REPORTS

Marine Pollution Bulletin Vol 15 No 9 pp 326–329 1984
Printed in Great Britain

0025-326X/84 $3.00+0.00

A New Technique to Estimate Initial Spill Size Using a Modified Fay-type Spreading Formula

W J LEHR, R J FRAGA*, M S BELEN and H M CEKIRGE
Water and Environment Division, Research Institute, University of Petroleum and Minerals, Dhahran, Saudi Arabia

Estimating oil spill size is important for a variety of economic, environmental and legal reasons. One attempt to determine oil spill size by visually assessing the extent of colour regimes in the spill and multiplying the areas of these regimes by thickness values leads to unsatisfactory results. Previous efforts to estimate oil spill size by inverting spreading using formulae like those of Blokker and Fay have also incurred difficulties related to environmental conditions which influence spill spread rate. Data obtained during a series of field experiments, conducted off the Saudi Arabian coastline during the fall of 1982, were used to devise a modification of Fay's spreading formula. The results agree significantly better with the observed areas of the oil spill than Fay's original formula. The modified area formula is then inverted to obtain a formula for initial volume spilled.

An accurate estimate of the size of an oil spill is important for several reasons. Spill size will help to determine the type of clean-up response required, the overall pollution effect on the environment, and the amount of compensation owed by the party responsible for the spill. In some circumstances, an accurate estimate is provided from an examination of the spill source as, for example, the known capacity of an oil tanker before it is ruptured or the production rate of a leaking offshore well. In other circumstances, however, the spill source may be unknown or the initial spill volume may be a matter of dispute. In such cases indirect methods of estimating spill size must be used.

These indirect methods fall roughly into two categories.

One method attempts to determine the thickness of various regimes in the slick. When these thicknesses are multiplied by the areas of the corresponding regimes and the resulting regime volumes are summed, an estimate of the total current volume is produced. From this volume, it is possible to extrapolate back to an initial volume if a suitable weathering algorithm such as that of Mackay *et al* (1981) is utilized. Quite sophisticated techniques have been developed to estimate spill thickness by remote sensing techniques (Axelsson & Ohlsson, 1973, White & Schmidt, 1983). Unfortunately they often require apparatus which is not readily available during actual spills. Attempting to estimate oil thickness by visual observation and normal photography alone runs into several difficulties, and there is considerable dispute in the literature about the accuracy of this method (Munday, 1971, Estes *et al*, 1973). The other indirect method of estimating oil spill volume involves inverting standard oil-spreading formulas so that initial spill volume can be determined from the present spill area. Two frequently used formulas are those by Blokker (1964) and Fay (1971). Since a Fay-type formula will be utilized later in this paper, a brief review of the Fay model is provided.

Fay divides spreading into three phases with each phase determined by dominant spreading and retarding force on the slick. The first phase, known as gravity-inertial spreading, lasts only a few minutes for all except the largest spills. The last phase, the surface tension-viscous spreading, takes place after the slick has badly weathered and may have dispersed or broken into separate slicks. Therefore, the most useful phase for estimating oil spill size is the second phase known as gravity-viscous spreading. The formula for this phase is

$$A=k\{g\, V^2\, t^{3/2}\, \nu_w^{-1/2}\, [(\rho_w-\rho_o)/\rho_o]\}^{1/3} \quad (1)$$

where A=area of slick, g=gravitational acceleration, V=initial volume of slick, t=time, ν_w=kinematic viscosity of water, ρ_o=oil density, ρ_w=water density, and k=constant.

Inverting this formula provides an estimate of the initial spill volume based on the observed area. Field data from actual spills (Murray, 1972, Conomos, 1974) show that Fay's theory greatly underestimates slick growth. Hence the corresponding volume estimates would be too large.

Experiment Design

In order to determine the best way to estimate oil spill size by visual methods, a series of test spills was conducted by the end of 1982 in parts of the Arabian Gulf adjacent to the Saudi Arabian coastline. Parameters for the spills are presented in Table 1.

*Department of Mathematical Science

TABLE 1

Spill parameters

Initial size (barrels)	13 09	19 60	51 07
Oil type	Heavy	Light	Light
Spill date, 1982	5 December	12 December	21 December
Release time	8 59 a m	9 20 a m	8 25 a m
Duration (min)	121*	148*	329
Wind direction	ESE	NW	NW
Wind speed (knots)	15	14	10
Wave height (feet)	2–3	1–2	1–2
Sea temperature (°F)	70	68	62

*Area measurements only for shorter time period

All spills were made from tanks fastened to the aft deck of a 100-foot workboat The oil was gravity-driven through a 15-foot long pipe of 3-inch diameter The end of the pipe was fitted with a funnel held horizontal to the water surface to reduce entrainment of the oil in the water During the 51-barrel spill, an auxiliary 1½-inch diameter pipe was also used

As has been reported in other spills (Jeffery, 1973, and NAS, 1975), the oil is separated into two major regimes, a thick 'black oil' regime and a thin 'sheen' regime In some situations, a third regime which contained heavy sheen mixed with small spots of black and brown oil was also noticed The third region was more pronounced when the slick was observed at low altitudes

Thickness measurements were made by a two-man surface crew operating in a rubber dinghy launched from the workboat shortly before each spill commenced The sampler used to measure thickness in the various colour regimes was adapted from a prototype developed by Estes *et al* (1973)

Each spill was photographed throughout its duration by a WILD brand camera in an aerial survey plane flying at altitudes which varied from 2500 feet to 9500 feet, depending on spill size and cloud cover The photographs were electronically scanned and computationally analysed and area calculations resulting from this analysis were compared with standard oil-spreading formulas (Lehr *et al*, 1984)

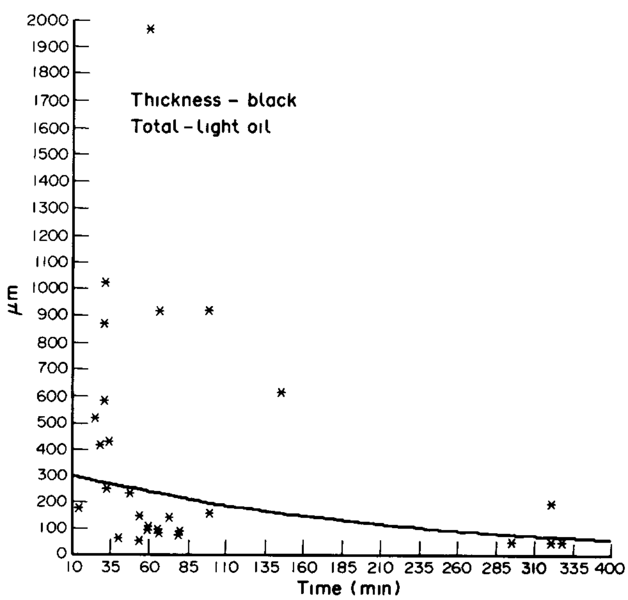

Fig. 1 Plot of thickness measurements versus time for the black oil regime from all light Arabian crude test spills

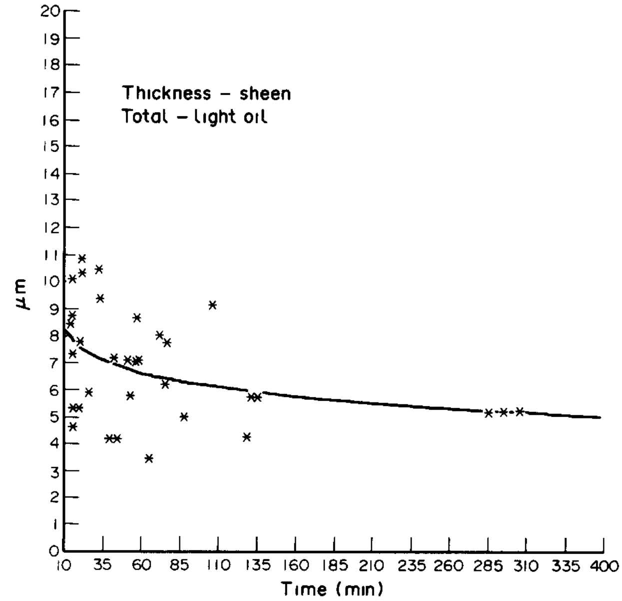

Fig. 2 Plot of thickness measurements versus time for the sheen from all light Arabian crude test spills

Results

The correlation between colour and thickness for the different slick regimes was poor Figure 1 presents the black regime thickness measurements for all the test spills involving Arabian Light crude As can be seen from the figure, there was considerable scatter, particularly at early times in the duration of the spill The *F*-ratio (the ratio of the regression mean squares to residual mean squares) for the least squares curve in the figure was 5 4

Similar circumstances prevailed in the sheen regime (Fig 2, *F*-ratio=6) and the test spill involving Arabian Heavy crude yielded the same type of results. Thus, colour is an imprecise measure of slick thickness and hence volume It might, perhaps, be of some use for old weathered spills where the thickness of the colour regimes are presumed to have approached an equilibrium value From the experimental spills, reasonable equilibrium values might be 100 μm for the black regime and 5 μm for the sheen

Use of Fay's spread algorithms to estimate spill size also proved inaccurate since the actual spread rate was much faster than the spread rate predicted from Fay's method In fact, for the 51-barrel spill of Arabian Light crude, the Fay formula underestimated the spill size by more than an order of magnitude (Lehr *et al*, 1984) and did not even match the spread rate of the smaller black regime area (Fig 3) Thus initial spill size estimates based on inverting Fay's formula would give a serious overestimate of initial volume

Development of Revised Fay Formula

It was hypothesized that the reason that the Fay formula worked so poorly is that it is designed to deal with the idealized case of a circular slick on calm seas In an actual spill, environmental conditions play a crucial role in determining slick area and shape One very important factor is the wind with all the field tests showing that the oil slick tended to be more or less elliptical

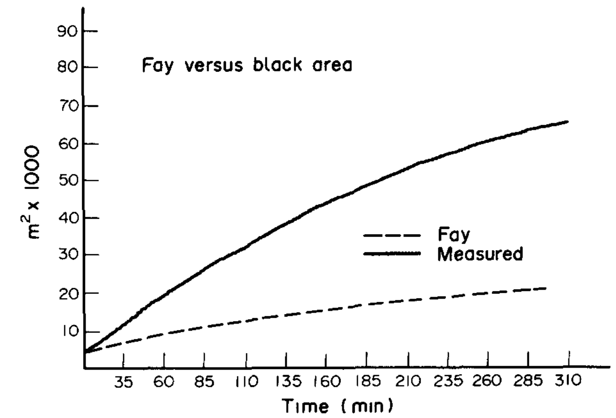

Fig 3 Plot of black oil area for the 51 barrel spill compared to Fay model prediction of total slick area

rather than circular in shape, with the major axis oriented in the direction of the wind

Hence a new type of Fay formula was proposed as follows

1 The area of the slick can best be represented as an ellipse with area

$$A=(\pi/4)\,QR \tag{2}$$

where Q and R are the lengths of the minor and major axes of the elliptical slick respectively

2 The length of the minor axis Q is proportional to a product of suitable powers of the relative density difference, initial spill volume and time, i e

$$Q=C_1\,[(\rho_w-\rho_o)/\rho_o]^{\alpha}\,V^{\beta}\,t^{\gamma} \tag{3}$$

where C_1, α, β and γ are positive constants to be determined

3 The length of the major axis R is proportional to a sum of the product in Equation 2 and a product of suitable powers of wind W and time t, i e

$$R=C_1\,[(\rho_w-\rho_o)/\rho_o]^{\alpha}\,V^{\beta}\,t^{\gamma}+C_2\,W^{\delta}\,t^{\varepsilon}$$

where C_2, δ and ε are positive constants to be determined

For the revised formula to reduce to a Fay-type formula for the zero-wind case, the constants β and γ are set as $\beta=1/3$ and $\gamma=1/4$ Since in all the test spills the dependence of area on time was nearly linear, it was concluded that $\varepsilon=3/4$ With wind speed measured in knots,

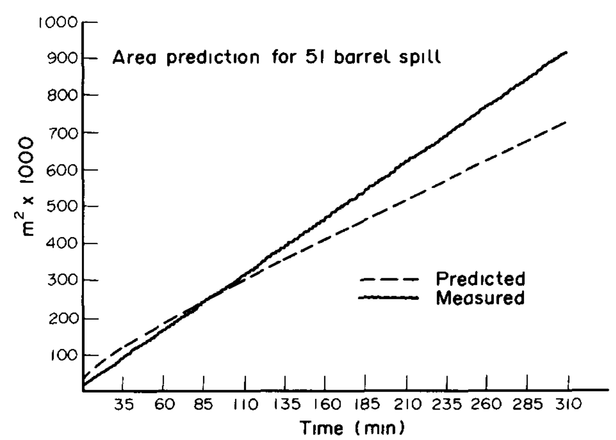

Fig 4 Plot of total slick area compared to predicted area of modified Fay formula

TABLE 2

Spill size estimates

Type of oil	Time after release (min)	Actual volume (barrels)	Volume prediction Fay gravity-viscous formula (barrels)	Volume predicted by equation 6 (barrels)
Arabian light	30	19 6	73	0 9
Arabian heavy	47	13 1	534	15 9
Arabian light	79	51 1	799	41 7
Arabian light	295	51 1	2369	78 6

t in min and area in 10^3 m², the empirically determined values for the other constants are

$$\alpha=1/3,\ \delta=4/3,\ C_1=1\ 7 \text{ and } C_2=0\ 03$$

Equation 2 can be written by incorporation of these values as

$$A=2\ 27\,[(\rho_w-\rho_o)/\rho_o]^{2/3}\,V^{2/3}\,t^{-1/2} \\ +0\ 04\,[(\rho_w-\rho_o)/\rho_o]^{1/3}\,V^{1/3}\,W^{4/3}\,t \tag{5}$$

Including the extra wind term greatly improved the agreement between predicted and actual area for the test spills Figure 4 presents the results for the 51-barrel spill of Arabian Light crude

Poorer correspondence between the formula and the actual area was observed for the 20-barrel spill of Arabian Light crude For this spill, strong currents coincided with the wind direction to produce a long narrow spill with small area Since the currents are often not known in the case of actual spill incidents, their effects are not incorporated in the formula and their omission, in this case, tends to overestimate the area of the spill

The authors also attempted to correlate other easily determined slick parameters, such as the black regime area or the ratio of black to sheen, to initial spill size, however, none showed as good a correspondence as the total spill area

Technique to Estimate Spill Size

Equation 5 can be inverted to give an algorithm to predict initial spill volume based on oil density, wind speed, time of spill and spill area

$$V=[\rho_o/(\rho_w-\rho_o)]\,\{(1/2b_2)\,[-b_1+(b_1^2+4Ab_2)^{1/2}]\}^3 \tag{6}$$

where $b_1=0\ 04\ W^{4/3}\,t$

and $b_2=2\ 27\ t^{1/2}$

Table 2 compares the results of Equation 6 with the results obtained by inverting the Fay gravity–viscous formula As will be noticed, neither formula worked well in estimating the 20-barrel Arabian Light spill The difficulty in using the new formula for this spill has already been mentioned For the other entries in the table, the new formula obviously gives a much better prediction than the use of the Fay formula

This research effort was supported by the Environmental Affairs Department of the Arabian American Oil Company under the University of Petroleum and Minerals, Research Institute agreement No 15805/00

Axelsson, S & Ohlsson, E (1973) Remote sensing of oil slicks *Ambio*, 70-76

Blokker, P C (1964) Spreading and evaporation of petroleum products on water *Proceedings of the Ninth International Harbor Conference* Antwerp

Conomos, T J (1974) Movement of spilled oil as predicted by estuarine nontidal drift *Limnol Oceanogr*, **20**, 522-530

Estes, J E, Mikolay, P G, Thaman, R R & Sanger, L W (1973) Determination of marine oil spills using co-ordinated airborne and surface sampling data *Proceedings of the Joint Conference on Prevention and Control of Oil Spills*, pp 117-125 American Petroleum Institute, Washington, D C

Fay, J A (1971) *Physical Processes in the Spread of Oil on a Water Surface Proceedings of the Joint Conference on Prevention and Control of Oil Spills*, pp 463-468 American Petroleum Institute, Washington, DC

Jeffery, P G (1973) Large-scale experiments on the spreading of oil at sea and disappearance by natural factors *Proceedings of the Joint Conference on Prevention and Control of Oil Spills*, pp 469-474 American Petroleum Institute, Washington, D C

Lehr, W J, Cekirge, H M, Fraga, R J & Belen, M S (1984) Empirical studies of the spreading of oil spills, oil and petrochemical pollution *Oil and Petrochemical Pollution*, in press

Mackay, D, Peterson, S & Trudel, K (1981) A mathematical model of oil spill behaviour Report for Environmental Control Directorate, Canada

Munday, J (1971) *Oil Slick Studies Using Photographic and Multispectral Scanner Data Proceedings of the Seventh International Symposium on Remote Sensing of Environment*, University of Michigan, Ann Arbor, Michigan, p 1027

Murray, S P (1972) Turbulent diffusion of oil in the ocean *Limnol Oceanogr*, **27**, 651-660

National Academy of Sciences (1975) *Petroleum in the Marine Environment* NAS, Washington, D C

White, J R & Schmidt, R E (1983) *United States Guard Progress in Oil Spill Surveillance Proceedings of 1983 Oil Spill Conference* pp 341-344 American Petroleum Institute, Washington, D C

Marine Pollution Bulletin Vol 15 No 9 pp 329-334 1984
Printed in Great Britain

0025-326X/84 $3 00+0 00

Synoptic Survey on Dissolved Trace Metal Levels in Baltic Surface Waters

KLAUS KREMLING and HARALD PETERSEN
Institut fur Meereskunde, Dusternbrooker Weg 20, D-2300 Kiel 1, Federal Republic of Germany

A total of 95 surface water samples (6 m depth) was collected during a transect from the Bothnian Bay to Kiel between 28 August and 5 September 1982. This report presents the dissolved trace metal (<0.4 μm) and the associated hydrographic and nutrient data. Except for aluminium, all other metals determined (Zn, Cd, Cu, Ni, Fe, Mn) showed a rather homogeneous distribution within the subregions, with highest values in the Bothnian Bay (except for Mn) and net variations of the individual samples of about 20%. Cadmium, copper and nickel reveal conservative behaviour when values from this study and literature data from the Kattegat and North Sea area are plotted against salinity.

Baltic waters show a broad diversity in chemical properties exhibited by the horizontal salinity range from almost zero in the Bothnian Bay to nearly ocean water in the Skagerrak area, and by the anoxic conditions in the deeper layers (Voipio, 1981) An essential step in understanding the geochemical processes of potential pollutants in this environment is to gain a knowledge on its distribution and chemical behaviour A great many data associated with trace metal occurrence in the Baltic waters has been reported, but only a small fraction can be considered reliable, as critically reviewed by Brugmann (1981)

Since the analytical techniques have been refined, trace metal distributions appear increasingly more well defined and systematic A detailed study on the behaviour of redox-dependent elements in stagnant Baltic waters has been presented recently (Kremling, 1983b)

The present research was undertaken in an attempt to provide, by means of a new sampling technique, reliable data on the surface water distribution of dissolved Zn, Cd, Cu, Ni, Fe, Mn and Al The major questions to be answered are (i) do significant concentration differences actually exist in the Baltic subregions? (ii) how large are the spatial fluctuations within the different areas and with respect to the prevailing hydrochemical situation? (iii) are there any marked correlations with salinity?

Methods of Sampling and Analysis

Seawater samples were collected from the R/V *Poseidon* in a horizontal transect from the Bothnian Bay to Kiel between 28 August and 5 September 1982 Locations of the 95 stations are given in Fig 1 together with the Baltic Sea subregions (according to Wattenberg, 1949) To save time and to avoid possible contamination, the water was pumped from 6 m depth (at 0 3 m^3 h^{-1}) through polyethylene tubing (from a towed stainless steel shell suspended underneath the hull) while the ship was steaming All subsamples for trace metal analysis were pressure filtered through precleaned 0 4 μm Nuclepore filters (with N_2 on clean benches) The filtrates were acidified by addition of subboiled HNO_3 to a final pH of around 1 7, and stored in 500 cm^3 quartz bottles at 5°C until analysis

Zinc was analysed by differential pulse anodic stripping voltammetry at a processing pH between 5 and 6 Cadmium, copper, nickel and iron were subjected to a