# The effects of crude oil pollution on marine organisms

## A literature review in the South African context: Conclusions and recommendations

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Review prepared under the auspices of the Oil Pollution Committee of the South African National Committee for Oceanographic Research (SANCOR)

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## PREFACE

Some three years ago it was suggested to the Oil Pollution subcommittee of the Committee for Marine Pollution of the CSIR that, before further research was initiated in South Africa on the biological effects of crude oil pollution in the sea, a review should be undertaken of the international literature relevant to the South African situation. This was agreed to by the Department of Transport, the Department charged with combating oil pollution, and was financed by them. It was expected that the work involved would take about a year. In the event, however, the literature proved to be so voluminous that at times the project nearly foundered and three years were required for its completion. The final result has been an extensive card-index catalogue, which includes summaries of papers, detailed reviews in manuscripts of certain aspects of the subject and several hundred pages of rough notes. What is published here is essentially a summary, divided into major conclusions reached from the literature and recommendations to appropriate bodies and individuals based on those conclusions. In selecting some one hundred references from the twelve thousand available, the aim has been to choose what might be described as the essential reading for a South African scientist wishing to become acquainted with those effects of marine oil pollution which might apply to the South African environment.

## ACKNOWLEDGEMENTS

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## ABSTRACT

This review of international literature on the biological effects of crude oil pollution in the sea relevant to the South African situation is based on some one hundred selected references (from the twelve thousand available). The final result is essentially a summary, divided into major conclusions reached from the literature and recommendations to appropriate bodies and individuals based on these conclusions.

## OPSOMMING

Hierdie literatuuroorsig is saamgestel uit 'n uitgekose honderd verwysings (van die twaalfduisend beskikbaar) van internasionale literatuur wat handel oor die biologiese effekte van ru-oliebesoedeling in die see wat op die Suid-Afrikaanse situasie van toepassing is. Die finale produk is hoofsaaklik 'n opsomming, ingedeel in belangrike gevolgtrekkings wat uit die verwysings gemaak is sowel as aanbevelings aan toepaslike liggame en individue, gebaseer op hierdie gevolgtrekkings.

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# CONCLUSIONS

## 1. Extent of the world literature

The total number of publications on the effects of crude oil and fractions of crude oil on marine and estuarine organisms, communities and ecosystems is in excess of 12 000. This figure includes books, research papers and reviews, in all languages, but excludes popular articles and unpublished reports, which appear to be very numerous. While a few worth-while publications exist from before 1968 (see Nelson-Smith 1968), the literature really begins with the wreck of the **Torrey Canyon,** since when its growth has been roughly exponential. The rate at which new papers are being published shows no sign of declining and indeed a new journal devoted to this type of pollution has recently appeared (Oil & Petrochemical Pollution, established 1982). There have been numerous alleged reviews of the literature but none is satisfactory. This is partly because most are in English and show a marked bias in favour of papers written in English. This is particularly true of the American literature, where even the most important foreign-language papers tend to be ignored. The relatively poor quality of reviews is also partly due to the fashion in this field of using reviews as a vehicle for presenting the authors' own research results in considerable detail, a biased "review" providing a setting for them.

## 2. Value of the literature: field studies

There is possibly no other field of modern scientific research in which so many valueless or almost valueless papers have been published. About a third of the papers simply report numbers of animals killed or washed ashore following oil spills; the avifauna in particular has been the subject of such treatment. All these papers may be summarised in a single sentence: crude oil pollution kills marine organisms. Longer, ecological dissertations mostly suffer from a failure of the authors to characterise the oil concerned and its history following the spill, and the absence of rigorous long-term follow-up investigations. Exceptions, such as the work of Sanders *et al* (1980) on an oil spill in Massachusetts, are rare and extremely valuable. It is implied in Sanders' paper that virtually all previous ecological studies on oil spills are of little merit and in many cases positively misleading, a view with which, regrettably, it is necessary to agree.

## 3. Value of the literature: laboratory studies

The situation with regard to experimental studies in the laboratory is at least as bad and tends to be even more misleading as many papers reveal cardinal errors only after detailed study. Many workers report the effects of "nominal concentrations" of petroleum fractions, fractions which are usually unspecified. Some workers have even failed to maintain control organisms or have used tests in which unmonitored oil concentrations decreased in an unknown way with time. Many laboratory studies have employed concentrations of "soluble" oil fractions which are unrealistically high and on the whole there has been little discrimination between water-soluble fractions, water-accomodated fractions and oil-in-water dispersions, so that the results gained are in general not reproducible and cannot be related to field conditions. Again there have been a few notable recent exceptions, such as some of the work of Neff & Anderson (1981), Bayne *et al* (1982) and Patin (1982). The analysis of results and the planning of experiments in order to fit the most powerful and reliable statistical techniques has also left a great deal to be desired. In particular, toxicological studies involving the use of probit analysis, which would overcome many of the difficulties and inconsistencies otherwise encountered, are virtually non-existent in the literature.

## 4. Selection of the literature

In addition to those results which may be classified as faulty or invalid, or which have no relevance in that they cannot be related back to conditions in the field, we can, from the South African viewpoint, ignore a further section of the literature which has little application to conditions in our region. These include accounts of oil spills in the Arctic or toxicity experiments conducted at 4°C, as has been common in Europe and Canada. We are left with perhaps a thousand publications which are worthy of detailed study in the South African context.

## 5. Toxicity studies

Turning first to the literature dealing with laboratory studies on the toxicity of dissolved and emulsified crude oils, results may be summarised in a single figure (see Fig 1). Although only apparently reliable results have been used in the construction of this figure, it should be stressed that techniques, temperatures, length of exposure and other factors (including analysis of results) varied between different sets of data, as did the source of the crude oil used in the preparation of the fractions. If a standard method, a single crude oil and one set of conditions had been employed, there is no doubt that the apparent range of toxicity would have been much reduced. As matters stand, the lower threshold values must be treated with much more respect than the higher values. The difficulty of measuring accurately concentrations of hydrocarbons below $10^{-1}$ ppm should, however, be noted.

## 6. Toxicity thresholds

Concentrations of dissolved oil fractions below $10^{-3}$ ppm have not been shown to have any adverse effects on any marine organism either in the short or long term, at any stage of development or at a cellular or sub-cellular level. However, between $10^{-3}$ and $10^{-2}$ ppm, some adult animals show sub-lethal behavioural and physiological disturbances, while developmental stages may show retarded growth or an increased number of abnormalities. Patin (1982, Appendix 1) has extracted from the literature a large number of threshold values for a number of marine organisms. In general, the developmental stages of a species are far more susceptible than are the adults, frequently by one or two orders of magnitude; this is indeed true of all forms of pollution (see Brown 1976).

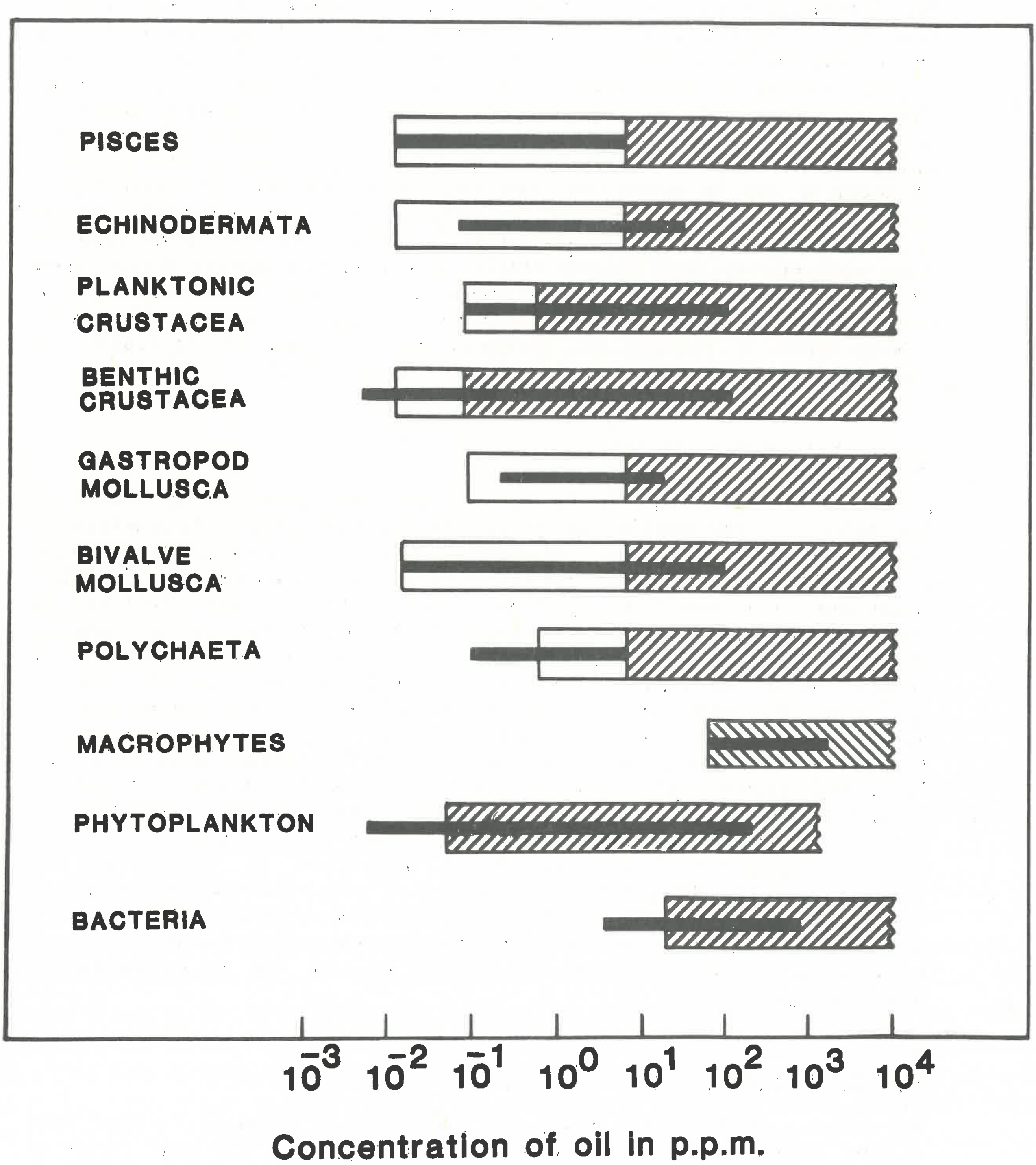


FIGURE 1

Range of toxic concentrations (rectangles) and threshold concentrations (solid bars) of dissolved and emulsified crude oils for some groups of marine organisms. The non-hatched sections are regions of toxic concentration for developmental stages.

## 7. Phylogenetic considerations

The differences between different groups of animals are probably less than those indicated in Fig 1. Certainly different species differ in their susceptibilities to a far greater extent than do different phyla, classes or even orders. Neff & Anderson (1981) also conclude that sensitivity to oil is unrelated either to phylogenetic position or to habitat. The phytoplankton, also, shows a range of sensitivity which is not statistically different from that of the animal groups, although it may be noted that low concentrations may, at least for a while, enhance growth either by making nutrients available or by stimulating metabolic processes (Patin 1982). This is also true of some macrophytes (see Hilmer 1981). However, the marked differences in tolerance shown between macrophytes and some bacteria, on one hand, and phytoplankton and animals on the other, are certainly real; indeed quite a variety of bacteria may increase dramatically in numbers following an oil spill (Vacelet *et al* 1981).

## 8. Sub-lethal effects of oil

At a sub-lethal level, it is safe to say that there is no aspect of the behaviour and physiology of marine organisms which is unaffected by hydrocarbon pollution. Frequently the first sign of disturbance in animals is reduced feeding activity (Widdows *et al* 1982), sometimes as a result of impaired chemoreception (Atema 1976) or, in the case of filter-feeders, through inhibition of the cilia (Johnson 1977). Such ciliary impairment may be due to the inhibition of membrane-bound enzymes (Stekoll *et al* 1980). Absorption efficiencies may also be markedly depressed at quite low concentrations of hydrocarbons (0,03 ppm) (Widdows *et al* 1982). Correlated with decreased absorption are histopathological abnormalities such as increased vacuolisation of the digestive cells (Stainken 1978) or accumulations of lipid and of lysosomal residual bodies (Wolfe *et al* 1981). There may also be a loss of synchrony between digestive tubules (Lowe *et al* 1981) and/or a reduction in height of the digestive cells (Bayne *et al* 1982). A simultaneous reduction in lysosomal stability has been recorded (Widdows *et al* 1982). These and related phenomena are frequently reversible when the pollution is removed but in any case put the animal at risk and at an energetic disadvantage.

## 9. Effects on respiration

The effects of dissolved crude oil fractions on respiration have been widely studied. At low concentrations (0,01 to 0,1 ppm) rates of oxygen uptake may be decreased but appear to be more frequently increased (Hargrave & Newcombe 1973, Gilfillan & Vandermeulen 1978, Widdows *et al* 1982). This increase is probably due to an uncoupling of oxidative phosphorylation (Stainken 1978). At higher concentrations oxygen consumption is usually reduced (Sabourin & Tullis 1981, Brown 1982). Often this decrease is due in part to avoidance behaviour, such as retraction into the shell in gastropod molluscs or valve closure in bivalves. However, changes in the behaviour of the animal do not account fully for changes in the rate of oxygen uptake and there can be no doubt that hydrocarbons have a direct effect on the functioning of the respiratory enzymes (Stekoll *et al* 1980).

## 10. Other effects

Other physiological and behavioural effects resulting from crude oil pollution which have been investigated include changes in heart rate (Sabourin & Tullis 1981), increased opercular rates (Thomas & Rice 1975) and increased reflex coughing rates in fish (Rice *et al* 1977). Weakened attachment to the substrate is frequently encountered, often at very low concentrations (Linden 1977), and may be highly significant in resulting in the death of animals in the field. Locomotory rates are commonly affected, decreased swimming or crawling being commonly recorded at low concentrations, increased activity at higher levels (Hargrave & Newcombe 1973, Linden 1977).

## 11. Energetics and growth

The effects of hydrocarbons noted above result in general in less energy being available for growth or reproduction, or both, than would otherwise be the case (Bayne *et al* 1982). In fact, reduced growth rate due to low-concentration, chronic hydrocarbon pollution has been noted in a wide variety of animals, including juvenile clams (Keck *et al* 1978), shrimps (Edwards 1978), crabs (Cucci & Epifanio 1979) and fish (Kuhnhold 1972), as well as other organisms (Hyland 1976). Gilfillan *et al* (1977) and Gilfillan & Vandermeulen (1978) have demonstrated a reduction in carbon flux and tissue growth in the clam *Mya* following oil spills, while Bayne & Worral (1980) have shown a close correlation between scope for growth and measured tissue growth in the mussel *Mytilus*. Assessment of the adenylate energy charge correlated well with the physiological measurement of scope for growth and provides a direct indication of the energy available to the cells.

## 12. Developmental stages

The literature on the effects of crude oil on gametes, embryonic and developmental stages and larvae is as vast as that on adult and juvenile animals. Apart from the ubiquitous mortality studies, observations have been made on the viability of gametes, percentage fertilisation, rates of development, the types and percentages of abnormalities that occur and the success in passing through various developmental stages (Allan 1971, Byrne & Calder 1977, Caldwell *et al* 1977, Christiansen & Stormer 1978, Katz 1973, Linden 1978, Smith & Cameron 1979, Wells & Sprague 1976). Forty-eight hour $LC_{50}$ values as low as 0,04 ppm (of crankcase motor oil) have been reported for bivalve embryos (Byrne & Calder 1977), while 0,1 or 0,2 ppm retards growth and increases the incidence of abnormalities (Lucas & Roux 1975, Byrne & Calder 1977). Similar concentrations retard the growth of some crustacean embryos and larvae (Linden 1976, Caldwell *et al* 1977). Different oils and different species vary considerably in this regard, larvae of the crab *Hyas* being allegedly tolerant up to about 3 ppm of the soluble fraction of Ekofisk crude (Christiansen & Stormer 1978). Dissolved fractions of No 2 fuel oil led to reduced sperm motility, interfered with fertilisation and cleavage, retarded larval development and depressed respiration in the sand dollar *Melitta* at concentrations of 0,6 ppm (Nicol *et al* 1977), although Kuwait crude was far less toxic. Katz (1973), Cucci & Epifanio (1979) and Neff & Anderson (1981) have all reported delayed moulting in crab larvae surviving exposure to crude oil. Changes in moulting rate may, in fact, constitute a sensitive indication of pollution stress in decapod Crustacea (Epifanio 1971).

Although in general embryos and larvae are more sensitive to pollution than are the adults of the same species, this does not mean that tolerance necessarily increases with each successive stage in the life history. Indeed a few cases are known in which crustacean post-larvae are more tolerant than the adults. For example the adults of the mysid *Mysidopsis almyra* have a 96-hour $LC_{50}$ to No 2 fuel oil water-soluble fraction of only 0,65 ppm, yet their post-larvae have a 96-hour value of 1,75 ppm (Neff & Anderson 1981). There is frequently, perhaps usually, a critical stage in the development of an animal which is more sensitive than other stages (including the adult). Gastrulation in both fishes and invertebrates is commonly such a critical stage, being more sensitive than either the early cleavage stages or the later stages (Kuhnhold 1974, Lonning & Hagstrom 1975, Neff & Anderson 1981). However, in some species fertilisation is the most critical stage and in some Crustacea the first moult.

## 13. Diseases

A number of authors have considered various diseases in relation to oil pollution and particularly the incidence of malignant conditions. The work of Lowe & Moore (1978), linking bivalve neoplasia to oil pollution appeared at the time to be conclusive, yet in fact the possible relationship remains perplexing (Sindermann 1979). There have been numerous reports of the involvement of oil in malignancies in other animals also, including fish and various invertebrate groups (Sullivan 1974, Yevich & Barszcz 1977, Stich *et al* 1977, see also BNCOR 1980), while Kinae *et al* (1980a, b) report studies which indicate a relationship between sediment hydrocarbons, tissue hydrocarbons and the incidence of skin melanomas in fish. Cytolytic effects of oil have also been reported (Mackie *et al* 1975). Other alleged pathological effects of crude oil pollution include, in fish, fin erosion, fin ray deformation, ovarian histopathology, olfactory lesions, degeneration of the ventricular myocardium and cytogenetic abnormalities, while in invertebrate animals gill and gut epithelial necrosis and kidney tubule occlusion have been reported (Sindermann 1982). In general, however, evidence for the occurrence of disease as a result of oil pollution remains circumstantial and the results obtained could in nearly all cases be explained on the grounds that oil pollution lowers the resistance to disease. This is certainly the case in fin erosion in fish, the disease being actually caused by a bacterium (Giles *et al* 1978). A primary response to pollution often includes the formation of lesions in epithelial and sub-mucosal tissues (Gardner 1978), making it easier for parasites and pathogens to enter the animal. Furthermore, some constituents of oil, such as 3-methylcholanthrene, are strong immunosuppressive agents, which could seriously lower resistance to disease (BNCOR 1980). There is no evidence of any risk to man through consuming oil-contaminated seafood or coming into contact with oil-polluted seawater (Royal Commission 1981), although some risk may be incurred by those engaged in physically cleaning the shore following a large spill.

## 14. Inherited resistance

In some cases at least, exposure of adults to low concentrations of dissolved crude oils leads to increased resistance of adults in the $F_1$ generation. However, resistance does not necessarily increase in successive generations, nor does the increased resistance apply to larvae or juveniles (Neff & Anderson 1981).

## 15. Toxicity and solubility

In evaluating the biological consequences of oil pollution, it must be recognised that the soluble components, although usually constituting only a small percentage of the whole, are by far the most toxic (Mazmanidi & Kovaleva 1972, Patin 1982). It is often said that the toxicity of oils, measured in terms of concentration, is inversely proportional to their solubility in seawater (Currier 1951). However, such generalisations are dangerous, particularly in view of the large number of types of compound present in oil and the statement is best forgotten.

## 16. Effects of hydrocarbons on lipids

Many of the biochemical, physiological and behavioural changes associated with exposure to dissolved fractions of crude oil may be explained as reactions at the cellular level to changes in membrane permeability (Sanders *et al* 1980). Interference with membrane function is associated with the fact that hydrocarbons accumulate selectively in lipids, and may alter lipid structure. This fact is also germain to the study of embryos and larvae, as the hydrocarbons tend to accumulate in the lipid component of the yolk, interfering with subsequent lipid mobilisation and metabolism after hatching (Smith 1957). This may partly explain the observed instances of increased sensitivity in fish after hatching (Neff & Anderson 1981).

## 17. Hydrocarbon accumulation in tissues

In general, marine organisms exposed to petroleum hydrocarbons accumulate these substances rapidly but gradually release them again once the pollution has been removed (Anderson 1975, Palmork & Solbakken 1979). The higher the lipid content the greater the accumulation of hydrocarbons. However, up to 90% of the accumulated material may be released within two weeks in unpolluted seawater (Stegeman & Teal 1973, Fossato & Canzonier 1976). Rates of release vary considerably from species to species and with different conditions. There is evidence that a slower rate of release may occur after ingestion of hydrocarbons as compared with uptake directly from seawater (Corner *et al* 1976). In the fish *Fundulus similis*, the concentration of naphthalenes reached a maximum after exposure of about an hour; the highest concentrations were found in the brain and gall bladder and these organs released the pollutant much more slowly than other tissues when the fish were transferred to clean seawater (Neff *et al* 1976).

18. Mixed function oxygenases

Microsomal mixed function oxygenases, capable of transforming aromatic hydrocarbons into more water-soluble metabolites, are wide-spread in both vertebrates and invertebrates (Palmork & Solbakken 1979, Walters *et al* 1979, Stegeman 1979). They may also occur in some algae (Cerniglia *et al* 1979). However, their presence in Mollusca appears to be uncertain (Payne & May 1979). A number of workers have shown that the mixed-function oxygenases are actually induced by exposure to oil (see Neff & Anderson 1981); such induction may clearly be of paramount importance in the development of resistance to oils by marine organisms. However, it seems that mixed function oxygenase activity alone is not sufficient to clear the tissues of accumulated hydrocarbons within the life-span of the individual (Burns 1976) and the subject thus remains controversial.

19. Toxic hydrocarbon metabolites

The possibility of some marine animals retaining small amounts of hydrocarbon metabolites over long periods indicates that measuring contamination solely in terms of the parent hydrocarbons could be misleading. In addition, it is problematic whether water-soluble metabolites released from marine organisms into the sea are easily biodegraded or whether they may accumulate and eventually give rise to an environmental hazard (BNCOR 1980). The nature of this possible hazard is compounded by the fact that such hydrocarbon metabolites are frequently more toxic than the parent compound (Neff & Anderson 1981). However, it is felt in some quarters that this fear has been exaggerated and may be groundless (Royal Commission 1981).

20. Relating experiments to field conditions

Observations of lethal concentrations and sub-lethal stresses in the laboratory are of purely academic interest unless they can be related with confidence to what actually happens in the field. However, attempts to relate the experimental data to field conditions are very rare indeed and those that have, in fact, been made serve to stress the extreme difficulty of doing so. This dificulty is compounded by the fact that our knowledge of the behaviour of crude oil at sea, including weathering, is poor (BNCOR 1980, Royal Commission 1981). Low molecular weight hydrocarbons disperse and evaporate so rapidly after an oil spill that it has been doubted whether the concentrations needed to produce statistically significant effects in the laboratory, at least with many species, are to be found in the vicinity of an oil slick (Neff & Anderson 1981). It should also be noted that the hydrocarbon composition of an oil-in-water dispersion resembles that of the parent oil, whereas that of the water-soluble fraction does not. Because aromatic hydrocarbons are more soluble in water than are alkanes of similar molecular weight, they will tend to be enriched in the water-soluble fraction as compared with the alkanes (McAuliffe 1966). However, the water-soluble fraction is never saturated with hydrocarbons, because the oil-water partition coefficients of hydrocarbons favour their retention in the oil (Rossi & Neff 1978). Thus the way in which the mixture is prepared and maintained in the laboratory is critical. There is also considerable variation in conditions at sea but the two sets of circumstances, in the laboratory and in the field, have never been matched. Added to this difficulty is the fact that the different physical properties of different oils cause them to behave differently.

21. Validity of laboratory experiments

A further major difficulty in matching laboratory studies with what happens in the field focuses on the conditions under which the animals are kept in the laboratory. Early experiments (pre-1970) undoubtedly placed the animals under greater stress than they would experience in the sea. However, recent work has become so sophisticated that the captive animals, through the absence of predation, competition, changes in temperature, wave action, etc, and the presence of an abundance of food, may be at a distinct advantage (Bayne *et al* 1982). Results gained from such studies will inevitably be biased one way or the other and to an unknown degree. A related problem is that some effects of low oil concentrations may pass unnoticed in the laboratory yet prove lethal in the field; for example, tens of thousands of sea urchins *(Parechinus angulosus)* washed ashore and died after the wreck of the **Oriental Pioneer** because their attachment to the substratum is weakened at such low concentrations of oil that no symptoms are apparent in stagnant water in the laboratory (Brown, unpubl.).

22. Effects of direct contact with crude

Compared with the voluminous literature on the effects of dissolved oil and oil-in-water dispersions on marine animals, there is relatively little work on the effects of direct contact with the crude, despite the fact that following an oil spill, more organisms are almost certainly killed by being blanketed with oil than are killed by the water-soluble fraction alone. An exception in this regard is the avifauna, where the effects are well known (see Erasmus *et al* 1980). As far as invertebrates are concerned, experiments in the laboratory as well as observations in the field show that direct contact with the crude, even in very small amounts, may quickly cause death from purely physical (as opposed to chemical) reasons, notably the clogging of delicate mechanisms involved in feeding and/or respiration, or in flotation. Some animals which are relatively tolerant of the dissolved fraction cannot tolerate direct contact with the slick, even when this has weathered to a considerable extent (Brown *et al* 1974). Algae, and particularly filamentous algae, are highly susceptible to being smothered with oil (Baker 1982), although populations recover rapidly by vegetative reproduction and growth of any unharmed fragments or spores. Salt marsh plants show a very wide range of susceptibilities, ranging from death to partial destruction to stimulated growth (Baker 1979, 1982).

23. The criterion of reproductive potential

In the attempt to relate laboratory experiments to field observations, and also with respect to assessing damage and predicting damage, a single criterion is essential. There appears to be no question that the most appropriate criterion is change to the reproductive potential of the population under consideration (Bayne *et al* 1982). Death of adults, retardation of larval growth, reduction in feeding rate or of assimilation, physiological stress which channels energy away from reproduction, etc, will all reduce reproductive potential; and this will inevitably result in a decline of the population. It may, in fact, be stated that if an observed response to pollution has no effect on reproductive potential then it has no ecological significance (Brown 1984). If this criterion is accepted then there is much to be said for studying directly the effects of oil on various aspects of reproduction and a number of workers have done just that. Linden (1976) showed that exposure to 0,3 to 0,4 ppm of the soluble fraction of Venezuelan crude decreased the fecundity of female *Gammarus* as well as the frequency with which the amphipods entered the precopulatory condition. Female estuarine copepods exposed to 3 ppm soluble fraction for 80 minutes displayed, in addition to a reduced life span, reduced fecundity, a decrease in the mean brood size and a decrease in the rate of egg production (Ott *et al* 1978). In the Mollusca, also, a number of direct and indirect effects of oil on reproductive capacity have been reported (Bayne *et al* 1982), and this is also the case with fishes (Struhsaker 1977, Neff & Anderson 1981).

## 24. Adaptive responses and genetic variability

An error commonly made in the literature is to assume that any response observed in the laboratory or in the field is of necessity harmful. On the contrary, some responses are not a measure of damage at all but may be regarded as adaptive responses to environmental change, although it is often very difficult to distinguish between them (Clark 1982). Related to this concept is the evidence that genetic variability, with the local selection of successful genotypes, is an adaptation to an unpredictably variable environment (Grassle & Grassle 1978). However, in most cases it is not yet possible to evaluate the importance of genetic variability in relation to survival under polluted conditions (Clark 1982).

## 25. Enclosed water column studies

Midway between controlled laboratory testing and uncontrolled field measurements following a spill, are the enclosed water columns known as CEPEX (Controlled Environmental Pollution Experiment) and MERL (Marine Experimental Research Laboratory). The former enclose water columns, together with their natural communities, in the sea itself, while the MERL systems are housed in tanks on land. The advantages of these are that they are multispeciate, enclosing natural communities under conditions which are as natural as possible. The MERL system in particular has been used to investigate hydrocarbon pollution (Elmgren & Frithsen 1980). While such systems may have added appreciably to our knowledge of the changes that occur in marine ecosystems, the results gained from studies of oil pollution are extremely difficult to interpret, not least because it is impossible even to attempt to match the complex physical properties of oil in seawater resulting from a genuine spill (Mironov 1972). Research using such mesocosms has been the subject of a recent volume (Grice & Reeve 1982). A great disadvantage of such systems is the expense involved in their construction, installation and maintenance;

indeed already established CEPEX systems in some parts of the world have been abandoned due to their excessive running cost. Such experimental systems should not be set up in South Africa. Related work on a much smaller scale, and very much cheaper to run, involves experimentation on sand columns in the laboratory, so as to study the effects of pollution on the meiofaunal communities of sandy substrata (see McLachlan *et al* 1981). Results from such columns in the presence of hydrocarbon pollution do not yet appear to have been evaluated.

26. Field monitoring

While laboratory experiments and toxicity tests form an essential part of pollution research, they can never be a substitute for monitoring changes in the field. However, to draw conclusions from such changes may be extremely difficult because of natural variability and other problems (McIntyre & Pearse 1980), so that in practice attempts at impact assessment all too often follow the circular and valueless arguments illustrated by Lewis (1980). A very large proportion of the literature is concerned with the mortality of particular species of plants and animals at the time of the pollution. However, comparatively little attention has been paid to the population dynamics of such affected species or to their initial standing stock, both of which need to be known in order to put the observed mortality into perspective (Cushing 1979). Even if it were possible to estimate actual mortality following a spill, this would not relate directly to pollution impact, as such impact ultimately depends not on mortality but on the numbers and fate of the survivors (Clark 1982). In other words, the most important aspect of a spill is not the immediate damage it causes but the length of time taken to restore the ecosystem to a state approaching normality. A change that is restored within a few months must be regarded quite differently from one that persists for many years.

27. Long-term recovery studies

The words "long term" have meant very different things to different investigators. In particular, those undertaking toxicity tests have usually regarded experiments lasting days, weeks or at the most a few months as being long-term. In contrast long-term field studies aimed at assessing recovery following a spill must be measured in years or even decades. Such long-term field studies have been rare. Nevertheless, it may be stated that in temperate waters even massive pollution damage to coastal ecosystems is reversed in about two years (Mann & Clark 1978, Vandermeulen 1982), although subtle changes persist for at least a decade (Sanders *et al* 1980). The timescale may be very different for polar or for tropical regions and for special ecosystems such as coral reefs and some estuaries and salt marshes.

28. Rocky shores

On high-energy rocky shores, a single oil spill is transient and the oil has usually disappeared from most of the shore within one to two years. However, in the supralittoral fringe and splash zone, some oil may persist for from five to ten years. Events follow much the same course, regardless of the type of crude or petroleum product, whether it is fresh or weathered, or whether it has been treated with dispersants (Southward 1982). The slick kills most of the animals but normally fails to eliminate all the algae. These, because of their rapid growth and the absence of herbivores, soon recover and recolonise the shore luxuriantly and to a far greater extent than before the spill. Thus to the uninitiated observer the shore seems to have regained its health with remarkable rapidity. The algae are followed by the return of grazing herbivores, often in larger numbers than before but initially with fewer species. The ecosystem then displays slow fluctuations of different dominant species until equilibrium is restored (Southward & Southward 1978, Glemarec 1981). The length of time required for virtually full recovery depends not only on the rate of recruitment of the longest-lived species but also on how long it takes to disrupt the long-shore uniformity imposed by the pollution (Southward 1982). The rate of recovery of sheltered rocky shores may be slower than that of high-energy shores (Gundlach *et al* 1981), although this is more apparent in cold waters than in temperate or tropical regions.

29. Sandy substrata

The effects of oil are felt least on open, high-energy sandy beaches where there is relatively little macrofauna and no attached plants. In such beaches the meiofauna may be affected to a greater or lesser degree by a spill but is likely to recover within a year (McLachlan & Harty 1981a, Le Moal 1981). It should, however, be noted that the oil not only has a toxic effect on the fauna but may also interfere with the filtration of water through the beach (McLachlan & Harty 1981b). Low energy, sheltered beaches show a much higher initial mortality, with the possible elimination of some species, although a few animals - notably some polychaete worms - may not only survive but actually increase in numbers. The animals of fine subtidal sediments appear to be particularly intolerant of oil, the effects of which on a large number of such species have been well documented (see Southward 1982). In both intertidal sands and subtidal sediments, recolonisation begins with opportunistic species and such a pollution fauna may persist for years under some circumstances (Le Moal 1981). This is particularly true where oil has been trapped in the sediment, for it may then continue to affect the fauna for six years or more (Thomas 1978). As other species invade the area, biomass and species composition undergo a series of fluctuations which decrease in amplitude over a number of years until relative stability is regained (Sanders *et al* 1980, Southward 1982). The largest, most long-lived species are usually the slowest to return. Hydrocarbons can be detected in the tissues of both resistant and recolonising animals five years after the spill (Beslier *et al* 1980, Elmgren *et al* 1980). Little is known about the impact of oil on deeper sediments (below 25 meters), and nothing about recovery. The amount of oil reaching such depths is often negligible, even when it has been chemically dispersed (Chapman 1984), although under some circumstances up to 30% of a slick may be carried to the sea bed following adsorption onto suspended sedimentary particles (Mironov 1972).

30. Estuaries and lagoons

In estuaries and sheltered lagoons, oil persists for much longer than in relatively high-energy environments such as the seashore (Vandermeulen 1982). Wave-action ceases to be a significant factor in such "hydrocarbon sinks" and instead microbial degradation becomes prominent. Different hydrocarbon fractions are affected disproportionately by such degradation and by dissolution, so that the larger polynuclear aromatic hydrocarbons are by far the most persistent. Furthermore, the transformation compounds of these hydrocarbons may assume greater ecological significance. The organisms thus suffer from chronic pollution as a result of the continual re-entry of hydrocarbons but the actual substances change with time as a result of long-term degradative processes (Teal *et al* 1978, Vandermeulen 1982). The overall sequence of events may not be very different from those observed on rocky or sandy shores but the time scale may be extended to decades instead of a few years. Beyond this it is impossible to generalise, particularly about estuaries, because of the very wide range of conditions and biota encountered.

31. Salt marshes

Salt marshes and similar environments are commonly represented as the most extreme form of hydrocarbon sink, and the most vulnerable to oil pollution. This is due to a combination of factors, including the relative lack of water movement, the fineness of the sediment and the peculiar disposition of the biota. Annual salt-marsh plants are affected very severely indeed, while some other plants may, in fact thrive after a spill (Baker 1979, Burns *et al* 1979). Nevertheless there is usually an overall reduction in vegetative cover, sometimes to an extreme degree, and this leads to soil erosion which may eventually cause the destruction of the marsh. The interstitial fauna is decimated by the long-term presence of hydrocarbons; Hampson *et al* (1978) found only 21 individuals of a meiofauna in oiled sediment cores from Winsor Bay, compared with 261 individuals in comparable cores from control sites. The effect on macrofaunal species depends to a large extent, as in other environments, on their habits. Crabs such as *Uca* may be particularly affected, for example, because they moult within their burrows, thus exposing their soft and permeable post-moult integuments directly to the oiled sediment (Krebs *et al* 1977). Indeed Crustacea appear to suffer the heaviest mortality rates of all the macrofauna and are also the last group to return to the contaminated area (Burns 1976).

32. Plankton

Far less work has been attempted on off-shore planktonic communities than on shore organisms. This has partly been due to problems of accessibility but chiefly because oil slicks at sea are almost invariably sprayed with oil dispersants which, themselves being more or less toxic, complicate the interpretation of results. However, there is some evidence from unsprayed slicks and in one case a small spill was deliberately left untreated so that its effects on the plankton could be assessed (Johannson *et al* 1980). Close to the wreck, zooplankton biomass fell drastically in the first days after the spill but within five days there appeared to be full recovery.

In contrast, phytoplankton biomass and productivity rose; this may have been due to curtailment of grazing by zooplankton. Accompanying this rise was a marked increase in bacterial numbers. These transient changes are thought to be fairly typical (Davenport 1982). It is not only bacteria that can benefit from oil spills; planktonic yeast populations usually also increase as they thrive upon paraffinic substrates (Scheda & Bos 1966, Davenport 1982). However, changes in yeast populations are dependent to a considerable extent on the type of oil spilled, for yeasts are inhibited by certain aromatic fractions (Ahearn & Crow 1980). In general, then, changes in planktonic communities at sea are short-lasting, although some of the larger forms, such as *Dentalium* may be more seriously affected (Koster & Van den Biggelaar 1980). We know nothing, however, about the effects of oil on the neuston and this might repay further study.

## 33. Birds

The effects of spilled oil on the marine avifauna have been more thoroughly documented than for any other group of organisms. There is, of course, no question that large-scale mortality of birds occurs from this cause. Nevertheless, the effect on bird populations remains controversial. The Royal Commission on Environmental Pollution (1981), after weighing a considerable body of data and taking into account the views of numerous workers in the field, came to the conclusion that there is no evidence that oil spills have significantly affected populations of seabirds (or indeed other marine species). Not all authorities would agree. In an extremely well-balanced and non-partisan recent review, Dunnet (1982) is more cautious, pointing out that seabirds are long-lived, may not breed until they are several years old, and have a low mean adult mortality rate. Nevertheless, he points out that the numbers of birds killed by oil pollution (in European waters ) is only about a tenth of the natural mortality rate. Furthermore, several species of seabirds have been increasing in numbers for decades, despite oil and other forms of pollution. In the opinion of the present reviewer, mortality due to oil pollution is unlikely to have far-reaching effects on the populations of flying birds while other factors are favourable but may become significant if the populations are at the same time under stress from other circumstances. It may also be noted that penguins may present a special case and are seldom mentioned by reviewers due to their absence in the northern hemisphere.

## 34. Chronic oil pollution

Much less is known about the effects of low-level, chronic oil pollution in the marine environment than about those following single oil spills, although the classic work on the oil port of Milford Haven showed the overall effect of repeated small oil spills to be relatively slight (Nelson-Smith 1972, Baker 1976, Dicks & Hartley 1982). There has been a shift in population balance, however, with algal cover increasing and grazing herbivores decreasing (Nelson-Smith 1979). In general, it seems that the community that persists under conditions of chronic pollution is similar to that found during the recovery stage after a major spill (Southward 1982). Repeated small spills have much the same effect (Dicks &

Hartley 1982). However, chronic conditions present much greater interpretive problems than the aftermath of a severe spill, because the detection of subtle effects has to be made against usually unknown scales of natural changes (Lewis 1982). There is a growing literature on the effects of chronic pollution from off-shore drilling platforms and from natural seepage of oil. These effects are ignored here as being irrelevant to the present South African situation, while pollution from oil refineries, while relevant, falls outside the scope of the review. It may be noted, however, that the chronic pollution of some sheltered lagoons and estuaries due to the use of motorised vessels is a possible cause for concern, resulting not only in the addition of volatile petroleum products to the system but also pollution from certain metals, notably lead.

## 35. Toxicity of dispersants

The toxicity of oil dispersants and emulsifiers is very relevant to the present review in that such products are commonly used on oil spills in South Africa, as in other countries. The literature on dispersant toxicity is less voluminous than that on the toxicity of crude oils, although it is suspected that in this particular field most of the work resides in unpublished, and often confidential, reports. Patin (1982) has summarised a large portion of the published data. However, dispersant toxicities by themselves are of little interest and no practical application, as dispersants should occur in the marine environment only in the presence of spilled oil. The relatively small amount of published literature on the toxicities of oil/dispersant mixtures is difficult to interpret and even more difficult to relate to field conditions. Although dispersant toxicity has decreased markedly since such substances were used on the oil spilled from the **Torrey Canyon** (Beynon & Cowell 1974, Patin 1982), there is still no such thing as a non-toxic dispersant. Some organisms which are very tolerant of oil pollution may be highly susceptible to dispersants (Reish & Foret 1971, Bodin & Le Moal 1982), and thus to oil/dispersant mixtures. In principle every mixture of oil and dispersant is more toxic than is the oil itself (Beynon & Cowell 1974, Norton & Franklin 1980), although in some animals behavioural considerations, related for example to oil-droplet size, may give different results (Chapman, pers comm). Methods of conducting toxicity testing of oil-spill dispersants have been briefly reviewed by Moldan & Chapman (1983), who also outline the modifications deemed necessary to suit the South African situation. Of fundamental, but previously largely neglected, concern is the fact that in general the more effective the dispersant, the more toxic it is to the biota (Lee 1980). On the other hand, the more effective, the less that has to be used under given circumstances. A balance between effectiveness, toxicity and quantity to be sprayed must therefore be struck.

## 36. Synergistic and other effects

The effects of oil and dispersant tend to be markedly synergistic (Beynon & Cowell 1974, Malins & Collier 1981). This is not too surprising in view of the fact that dispersants, like hydrocarbons, tend to act largely on lipids, including the lipids of the cell membrane (Ernst & Arditti 1984). The primary mechanism by which dispersants affect organisms may be the decreased surface tension at the tissue/water interface, accompanied by impairment of osmotic regulation abilities (Patin 1982). Synergistic effects may also be due to enhanced biological accessibility and penetrating power of hydrocarbons in the presence of dispersants (Wilson 1972, Griffith 1972). It has been suggested that other forms of pollution, including heavy metals, should also increase the toxicity of oils (Malins & Collier 1981). No work appears to have been done on this, despite the fact that oils themselves may contain toxic metals. It should also be noted that spraying dispersants on or near the shore not only affects the biota directly but may actually increase the retention of oil by sand and finer sediments (Southward 1982).

37. Unknown effects

The known and recognised effects of oil and oil-dispersant pollution are probably only representative of a much wider range of possible disorders that have occurred but which have not been detected (Vandermeulen 1982). This is mainly due to the inevitably selective nature of pollution studies. However, so many effects are known and well documented that to deliberately seek others may be regarded as of academic interest only.

38. Cleanup procedures

Much has been written about cleaning procedures following oil spills. Initial practices were crude and caused a great deal of additional harm to marine ecosystems. Increasing sophistication led to the famous table of Gundbach & Hayes (1978) and eventually to definitive and simple handbooks, such as that published by CONCAWE (1981). Having read the recent literature, it is satisfying to be able to conclude that the philosophy and procedures of cleaning oil adopted by the South African Department of Transport are thoroughly consistent with those employed in Europe and North America. This may not always be true, however, where local authority takes a hand (see Brown *et al* 1974). It is also true that although general cleaning techniques can be laid down for different marine environments, every situation is different and there is no substitute for expert biological advice, preferably given on site.

39. The overall threat of oil pollution

The key publications of the last five years are undoubtedly the documents prepared by the Royal Commission on Environmental Pollution (1981) and by the Royal Society of London (1982). The Royal Commission's chief conclusion was that oil pollution entails no permanent threat to the marine environment and that complete recovery will eventually take place following even the largest oil spills. Effects may be extremely dramatic but are always relatively short-term and local. It is implied that temporary loss or damage to public amenities may be far more (economically) serious than the biological damage caused to the marine environment. The meeting of the Royal Society (1982) was a direct reaction to these conclusions of the Royal Commission and in some ways their publication presents a more balanced viewpoint, stressing the gaps in our knowledge - for example with respect to the productivity of damaged ecosystems - which should be at least partially filled before such sweeping conclusions can be made with confidence. Nevertheless, none of the experts present at the Royal Society meeting were able to put forward any evidence to challenge the findings of the Royal Commission in principle, and no speaker expressed a clearly contrary view. It may certainly be concluded that, because of the dramatic effects of oil spills on the biota and particularly public concern over such incidents as the oiling of birds, research input into the effects of oil pollution has been far greater than warranted and has been at the expense of vital research on other less visually obvious but more serious pollutants.

40. Priorities

Further conclusions and recommendations reached by the Royal Commission (1981) relate to the prevention of oil spills and in particular the problem of enforcing internationally agreed standards for shipping. The Commission also considered arrangements for dealing with oil spills once they have occurred, concluding that they are in general inadequate and can be greatly improved. These matters are beyond the scope of the present review and the Commission's report should be studied in detail by interested persons, as being the most definitive document of its kind so far published.

41. Extrapolation to the South African environment

It has not been possible for the present reviewer to reach new conclusions of international validity. This is hardly surprising in view of the number of workers in the field and the very large numbers of reviews that have been published. An important conclusion in the South African context, however, is that in general findings from other parts of the world may be extrapolated to the South African situation, providing such extrapolation is undertaken selectively and with caution by a scientist experienced in the field.

## RECOMMENDATIONS

1. Further research in South Africa on the effects of crude oil pollution on individual marine organisms, populations and ecosystems, whether conducted in the laboratory or in the field, should not be given a high priority as compared with research on other, potentially more serious, forms of marine pollution.

2. Where such research is, indeed, financed, it should concentrate either on problems peculiar to South Africa (of which there are few) or on gaps in the international literature. Perhaps the most serious gap is our lack of knowledge of the toxicity of oils to the neuston and in particular to the eggs and larvae of the more important commercial fishes. Studies on the effects of oil pollution on penguin populations might also be extremely relevant. On the other hand, other obvious gaps, such as our comparative ignorance of the mutagenic effects of oil and the dynamics of genotype selection following pollution are almost certainly best left to richer countries with a higher population of pollution scientists.

3. Toxicity studies, if they are to be undertaken at all, should concentrate on sub-lethal effects and specifically responses which will in one way or another reduce reproductive potential.

4. If considered carefully and critically, results obtained and conclusions reached in other parts of the world, and particularly in temperate waters, may be extrapolated to the South African situation. A watchful eye should thus be kept on the international literature, in the knowledge that the cost of doing so is negligible compared with the cost of actually undertaking research.

5. Routine testing of the toxicity of oil/dispersant mixtures should continue where strictly relevant. No testing of dispersants alone should be contemplated.

6. Further research on the most appropriate treatment of oiled birds may be indicated, particularly in response to public demand, although once again developments overseas may well render this unnecessary.

7. Research on the effects of chronic petroleum pollution (as opposed to oil spills) should be supported and in particular research into the chronic pollution of certain enclosed or semi-enclosed bodies of water from petrol engines should continue. This could well influence legislation concerning the use of motor craft for recreational purposes.

8. While clean-up procedures employed in South Africa are consistent with those used elsewhere, it must be stressed that no two sites are identical. Thus while the current procedures are in general very sensible, some modification at a particular site may bring considerable ecological benefit (e.g. the height at which smothered plants are cut). It is thus recommended that, whenever possible, a senior and expert ecologist should be called on to give advice on oil-cleaning procedures, preferably on site. It must be accepted that sometimes the only reason for oil-cleaning will be to restore public amenities; the concern must then be to do as little additional harm as possible to the biota.

9. There is no question that the time and money spent on the oil-spill problem should be directed into non-biological areas, specifically improved legislation aimed at preventing oil spills and tanker accidents, on one hand, and physical considerations aimed at the detection of oil slicks and preventing them reaching the shore, on the other. In South Africa, top priority should be given to the prevention of oil entering estuaries and lagoons.

10. In the opinion of the present reviewer, the most urgent need in southern Africa with regard to marine pollution is contingency planning (and where possible legislation) to combat spills of noxious substances other than crude oil. These substances include refined petroleum products, which are a great deal more damaging than crude, substances derived from crude oils and a variety of unrelated compounds. At the present time it would appear that we have little knowledge of the nature of cargoes shipped around our coasts and no plans for dealing with them should an accident occur.

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