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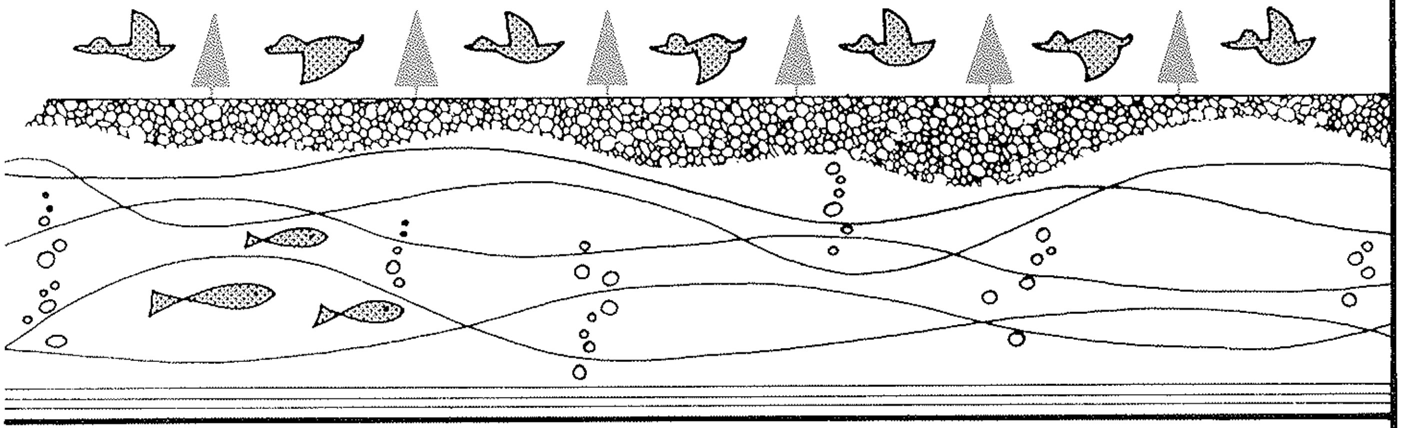
SPILL TECHNOLOGY NEWSLETTER



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The Spill Technology Newsletter was started with modest intentions in 1976 to provide a forum for the exchange of information on oil spill countermeasures and other related matters. We now have over 2000 subscribers in over 40 countries.

To broaden the scope of this newsletter, and to provide more information on industry and foreign activities in the field of oil spill control and prevention, readers are encouraged to submit articles on their work and views in this area.

INTRODUCTION

The first paper in this issue is by Ian Buist and Steve Potter who report on a study on oil submergence. They have confirmed earlier studies that heavier oil can be overwashed by water. This occurs more frequently as the waves become higher and the oil becomes heavier. The phenomenon is already well-established at an oil density of 0.96 and is virtually continuous when density is 0.99, with any significant wave action. One effect of the overwashing is to remove the oil from the view of observers at oblique angles and also from many types of remote sensing instruments. At higher densities the oil remains submerged and can drift below the surface.

The second paper by Ed Owens, Wish Robson and Blair Humphrey reports on a revisit to the METULA spill in the Strait of Magellan in southern Chile. Much of the "asphalt pavement" remains with some relatively unweathered oil below the surface. Revegetation has occurred over much of the oiled area.

OIL SUBMERGENCE

Submitted by: **I.A. Buist and S.G. Potter**
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Introduction

Given appropriate oceanographic conditions and oil properties, it is possible for oil slicks to submerge beneath the sea surface. This renders spill detection, tracking and countermeasures extremely difficult, if not impossible. The objective of this study was to validate and extend the work of previous studies on the formation and submergence of "sinkable" oil forms, and to develop operationally useful process equations to predict the conditions under which an oil spill might be expected to submerge.

Historical Perspective. Several oil spill incidents have had reports of sinking or disappearance of oil slicks. These include the ARROW (Forrester, 1971) (large drops of emulsified Bunker C were detected at depths up to 80 m); the US/NS POTOMAC (Petersen, 1978) (Bunker C formed pancakes that eventually sank); the IXTOC-1 blowout (large subsurface mats of weathered mousse were observed) (Payne and Phillips, 1985); the KURDISTAN incident which sparked the current interest in oil submergence (C-CORE, 1980); the KATINA incident (heavy fuel oil submerged only to appear on shore later) (Rijkwaterstaat, 1982); and the recent THUNTANK 5 incident in Sweden (36 to 40 tons of heavy fuel oil sank in icy waters) (OSIR, 1987).

The common thread among these incidents is that all involved very low or neutrally buoyant oils or water-in-oil emulsions that, through weathering, formed into particles or mats ranging in size from $\leq$ 1 mm to several metres. The criteria for oil submergence seems to be low or neutral buoyancy and the formation of particulate oil forms.

The State-of-the-Art. Several studies have addressed various aspects of sinking or submergence of oil spills. Juszko et al. (1983) and Juszko (1985) have extensively reviewed both the oceanographic conditions conducive to oil submergence and the occurrence and frequency of those conditions in Canadian waters. Mackay et al. (1985 and 1986) presented an excellent literature review and conducted both small-scale tests with oils and mid-scale tests with surrogates that identified the mechanisms that result in oil submergence. These two most recent studies laid the groundwork for this study.

Other studies (WSL, 1978; WSL, 1981; S.L. Ross, 1984, 1985; S.L. Ross and DMER, 1987) have addressed the behaviour and weathering of oils that, when spilled, form into mats and droplets.

Rationale for the Study. To date, the oceanographic conditions studies and the small and mid-scale studies on oil pan/droplet formation and submergence have included extensive theoretical treatment, some small-scale testing and limited meso-scale testing with surrogates. Extensive meso-scale testing with actual oils was required to validate the previous studies and permit the development of operationally useful equations to predict what percentage of the "slick" is submerged at various depths as a function of environmental conditions.

Study Methods

Test Tank. Experiments were conducted in a wind-wave tank 1.2 x 11 x 1.9 m (w x l x h) (Figure 1). The tank was filled with approximately 10 000 L of fresh water to a depth of 0.85 m. Saltwater was not used as it was thought that the oil water density difference (i.e., buoyancy) rather than absolute densities was the key to submergence processes. This significantly reduced the complexity of the testing.

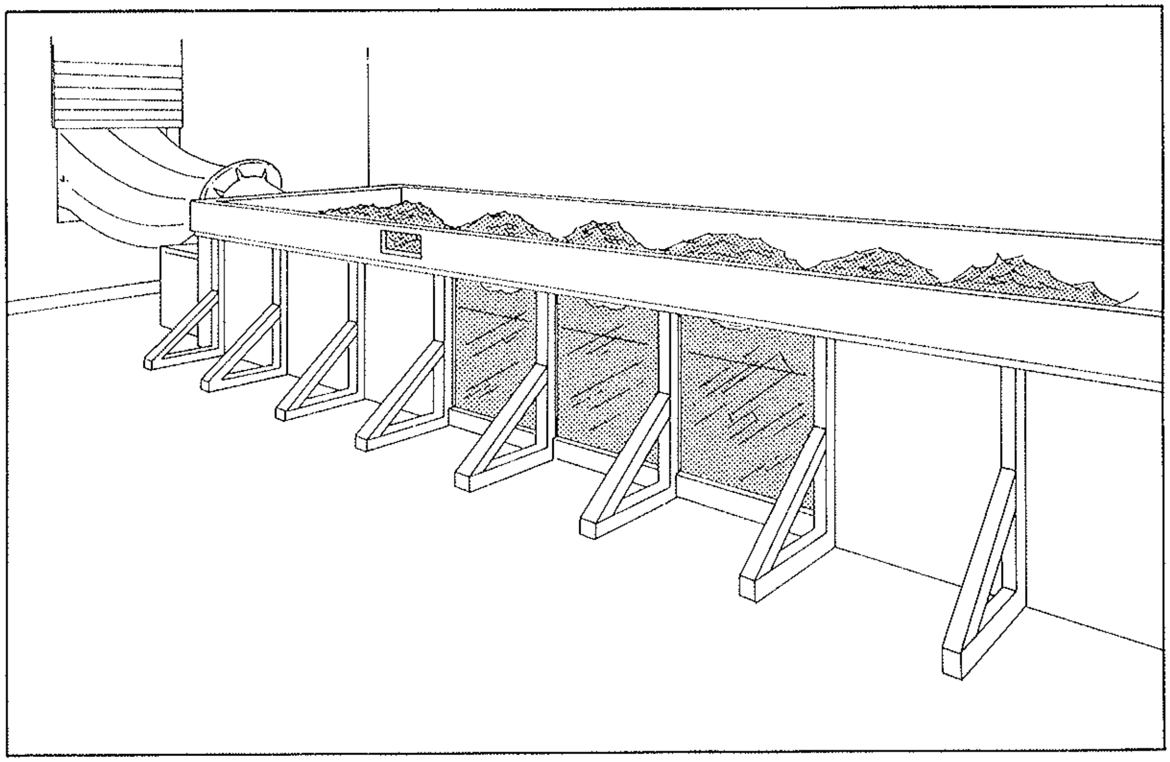

FIGURE 1 WIND/WAVE TANK

The tank was fitted with a submerged air-bubbler system in the glass-walled test section to prevent the sticky oils from quickly adhering to the sides of the tank; this permitted test runs of several hours. Waves were generated in the tank by a paddle at one end driven by a continuously variable speed electric motor. Table 1 lists the wave characteristics measured (photographically) for the paddle settings used in the tests.

TABLE 1 TEST WAVE CHARACTERISTICS

Wave Generator Setting	Wave Height (m)	Wave Length (m)	Steepness Ratio
40	0.12	4.25	0.055
50	0.14	3.25	0.086
60	0.15	3.20	0.094
80	0.23	1.45	0.33*

* Waves were breaking in the test section.

Test Oils. Since the majority of Canadian spills involve Bunker C (fuel oil number 6), an oil that offers the greatest potential for sinking, it was concentrated on in the test program. Properties of the uncut heavy Bunker C used are given in Table 2. The density, and concomitant viscosity, of the Bunker C were varied by diluting the oil with automotive diesel fuel. In order to investigate the effect oil viscosity independent of buoyancy, a waxy Grand Banks crude oil (J-34) was emulsified with different percentages of 35 parts per thousand (ppt) artificial seawater.

TABLE 2 TEST OIL PHYSICAL PROPERTIES

Oil	Temperature (°C)	Density (kg/m^3)	Viscosity (mPa•s = cP)
Bunker C	10	1018	111 000
	5	1022	752 000
	1	1025	2 310 000
Auto Diesel	10	831	2.9
	5	835	3.5
	1	837	3.8
J-34	10	881	12 000
(from S.L. Ross	5	885	42 000
and DMER, 1987)	1	888	not measured

Test Procedures and Analytical Techniques. In a typical test run, the tank was filled with cold tap water to a depth of 85 cm. A 400-mL sample test oil was warmed to about 45°C (to facilitate pouring and initial distribution on the water surface), then poured onto a spill plate on the water surface; three or four distinct slicklets were created. Fifteen minutes were allowed for the temperature of the slicklets to equilibrate with the water.

The waves were then turned on at setting 40 (see Table 1); the bubbler was turned on once the slicklets moved towards the walls of the tank or began to drift out of the test section. The oil behaviour and position were recorded simultaneously by two video cameras: one positioned above the tank looking down on the test section and one under water at one end looking along the underside of the slicklets. Photographs were taken through the glass-walled test section and visual observations were noted throughout each test.

After a 1/2-hour test period with the wave generator setting at 40, it was increased to 50. This procedure was repeated up to a wave generator setting of 80.

Samples for physical property analysis were obtained prior to each run for those tests involving Bunker C (since the change in properties of this oil with exposure is negligible) and after each run for those tests involving crude oil emulsions. Oil density was determined using a Parr Densitometer. Viscosities for the more viscous samples (> 20 000 mPa•s) were determined at 1, 5 and 10°C using a Brookfield viscometer at a shear rate of 0.3 s^{-1}. The viscosities of the more fluid samples were measured, at the test temperature, using cross-arm viscometers. Although attempts were made to measure interfacial tensions using a ring tensiometer, these proved futile for most of the samples because of their high viscosity. Since it is known that interfacial tension varies only slightly as a function of oil type and weathered state, no attempts were made to use more sophisticated techniques.

Originally measurement of dispersed oil concentrations and drop sizes had been planned, but this was abandoned when it was observed that, because of the low buoyancy and high viscosity of the test oils and emulsions, the drops of oil permanently suspended in the water were very large and widely separated. The usual technique for measuring dispersed oil concentration and drop size distribution involves sampling and analysing a small volume of water beneath the slick but is only valid if the small sample is considered to be representative of the whole system. This is the case for homogeneously dispersed oil involving small droplets but not for heterogeneous distributions such as those observed in these tests.

Results and Discussion

Blended and Emulsified Oil Properties. The measured physical properties for the blended or emulsified oil used in each run are listed in Table 3. The buoyancy ratio (the density difference between oil and water divided by the density of water) ranged from 0.001 (Runs A3, A9) to 0.042 (Run A5); the oil viscosity ranged from 430 to 842 000 mPa•s.

TABLE 3 BLENDED AND EMULSIFIED OIL PROPERTIES

Run	Oil Type*	Test Temperature (°C)	Density (kg/m^3)	Viscosity (mPa•s)
A1	uncut Bunker C	5.0	1022	752 000
A2	Bunker C/11% diesel	5.5	998	5 640
A3	bunker C/10% diesel	7	999	6 280
A4	Bunker C/19% diesel	7.5	9811	480
A5	Bunker C/29% diesel	9	958	430
A6	Bunker C/5% diesel	4	1016	16 300
A7	Bunker C/14% diesel	4	994	2 570
A8	J-34/71% saltwater	5.5	980	842 000
A9	J-34/85% saltwater	9	999	591 000
A10	J-34/78% saltwater	9	990	666 000

* Blended as mass percent.

Summary of General Behaviour. A complete description of each run and results may be found in the project report (S.L. Ross, 1987). Based on the observations from the test runs, three criteria must be met for overwashing and transient submergence (i.e., "deep episodes") to occur: 1) the oil must have a density close to that of the water; 2) the oil must be viscous enough to break into slicklets or blobs that have the potential to be overwashed; and 3) the energy in the waves must be sufficient to actually submerge these high density oil forms. The data from these and other tests were used to develop equations that mathematically describe these processes.

Development of Process Equations. Two groups of process equations have been developed: one to predict whether a given oil in a given sea state will break into slicklets and blobs and to estimate the size of these oil forms; and the second to predict the depth of overwash, maximum transient submergence depth and the distribution of temporarily submerged oil with depth.

Slick Breakage. Raj (1977) presents a mathematical model in which the maximum normal tensile stress in a slick (caused by the stretching and thinning action as waves pass beneath) is compared with the molecular cohesion of the slick to determine whether or not a given slick in a given sea state will break into slicklets. In his analysis, he uses the surface tension (i.e., oil/air interfacial tension) of the slick divided by the slick thickness as a measure of slick cohesion. Unfortunately, this implies that thicker slicks are easier to break than thinner slicks, a result that contradicts intuition and experience. Rather than divide surface tension by slick thickness, it is more appropriate to divide by a measure of the surface length that the force is acting along; in this case wave amplitude seems reasonable. Starting from Raj's (1977) equation, modified to replace thickness with amplitude, which gives as the slick breakage criteria:

$$C_1\sigma/a < 2\mu_o\Gamma\,\mathrm{max} \tag{1}$$

where: σ = surface tension (N/m)
a = wave amplitude (m)
μ_o = oil viscosity (Pa•s)
C_1 = a constant
$\Gamma\,\mathrm{max}$ = maximum strain rate in a slick subjected to a sinusoidal wave (s^{-1})

and substituting:

$$\Gamma\,\mathrm{max} = W/2(A^2-1)^{1/2} \tag{2}$$

where: W = wave frequency (rad/s)
A = steepness parameter
= $\dfrac{1+(\pi s)^2}{2\pi s}$
s = wave steepness
= $2a/\lambda$
λ = wavelength (m)

and, for deep-water gravity waves:

$$W = (2\pi(1-s)g/\lambda)^{1/2} \tag{3}$$

where: λ = acceleration of gravity (m/s^2)

yields, for the oil viscosity limit for slick breakage:

$$\mu_o > C_1(\sigma^2(A^2-1)/\pi a s(1-s)g)^{1/2} \tag{4}$$

Examination of the test data (S.L. Ross, 1987a) shows that oils with viscosities < 1500 mPa•s (Runs A4, A5) did not form into slicklets or blobs at any non-breaking wave condition while oils with viscosities > 2500 mPa•s did. The value of C_1 is, therefore, tentatively set at 30. This gives a minimum oil viscosity for breakage of 2000 mPa•s at a wave generator setting of 60. As the waves begin to break, A approaches 1 thus predicting, correctly, that even the lowest viscosity oils will fracture, though the mechanism of fracture in breaking waves is not stretching and thinning of the slick.

Equation 4 predicts that, for a given continuous slick on the sea, breakage will occur as the oil weathers (increasing the viscosity), as the wave amplitude increases (for a given wave steepness), as the wave steepness increases (for a given amplitude) or as the surface tension of the oil decreases. For the purposes of this study (because of the difficulties encountered in measuring the interfacial tension of viscous oils) the surface tension of any oil is assumed to be constant at 30 mN/m.

Slicket/blob size. Raj (1977) gives an equation for the strain rate a slick undergoes as sinusoidal waves pass beneath it:

$$\Gamma(\theta) = W \sin\theta / 2(A - \cos\theta) \tag{5}$$

where: θ = Kx (angular displacement)
x = distance from origin (m)
K = wave number (m^{-1}) ($2\pi / \lambda$)

using the breakage criteria given in Equation 1:

$$C_2 \sigma / a = \mu_o W \sin\theta / (A - \cos\theta) \tag{6}$$

or

$$\sin\theta / (A - \cos\theta) = C_2 \sigma / aW \mu_o$$

in order to simplify, for x between 0 and $\lambda/8$, θ is between 0 and $\pi/4$. In this range $\sin\theta \approx \theta$ and $\cos\theta \approx 1$ or:

$$\frac{\theta}{(A-1)} \approx C_2 \sigma / aW \mu_o \tag{7}$$

or

$$\theta \approx (A-1) C_2 \sigma / aW \mu_o \tag{8}$$

substituting for 0 and W (for deep-water gravity waves) yields:

$$x = C_2 (A-1) \sigma \lambda^{1/2} / \mu_o \pi s (2\pi(1-s)g)^{1/2} \tag{9}$$

Figure 2 shows a plot of the data for those runs where slick breakage occurred at wave settings less than 80 (breaking waves make A approach 1), and Equation 9 with $C_2 = 3$. Also shown are data from two runs with waxy crude oils (S.L. Ross and DMER, 1987). Although the fit is far from perfect, the equation predicts the trends in the data and can be used to obtain order of magnitude estimates of slicklet and blob sizes. Equation 9 is not suitable for use with very viscous oils or emulsions since these behave almost as solids. The viscosity cutoff, above which Equation 9 is no longer valid, was arbitrarily chosen as 50 000 mPa•s.

Overwash depth. Overwashing is defined as the minimum thickness of water on top of slicklets and blobs in a wave field. By dimensional analysis, including wave energy, oil/water density difference, slicklet/blob size and gravity as factors that influence overwashing in non-breaking waves, it was determined that:

$$\frac{d}{x} = C_3 (\rho_w a^2 / 2x^2 (\rho_w - \rho_o))^{C_4} \tag{10}$$

where: d = overwash depth (m)
ρ_w = water density (kg/m^3)
ρ_o = oil density (kg/m^3)

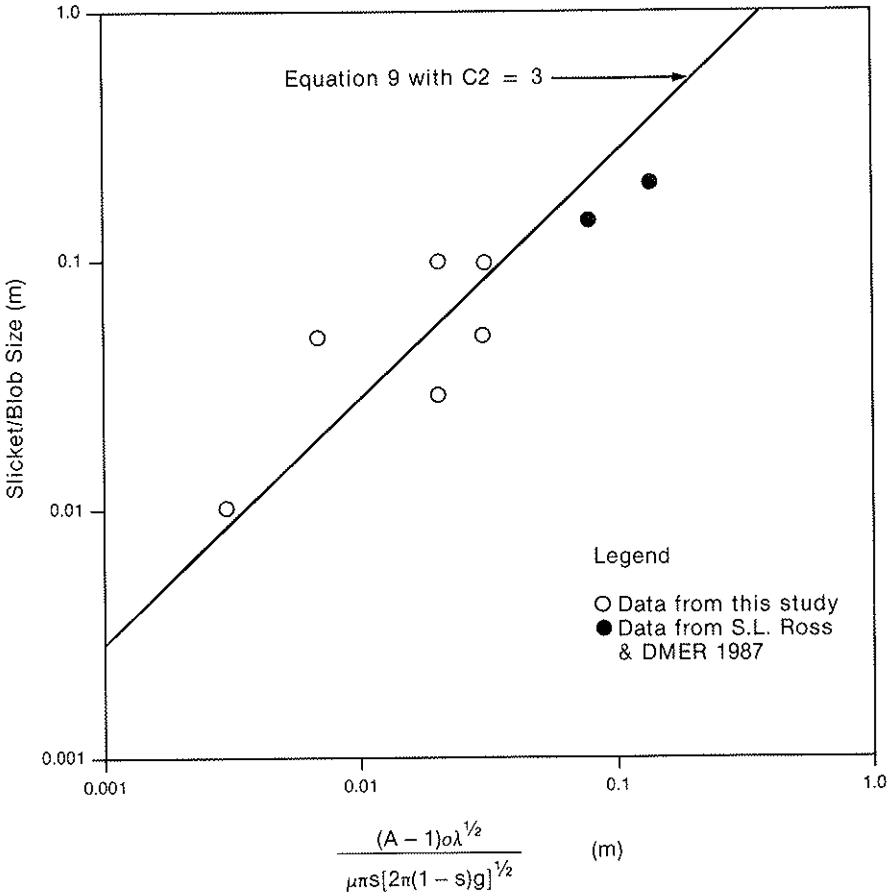

FIGURE 2 EXPERIMENTAL SLICK BREAKDOWN

Figure 3 shows a plot of the data points for those runs that involved overwashing (i.e., those in which the oil was in the form of slicklets or blobs). Also shown in Equation 10 with $C_3 = 7.5 \times 10^{-4}$ and $C_4 = 0.725$ and the data of Mackay et al. (1986) for lard pans. The scatter is due to imprecision in measuring both the submergence depth and slicklet or blob size in a moving system. It should be noted that slicklets in a previous study with viscous, waxy oils (S.L. Ross and DMER, 1987) were not overwashed due to their low density relative to the oil used in this study. This is dealt with in the modelling section later by setting the minimum overwash depth as 1 mm (i.e., if Equation 10 predicts an overwash less than 1 mm, it is designated as not being overwashed). This cutoff was selected on the basis of observations made during runs A8 and A10 where the slicklets were slowly overwashed. The portions of the slick overwashed by water were covered by at least 1 mm; the above water portions were dry; no areas were covered by less than 1 mm of water. As well, conventional aerial remote sensors for oil spills will not detect oil with more than 1 mm of water overwashing the slick (Fingas, 1987).

Equation 10 is intuitively correct in that the overwash depth increases with increasing wave height and oil density and decreases with increasing slicklet size.

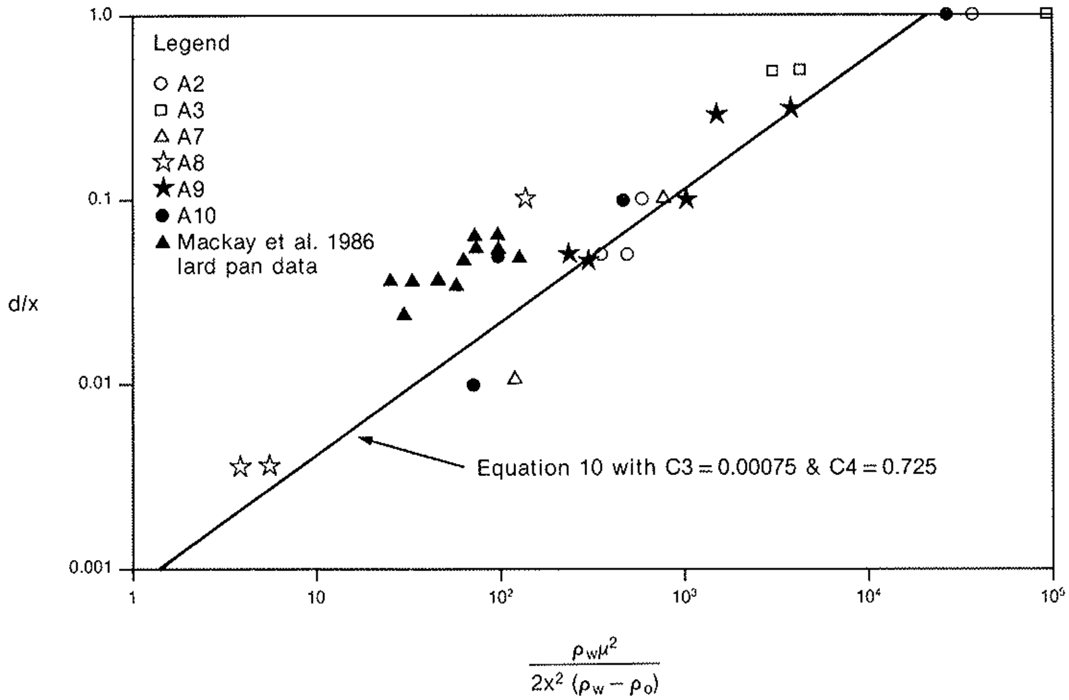

FIGURE 3 EXPERIMENTAL OUTWASH DATA

Maximum transient submergence depth. Maximum transient submergence depth is the deepest that a buoyant slicklet or blob was propelled during a "deep episode". By dimensional analysis it was found that submergence depth could be correlated with the same factors as overwash depth:

$$\frac{d^1}{x} = C_5(\rho_w a^2/2x^2(\rho_w - \rho_o))^{C_6} \tag{11}$$

where: d^1 = maximum transient submergence depth (m)

Figure 4 shows the data from the test runs and Equation 11 with $C_5 = 2.9 \times 10^{-2}$ and $C_6 = 0.615$. Also shown are the data from Mackay et al. (1986) for lard pans and the range of data for plastic spheres, both under wave conditions.

Equation 11 is consistent with the correlations presented by Mackay et al. (1986) for lard pans:

$$d^1 = 0.009\ U^2/(\rho_w - \rho_o)^{0.8} \tag{12}$$

with d (cm), the wind speed U (m/s) and densities (g/cm^3)

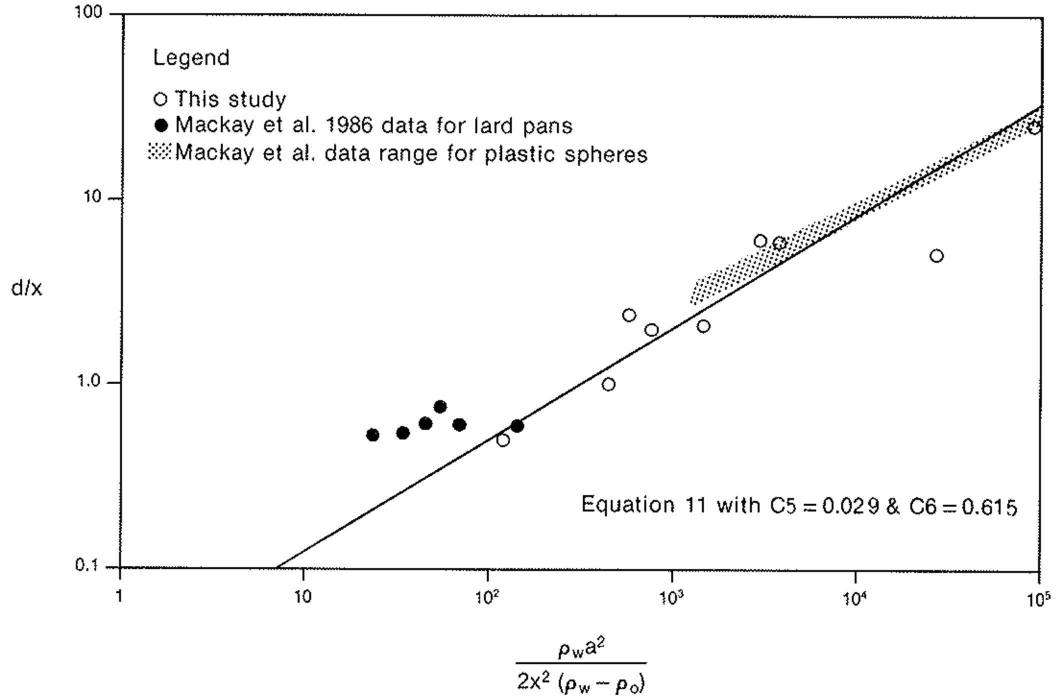

FIGURE 4 EXPERIMENTAL MAXIMUM SUBMERGENCE DATA

and, for plastic spheres:

$$d^1 = 0.2/(\rho_W - \rho_o) \qquad (13)$$

Depth distribution of oil. The probability of an oil form being below a certain depth d (or alternatively, for a slick containing many slicklets or blobs, the fraction of the oil below depth (d) can be expressed as (Mackay et al. 1986):

$$P = \exp - (d/c)^b \qquad (14)$$

where: P = probability
c = characteristic length (m)
b = a constant

Assuming that Equation 10 (overwash depth) represents the depth below which the oil spends 95% of its time and Equation 11 (maximum transient submergence depth) represents the depth above which the oil spends 95% of its time, substituting into Equation 14 yields:

$$0.95 = \exp - (7.5 \times 10^{-4} \times(\rho_W\ a^2/2x^2(\rho_W - \rho_o)^{0.725}/c)^b \qquad (15)$$

and

$$0.05 = \exp - (2.9 \times 10^{-2} \times (\rho_W\ a^2/2x^2(\rho_W - \rho_o)^{0.615}/c)^b \qquad (16)$$

Solving for c and b gives the probability distribution as:

$$P = \exp - \left[91.5d/x(\rho_w\ a^2/2x^2(\rho_w - \rho_o)\right]^{0.64467} \qquad (17)$$

with b = 1 within the accuracy of the data.

Example distributions for various oil and wave conditions are shown in Figure 5. At a constant oil buoyancy and wave height the effect of increasing slicklet or blob size is to shift the distribution towards the surface; at constant wave height and slicklet size the effect of reducing oil buoyancy is to shift the distribution deeper; at constant buoyancy and slicklet size the effect of increasing wave height is also to shift the distribution deeper.

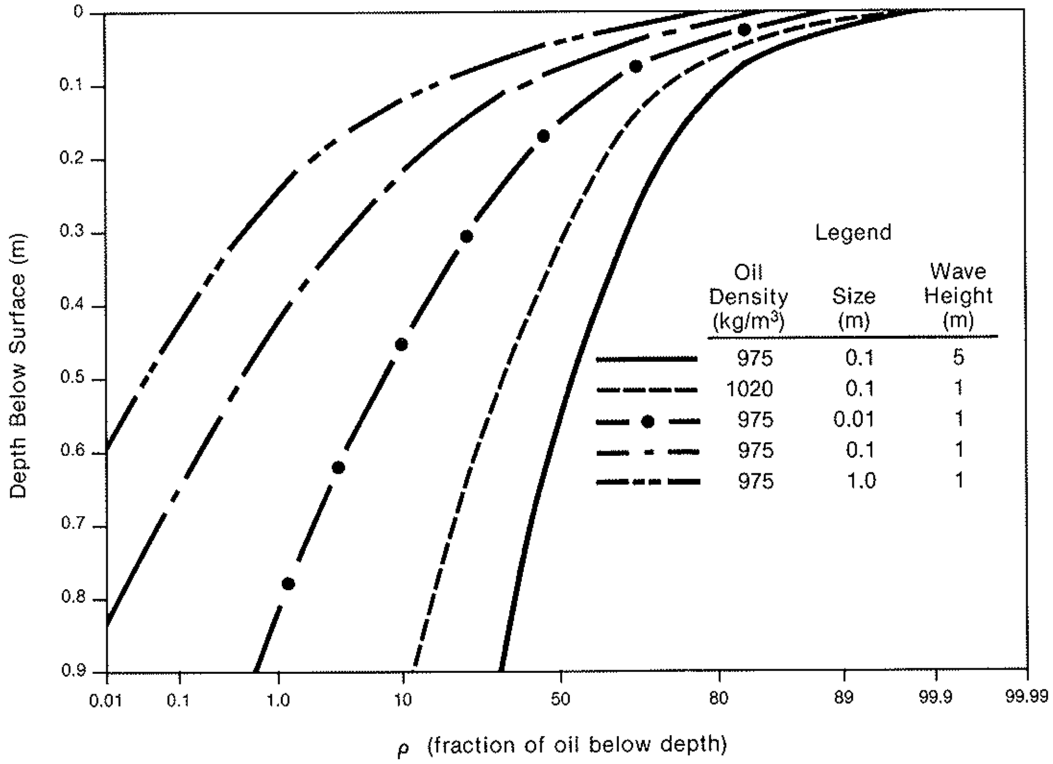

FIGURE 5 EXAMPLE CALCULATED OIL DEPTH DISTRIBUTIONS

Incorporation into an Oil Behaviour Computer Model

The Oil Fate Model. Incorporation of the process equations into a computer model was done to allow predictions of submergence behaviour as oil slicks weather, spread and emulsify with time. The approach taken in this study to predict transient oil submergence at sea was to modify an existing oil fate and behaviour model. The main features of this model are presented prior to discussing the modifications. A program listing in Fortran is given in the project report (S.L. Ross, 1987a).

The model is based primarily on work performed at the University of Toronto over the past decade; oil spreading is based on the model of Mackay et al. (1979) which utilizes the thick/thin approach; oil evaporation is based on the evaporative exposure approach of Stiver and Mackay (1983), and subsequent oil property changes are determined using the approach of Tebeau et al. (1983); sea state (i.e., wind speed) and oil properties are used to calculate natural dispersion (after S.L. Ross, 1984) and emulsification (after Mackay et al., 1979; modified to include a delay until the particular oil weathers to an emulsifiable state). A routine has also been included to assess chemical dispersion effectiveness (S.L. Ross, 1987), though this was not used for this study.

In its present form, the model requires a fairly large number of oil property inputs to be used to its full potential. Much of this information is presently available in oil property catalogues published by Environment Canada (S.L. Ross, 1985; Bobra and Chung, 1986) for many Canadian oils. Work is also underway at the University of Toronto (S.L. Ross and DMER, 1987) to develop a technique to fully quantify oil property changes with evaporation using only a simple distillation procedure.

Modifications to Predict Submergence

Data input and initialization. Primary modifications in this part of the program included changes to input the sea parameters of swell height (a^1) and wavelength ($\lambda 1$), surface water density (ρ_S) and the depth to the pycnocline (d^{11}). In the initialization portion of the program, wave properties are calculated from wind speed (U = m/s at 10 m height), using the following equations given by Raj (1977) for a fully developed sea:

$$\text{RMS wave height} = \quad a^* = 7.83 \times 10^{-3}\, U^2 \text{ (m)} \qquad (18)$$

$$\text{average wavelength} = \quad \lambda = 1.06\, U^2 \text{ (m)} \qquad (19)$$

$$\text{average wave height} = \quad a = 1.77\, a^* \qquad (20)$$

$$\text{wave steepness} = \quad s = 2\, a/\lambda \qquad (21)$$

$$\text{swell steepness} = \quad s^1 = 2\, a^1/\lambda^1 \qquad (22)$$

The program then checks which is steeper, the swell or the waves and uses the amplitude and wavelength of the steeper to calculate the steepness parameter (A) using the expression given for Equation 2.

Mainline. The first step in the mainline calculation program is to check if the oil or emulsion density exceeds that of seawater (1025 kg/m^3); if so, the oil sinks and the program terminates. If the oil or emulsion density lies between that of the surface water and 1025 kg/m^3 the oil sinks to the pycnocline depth covering an area equal to the thick slick area calculated for that iteration and the program is terminated.

If the oil density is less than that of the seawater, the program checks to see if the oil or emulsion viscosity exceeds the minimum for slick breakage (Equation 4). If not, the program spreads and weathers the oil for one iteration and returns to the beginning; if the oil is viscous enough to break, the size of the slicklets/blobs is calculated (Equation 9).

Next the program calculates the overwash depth for the slicklets/blobs using Equation 10 (with rms wave height); if the overwash depth is < 1 mm the program spreads and weathers the oil for one iteration and returns to the beginning. If the overwash is > 1 mm, the program calculates the maximum transient submergence depth from Equation 11 and compares it to the pycnocline depth; the lesser of the two is used. The program then calculates the fractions of the oil between the surface and 10-cm deep, between 10-cm deep and 1-m deep, and deeper than 1 m below the surface. The fractions are adjusted if the pycnocline is < 1 m below the surface.

Finally, if the oil is overwashed, the program stops spreading the thick portion of the slick (i.e., the submerged portion); the thin sheen continues to exist on the surface, fed by the submerged slicklets/blobs. This latter feature is based on anecdotal accounts of actual spills rather than laboratory test data. Evaporation, emulsification and natural dispersion of the thick slick are assumed to continue as if the oil were on the surface. These oil fate processes for submerged oil need to be addressed in future studies.

Modelling Results

Figure 6 shows the predicted behaviour and properties for a crude oil with an initial density of 900 kg/m^3 and initial viscosity of 25 mPa•s that emulsifies when spilled on water with a surface density of 1020 kg/m^3 in a 5 m/s wind with no swell. Over the time period graphed the oil spreads, evaporates, emulsifies and naturally disperses until after 3 1/2 days about 50% of the original 1000 m^3 spill is left. Figure 7 shows the same spill in the same conditions except that a very steep ($s = 0.06$) swell has been added. In this case, after 18 hours the emulsion becomes viscous enough (2900 mPa•s) and dense enough (994 kg/m^3) to be broken into slicklets about 2.5 m in diameter overwashed by 2 cm of water. The predicted maximum transient submergence depth is about 0.5 m. Slicklet size decreases slowly with time; both overwash and maximum submergence depth increase with time.

Figure 8 gives the predicted results if the initial oil density is increased to 990 kg/m^3, the surface water density is reduced to 1015 kg/m^3 and all other parameters remain the same. In this situation, the oil breaks up into emulsion slicklets at the same time as the previous case (Figure 7) but the initial overwash and maximum transient submergence depth are about a factor of ten greater. After two days exposure, the emulsion density exceeds that of the surface water and the oil sinks to the pycnocline at a depth of 10 m.

Figure 9 shows the predicted behaviour of the Bunker C spilled by the KURDISTAN. Oil property information was taken from C-CORE (1980); environmental information at the time of the spill was obtained from Vandermeulen and Buckley (1985). In the high seas at the time of the incident, the model predicts that blobs in the size range of 0.6 m would be overwashed by about 10 cm of water. The maximum transient submergence depth is predicted to have been about 2 m. Very little weathering of the Bunker C is predicted; therefore, the oil would survive for a long time. These predictions are broadly consistent with the anecdotal accounts given by Reimer (1981).

Simplified Nomograph. In order to obtain quick estimates for emergency response purposes, the process equations have been simplified by substituting the predictive

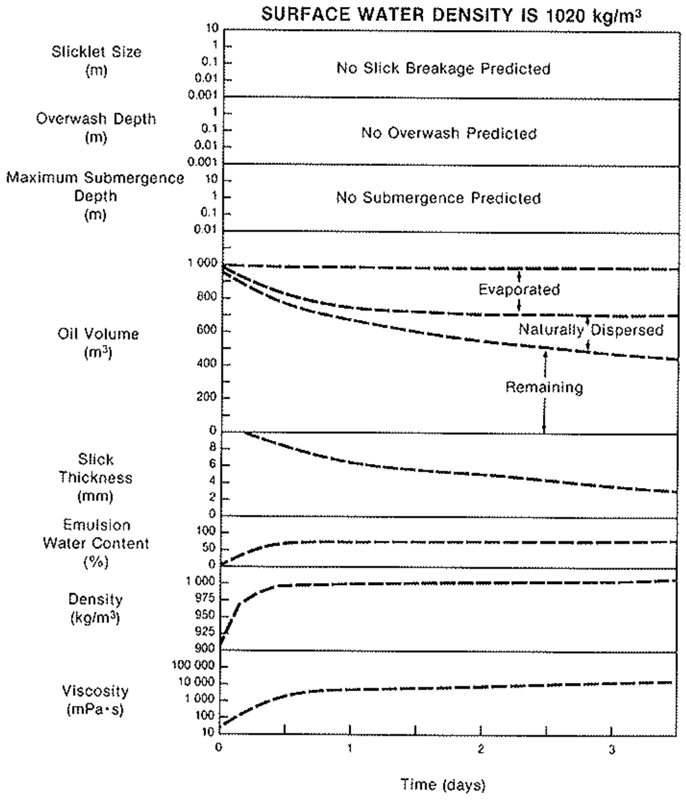

FIGURE 6 PREDICTED BEHAVIOUR OF 900 kg/m^3 CRUDE OIL SPILL IN A 5 m/s WIND AND NO SWELL

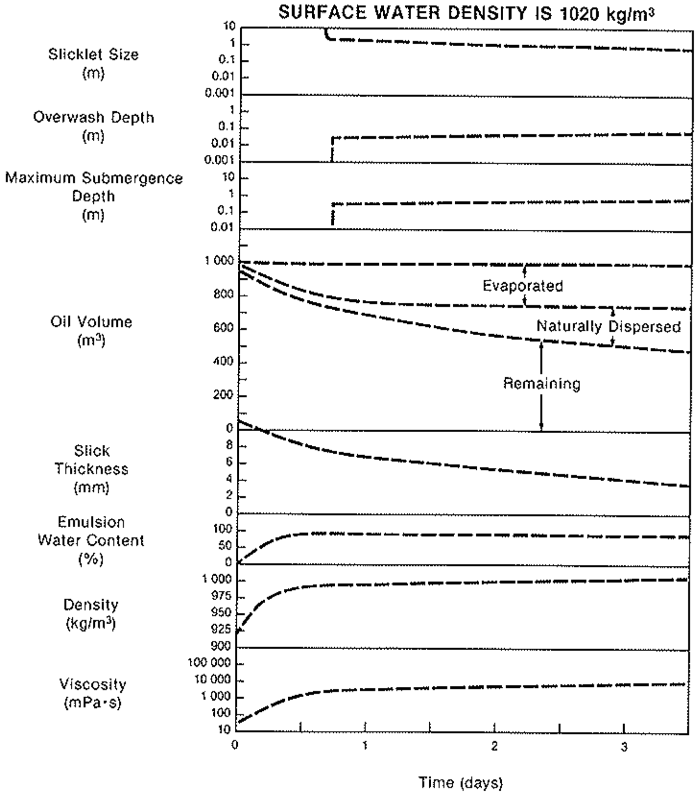

FIGURE 7 PREDICTED BEHAVIOUR OF 900 kg/m^3 CRUDE OIL SPILL IN A 5 m/s WIND AND 3-m SWELL

equations for rms wave height, average wave height and average wavelength for a fully developed sea into Equation 9 to predict slicklet/blob size and Equation 10 to predict overwash depth, yielding for non-emulsified oils:

$$d(c\ m) = 7.6 \times 10^{-5}\ U^{2.45}\ {}_{o}^{0.45} / \left[(\quad w - \quad o)/\quad w\right]^{0.725} \qquad (23)$$

and for heavily emulsified oils (which behave as solids and are not "broken" by waves):

$$d(c\ m) = 5.9 \times 10^{-4}\ U^{2.9} / \left[(\quad w - \quad o)\right]^{0.725 \times 0.45} \qquad (24)$$

The ratio of overwash depth to maximum transient submergence depth (Equation 11 divided by Equation 10) is approximately 40 since $C_6 - C_4$ is very small.

Figure 10 shows a nomograph for fully developed sea conditions with a surface water density of 1022 kg/m^3 (35 ppt) based on Equation 23 for a range of residual fuel oils. Figure 11 shows a nomograph based on Equation 24 for the submergence of emulsion mats/blobs of various sizes.

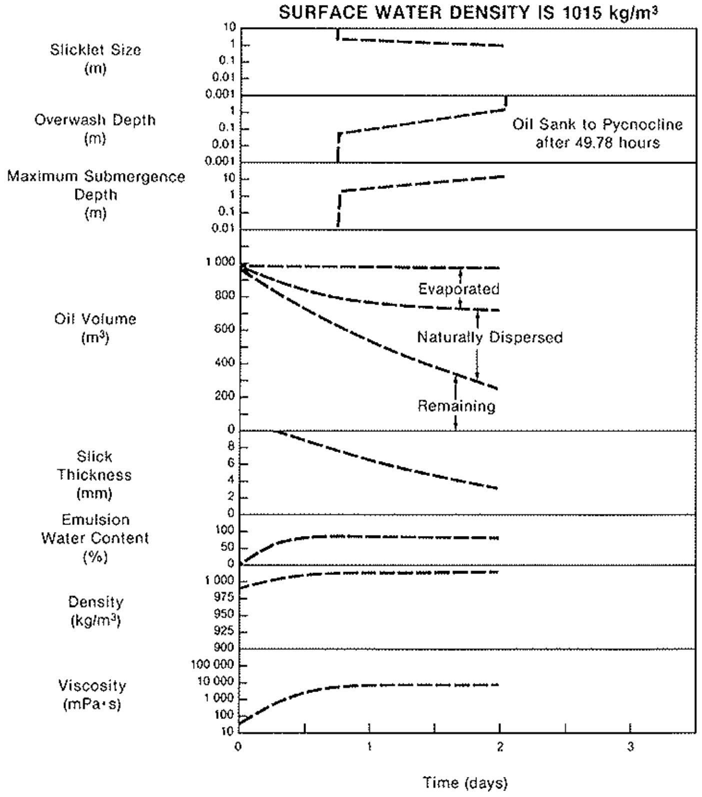

FIGURE 8 PREDICTED BEHAVIOUR OF 990 kg/m³ CRUDE OIL SPILL IN A 5 m/s WIND AND 3-m SWELL

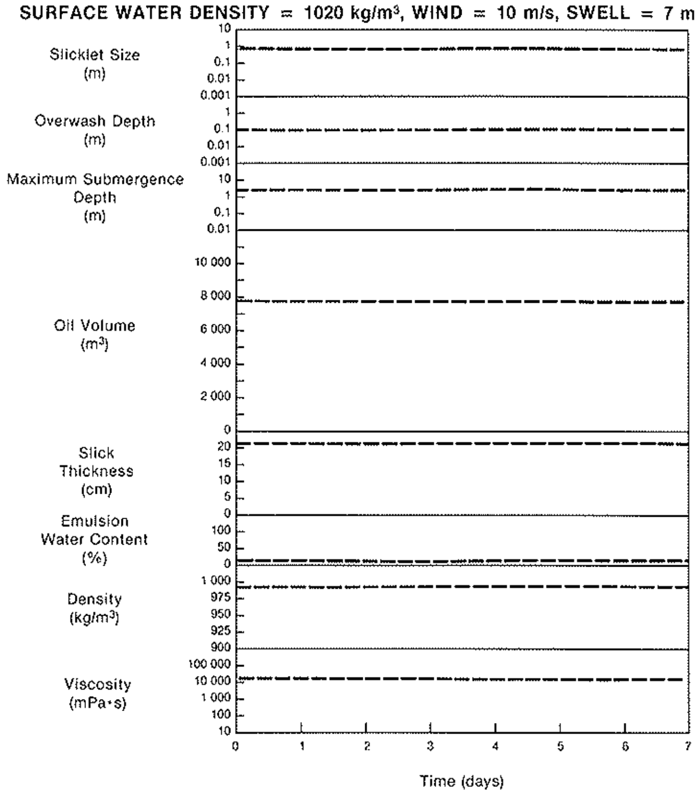

FIGURE 9 PREDICTED BEHAVIOUR OF KURDISTAN BUNKER C SPILL

The residual oil properties used were heavy Bunker C (from this study) medium Bunker C (from data on the KURDISTAN spill), light Bunker C (from Bobra and Chung, 1986), and heavy Bunker B, or No. 5 fuel oil (from Bobra and Chung, 1986). Predictions are given for 1000 kg/m³ emulsion with mat/blob sizes of 1, 0.1 and 0.01 m.

If oil property information is available during a spill response, Equations 23 or 24 can be used to obtain better estimates. If surface salinities are lowered, oil weathering or emulsification is expected to take place or other complicating factors exist, the computer model should be used with the best available input data.

Conclusions and Recommendations

The overwashing and transient submergence of oil spills on water depends primarily on the buoyancy of the oil or emulsion; the viscosity of the emulsion; and the sea state. A necessary condition for overwashing or transient submergence is that the oil be of sufficiently high viscosity so that it can be broken into discrete slicklets or blobs by wave action. Once this occurs, the degree of overwashing and transient submergence is controlled by the size and buoyancy of the slicklets or blobs and the prevailing sea state.

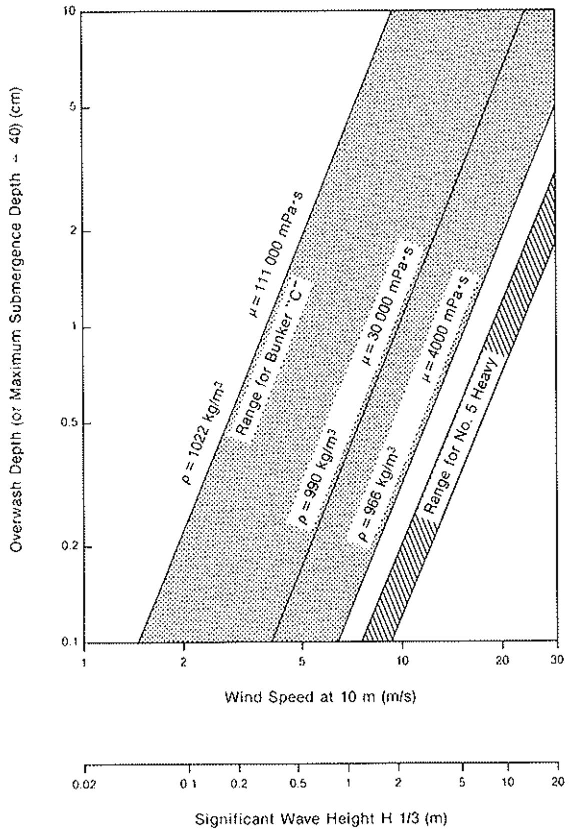

FIGURE 10 OVERWASH/SUBMERGENCE NOMOGRAPH RESIDUAL FUEL OILS

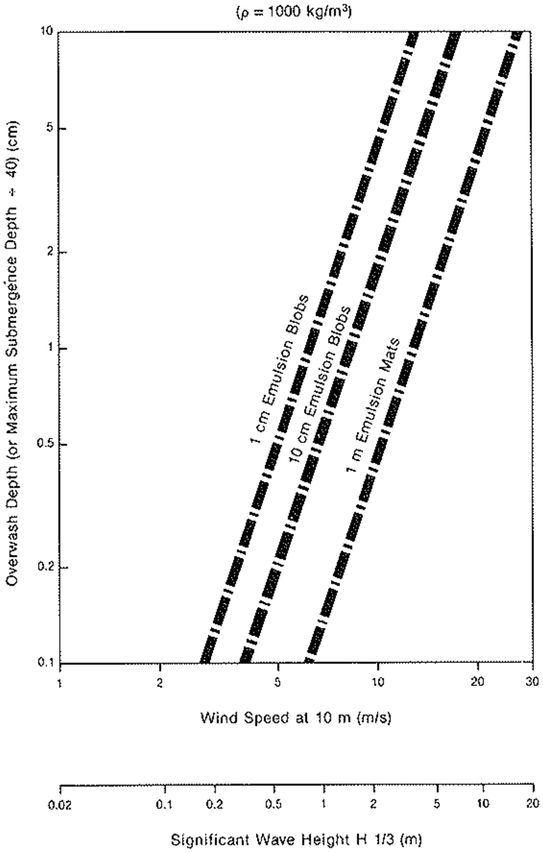

FIGURE 11 OVERWASH/SUBMERGENCE NOMOGRAPH EMULSIONS

For non-emulsified oils, the size of the slicklets or blobs is determined by sea conditions and the surface tension and viscosity of the oil. Emulsions, due to their enormous viscosities, behave almost as solids; emulsion mat or blob sizes are possibly only a function of sea conditions but this is unknown.

Based on theory and wind/wave tank test results, process equations incorporating oil properties and sea conditions, have been developed to predict: whether or not a particular oil slick will break up into slicklets or blobs; the size of the resultant slicklets and blobs; whether or not they are overwashed by water and to what extent; and the maximum transient submergence depth of the slicklets and blobs and their distribution as a function of depth. These process equations have been incorporated into an oil spill fate and behaviour computer model that calculates oil spreading, evaporation, emulsification and natural dispersion to allow state-of-the-art predictions of transient submergence. The process equations were also simplified to provide quick estimates for residual fuel oil spills and a range of emulsion mat sizes.

It is recommended that the models be updated as further field data become available, that a study on the processes of evaporation, emulsification and natural dispersion of submerged oil be undertaken, and that the results of this study be incorporated into an oil spill trajectory model for submerged oil.

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OBSERVATIONS FROM A SITE VISIT TO THE "METULA" SPILL 12 YEARS AFTER THE INCIDENT

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Abstract

The August 1974 spill of 415 000 barrels of light Arabian crude that resulted from the grounding of the VLCC "Metula" in the Strait of Magellan was, at that time, the largest oil spill from a tanker. The spill was neither contained nor cleaned up. A field study was conducted in the area January 1987 to evaluate the character of any remaining stranded oil and to collect samples for total hydrocarbon and GC analyses. It was believed that an asphalt pavement, observed by one of the authors in 1977 and by Gundlach et al. in 1981, was still present and would be a suitable comparison for data collected on a similar pavement that had formed following an experimental release of oil at Cape Hatt as part of the Baffin Island Oil Spill (BIOS) project.

Oil was found at several locations on the highest sections of the beach. Comparison with observations from the 1977 site visit indicates that there has been considerable natural cleaning at these sites over the past 10 years. The oil that remains is generally a narrow strip that was laid down by high spring tides and is now buried on the landward margin. A major exception to this pattern occurs in the Puerto Espora area on the south shore of the first narrows. Here extensive asphalt pavements remain in the intertidal and supratidal zones over a shoreline length of several kilometres. The surface of these pavements is characterized by a very weathered crust, but the oil contained within the pavements is very fresh in appearance and has a low viscosity in many cases.

1 Introduction

1.1 Objective and Rationale. The primary objective of the field study was to visit shoreline locations in the Strait of Magellan, Chile (Figure 1), to record the character of any remaining stranded oil 12-1/2 years after the "Metula" spill and to collect samples for subsequent chemical analyses.

Previous site visits to this sub-antarctic area had recorded the presence of extensive asphalt pavements on the south shore of the First Narrows in the Strait. A similar pavement had formed on an intertidal beach in an arctic environment at Cape Hatt following an experimental release of oil as part of the Baffin Island Oil Spill (BIOS) Project (Owens and Robson, 1987). Field studies at Cape Hatt commenced in August 1981 and were repeated in 1982 and 1983, with a further field survey in August 1985. The results from the "Metula" area would be used to provide a real-world comparison for the data from the BIOS experiment. As part of this overall program, a site visit to the "Amoco Cadiz" area had been carried out in March 1985 to record the character of

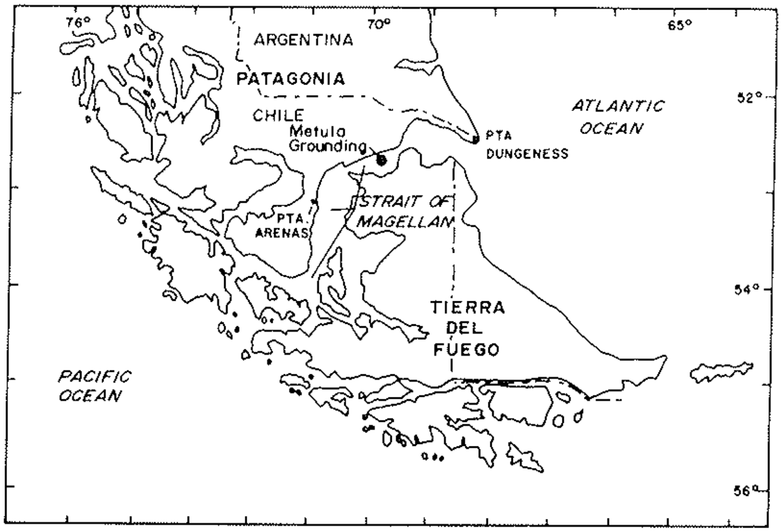

FIGURE 1 THE "METULA" SPILL SITE (Hayes and Gundlach, 1975)

asphalt pavements that had formed in the mid-latitude temperate environment (Owens and Robson, 1985). The sampling and analytical procedures used in all of these studies are identical in order to provide comparable data sets.

1.2 Methods. Nine coastal sites were visited in the eastern Strait of Magellan (Figure 2) (Owens and Robson, 1987). At each site, a series of systematic observations were recorded, photographs were taken and 28 samples were collected in plastic bags for total hydrocarbon analysis and 26 in clean glass jars for GC analysis.

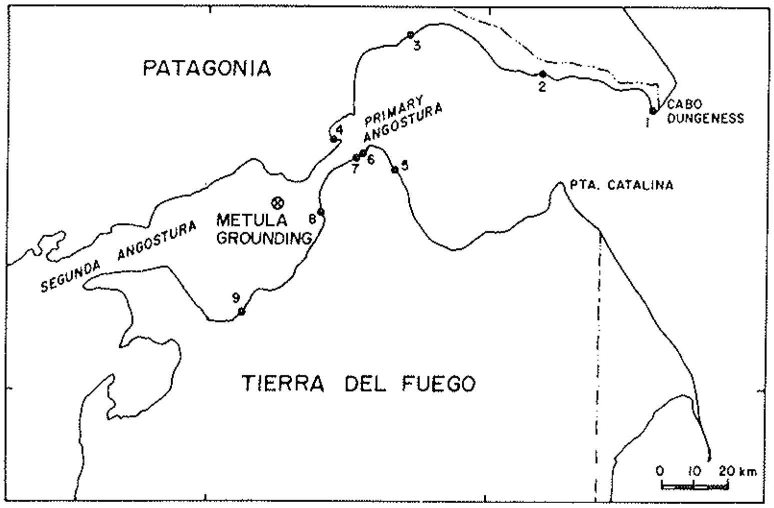

FIGURE 2 SHORELINE LOCATIONS VISITED IN JANUARY 1987

A preliminary set of compositional analyses was obtained for original Metula oil and for four selected samples to provide data on the present character of the pavement oil. A small subsample (0.5 g) of oiled sediment was extracted with carbon disulphide, and the extract analysed using a Hewlett-Packard 5830 gas chromatograph fitted with a 25 m SGE BP-5 bonded phase fused silica capillary column and a flame ionization detector (CG/FID). The resolved peaks were identified by comparison to a standard set of n-alkanes analysed in the same manner. Future work will include a total hydrocarbon determination by an infrared spectrophotometric procedure (Owens, Hope and Humphrey, 1986) and more detailed gas chromatographic analysis including fractionation and mass spectrometric determination of selected aromatic hydrocarbons.

2 The "METULA" Spill

2.1 The Spill Incident. The VLCC "Metula" grounded at full speed during the night of August 9, 1974 just to the west of the First Narrows in the Strait of Magellan, with a cargo of about 1.42 million barrels of light Arabian crude. Oil was spilled from the initial grounding and at intervals until the vessel was refloated on September 25th. This is an area of very strong tidal currents (up to 9 knots) and considerable hull damage was sustained during periods of spring tides on August 11, August 19 and September 4 (Gunnerson and Peter, 1976). The estimated total loss was about 400 000 barrels of crude and 15 000 barrels of Bunker C oil. Oil from the "Metula" was transferred to a small tanker, but no attempts were made to contain or disperse the spilled oil and no shoreline cleanup was undertaken.

The spilled oil was spread rapidly by strong winds and tidal currents and a "Mousse" was observed to have formed. Approximately 250 km of shoreline were contaminated, with the most severe impact occurring on the south shores of the Strait in the vicinity of the first narrows (Blount, 1978).

2.2 Environmental Background. Despite the relatively low latitude (53° S) this is a cold environment with a mean monthly mid-summer (January) temperature of 11.7°C and a mid-winter (July) temperature of +2.5°C. The shore zone is not affected by severe freezing (Gunnerson and Peter, 1976). Strong westerly winds are characteristic throughout the year with velocities commonly >50 km/h and frequently >100 km/h. The mean tidal range near the site of the grounding exceeds 8 m. A large proportion of the spilled oil was released at times of spring high tides and therefore became stranded at many sites above the limits of normal wave action.

The shorelines of the area are characterized by wide sand or sand-gravel beaches and at many locations by wide mud or gravel low-tide terraces. Wave-energy levels at the shoreline vary considerably depending upon exposure to local fetches within the straits and upon the orientation of the coast with respect to waves generated by the dominant westerly winds.

2.3 Previous Studies. Several shoreline surveys and some sampling programs were conducted during the two years immediately following the spill (e.g., Blount, 1976; Hann and Young, 1979; Straughn, 1981). The site was visited by one of the authors (Owens, 1978) and in 1981 by Gundlach et al. (1982). Blount collected a series of beach samples which were analyzed for total hydrocarbons and Gundlach et al. reported observations on the extent of the remnant stranded oil and asphalt pavements.

3 Summary of Field Observations

The field site visits were not intended to cover the entire area affected by the "Metula" oil, and, therefore, do not constitute a systematic or complete survey. However, on the basis of the observations made at the selected locations it is possible to present a review of the character of the remaining stranded oil which in turn provides useful information on the self-cleaning of the beaches of this region. The following paragraphs summarize the observations at the sites where oil was still present on the beach surface in January 1987. A more complete description of each site and photographs of the oil are given in Owens and Robson, 1987.

Punta Malvinas. This site is a spit system on the north shore at the eastern end of the First Narrows (Site 4 - Figure 2). Oil remains on relict recurved ridges in sheltered backshore areas above the normal limit of wave action. Narrow (1 to 2 m wide), hard pebble-cobble pavements were present near the spring high-water level at two locations and on one section the pavement was continuous alongshore for about 30 m. The oil was laid down at a time of high spring-tide water levels in a quiescent backshore location and has been virtually unaffected by marine processes since that time.

Banco Orange. This exposed beach has a steep pebble beach-face slope and a wide (500+ m) low-tide terrace (Site 5 - Figure 2). A pavement was found in the vicinity of the spring high-water level and was discontinuous alongshore for about 50 m. The pavement was soft and sandy in character, contained shell fragments, varied between 0.5 and 1.0 m in width and was buried on the landward margin by pebble-cobble sediments. An extensive pavement recorded in 1975 by Blount on the inner (landward) margin of the low-tide terrace could not be found.

Puerto Espora. This site has a spit system that has grown approximately 2 km towards the northeast on the south shore of the First Narrows (Site 6 - Figure 2). The most westerly section is a marsh (the West Estuary) that is connected to the ocean by a small tidal creek (Espora Creek). The backbeach section is protected from the ocean by the spit itself and the section referred to as Espora Beach is open directly to marine processes. The area was heavily contaminated by the "Metula" spill and still contains large amounts of oil. Pavements were found in all sections visited.

In the West Estuary the oil was deposited during spring high tides on the flat upper marsh surface as a 20 to 30 m wide band around the rim of the marsh basin. The upper marsh remains heavily contaminated by a continuous but thin (1 to 2 cm) layer of weathered oil. Some silts have been deposited on the surface of the oil. When samples were collected the oil under the surface crust appeared to be very fresh.

On the south bank of Espora Creek patches of soft sandy-pebble pavement remain between the mean and spring high-water levels. Towards the east this grades into a more continuous pebble-cobblel pavement that is about 10 m wide on the upper section just below and at the spring high-water level. Oil is also present at the spring high-water level at the base of low backshore scarp. This highest section of pavement varied within a few metres from a soft, sandy deposit that could be broken easily by hand to a hard pebble asphalt that could be sampled by chipping or chiselling.

The backbeach section, on the mainland in the lee of the spit, had a pavement on the upper beach-face slope that was continuous alongshore for about 700 m. The width varied between 5 and 15 m and the pavement was generally 5 to 10 cm, but up to 20 cm, thick. The seaward margin of the pavement usually coincided with a change in sediment type from sand-pebble or pebble-cobble to mud and the upper margin was, in most sections, an eroding scarp except at the western end where the upper parts of the pavement were buried by pebble-cobble sediments. In general, the pavement was harder and contained more pebbles in the upper sections than the middle sections of the beach-face slope which were softer and more sandy in character.

At the most easterly end of the backbeach several sections of buried and exposed hard pavements were found above the normal highwater level. At one location, a very soft oil was found above the mean high-water mark. This deposit was characterized by a thin (1 cm) weathered crust with a veneer of fines that overlay a fresh brown mousse which was observed to ooze with a minute of the hole being cut for the sample.

The exposed Espora Beach section has a steep pebble-cobble beach face and a wide (500 m) low-tide terrace of silt and pebble-cobble sediments. A pavement was present on the beach face that was continuous about 500 and 750 m alongshore. The eastern-most section was 25 m wide and was in the middle to lower portion of the beach-face slope, just landward of the low-tide terrace. The elevation of the pavement on the beach face increased towards the west so that at the westerly end the upper edge of the pavement coincided with the mean high-water level. Again some lower sections of the pavement were soft in character and generally were associated with a light brown mousse that had a dark, weathered surface crust. The harder pavement areas had a more pebble-like character but below the surface also had a fresh appearance. The low-tide terrace contained copious soft, mousse-like oil which varied considerably in character. Pebble-cobble areas on the higher elevations of the terrace were often hard, whereas the deposits associated with finer sediments (silts) were generally softer and contained more mousse.

Punta Baxa - Rio Oscar. These two sites (8 and 9 respectively on Figure 2) had similar narrow (0.5 to 1.0 m) pavements on the highest parts of the beach at the spring high-water level adjacent to the base of a backshore dune scarp. The pavement was continuous alongshore for about 100 m at Punta Baxa and for 50 m at Rio Oscar. At both sites the pavement was relatively hard and was buried on its landward margin by pebbles and windblown sands. Both beaches were oiled during spring tides (Owens, 1978) and all but the highest deposits have now been eroded.

4. Preliminary Analytical Results

Four oiled beach sediment samples and a sample of original "Metula" oil were analysed by gas chromatography. Table 1 describes the samples, and the resulting chromatograms are presented in Figure 3a-e.

It is clear that all samples collected on January 20, 1987 are weathered relative to original "Metula" oil. Three of the samples (Figures 3b, c and e) are of pavement material and consist of unresolved complex mixture with essentially no resolved components present. A single sample (Figure 3d, sample 10) indicates that some of the oil on the beach is not heavily weathered, retaining resolved alkanes from n-C 15 and higher.

TABLE 1 CHARACTERISTICS OF OILED BEACH SEDIMENT SAMPLES

Figure Number	Sample Number	Site	Location on Beach	Description
3a	METULA			- original oil sample
3b	3	Espora Marsh	- marsh flat above mean high water	- surface sample of thin (1-2 cm) "latex" layer over fresher oil
3c	8	Espora Spit	- sandy pebble beach near mean high water	2-4 cm subsurface sample from within a soft pavement on upper beach face slope
3d	10	Espora Spit	- sandy pebble beach above spring high water	- surface sample (0-3 cm) of mousse
3e	14	Espora Spit	- sandy pebble beach 5 m below spring high water	- surface sample of very hard pavement

Biodegradation is apparent in this sample, as shown by the apparent loss of n-C 18 relative to phytane, the adjacent peak, when compared to original oil.

5 Discussion

Although this was not a comprehensive survey of the entire coast it is evident that many sections of previously contaminated shoreline are now clean of visible oil and that significant amounts of oil remain at only a few locations. With the exception of the Puerto Espora area, oil was found only on the highest sections of the shoreline, in the vicinity of the spring high-water levels. At Puerto Espora oil is present: (1) in very large volumes (more than 100 m^3 in total); (2) over the entire area, which includes marsh, sheltered beach and exposed beach environments; (3) in all sections of the beach from the low-water level to the spring high-water level; and (4) generally as an apparently fresh deposit below a weathered surface crust.

The remaining oil is present in a variety of forms that range from fresh, almost fluid and apparently unweathered, mousse and oil to hard pavement (Sample 14) that could be sampled only by chipping or chiselling off small fragments. On the basis of this series of non-systematic observations there is an apparent relationship between sediment type and the viscosity of the remnant oil. The softer sections of pavement were generally associated with sands, whereas the harder pavements occurred more frequently with coarser (pebble and cobble) sediments.

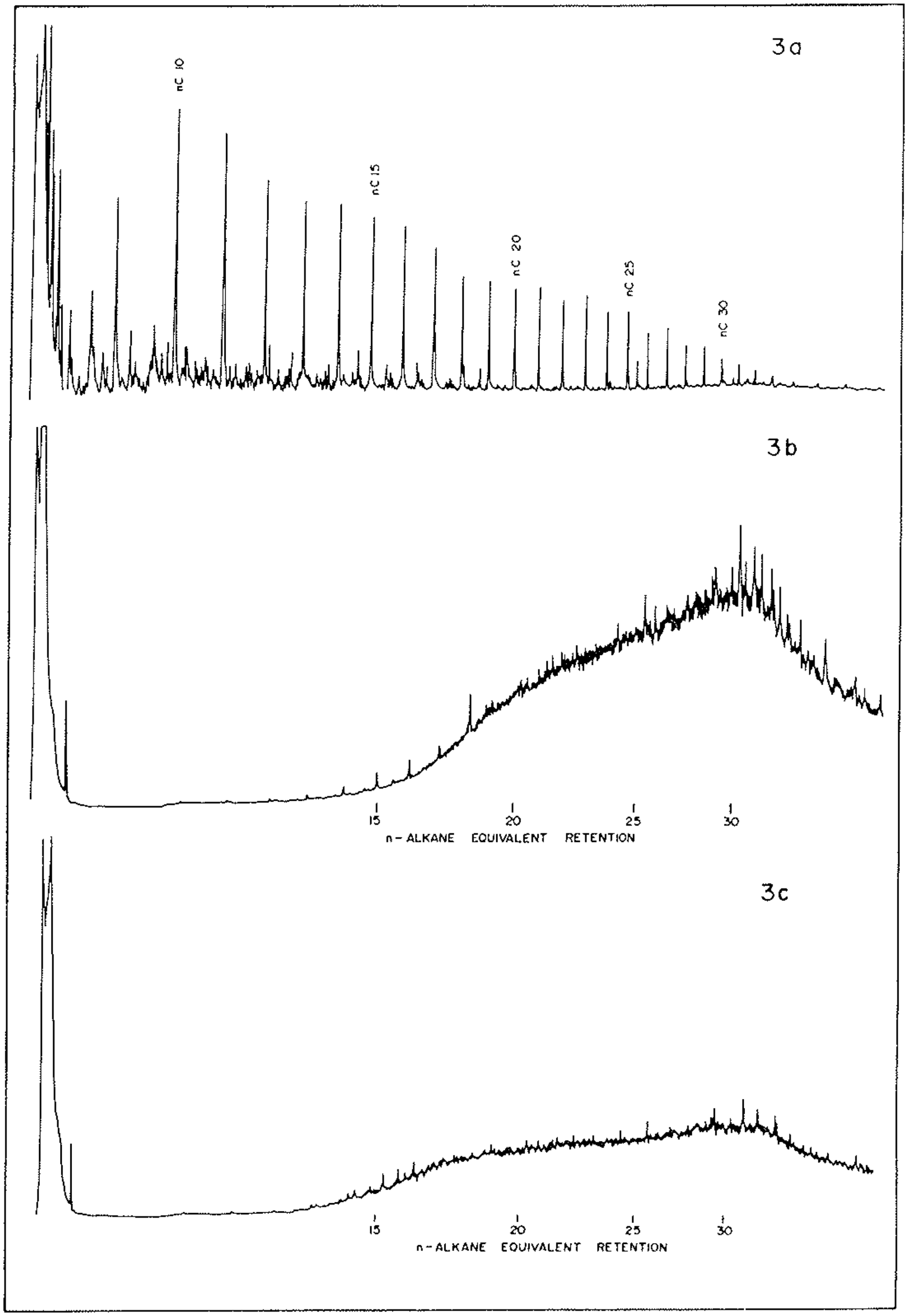

FIGURE 3 HYDROCARBON COMPOSITION

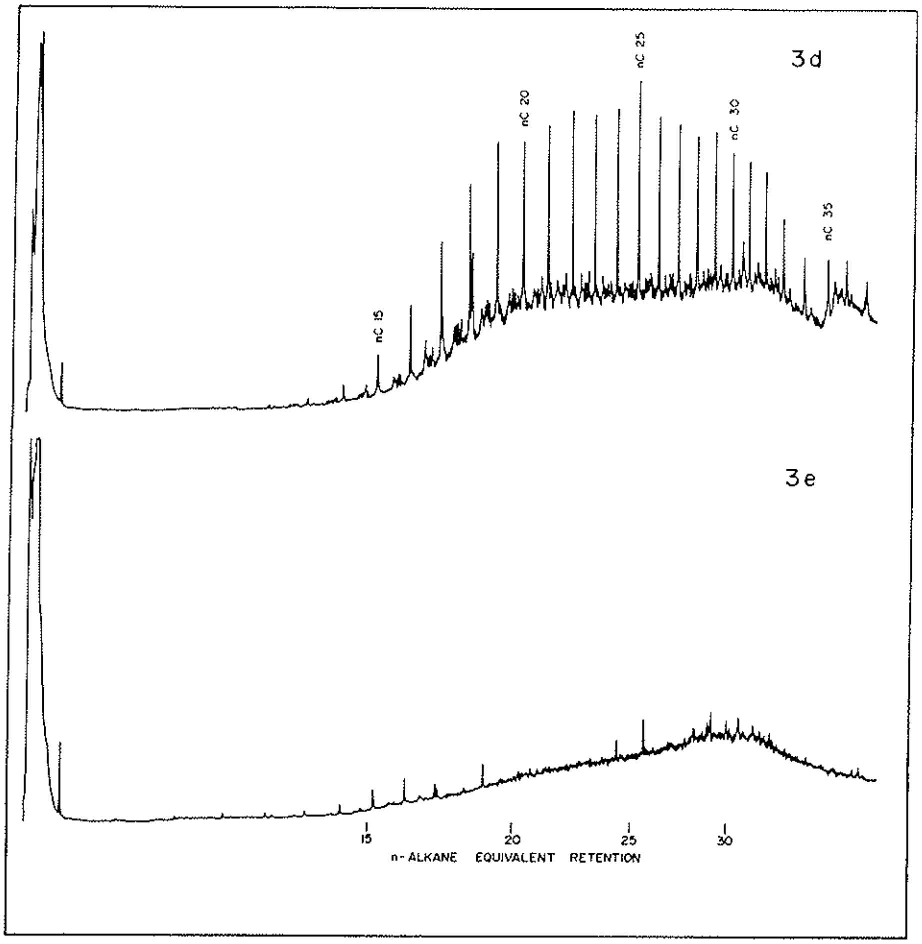

FIGURE 3 HYDROCARBON COMPOSITION (Cont'd)

Similarities in pavement characteristics between the Cape Hatt study site and the Puerto Espora area (the backbeach and open beach sections) were very evident. Both locations are low wave-energy environments with an intertidal beach-face slope of mixed sediments. At both locations there is: (1) a pebble-cobble pavement which is present as a continuous feature in the upper intertidal zone; (2) clear evidence of undercutting and erosion of the upper pavement edge by the action of wave backwash; (3) apparently "fresh" oil within the pavement; and there are (4) sections of soft pavement which can be easily broken off by hand but would not be dented or show footprints if walked over.

The three pavement samples (Samples 3, 8 and 14) are typical of pavement material seen elsewhere. The presence of only unresolved material has been observed in pavement samples from the "Amoco Cadiz" spill site (Owens et al., 1986) and from the "Arrow" site (Humphrey and Vandermeulen, 1986). The pavement material from the BIOS site is substantially less weathered than any of these samples. This is consistent with the difference in time available for weathering at the BIOS site, where only three months per year are warm enough for significant weathering to occur, for a total period of one year of weathering in the four years sampled whereas the other samples had been weathering for many years.

The pavements are not considered to be a major source of secondary contamination. Although the oil is still very fresh in appearance in many cases it is in fact heavily weathered. The rate of pavement erosion is evidently very slow and any release of oil would be in small quantities and would be weathered by physical processes during erosion.

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PHOTOGRAPHS OF THE STUDY AREA

PHOTO 1 Banco Orange, Discontinuous Sandy Pavement at the Spring High Water Mark; Pavement is Buried on the Landmark Margin by Sediments, the Arrow Indicates the Last High Water Swash

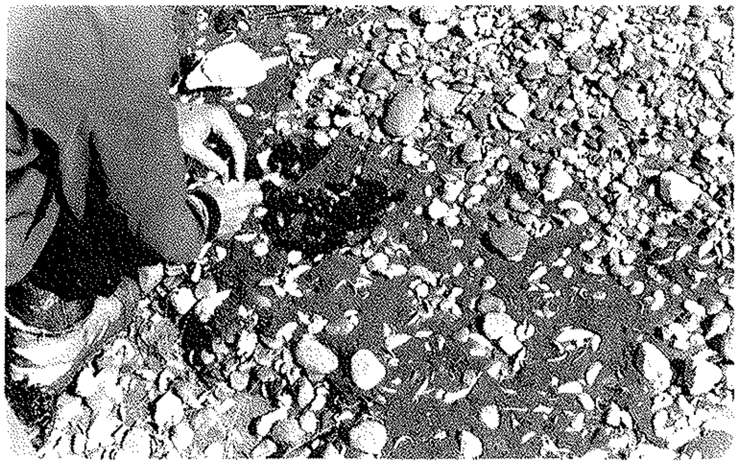

PHOTO 2 Close up of the Pavement Shown in Photo 1

PHOTO 3 View of the Espora Marsh. Person is Standing on Oiled Area

PHOTO 4 View of the New *Suaeda* Bushes that have Grown on the Previously Oiled Area in the Marsh

PHOTO 5 View of the Espora Creek Area Showing the Patchy Soft Asphalt Located Below the Spring High Tide Level

FIGURE 6 Sample Being Taken of Asphalt Just Above the Spring High Water Level at Espora Creek

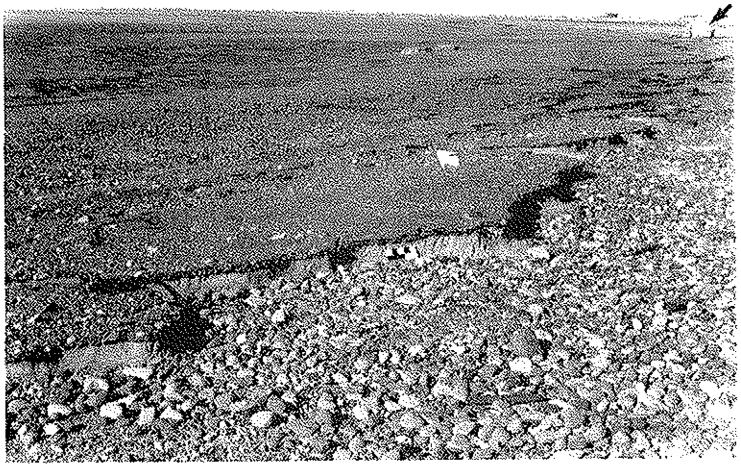

PHOTO 7 Upper Edge of Asphalt Pavement on Espora Spit Backbeach, the Edge of the Pavement and Sediment Substance has been Eroded by Backwash

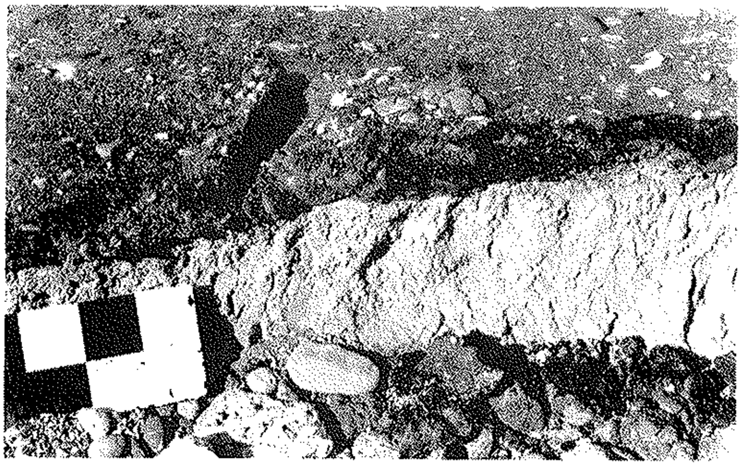

PHOTO 8 Close Up of Photo 7

PHOTO 9 View of Asphalt on Espora Beach, Arrow Marks the Last High Water Swash

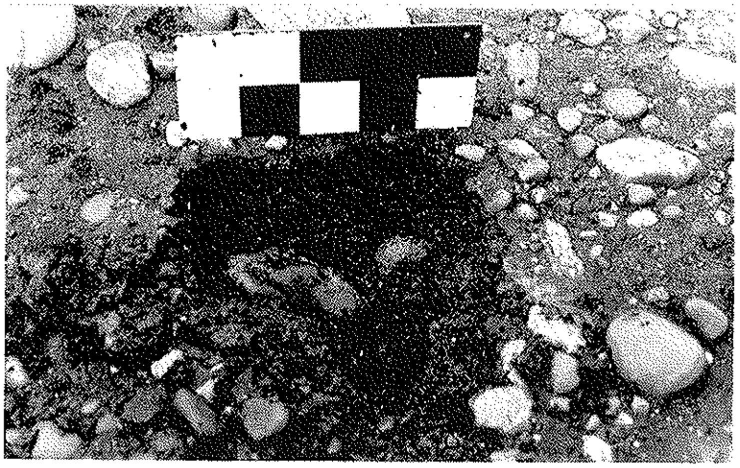

PHOTO 10 Close Up Through Asphalt Pavement on Espora Beach

PHOTO 11 Arrow Marks Pavement at the Spring High Water Mark at Rio Oscar, Sea Weed is Below this Mark