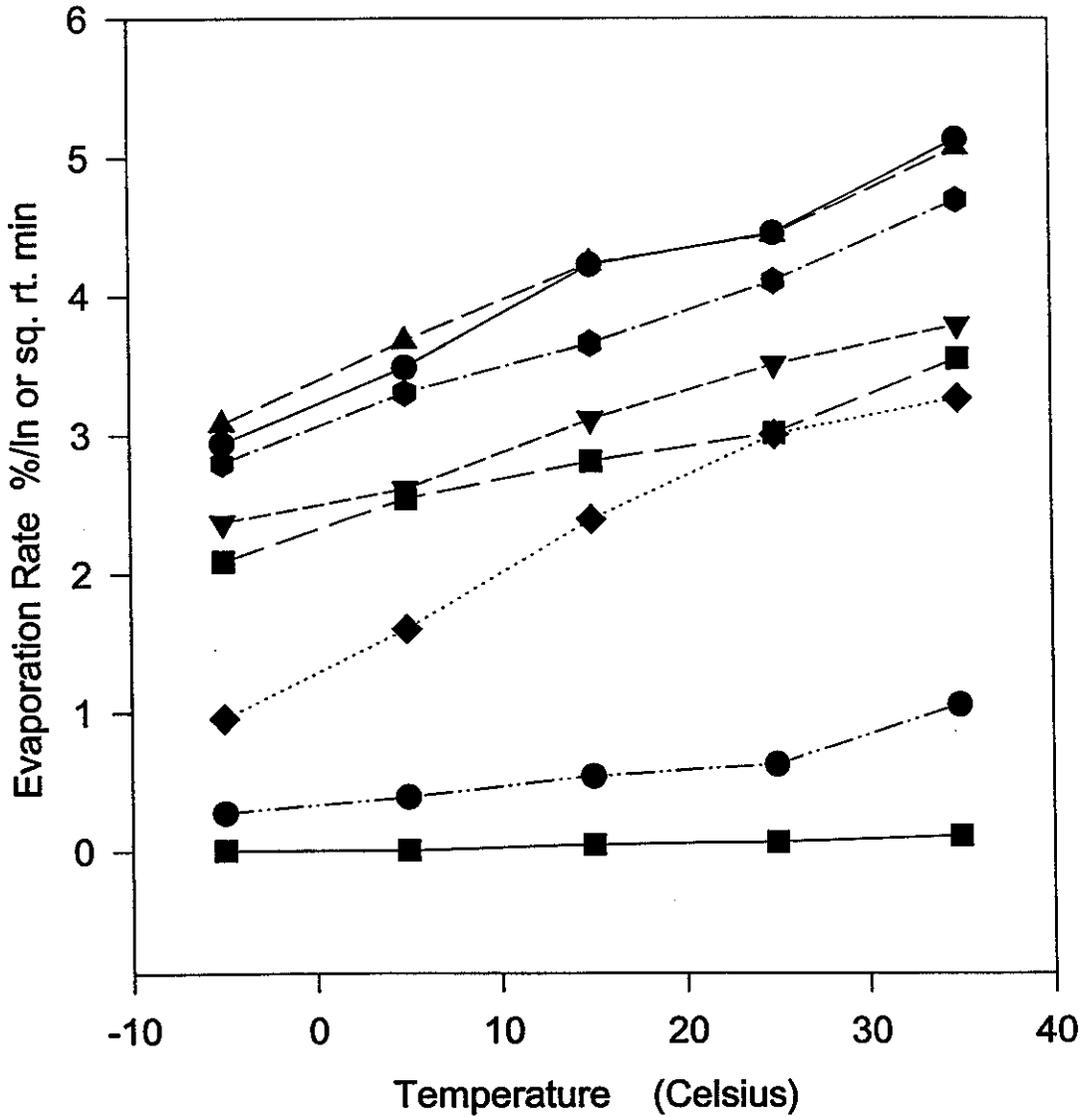
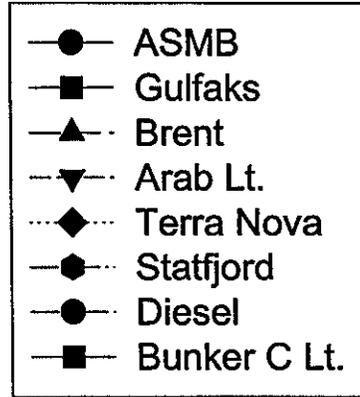


Figure 4

The Variation of Evaporation Rates with Temperature - Without Gasoline - Linear Regression

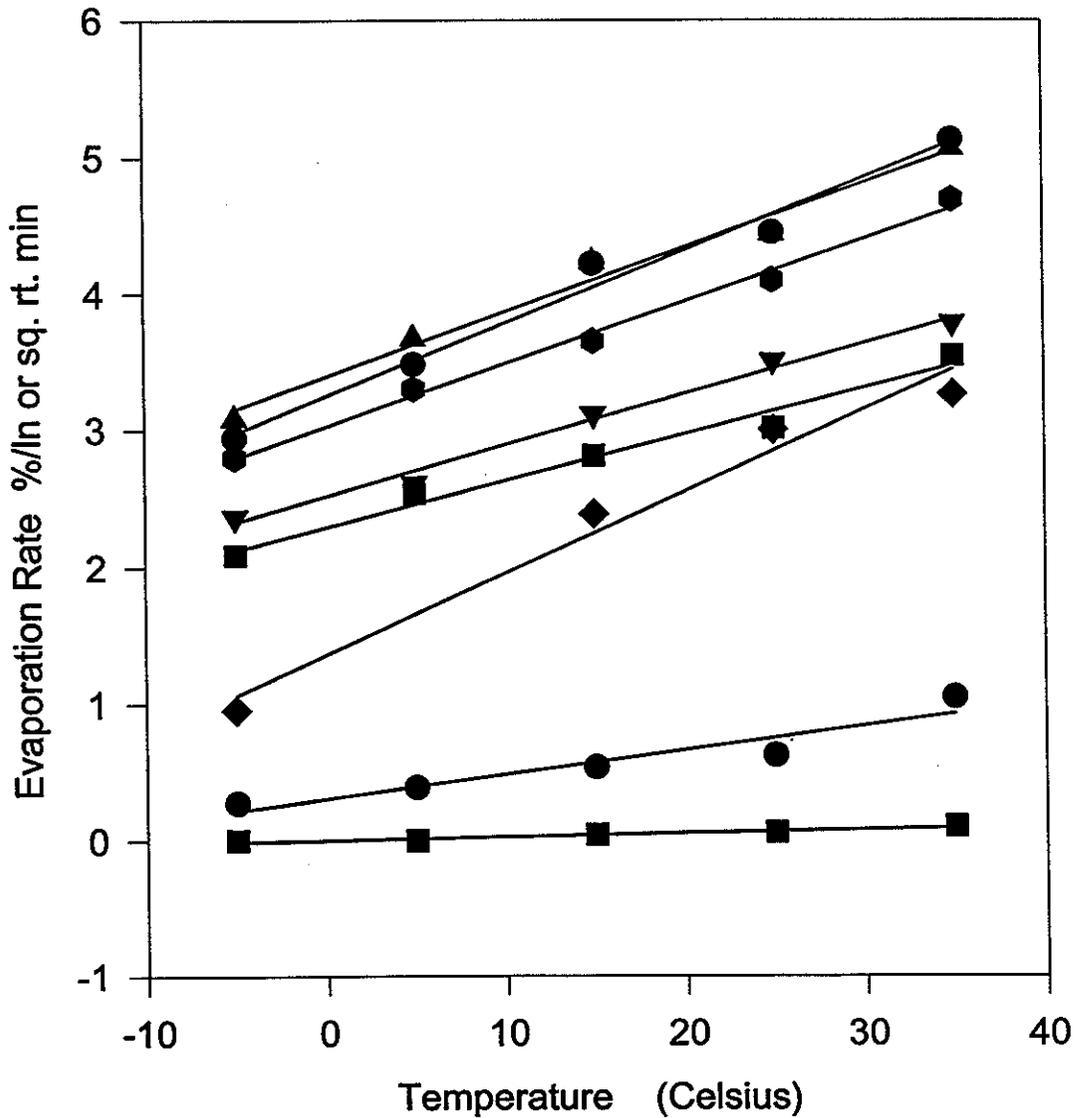
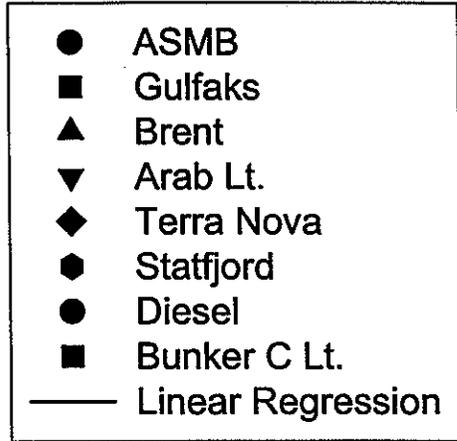


Figure 5

Correlation of ASMB Evaporation and Temperature

Rank 3 Eqn 1 $y=a+bx$
 $r^2=0.983$ FitStdErr=0.129 Fstat=1729
 $a=3.24$
 $b=0.0535$

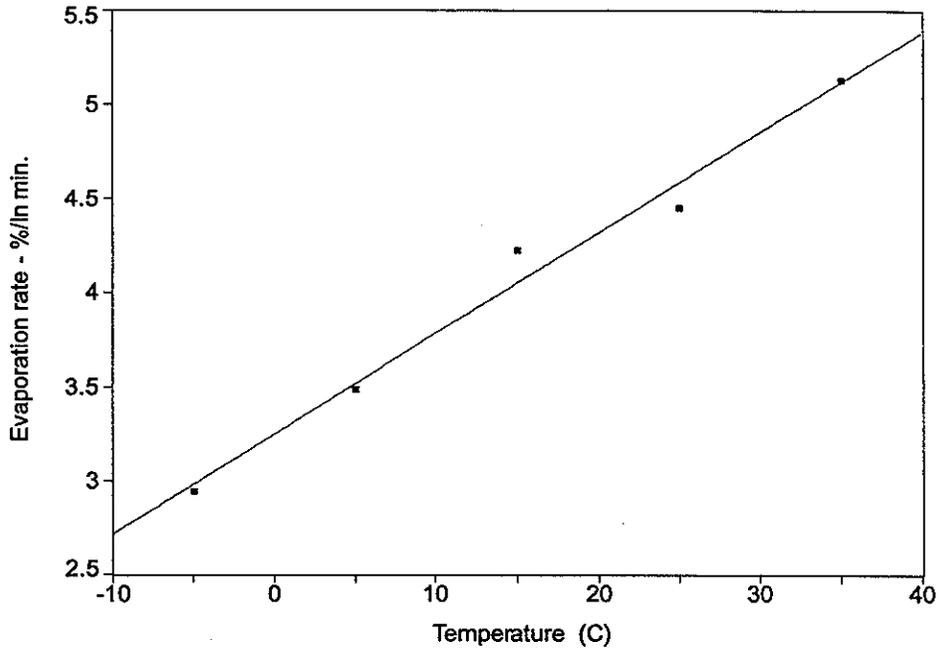


Figure 6

Correlation of Gullfaks Evaporation and Temperature

Rank 3 Eqn 1 $y=a+bx$
 $r^2=0.976$ FitStdErr=0.0962 Fstat=122
 $a=2.29$
 $b=0.0337$

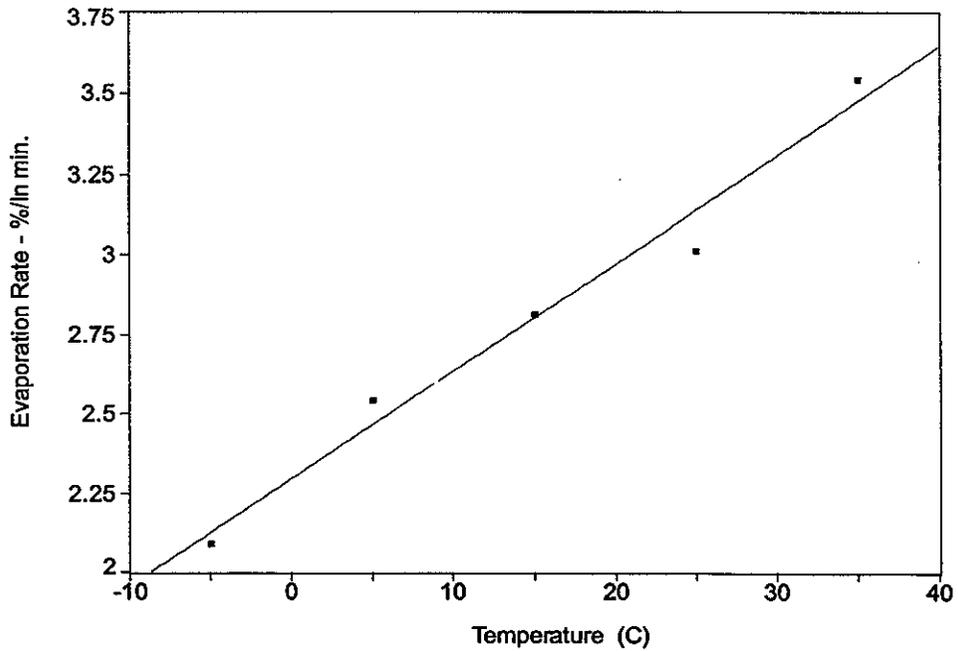


Figure 7

Correlation of Brent Evaporation and Temperature

Rank 4 Eqn 1 $y=a+bx$
 $r^2=0.982$ FitStdErr=0.119 Fstat=160
 $a=3.39$
 $b=0.0475$

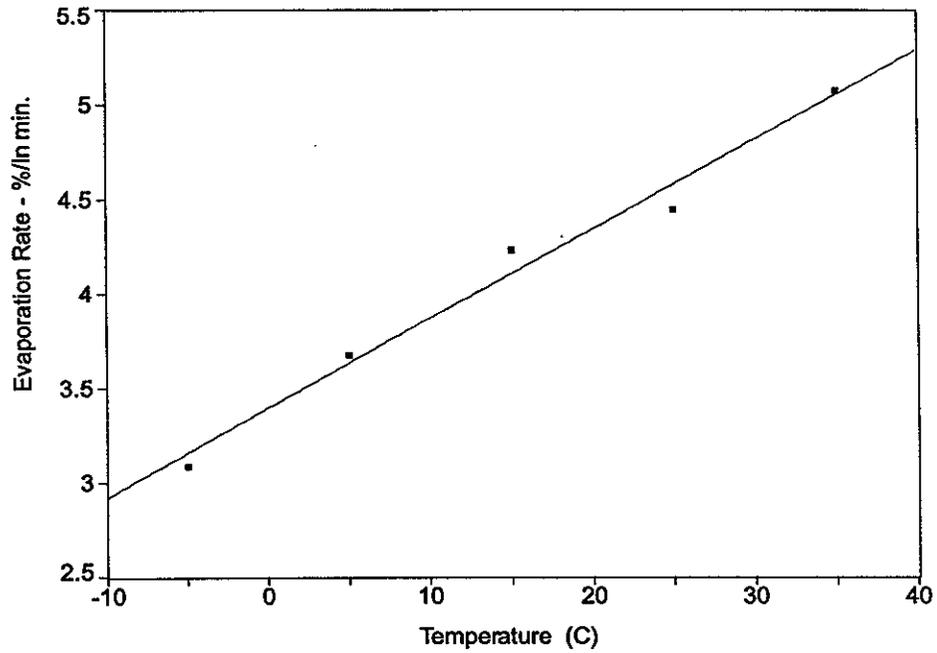


Figure 8

Correlation of Arabian Light Evaporation and Temperature

Rank 2 Eqn 1 $y=a+bx$
 $r^2=0.989$ FitStdErr=0.0725 Fstat=263
 $a=2.52$
 $b=0.0371$

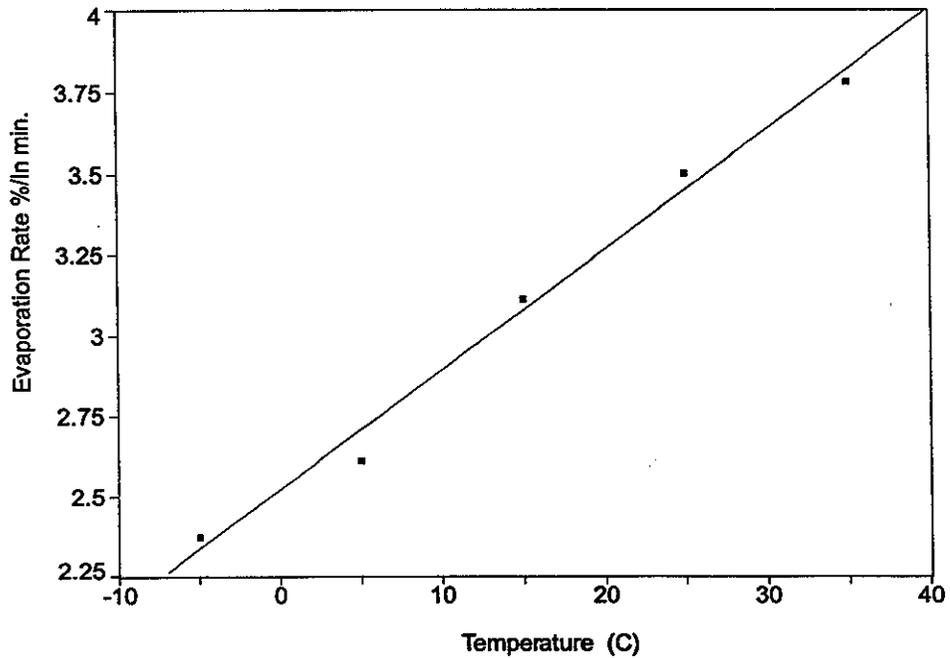


Figure 9 Correlation of Gasoline Evaporation and Temperature

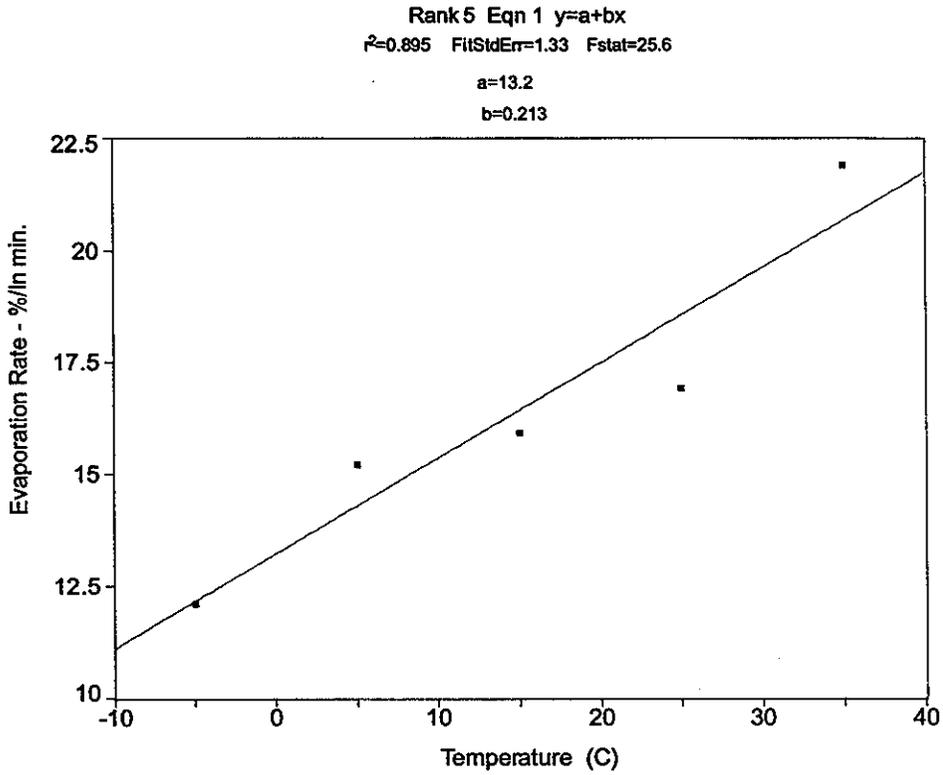


Figure 10 Correlation of Terra Nova Evaporation and Temperature

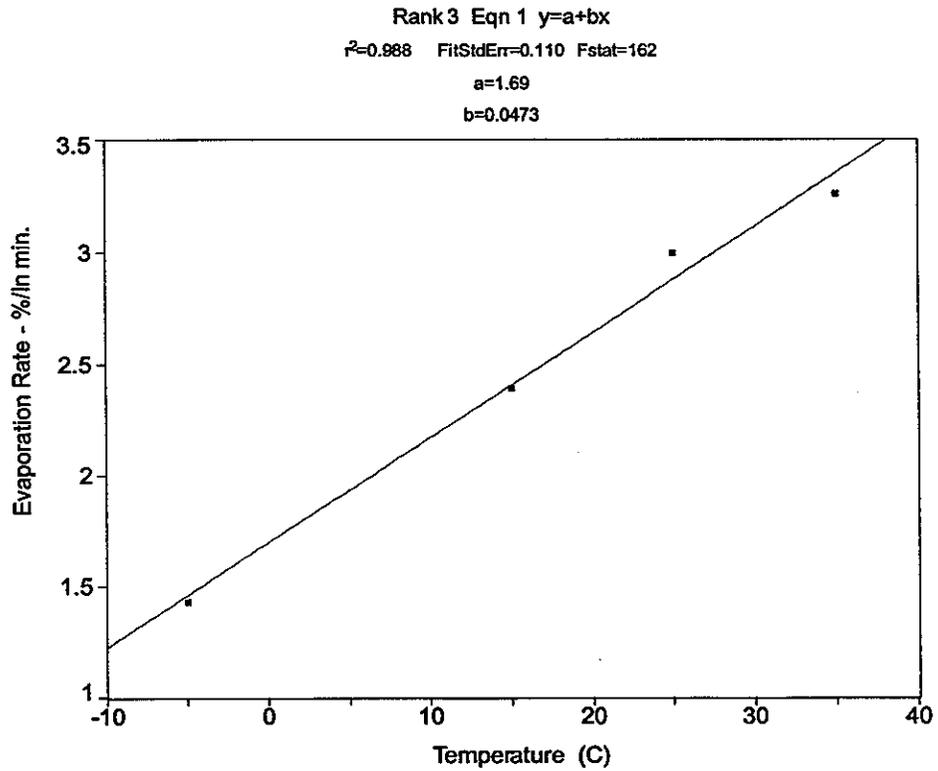


Figure 11

Correlation of Staffjord Evaporation and Temperature

Rank 2 Eqn 1 $y=a+bx$
 $r^2=0.992$ FitStdErr=0.0769 Fstat=390
a=2.97
b=0.048

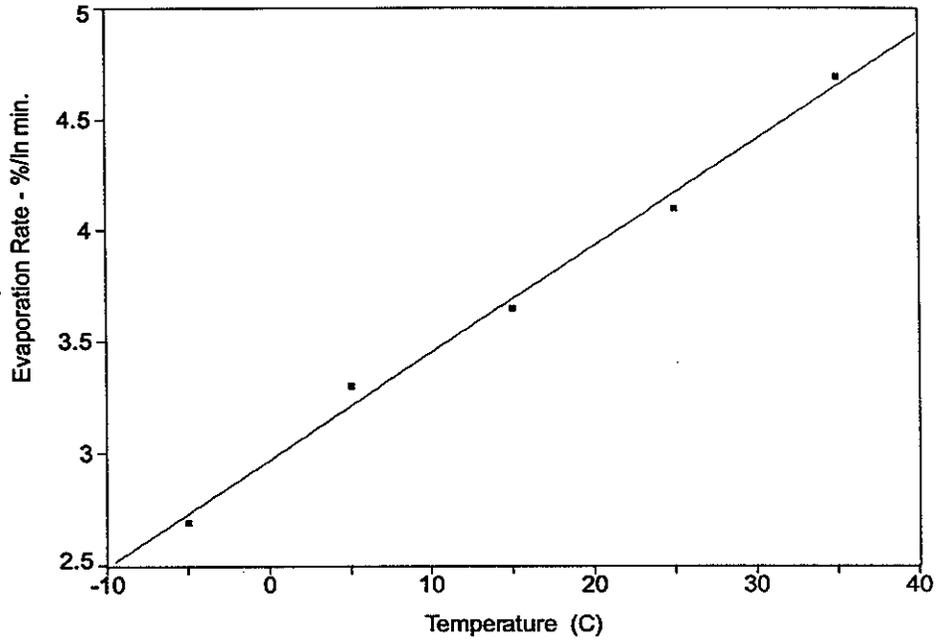


Figure 12

Correlation of Diesel Evaporation and Temperature

Rank 15 Eqn 1 $y=a+bx$
 $r^2=0.899$ FitStdErr=0.109 Fstat=26.7
a=0.308
b=0.0178

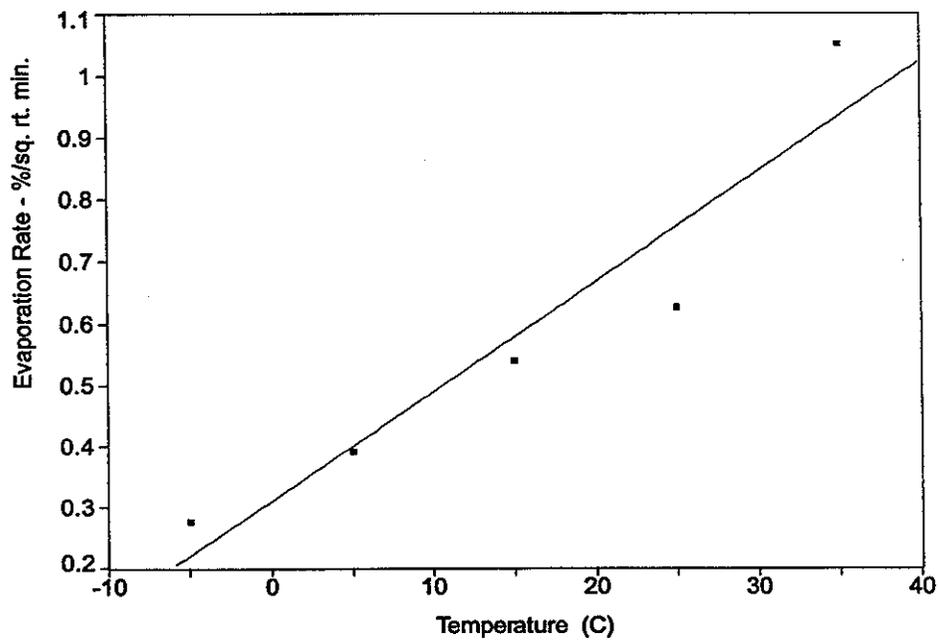


Figure 13

Correlation of Bunker C Light Evaporation and Temperature

Rank 8 Eqn 1 $y=a+bx$

$r^2=0.932$ FitStdErr=0.0130 Fstat=40.8

$a=0.0035$

$b=0.00262$

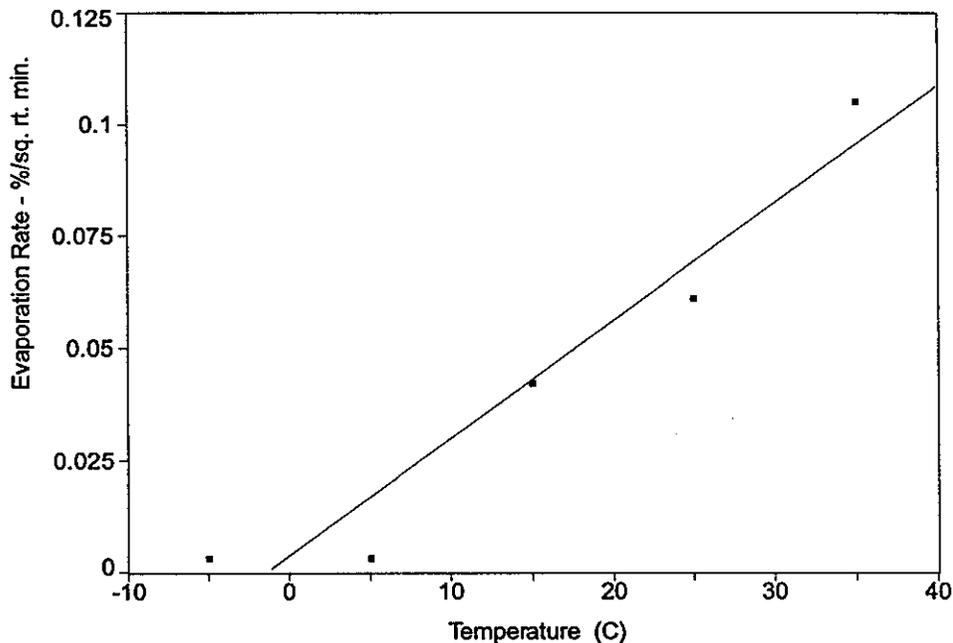


Figure 14

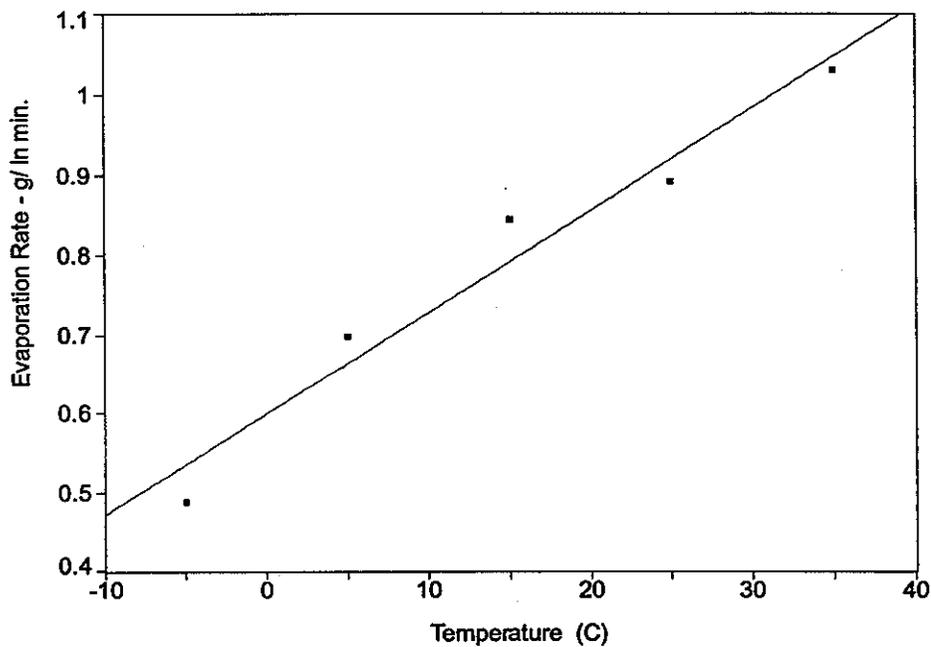
Correlation of ASMB Evaporation and Temperature
Loss of Weight Equation

Rank 3 Eqn 1 $y=a+bx$

$r^2=0.957$ FitStdErr=0.0494 Fstat=67.0

$a=0.598$

$b=0.0128$



very common and often are the only data used to characterize oils. This is because the data is crucial in operating refineries. Crudes may even be priced on the basis of their distillation data. New procedures to measure distillation data are very simple, fast and repeatable (Jokuty and Fingas, 1994). Two separate ways of using the distillation data will be tried, first a portion of the curve, and second, the entire distillation curve slope.

The first method involves correlating the empirically-measured parameters at 15°C with both the slopes and the intercepts of the temperature equations. The latter data are given in Table 4. The equation base parameters (single-factor equation constant determined at 15 °C) used for the correlation are listed in Table 3. The regressions for the percentage equations are shown in Figures 15 (slope) and 16 (intercept). The regressions for the weight equations are shown in Figures 17 (slope) and 18 (intercept). These figures display fit information and the plot itself. The rank (in terms of regression coefficient, r^2) of the linear equation used for the regressions appears directly below the captions. Then the regression coefficient, fit standard error and the F statistic are given. Finally, the equation constants are given. The regression coefficients, r^2 , are .86, .99, .76, and .99 for the four linear regressions. This indicates a very high correlation of the data and consequently, the fact that the temperature equations are relatively parallel. This is remarkable, especially since diesel and Bunker C light are best fit with square root curves rather than logarithmic ones. Gasoline was not included in this analysis because of the high rates involved (evaporation rates are an order of magnitude higher) and this skews the results, despite the increased regression coefficients with gasoline in the data set. The equations resulting from the regressions illustrated in Figures 15 to 18 were used to calculate rates. The empirical and calculated values are shown in Table 5. It can be seen that the calculated equation parameters are reasonable and are well within 5% of the empirical ones. This scheme could be used to estimate evaporation equations using only the rate at 15°C. The recalculation of the base equations is given in Table 6. The equations, in this case, were calculated using a direct linear factor in a spread sheet. The total difference squared between the calculated and the actual values was minimized. In the case of the percentage equation, the best relationship found, was 0.45 times the temperature and for the weight equation, the best relationship was 0.01 times the temperature difference plus the base found at 15°C. These might then be described as formulae:

$$\text{percentage equation factor} = (B + 0.045(T-15)) \quad (2)$$

$$\text{and weight equation factor} = (B + 0.01(T-15)) \quad (3)$$

where B is the equation parameter at 15°C and T is temperature in degrees Celsius.

This technique produces satisfactory results for all of the oils except for diesel and Bunker C light. These oils, as noted several times above, follow a square root equation rather than a logarithmic equation, so it is expected that correlation of logarithmic equations would not yield satisfactory results for these oils.

The second correlation noted was that of the distillation data and the equation parameters. The distillation data are taken from a standard reference work on oil (Whiticar et al., 1994). The form of the data used here is the percentage evaporated at a given temperature (the alternative form is the temperature at which a fixed distillation percentage is given). Distillation data are one of the few pieces of information that are routinely available for most oils because distillation data are used to rate petroleum products and feed-stock oils. The slopes of both the percentage and weight evaporation

Table 3 Evaporation Rates or Single-Factor Equation Parameters

Weight Percent Parameters									
Temp -°C	ASMB	Gulfaks	Brent	Arab Lt.	Gasoline	Terra Nova	Statfjord	Diesel	Bunker C Lt.
-5	2.94	2.09	3.08	2.37	12.1	1.43	2.69	0.276	0.003
5	3.48	2.54	3.67	2.61	15.2	not done	3.3	0.389	0.003
15	4.22	2.81	4.23	3.11	15.9	2.39	3.65	0.538	0.042
25	4.45	3.01	4.44	3.5	16.9	3	4.1	0.623	0.061
35	5.13	3.54	5.07	3.78	21.9	3.26	4.69	1.05	0.105

Absolute Weight Parameters									
Temp -°C	ASMB	Gulfaks	Brent	Arab Lt.	Gasoline	Terra Nova	Statfjord	Diesel	Bunker C Lt.
-5	0.487	0.407	0.615	0.475	2.52	0.313	0.449	0.054	0.0006
5	0.697	0.509	0.735	0.523	3.13	not done	0.66	0.078	0.006
15	0.844	0.562	0.846	0.621	3.29	0.351	0.73	0.109	0.008
25	0.891	0.601	0.888	0.699	3.39	0.482	0.82	0.125	0.012
35	1.03	0.715	1.01	0.757	4.39	0.651	0.938	0.198	0.021

Table 4 Equations Relating Evaporation Rate and Temperature

Oil	Equation Parameters - %		Equation Parameters - Wt.		Parameter at 15 °C	
	Intercept	Slope	Intercept	Slope	Percent	Weight
Arab Lt.	2.52	0.0371	0.504	0.0074	3.11	0.621
ASMB	3.24	0.0535	0.598	0.0128	4.22	0.844
Brent	3.39	0.0475	0.677	0.00943	4.23	0.846
Bunker C Lt.*	0.0035	0.00262	0.0025	0.00468	0.042	0.008
Diesel*	0.308	0.0178	0.0626	0.00335	0.538	0.109
Gasoline	13.2	0.213	2.74	0.04	15.9	3.29
Gulfaks	2.29	0.0337	0.453	0.00708	2.81	0.562
Statfjord	2.67	0.06	0.499	0.0134	3.65	0.73
Terra Nova	1.36	0.0595	0.235	0.0108	2.39	0.351

* fitted with square root equations

Table 5 Experimental and Calculated Temperature Equations

Oil	Equation Parameters - % *		Equation Parameters - Wt. *		Single-Parameter **	
	Intercept	Slope	Intercept	Slope	% Base	Wt. Base
ASMB	3.24	0.0535	0.598	0.0128	4.22	0.844
Gulfaks	2.29	0.0337	0.453	0.00708	2.81	0.562
Brent	3.39	0.0475	0.677	0.00943	4.23	0.846
Arab Lt.	2.52	0.0371	0.504	0.0074	3.11	0.621
Terra Nova	1.69	0.0473	0.308	0.0081	2.39	0.351
Statfjord	2.97	0.048	0.548	0.0111	3.65	0.73
Diesel	0.308	0.0178	0.0626	0.00335	0.538	0.109
Bunker C Lt.	0.0035	0.00262	0.0025	0.00468	0.042	0.008

* The equation parameters consist of a slope and intercept which when combined yield a regular single-parameter equation at the given temperature

** regular single parameter equations at 15°C

Calculated Values from Regression Equations

Oil	Equation Parameters - %		Equation Parameters - Wt.	
	Intercept	Slope	Intercept	Slope
ASMB	3.52	0.052	0.65	0.011
Gulfaks	2.37	0.038	0.435	0.008
Brent	3.53	0.053	0.652	0.011
Arab Lt.	2.62	0.041	0.48	0.009
Terra Nova	2.03	0.034	0.273	0.007
Statfjord	3.06	0.047	0.563	0.01
Diesel	0.52	0.014	0.088	0.005
Bunker C Lt.	0.12	0.009	0.011	0.004

Equations used to Calculate the Values

$$I = .00853 + .814 * \text{base}$$

$$S = .00894 + .0103 * \text{base}$$

$$I = .00476 + .765 * \text{base}$$

$$S = .00367 + .00849 * \text{base}$$

I = intercept S = slope

Figure 15

Correlation of Percent Temperature Equation Slope and Base Parameter
Rank 18 Eqn 1 $y=a+bx$

$r^2=0.858$ FitStdErr=0.00715 Fstat=36.3

$a=0.00894$

$b=0.0103$

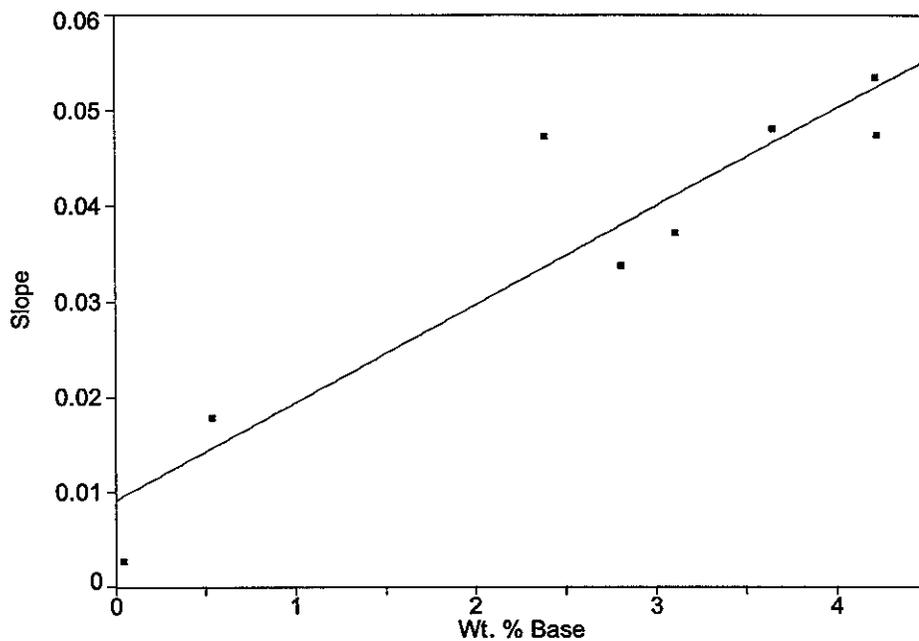


Figure 16

Correlation of Percent Temperature Equation Intercept and Base Parameter
Rank 6 Eqn 1 $y=a+bx$

$r^2=0.994$ FitStdErr=0.106 Fstat=1030

$a=-0.0853$

$b=0.814$

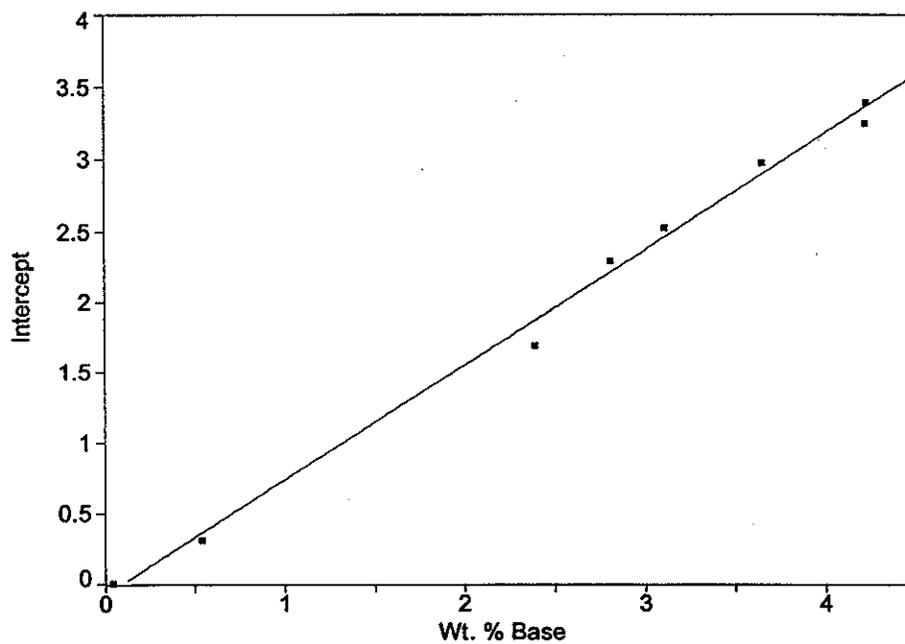


Figure 17

Correlation of Weight Temperature Equation Slope and Base Parameter

Rank 8 Eqn 1 $y=a+bx$
 $r^2=0.764$ FitStdErr=0.00164 Fstat=19.4
 $a=0.00367$
 $b=0.00849$

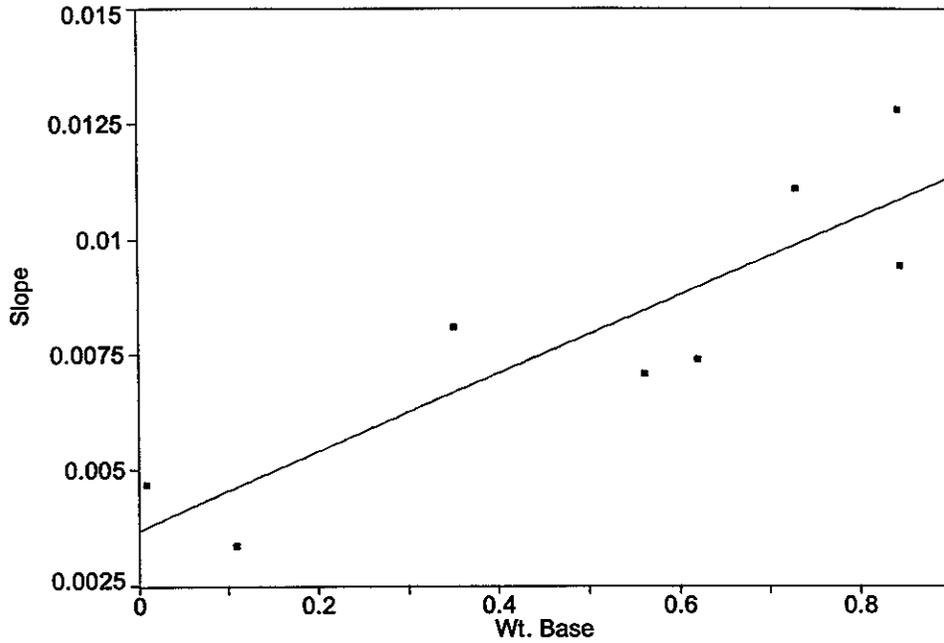
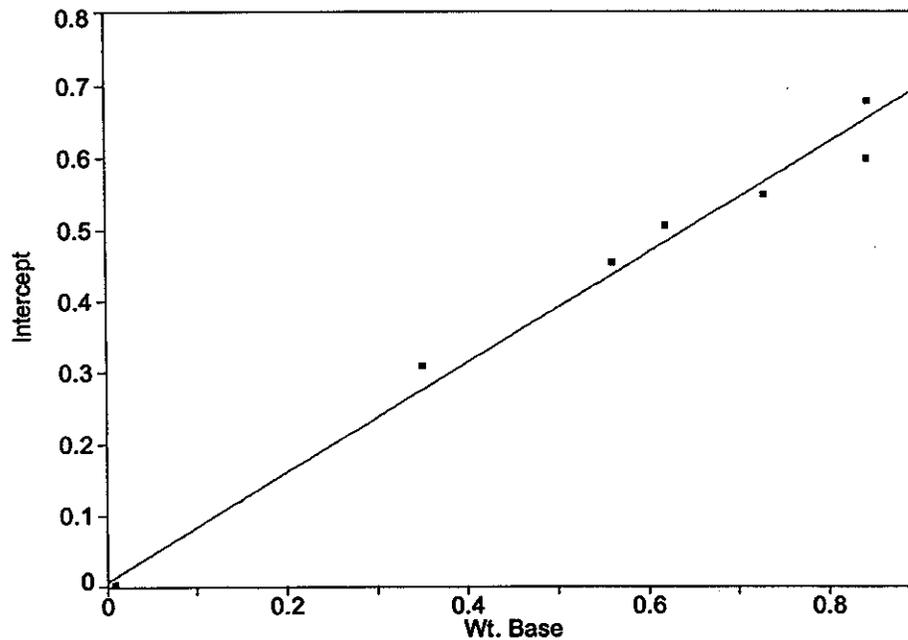


Figure 18

Correlation of Weight Temperature Equation Intercept and Base Parameter

Rank 10 Eqn 1 $y=a+bx$
 $r^2=0.985$ FitStdErr=0.0328 Fstat=395
 $a=0.00476$
 $b=0.765$



**Table 6 Evaporation Rates or Single-Factor Equation Parameters
- Prediction Using Base Equations**

Percent Parameters

Temp -°C	ASMB	Gulfaks	Brent	Arab Lt.	Gasoline	Terra Nova	Statfjord	Diesel	Bunker C Lt.
-5	2.94	2.09	3.08	2.37	12.1	1.43	2.69	0.276	0.003
5	3.48	2.54	3.67	2.61	15.2	not done	3.3	0.389	0.003
15	4.22	2.81	4.23	3.11	15.9	2.39	3.65	0.538	0.042
25	4.45	3.01	4.44	3.5	16.9	3	4.1	0.623	0.061
35	5.13	3.54	5.07	3.78	21.9	3.26	4.69	1.05	0.105
Base	4.22	2.81	4.23	3.11	15.9	2.39	3.65	0.538	0.042

Calculated Percent Parameters

Temp -°C	ASMB	Gulfaks	Brent	Arab Lt.	Gasoline	Terra Nova	Statfjord	Diesel	Bunker C Lt.
-5	3.32	1.91	3.33	2.21	15	1.49	2.75	-0.36	-0.86
5	3.77	2.36	3.78	2.66	15.45	1.94	3.2	0.09	-0.41
15	4.22	2.81	4.23	3.11	15.9	2.39	3.65	0.54	0.04
25	4.67	3.26	4.68	3.56	16.35	2.84	4.1	0.99	0.49
35	5.12	3.71	5.13	4.01	16.8	3.29	4.55	1.44	0.94

calculated using the equation value = base + .045 (T-15)

Absolute Weight Parameters

Temp -°C	ASMB	Gulfaks	Brent	Arab Lt.	Gasoline	Terra Nova	Statfjord	Diesel	Bunker C Lt.
-5	0.487	0.407	0.615	0.475	2.52	0.313	0.449	0.054	0.0006
5	0.697	0.509	0.735	0.523	3.13	not done	0.66	0.078	0.006
15	0.844	0.562	0.846	0.621	3.29	0.351	0.73	0.109	0.008
25	0.891	0.601	0.888	0.699	3.39	0.482	0.82	0.125	0.012
35	1.03	0.715	1.01	0.757	4.39	0.651	0.938	0.198	0.021
Base	0.844	0.562	0.846	0.621	3.29	0.385	0.73	0.109	0.008

Calculated Weight Parameters

Temp -°C	ASMB	Gulfaks	Brent	Arab Lt.	Gasoline	Terra Nova	Statfjord	Diesel	Bunker C Lt.
-5	0.64	0.36	0.65	0.42	3.09	0.19	0.53	-0.09	-0.19
5	0.74	0.46	0.75	0.52	3.19	0.29	0.63	0.01	-0.09
15	0.84	0.56	0.85	0.62	3.29	0.39	0.73	0.11	0.01
25	0.94	0.66	0.95	0.72	3.39	0.49	0.83	0.21	0.11
35	1.04	0.76	1.05	0.82	3.49	0.59	0.93	0.31	0.21

calculated using the equation value = base + .01 (T-15)

curves were correlated with the percentages of the product that distills at given temperatures. The resulting regression coefficient (r^2) was plotted versus the temperature at which it was taken. Figures 19 and 20 show the results of these calculations. The plot of regression coefficients versus the temperatures at which the distillation data was obtained, was used in TableCurve to optimize the value at which the regression coefficient is highest. In each of Figures 19 and 20, the first ranked equation used to perform this optimization is given, then the regression coefficient of this optimization equation, the corrected regression coefficient, corrected for the degrees of freedom for this particular case, the standard error of fit, and the F statistic (all rounded to 3 significant figures). Finally the parameters of the optimization equation itself are given. Both figures show that the regression coefficient is maximum when distillation data of approximately 140 °C are used.

The distillation data at 140 °C was then correlated with the slopes and intercepts of the temperature-dependent equations to yield predictor values. The correlations are shown in Figures 21 to 24. These figures were created using TableCurve and include: the equation chosen (always a one-parameter linear one here), the regression coefficient (r^2), the corrected regression coefficient, the standard error of fit, the F statistic, and finally, the value of the linear equation parameter, a ($Y=ax$). The regression coefficient in all four cases (Figures 21 to 24, slopes and intercepts of both the percentage and weight equations) ranges from a low of 0.91 to a high of .96, indicating strong correlation. This belies the fact, however, that there is a wide-gap between the values for the crude oils and that for gasoline. When gasoline is removed, the remaining data show significant noise.

The values from this correlation were used to estimate the values of the single-parameter temperature equations. The results are given in Table 7. The best fit equations are:

$$\text{percentage equation factor} = 0.161 D + 0.00262 TD \quad (4)$$

$$\text{and weight equation factor} = 0.329 D + 0.00502 TD \quad (5)$$

where D is the percent distilled at 140 °C.

Table 7 shows that, the results of this correlation are very good for ASMB and gasoline, but poorer for the other oils. The method could not be applied to Diesel and Bunker C light because there is no distillation data for 140 °C, however, a trial run at 160 °C, where there are data, shows that this calculation method was not successful. This is probably due to the difference in equations for these two oils (square root versus logarithmic) and a separate procedure would be needed to perform this calculation. Despite the variability in the fit qualities, the prediction of the temperature-equations using only distillation data implies that the evaporation and distillation data are indeed strongly related. In practical terms, this also implies that evaporation for oils where no evaporation data exist, can be predicted, with accuracy better than 50%, using only distillation data. No other alternatives are available at the moment. The specific distillation data are listed in Table 8.

In the second part of the study, distillation data were directly correlated to the evaporation rates determined by experimentation. Empirical rates, given as a percentage evaporated, are listed in Table 2. In addition, evaporation rates as absolute weight (in grams) were also calculated and used in these studies. The latter data are generally not available in as accurate form as the former and to interpret them, total mass of the oil evaporating must be divided by the amount used in the experiment, typically 20 g. Thus,

Figure 19 Optimization of Distillation and Temperature Slope - Percent Equation

Rank 1 Eqn 8006 $y=a+b\exp(-\exp(-((x-c)/d))-(x-c)/d+1)$ [ExtrVal]
 $r^2=0.608$ DF Adj $r^2=0.497$ FitStdErr=0.0138 Fstat=7.77

a=0.522 b=0.474
 c=138 d=-248

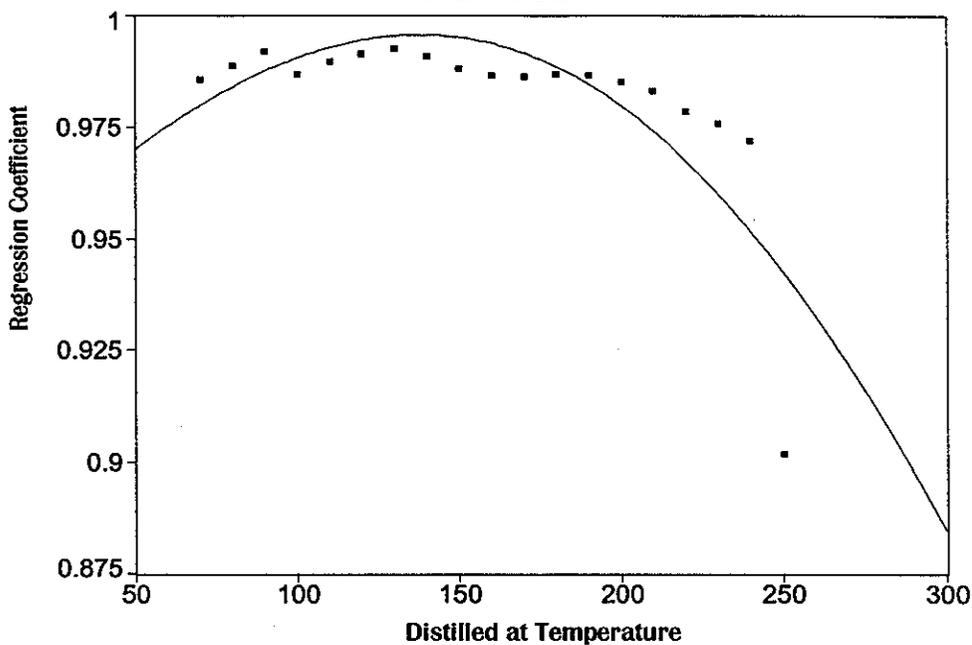


Figure 20 Optimization of Distillation and Temperature Slope - Weight Equation

Rank 1 Eqn 8008 $y=a+\text{berfc}(((x-c)/d)^2)$ [Erfc Peak]
 $r^2=0.572$ DF Adj $r^2=0.450$ FitStdErr=0.0298 Fstat=6.68

a=-7.38 b=8.38
 c=138 d=1050

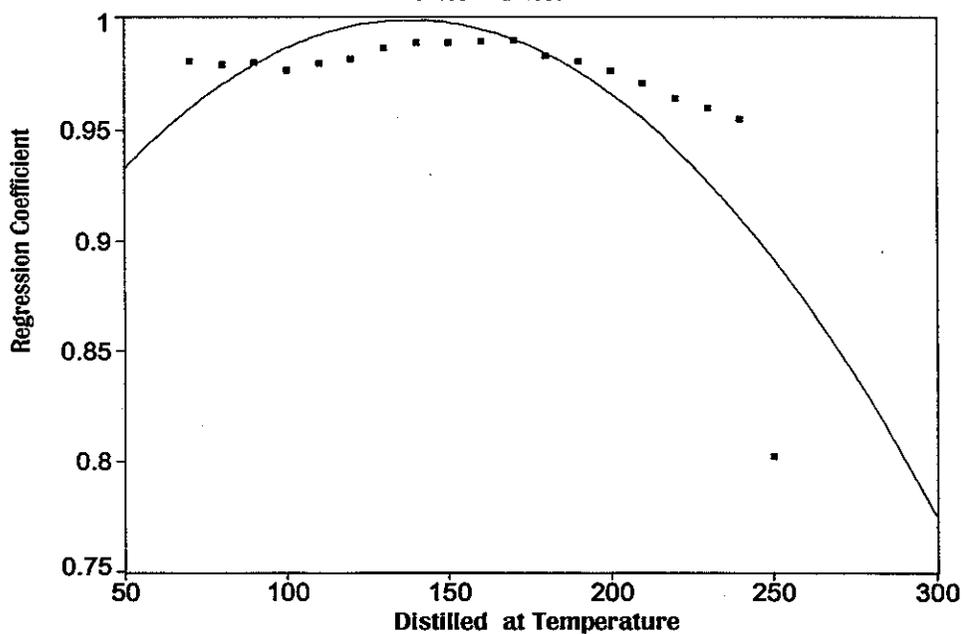


Figure 21

Correlation of Slope of Percent Equation and the Percent Distilled at a Given Temperature

Rank 1 Eqn 8001 y=linear()

$r^2=0.949$ DF Adj $r^2=0.939$ FitStdErr=0.0144 Fstat=+ INF

a=0.00262

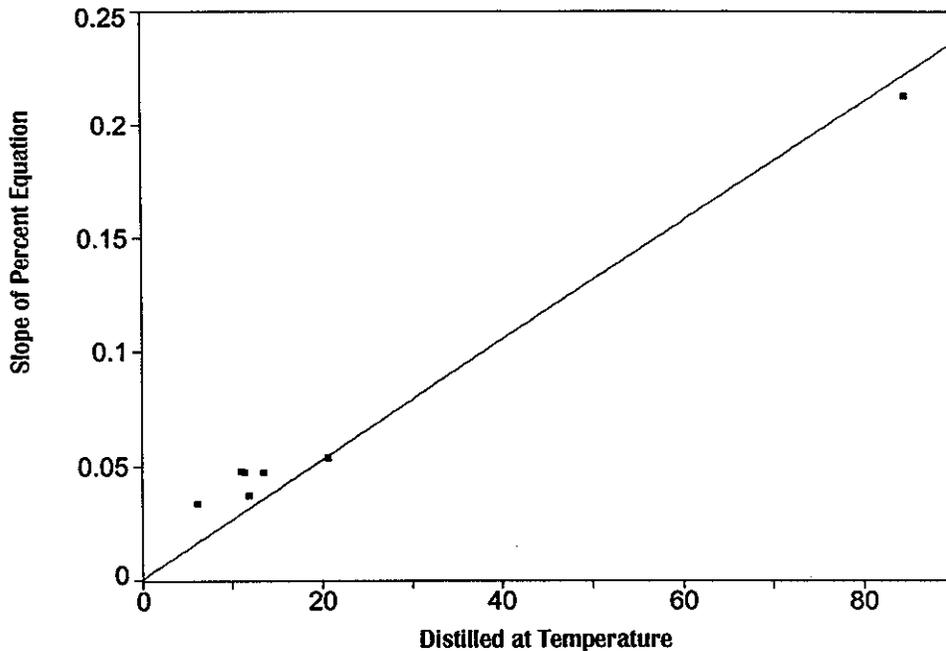


Figure 22

Correlation of Intercept of Percent Equation and the Percent Distilled at a Given Temperature

$r^2=0.952$ DF Adj $r^2=0.942$ FitStdErr=0.893 Fstat=+ INF

a=0.161

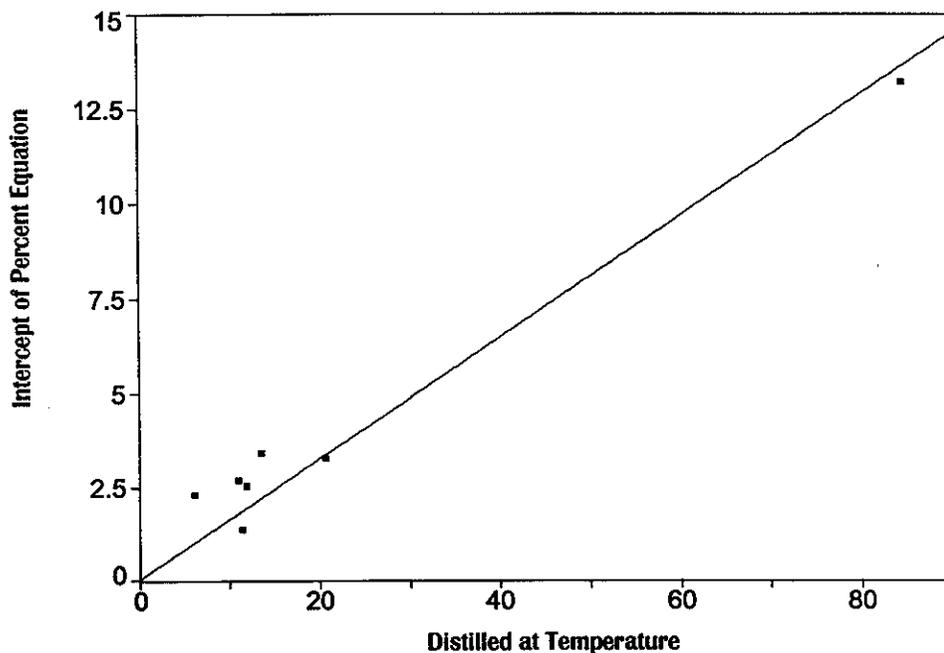


Figure 23

Correlation of Slope of Weight Equation and the Percent Distilled at a Given Temperature

Rank 1 Eqn 8001 y=linear()

$r^2=0.911$ DF Adj $r^2=0.893$ FitStdErr=0.00352 Fstat=+INF

a=0.000502

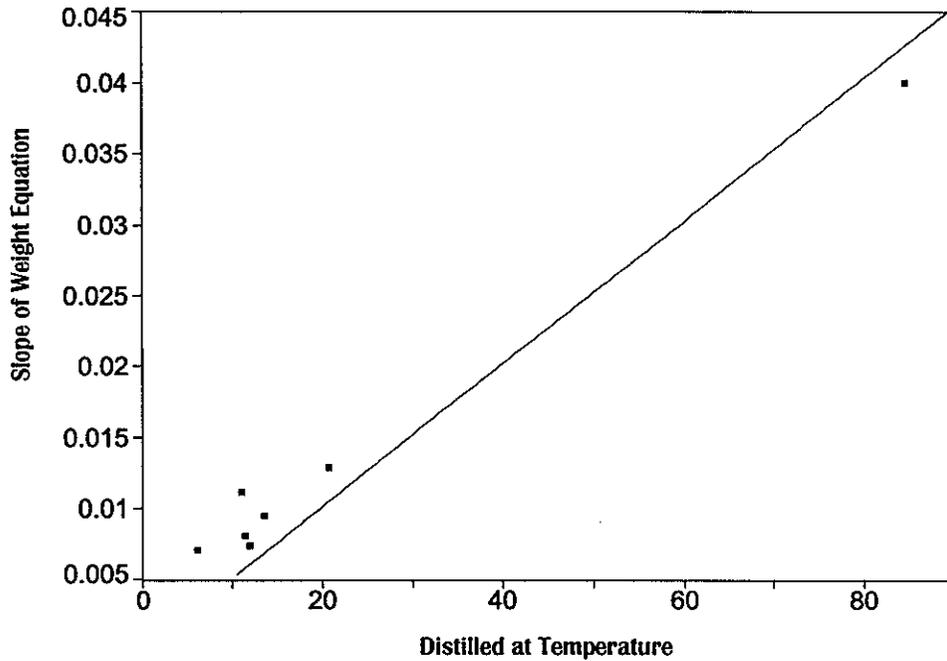


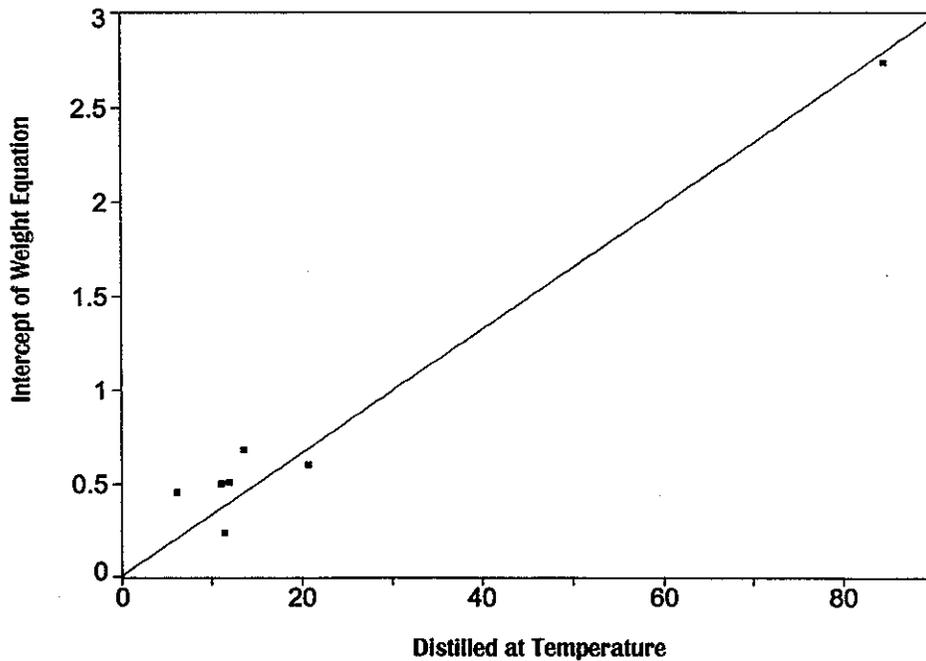
Figure 24

Correlation of Intercept of Weight Equation and the Percent Distilled at a Given Temperature

Rank 1 Eqn 8001 y=linear()

$r^2=0.960$ DF Adj $r^2=0.952$ FitStdErr=0.172 Fstat=+INF

a=0.0329



**Table 7 Evaporation Rates or Single-Factor Equation Parameters
- Prediction By Use of Distillation Data**

Percent Parameters

Temp -°C	ASMB	Gulfaks	Brent	Arab Lt.	Gasoline	Terra Nova	Staffjord	Diesel	Bunker C Lt.
-5	2.94	2.09	3.08	2.37	12.1	1.43	2.69	0.276	0.003
5	3.48	2.54	3.67	2.61	15.2	not done	3.3	0.389	0.003
15	4.22	2.81	4.23	3.11	15.9	2.39	3.65	0.538	0.042
25	4.45	3.01	4.44	3.5	16.9	3	4.1	0.623	0.061
35	5.13	3.54	5.07	3.78	21.9	3.26	4.69	1.05	0.105
Distilled at 140 °C	20.6	6.6	13.5	11.9	84.7	11.4	12.2	0	0

Calculated Percent Parameters

Temp -°C	ASMB	Gulfaks	Brent	Arab Lt.	Gasoline	Terra Nova	Staffjord	Diesel	Bunker C Lt.
-5	3.05	0.98	2	1.76	12.53	1.69	1.8	0	0
5	3.59	1.15	2.35	2.07	14.75	1.98	2.12	0	0
15	4.13	1.32	2.7	2.38	16.97	2.28	2.44	0	0
25	4.67	1.49	3.06	2.7	19.18	2.58	2.76	0	0
35	5.21	1.67	3.41	3.01	21.4	2.88	3.08	0	0

calculated using the equation value = .161 Distill + .00262 T Distill

Absolute Weight Parameters

Temp -°C	ASMB	Gulfaks	Brent	Arab Lt.	Gasoline	Terra Nova	Staffjord	Diesel	Bunker C Lt.
-5	0.487	0.407	0.615	0.475	2.52	0.313	0.449	0.054	0.0006
5	0.697	0.509	0.735	0.523	3.13	not done	0.66	0.078	0.006
15	0.844	0.562	0.846	0.621	3.29	0.351	0.73	0.109	0.008
25	0.891	0.601	0.888	0.699	3.39	0.482	0.82	0.125	0.012
35	1.03	0.715	1.01	0.757	4.39	0.651	0.938	0.198	0.021
Distilled at 140 °C	20.6	6.1	13.5	11.9	84.7	11.4	11	0	0

Calculated Weight Parameters

Temp -°C	ASMB	Gulfaks	Brent	Arab Lt.	Gasoline	Terra Nova	Staffjord	Diesel	Bunker C Lt.
-5	0.63	0.2	0.41	0.36	2.57	0.35	0.37	0	0
5	0.73	0.23	0.48	0.42	3	0.4	0.43	0	0
15	0.83	0.27	0.55	0.48	3.42	0.46	0.49	0	0
25	0.94	0.3	0.61	0.54	3.85	0.52	0.55	0	0
35	1.04	0.33	0.68	0.6	4.27	0.58	0.62	0	0

calculated using the equation value = .0329 Distill + .000502 T Distill

the more accurate form is used here. The distillation data are available in two forms, percent evaporated at a given temperature value (as used here) and as temperature at which a fixed amount of material is lost. The distillation curves are illustrated in Figure 25. Several trends are evident. Gasoline, the most volatile of the petroleum products, shows this volatility as a distinct curve on the left of the other curves. Diesel and FCC Heavy Cycle show a narrow boiling point range between about 160 and 260 degrees. It is interesting that these two products, of all those listed here, show best-fit evaporation equations with the square root of time, rather than the logarithm. This was shown in earlier works to be the result of the number of components evaporating. This conclusion is confirmed by the distillation curve, which indicates that the products in question consist of a few components over a narrow boiling point range. Figure 25 shows that most crude oil distillation curves are similar. Two curves which are slightly different than the others and pass through the bulk of the other curves are: Amauligak and Issungnak, both waxy, but light, Beaufort Sea crude oils. Bunker C and Bunker C light show the typical expected behaviour of heavy residual products.

The percentage distilled at each temperature was correlated with the equation parameter (sometimes referred to here as the evaporation rate). An example of such a correlation is shown in Figure 26. This figure shows the correlation of the percentage equation factor versus the distillation percentage at 150, 180 and 200 °C. As can be seen by the regression line, the correlation is high. This same correlation was repeated for both the percentage and weight equation factors and for several different temperatures. The regressions were also repeated without gasoline, which has a higher evaporation rate than the other values and could possibly skew the results. The data are referred to in figures and tables as "full set" when gasoline is included and "partial set" when gasoline is not. The regression coefficients (r^2) are listed in Table 9. This table shows that regression is highest when the distillation data are near 200 °C. This is illustrated by a plot of the regression coefficients versus temperature as shown in Figure 27. This figure shows that the regression coefficient peaks when the distillation temperature is about 180 °C, irrespective of whether the data is for the percentage or weight equations or whether gasoline is included or not. The optimal point, or point at which the regression coefficient is maximum, was found to be 180°C by using peak functions. These functions were also applied using the program, TableCurve. The results are shown in Figures 28 to 29. These figures include the rank of the peak equation selected by the program based on the highest regression coefficient, the regression coefficient (r^2), the standard error of fit, the F statistic and the constants for the equation.

The percent mass distilled at 180 degrees was used to calculate the relationship between the distillation values and the equation parameters. The equations used were derived from correlations of the data. Figures 30 to 33 show the correlations for the distillation data (percent distilled) at 180 °C. These figures include the rank of the linear equation selected for this exercise, the regression coefficient (r^2), the corrected regression coefficient for the current degrees of freedom, the standard error of fit, the F statistic and the constants for the equation.

The data from those oils which were better fitted with square root equations, diesel, Bunker C light and FCC Heavy Cycle, were separated and calculated separately. Since there are only three data points, the reliability and accuracy are lower than for the other set. Table 10 shows the equation parameters determined experimentally and those calculated using the function obtained from the regression. Table 10 shows the same data

Table 8 Distillation Data on Oil Used In Study

(data are percentages boiled off at the specified temperature)

Temp	Amuligak Arab Lt.	ASMB	Avalon Brent	Bunker	Bunker C I Diesel	Endicott	Federated	FCC heavy Gasoline	Gulfinks	Isungnak	Kominetf	Prudhoe	Santa Clara	Statford	Terra Nova
40	2.1	3.80				1.00	2.8	0.60	26.2			0.90	1.90		1.40
50	2.2	4.20				1.00	3.2	0.70	28.2			1.00	2.10		1.50
60	2.3	4.70	0.7			1.10	3.6	0.90	29.6			1.10	2.30		1.70
70	3.8	6.60	1.3	2.5		2.00	5.9	0.90	35.6	0.6	1.60	2.6	3.20	1.9	2.80
80	4.3	8.40	2	3.6		3.30	7.4	1.10	44.4	0.6	4.60	7.5	5.50	2.7	5.40
90	5.4	10.30	2.7	4.1		4.40	9.4	1.30	67.9	1	5.80	10.5	6.50	3.1	6.40
100	7	12.70	3.9	4.6		4.90	12	1.40	70.1	1.2	7.00	13.1	7.70	3.4	7.60
110	7.8	14.20	4.5	7.2		5.90	14.1	1.80	73.2	2	8.50	14.3	8.40	5.1	9.20
120	9.2	16.30	5.5	8.9		6.70	16.4	2.40	84.1	3	9.70	15.4	9.50	6.6	10.60
130	10.6	18.20	6.5	11.9		7.00	18.3	2.50	84.5	4.6	10.40	16.7	10.00	9.1	11.00
140	11.9	20.60	7.4	13.5		7.10	20.6	2.50	84.7	6.1	10.60	16.8	10.20	11	11.40
150	13.1	22.30	8.4	14.8	0.4	7.10	22.3	2.50	84.7	6.9	10.80	16.8	10.30	10.80	12.2
160	15.4	24.80	10	17.5	0.60	7.80	25.2	3.30	88.3	9	12.30	18.1	11.30	11.80	14.6
170	16.9	27.00	11.1	19	1.00	8.50	27.6	4.40	92.5	10.5	13.90	19.3	12.40	12.70	16.3
180	18.8	29.20	12.6	20.8	1.40	9.30	30	5.40	94.6	11.8	16.00	21.5	13.70	13.70	18
190	20.4	30.90	13.7	22.6	1.80	10.00	31.6	7.10	96.2	13.7	17.60	22.4	14.80	14.50	19.9
200	22.2	33.10	15.1	25	2.40	10.90	34.1	11.10	97.7	15.7	19.90	24.7	16.20	15.40	22.2
210	23.7	34.80	16.4	28.1	2.90	11.70	35.7	18.60	98.4	18.7	22.00	25.7	17.40	16.30	20.80
220	25.7	37.20	17.9	30.5	3.30	12.70	38.2	25.30	98.9	21.2	24.90	27.9	18.90	17.40	22.70
230	27.2	39.10	19.4	32.1	4.00	14.00	40.1	39.90	99.3	23	27.60	29.2	20.50	18.40	24.40
240	29	41.20	20.9	33.9	4.50	15.20	42.4	46.50	99.5	24.6	31.20	31.4	22.10	19.50	26.30
250	30.6	43.20	22.5	35.4	5.20	16.60	44.4	59.40		26.7	34.50	32.9	23.80	20.50	28.10
260	32.5	45.30	24.1	37.2	5.60	17.90	46.4	67.40		28.4	38.90	35.1	25.60	21.60	30.20
270	34.1	47.50	25.7	38.8	6.20	19.40	48.7	76.80		30.4	42.70	36.7	27.30	22.70	31.90
280	36	49.40	27.4	40.5	6.80	20.90	50.8	84.80		32.2	46.70	38.8	29.10	23.80	34.10
290	37.9	51.50	29.2	42.2	7.50	22.50	52.8	90.30		33.9	50.50	40.8	31.00	24.90	36.10
300	39.5	53.40	30.7	43.7	8.1	24.00	54.7	94.90		35.8	53.80	42.4	32.70	26.10	37.90
310	41.5	55.90	32.8	45.7	8.80	26.00	57.2	97.50		37.9	58.30	45	34.80	27.70	40.20
320	43.5	58.20	34.8	47.6	9.70	27.90	59.5	98.90		39.8	62.00	47.2	36.90	29.30	42.50
330	45.1	60.30	36.4	48.9	10.60	29.50	61.2	99.50		41.6	64.70	48.7	38.60	30.40	44.20
340	46.9	61.90	38	50.4	11.50	31.30	63.1			43.2	67.90	50.6	40.50	31.60	46.20
350	48.8	63.90	39.7	51.9	12.60	33.30	65.1			44.9	70.80	52.3	42.40	32.80	48.10
360	50.6	65.80	41.4	53.4	13.80	35.20	66.9			46.6	73.50	53.9	44.30	34.10	50.00
370	52.3	67.60	43.1	54.9	15.30	37.20	68.8			48.2	76.00	55.6	46.10	35.40	52.00
380	53.9	69.40	44.7	56.2	16.70	39.00	70.4			49.8	78.10	57.1	47.80	36.70	53.70
390	55.5	71.00	46.2	57.5	18.30	40.90	72			51.3	80.30	58.6	49.60	37.90	55.50
400	57.2	72.60	47.9	58.9	19.90	43.00	73.7			52.9	82.30	60.3	51.40	39.20	57.40

Figure 25 Plot of Distillation Curves

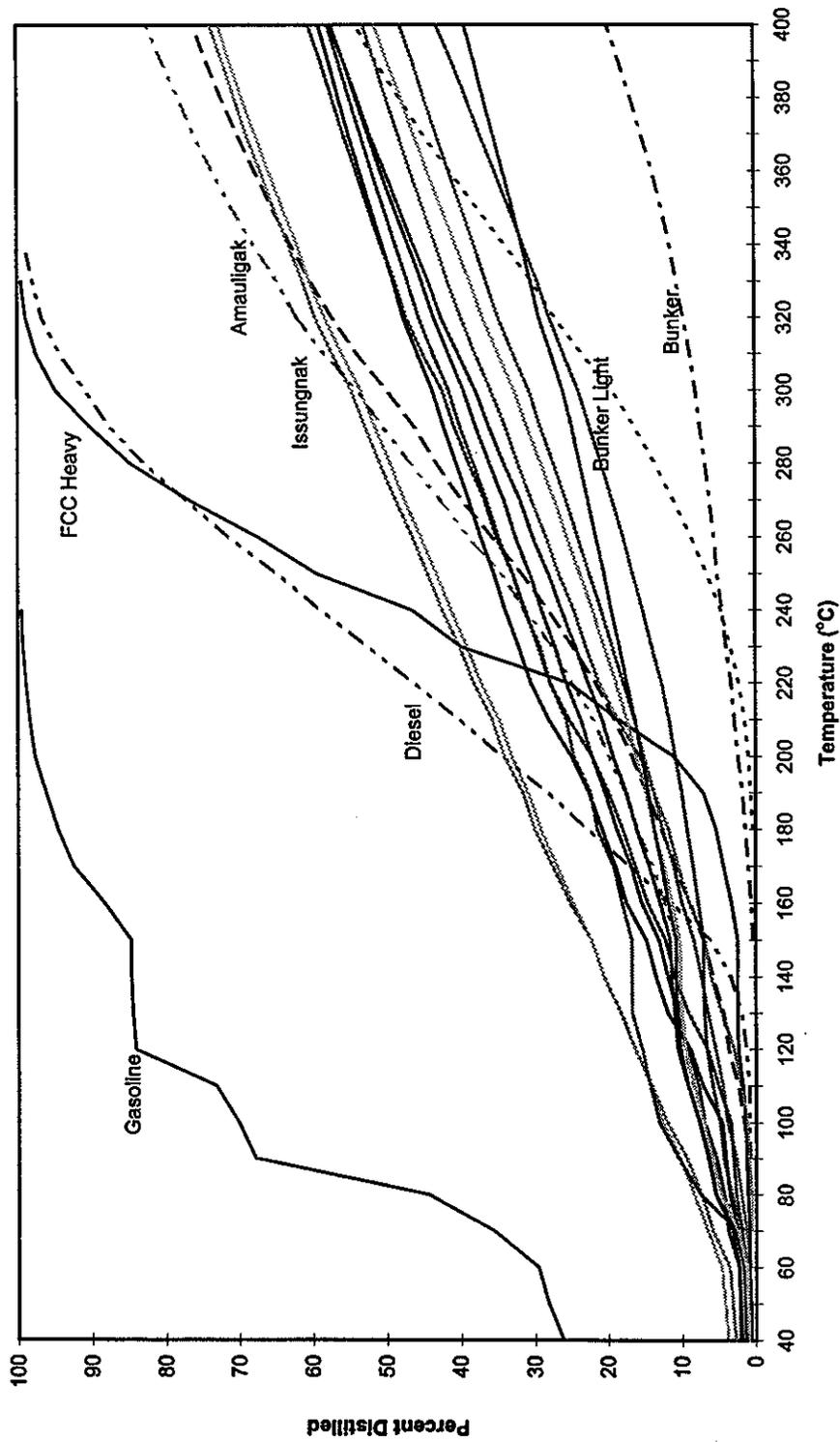


Figure 26

Correlation of Evaporation Parameters with Distillation Data

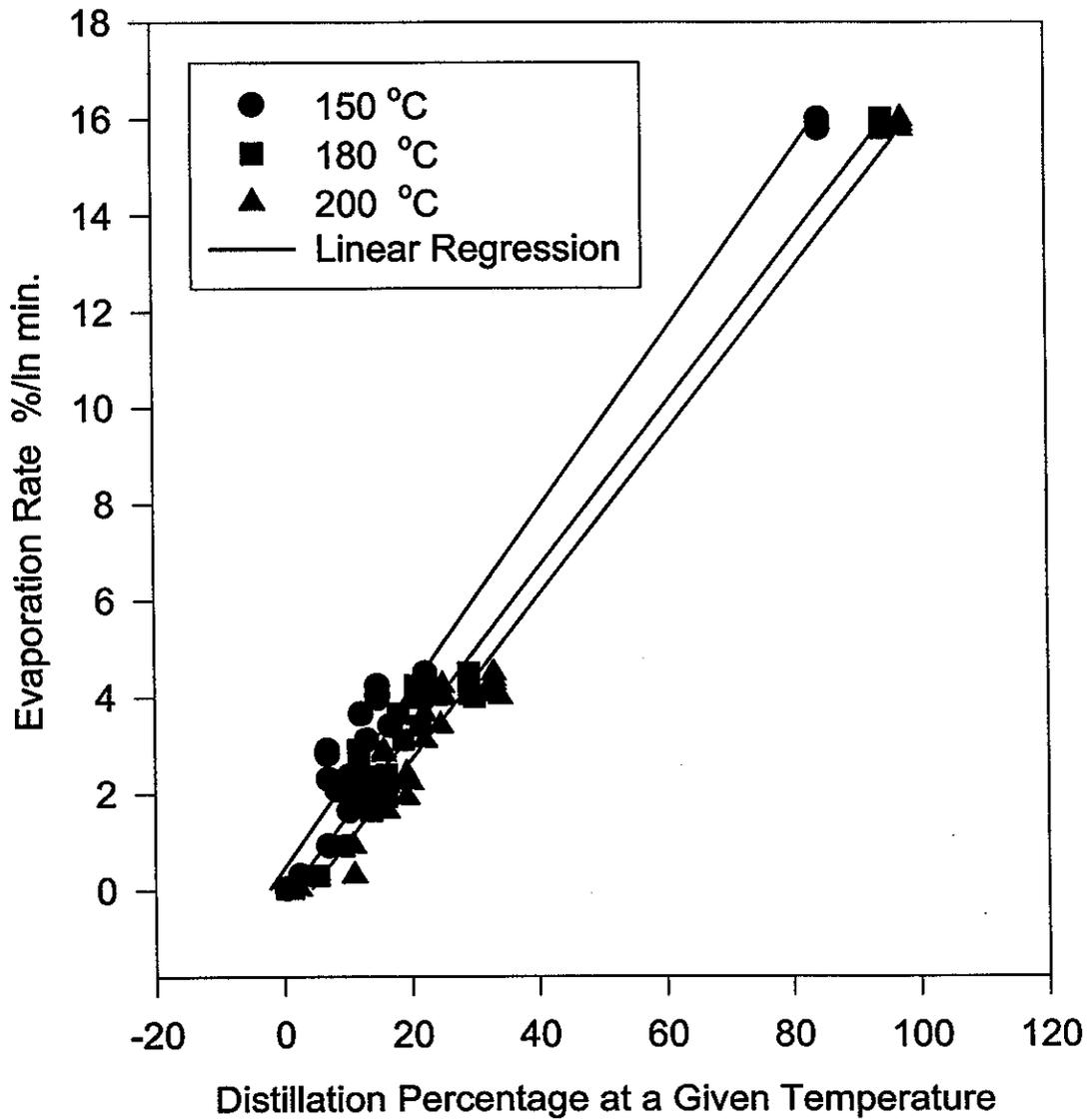


Table 9

Correlation Between Distillation Data and Evaporation

Boiling Temperature	Percentage		Weight	
	r ² Percent Full Set	r ² Percent Partial Set	r ² Percent Full Set	r ² Percent Partial Set
150	0.9796	0.7958	0.9626	0.6605
160	0.9839	0.8414	0.9668	0.7043
170	0.984	0.8448	0.9662	0.7037
180	0.9838	0.8665	0.9652	0.7352
190	0.9847	0.8805	0.9659	0.7477
200	0.9828	0.8803	0.9628	0.7413
210	0.9792	0.8684	0.9588	0.7309
220	0.9678	0.825	0.9456	0.6845
230	0.9327	0.6565	0.9089	0.5309
240	0.9085	0.5894	0.8829	0.4673
250	0.4432	0.4432	0.3398	0.3398
300	0.2011	0.2011	0.1332	0.1332
350	0.6194	0.6194	0.4615	0.4615
400	0.5158	0.5158	0.3732	0.3732

Figure 27

Distillation Regression Coefficients versus Temperature

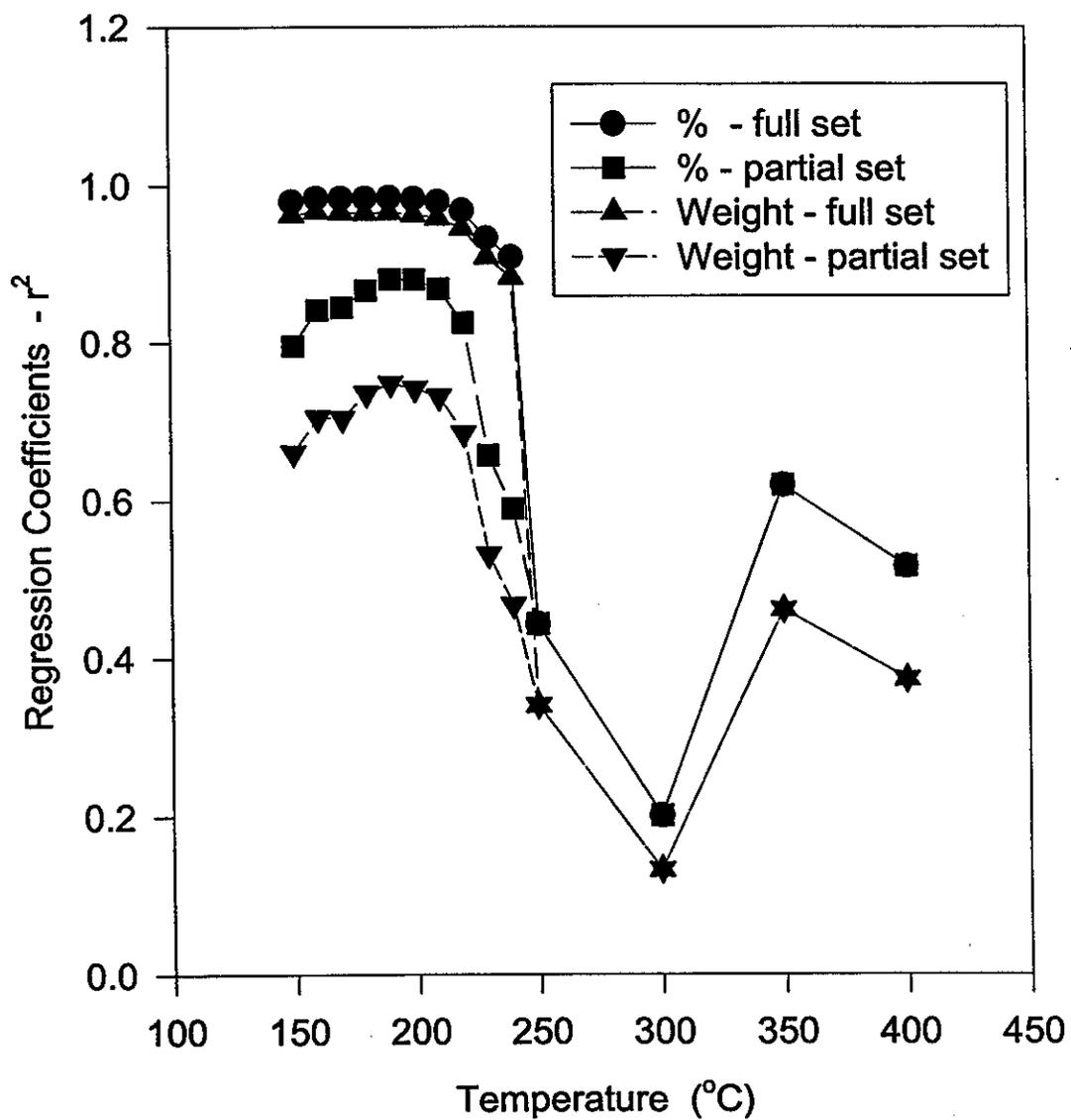


Figure 28

**Comparison of Regression Coefficients
and Temperatures at Which These Occur
- Percentage Curves and Full Set**

Rank 1 Eqn 8007 $y=a+b*4n/(1+n)^2 n=\exp(-(x-c)/d)$ [Logistic]

$r^2=0.939$ FitStdErr=0.00797 Fstat=310

a=-73.2 b=742

c=179 d=944

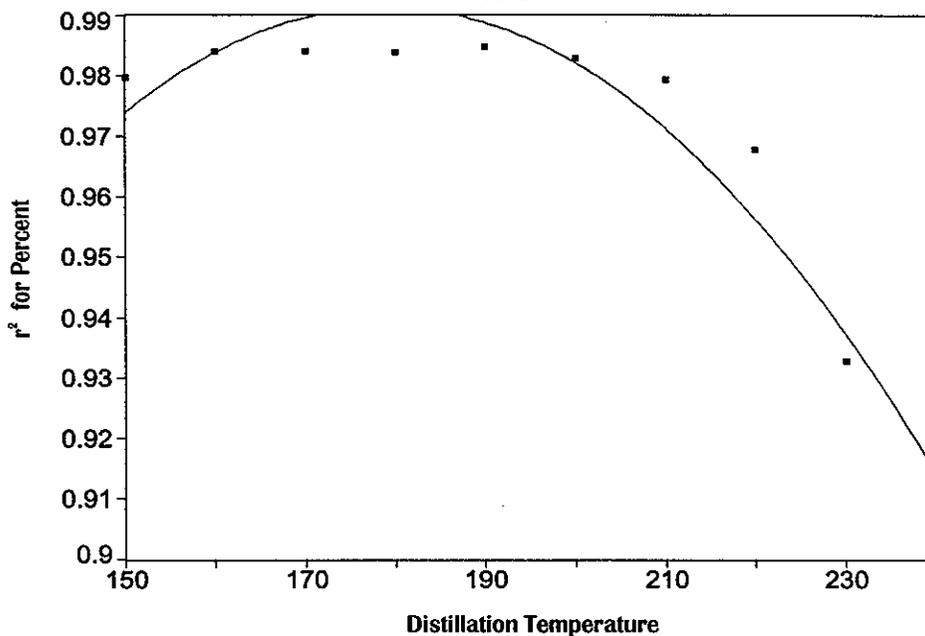


Figure 29

**Comparison of Regression Coefficients
and Temperatures at Which These Occur
- Percentage Curves and Partial Set**

Rank 1 Eqn 8008 $y=a+berfc(((x^2-c)/d))$ [Erfc Peak]

$r^2=0.917$ FitStdErr=0.0354 Fstat=22.1

a=-8.49 b=9.39

c=185 d=327

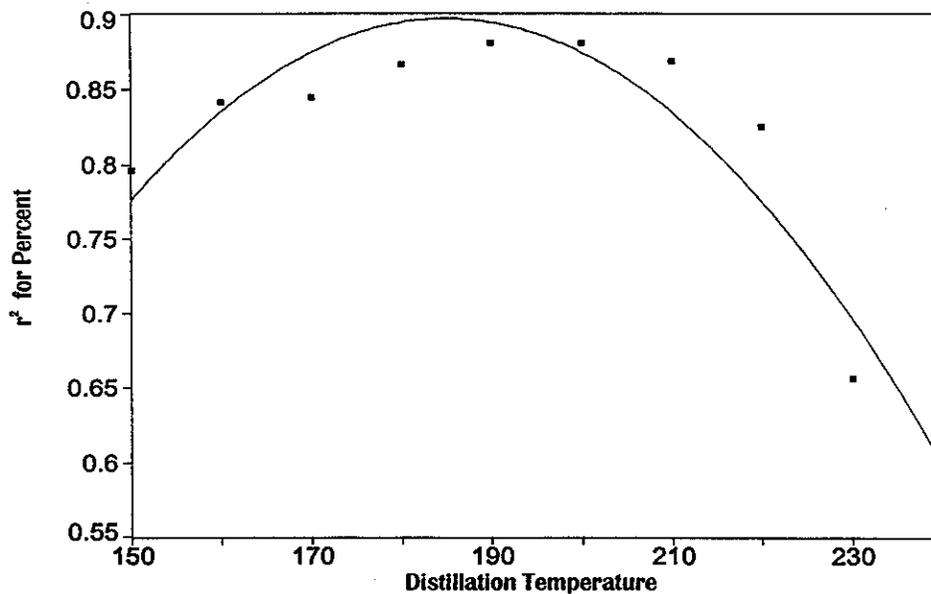


Figure 30

Correlation of Percent Equation and
the Percent Distilled at 180 °C

Rank 1 Eqn 8001 y=linear()

$r^2=0.983$ DF Adj $r^2=0.982$ FitStdErr=0.533 Fstat=+INF

a=0.165

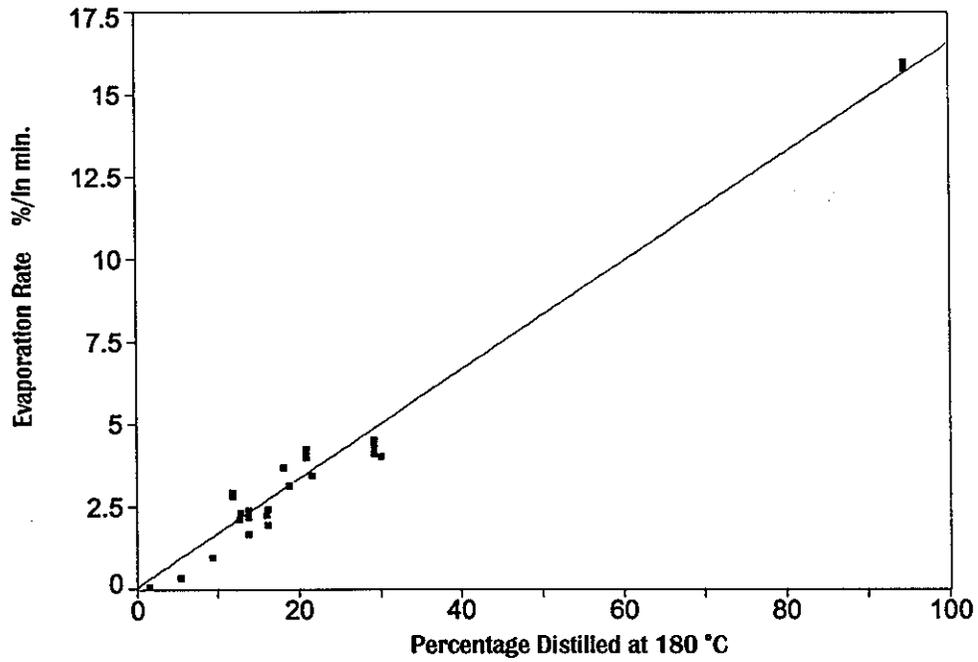


Figure 31

Correlation of Weight Equation and
the Percent Distilled at 180 °C

$r^2=0.964$ DF Adj $r^2=0.963$ FitStdErr=0.157 Fstat=+INF

a=0.0341

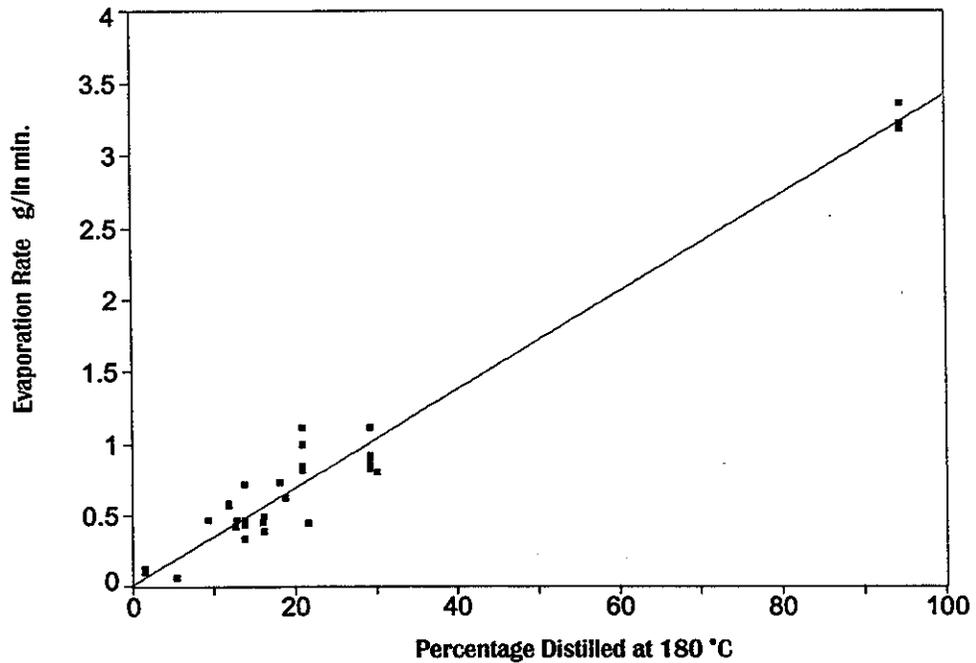


Figure 32

Correlation of Percent Equation and the Percent Distilled at 180 °C - Narrow-cut Products

Rank 2 Eqn 8001 y=linear()

$r^2=0.735$ DF Adj $r^2=0.471$ FitStdErr=0.128 Fstat=+INF

a=0.0254

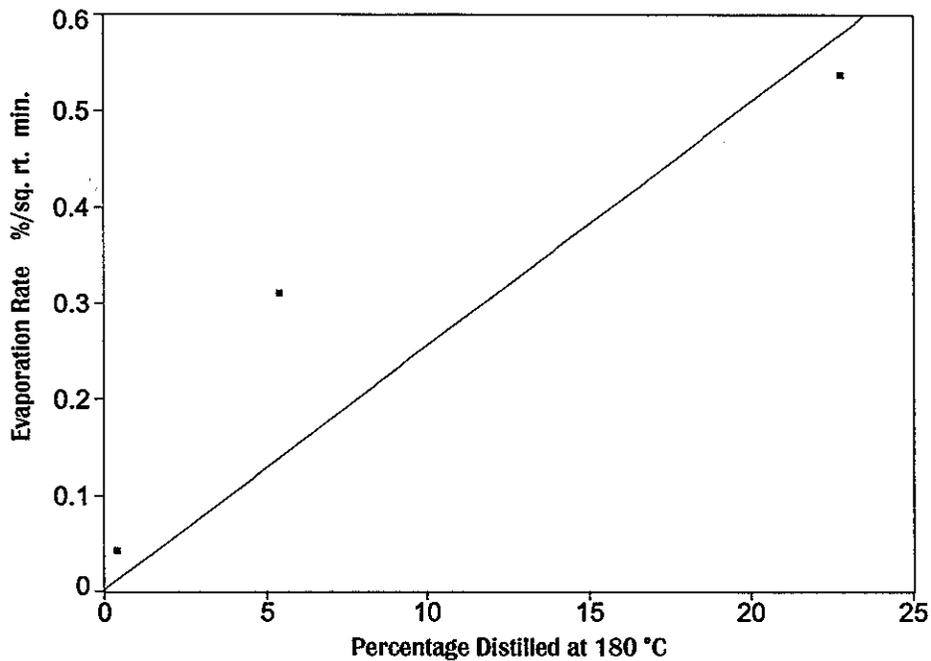
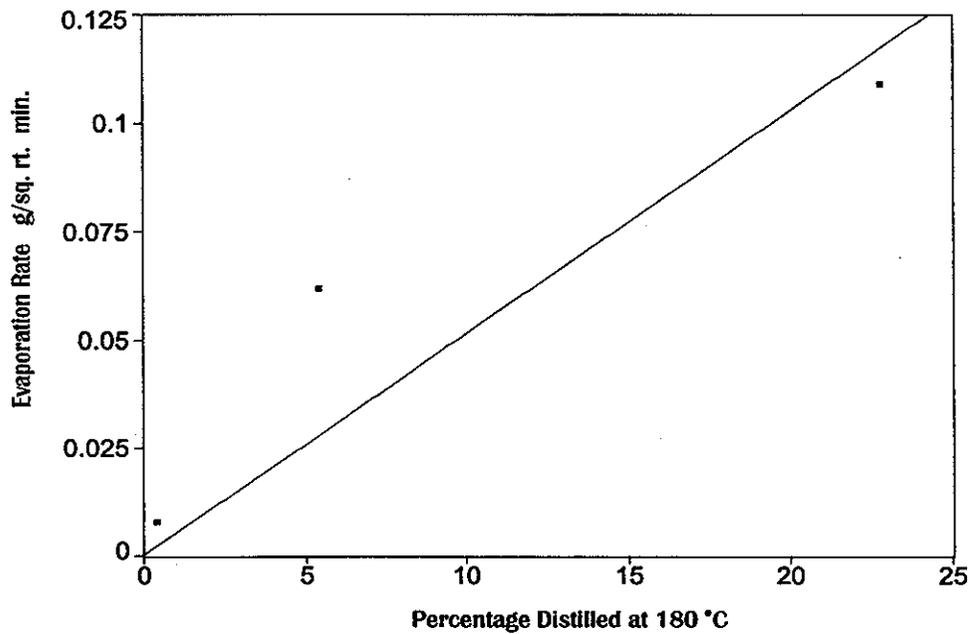


Figure 33

Correlation of Weight Equation and the Percent Distilled at 180 °C - Narrow Cut Products

$r^2=0.750$ DF Adj $r^2=0.501$ FitStdErr=0.0252 Fstat=+INF

a=0.00514



for the square-root equation products.

The equations derived from the regressions (parameters from Figures 30 to 33) are as follows:

For oils that follow a logarithmic relationship:

$$\text{Percentage evaporated} = 0.165(\%D) \ln(t) \quad (6)$$

$$\text{Weight evaporated} = 0.0341(\%D) \ln(t) \quad (7)$$

For oils that follow a square root relationship:

$$\text{Percentage evaporated} = 0.0254(\%D)\sqrt{t} \quad (8)$$

$$\text{Weight evaporated} = 0.00514(\%D)\sqrt{t} \quad (9)$$

where the weight evaporated is in grams per 20 grams evaporated and %D is the percentage (by weight) distilled at 180°C.

These equations can be combined with the equations generated in above to account for the temperature variations:

For oils that follow a logarithmic relationship:

$$\text{Percentage evaporated} = [.165(\%D) + .045(T-15)]\ln(t) \quad (10)$$

For oils that follow a square root relationship:

$$\text{Percentage evaporated} = [.0254(\%D) + .01(T-15)]\sqrt{t} \quad (11)$$

where %D is the percentage (by weight) distilled at 180°C.

The distillation data correlates well with the evaporation rate equations except for one or two select oils. The data shown in Table 10 and 11 show an average variance of calculated equations parameters (or evaporation rates) from the experimental values of 3% for the percent equations and 1.5% for the weight equations. The maximum value is 66% for the percent equation for Endicott oil. Some variance like this is expected by examination of the distillation curves in Figure 25. It can be seen here that the slopes of the distillation curves are not constant and furthermore contain some anomalies due to unique blends of constituents. Despite this, most oil evaporation can be predicted much more accurately using this method than by the methods noted in the literature search. The prediction scheme historically used only the slope of a nonstandard boiling curve and historically resulted in errors as large as several hundred percent.

The high correlation of distillation data and evaporation data suggest a strong relationship between the processes. Distillation does not involve the influence of environmental relationships such as boundary-layer regulation. This is suggestive that the evaporation of oil follows similar processes and that the evaporation process is largely (if not exclusively) governed by oil properties rather than environmental properties.

The utility of the calculation scheme is illustrated by taking two sets of data at random (chosen were ASMB and gasoline, taken respectively on December 8, 1993, and March 20, 1995). The actual data, the best curve fit, using a single logarithmic equation and the predicted data using the distillation values were plotted as shown in Figures 34 and 35. Figure 34 shows the gasoline data, which were recent data and where the test run was performed in a constant temperature chamber. The actual data, curve fit and the predicted values are very close. Figure 35 shows the ASMB data. The fit is also good.

All the evaporation data in this paper and that from some other experiments was used to prepared evaporation equations for the oils. Where, the temperature effect was not directly measured, it was added using equation 2 and its equivalent for the square root equations. These equations are presented in Table 12. It is important to note that the square root equations work well for the short-term (up to 5 or 10 days) after that

Table 10 **Experimental and Calculated Evaporation Rates**

Date	Oil Type	Single % Parameter	Single Wt. Parameter	Distillation 180°C	Calculated Rates			
					Percentage	% Variation	Weight	% Variation
Jan 21	Arnauligak	2.3	0.464	12.7	2.1	9	0.43	7
Mar 22	Arabian Lt	3.11	0.621	18.8	3.11	0	0.64	-3
July 2	ASMB	4.05	0.818	29.20	4.82	-19	1	-22
Sept 22	ASMB	4.49	1.11	29.20	4.82	-7	1	10
Nov 1	ASMB	4.28	0.898	29.20	4.82	-13	1	-11
Dec 8	ASMB	4.37	0.85	29.20	4.82	-10	1	-18
Dec 10	ASMB	4.28	0.912	29.20	4.82	-13	1	-10
April 25	ASMB	4.22	0.844	29.20	4.82	-14	1	-18
Jan 11	Avalon	2.08	0.416	12.6	2.08	0	0.43	-3
Jan 10	Brent	4.06	0.812	20.8	3.44	15	0.71	13
Jan 12	Brent	4.03	1.11	20.8	3.44	15	0.71	36
Jan 15	Brent	3.97	0.99	20.8	3.44	13	0.71	28
Jan 18	Brent	4.23	0.846	20.8	3.44	19	0.71	16
Dec 24	Bunker	0.28	0.12	1.40	0.231	18	0.05	58
Dec 29c	Bunker	0.23	0.095	1.40	0.23	0	0.05	47
Jan 18	Endicott	0.926	0.463	9.30	1.54	-66	0.32	31
Jan 3	Federated	3.99	0.797	30	4.96	-24	1.02	-28
Dec 29b	Gasoline	15.9	3.18	94.6	15.63	2	3.23	-2
Mar 30a	Gasoline	16	3.36	94.6	15.63	2	3.23	4
Mar 30b	Gasoline	15.8	3.22	94.6	15.63	1	3.23	0
Jan 14	Gulfaks	2.89	0.58	11.8	1.95	33	0.4	31
Mar 10	Gulfaks	2.81	0.562	11.8	1.95	31	0.4	29
Jan 20c	Issungnak	2.23	0.448	16.00	2.64	-18	0.55	-23
Dec 23	Komineft	3.4	0.438	21.5	3.55	-4	0.73	-67
Jan 1	Prudhoe	1.65	0.33	13.70	2.26	-37	0.47	-42
Jan 3	Prudhoe	2.17	0.434	13.70	2.26	-4	0.47	-8
Jan 28b	Prudhoe Bay	2.36	0.707	13.70	2.26	4	0.47	34
Feb 5	Santa Clara	2.3	0.461	13.70	2.26	2	0.47	-2
Feb 15	Statfjord	3.65	0.73	18	2.97	19	0.61	16
Jan 22	Terra Nova	1.93	0.385	16.10	2.66	-38	0.55	-43
Jan 26	Terra Nova	2.39	0.482	16.10	2.66	-11	0.55	-14

Table 11 Experimental and Calculated Rates For Narrow-Cut Products

Date	Oil Type	Single % Parameter	Single Wt. Parameter	Distillation 180 °C
March 26	Bunker C Light	0.0422	0.008	0.4
March 30c	Diesel	0.538	0.109	22.8
April 14	FCC heavy	0.31	0.062	5.40

Date	Oil Type	Calculated Rates			
		Percentage	% Variation	Weight	% Variation
March 26	Bunker C Light	0.01	76	0	100
March 30c	Diesel	0.58	-8	0.12	-10
April 14	FCC heavy	0.14	55	0.03	52

Figure 34

Comparison of Gasoline Evaporation- Data Taken March 20, 1995

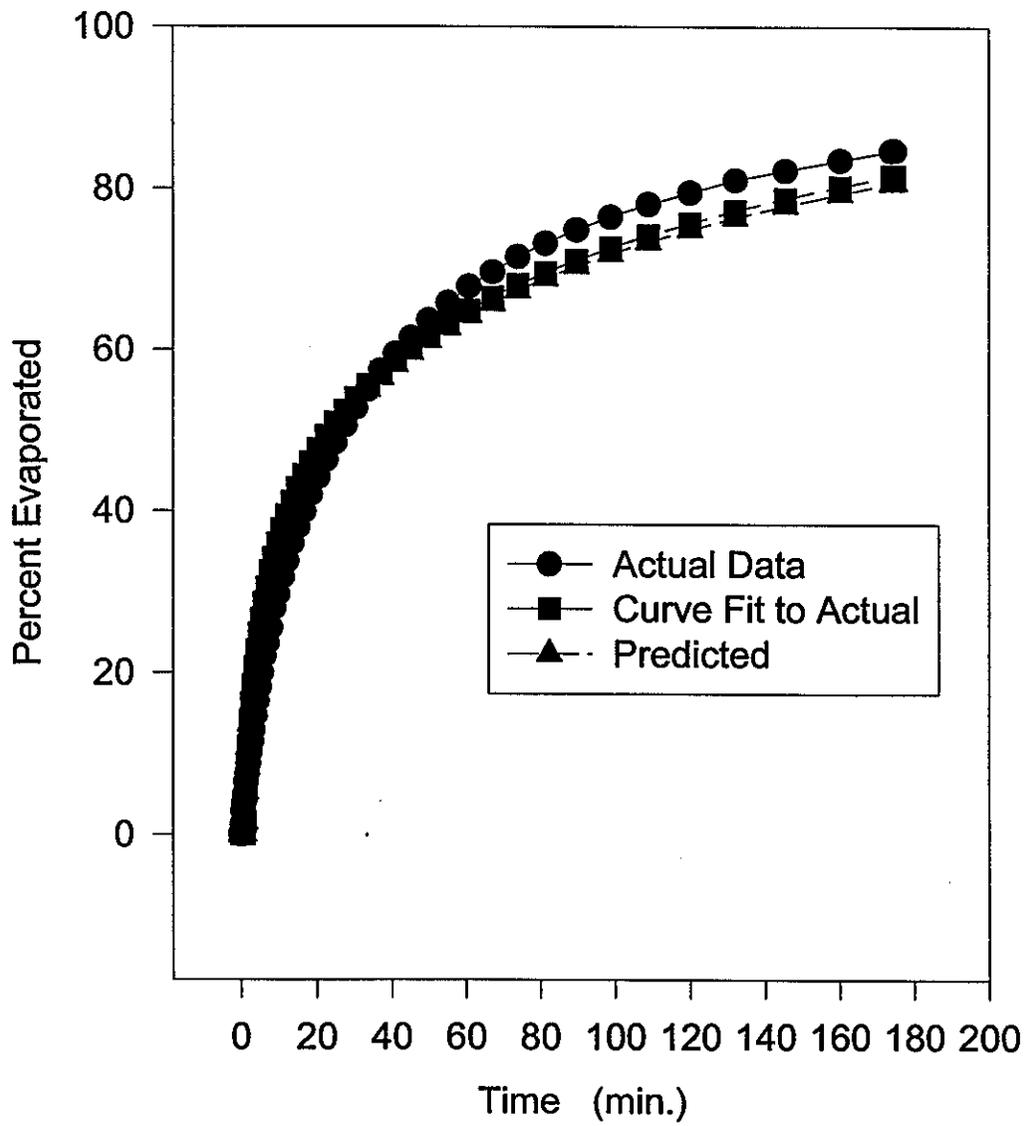
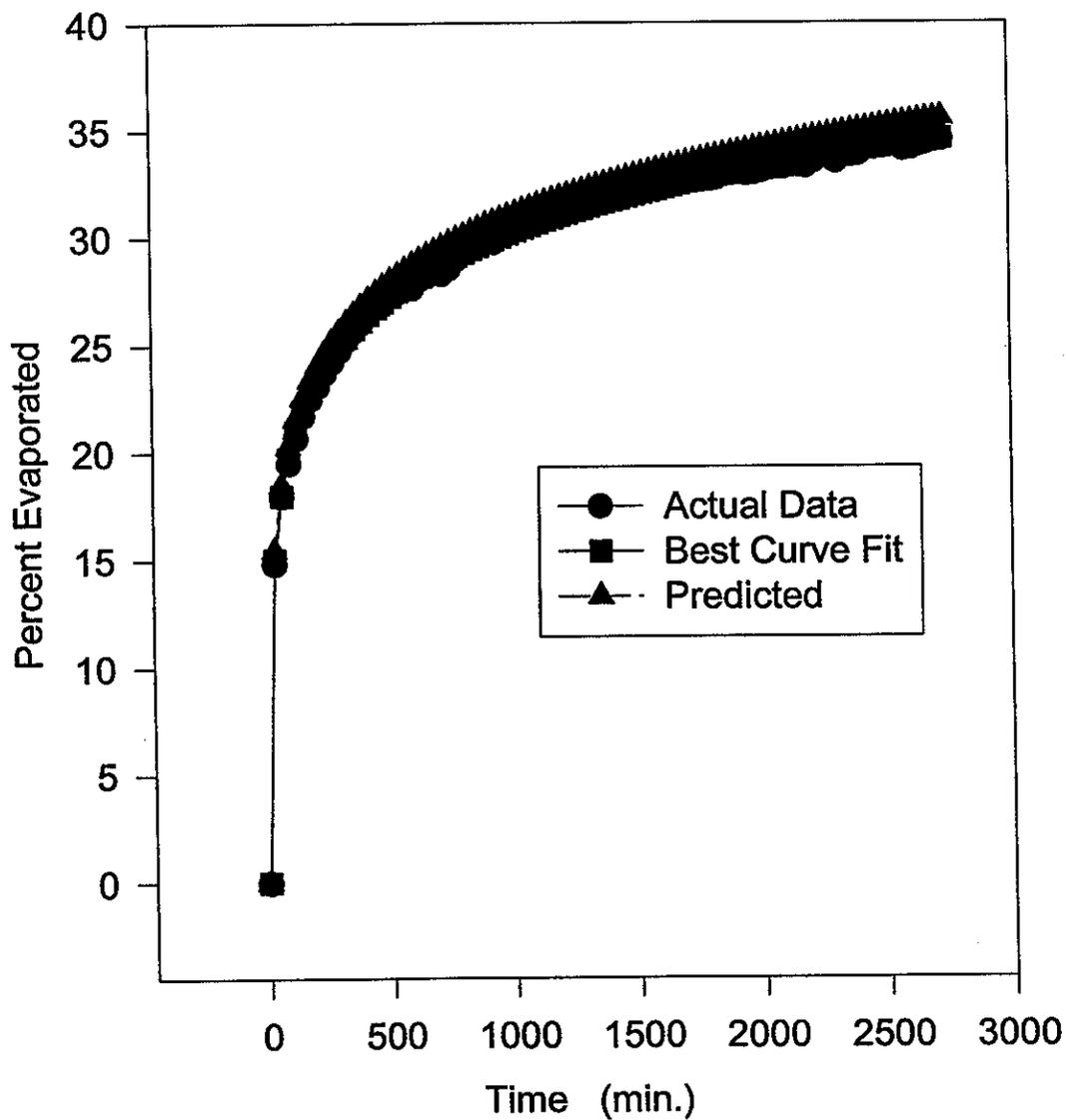


Figure 35

Comparison of ASMB Evaporation- Data Taken December 8, 1993



logarithmic equations are required to correctly predict long-term evaporation.

Conclusions

Literature indicates that the relation of evaporation rate and temperature to be $\log T/T$ or T^2 . An examination of thermodynamics indicates that the relationship may be linear. Experimental evidence confirms that the relationship between evaporation rate and temperature is linear.

The rate of evaporation change with temperature is similar for the crude oils tested. Diesel fuel and Bunker C light, were fitted with square root equations, and show similar behaviour to the other test oils, all of which were best fit with logarithmic equations. Prediction methods for diesel fuel and Bunker C light would require separate analysis.

The change of evaporation rate (both as percentage and as absolute weight) can be predicted using two entirely different methods. First, the rate of temperature change correlates with the values of the evaporation rate at 15 °C. Equations deriving from this correlation yield predictions that are within about 10% of their empirical counterparts.

The best fit equations are:

$$\text{percentage equation factor} = (B + 0.045(T-15)) \quad (2)$$

$$\text{and weight equation factor} = (B + 0.01(T-15)) \quad (3)$$

where B is the equation parameter at 15°C and T is temperature in Celsius.

Second, the slopes and intercepts of the temperature equations correlate strongly with oil distillation data. These correlations yield predictions of the temperature-dependant evaporation equations that show good agreement with their empirical counterparts. The variability ranges from a high of about 50% for Gullfaks oil to a low of about 3% variance for ASMB. The equations based on distillation data are:

$$\text{Percentage equation factor} = 0.161 D + 0.00262 TD \quad (4)$$

$$\text{and weight equation factor} = 0.329 D + 0.00502 TD \quad (5)$$

where D is the percent distilled at 140 °C.

The correlations with distillation data indicate that evaporation is a similar or related process to distillation. The correlation with the evaporation data itself at 15 °C shows that the temperature effect is somewhat similar for most oils. This also indicates that the evaporation rate itself is correlated with the variance with temperature.

The equation parameters found experimentally for the evaporation of oils can be related to commonly-available distillation data for the oil. Specifically, it has been found that the distillation percentage at 180 °C correlates well with the equation parameters. Regression coefficients (r^2) range from 0.74 to 0.98, depending on the type of equation and the selection of data. Relationships enabling calculation of evaporation equations directly from distillation data have been developed:

For oils that follow a logarithmic relationship:

$$\text{Percentage evaporated} = 0.165(\%D) \ln(t) \quad (6)$$

$$\text{Weight evaporated} = 0.0341(\%D) \ln(t) \quad (7)$$

For oils that follow a square root relationship:

$$\text{Percentage evaporated} = 0.0254(\%D)\sqrt{t} \quad (8)$$

$$\text{Weight evaporated} = 0.00514(\%D)\sqrt{t} \quad (9)$$

where the weight evaporated is in grams per 20 grams evaporated and %D is the

Table 12 Equations For Predicting Evaporation

Oil Type	Equation	Oil Type	Equation
Adgo	$\%Ev = (.11 + .013T)\sqrt{t}$	Eugene Island 43	$\%Ev = (1.64 + .045T)\ln(t)$
Adgo - long term	$\%Ev = (.68 + .045T)\ln(t)$	Eugene Island Block 32	$\%Ev = (.077 + .045T)\ln(t)$
Amauligak	$\%Ev = (1.63 + .045T)\ln(t)$	Eugene Island Block 43	$\%Ev = (1.57 + .045T)\ln(t)$
Amauligak - f24	$\%Ev = (1.91 + .045T)\ln(t)$	FCC Heavy Cycle	$\%Ev = (.35 + .013T)\sqrt{t}$
Arabian Light	$\%Ev = (2.52 + .037T)\ln(t)$	Federated	$\%Ev = (3.47 + .045T)\ln(t)$
Arabian Medium	$\%Ev = (1.89 + .045T)\ln(t)$	Gasoline	$\%Ev = (13.2 + .21T)\ln(t)$
Alberta Sweet Mixed Blend	$\%Ev = (3.24 + .054T)\ln(t)$	Green Canyon Block 109	$\%Ev = (1.58 + .045T)\ln(t)$
Av Gas 80	$\%Ev = (15.4 + .045T)\ln(t)$	Green Canyon Block 65	$\%Ev = (1.56 + .045T)\ln(t)$
Avalon	$\%Ev = (1.41 + .045T)\ln(t)$	Gulfaks	$\%Ev = (2.29 + .034T)\ln(t)$
Avalon J-34	$\%Ev = (1.58 + .045T)\ln(t)$	Issungnak	$\%Ev = (1.56 + .045T)\ln(t)$
Barrow Island	$\%Ev = (4.67 + .045T)\ln(t)$	Jet 40 Fuel	$\%Ev = (8.96 + .045T)\ln(t)$
BCF-24	$\%Ev = (1.08 + .045T)\ln(t)$	Komineft	$\%Ev = (2.73 + .045T)\ln(t)$
Belridge Crude	$\%Ev = (.03 + .013T)\sqrt{t}$	Main Pass Block 306	$\%Ev = (2.86 + .045T)\ln(t)$
Bent Horn A-02	$\%Ev = (3.19 + .045T)\ln(t)$	Mississippi Canyon Block 194	$\%Ev = (2.62 + .045T)\ln(t)$
Brent	$\%Ev = (3.39 + .048T)\ln(t)$	North Slope - Middle Pipeline	$\%Ev = (2.64 + .045T)\ln(t)$
Bunker C - long term	$\%Ev = (-.21 + .045T)\ln(t)$	North Slope - Northern Pipeline	$\%Ev = (2.64 + .045T)\ln(t)$
Bunker C	$\%Ev = (-.03 + .013T)\sqrt{t}$	Offshore ASMB	$\%Ev = (2.2 + .045T)\ln(t)$
Bunker C - Light (IFO-250)	$\%Ev = (.0035 + .0026T)\sqrt{t}$	Orimulsion plus water	$\%Ev = (3 + .045T)\ln(t)$
Carpenteria	$\%Ev = (1.68 + .045T)\ln(t)$	Prudhoe Bay - old stock	$\%Ev = (1.69 + .045T)\ln(t)$
Cook Inlet - Swanson River	$\%Ev = (3.58 + .045T)\ln(t)$	Prudhoe stock b	$\%Ev = (1.4 + .045T)\ln(t)$
Cook Inlet Trading Bay	$\%Ev = (3.15 + .045T)\ln(t)$	Santa Clara	$\%Ev = (1.63 + .045T)\ln(t)$
Delta West Block 97	$\%Ev = (6.57 + .045T)\ln(t)$	Ship Shoal Block 269	$\%Ev = (3.37 + .045T)\ln(t)$
Diesel	$\%Ev = (.31 + .018T)\sqrt{t}$	South Pass Block 60	$\%Ev = (2.91 + .045T)\ln(t)$
Diesel - long term	$\%Ev = (5.8 + .045T)\ln(t)$	South Pass Block 93	$\%Ev = (1.5 + .045T)\ln(t)$
Dos Cuadros	$\%Ev = (1.88 + .045T)\ln(t)$	South Timbalier Block 130	$\%Ev = (2.77 + .045T)\ln(t)$
Empire Crude	$\%Ev = (2.21 + .045T)\ln(t)$	Statfjord	$\%Ev = (2.67 + .06T)\ln(t)$
Endicott	$\%Ev = (.09 + .045T)\ln(t)$	Terra Nova	$\%Ev = (1.36 + .06T)\ln(t)$

T = Temperature in Celsius
t = time in minutes

percentage (by weight) distilled at 180°C.

These equations were combined with the equations generated to account for the temperature variations:

For oils that follow a logarithmic relationship:

$$\text{Percentage evaporated} = [.165(\%D) + .045(T-15)]\ln(t) \quad (10)$$

For oils that follow a square root relationship:

$$\text{Percentage evaporated} = [.0254(\%D) + .01(T-15)]\sqrt{t} \quad (11)$$

The high correlation of distillation data and evaporation data suggests that the two processes are analogous and that evaporation, like distillation, is largely governed by intrinsic oil properties rather than environmental properties such as boundary-layer factors.

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