Oil in the Beaufort and Mediterranean Seas

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ABSTRACT. Spillage of oil into the Beaufort Sea in the course of exploration and exploitation of offshore resources may occur at an estimated rate of 20 milligrams per square metre per year, or about one-fifth the rate of spillage into the Mediterranean Sea. Overall rates of degradation and dispersion of spilled oil under the conditions prevailing in the Beaufort Sea are however likely to be significantly slower than under the conditions in the Mediterranean. The various input, degradation and dispersion rates may be interrelated in the form of a simple algebraic equation. From current estimates of these rates it is suggested that standing concentrations of oil in the Beaufort Sea could in time become comparable to those in the Mediterranean.

RÉSUMÉ. *Le pétrole dans les mers de Beaufort et Méditerranée.* Le déversement du pétrole dans la mer de Beaufort au cours de l'exploration et de l'exploitation des ressources situées à une certaine distance des côtes peut se produire à un débit estimé à 20 milligrammes par mètre carré par an, c'est-à-dire à un débit d'environ un cinquième de celui de la Méditerranée. Cependant, étant donné les conditions qui règnent dans la mer de Beaufort, il est probable que l'ensemble des vitesses de dégradation et de dispersion du pétrole déversé est nettement plus lent que dans la Méditerranée où ces conditions sont différentes. Les diverses vitesses des quantités déversées, de dégradation et de dispersion peuvent être reliées entre elles sous la forme d'une simple équation algébrique. Des estimations courantes de ces vitesses on déduit que les concentrations actuelles du pétrole dans la mer de Beaufort pourraient, avec le temps, devenir comparables à celles de la Méditerranée.

РЕЗЮМЕ. *Нефтяные пятна в море Бофорта и Средиземном море.* Скорость образования нефтяных пятен в море Бофорта при исследовании и разработке месторождений нефти в открытом море оценивается в 20 мг/м^2 в год, что приблизительно в пять раз меньше скорости в Средиземном море. В условиях, преобладающих в море Бофорта, общий процесс деградации и дисперсии нефтяных пятен идет значительно медленнее, чем в условиях Средиземного моря. Скорости образования нефтяных пятен, их дисперсия и деградация нефти могут быть описаны простым алгебраическим уравнением. На основе текущих оценок этих скоростей делается предположение о том, что стационарные концентрации нефти в море Бофорта могут со временем стать сравнимыми с концентрациямн нефти в Средиземном море.

INTRODUCTION

The Beaufort and Mediterranean Seas conjure up very different images — the one of cold and ice and the other of warm, sunny beaches. They share, however, the common problem of oil. The Mediterranean has suffered considerable stress from oil and other industrial, municipal and domestic discharges. It is now generally accepted that it has passed the level of "acceptability" and is "polluted". The extent of the problem has been revealed by Ritchie-Calder (1972). In contrast to the Mediterranean with its 4,000 years of use and abuse, the Beaufort Sea is in a relatively pristine state. The increasing need for oil and gas from Canada's

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frontier regions, however, raises the possibility of its contamination by oil. Perhaps there is a lesson to be learned from the Mediterranean, not only in the matter of avoiding environmental abuse, but possibly in providing a quantitative model or full-scale experiment against which the Beaufort Sea can be compared. From a study of the Mediterranean, it may be possible to deduce the extent to which the Beaufort Sea can be environmentally stressed without it, too, becoming unacceptably polluted.

In the present essay, a comparison is made between present oil-pollution in the Mediterranean and possible future oil-pollution in the Beaufort Sea, with some speculation on the relative assimilative capacities for oil of the two seas. Mathematically the exercise amounts to the formulation of a simple model of conditions in these two seas in which a number of parameters are compared.

In discussing the effects of oil on the marine environment of the Canadian Arctic, no attempt is made to answer any questions; rather the questions are asked and a mechanism indicated for obtaining some answers. This essay is written to increase awareness of the environmental impact of oil discharges in the Arctic marine environment in the hope that that environment, and thus the lives of whose who depend on it, will not be unduly disrupted.

OIL RESERVES AND SPILLS

It is first necessary to speculate about quantities of oil which may be produced and spilled. By the late nineteen-eighties, Canada could be in the position of supplying only half its domestic oil requirements. Balance-of-payments considerations and Middle East political uncertainties may dictate that Canada exploit its frontier oil reserves more rapidly than it has to date. The most promising sedimentary basins are those of the Mackenzie Delta — Beaufort Sea area and of the Canadian Arctic Archipelago. Notable in this effort is the drilling programme of Dome Petroleum Ltd. in the Beaufort Sea, initiated in the summer of 1976. For present purposes, it may be assumed that, by the late nineteen-eighties, production of oil in the Beaufort Sea region could reach 300-500 thousand barrels (48-80 thousand m^3 approx.) per day. It is furthermore possible that production of oil will have commenced in the Arctic Archipelago, where there have been significant finds on Cameron Island (76°30′N, 104°W).

It may be assumed that in the course of the exploration for and production of this oil a fraction of the total volume handled will be spilled. This fraction may be greater in the hostile Arctic environment than in temperate regions, since working conditions in the North are difficult, ice may invade offshore activities, clean-up measures may be less effective, long periods of cold and darkness will reduce the effectiveness of counter-measures and a higher proportion of human effort must be devoted to mere survival.

Various analyses of oil-spill statistics have been compiled, one of the best being that provided in a report by the Council on Environmental Quality (C.E.Q. 1974). In it, assumptions are made of volumes of oil produced, and from them calculations are made of the quantities which will be spilled: if the Beaufort Sea produces about two billion ($2x10^9$) barrels of oil over a period of twelve years, or nearly

500 thousand barrels per day (a "large find"), then there will be about ten major marine spills of average volume 37,000 barrels and a large number of small insignificant spills; the total amount of oil spilled in the marine environment will be about 0.02% of the amount of oil recovered, or 200 barrels out of every million. This is about the same total spillage rate as that which occurs during production and transportation of oil in temperate areas of Canada, and it can thus be regarded as a rather conservative estimate. A recent review of spills in the Gulf of Mexico (Danenberger 1976) cites a somewhat lower spillage rate, but this is to be expected in that less hazardous environment. Intuitively one would expect higher spillage rates in the North where adverse working conditions are more conducive to human error, the principal cause of spills. The most useful basis of assessment of the marine impact of this oil is the spillage rate per unit area per year. This raises the problem of deciding on the appropriate area for the Beaufort Sea. For present purposes, an area of about 200,000 square kilometres may be considered, consisting of the seas extending over the continental shelf, about 200 km north, and 700 km from the Canadian-Alaskan border to Banks Island and Cape Parry (70°N, 125°W). This amounts to about one-tenth the area of the Mediterranean Sea. In relation to this area, the spillage rate is about 20 milligrams per square metre per year, which is about one-fifth the value calculated for the Mediterranean (108 mg per m^2 per year), and about equal to the North Atlantic value of 17.5 mg per m^2 per year quoted in a recent review (N.R.C. 1975).

OIL DEGRADATION AND DISPERSION

Oil spilled in the sea is subject to a number of conversion processes, and is ultimately dispersed and degraded. Some spilled oil may be recovered, but with present technological resources it is doubtful if the proportion would be substantial, except under the most favourable conditions, (Logan *et al.* 1975). To its credit, Dome Petroleum through its subsidiary Canmar (Canadian Marine Drilling Ltd.) is undertaking some of the necessary research. A five-year $7 million Arctic Marine Oilspill Program has recently been announced by Environment Canada which has the objective of developing capabilities for countermeasures. Presumably, the toxicity or environmental impact of the oil can be related to the standing concentration of oil in the marine environment, which in turn is controlled by the rate of oil input and degradation. These processes are exceedingly complex, and much will have to be done before it will be possible to predict their rates and formulate a reliable model. However, it is interesting to attack the problem using a very simplified model.

Of the spilled oil, possibly one-third becomes tar floating on the sea surface, where it is thought to have a residence time of about one year (N.R.C. 1975). This belief is supported by the fact that tar is found at a concentration (mg per m^2) of about one-third to one-fifth that of the spillage rate (mg per m^2 per year) in most marine environments. The remaining two-thirds of the oil evaporates, dissolves or emulsifies and is subject to biodegradation, chemical conversion and sedimentation or is removed from the region by currents.

The relationships may be expressed in the steady-state equation

$$\tfrac{2}{3}\frac{I}{D} + \frac{C_I}{\tau} = C(K_E + K_B + K_C + K_S + \frac{1}{\tau})$$

where I is the spilled oil input rate (mg per m^2 per year), C_I the oil concentration in the inflowing water (mg per m^3), C the standing oil concentration in the surface waters (mg per m^3), K_E, K_B, K_C and K_S the first-order rates of evaporation, biodegradation, chemical conversion and sedimentation respectively (all per year), τ (years) the average residence time for surface water in the sea, representing the rate of flushing or exchange with other water bodies (mainly by current), and D (m) the depth of the surface waters.

The equation may be rearranged to provide an expression for C, which is proportional to the input rate, inversely proportional to the rates of the degradation processes, and influenced by the sea's flow-through or residence-time characteristics.

$$C = \frac{\left(\tfrac{2}{3}\frac{I}{D} + \frac{C_I}{\tau}\right)}{\left(K_E + K_B + K_C + K_S + \frac{1}{\tau}\right)}$$

Each rate constant can be examined in turn. Although it is impossible to assign absolute values, one can speculate about the ratio of the Mediterranean to Beaufort Sea values.

The biodegradation rate K_B is a function of temperature, the nature of the decomposing microorganisms and the availability of oxygen and nutrients. Some oil biodegradation data were obtained by Bunch and Harland (1976) as a function of temperature, as part of a study of the Beaufort Sea using indigenous flora. The results show the significantly slower degradation rate at 0°C when compared to the rates from 20°C to 30°C, the corresponding K_B values being approximately 0.05 and 0.3 per day. It is impossible to assign an accurate value to the ratio of the rates of biodegradation in the Beaufort and Mediterranean Seas, since there are, or may be, differences in the organisms, in temperature, in nutrient and oxygen contents; however, it would not be surprising if the degradation rate constant K_B proved to be a factor of five to ten higher in the Mediterranean. Clearly more information is needed on the rate of this fundamental process.

A similar analysis can be applied to the evaporation-rate constant K_E which must be lower since low temperatures result in low vapour pressures and thus low volatilization rates. In addition, the presence of ice cover will prevent evaporation for much of the year. A factor of about five seems reasonable.

A similar argument can be applied to chemical or photochemical conversion in which the rate at low temperatures is probably at least a factor of three lower than that at the high temperatures which occur in the Mediterranean Sea.

Sedimentation, on the other hand, may be faster in the North (by an unknown amount) because of the large amount of sediment carried into the Beaufort Sea by the Mackenzie River. Although this serves to deplete the hydrocarbon content of the water column, it merely moves the problem into another area and possibly could have severe effects on benthic organisms. The studies by Vandermeulen and Gordon (1976) at Chedabucto Bay, Nova Scotia clearly show that the most persistent oil-contamination problem is that associated with the incorporation of oil into sediments where degradation is very slow.

Wong *et al.* (1976) and Macdonald (1976) have established that the baseline levels of certain hydrocarbons in the Beaufort Sea are very low when compared to those for other areas — the environment is essentially uncontaminated. C_i can therefore be taken to be zero, at least at present.

The final factor is the residence time τ of surface water. Calculation of this quantity is complicated by the fact that the present study is concerned with surface waters and not necessarily the deep sea. MacNeill and Garrett (1976) have measured wind-dependent surface currents in the Beaufort Sea and concluded that "considerable further study would be necessary to derive a more complete and coherent picture of the various time scales of surface water movement". The Mediterranean, being more landlocked, has a longer water-residence time — possibly 80 years. Fortunately, there is a greater flow of water through the Beaufort Sea. This is obviously one of the variables which mitigates the impact of oil, and which must be quantified if a reliable model of the system is to be developed.

It is easy to criticize the simple model presented in this paper. None of the rates is likely to be truly first-order. Oil is a complex mixture of compounds, each with its own rate constants and synergisms. Toxicity is not necessarily related directly to oil concentration, since some components are much more toxic than others. No account is taken of sulphur, nitrogen, metal compounds or metabolites. Species are affected differently, may be more vulnerable at immature stages or at certain seasons, may migrate from the contaminated area, and may be affected through the food chain rather than directly by oil. Many years have still to elapse before it will be possible to construct a reasonable physical or biological model of the impact of oil on a well-studied marine ecosystem, let alone the poorly-understood Beaufort Sea. The present alternative to the model is therefore no model at all.

In summary, it appears that the rate of input of oil into the Beaufort Sea will be less by about a factor of five than that into the Mediterranean, but the rates of the degradation processes will also be slower by about the same factor. It can thus be argued that the degree of oil contamination of the Beaufort Sea, as quantified by the standing oil concentration, could be about equivalent to that of the Mediterranean at present.

It seems likely that the effect of the residence time will be to reduce the level of contamination in the Beaufort Sea. This mitigating effect is probably a dominating factor in other areas such as the Gulf of Mexico, but the extent to which it applies in the Beaufort Sea is unknown. It should also be noted that this effect serves merely to move the problem elsewhere — possibly into a more vulnerable region.

THE PRESENT STATE OF THE MEDITERRANEAN

There are three convenient indicators of the state of pollution of a sea: the amounts of floating tar, the hydrocarbon content of the surface waters, and qualitative accounts of the effects of oil.

The amounts of tar found in the Mediterranean have varied with time and location, averaging about 20 mg per m^2 in 1969, but 10 mg per m^2 in 1975 (Morris *et al.* 1975). It thus appears that the incidence of tar in the Beaufort Sea, with its lower oil-input rate, may be 2-4 mg per m^2, or 20% of that in the Mediterranean. The impact of this tar, or its residence time, is unknown. If the residence time of the tar is greater in the Beaufort Sea (and one can postulate reasons for this to be the case), then the tar concentration will be correspondingly higher.

Recent analyses of hydrocarbons in the Mediterranean Sea have been described by Brown *et al.* (1975). In August 1972, samples found more than ten metres below the surface showed values of only a few milligrams per cubic metre, whereas surface samples showed more variation, with values as high as 195 mg per m^3. Values obtained in the Atlantic off Bermuda showed generally less surface concentration. Although there is no oil-concentration threshold which is "unacceptable", the opinion is often expressed that concentrations as low as 50 mg per m^3 are sufficient to cause sublethal toxic effects. This complex issue has been discussed elsewhere (Moore and Dwyer 1974; N.R.C. 1975). The implication is that oil is present in sufficient quantities in some locations in the Mediterranean to exert a measurable or observable effect on the ecosystem. Whether this effect is socially, economically or aesthetically deleterious is often a matter of subjective judgement.

There have been several accounts of the adverse effects of oil on the Mediterranean, with adequate documentation of fouling of fishing nets and beaches, effect on the taste of fish and shellfish, adverse effects on tourism, and reduction in species diversity (Ritchie-Calder 1972; G.F.C.M. 1972a, 1972b). Clearly, the Mediterranean is an excellent and convenient example of an unacceptably polluted sea which can serve as a yardstick in determining the stress to which other bodies of water, such as the Beaufort Sea, may be subjected.

CONCLUSION

This essay raises rather than answers questions. In no sense does it present a future scenario of the Beaufort Sea, since the values assigned to the rate constants are speculative. It does, however, suggest the most critical quantities which must be estimated in any attempt to predict the impact of oil on the Beaufort Sea — or indeed on any Arctic marine environment (see equation given above).

(i) Fundamental to the assessment is an estimate of the likely oil-emission rate I. Although massive spills may attract more publicity, chronic low-level emissions which may have profound lasting effects on ecosystems may be as significant.

(ii) More information is needed on the rate of the degradation and the dispersion processes — particularly biodegradation and evaporation (K_B and K_E).

(iii) The residence time τ can only be estimated on the basis of a much better understanding of surface currents and their temporal variation.

(iv) Regardless of present ability (or inability) to predict the effect of the oil, there is a strong case for extra effort to reduce the input rate I, both by the prevention of spills and by developing clean-up technology to recover and destroy a significant fraction of the spilled oil.

(v) With an understanding of these rate processes, it may be possible to predict water-column oil concentrations, or at least make semi-quantitative statements about the magnitude of this concentration relative to those encountered in other seas, such as the Mediterranean, the Gulf of Mexico or the North Atlantic. Perhaps some deductions can then be made about the probable impact of this oil on the ecosystem of the Beaufort Sea, recognizing the very significant differences between Arctic and temperate marine ecosystems. Perhaps the Mediterranean is useful as a specimen of an undesirably overstressed ecosystem against which the Beaufort Sea can be compared. If this analysis has any validity, a situation is faced in which there is little room for complacency. Although the oil inputs to the Beaufort Sea are likely to be relatively small, there are compelling arguments which lead to the conclusion that the degradation rates may also be correspondingly low. The relative vulnerabilities of marine species are in doubt. There is a possibility that the ecological effect of oil on the Beaufort Sea may be comparable to that which has been suffered by the Mediterranean. It is surely fitting that Arctic oil should be exploited with as full an understanding as possible of its behaviour and of its effects in that environment, so that the errors made in the Mediterranean can as far as possible be avoided. Interestingly, setting up a model is not a new idea. Over four hundred years ago, Leonardo da Vinci wrote with characteristic foresight: "Thus you made a model of the Mediterranean Sea" (Ritchie-Calder 1972). He had a good excuse for not adding "and compare it with a model of the Beaufort Sea". We have no such excuse.

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