FOREWORD

Marine contamination by petroleum, whether by natural seepage or by spills from ships at sea, by accidents in harbour or at offshore installations or by atmospheric or terrigenous input is by no means a new or rare phenomenon. In recent years however, the problems have been highlighted not only by the increased utilisation and marine transport of oil but also by a number of spectacular accidents which have raised questions about possible effects on the ecosystem. A number of detailed studies have been carried out in an attempt to answer these questions. The demands for such knowledge have been further increased by the various questions raised as a result of expansion of offshore exploration and exploitation for oil, particularly in environments hostile to these operations, in regions as far apart as the northern North Sea and the coast of Alaska.

Consequently, diverse aspects of the problem are being studied in several parts of the world by chemists and biologists who are often asking the same questions but using different approaches and sometimes producing conflicting views. Against this background, it seemed timely therefore to bring together a group of scientists from university, industry and government, actively engaged in such work, to examine and discuss common problems relevant to petroleum hydrocarbon contamination of the marine ecosystem and so a Workshop was sponsored by the International Council for the Exploration of the Sea, and held in Scotland at Aberdeen in September 1975.

The Workshop considered methodology, occurrence and fate in the environment, and effects on the ecosystem of petroleum hydrocarbons in the sea. Most of the papers presented and updated where necessary, are brought together in the present volume together with an edited version of the recorded discussion that followed each session. Of necessity, the reportage of the discussion is very brief although the proportion of time available for discussion compared favourably with that set aside for formal presentation of the papers. In preparing the discussion reports, the editors were assisted in particular by Dr R. Hardy, Dr R. Johnston, Mr P. R. Mackie and Dr I. C. White, and by comments from several contributors.

No attempt was made to produce specific recommendations but a study of the papers in this volume does give a clear indication of several lines of research which must be followed up before an adequate understanding can be reached of the effects of petroleum in the sea and it is evident that widespread monitoring operations will be fully effective only when the basis of our knowledge has been thus extended.

A list of participants to the workshop may be found in Appendix I.

A. D. McIntyre
K. J. Whittle

Rapp. P.-v. Réun. Cons. int. Explor. Mer, 171: 212–223. 1977.

WHAT NORTH SEA OIL MIGHT COST FISHERIES

R. Johnston
Marine Laboratory, P.O. Box 101, Aberdeen, AB9 8DB, U.K.

There is an urgent need for a reasoned assessment of the impact of oil and oil-related developments on the fisheries of the North Sea. The available information is inadequate for a valid simulation and instead a number of theoretical relationships are assumed between fish production and its underlying food web. On this basis, taking account of the more important proven or probable modes of action of North Sea oil, a tentative appraisal is made of the possible loss as equivalent fish resulting from oil spillages of various magnitudes and probabilities.

The physical encumbrance of oil-related developments on fishing is then assessed.

A third factor is natural gas exploitation and its attendant risks and interferences.

Losses reckoned as fish production or its approximate cash equivalent are shown to be small even for a catastrophic oil spill. Physical obstruction to fishing might be construed as a more serious interference.

INTRODUCTION

Current and imminent developments of North Sea oil threaten fisheries by increasing the amount of oil, by mechanical interference and by escapes of natural gas. The objectives of this paper are to attach realistic estimates of quantitative losses to the fisheries and of financial losses to the fishing community as the result of these developments.

This paper represents only one, the first, assessment of the costs to fisheries and fishing. Other approaches and other assessments are possible and desirable.

It has not been possible to include likely major factors such as the effects of oil or contaminated food on pelagic species especially sprats, sandeels, herring and their larvae. Oil may also disrupt the ecological balance in the sea, possibly by stimulatory as well as inhibitory effects. For example, oil could alter a phytoplankton population just at a critical stage of food supply for newly hatched larvae. Ecological effects are most likely to alter the impact of oil on fisheries by amplifying the response of the marine species and by giving rise to unforeseen chain reactions.

NORTH SEA OIL AND FISH

The interactions between hydrocarbons and marine life are complex. Some of the main pathways are summarised in Figure 117. It is relevant in this exercise to limit the range of interactions covered to those directly involving North Sea oil deliberately or accidentally liberated and commercial fish species or pathways to fish. This is done recognising that the exclusion of the many minor complexities shown in Figure 117 may be a serious oversimplification.

The stimulus for this paper is that there is a real need for an appraisal of the risks arising from North Sea oil, a finite resource, which might damage a major European or international food supply that skilfully husbanded could go on yielding indefinitely.

In order to make estimation possible the complexities of the real situation must be greatly reduced and the mechanisms of these remaining interactions greatly simplified. To this end simple relationships between primary and secondary production and the production of fish have been adopted. It is also assumed that damage to fish eggs and larvae results in a proportionate loss of catchable fish.

To keep the reading of the text uncluttered, the detailed calculations have been set out below each Table; the main facts used (dimensions, oil characteristics, food web relationships, spill statistics, spread of oil etc.) are set out in various Appendices.

The interactions considered will be limited to

- A short-term effects of fresh crude oil
- B long-term effects of residual crude oil
- C behavioural responses to crude oil
- D tainting of fish and shellfish
- E mitigating processes

and little attention will be devoted to onshore or offshore continuous discharges or to the effects of dispersant spraying, if practised. To this extent this assessment sets out as a deliberate underestimate of the total effect on fisheries.

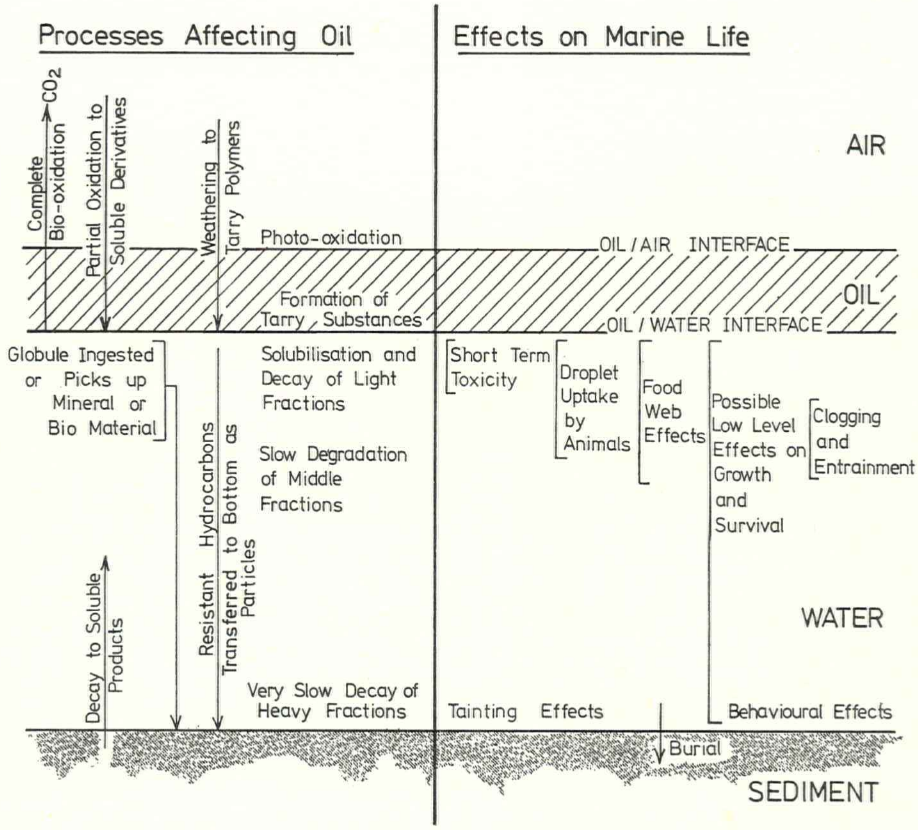

Figure 117. Diagrammatic representation of (left) the various processes affecting oil as a pollutant; (right) interactions between oil components and marine life.

A. SHORT-TERM EFFECTS OF FRESH CRUDE OIL

The short-term effects of freshly spilled North Sea oil will be treated under four sub-heads each to be considered as distinct and additive.

(i) *The toxicity of whole fresh crude oil.*

This mechanism of toxicity relates to a fresh spill of North Sea oil at the surface and spreading as a film which gives rise to a shallow layer of hydrocarbons dispersed in sea water at relatively high concentrations.

This is the condition at sea envisaged as equivalent to the laboratory 48 or 96 hour toxicity test in which animals are confined in a vessel having a few centimetres of sea water beneath a gently stirred layer of oil. In this condition crude oil is widely reported as having these ranges of short-term toxicity for the following organisms:

marine fish	10^4 to 10^5 mg dm^{-3} (ppm)
crustaceous plankton	10^3 to 10^5 mg dm^{-3} (ppm)
larvae	10^2 to 10^3 mg dm^{-3} (ppm)
	(e.g. MIT, 1973).

In envisaging the effect on marine life the most vulnerable category has been deemed "sensitive crustaceous plankton" and a level of 10^3 mg dm^{-3} is used assuming an oil spread area at 24 hours as shown in Figure 118. The calculations giving equivalent fish loss are summarised in Table 73 using data from Appendices as necessary.

The losses by this mechanism are negligible. Even major oil spills do not sustain short-term toxic conditions to more than a fraction of one metre depth.

(ii) *Inhibition of primary production by pentane-like fractions.*

The lower hydrocarbons typified by pentane inhibit phytoplankton, photosynthesis and multiplication. This inhibition is of limited duration, usually described as a few hours or days because of the volatility of these oil fractions. It has been shown that violent weather greatly increases the solubilisation of pentane-like fractions and that hot tranquil weather aids evaporation and minimises solution. No quantitative allowance has been attempted for the weather factor. According to the

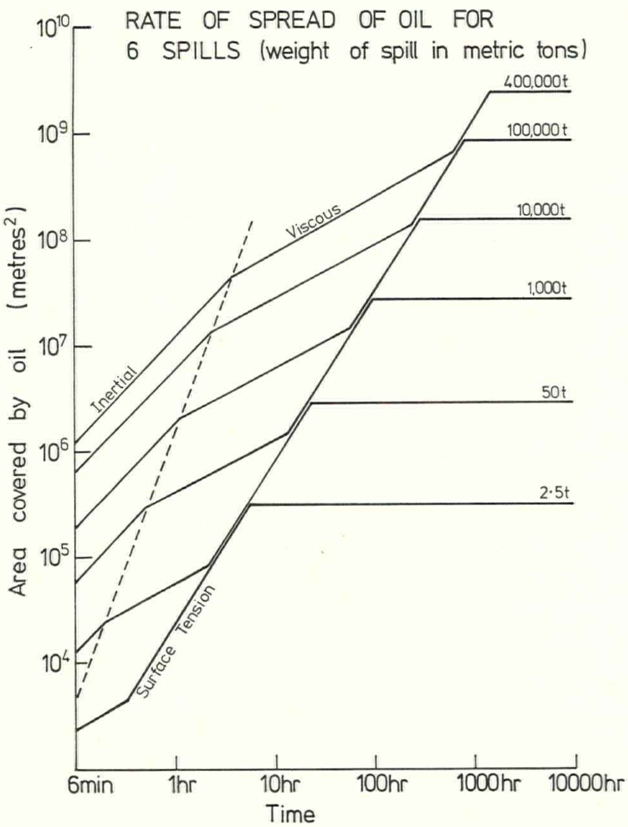

Figure 118. The theoretical rate of the spreading of oil on still water, recalculated from MIT, 1973.

shipboard experiments of Brooks and Sackett (1974) a solution of 1 mg dm^{-3} pentane in open sea water will cause 50 % inhibition of $^{14}CO_2$ fixation by the natural diatom population.

A limiting duration of 4 days has been ascribed to the larger oil spills (Table 74). The equivalent loss as fish production is significant for the largest spills but at a low level of loss per unit area. The overall mean annual loss is estimated to be 26·2 tonnes.

(iii) *Inhibition of primary production by octane-like fractions.*

Hydrocarbons typified by octane are more inhibitory than the lighter fractions and they are less volatile and less soluble. In crude oil the alkanes like octane are accompanied by aromatic hydrocarbons of equal volatility, greater solubility and greater toxicity. As before, dispersion in the open sea is greatly modified by weather conditions. Brooks and Sackett (1974) found 0·02 mg dm^{-3} octane caused 50 % inhibition of open sea diatom $^{14}CO_2$ productivity. At this concentration, taking into account the likely spread and movement

Table 73. Equivalent fish loss due to the toxicity of fresh crude oil to sensitive crustaceous plankton in the short term

M	*A*	*Z*	*L*	*I*	*I* x *L* x *A*
2·5	$3{\cdot}2\times10^5$	0·008	$3{\cdot}5\times10^{-5}$	100	0·0011
50	$2{\cdot}9\times10^6$	0·017	$7{\cdot}4\times10^{-5}$	10	0·0021
1 000	$3{\cdot}8\times10^6$	0·026	$1{\cdot}13\times10^{-4}$	1	0·0043
10 000	10^7	0·100	$4{\cdot}38\times10^{-4}$	0·2	0·0088
100 000	$4{\cdot}4\times10^7$	0·227	$9{\cdot}9\times10^{-4}$	0·04	0·0175
400 000	$1{\cdot}2\times10^8$	0·333	$1{\cdot}46\times10^{-3}$	0·02	0·0350

hence the total loss as fish is 0·069 t if all spill categories are envisaged i.e. 0·0109 t km^{-2} per year.

- *M* magnitude of spill in tons (see Appendix D).
- *A* area of slick at 24 hours (m^2) from Figure 118.
- *Z* depth of layer (m) yielding a concentration of 10^3 g m^{-2}
- *L* loss as fish (t) using 7g m^{-2} standing crop of zooplankton equivalent to 0·875g m^{-2} fish assuming 50% mortality and uniform vertical distribution of zooplankton to 100 m depth.
- *I* incidence of oil spill per year (see Appendix D).
- *I* x *L* x *A* loss as fish per year (t $year^{-1}$).

of oil slicks the duration of the inhibition may be as long as many weeks or months. On this time scale the dimensions of dispersion are extremely difficult to assess and it becomes important to bring into consideration the movement of the oil relative to the water, or more precisely the diatom populations in the water.

In the temperate and relatively disturbed waters of the North Sea the indications are that an oil film will separate into patches and be churned into a coarse suspension of oil droplets (which may possibly reform a thin film in still weather) in a period of time unlikely to exceed that of the theoretical period required to reach the stable maximum slick area (Fig. 118). This stable slick area may therefore be taken as the maximum area affected if the mechanism is to be envisaged as related to an oil slick. An alternative approach is to regard the distribution of these not too insoluble substances as being determined in the same way as the distribution of a solute, such as a dyestuff. Preliminary calculations based on these approaches lead one to conclude that a catastrophic oil spill would create a diffuse but significant inhibition of primary production over a very wide area of the North Sea for a considerable period. This period will be of such duration that appreciable bacterial breakdown might be expected to take place. This decrease in phytoplankton inhibition due to biodegradation will be considered in a later section. The assessments are summarised in Tables 75a and 75b.

Table 75a shows from A_{20}—A_{ult} that even assuming mixing throughout a 20 m column of water, the spread of the octane fraction necessary to attain a non-inhibitory concentration must be many times the maximum slick area. If the slick is envisaged as drifting always over clean water at 20 km day^{-1}, maintaining its size as at 24 hours, periods of inhibition of almost 2 years emerge. By this time the slick would have moved out of the North Sea, or more probably on to some coast. This would seem to indicate a mechanism of conspicuous size and importance. On average loss of about 200 t fish per year is indicated.

In the interpretation in Table 75b the octane-like substances are envisaged as soluble fractions originating from a point source and diffusing like dye over a period of time (T days) until a patch σ^2 is reached such that $\sigma^2 \times 20\ m = V_{tox}$ (the volume of concentration 0·02 g m^{-3} containing the octane-like fraction).

The dispersion dimensions are based on Kullenberg (1974). Since σr^2 is the area to be considered and the area of spread increases exponentially with time, VA_{20} is regarded as the area in which 50 % inhibition takes place for T days. An average loss of about 60 t fish per year is indicated. Using a log-linear interpolation of Kullenberg's data the loss approaches 10 times this amount. This shows how uncertain prediction of time and spread is at the upper end of the scale.

Table 74. Equivalent fish loss due to the inhibition of primary production by pentane-like substances

M	A_{tox}	T	I	$ATLI$
2·5	4×10^4	1·4	100	$7{\cdot}3\times10^{-3}$
50	8×10^5	10	10	$1{\cdot}1\times10^{-1}$
1 000	$1{\cdot}6\times10^7$	70	1	1·7
10 000	$1{\cdot}6\times10^8$	96	0·2	0·4
100 000	$1{\cdot}6\times10^9$	96	0·04	8
400 000	$6{\cdot}4\times10^9$	96	0·02	16

Total 26.2 t

0·0032 t km^{-2} $year^{-1}$

M magnitude of spill in tons.

A_{tox} assuming 10 m layer, area of patch attaining 1g m^{-3} "pentane" (this mean depth represents a compromise between greater inhibition at lesser depth and lesser inhibition at depths greater than 10 m) and the total primary production present is exposed.

I incidence of oil spill per year.

L primary production 100 g Cm^{-2} $year^{-1}$ = 0·001305 t fish per km^2 per hour.

(assuming 50% inhibition, 1 g C = 16 g wet wt phytoplankton)
(70 t wet phytoplankton production = 1 t wet fish production)
Pentane-like fraction amounts to 16 t for every 100 t crude oil.

T assumed/calculated duration of effect in hours (see text).

(iv) *The toxicity of soluble oil components to fish eggs and larvae.*

The short-term toxicities just discussed incur only short-term effects. Short-term toxicity to fish eggs and larvae may have a long-term effect if the decrease in the number of larvae reduces stock recruitment. Since there is a finite supply of food for the developing larvae and young fish, there will be an optimum number of eggs, larvae and juveniles which will yield the best number of recruits. To this extent a proportionate reduction in the total numbers of larvae and of very young fish uniformly in all areas to a certain threshold for stock recruitment would be of little account. However, even the very largest oil spill can be deemed a local event in the context of the total spawning or nursery area, so that local damage beyond this threshold could result from quite small spills. Since the natural success of the whole process from reproduction to recruitment to the fishing stock varies greatly from year to year, the best grounds for assessing the effects of oil would seem to be in relation to spawning area; in highly successful brood years any loss due to oil would be less serious than for years of meagre recruit production.

The toxicity of the soluble components of several crude oils towards pelagic and demersal fish has been studied by Kühnhold (1974) (see Appendix B). Since the main spawning grounds for herring are at the seabed in areas rather remote from the main oil developments, and the larval and early juvenile stages are to some extent less exposed to open-sea oil spills, attention will be focussed mainly on gadoid eggs. Kühnhold studied cod eggs but haddock, whiting, saithe and industrial small gadoids could be regarded as comparable in their likely patterns of response to oil.

The eggs of cod, haddock, saithe and whiting and the smaller gadoids are to be found in waters near the main areas of oil development during the period January to the end of April. Flatfishes, sprats and many less important species spawn at other times of the year in these areas so that some species is usually at risk.

It is difficult to extrapolate from the laboratory experimental data on small amounts of oil in small containers to the open sea where very different mixing conditions prevail and there are no wall effects. It is difficult to decide whether the laboratory processes used by Kühnhold lead to (1) complete extraction of soluble material, (2) complete exclusion of oil droplets and (3) accentuated or suppressed loss by volatilisation.

In the sea it is possible that the soluble material could affect more than one standing crop of eggs or larvae, that oil droplets could intensify the effect of soluble materials and finally the incompleteness of the experiment does not eliminate the possibility of longer term after effects on exposed larvae which survived the relatively short experimental period. Since the open sea would appear to offer more severe mixing condi-

Table 75. Equivalent fish loss due to the inhibition of primary production by octane-like fractions

(a) Octane regarded as associated with an oil slick

M	V_{tox}	A_{20}	A_{ult}	D_{24}	V_{24}	T_{drift}	A_{20}/A_{ult}	L	$LxIxT$
2·5	2×10^{7}	10^{6}	$3{\cdot}2\times10^{5}$	$6{\cdot}5\times10^{2}$	$2{\cdot}6\times10^{8}$	0·077	3·1	0·031	3·1
50	4×10^{8}	2×10^{7}	$2{\cdot}9\times10^{6}$	$1{\cdot}9\times10^{3}$	$7{\cdot}6\times10^{8}$	0·526	6·9	0·62	6·2
1 000	8×10^{9}	4×10^{8}	$2{\cdot}8\times10^{7}$	$2{\cdot}2\times10^{3}$	$8{\cdot}8\times10^{8}$	9·09	14·5	12·5	12·5
10 000	8×10^{10}	4×10^{9}	$1{\cdot}6\times10^{8}$	$3{\cdot}5\times10^{4}$	$1{\cdot}4\times10^{9}$	57·1	25·0	124·7	24·9
100 000	8×10^{11}	4×10^{10}	$8{\cdot}6\times10^{8}$	$7{\cdot}5\times10^{3}$	$3{\cdot}0\times10^{9}$	267	46·5	1 250	50·0
400 000	$3{\cdot}2\times10^{12}$	$1{\cdot}6\times10^{11}$	$2{\cdot}4\times10^{9}$	$1{\cdot}25\times10^{4}$	$5{\cdot}0\times10^{9}$	640	66·7	4 992	100

mean annual loss as fish = 195·7 t

M = magnitude of oil spill in tons.
V_{tox} = volume (m^3) sustaining 0·02 gm^{-3} for octane-like fractions taken as amounting to 16 t per 100 t crude oil.
A_{20} = area (m^2) corresponding to 20 m depth layer of inhibitory octane solution.
A_{ult} = maximum slick area from Figure 118.
D_{24} = diameter (m) of a circular oil slick at 24 hours.
V_{24} = volume (m^3) of water below slick to 20 m at 24 hours.
T_{drift} = number of days at a drift rate of 20 km day^{-1} to generate V_{tox}.
L = loss as fish assuming $D_{24}\times20$ km area, T_{drift} and 0·03132 t equivalent fish per day per km^2.

(b) Octane regarded as a dispersing solute (based on Kullenberg 1974, Table 19b)

M	$\sqrt{A_{20}}$	log T_{sec}	T	LxT	I	$LxIxT$
2·5	10^{3}	4·80	0·83	0·026	100	2·6
50	$4{\cdot}5\times10^{3}$	5·50	5·54	0·781	10	7·8
1 000	2×10^{4}	6·20	13·34	11·49	1	11·5
10 000	$6{\cdot}5\times10^{4}$	6·45	32·6	66·37	0·2	13·3
100 000	2×10^{5}	6·60	45·0	282	0·04	11·3
400 000	$4{\cdot}4\times10^{5}$	6·70	51·7	712	0·02	14·2

mean annual loss as fish = 60·7 t

$\sqrt{A_{20}}$ The square root of the area, assuming layer depth 20 m, affording 0·02 gm^{-3} octane-like fraction is taken to be appropriate for the duration T of the noxious body of water.
$\log_{10}T$(sec) taken from a graph of σ_r^2 (the symmetrical variance for the diffusion of a solute).
T time in days for area A_{20} to be attained.
L(tons) = loss as equivalent fish assuming T days, area $\sqrt{A_{20}}$. and 0·03132 t fish per day per km^2.
I = incidence of spill of the indicated magnitude.

tions, more complete extraction, greater persistence, exposure to more than one standing stock and background long-term sub-liminal exposure to oil products, all or most of the factors would suggest that extrapolation from the laboratory situation to the open sea results in an underestimate of the likely effect.

North Sea oil would seem likely to resemble Agha Jari crude oil. No evaluation of the toxicity of North Sea oil soluble fractions has as yet been reported but the Kühnhold data do not clearly define the 50 % point for survival from egg to larva and 0·020 g North Sea oil (0·025 ml) in 1 dm^3 of sea water has been taken as a best estimate (Appendix B). The range of solubility of oil in seawater is given as 0·1 to 10 % (MIT, 1973) and the high aromatic content of North Sea oil would indicate a figure towards the higher end, for example 5 % in accord with the value found in the MOD Trials using Kuwait crude (CDL, 1971). The volume of sea water to 20 m, containing 20 g soluble fractions per m^3 is regarded as persisting for a sufficient period to affect 50 % of developing eggs or larvae. The incidence (I) of an oil spill is ascribed only to 4 critical months out of the year.

The outcome of these calculations (Table 76) puts the damage on average at just below one part per million or in the event of a 400 000 t spill about 0·14 %. On many counts this is an unavoidable underestimate.

B. LONG-TERM EFFECTS OF RESIDUAL CRUDE OIL

There are no field observations to illustrate the long-term effects of weathered crude oil on open-sea organisms nor would these be readily distinguishable from countless natural and imposed effects. An important observable fact is the progressive disappearance of much of the oil from the sea surface. It is possible that this mechanism may involve small marine organisms. Surface oil becomes dispersed as small droplets covering a wide size range (from mm^3 to colloidal). A proportion of these droplets is eaten by filter feeding organisms along with other particles and excreted in faecal pellets which may sink or be eaten in turn. Some droplets acquire inorganic or inanimate particles or a heavy coating of bacteria and sink; others may become coated with algae or stick to zooplankton organisms.

It is assumed that the concentration of detritus plus

Table 76. Loss of fish eggs and larvae due to the toxicity of the soluble fraction

M	m_{tox}	$I\times{}^1/_3$	A_{tox}	T	$AxTxI$	Depth layer	$AxTxIxZ$
2·5	0·125	33·3	$3{\cdot}2 \times 10^2$	0·83	$0{\cdot}045\times10^{-8}$	$\times{}^2/_3$	$0{\cdot}030\times10^{-8}$
50	2·5	3·33	$6{\cdot}25\times10^3$	5·54	$0{\cdot}596\times10^{-8}$	$\times{}^2/_3$	$0{\cdot}40 \times10^{-8}$
1 000	50	0·33	$1{\cdot}25\times10^5$	13·34	$2{\cdot}87 \times10^{-8}$	$\times{}^2/_3$	$1{\cdot}91 \times10^{-8}$
10 000	500	0·067	$1{\cdot}25\times10^6$	32·6	$14{\cdot}0 \times10^{-8}$	$\times{}^2/_3$	$9{\cdot}3 \times10^{-8}$
100 000	5 000	0·013	$1{\cdot}25\times10^7$	45·0	$38{\cdot}7 \times10^{-8}$	$\times{}^2/_3$	$25{\cdot}8 \times10^{-8}$
400 000	20 000	0·007	5×10^7	51·7	$89{\cdot}1 \times10^{-8}$	$\times{}^2/_3$	$59{\cdot}7 \times10^{-8}$
							97 t

m_{tox} = weight of soluble fraction (t).
$I\times{}^1/_3$ = incidence $\times{}^1/_3$.
A_{tox} = Area (m^2) of 20 m layer of solution of m_{tox} yielding 20 gm^{-3}.
T = duration of patch (total spawning period 121 days) from Table 75b.
Area of egg production = $8\times10^{10}m^2$.
Z = Layer depth of eggs and larvae = 30 m.
${}^2/_3\times$depth layer—because the depth of the egg/larval layer is 30 m while that of the polluted water is 20 m.

inorganic material is 9 times more abundant than live plankton and that both are equally likely to attach to oil. As a tentative approach an organism becoming burdened with 10 % of its weight of oil is assumed to prematurely die and/or sink to the bottom; similarly an oil globule acquiring a coating of 9 times its weight of inanimate material will sink. Below 1 m^2 there is on average 60 g wet weight plankton regarded as renewable 25 times per year.

The amount of oil in sea water is approximately 3 µg dm^{-3} or 67 500 t in the northern North Sea. The annual turnover of plankton is about $3{\cdot}1\times10^8$ t wet wt in the area ($225\times10^3km^2$). If the probability of plankton and inanimate matter acquiring 10 % oil is 0·0001 then the background level of oil would have to be replenished every 22 years, or at 0·001 every 2·2 years or at 0·01 every 0·22 years. The likely age of weathered oil is between 5 and 20 years and a probability of 0·00025 (8·8 years) would seem appropriate. This means that one organism in 4000 would acquire 10 % of its weight of oil. At this probability 77 625 t of plankton would be lost per year or 1109 t fish equivalent in relation to background oil alone. Oil spills would increase these losses as shown in Table 77.

The mean annual additional loss is seen to be 259 t with very substantial losses (cf Table 77) in years of major oil spills.

This loss mechanism assumes that contaminated organisms no longer contribute to the food web. While this may be untrue there is evidence that oil acquired through food may affect the growth and survival of marine animal life and, more important, its capacity and success in reproduction. This mechanism would include these related effects.

Table 77. Equivalent fish loss due to the attachment of weathered oil to plankton

M	M'	TL_p	TH_f	Lf	Lf'
b	67 500	77 625	1 109	–	–
2·5	67 750	77 912	1 113	4	4
50	68 000	78 200	1 117	8	8
1 000	68 500	78 775	1 126	17	17
10 000	69 500	79 925	1 142	33	165
100 000	71 500	82 225	1 175	66	1 650
400 000	75 500	86 825	1 240	131	6 550

mean annual equivalent fish loss is 259 t

b = baseline (or background) level of weathered oil is 67 500 t.
M' = aggregate amount of oil + spills ($b+MI$) in tons.
TL_p = total plankton loss (annual mean turnover $3{\cdot}105\times10^8$t) in tons.
TL_f = total fish equivalent (tons).
Lf = fish loss equivalent to spilled oil (annual mean) in tons.
Lf' = fish loss for major spills in the year of the incident.

C. BEHAVIOURAL RESPONSES TO CRUDE OIL

Crude oil and its sea water extracts interrupt the normal behaviour of marine animals in a variety of ways. Of the few fish species studied most have displayed avoidance of water containing more than 100 µg/ml oil. Bullheads (small fish) which have a complex social behaviour, are sensitive in the microgram per litre range to crude oil and various other chemical pollutants which interfere with their highly developed olfactory senses. Both communal and sexual activities are disrupted. Many other kinds of aquatic animals are similarly dependent on chemical senses which guide their activity. Those activities modified by oil include: lobsters — searching, feeding, grooming; crabs — "mating" stance; oysters — feeding rhythms; barnacle larvae — phototactic response. Many shellfish exposed to somewhat higher levels of oil respond by retreating, by shell closure or other means of excluding tainted water; on transfer to clean conditions the animals resume normal behaviour. Many of these behavioural activities are affected by oil in 10—100 µg dm^{-3} concentrations. An oil spill of 400 000 t would generate 20 µg dm^{-3} if uniformly distributed throughout the water column over the entire northern North Sea, but this is an overidealistic approach. It would require only a few thousand tons to have a temporary but pronounced effect on a major part of the inshore fish and shellfish population. The extent of the *permanent* damage that would result cannot be quantified at present though probably the effects would be highly variable depending on factors like the timing of the spill, the degree of mixing, the duration of the exposure and the particular odour qualities of North Sea oil. The permanent damage could include poor reproductive success and if the oil pollution was persistent a diminution of growth.

D. THE TAINTING OF FISH AND SHELLFISH

Fish and shellfish experimentally dosed with crude oil through their food, gradually build up hydrocarbons in their tissues, especially in the liver and gut. The acquired hydrocarbons are eliminated from the muscle and gut of fish in 2—3 weeks but much more slowly from the liver. Unfed fish held in tanks covered with oil did not acquire hydrocarbons. Shellfish also lose much of their taint in a few weeks but contamination can be detected chemically for many months afterwards. Filter feeding shellfish can acquire objectionable "off"flavours (10—50 mg oil kg^{-1} tissue) in their edible tissues after an exposure of only a few days in water containing 1—10 µg dm^{-3} oil. Tainting of edible marine produce would probably be related to the magnitude of an oil spill but many factors affect the rate and intensity of tainting — both of which are greatly increased if the oil is dispersed. Tainting may be acquired by skin transfer or through contaminated food, but tainting of commercial catches can also result from contact with oil-fouled fishing gear or deck.

An important side effect relates to the accidental or deliberate marketing of contaminated products — an event that could cause severe reaction among fish consumers and could trigger financial repercussions on the fishing industry far beyond the value of the initial, tainted catches. It is highly desirable, therefore, that no fishing should be permitted in an oil spill area until any taint has been proved to have cleared up.

On this basis, assuming that 1 km^2 of fishing ground in the northern North Sea is worth £50 per week, the value of fishing grounds temporarily lost would be as in Table 78. The approximate mean weekly value is £9.62 per 1 km^2 (after Parrish, 1974) for the whole North Sea but the favoured fishing spots are only a small fraction of the whole area.

Table 78. Denial of fishing grounds—potential value of areas obscured by oil slicks

M	A_{ult}	T_{ult}	I	$T'xI$	C
2·5	$3{\cdot}2\times10^5$	0·6	100	3·6	58
50	$2{\cdot}9\times10^6$	25	10	1·49	216
1 000	$2{\cdot}8\times10^7$	95	1	0·57	791
10 000	$1{\cdot}6\times10^8$	250	0·2	0·30	2 384
100 000	$8{\cdot}6\times10^8$	900	0·04	0·21	9 202
400 000	$2{\cdot}4\times10^9$	1 100	0·02	0·13	15 720

mean annual cost £ 28 371

M = magnitude of oil spill (t).
A_{ult} = maximum oil slick area (m^2)
T_{ult} = time to attain A_{ult} (hours).
I = incidence of oil slick.
$T'xI$ = time in weeks xI.
C = potential value in £'s, (£ 50 per 10^6m^2).

The effect of a small spill on the fishing activities is negligible and the endurance of such a spill would be short (less than 1 week); for a large spill not only would the effect of a ban on the area be severe but the persistence of the larger amount of oil might necessitate the ban being enforced for several weeks. This evaluation is based on a "static" oil patch and no allowance has been made for a safety margin around the affected area. Since a factor of at least ×5 would be necessary to accommodate the movement of an oil slick and a safety zone around it, the evaluations are not unreasonably amplified.

E. MITIGATING PROCESSES

Four processes that might be considered as mitigating the effects of crude oil on the sea are discussed below.

(i) *Reduction of crude oil toxicity.*

The most rapid short-term reduction of crude oil toxicity takes place by evaporation of the light ends (lower alkanes and aromatics). These fractions have most effect near the sea surface and consequently phytoplankton are the part of marine life to be affected. These light fractions must inevitably return to the sea in precipitation or by solution. The instantaneous amount of light ends needed to create a toxic layer 10 m deep at 1 g m^{-3} for the North Sea would be about 6 million tons, compared to an annual oil requirement in UK of 100 million tons crude yielding perhaps 30 million tons light ends. The inefficiency of petroleum use on land is probably not more than a few percent so that even if inhibitory concentrations could be created momentarily they would not be sustained by this input.

Irreversible but much slower detoxification mechanisms are photo-oxidation, the polymerisation of oily products to tar balls, the physical absorption of oil on shore mud, sand and rock and on flotsam and jetsam. These and kindred processes are probably important mechanisms for reducing the effects of oil on open-sea marine life at some expense of inshore life. These processes may assist the microbial breakdown of hydrocarbons.

On reflection therefore these mechanisms are not much better than marginally mitigating. They are also at present unquantifiable.

(ii) *Dispersion to safe oil concentrations.*

It is easier to define what may be a toxic concentration of oil components for marine life than to be assured of non-toxic concentrations. Crude oil is a natural pollutant and life in the sea has evolved despite its presence, perhaps even because of its presence as a potential participant in organic evolution. The biogenic involvement of hydrocarbons is too complex for this simple model and a solution of this problem will not be attempted. Like DDT and organochlorines generally, the physical state of oil does not comply ideally with the concentration rules that apply to solutes so that to some extent a particle or globule of insoluble pollutant in a given volume of water will always be potentially more noxious than a solute which was equitoxic when both were compared at higher concentration. Coagulation of oil and particulate pollutants is possible but soluble pollutants are not physically reconcentrated.

Thus dispersion by itself is not a proven mechanism for mitigating the long-term effects of oil though it conveys a useful measure of anonymity and protection from public gaze.

(iii) *Oil degradation.*

Changes in the chemical nature of oil are promoted by photo- and chemical oxidation and polymerisation at the sea surface but the main agents leading to its ultimate breakdown to fractions that are readily metabolised are micro-organisms of many kinds. Degradation rates are influenced by the nature of the oil, ambient conditions, including nutrients and oxygen, oil dispersion conditions and the prior degree of weathering. The light ends are rapidly degraded with values near that for toluene namely 63 % loss in 20 days under the conditions of the BOD test, perhaps equivalent to a half-life of a month under seawater conditions. Gibbs (1975) shows *n*-alkanes in the ranges C_{17-20}, C_{21-24}, C_{25-28} to be progressively less degradable, C_{33-37} much less degradable. The asphaltene content of the residual oil increases as degradation removes more amenable fractions. The time scale of half-lives probably ranges from 10—100 days for light/middle ends to 5000 days for asphaltenes; residue after distillation is 50 % of North Sea oil; half the mitigation takes place within one year and might alleviate oil pollution in the North Sea, the other half takes a very long time and becomes essentially a global problem. In view of the uncertainty of biodegradation rates (Floodgate, 1972) no attempt has been made to adjust the assessments in the foregoing sections. In the following estimates only the degradable half of the oil is regarded as lost from the system. The rates chosen are the author's personal selection from a wide range of published values.

(a) At the sea surface —

Rate of biodegradation $0{\cdot}05\ \text{gm}^{-2}\ \text{day}^{-1}$

Area of North Sea (N.S.) $575 \times 10^3\ \text{km}^2$

Area of N. North Sea (N.N.S.) $225 \times 10^3\ \text{km}^2$

Capacity to remove degradable 50 % is $10{\cdot}5 \times 10^6$ t (N.S.) $4{\cdot}1 \times 10^6$ t (N.N.S.)

(equal amounts of weathered residue will remain).

(b) Throughout the water column —

Oil found dispersed in the water column is in a transitory stage of transfer from the surface to the bottom and to some extent also from the bottom to the surface. Little is known about this transfer stage or about the appropriate rate of biodegradation. In estuarine waters the highest concentration of oil is in the surface microlayer and the largest accumulation is associated with recent bottom sediments. Therefore the breakdown rate in the water column is less than the deposition rate for such conditions. It is uncertain whether a similar distribution of oil can be ascribed to the open sea. The nutrient status surrounding the oil will usually be superior to that at the surface but oxygen availability will be less although usually not limiting in the North Sea. A rate of $0{\cdot}6\ \text{mg m}^{-3}\ \text{year}^{-1}$ might be applicable to the biodegradable portion; this would put the capacity for degradation in the North Sea at $32 \times 10^3\ \text{t year}^{-1}$.

(c) At the sea shore and bottom —

A uniform decay rate of $0{\cdot}01$ g weathered oil $\text{m}^{-2}\ \text{day}^{-1}$ has been assumed for all intertidal shores. The Scottish shoreline is taken to be 750 km long by on average 20 m broad as a compromise between rocky cliffs and sandy beaches. A removal rate of $55\ \text{t year}^{-1}$ is sustained for light oiling; for a thousandfold increase in oil deposition the decay rate would perhaps be increased tenfold.

If the same light oiling rate is applied to subtidal bottom areas then the capacity for oil removal is vast, about $8{\cdot}2 \times 10^6$ t weathered oil per year.

(iv) *Oil spill clean-up.*

As deduced above the removal rate for the intertidal zone is modest ($55\ \text{t year}^{-1}$) and the capacity for storing oil out of harm's way is not very large, only 150 t at 10 g m^{-2}; higher rates of contamination would have serious amenity effects. Oil is also removed on flotsam and jetsam but again this is a trifling amount. Much work has also gone into the retrieval of spilt oil but once more this cannot be regarded at present as a significant mitigating factor except in an unbelievably favourable coincidence of ideal weather, preparedness and proximity. Oil thickeners and absorbing substances may produce some marginal benefit.

For oil spill clean-up by use of dispersants the efficiency of the mitigating processes is reduced and it is possible that the dispersal of oil in water will hinder rather than assist its biodegradation as has been commonly assumed. The short-term toxicity of the oil (Tables 73 to 76) will be increased.

MECHANICAL INTERFERENCE OF OIL DEVELOPMENTS WITH COMMERCIAL FISHING

The area of fishing grounds immediately and directly physically denied to fishermen amounts to the area of exposed pipelines, submerged wellheads, platforms and rigs and minor related structures. This area is a trifling fraction of the total North Sea fishing grounds; perhaps 200 000 m^2 in 200 000 square miles or 3 parts in one million.

The law at present does not require a safety margin alongside pipelines, feeder lines, flexible hoses or around suspended wellheads but it does require the fisherman to pay compensation for any damage they may cause to pipelines and oil installations and for the costs of any incidental oil spill clean up. The law also stipulates a 500 m safety zone around the centre of platforms and around the anchor systems of semi-submersible platforms. Thus there are legal barriers denying fishermen access to parts of the sea and barriers created by fears of loss of gear and of possible colossal claims for any damage done. If law requires a 500 m safety zone for platforms, caution demands a similar margin on either side of pipelines and around other impediments. This denies the fisherman 1·6 km^2 for each mile of pipeline and about 0·8 km^2 round each oil-related equipment. In round numbers there will be in the early 1980's about 400 miles of gas and oil pipelines in the northern North Sea together with some 200 miles in the south, making in all a no-go area of 1000 km^2. There are in 1975 already 58 suspended wellheads and by 1980 the number will exceed 70 which is equivalent to 56 km^2 and the various production and exploratory equipments would add a further 64 km^2. This makes a total of 1120 km^2 out of 520 000 km^2 of the North Sea or 0·22 %. More developments are situated in the northern part entailing perhaps 0·5 %, more if areas such as the Norwegian Deeps regarded as unfit for trawling are excluded. A further increase in lost fishing ground is needed to account for optimum directions of towing in relation to bottom contours, wind and tidal drift, room for shooting and hauling (Bennett, 1974). Exact calculation is difficult but an overall loss ranging from 0·3 to 1 % is indicated. This denial of fishing area does not mean that the standing stock of fish is less or that catches need be less since 99 % unhampered area remains. These safety zones may be regarded as conservation areas for a small proportion of the population of fishes.

Table 79. Summary of equivalent fish losses and 400 000 t disaster assessment

a)	73 Fresh crude oil		74 Pentane inhibition		76 Eggs and larvae	
b)	t	£ 000's	t	£ 000's	t	£ 000's
Annual mean	0·069	0·008	26·2	3·233	97	11·970
Disaster	3·45	0·043	800	98·720	2 985	268·349

a)	75a) Octane inhibition		75b) Octane inhibition		Attachment	
b)	t	£ 000's	t	£ 000's	t	£ 000's
Annual mean	195·7	24·149	60·7	7·490	25·9	31·961
Disaster	4 990	615·766	712	87·860	6 550	808·270

6

Behavioural responses	Tainting, fishing diverted	Loss of fishing grounds[c] (potential loss)		
Believed to be small, nominally £ 5 000 to £ 250 000	(potential loss)	min.	t	£ 000's
	£ 28 371	0·3 %	3 646·5	449·978
	£ 786 000	max 1 %	12 155	1 499·927

Natural gas—believed to be negligible—ignored.

Totals		using 75a)	using 75b)
Accountable losses	mean	£ 76 321	£ 59 662
	disaster	£ 2 141 148	£ 1 613 242
Potential losses	mean	£ 478 349	
	disaster	£ 2 285 927	

a) The numbers refer to the preceeding detailed Tables.
b) The value of fish is taken as £ 123·40 per ton (Parrish, 1974).
c) Only demersal fish is relevant in 1 215 000 t total for the North Sea.

NATURAL GAS AND FISHERIES

Natural gas is mainly composed of simple C_1 to C_5 hydrocarbons with the *n*-alkanes methane to pentane predominating. The solubility of this mixture will vary according to its composition usually in the region of about 50 to 200 ml per litre of sea water (by weight roughly 100 to 400 mg dm^{-3}). Methane is a normal component of sea water in concentrations of about 5×10^{-5} ml per litre but in anoxic waters 10 to 20 times higher.

Table 80. Nominal catches (in 000's metric tons) and index of value (in £ millions)[a] for North Sea pelagic, demersal and shellfish fisheries, by country, in 1973. Catch data from Advance Release Tables of ICES, Bulletin Statistique

	Pelagic Fish[b]		Demersal Fish[c]		Shellfish	
	Nominal catch	Index of value	Nominal catch	Index of value	Nominal catch	Index of value
Belgium	2·3	0·1	30·9	5·1	3·3	1·1
Denmark	329·5	16·5	682·9	112·0	26·1	8·6
Faroes	67·4	3·4	63·6	10·4	–	–
France	10·5	0·5	82·4	13·5	0·5	0·2
Germany, Fed. Rep.	21·6	1·1	46·5	7·6	41·9	13·7
Iceland	41·1	2·1	+	+	–	–
Netherlands	32·4	1·6	132·5	21·8	120·4	39·5
Norway	396·2	20·0	233·1	38·3	1·6	0·5
Poland	6·5	0·3	10·9	1·8	–	–
Sweden	84·9	4·3	37·3	6·1	2·7	0·9
UK (England & Wales)	38·6	1·9	121·2	19·9	24·1	7·9
(Scotland)	71·3	3·6	203·2	33·3	7·4	2·5
USSR	84·4	4·3	145·3	23·9	–	–
Total	1 186·7	59·7	1 789·8	293·7	228·0	74·9

a) The average Scottish price figures for 1973 are used as the Index of Value at first sale.
b) Pelagic fish comprises herring, sprat, pilchard, mackerel, horse mackerel, tuna.
c) Demersal fish comprises all other species reported in published statistics, of which gadoids total 1 215 500 metric tons.

Sea bed escape of natural gas will be under considerable pressure and local concentrations of 3000 mg dm^{-3} might be generated at 100 m depth. Local accumulations would be rapidly dispersed to harmless concentrations.

The short-term toxicity of natural gas towards marine organisms has been little studied. On the basis of chemical analogy, the most likely range for plankton would be 50 to 500 mg dm^{-3}. In part this toxicity might be reversible on transfer to clean water. Natural gas contains trace substances likely to smell unfamiliar to fish and would cause avoidance.

Natural gas hydrocarbons at sub-lethal concentrations would be readily metabolised by micro-organisms; compare for example their commercial use for the manufacture of microbial protein.

Except in the immediate vicinity of a serious gas escape it is unlikely that any significant damage to fisheries would take place. There would be local damage to plankton over a limited radius, perhaps at worst a few hundred metres, but conditions would seem likely strongly to deter the approach of fish. No significant loss is thus attributable to the interaction of natural gas and fisheries.

MATERIAL AND FINANCIAL LOSSES TO FISHERMEN

The equivalent losses as fish are summarised in Table 79 showing the mean annual loss and the loss attaching to a 400 000 t disastrous oil spill. Two estimates are shown for octane inhibition Tables 75a, 75b, each costed separately.

These assessments show clearly that a legally or psychologically imposed safety zone around all oil-related equipment and banning of fishing in the areas of oil slicks would indeed create a sizeable *potential* loss to European fisheries. It is by no means proved that this possible loss would materialise to any significant extent because the vast majority of fishing space remains unimpaired.

The other losses however, are accountable. Of these, phytoplankton inhibition, damage to eggs and larvae and loss by attachment of oil to plankton are, in ascending order, the main foreseeable biological effects. These and other minor factors add up to losses estimated at about 500 or 600 t fish or £60 000 to £76 000 on average but up to 13 000 t fish or £2 100 000 for a disastrous spill. These numbers should be compared to total fish (pelagic + demersal + shellfish) values of 4·36 million tons and £550 000 000 (Table 80).

Thus on average or even at worst the impact of offshore oil pollution on fisheries will be negligible or small, much less than factors such as over-exploitation or unsuccessful stock recruitment.

Apart from a proportion of oil-related installations which must remain as permanent obstacles to fishing, the remainder of the potential and material losses will prevail only as long as North Sea oil lasts. However, certain material losses will continue in response to worldwide use of oil.

Where, when and how oil spills strike may decide which fishermen out of all the European fishing communities have to bear the ensuing losses since it is most unlikely that these will be equally shared.

It is evident that there remain many facets of this perplexing problem to be explored.

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APPENDIX A. BIOLOGICAL DATA

Fisheries yields and values are shown in Table 80.

FOOD CHAIN EQUIVALENTS

[1]Primary productivity is taken as 80 gC m^{-2} $year^{-1}$.

Annual primary production of the area north of 55°30' N is $2{\cdot}88\times10^8$t wet weight; secondary production is $3{\cdot}8\times10^{-1}$t wet weight.

Phytoplankton standing crop is 53 g m^{-2} (wet weight).
Zooplankton standing crop is 7 g m^{-2} (wet weight).
hence biomass is 60 g m^{-2} (wet weight).

The biomass is regarded as renewable 25 times per year.

Nominal fish catch (Parrish, 1974) $3{\cdot}2\times10^6$t.
catch per unit area 5·57t km^{-2}.

APPENDIX B. TOXICITY OF OIL

	Soluble aromatics	No. 2 fuel oil or kerosene	Fresh crude oil
Algae	10 to 100	50 to 500	10^4 to 10^5
Fish	5 to 50	25 to 250	10^4 to 10^5
Pelagic crustaceans	1 to 10	5 to 50	10^3 to 10^4
Larvae	0·1 to 1·0	0·5 to 5	10^2 to 10^3

[1] Fish equivalent for North Sea is $10{\cdot}5\times10^6$t.

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Table 81. General characteristics of some crude oils

Percentage yield (by volume)	Kuwait	Arabian Light	Libyan Brega	North Sea
Motor gasoline and naphthas	27	24	33	27–38
Middle distillate	30	34	35	33–46
Fuel oil	41	39	28	23–33
Other	2	3	4	3– 5
Sulphur (by weight)	2·5	1·7	0·2	0·2– 0·4

Table 82. Recent analyses of North Sea Oils

Oilfield	AUK	Piper	Forties	Ekofisk
Developer	Shell/ Esso	Occidental	B.P.	Phillips
Reference source	1 & 2	2	1, 2, 3	3
Physical characteristics				
Specific gravity 15°/4°C	0·837	0·849	0·833	0·847
Gravity °API	37·5	35·2	37·35	35·6
Viscosity cs at 50 °C	3·65	3·55	3·7	4·25
Pour point °C	− 1	− 9	− 1	− 5
Maximum wax content % wt	7	4	9	6·5
Sulphur % wt	0·4	0·92	0·29	0·18
Composition of distilled fractions				
Fraction 5–100 °C % wt	9·5	8·4	7·9	7·0
Alkanes	–	85	70	75
Naphthenes	–	12·5	26	19
Aromatics	–	2·5	4	6
Fraction 100–160 °C % wt	10·6	17·6	11·7	11·1
Alkanes	50	50	44	47
Naphthenes	37·5	33	39	35
Aromatics	12·5	17	17	18
Fraction 160–250 °C % wt	16·6	11·9	12·5	15·1
Alkanes	–	35	–	–
Naphthenes	–	40	–	–
Aromatics	18	25	21	17–19
Fraction 250–350 °C % wt				
Alkanes	18·8	17·9	21·9	19
Naphthenes	–	–	–	–
Aromatics	–	–	–	21
Residue from distillation (BP > 360 °C) % wt	43·8	42	43·3	46·5

References:

1. Petroleum and Petrochemical International.
2. Petroleum International.
3. Oil and Gas Journal.

(By courtesy of British Petroleum Ltd.)

These values (mg dm^{-3}) are drawn from 48 hour or longer toxicity tests. Weathered crude oil displays almost no toxicity.

100% mortality of herring larvae in $2^1/_2$ to $3^1/_2$ days when in water containing 1 000 to 20 000 mg dm^{-3} crude oil.

100% mortality of cod eggs in water containing 10 000 mg dm^{-3} crude oil; the soluble oil was 10 mg dm^{-3}.

The effects of soluble crude oil fractions on cod eggs has been derived from data using Iranian crude oil in Kühnhold, 1974. In the assessments these values have been attributed to all gadoid species.

Oil added per dm^3 sea water (ml)	Soluble (3 days) mg dm^{-3}	Relative survival to hatching %	Distorted larvae %	Viable larvae per 100 eggs
10	2·25	33	97	1
1	0·41	67	52	34
0·1	0·03	75	45	41
0	0	100	20	80

APPENDIX C. DIMENSIONS

North Sea area $0{\cdot}575 \times 10^6$ km^2
North Sea, north of 55°30' N $0{\cdot}225 \times 10^6$ km^2
North Sea, north of 55°30' N mean depth 100 m
1 nautical mile = 1·853 km
1 n mile square = $3{\cdot}43 \times 10^6 m^2$

APPENDIX D. DATA ON NORTH SEA OIL AND SPILL PROBABILITIES

Crude oil weighs approximately 0·8t m^{-3}.
General characteristics of some crude oils (see Table 81).
Recent analyses of North Sea oils (see Table 82).
Rate of spread of oil as in Figure 118 which is redrawn and recalculated in metric units from MIT, 1973.
Rate of drift of oil slick 20 km day^{-1}.

Probability of oil spills in northern North Sea in 1980; onwards

M	400 000	100 000	10 000	1 000	50	2·5
I	0·02	0·04	0·2	1	10	100

M = magnitude in metric tons.
I = annual frequency of occurrence.

These probabilities are based on MIT, 1973 and are broadly in line with unpublished UK figures.