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Oil on the Bottom of the Sea

A Simulation Study of Oil Sedimentation and Its Effects on the Bristol Bay Ecosystem

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ABSTRACT

Oil budget studies of some recent oil spills show that a considerable amount of oil sedimentizes to the bottom, where it has some immediate as well as long term effects on the benthos and demersal fish.

The relatively meager available quantitative data on the sedimentation of oil and of factors affecting it, are summarized. Based on this knowledge, a numerical model was designed to estimate the quantity and rate of oil sedimentation, including the decay (weathering) of the oil. The computer programme is given in FORTRAN.

The possible effects of oil on demersal fish and on benthic ecosystem, as deduced from laboratory experiments and from a few field observations, are evaluated and summarized.

1. INTRODUCTION

1.1 Purpose of this study

The sinking of oil and its pollution of sea bottom sediments has been demonstrated in a number of oil transportation accidents (FLORIDA; Blumer et al., 1971: ARROW; Keizer et al., 1978: AMOCO CADIZ; D'Ozouville et al., 1979: ARGO MERCHANT; Hoffman and Quinn, 1978: TSESIS; Linden et al., 1979: SEFIR; Linden et al., 1983). Estimates of sedimented oil were also obtained for the well blowouts at IXTOC I (Jernelöv and Linden, 1981) and Platform Bravo (Ekofisk) in the North Sea (Mackie et al., 1978). Studies done in large, controlled mesocosms have also demonstrated the sedimentation of oil in sea water (Elmgren et al., 1980; Grassle et al., 1980; Elmgren and Frithsen, 1982). Whereas oil polluted pelagic environments have been observed to recover relatively rapidly (e.g., about a month after the TSESIS spill and within 4 months after the AMOCO CADIZ spill), oil residues on or in the bottom have been shown to persist for many years (Linden et al., 1979; Laubier, 1980). Oil incorporated into bottom sediments is now generally recognized as presenting the single greatest and long term threat to the environment from oil spill accidents (Linden et al., 1979; D'Ozouville et al., 1979; Conan, 1982; Elmgren et al., 1983; Gundlach et al., 1983; Linden et al., 1983).

In spite of the long term threat to the epipelagic and benthic biota from oil residues on and in the sediment, there is comparatively little knowledge regarding the sedimentation of oil. Direct measurements of oil sedimentation from past spills are very few and even when done, they were incomplete in sampling the temporal and areal dimensions of the spills. Therefore, estimates obtained from past spills which were extrapolations of data from sediment traps or bottom grab samples, generally underestimated the amount of oil sedimentation (e.g., TSESIS and AMOCO CADIZ spills).

The pathways and processes of oil sedimentation have been discussed by many authors and summarized by Clark and McLeod (1977). We have, therefore, very positive evidence for the sedimentation of spilled oil and some approximations of the quantities sedimented. We also have some knowledge regarding the pathways and processes of oil sedimentation. We are not aware, however, of any generalized models for quantifying the rate or amount of oil sedimentation from surface slicks.

The purposes of our study are to: 1) develop models for quantifying the amount and rate of oil sedimentation; 2) simulate the fate of oil on the bottom using available information; 3) summarize and analyze the effects of oil on and in the bottom on demersal fish and benthic ecosystems. The results of these studies will be incorporated together with other analyses into a report which will assess the possible effects of two hypothetical oil spill scenarios at three locations on several commercially valuable fishery resources of southeastern Bering Sea.

The three hypothetical spill sites are seaward of Port Moller, Port Heiden and Cape Newenham in Bristol Bay. One spill scenario is an instantaneous spill of 200,000 bbls of automotive diesel fuel and the other a well blowout of 300,000 bbl of Prudhoe Bay crude oil discharged at a rate of 20,000 bbl/day for 15 days. The volume of oil spilled in the hypothetical tanker accident is exceeded only by the spill of the AMOCO CADIZ (about 1.6 million bbl) and the IXTOC I well blowout (about 3.5 million bbl). Both of these accidents involved crude petroleum. The hypothetical spill of automotive diesel fuel exceeds by far any past spills of middle or heavy distillate petroleum fuels. The total volume (300,000 bbl) of the well blowout scenario is also considerably less than that discharged from the IXTOC I well blowout or the spill from the AMOCO CADIZ. The volume is comparable to the Ekofisk Bravo blowout (146,000 - 219,000 bbl, Mackie et al., 1978). The discharge rate in the hypothetical scenario (20,000 bbl/day) is less than the maximum daily loss from IXTOC I (about 32,000 bbl/day) but somewhat comparable to the estimated rate of discharge in the Ekofisk blowout (19,500 - 29,200 bbl/day).

Initial calculations indicate that the oil concentrations in the water column (both soluble and emulsified) above the thermocline from a blowout of 300,000 bbl of Prudhoe Bay crude oil will be less than 1 ppm in most areas. The rather low concentrations seen in the hypothetical spill are not unlike those estimated for past oil spills and blowouts at sea.

These low concentrations may result in tainting but should inflict little if any mortality to adult fish nor affect the long term productivity of fish stocks. Certain invertebrates and ichthyoplankton, however, may be drastically affected. As previously mentioned, however, the damage to these pelagic communities can be expected to be acute but relatively short term. Even with these low concentrations of oil in the water column, empirical observations have demonstrated that concentrations in deeper soft bottoms can be considerably higher and of much longer duration. The assessment of the effects of possible oil spills in eastern Bering Sea must, therefore, focus upon the extent and duration of oil on the bottom and its short and long term consequences to the abundant and valuable fish and shellfish resources.

1.2 <u>Existing knowledge on sedimentation of oil and its effects.</u>

An oil slick is dynamic, changing not only in physical dimensions but also in chemical composition primarily due to the loss of certain components through evaporation into the atmosphere and dissolution into the sea. The rate of processes is dependent upon such local environmental factors as air and sea temperature, wind strength, surface agitation and currents as well as physical (e.g., viscosity) and chemical characteristics (e.g., hydrocarbon composition) of the oil. The lower molecular weight components will immediately begin to vaporize or leach into the water. Virtually all hydrocarbons C_{15} and shorter will volatilize from the sea surface within 10 days, many of the lighter, volatile materials disappearing within hours. Most components in the C_{15} to C_{25} range and all hydrocarbons longer than C_{25} will be retained in the slick. Evaporation alone will remove about 30 to 50% of the hydrocarbons from a typical crude petroleum slick. About 75% of the hydrocarbons from No. 2 fuel (automotive diesel) and 100% of the hydrocarbons from kerosene or gasoline will vaporize (Clark and McLeod, 1977).

Surface oil enters the sea as dissolved fractions, oil droplets or emulsions (oil-in-water or water-in-oil), the dominant processes being the latter two. In order for the petroleum in the water to sink, processes must intervene to disrupt its positive or neutral buoyancy. The specific gravity of oil may be increased by evaporation and dissolution of low molecular weight hydrocarbons, degradation and oxidation of oil components, formation and agglomeration of dispersed particles and the uptake of sea water during emulsification (Clark and McLeod, 1977). Fresh and weathered oil may be vertically transported through the water column, however, the particles cannot remain near the bottom or be incorporated into bottom sediments unless they adhere to suspended particulate matter which is heavier than sea water. Pathways by which oil is sedimented include the adsorption of oil droplets on suspended mineral matter such as clay, incorporation of oil droplets in the fecal pellets of zooplankton and the oiling of dead siliceous phytoplankton or zooplankton. The relative importance of these pathways of oil sedimentation will depend to some extent upon the area, timing and environmental circumstances of a spill. In most nearshore and estuarine spills in subarctic environment, particularly during the late fall through early spring months when seas are most turbulent, adherence of oil droplets to particulate, mineral matter would seem the most substantial process of oil sedimentation. In our study we will assume that sedimentation is entirely attributable to adsorption of oil onto particulate mineral matter.

It should be noted that Prudhoe Bay crude oil is relatively viscous. Rice et al. (1976) observed that under identical conditions of mixing, the yield of water soluble fractions from Prudhoe Bay crude were about half the concentrations from Cook Inlet crude.

There is no well-substantiated data available on the relative quantities of oil reaching the bottom; the few reported data are indirect estimates. Elmgren (pers. comm.) estimates that 10 to 30% of the spilled TSESIS oil reached the bottom. Of the AMOCO CADIZ spill, 8% is estimated to have gone into subtidal sediment, 28% went on shore, and 20.5% is unaccounted for (Grundlach, et al., 1983) (Figure 1). If the oil had not reached the shore, it could be assumed that the greatest portion of the two last components might have ultimately sedimentized (i.e., 30 to 50% of total oil). Some direct quantitative data on sedimentation of the oil has been obtained in large experimental tanks (5 m. deep), where Elmgren and Frithsen, 1982, found that 40 to 50% of the oil added to the water in the tanks reached bottom (Figure 2). Boehm and Fiest (1980) concluded that only 1 to 3% of IXTOC I oil was to be found in offshore sediments, although near the well blowout high concentrations of oil in the sediment (100 ppm) were detected. Jernelöv and Linden (1981) estimated that 25% (120,000 mt) of the IXTOC I blowout sank to the bottom.

Elmgren et al., 1983, found that the oil from TSESIS spill sedimentized (sank) to the bottom relatively rapidly. There was at least 0.5 g oil per m^2, and in heavily oiled areas possibly considerably more.

If we assume that the oil was accumulating initially in a nepheloid layer near the bottom, say 15 cm thick (the thickness of this layer is variable indeed), the resulting concentration from 0.5 g/m^2 on the bottom would give an oil concentration in this relatively thin nepheloid layer of 3.3 ppm, which is about ten times higher concentration than normally found in the water in oil spill areas. This simple calculation thus demonstrates the importance of the consideration of oil on the bottom.

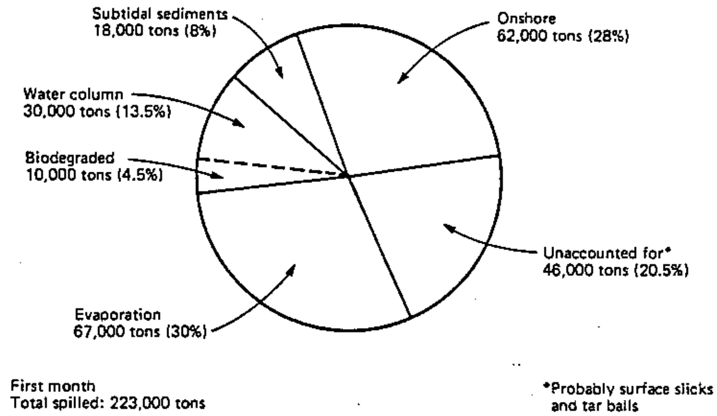

Figure 1.--Quantitative estimate of Amoco Cadiz oil dispersal components for the first month of the spill (Gundlach, et. al., 1983).

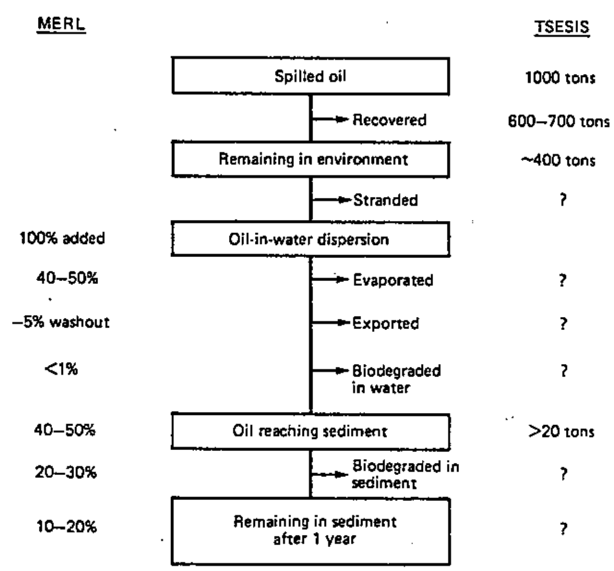

Figure 2.--Fate of oil (Elmgren and Frithsen, 1982).

Some aspects of the oil sedimentation process has been studied in the laboratory. Gearing et al., 1979, found that minerogen (e.g., silt and clay) particulate matter absorbed ca 15% of oil from the tank and carried it to the bottom. Low molecular weight aromatic compounds were not found in this sedimented oil.

The oil on the bottom accumulates first in a flocculent (nepheloid) layer, which floats immediately above the bottom and is difficult to sample. This flocculent layer has a tendency to accumulate in small deepenings in the bottom (Elmgren, pers. comm.) where near-bottom current is absent. The newly sedimented oil contains little toxic aromatic components (Elmgren and Frithsen, 1982). These components decay relatively quickly in the water and near and on the bottom. Therefore, the sedimented oil can be considered as weathered oil. Moore and Dwyer, 1974, also found that oil in water weathers by losing its toxic fraction very rapidly, mostly by evaporation. However, Falk-Petersen and Loenning (MS) have found that sea water extracts of photo-oxidized (weathered) oil is more toxic than extract of unweathered oil.

Oil will penetrate the sediments to 5 to 7 cm depth (and occasionally deeper, depending on the type of the sediment). This penetration of oil into sediment is assumed to be caused by "reworking" of the sediment by burrowing animals (infauna). Higher amounts of oil are found in fine-grained sediments (where the infauna biomass is also expected to be higher) and lower amounts in coarse-grained sediments (sand and gravel) (D'Ozouville et al., 1979).

The absorption and agglomeration of the oil in sediment is accompanied by further fractionation of the original oil mixture. Zürcher and Thüerer, 1978, found that 200 ppm of oil in dry clay is close to "saturation absorption" of this material. In addition to oil adhering to sediment, there is also oil in interstitial water. Vandermeulen and Gordon, 1976, found 10 mg oil per gram natural sediment. Hayes et al., 1979, also found that interstitial water gets heavily oiled, from where it can reenter the water above.

The longevity of oil in sediment is not known. According to Vandermeulen and Gordon, 1976, flow experiments (of interstitial water) indicate that stranded oil could remain in sediment in excess of 150 years (by which time it is fully buried).

In tank tests 10 to 20% of the total oil added to tanks (of which 40 to 50% sedimentized) remained in sediment after 1 year (Elmgren and Frithsen, 1982). In AMOCO CADIZ oil spill area, some oil remained in fine-grained sediments 3 years after spill (Grundlach et al., 1983). Oil degraded (weathered) slower in muddy sediments than in sandy sediments. Whether the more rapid degradation in sandy sediment is due to more intensive microbial action, is unknown at present.

Biodegradation of oil might be one of the main factors for "depuration" of oily bottoms. Biodegradation is known to increase with increased temperature (Gearing et al., 1979).

Laboratory research on the short term effects of weathered oil on benthos seems to be difficult to interpret (Kalko, Duke, and Flint, 1982). The best observations on the effect of oil on bottom on benthos originate from the studies of the TSESIS spill (e.g., Elmgren et al., 1983).

Among initial effects of the TSESIS spill were the disappearance of amphipods (especially *Pontoporeia affinis*) and polychaetes. Bivalves (e.g., *Macoma balthica*) contained high amounts of hydrocarbons (obs. these animals accumulate hydrocarbons from water while filtering food). Their biomass increased rapidly a year after the spill and continue at above prespill levels. Full recovery of the benthos community (in respect to species composition) had not yet occurred 5 years after the TSESIS spill; Pontoporeia have still not returned to prespill levels.

The response of benthos to AMOCO CADIZ oil spill was similar (Conan, 1982). Immediate mortalities of bivalves, periwinkles, limpets, peracarid crustaceans, and heart urchins were observed in heavily oiled shallow water. Populations of clams and nematodes in the meiofauna declined after the spill, and for several clam populations recruitment remained unstable. Benthic species with short life cycle tended to replace long-lived species.

The effects of oil on the bottom on the demersal fish species is difficult to observe in nature. In the TSESIS spill area some flounders (Pleuronectes flesus) showed 50 ppm hydrocarbons in liver and muscle one year after the spill (obs. flounders are feeding on Macoma sp.) (Linden et al., 1979). In the AMOCO CADIZ oil spill area, estuarine flatfishes and mullets had reduced growth, fecundity, and recruitment; and were affected by fin rot (Conan, 1982). An absence of young sole in shallow water a year after the spill was noticed (Grundlach et al., 1983). Changes in the availability of flatfish (sole) in shallow water were noted, however, no changes were noticed in fish populations in deep water. A taste panel detected tainting in haddock, plaice, gurnard, and lemon sole after the Ekofisk blowout, however, no oil derived hydrocarbons could be found in the muscles (Mackie, 1978). This may be confirmation that some of the major flavor components of oil are not hydrocarbons (Howgate et al., 1977) and are, therefore, not measured.

Any reduction in "worst case" spill on fish stocks is difficult to detect against the background of normal variability in the sea. It is, in general, agreed that commercial stocks in the open parts of the shelf are not at risk from oil (McIntyre, 1982).

The large experimental ecosystems (in tanks) offer some possibility to test the sensitivity of benthic organisms to weathered oil on the bottom (e.g., Elmgren and Frithsen, 1982; Grassle, Elmgren, and Grassle, 1981). So far long-term tests of the toxicity of oil on demersal fish have been more the exception than the rule. The toxicity tests on fish have mostly been done in small laboratory tanks and the duration of which were measured in hours and days rather than in weeks or months (see Chapter 4). The translation of these results to field conditions is often questionable.

2. SEDIMENTATION OF OIL AND FACTORS AFFECTING IT

2.1 Factors affecting sedimentation

The oil from a well blowout or from a tanker accident rises to the surface, where gravity and surface tension promote spreading on calm water while inertia and viscosity retard spreading. The transportation, dissolution, and weathering of the surface oil slick depends upon the characteristics of the oil, and such environmental factors as air and water temperature, wind velocity and direction, surface turbulence, and surface and subsurface currents. The oil which sedimentizes (sinks) to the bottom originates from this oil slick on the surface. (Note: Beached oil which has been shown to cause catastrophic mortalities to intertidal and subtidal fauna is not considered in this paper.) The sedimentizing oil must pass the water mass between the surface and the bottom. The processes of the solution and dispersion of oil from the surface slick into the water have been summarized by Clark and McLeod (1977). Payne, Kirstein, McNabb, Lambach, de Olivera, Jordan, and Hom (1982) had a more recent summary with procedures for quantifying the weathering of oil.

The amount of dissolved and emulsified oil in the water is about 10% (and slightly more) of the oil on the surface at any given time and location. One of the main factors "forcing" emulsified oil into the water is turbulence caused by waves (and currents). The latter are a function of wind (wind energy). The turbulence caused by wind-generated waves determines also the thickness of the near-surface turbulent mixed layer (depth of the thermocline). Obviously there are other factors besides wind waves contributing to space and time variable mixed layer depth and turbulent mixing, such as convective turnover, tidal currents, etc. (for a summary on mixed layer processes see Laevastu, 1976). In the 9 months plus duration of the IXTOC I blowout, a release of 475,000 metric tons of oil escaped, of which 120,000 mt (or 25%) was estimated to have sunk to the bottom (Jernelöv and Linden, 1981). (Some empirical data on the quantitative distribution of oil in the water from IXTOC I blowout is given by Boehm and Fiest, 1982.) Grundlach et al., 1983, found that 13.5% of AMOCO CADIZ oil got into the water, and this amount is considered to present a maximum, due to heavy wave action in the location and time of the AMOCO CADIZ accident.

Only very few crude oils have a specific gravity higher than sea water and can sink (e.g., Michel, 1984). In most cases the oil is lighter than water and rises to the surface, from which it must pass through water column and must be made heavier than water by various processes, in order to sedimentize to the bottom.

The minute oil droplets present in water as oil-in-water may be transported toward the bottom by entrainment in vertical currents. However, unless they become heavier than water, emulsion or droplets cannot remain near or become incorporated into bottom sediments. It has been observed that oil absorbs to minerogen suspension (clay) present in the water. The amount of oil which sediments can carry down is inversely proportional to grain size (Poirier and Thiele, 1941). The clay particles, which are heavier than water, can agglomerate and accelerate sedimentation. Thus, the sedimentation rate depends not only upon the quantity and characteristics of oil, but also on the amount and nature of suspended minerogen particles present. The coagulation of the particles is faster in salt water than in fresh water due to electrolytic action (Bassin and Ichiye, 1977). The collision of the clay particles (and/or oil particles containing minerogen particles) due to differential settling rates are the governing nonbiological processes in formation of natural aggregates (Hawley, 1982). These aggregates fall significantly faster than Stokes Law predicts (Hawley, op. cit.).

It has also been postulated (but not experimentally proven) that fecal pellets of zooplankton will facilitate the sedimentation of oil. This mechanism might work if these pellets were made heavier, e.g., by incorporation of diatom shells in fecal pellets.

The amount of suspended minerogen matter present is a function of depth, bottom type, turbulent mixing (e.g., by tidal currents), and specific locations (e.g., estuaries where suspended matter is carried by river runoff) (Baker, 1983). Baker (1983) measured sedimentation rates of suspended matter <2 to >9 g m^{-2} day^{-1}. Forty to fifty percent of the suspended matter was organic. Furthermore, Baker found experimentally that the sedimentation rate of oil was 0.5 to 32 mg m^{-2} day^{-1}. There is a turbid boundary layer near the sediment surface. This layer and its dynamics was extensively studied in the 1950's (re. Kuenen's turbidity currents). Some later studies of the turbid bottom boundary layer (or nepheloid layer) have been empirical (e.g., Baker, 1983) as well as theoretical (Adams and Weatherly, 1981).

There would obviously be some direct absorption of oil to sediments if and when the mixed layer reaches the bottom.

The sedimentation of oil is a function of time. Ultimately 30 to 50% of the oil residue may reach the bottom (Elmgren and Frithsen, 1982). However, much of the sedimentation of the oil occurs after the surface slick is broken up and transported long distances. Thus, expectedly the sedimented oil will cover large areas and the resulting concentrations of oil on the bottom would be low over most of these areas. In our study we are interested in the sedimentation in the first 15 days (to maximum 30 days for a long-lasting blowout) before the surface slick is broken up and disappears as a semicontinuous layer.

2.2 Quantitative formulation of oil sedimentation.

The distribution of oil on and in the water is computed and given in model grids (about 2.3 km grid size) either in 12-hour or daily time steps (Liu, 1983). The oil in the water column is converted to concentrations (e.g., ppb) to facilitate the evaluation of its effects to biota. Thus, we need to give the quantities of oil on or in the bottom also in terms of concentrations.

Sedimented oil accumulates initially in a flocculus nepheloid layer near the bottom (Elmgren, pers. comm.). For our present purpose we assume that the thickness of this layer is 10 cm, with the concentration of the oil in this layer expressed in the same units as in the water (ppb). The thickness of this nepheloid layer is not uniform and might even be absent in many locations. Further research is required in this matter.

The following formulas for time-dependent computation of the sedimentation of oil have been derived on the basis of the available meager information, most of which is summarized in Chapter 1.2 and 2.1. It is neither possible, nor justifiable to devise theoretical formulas for which necessary parameters are not available, nor verification/validation possible. The various earlier theories on sedimentation are not valid, mainly due to complex flocculation processes as shown in earlier chapters. The following proposed empirical (or, rather, rational) formulas are derived on the premises that the parameters, which can be estimated, are related to the processes of sedimentation of oil. For example, the turbulence in the water, which enhances the collision between minerogen suspended particles and oil droplets, is a function of wind speed. Furthermore, the higher the wind speeds the deeper the surface mixed layer, which might reach bottom in shallower water. In this case the turbulence will bring oil emulsion into contact with the bottom and enhance adsorption of oil to bottom sediments. Furthermore, higher turbulence (equated here with wind) might suspend (erode) more sediment, thus enhance oil sedimentation.

The rate of deposition of oil is made a function of turbulence, which is approximated with wind speed (W), depth of water (D), and concentration of oil in the water (S). The time step is selected either as 12 or 24 hours. Computations are made at each grid point at each time step. The balance of oil is not preserved in the following formulation. The reason for this is that there is an excess of oil on the surface which might go in emulsion into the water (or might be transported away with surface wind and currents).

In order to simulate known differences in sedimentation rate, slightly different constants are used in the continuous source (blowout) and instantaneous source (e.g., tanker accident) cases. Some constants also differ, depending upon the presence or absence of a thermocline (re. suspended oil coming into direct contact with sediment).

Instantaneous source without thermocline:

$$AO = AO_{t-1} + S_t * F_s * P * R * B \qquad (1)$$

where: $F_s = (0.0015W + 015/D^{0.7}) * TK_s$ (2)

and: $TK_s = K/(3 + 0.2K)$ (3)

AO_t is the concentration of oil in "nepheloid layer" at time t; AO_{t-1} is the same concentration in previous time step after decay (see Chapter 3 below);

S_t is the concentration of oil in the water in the surface mixed layer;

P is the zooplankton abundance index (relative values from 1.0 to 2.0, estimated on the basis of expected zooplankton abundance in the location and season);

R is the minerogen suspension index (abundance of minerogen matter) and is made a function of depth: $R+0.2D/\sqrt{D)}$, whereby R is selected between 20 and 50 (Note: the amount of minerogen suspended matter is seldom measured, thus a relative abundance index (turbidity index) must be estimated);

B is the bottom type index (0.3-rocky; 0.6-coarse sand and gravel; 1.5-fine silt and clay); (this index simulates the adherence of oil to the bottom);

F_s is the sedimentation rate factor;

TK_s is the time factor;

W is wind speed (in m/sec);

D is depth in meters;

K is number of time steps (in days).

No computation of oil sedimentation is made for first 12-hour period.

Instantaneous source with thermocline:

$$AO_t = AO_{t-1} + S_t * F_d * P * R \quad (4)$$

where: $F_d = (0.001W + 0.20/D^{0.7}) * TK_d$ (5)

and: $TK_d = 6/(3 + 0.5K)$ (6)

F_d is the sedimentation rate factor;

TK_d is the time factor.

All other symbols (and parameters) are the same as in Formulas 1 to 3. No computation of oil sedimentation is made for the first 24-hour period as sedimentation through the thermocline is a time-dependent process.

The relationship of sedimentation factor to depth is shown in Figure 3 and the increase (growth) of time factor with time is given graphically in Figure 4.

Continuous source, no thermocline present:

$$AO_t = AO_{t-1} + S_t * F_{cs} * DF * P * R * B \quad (7)$$

where: $F_{cs} = (0.0001W + 0.25/D^{0.74}) * TK_s$ (8)

and: $DF = (Dis + 4)/20 + 0.1Dis$ (9)

DF is the "distance from source" factor;

Dis is distance (of the grid point) from source in km.

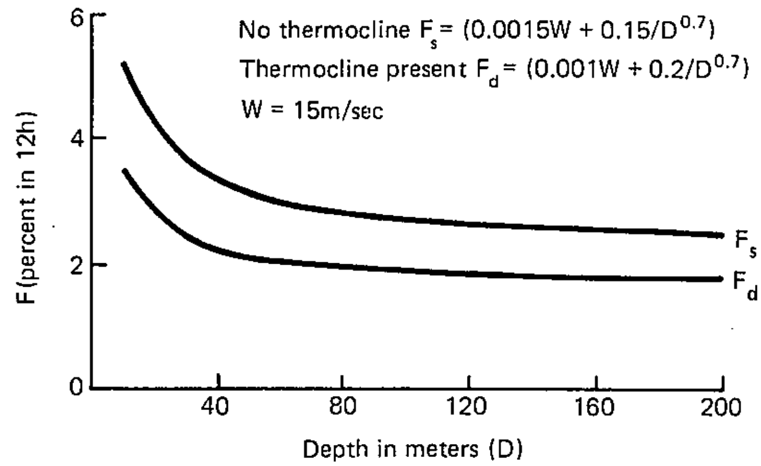

Figure 3.--Oil sedimentation factor F, Instantaneous source.

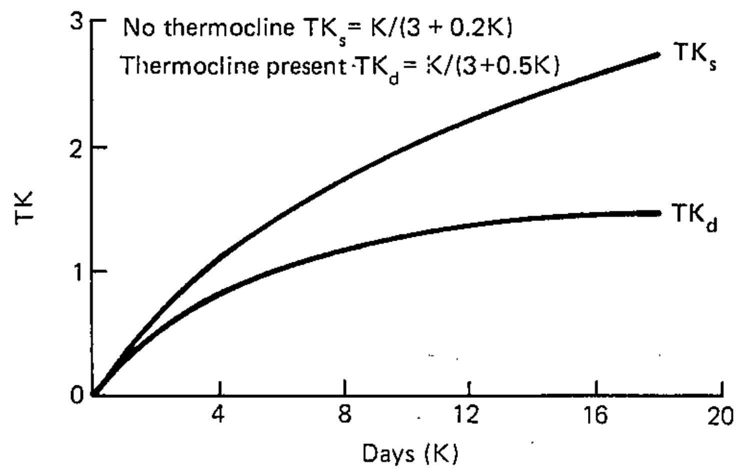

Figure 4.--Time factor for oil sedimentation.

All other symbols correspond to the symbols in Formulas 1 to 3. No computation is made for the first 12-hour period. The dependence of sedimentation rate factor (F_{cs}) on depth is shown in Figure 5, and the distance factor is shown in Figure 6.

Continuous source, thermocline present:

$$AO_t = AO_{t-1} + S_t * F_{cd} * DF * P * R \quad (10)$$

where: $$F_{cd} = (0.0008W + 0.035/D^{0.74}) * TK_d \quad (11)$$

No computation is made in the first 24-hour period as sedimentation through the thermocline is a time-dependent process. All symbols correspond to those in Formulas 1 to 3 and 7 to 9.

3. FATE OF OIL ON THE BOTTOM

3.1 Some observations of the fate of oil on the bottom.

The initial accumulation of oil in the bottom nepheloid layer is difficult to observe and sample. These flocculous accumulations are not retained by conventional grabs and other bottom sampling devices. Some conclusions about its existence can be drawn from laboratory tests and from uptake of hydrocarbons by sessile filering organisms, such as clams and polychaetes.

The oil-containing nepheloid layer is expected to move around along the bottom with currents near the bottom and may accumulate in deeper holes (deepenings) in the bottom. Linden, et. al., 1979, found ten months after the TSESIS spill that hydrocarbon concentrations in *Macoma balthica* increased unexpectedly at a given sampling station. Such an event may be the result of the exposure of the clams to recontamination from oil in the drifting bottom

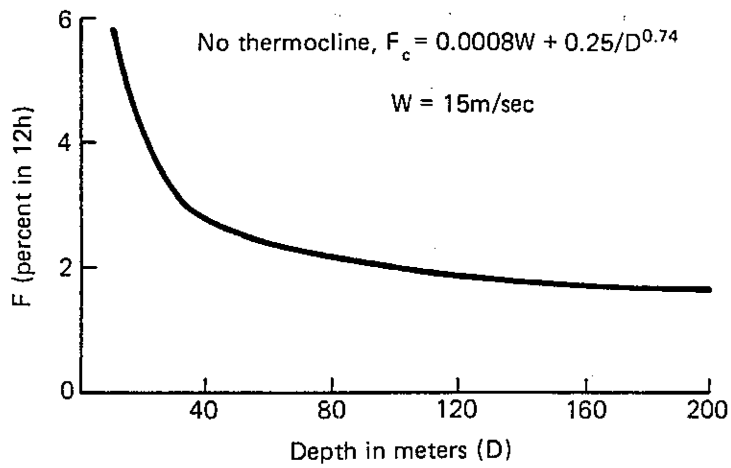

Figure 5.--Oil sedimentation factor F, Continuous source.

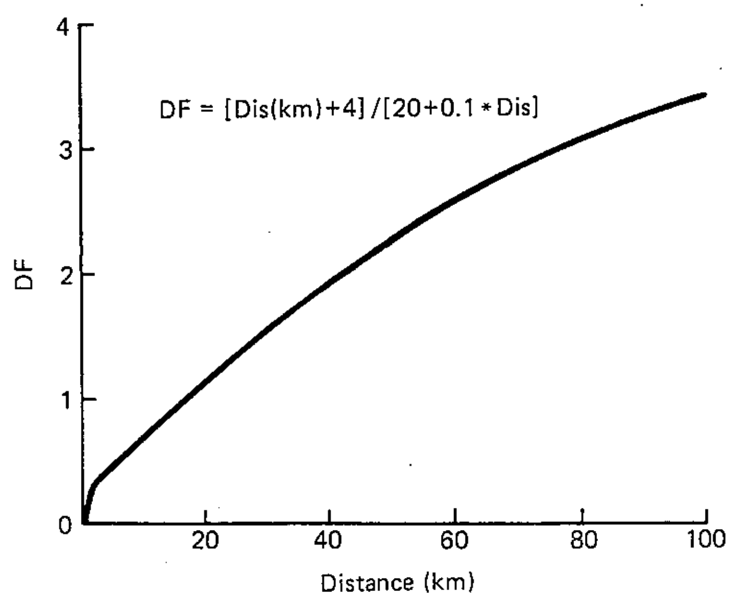

Figure 6.--Distance factor, Continuous source.

nepheloid layer. However, the oil concentrations associated with the nepheloid layer and with sediments is in ppb range and cannot be a major pathway for dispersal of oil (Malinky and Shaw, 1979).

The oil from the nepheloid layer gets absorbed into the sediment, and is carried deeper into it by burrowing animals. In experimental tanks, where the oil concentration in water was kept about 190 ppb for 25 weeks, the top 2 cm of sediment had a hydrocarbon concentration of 109 ppb after 20 weeks (Grassle, et al., 1981). In the area of AMOCO CADIZ spill, oil was found to 5 to 7 cm depth in the sediment five months after the spill. Higher concentrations were found in fine sediments (D'Ozouville, et al., 1979).

The oil in the sediment undergoes decay (weathering); biodegradation being probably the most important decay process. Biodegradation is known to increase with temperature (Gearing, et al., 1979). Furthermore, the decay is assumed to be a function of depth (the "aeration" of sediments and the amounts of biota in them are both in general functions of depth). After concentrations are reduced to some tolerable range, the weathering rate of sedimented oil may be accelerated by the activities of deposit feeders such as polychaetes (Gordon et al., 1978).

Some of the oil gets back into the water above via interstitial water (Vandermeulen and Gordon, 1976). In experimental tanks, 10 to 20% of the oil remained in the sediments after one year (Elmgren and Frithsen, 1982), and in AMOCO CADIZ oil spill area some oil remained in fine-grained sediments three years after the spill (Gundlach, et al., 1983). Residues of Bunker C were identifiable in some locations off Nova Scotia 6 years after the spill from the ARROW (Keizer et al., 1978).

3.2 Computation of the decay of oil on the bottom.

In the oil-on-bottom simulation model (Chapter 5) the "decay" of oil from previous time step is decayed before new oil is added. The "decay" signifies the photo-oxidative degradation of aromatic more toxic components, biodegradation, as well as oil being buried into the sediment. The following formula (12) gives the decay in 12-hour time step which is repeated for the 24-hour time step.

$$AO_{to} = AO_{t-1}\ e^{-(t+d)} \qquad (12)$$

where: $t = T^{2.7} * 10^{-4}$ (13)

and: $d = 0.15/\sqrt{D}$ (14)

t is temperature factor;

T is temperature in °C;

d is depth factor;

D is depth in meters;

The relations between t and T, and d and D are given in Figures 7 and 8, respectively.

Examples of computed distribution of oil in the water and in the bottom are given in Figures 9 and 10. Figure 9 gives the distribution of oil in the water 10 days after a blowout. Corresponding to the same event, the distribution of oil on the bottom is given in Figure 10. The bottom slopes up from the blowout to the north, causing the higher values in the northern part of the field. Figure 10 shows that the concentrations of oil in the bottom nepheloid layer can be considerably higher than the concentrations of oil in the water, thus demonstrating the greater importance of oil in the bottom in respect to its effects on marine biota.

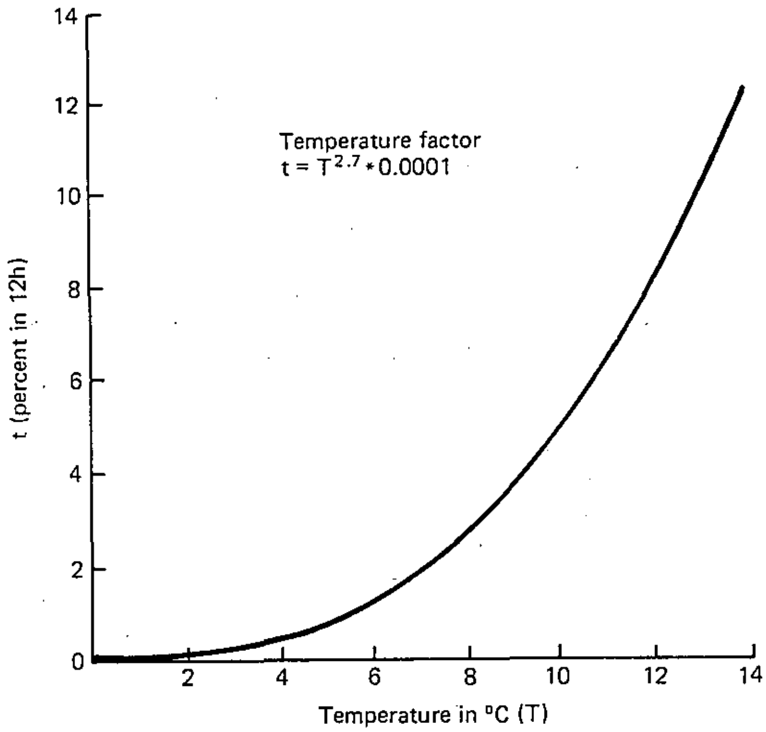

Figure 7.--Effect of temperature on the "decay" of oil on the bottom (time step 12 hours).

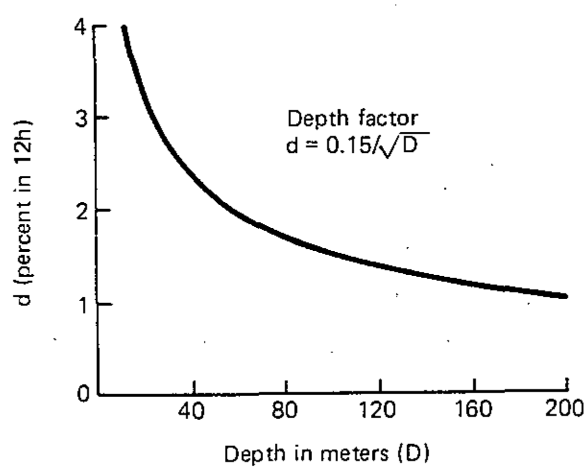

Figure 8.--Effect of depth on the "decay" of oil on the bottom (time step 12 hours).

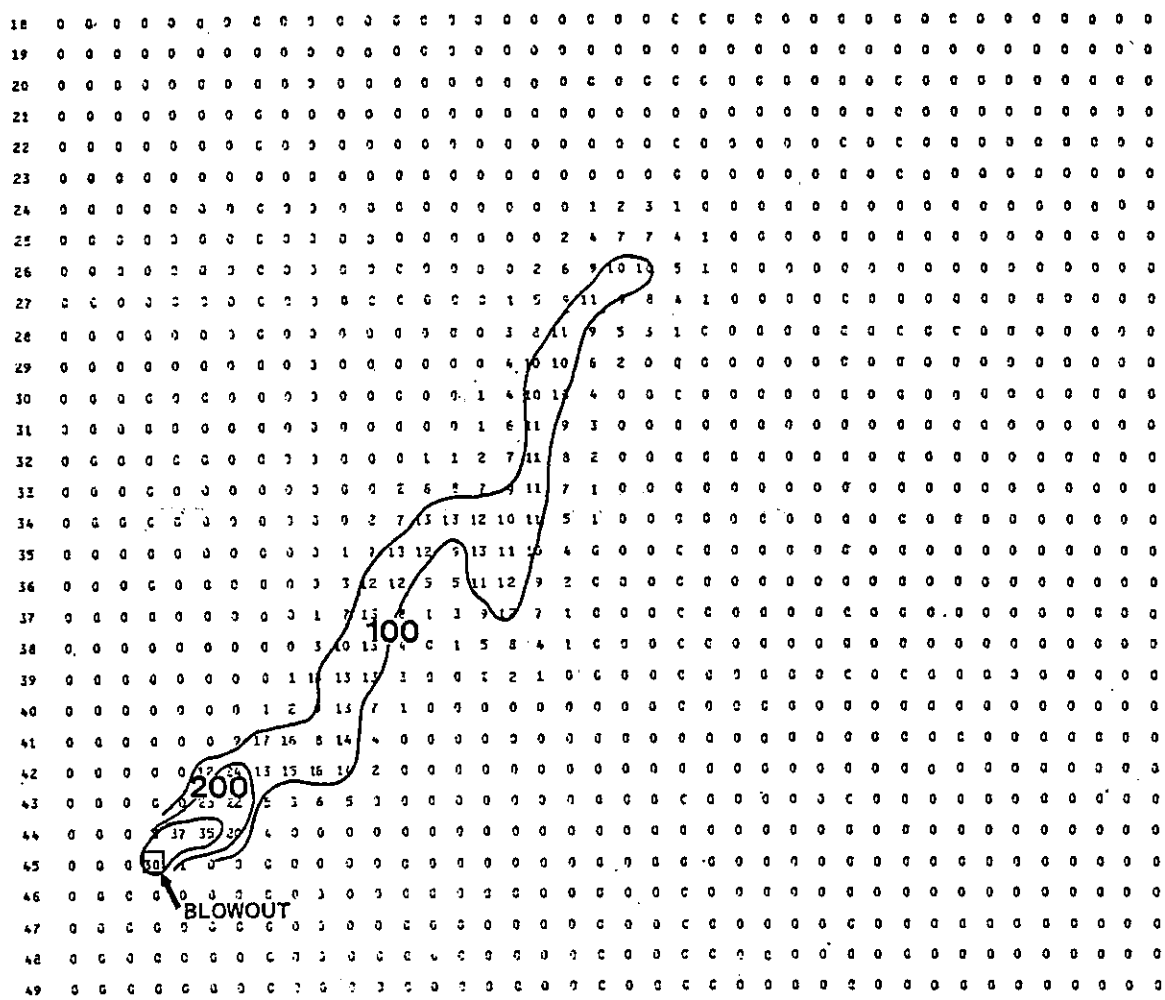

Figure 9.--Distribution of oil from a blow-out (20,000 bbl/day) after 10 days (concentrations in ppb in water - from surface to 15 m; grid size 2.3 km).

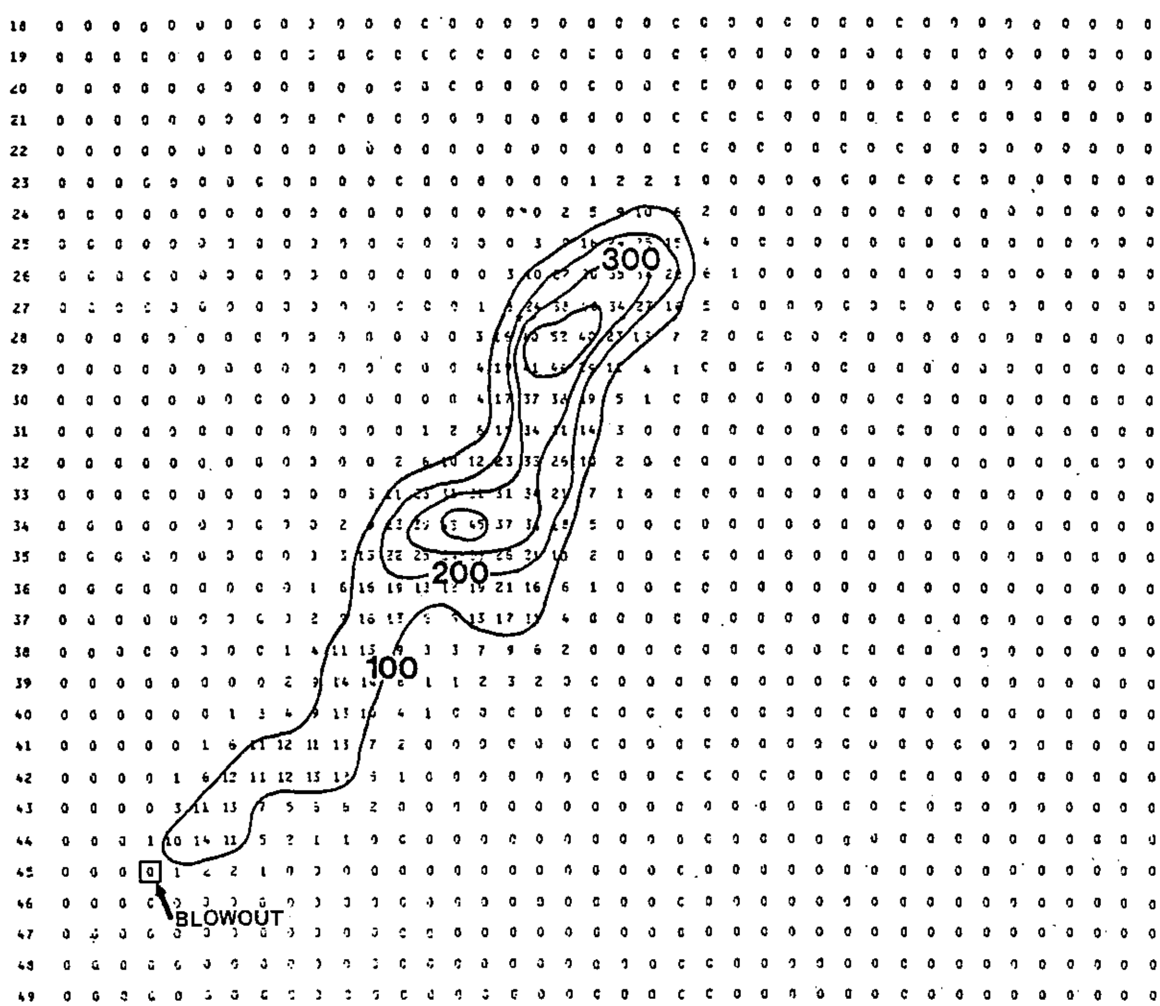

Figure 10.--Distribution of oil in the bottom nepheloid layer (10 cm) in ppb 10 days after a well blowout (see Figure 9); grid size 2.3 km.

The empirical formulae for the time-dependent simulation of the sedimentation of oil, given in this chapter, are based on meager semi-quantitative information (mostly estimates) available in this subject. Further quantitative experimental studies are needed to improve the provisional values for the parameters and coefficients proposed in this paper, and to validate the numerical model in general.

4. EFFECTS OF OIL ON THE BOTTOM ON DEMERSAL FISH AND BENTHIC ECOSYSTEMS

4.1 Avoidance of oiled bottoms by fish and other marine animals.

Some laboratory tests show that fish (e.g., cod) can detect very low concentrations of hydrocarbons, indicating this detection by snapping, darting, coughing, and restless swimming (Hellstrom and Doving, 1983). It is thus possible that some fish (especially semi-demersal species) might avoid oiled bottoms by vertical (upwards) movement into the water mass above the oiled nepheloid layer. The changes of availability of flatfish (sole) in shallow abers after the AMOCO CADIZ spill might be an indication of avoidance of these oiled areas by fish (Gundlach, et al., 1983). On the other hand, laboratory experiments with oiled and clean sediments do not indicate a definite choice of clean sediments by flatfish (Fletcher et al., 1981).

Some epibenthic crustaceans might also use the escape from oiled sediments by movement into water mass above, which might partly explain the disappearance of amphipods from TSESIS spill area.

Burrowing clams do not burrow deep in oiled sediments. This behavior might also be considered as an escape behavior (Olla and Bejda, 1983). Many animals remain, however, on and in oiled bottoms and get contaminated by hydrocarbons by direct adsorption as well as *via* food chain. Other known effects of oiled bottoms on animals are given in Chapters 4.3 and 4.5.

4.2 Uptake of hydrocarbons from oiled bottom.

Hydrocarbons are taken up by biota with different processes, such as adsorption and absorption (especially through gills) and through food chain. Many filtering animals (such as bivalves) will take up hydrocarbons from the nepheloid layer in their filtering process.

Considerable bioaccumulation of hydrocarbons in the benthic animals in oiled areas has been observed in numerous studies. These studies on the uptake and bioaccumulation of hydrocarbons from sediments are reviewed by Connell and Miller (1981). The food chain transfer predominates the hydrocarbon transfer processes (Fowler, 1982). For the purpose of computation of hydrocarbon transfer through the food chain, a conservative bioaccumulation ratio of 50 is assumed. The uptake and decay (depuration) of hydrocarbons by fish and its effects (e.g., tainting) are described in another report in this project report series.

4.3 Effects of oil on the bottom on benthic organisms and demersal fish.

The effect of oil studies have been mostly toxicity studies, using high oil concentrations in laboratory tanks which cannot occur in any accidental release of oil in nature. The concentrations of oil on the bottom, though higher than in water, rarely reach 1 ppm (except in case of beaching of oil) (see Figure 10). Usually less than 10% of the oil initially reaching the bottom is soluble aromatic derivatives (SAD), which are more toxic. Furthermore, SAD disappear quickly from the "weathered" oil on the bottom. Moore and Dwyer, 1974, give the following tables of toxic concentrations of SAD.

5 to 50 ppm	fish
0.1 to 1 ppm	larvae
1 to 10 ppm	crustaceans
5 to 50 ppm	bivalves

Feeding and reproduction can be "disrupted" with lower concentrations (10 to 100 ppb). One recent study by Kanter et al. (1983) has, however, used low levels of petroleum hydrocarbons (6 to 760 ppb) and longer exposure times (about a month) in the studies of the effects of oil on larval and adult stages of California halibut, northern anchovy, and mussels. Results show that larval stages are more sensitive to the exposure to hydrocarbons than previously expected. However, these results are in conformity with Norwegian investigations on the effects of hydrocarbons on eggs and larvae (50 ppb and up), where the effects occur years later as lower exploitable biomasses. However, these later effects are difficult to qualify and separate from changes of natural mortality, effects of fishing, and other natural fluctuations.

Benthic animals are considered to be less sensitive to the toxicity of oil than the pelagic animals (Rice et al., 1979). On the other hand, filtering animals can accumulate hydrocarbons rapidly from relatively low concentrations in bottom nepheloid layer. Oysters can get tainted from 10 ppb of hydrocarbons in water if exposure is of sufficient duration. The tainting levels for fish, crustaceans, and clams is between 4 to 300 ppm (Connell and Miller, 1981; see also summary of various sublethal effects by these authors).

Oil on the bottom can affect the reproductive capacity and embryonic development of benthic and demersal animals. Linden et al., 1979, found that the amphipods Pontoporeia affinis and P. femorata had abnormal eggs 5 months after the TSESIS spill. After the AMOCO CADIZ spill, low percentage of egg-carrying female oysters were observed in 1978/79 (Gundlach et al., 1983).

Augenfeld (1980) found that very high levels of oil concentration in sediment (500 to 1000 ppm) caused some reduction in feeding of Abarenicola pacifica. Reduced feeding by winter flounder on heavily oiled sediments

(2300 to 4500 ppm) were also reported by Fletcher et al., 1981. Such heavy concentrations of oil can be found only in shallow water in case of beaching of oil slicks. On the other hand, Payne et al., 1983, found that the sublethal effects of hydrocarbons on American lobster were minor indeed, only gill browning might have been considered pathological in nature. In similar studies with fish by Payne et al., 1978, no histopathological changes were observed after 6 months and no serious differences in growth and reproduction between oil exposed and control experiments were observed.

Eggs and larvae might be most susceptible to exposure to oil. McIntyre, 1982, states that growth and buoyancy in cod eggs and larvae were affected by oil concentration of 50 ppb, and at 250 ppb malformation of larvae occurred. There are relatively few species with demersal eggs (e.g., herring, egg-carrying females of crabs). The problems of pelagic eggs are dealt with elsewhere in this report series (see REEST, 1983).

4.4 Decay of hydrocarbons in marine organisms.

The knowledge on the metabolism of hydrocarbons in marine organisms has been summarized by Connell and Miller, 1981. Numerical studies of the decay of hydrocarbons is described in another report in this series pertaining to the effects of oil on fish (see REEST, 1983).

The decay of hydrocarbons in demersal fish and benthic organisms is complicated by the continuous uptake of oil from sediments. Filtering and burrowing animals effect the uptake of the weathered oil, which is transferred to fish feeding on them. Linden et al., 1979, found that flounders (Pleuronectes flesus, which feed on Macoma balthica, showed 50 ppm of hydrocarbons in liver and muscles one year after TSESIS spill.

The accumulation, as well as decay of hydrocarbons in fish, is a function of temperature (Varanasi, Gmur, and Reichert, 1981). Retention is higher and decay slower at lower temperatures. In general, the hydrocarbons are lost at a slower rate than they are accumulated (Fowler, 1982).

The computations of decay of hydrocarbons in fish was done in this study with the following general exponential formula, corresponding to the findings of Fowler, 1982:

$$C_t = C_{t-1} e^{-b} \quad (15$$

where: $b = 0.0015T^2$ for demersal fish (16)

and: $b = 0.002T^2$ for pelagic fish (17)

t is time step (12 hours);

C is concentration of hydrocarbons in fish (mainly muscle);

b is decay factor;

T is temperature in °C.

This formula gives about 8% decay in 12 hours at about 10°C. The dependence of the decay from temperature is shown in Figure 11.

4.5 The effect of oil on the bottom on the benthic ecosystems.

Most of the knowledge of the effect of oil on benthic ecosystems originates from tank experiments and field research in TSESIS spill area. Elmgren et al., 1980, found in tank experiments that benthic macrofaunal and metazoan meiofaunal populations declined drastically in "oiled sediments", whereas benthic diatoms and protozoa increased considerably. Benthos biomass in oiled tanks was only about 10% of that in control tanks. Amphipods were sensitive to oil, harpacticoids were not (Elmgren and Frithsen, 1982).

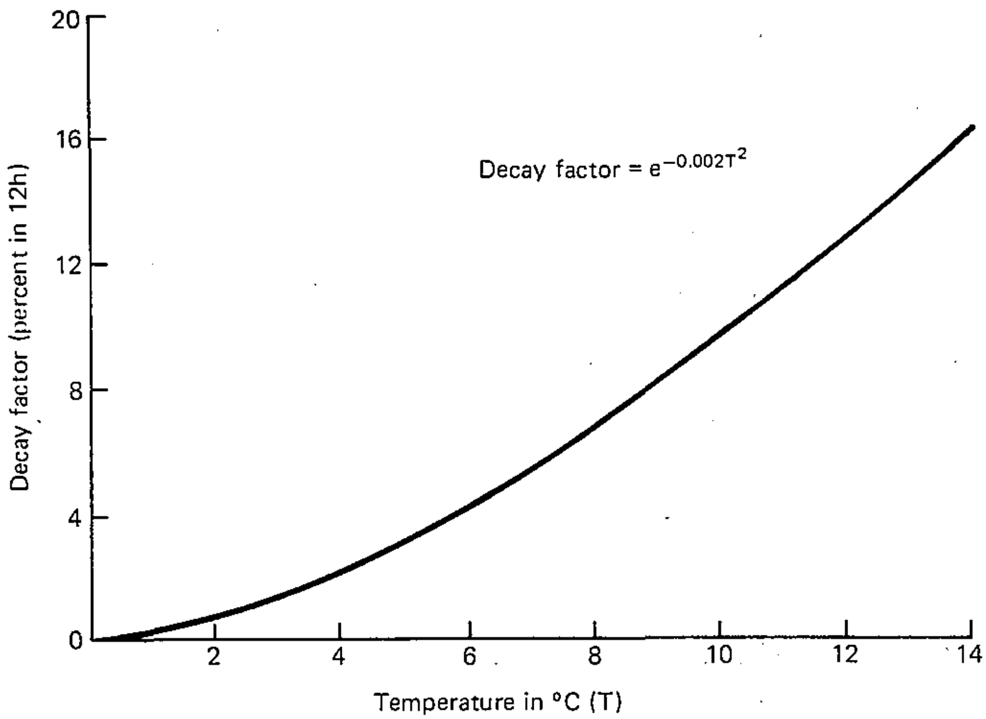

Figure 11.--The effect of temperature on the decay of hydrocarbons in fish.

Middleditch et al., 1982, found that shrimp populations in Buccaneer oil field were not affected by oil developments. On the other hand, changes in benthos in shallow water were rather profound in AMOCO CADIZ spill area, and after three years benthos communities had not reached their former nor new equilibria (Conan, 1982). Species with short life cycles tend to replace long-lived species.

In TSESIS spill area, mobile epibenthic macrofauna was drastically reduced. However, bivalves (*Macoma balthica*) increased greatly (Linden et al., 1979). Small bivalves serve as food source for many demersal fish species. Thus, it cannot be assumed that the changes in benthic ecosystem are always negative from the fisheries production point of view.

5. NUMERICAL SIMULATION OF THE SEDIMENTATION OF OIL

5.1 Overview of the computer programme.

General

The subroutine OILBOT for sedimentation of oil is a part of a larger programme for numerical computations of the effects of oil on marine fisheries ecosystem (DEMOIL). Only the subroutine OILBOT and a few other subroutines essential to it are described and documented herein.

The control programme DEMOIL sets various parameters and calls other subroutines. The computations in the enclosed model are done in a 49 x 54 grid, with a grid size of 2.3 km.

The index BLO (input in control programme) determines whether the oil source is continuous (well blowout) or instantaneous (tanker accident). There are several indices to select for the mode of transport of oil on the bottom with currents. A current subroutine (CUROIL) is used for computation of movement of oil on the bottom, which is essentially the same as that used for advection of smell from baits, and is documented by Olson and Laevastu, 1983.

The oil distribution in the water is computed by Rand Corporation (Liu, 1983) and provided to this project in a grid in 24-hour time step. This oil concentration field (S) in water is read in every time step and converted to concentrations of ppb. The field is printed out with printing subroutine PRIMFS (output see Figure 9). The field is scaled with scaling index LU for convenient printing of the array.

The subroutine EGGLAR is for computation of the exposure of eggs and larvae in water to different concentrations of oil. Subroutine STAFIE computes the corresponding exposure of fish, both to oil in the water as well as oil on the bottom. Subroutine CONFOOD computes the contamination (and tainting) of stationary as well as migrating fish through the food chain. The last-mentioned three subroutines will be documented in NWAFC/REEST Programme Documentation series.

Subroutine SILITA, included in Chapter 5.3, is a 5-point Laplacian type smoother.

Subroutine OILBOT

This subroutine, reproduced in Chapter 5.3, includes a simulation of depth in first time step. In the operational mode, depth should be read in from a prepared data statement or from tape or cards.

Four different bottom temperatures, two mixed layer depths, and three wind speeds are introduced with statements (see Input Parameters) which can be selected for the runs by the "selection parameters" (KT, KP, and KW). Indices for plankton concentrations, suspended minerogen matter, and type of bottom are also introduced in the first time step.

In all other time steps, except the first, the decay of the oil on the bottom left from previous time step, is computed before adding new oil (formula - see Chapter 3.2).

The computation of the sedimentation of the oil is done in 12-hour time steps (repeated if 24-hour time step for calling of the subroutine is used). The selection of the computation formula (see Chapter 2.3) depends on the nature of the spill (continuous or instantaneous) and whether thermocline is present at the grid point or not.

After time step computations, the field is smoothed (subroutine SILITA) and printed (subroutine PRIMFS).

5.2 Symbols and abbreviations used.

Note: Symbols marked with * are input parameters.

*ALPHA - Smoothing parameter (0.78)

AO(N,M) - Concentration of oil in the bottom nepheloid layer (ppb)

*APD - Minimum distance from blowout where sedimentation is computed (2.5 km)

*BB - Bottom type index (0.3-rocky, 0.6-coarse sand and gravel, 1.5-fine silt and clay)

*BCF - Wind speed coefficient (0.0015, 0.001)

*BLO - Index of the mode of computation; 2-continuous source, 1-instantaneous source

*BWF - Wind speed coefficient (0.0016, 0.001)

*CCF - Depth coefficient (0.15, 0.2)

*CDF - Depth coefficient (0.15, 0.2) (Possibility to select different values with continuous source)

*D(N,M) - Depth in meters

DDP - Intermediate (depth factor)

DFA - Intermediate (depth exponent)

DIFAC - Intermediate (distance factor)

DIS - Distance factor (from blowout)

*DL - Grid size (m)

EFA - Intermediate (decay exponent)

FDD - Intermediate (turbulence factor) (F_d)

FS - Intermediate (turbulence factor) (F_s)

K - Counter of 24 h time steps

*KA - Index for type of bottom current; 1 - laminar (used in this programme) (2 layer thickness increasing with distance from "source" - used in computation of distribution of smell from baits)

*KAL	- Index for computation of oil advection on the bottom; 0-no advection, 1-compute advection
*KP	- Index for potential mixed layer depth value
*KT	- Index for bottom temperature value
*KU	- "Type of current" indicator; (1 - uni-directional in u direction, 2 - uni-directional in v direction), 3 - current in both components (u and v) - used in this programme
*KW	- Index for wind speed value
*LU	- Printing and scaling index (see listing in the beginning of subroutine OILBOT)
*ME	- Total number of grid points in x direction
*MO	- m coordinate of blowout location
*NE	- Number of grid points in y direction
N	- Grid point counter (y axes)
*PLD(i)	- Potential mixed layer depth (m) (2 values given)
*PP	- Relative concentration of plankton (1.0 to 1.8)
*R	- Relative amount of minerogen suspended matter in the water (20 to 30)
RR	- Intermediate (minerogen suspension coefficient)
*S(N,M)	- Oil concentration in water in ppb
SK	- K, time step counter
STK	- Intermediate (time step coefficient) (TK_s)
T	- Time counter in minutes
*TAT	- Time step in hours
*TB(i)	- Bottom temperatures (°C) (4 values given)
*TD	- Time step in minutes, for computation of advection of oil (subroutine CUROIL)
TDK	- Intermediate (time step coefficient) (TK_d)

TFA	- Intermediate (temperature exponent)
*UI	- u component of the current on the bottom (in m/min)
*VI	- v component of the current on the bottom (in m/min)
*W(i)	- Wind speed (m/sec) (3 values given)

5.3 Programme DEMOIL and subroutines OILBOT, SILITA and PRIMFS.

```
$RESET FREE
$SET LINEINFO OWN LIST
FILE  6(KIND=PRINTER)
FILE  66(KIND=PRINTER)
FILE  5(TITLE="PERM/RAND/DATSUM/SUBSURFACE/D1",KIND=DISK,FILETYPE=7)
C     PROGRAM DEMOIL
      DIMENSION S(49,54),PF(49,54),D(49,54),AO(49,54),TB(4),PLD(2),W(3)
     2,E(5,2),SE(5,14),FE(5),DIF(5,2)
      COMMON S,PF,D,AO,TB,PLD,W,E,SE,FE,DIF,
     2K,T,TD,DL,UI,VI,BLO,KAL,KU,KA,TAT
      PRINT 30
   30 FORMAT(1H1,5X,20HWIND SPEED 10 M/SEC //)
      PRINT 31
   31 FORMAT(/5X,20HBOTTOM TEMP.  8 DEG.C//)
      PRINT 32
   32 FORMAT(/5X,22HTHERMOCLINE DEPTH 20M//)
      NE=49
      ME=54
      K=1
      BLO=2.
C     BLO=2 CONTINUOUS SOURCE, BLO=1 INSTANTANEOUS SOURCE.
      DL=2300.
C     TAT TIME STEP IN HOURS
      TAT=24.
      TD=20.
   10 T=K*1440.
C     TIME IN MINUTES
      KAL=1
C     KAL=0 - NO OIL MOVEMENT ON THE BOTTOM, 1 OIL ADVECTED ON BOTTOM
C     KU - CURRENT INDEX, SEE CUROIL; KA - TURBULENCE INDEX(NOT USED);
C     LU - PRINT SCALING INDEX
      KU=3
      KA=1
      LU=0
      UI=0.
      VI=0.
      READ(5,12)((S(N,M),M=1,54),N=1,49)
   12 FORMAT(9F8.0)
C     CONCENTRATIONS IN PPM, CONVERTED TO PPB
      DO 11 N=1,NE
      DO 11 M=1,ME
      S(N,M)=S(N,M)/1500000.
```

```
   11 CONTINUE
      CALL PRIMFS(S,T,UI,VI,DL,K,KA,KAL,BLO,LU)
      CALL OILBOT(S,K,TD,DL,D,AO,TB,BLO,UI,VI,KU,KAL,T,KA,TAT)
      CALL EGGLAR(S,DL,K,SE,E,FE,DIF)
      CALL STAFIE(S,AO,K,DL)
C     MOVE THE OIL ON THE BOTTOM TO THE RIGHT OF SFC FLOW
      UI=60.
      VI=8.
C     KAL=1  COMPUTE OIL MOVEMENT ON BOTTOM
      IF(K-1)15,15,14
   14 CONTINUE
      CALL CUROIL(AO,KU,UI,VI,DL,K,BLO,T,KAL)
      CALL CONFOO(S,AO,K,DL,BLO,TAT)
   15 K=K+1
      IF(K-15)10,10,20
   20 STOP
      END
```

```
      SUBROUTINE OILBOT(S,K,TD,DL,D,AO,TB,BLO,UI,VI,KU,KAL,T,KA,TAT)
      DIMENSION S(49,54),D(49,54),AO(49,54),TB(4),PLD(2),W(3)
C     D-DEPTH
C     AO-OIL ON THE BOTTOM
C     TB-BOTTOM TEMPERATURE, FOUR VALUES GIVEN
C     PLD-THERMOCLINE DEPTH, TWO VALUES
C     W-WIND SPEED, THREE VALUES
C     KT-INDEX OF TB VALUE CHOSEN FOR THE RUN
C     KP-INDEX OF PLD VALUE
C     KW-INDEX OF WIND VALUE
C     BLO=1 INSTANTANEOUS SOURCE, =2 CONTINUOUS SOURCE
C     UI-SURFACE CURRENT SPEED
C     KAL=1 COMPUTATION OF OIL MOVEMENT ON BOTTOM
C     LU=1 DEPTH DATA
C     LU=2 DECAY OF OIL ON THE BOTTOM
C     LU=3 OIL ON THE BOTTOM BEFORE ADVECTION
C     LU=4 OIL ON THE BOTTOM,LAYER THICKNESS DECREASING, ADVECTED
C     LU=5 ADVECTED OIL ON THE BOTTOM
C     LU=6 CONTAMINATION INDEX, PELAGIC FOOD
C     LU=7 CONTAMINATION INDEX, DEMERSAL FOOD
      NE=49
      ME=54
      MO=3
C     MO IS THE M LOCATION OF BLOWOUT
C     SIMULATION OF DEPTH, SLOPING TOWARDS HIGHER N
C     DEPTH CAN BE READ IN
      IF(K-1)16,16,20
   16 DO 11 N=1,NE
      DO 11 M=1,ME
      IF(43-N)12,12,13
   12 D(N,M)=50.
      GO TO 11
   13 IF(36-N)14,14,120
   14 D(N,M)=D(N-1,M)+4.
      GO TO 11
  120 IF(29-N)122,122,15
  122 D(N,M)=D(N-1,M)+2.
      GO TO 11
   15 D(N,M)=8.
   11 CONTINUE
CXXXXXXXXXXXXXXXXXXXXXX
      LU=1
      CALL PRIMFS(D,T,UI,VI,DL,K,KA,KAL,BLO,LU)
CXXXXXXXXXXXXXXXXXXXXXXX
   17 DO 18 N=1,NE
      DO 18 M=1,ME
      AO(N,M)=0.
   18 CONTINUE
C     INPUT PARAMETERS
   20 TB(1)=1.
      TB(2)=4.
      TB(3)=8.
      TB(4)=12.
      PLD(1)=20.
      PLD(2)=40.
      W(1)=5.
      W(2)=10.
      W(3)=15.
C     PP - RELATIVE CONC. OF PLANKTON
C     R - INDEX OF SUSPENDED MATTER
```

```
C       BB - BOTTOM TYPE INDEX
        PP=1.5
        R=20.
        BB=0.8
C       SETTING OF INDICES FOR INPUT PARAMETERS
        KT=3
        KP=1
        KW=2
CXXXXXXXXXXXXXXXXXXXXXXX
C       DECAY OF OIL ON THE BOTTOM
        IF(K-2)30,25,25
   25   DO 29 N=1,NE
        DO 29 M=1,ME
        IF(AO(N,M))29,29,26
   26   TFA=(TB(KT)**2.7)*0.0001
        DFA=0.15/SQRT(D(N,M))
        EFA=-(TFA+DFA)
        AO(N,M)=AO(N,M)*EXP(EFA)
        IF(TAT-12.)29,29,27
   27   AO(N,M)=AO(N,M)*EXP(EFA)
   29   CONTINUE
CXXXXXXXXXXXXXXXXXXXXXXXX
        LU=2
C       CALL PRIMFS(AO,T,UI,VI,DL,K,KA,KAL,BLO,LU)
CXXXXXXXXXXXXXXXXXXXXXXXXX
   30   IF(BLO-1)31,31,51
C       INSTANTANEOUS SOURCE (TANKER ACCIDENT)
   31   DO 45 N=1,NE
        DO 45 M=1,ME
        IF(PLD(KP)-D(N,M))40,33,33
C        NO PYCNOCLINE
   33   SK=K
   35   STK=SK/(3.+0.2*SK)
   56   BCF=0.0015
        CCF=0.15
        RR=(R+0.1*D(N,M))/SQRT(D(N,M))
        FS=(BCF*W(KW)+CCF/(D(N,M)**0.7))*STK
        AO(N,M)=AO(N,M)+S(N,M)*FS*PP*RR*BB
        IF(K-1)45,45,131
  131   IF(TAT-12.)45,45,37
   37   AO(N,M)=AO(N,M)+S(N,M)*FS*PP*RR*BB
        GO TO 45
C       THERMOCLINE PRESENT
   40   IF(K-1)45,45,38
   38   SK=K
        TDK=SK/(3.+0.5*SK)
        BCF=0.001
        CCF=0.20
        RR=(R+0.1*D(N,M))/SQRT(D(N,M))
        FDD=(BCF*W(KW)+CCF/(D(N,M)**0.7))*TDK
        AO(N,M)=AO(N,M)+S(N,M)*FDD*PP*RR*BB
        IF(K-1)45,45,132
 132    IF(TAT-12.)45,45,44
   44   AO(N,M)=AO(N,M)+S(N,M)*FDD*PP*RR*BB
   45   CONTINUE
        GO TO 70
C       CONTINUOUS SOURCE (BLOWOUT)
   51   DO 65 N=1,NE
        DO 65 M=1,ME
        DIS=((M-MO)*0.001*DL)
```

```
      IF(DIS)53,53,54
   53 DIS=0.001
   54 APD=2.5
C     NO COMPUTATION IN IMMEDIATE AREA OF BLOWOUT
C     I.E. 2.5KM FROM THE SOURCE
      IF(DIS-APD)65,59,59
   59 IF(PLD(KP)-D(N,M))60,55,55
C     NO PYCNOCLINE
   55 SK=K
   57 STK=SK/(3.+0.2*SK)
   58 BWF=0.0016
      CDF=0.15
      RR=(R+0.1*D(N,M))/SQRT(D(N,M))
      DIFAC=(DIS+4.)/(20.+0.1*DIS)
      FS=(BWF*W(KW)+CDF/(D(N,M)**0.7))*STK*(DIFAC)
      AO(N,M)=AO(N,M)+S(N,M)*FS*PP*RR*BB
      IF(K-1)65,65,69
   69 IF(TAT-12.)65,65,71
   71 AO(N,M)=AO(N,M)+S(N,M)*FS*PP*RR*BB
      GO TO 65
C     COMPUTATION WITH THERMOCLINE PRESENT
   60 APD=2.5
      IF(DIS-APD)65,61,61
   61 SK=K
   62 STK=SK/(3.+0.5*SK)
   64 BWF=0.001
      CDF=0.20
      DDP=D(N,M)**0.74
      RR=(R+0.1*D(N,M))/SQRT(D(N,M))
      DIFAC=(DIS+4.)/(20.+0.1*DIS)
      FS=(BWF*W(KW)+CDF/DDP)*STK*(DIFAC)
      AO(N,M)=AO(N,M)+S(N,M)*FS*PP*RR*BB
      IF(K-1)65,65,66
   66 IF(TAT-12.)65,65,67
   67 AO(N,M)=AO(N,M)+S(N,M)*FS*PP*RR*BB
   65 CONTINUE
CXXXXXXXXXXXXXXXXXXX
   70 ALPHA=0.78
      CALL SILITA(AO,ALPHA)
CXXXXXXXXXXXXXXXXXXXXXXXXX
      LU=3
      CALL PRIMFS(AO,T,UI,VI,DL,K,KA,KAL,BLO,LU)
CXXXXXXXXXXXXXXXXXXXXXXXXX
  100 RETURN
      END
```

```
      SUBROUTINE SILITA (S,ALPHA)
      DIMENSION S(49,54)
      NE=49
      ME=54
      NEH=NE-1
      MEH=ME-1
      BET=(1.-ALPHA)/4
      DO 123 N=2,NEH
      DO 123 M=2,MEH
  103 IF(1-N)105,107,105
  105 VAUP=S(N-1,M)
      GO TO 108
  107 VAUP=S(N,M)
  108 IF(NE-N)110,112,110
  110 VALO=S(N+1,M)
      GO TO 113
  112 VALO=S(N,M)
  113 IF(1-M)115,116,115
  115 VALE=S(N,M-1)
      GO TO 117
  116 VALE=S(N,M)
  117 IF(ME-M)119,121,119
  119 VARI=S(N,M+1)
      GO TO 122
  121 VARI=S(N,M)
  122 S(N,M)=ALPHA*S(N,M)+BET*(VAUP+VALO+VALE+VARI)
  123 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE PRIMFS(S,T,UI,VI,DL,K,KA,KAL,BLO,LU)
      DIMENSION S(49,54),IS(49,54)
      NE=49
      ME=54
C     IF(LU-1)202,401,420
      IF(LU-1)270,401,420
  202 PRINT 201,K,T,UI,VI,DL,KA,KAL
  201 FORMAT(1H1,5X,18HOIL CONCENTRATIONS,2X,2HK=,I5,3X,2HT=,F6.0,3X,3HU
     2I=,F6.4,3X,3HVI=,F6.4,3X,3HDL=,F6.0,3X,3HKA=,I3,3X,4HKAL=,I3)
  270 PRINT 271,K,DL
  271 FORMAT(1H1,5X,18HOIL CONCENTRATIONS,2X,2HK=,I5,3X,3HDL=,F6.0)
C     PRINT 203
      PRINT 504
  203 FORMAT(/5X,12HCONC.  IN PPB/)
  504 FORMAT(5X,19HPRINT FACTOR = 0.1,4X,7HPPB/10./)
CXXXXXXXXXXXXXXXXXXXXXXX
      GO TO 212
  401 PRINT 402
  402 FORMAT(1H1,5X,16HDEPTHS IN METERS,)
      GO TO 320
  420 IF(LU-3)421,425,430
  421 PRINT 422,K
  422 FORMAT(1H1,5X,34HDECAY OF OIL ON THE BOTTOM,  PERIOD,I5)
      GO TO 212
  425 PRINT 426,K
  426 FORMAT(1H1,5X,41HNEW OIL ON BOTTOM BEFORE ADVECTION,PERIOD,I5)
      GO TO 212
  430 IF(KAL-1)202,431,431
  431 PRINT 432,K
  432 FORMAT(1H1,5X,34HADVECTED OIL ON THE BOTTOM,  PERIOD,I5)
      PRINT 272,UI,VI
  272 FORMAT(5X,3HUI=,F5.2,3X,3HVI=,F5.2)
      GO TO 212
CXXXXXXXXXXXXXXXXXXXXXXX
      IF(KA-1)210,210,215
  210 PRINT 211
  211 FORMAT(5X,12HLAMINAR,FLOW/)
      GO TO 212
  215 PRINT 216
  216 FORMAT(5X,26HLAYER THICKNESS INCREASING/)
CXXXXXXXXXXXXXXXXXXXXXXX
C 212 IF(KAL-1)230,220,220
  212 IF(KAL-1)530,220,220
  220 IF(BLO-1)250,250,252
  250 DO 225 N=1,NE
      DO 225 M=1,ME
      IS(N,M)=S(N,M)*1000.
  225 CONTINUE
      PRINT 260
  260 FORMAT(5X,16HPRINT FACTOR = 1/)
      GO TO 240
  252 DO 253 N=1,NE
      DO 253 M=1,ME
      IS(N,M)=S(N,M)*100.
  253 CONTINUE
      PRINT 261
  261 FORMAT(5X,18HPRINT FACTOR = 0.1,4X,7HPPB/10./)
      GO TO 240
```

```
  320 DO 321 N=1,NE
      DO 321 M=1,ME
      IS(N,M)=S(N,M)
  321 CONTINUE
      GO TO 240
  230 DO 205 N=1,NE
      DO 205 M=1,ME
      IS(N,M)=S(N,M)*1000.
  205 CONTINUE
  530 DO 531 N=1,NE
      DO 531 M=1,ME
      IS(N,M)=S(N,M)*100.
  531 CONTINUE
  240 PRINT 206,(N,N=1,40)
  206 FORMAT(/4X,40I3)
      PRINT 207,(N,(IS(N,M),M=1,40),N=1,49)
  207 FORMAT(/1X,I2,1X,40I3)
C    XXXXXXXXXXXXXXXXXXX
      GO TO 300
C    XXXXXXXXXXXXXXXXXXXX
      PRINT 208,(N,N=41,54)
  208 FORMAT(1H1,//4X,14I3)
      PRINT 209,(N,(IS(N,M),M=41,54),N=1,49)
  209 FORMAT(/1X,I2,1X,14I3)
C     XXXXXX
      GO TO 300
C     XXXXXX
      PRINT 208,(N,N=81,120)
      PRINT 207,(N,(IS(N,M),M=81,120),N=1,100)
  300 RETURN
      END
```

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