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How can a potential oil pollution affect the recruitment to fish stocks?

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ABSTRACT

Eggs, larvae and the larvae's first search for food are the most critical stages in a fish life, both to threats from natural causes and pollution.

Based on experimental studies of several species of fish eggs, larvae and zooplankton, and their *in situ* abundance, calculations of potential reduction of the affected year class or stock are demonstrated.

The organisms exposed to oil concentrations likely to be found in the marine environment show considerably variation from species to species. While our experiments show little or no impact on herring eggs and larvae, eggs of saith and cod do not tolerate even short term (2-24 hour) exposure to low oil concentrations (50 ppb WSF).

In some areas the majority of the years spawning products are restricted both in time and space, and therefore the potential for reduction in the recruitment of these stocks is considerable. Based on registered distributions of fish eggs and larvae, our calculations show a fairly low percentage of potential reduction using a worst case concept.

Although the statistically calculated risk for an accident resulting in serious oil pollution is very low, real and severe accidents remind us that this may happen every so often regardless of the statistics. It is our hope that the experimental results presented can be used in predicting and assessing the impact of serious oil spills.

INTRODUCTION

Norwegian law requires presentation to the norwegian parliament of an assessment of the possible effects of an oil exploitation and exploration, both environmental and sosio - economical, prior to the opening of a new offshore oil field. The Ministry of Oil and

Energy, responsible for this presentation, have for the benefit of better coordination of the assessments, established an inter departmental advisory group, AKUP, through which funds are made available for research in the various fields of the assessments.

The Institute of Marine Research, IMR, has, as adviser to the Ministry of Fisheries, a responsibility regarding effects in the marine environment and on the fisheries in particular. Environmental impacts are most often expressed as effects on individuals of different species, as this is observed in laboratory experiments or in the field . The difficulties connected with field studies of impacts and the assessment of these, in the marine environment caused by an oil spill are well known. Effects on bird populations and the littoral flora and fauna are fairly well recognized and may, to some extent, be quantified. Effects on organisms in the water masses, plankton, pelagic and demersal fish, are hardly recognized, and a quantification of the anticipated loss in a fish stock or the affected plankton biomasse is even harder to give.

An assessment of potential damages in a population or an area is most often based on speculations and seldom quantified. In our advisory capacity, realistic quantifications of potential damages caused by an oil pollution is seen as a necessity. Through the years, work at our institute (Føyn & Serigstad, 1987 & 1988) have established a way of handling assessments in order to present reliable figures that may combine both the aspects of science and the bureaucratic/political needs as well.

MATERIALS AND METHODS

The basic philosophy in our assessments is to present a *worst case* situation. Thereby knowing that in an actual accident there will not be more damage than what we have already described. Also knowing that the authorities have considered our *worst case* description and may base their regulations on this information, even if this situation statistically is likely not going to happen. Our work is then based on the following:

a) The condition for a conflict between marine resources and an oil spill is that harmful oil concentrations must coincide with a critical resource parameter.

b) Biotests will give values for harmful oil concentrations and define critical organisms (fish, zooplankton) and critical development stages (length/weight/age).

c) Field observations will give data on geographical distribution (horizontal and vertical) and the critical period of time for the critical resource parameter.

d) Simulated oil drift will give data on the distribution (horizontal and vertical) of the harmful concentrations of oil in the water.

e) Calculations of the percentage of coincidence between water with the harmful oil concentrations and water with the critical resource parameter will give the percentage of the reduction in the actual marine resource.

Theoretical background

The transformation of a modelled percentage of coincidence between a watermass containing a harmful oil concentration and a watermass with the defined critical resource parameter, into a possible reduction in recruitment to the actual fish stock

may be verified and calculated based on the following assumptions by Berge *et al.* (1979):
The relationship between the number of recruits N_1 and the number of fish larvae N_0 may be explained by,

(I) $$N_1 = N_0 (1 - p)$$

where p is the percent of larvae at a given time which are removed by natural mortality before recruitment to the fishery. Assuming that at this given time a percent q of the larvae die spontaneously from oil pollution, the number of larvae will immediately be reduced to $N_0 \cdot (1 - q)$ and the number of recruits, N_1^x, will be reduced to

(II) $$N_1^x = N_0(1 - (p+q) + p \cdot q)$$

This expression is only valid if p and q are independent, meaning that the natural mortality of fish larvae are not density dependent. If there is a density dependency, this factor may then reduce the effect of the oil induced mortality on the recruitment correspondingly. However, by applying a *worst case* philosophy in the assessments, Berge *et al.* (1979) concluded that p and q had to be regarded as independent factors.
The natural mortality between the early life stages and the recruit is scarcely known for most of our fish species. Calculations by Dragesund and Nakken (1971 & 1973) on the natural mortality of herring larvae during the first weeks after hatching showed a variability between 70 and 95 percent from year to year. Other species, like cod, are anticipated to have an early natural mortality of up to 99 percent.

Even if the natural mortality is considerable, and the natural variations will dominate the recruitment to the various fish stocks, Berge *et al.* (1979) found it verifiable to calculate the damage caused by an oil pollution as an extra reduction in the recruitment, and by combing (I) and (II),

$$\frac{N_1 - N_1^x}{N_1} = q$$

it is shown that a spontaneous larvae damage, from an oil spill, is equal to a recruit reduction in percent of the total recruits.

Basis for the experimental work

During the last decades a lot of work has been done to clarify the problem of possible effects from crude oil and oil products on fish development. A short review of the part of the research dealing with metabolism and oxygen transport is given by Serigstad (1986). No effects of oil exposure are found on the ion transport or osmo-regulation in cod eggs/larvae after long term oil exposure to concentrations from 50-280 ppb WSF (water soluble fraction) of Statfjord Crude Oil (Mangor-Jensen, 1986). Anatomical

studies on the same larvae, using scanning- and transmission- electron microscopy was also negative according to oil effects (Adoff, 1986). No difference was found in protein content or ammonia content of cod eggs or larvae, and no clear effect was found on the free amino acid content (Fyhn *et al.* 1986, Fyhn & Serigstad, 1987). The only clear negative oil effect found on cod, were reduced oxygen uptake of the yolk sac larvae (Serigstad, 1986; 1987a; Serigstad & Adoff, 1985). The oxygen uptake and thus the metabolic activity of a fish larvae depends on a sufficient oxygen supply from the ambient sea water to the mitochondria in the cells where the aerobic energy production for synthesis, regulatory processes and locomotory activities take place. An impact of oil on the oxygen uptake of yolk sac larvae may therefor have a severe negative effect in the sensitive developmental stage where the larvae are changing from endogenous to exogenous food uptake.

Oil concentrations

Experimental studies have to be as close to reality as possible. Consequently we have to use oil concentrations which are likely to occur in the field during an oil spill. Field experiments (Anon,1984) showed concentrations up to 90 ppb WSF (water soluble fraction) of Statfjord crude oil in 1 m depth 10 hours after the release of the oil. This concentration was reduced to 20 ppb after 170 hours. Børresen *et al.* (1988), quote a typical oil concentration in the wave zone of 100 ppb in 5 m depth under fresh released oil and they refer to measurement of 300 ppb just under fresh oil. By using oil concentrations of as low as 50 ppb in our experiments we are dealing with concentrations that may be found in the field due to an oil spill.

Species tested

Cod (*Gadus morhua* L.) Eggs and sperm were stripped from single male and female fishes to ensure homogeneity of the groups. The cod eggs were incubated as described by Solberg & Tilseth (1986).

Ripe **herring** (*Clupeae harengus*) Single male and female herring were stripped for sperm and eggs. The sperm were mixed with seawater in 30 liters plastic beakers with the bottom covered with object glasses. The eggs were stripped directly in to the beaker, were fertilized and stuck to the glass plates. The eggs were flushed with clean seawater. Live mature herring were transferred to a tank at the IMR.

Ripe **capelin** (*Malotus vilosus*) In principal the procedure for stripping and fertilization was similar to that of herring.

Saith (*Polachius virens*) Eggs and sperm were stripped, and fertilization followed the same procedure as for cod.

Krill and **copepoda** of the three species *Calanus finmarchicus, C.glacialis* and *C.hyperboreus*, all in different stages from nauplii to stage 6, were obtained and tested on a cruise with R/V G.O. Sars in the Barents Sea the summer 1988.

The biotest setup

The oil experiments were performed in the biotest laboratory at the IMR. Parts of the biotest setup was built at the University of Bergen under the project: "Fish larval physiology and anatomy. Basic studies and effects of oil". (Fyhn *et al.* 1987). When

moved to IMR the biotest setup was completed and modified. The setup is a multi-aquarium system with precise temperature control and dosed inputs of water soluble pollutants. The system has been built for long term effect studies on marine organisms. The biotest system holds the potential for effect studies of almost any water soluble toxicant on marine organisms within a size rang of 0,1 mg to 1 kg. All fluid flow and oil extraction occur under closed conditions in darkness to minimize evaporation and photo-chemical reactions.

The eggs larvae and post larvae of the different species were transferred to the biotest exposure systems for continuous exposure to 50-280 ppb WSF of Statfjord crude oil. The oil analyses is described by Westrheim & Palmork (1986).

Juvenile cod, fish larvae and eggs were all kept in 34 $^{0}/_{oo}$ sea water at 5°C, mature herring were kept at 10°C.

Oxygen uptake measurements

Two different principles (closed and open respirometry) and three different experimental designs were used, to fit the different size of the animals ranging from 450 µg to 600 gram wet weight (Serigstad, 1986; 1987b). All the oxygen measurements were performed using a polarographic oxygen electrode (Radiometer E-5046) connected to a meter (Radiometer PHM 73).

Experiments with oil-based drilling mud

Recruitment to fish species with demersal eggs may, in addition to the consequences of an oil spill situation, be harmed by discharges of oil-based drilling mud under normal operational conditions. Therefore a complete picture of possible recruitment changes, due to oil explorations, necessitate tests on this component as well. For several operational and safety reasons, oil-base drilling fluid are sometimes used in offshore oil drilling. The drilling fluid are recycled, but stones and smaller particles are separated from the fluid and discharged. This material still contains chemicals (oil) from the drill fluid, and may have an impact on benthic marine organisms, or demersal fish eggs. In our experiments we tested fish eggs and larvae for effects from oil-base drilling mud used by Statoil on the Gullfaks-A rig. Chemical analysis of hydrocarbons from the drill mud shows that it mainly contains normal and iso- alkanes (Westrheim pers.com.). Hydrocarbon analysis were performed on seawater contaminated with drilling-mud (1.33 g/l). The cuttings were allowed to settle before the water samples was taken. Analysis showed that the water contained 400 µg hydrocarbons/l. Five percent of the hydrocarbons was BTX-components (benzene, toluene and xylenes), while the remaining 95% was made up of heavier components. In contrast to this hydrocarbon composition, the water used in the oil exposure experiments contains approximately 80% of BTX-components, while only 20% are heavier components.

RESULTS

Cod

Eggs

No effects of oil exposure (50-280 ppb WSF) has been found on the oxygen uptake rate

of the cod eggs after continuously exposure from day 2 after fertilization (7 series); (Serigstad 1986). However, eggs exposed to oil for a short period (24 h) and transferred to clean water showed no recovery after hatching. A typical set of data is given in fig.1.

Larvae

The oxygen uptake of long term oil exposed larvae is affected by oil exposure (fig. 1). The exposure started between day 2 and 7 for the 7 different groups. The oxygen uptake is markedly suppressed compared to the controls. The control larvae have a peak value in the oxygen uptake at the time of final yolk absorbtion (this take place at day 6-8 post hatching according to (Fossum, 1986). A slight increase but no peak value is observ in the oxygen consumption of the oil exposed cod larvae, during the yolk sac stage. The oi effect on the oxygen uptake is independent of oil concentrations in the range 50-280 ppb of the WSF of Statfjord crude oil (fig. 1.).

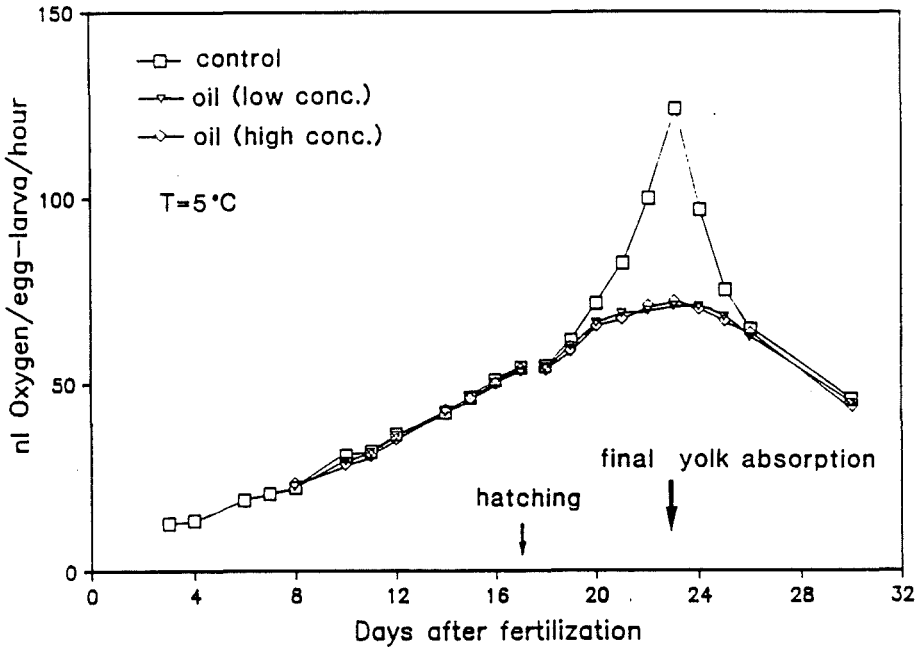

FIGURE 1.

Oxygen uptake of control and oil exposed cod eggs/larvae. Oil exposure at low concentration: 50±20 ppb WSF and high concentration: 230± 110 ppb WSF). Each point represent the mean of 4 parallels with 10 eggs or 5 larvae each. (SD is less then 5% for all the means).

T = 5°C, Salinity = 34o/oo.

In short term exposure experiments, control larvae of cod were transferred to oil contaminated water (50±20 ppb WSF), on the first day after hatching and on day 4 and 6 post hatching. Measurements on long term oil exposed larvae(230±110 ppb WSF) and control larvae were included in the test. The results show that the oxygen uptake of the short term oil exposed larvae is suppressed to the same extent as that of the long term oil exposed larvae.

Already within 24 hours of exposure to oil (50 ppb WSF), the oxygen uptake of the

exposed larvae is strongly reduced compared to the control larvae. No further reduction occurred over the next days in oil contaminated seawater.

In recovery experiments oil exposed cod larvae (exposed to 230±110 ppb WSF for 10 days before hatching) were transferred from the oil water to control water in the biotest setup at the first day after hatching and at day 4 and 6 post hatching. Daily measurements of the oxygen uptake were performed under control conditions. No signs of recovery of the oil exposed cod larvae were found. Apparently even 6 days in clean seawater is not enough to remove the suppressive effect of the oil exposure on the oxygen uptake of the cod larvae.

Post larvae

The oxygen uptake of growing larvae raised under semi-natural conditions in Hyltropollen, Austevoll (Folkvord *et al.* 1985) has been measured both under control conditions and after oil exposure. Measurements have been done on larvae with a body wet weight ranging from 6 - 1350 mg. A 30 mm long larvae has a body wet weight of about 270 mg. The post larvae were oil exposed from 3 to 6 days in the biotest system, to an oil concentration of 50±20 ppb WSF (Serigstad, 1987a). No difference in the oxygen uptake was found between control and oil exposed larvae (fig. 2). The critical size of the cod larvae is found to be 20 mm, meaning that cod larvae bigger than 20 mm were not effected by our used oil concentrations.

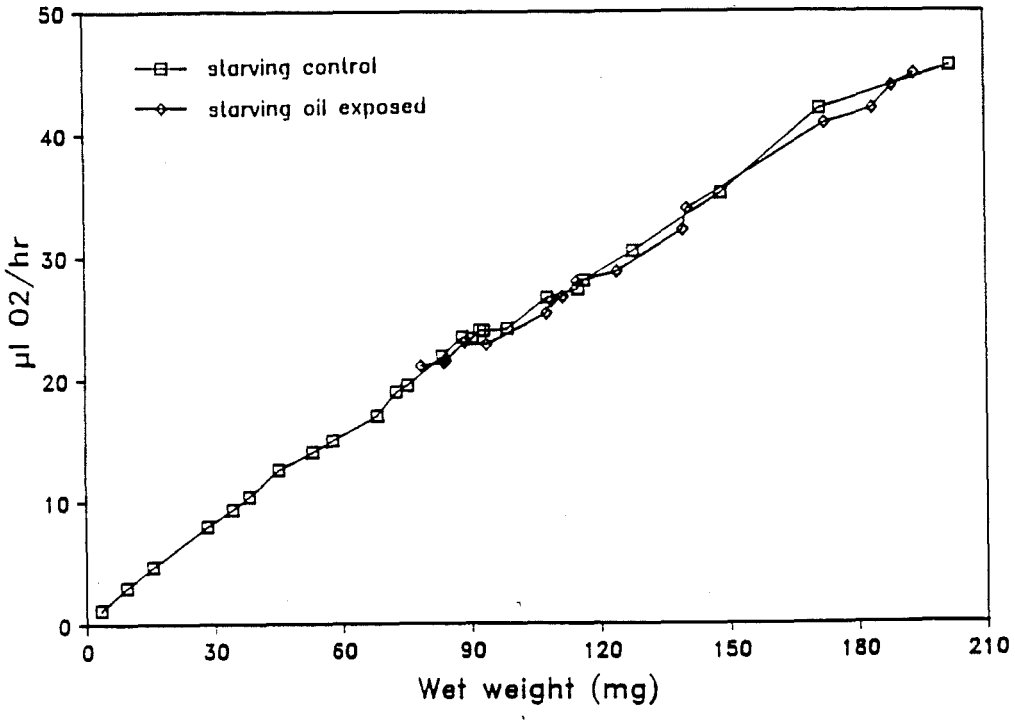

FIGURE 2.

Oxygen uptake of control and oil exposed (50±20 ppb WSF) post-larvae of cod as function of body wet weight. The larvae were not fed during the last 3 days before measurements (6 days for some oil exposed larvae). Each point represent an individual larva. T = 5°C, Salinity = 34 o/oo.

O-group cod.

There were no significant difference in the oxygen uptake of O-group cod exposed to Statfjord crude oil extract (100 ppb WSF for one week), (Serigstad & Ellingsen, 1987). The fish ranged in weight from 24-63 gram.

Experiments with juvenile cod (body weight of about 0.5 kg) showed that upon an abrupt exposure to oil contaminated sea water (100 ppb WSF) they react immediately with a pulse of increased oxygen uptake, followed by a stabilized level below the average oxygen uptake before oil exposure took place (fig. 3).

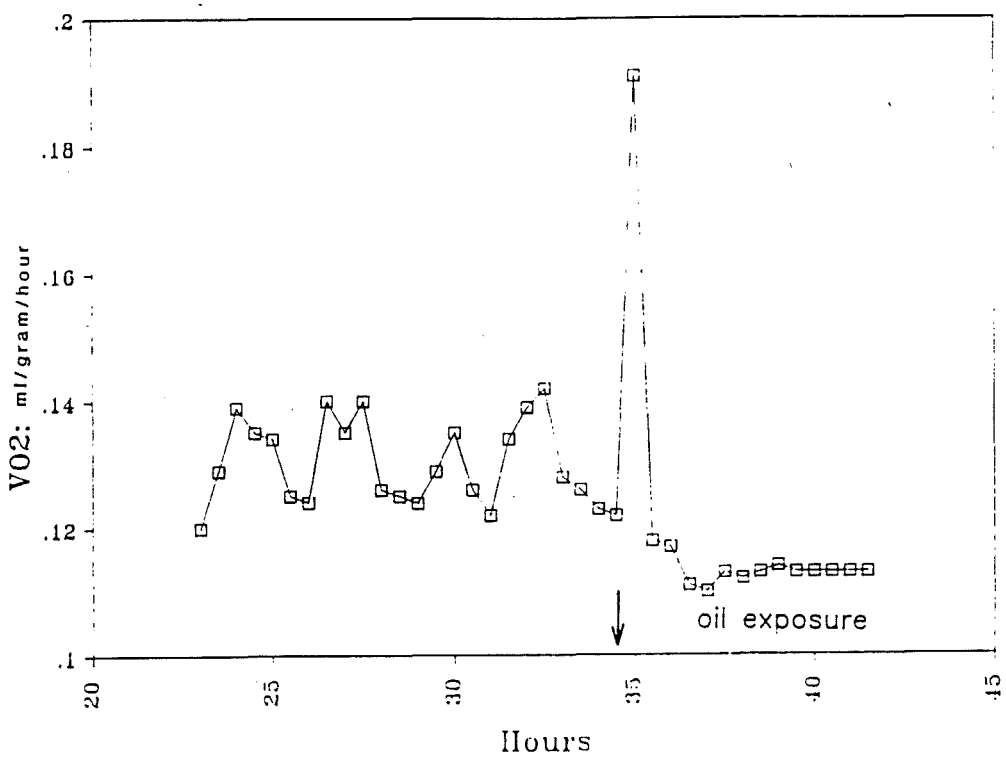

FIGURE 3.

Oxygen uptake of juvenile cod (0.5 kg) before and after oil contaminated sea water (100 ppb WSF) was introduced in to the respirometer system at 34.5 hours of incubation. T = 10°C, Salinity = 34 o/oo.

Herring

Oil

We did not find any significant effects of oil exposure (> 200 ppb WSF) on the oxygen uptake of herring eggs and larvae. Four different series are tested, three series in 1987 and one in 1988. All the different series show a similar shape of the oxygen consumption curve, but there are great deviations in the consumption rate, probably due to differences in the egg and larval size of the different series.

The difference in weight between two egg/larvae series is reflected in difference in the

oxygen uptake. The weight specific oxygen uptake is about the same for a large and a small herring larvae at the yolk sac stage. There is an increase in the oxygen uptake from fertilization until about 1 week post hatching. After this time the yolk sac is almost depleted, and the oxygen consumption rate levels off. In our experiments with no feeding the oxygen consumption starts to decrease due to insufficient food supply.

Oil-base drilling
The oxygen consumption is increasing from fertilization until approximately one week post hatching, then the yolk sack is absorbed and the oxygen consumption decreases due to insufficient food supply in our experiments as reflected in both the exposed larvae and controls. There is no significant difference in oxygen uptake between controls and drilling mud exposed herring eggs/larvae.

Capelin
Oil
The capelin eggs showed a steady increase in their oxygen uptake from fertilization until hatching. The hatching took place over a period of 5 days, from day 27 to day 32. After hatching the oxygen uptake rate leveled off, and it was kept stable for approximately 2 weeks even if the yolk sac was empty after approximately 1 week. After day 45 the oxygen uptake decreases. There is no observed difference in the oxygen uptake between controls and oil exposed (70 ppb WSF) capelin eggs. After hatching there is a significantly reduced oxygen uptake of the oil exposed larvae. The difference is approximately 20% and it is kept at that level for about 2 weeks.

Drilling mud
The hatching success for the drilling mud exposed (1.33 gram/liter) capelin eggs were better than for the control eggs. In the control group there were approximately 80% hatching while the drilling mud exposed eggs had a hatching success of approximately 90%. The drilling mud covered the bottom of the experiment aquarium in a 1-2 mm tick layer. The eggs were therefor completely covered with mud. In the control aquarium the eggs lied uncovered on the bottom. After hatching the control larvae swam around in the aquarium, while the drilling mud exposed larvae were buried down in the mud, and swam up only when they were disturbed. Similar observations were done with capelin larvae in the biotest setup. The larvae seemed to prefer to stay in the bottom layer with dead eggs and egg shells.

Saith
The oxygen uptake of saith eggs was similar for controls and oil exposed (30 ppb WSF) eggs. After hatching the oxygen uptake of the oil exposed larvae were reduced and the larvae died a few days after hatching. This was found in 3 different experimental series.

Copepodes.
The experiments with copepoda (*C.finm., C.glac., C.hyperb.*) and krill were done with very high oil concentrations 3-5 ppm WSF. We saw reduced oxygen uptake of all the exposed species and stages. The oxygen uptake was reduced by 10 to 30 % for the exposed animals compared to the controls. There were no mortality of the animals even at this very high oil concentrations. The nauplii, however, seems to be much more sensitive to oil, they died in these high oil concentrations. Experiments with *Calanus finmarchicus* stage 6 in the biotest system did not show any effect of oil when kept at 100 ppb WSF for 14 days.

Field observations.
As a consequence of the plans for opening new off-shore oil fields both in the Barents Sea and on the continental shelf off mid- and northern Norway, the Institute of Marine Research have intensified its surveys on fish eggs and larvae in the area. This extended effort is based in a five year and a 40 million NOK program (Føyn, 1983), adopted by the Ministry of Fisheries and proposed on their budget from 1986. The program, HELP, (Havforskningsinstituttets Egg og Larve Program) have, from its first year 1986, contributed considerably to a better understanding of the transport and distribution of fish eggs and larvae along the norwegian coast from the spawning grounds to the nursery area further north.

The typical spawning pattern for the fish stocks spawning in norwegian coastal waters north of 62° N is that the spawning period is fairly short and take place within a few limited areas.

DISCUSSION

In our assessments of a possible effect from an oil pollution on the fish resources we have, through experiments based on measurements of the oxygen uptake, defined critical species and critical stages in the development from egg to recruit in the fish population. The use of oxygen uptake is to our purpose a well suitable method in that the method is sensitive to the metabolic activity and fairly simple to handle.The metabolic activity of a fish larvae depends on sufficient supply of oxygen from the ambient sea water to the mitochondria in the cells, where the aerobic energy production for synthesis, regulatory processes and locomotor activity take place. Oxygen uptake is thus a direct measurement of the aerobic energy production of the fish larvae and a quantitative expression for the rate of consumption of its energy stores. We assume that the normal oxygen uptake of the fish larvae is optimized for its growth and development, and that any deviation from these normal conditions have a serious impact on the survival of the animal. Experiment with oil exposure of cod larvae have shown that the oxygen uptake of oil exposed larvae are depressed compared to the controls (Serigstad 1987a). This effect on the oxygen uptake is seen already after 24 hours exposure to 50±20 ppb WSF of Statfjord crude oil. There is not shown any recovery of the oxygen uptake of oil exposed cod larvae after transfer to clean seawater.

Cod eggs accumulate oil hydrocarbons in the yolk sac rapidly. Some hydrocarbons are concentrated with a factor of about 400 after one hour of exposure to water containing oil hydrocarbons while the discharge rate is much slower (Solbakken *et al.* 1984). Fish eggs exposed to oil hydrocarbons may therefore already bee damaged by oil, even if this is not recorded on the oxygen consumption of the eggs. As our experiments show (Serigstad 1987c, Føyn & Serigstad, 1987), effects will not be detectable as a reduced oxygen uptake until the eggs are hatched, and the larvae starts to swim searching for food.

Experiments with oil exposure (<300 ppb WSF) of **herring** eggs and larvae did not show any effects on the oxygen uptake, neither on the egg stage nor on the yolk sac stage. Four different herring series are tested for effects, and all the series show the same, no

observed negative effects. The difference in oxygen uptake between controls and oil exposed cod larvae observed just after hatching (Serigstad, 1987c) when the larvae still lives on the yolk sac, but has to start exogenous feeding, may be due to differences in activity.

Cod larvae feed mainly on crustacean nauplii, rotiferes and other invertebrate larvae (Fyhn & Serigstad, 1987). Those zooplankton food organisms are swimming and the cod larvae need to do fast attack to catch their prey. Observation of cod larval behavior shows that the larvae have a rapid increase in activity at the developmental stage where we find the difference in oxygen uptake between controls and oil exposed larvae. We assume that the oil exposed cod larvae are unable to increase their oxygen uptake, and thus also the locomotor activity at this important period of development, resulting in non or reduced feeding success and later on, death.

The herring larvae which does not show any reduction in oxygen uptake may have an other feeding pattern than the cod. If it is not feeding on fast swimming organisms, an effect on the ability to take up oxygen, or any kind of metabolic problems could bee masked by low swimming activity in the early life. Even if no effects is shown in our experiments, there may bee a hidden damage that will be discovered when the larval activity increases at a later occasion. Feeding experiments for studying a possible late effect are planned. In fact there is reported an exogenous uptake of free amino acids from sea water by herring eggs/larvae (Siebers & Rosenthal, 1977). No such uptake is found in cod eggs/larvae (Mangor-Jensen, 1986).

There is a large effect of oil exposure on cod larvae. The oxygen uptake is reduced with 40-50% for all the seven experimental series (Serigstad, 1987a), while there is no effects seen on any of the four herring series. Saith eggs and larvae seems to be even more sensitive. Saith larvae exposed to oil concentrations as low as 30 ppb WSF died a few days after hatching. The controls had no mortality at this stage, and the same thing happened in three parallel experimental series. From our experiments we may anticipate that in assessment of pollution damages, cod/saith and herring may serve as the lower and upper limits, respectively, for effect registrations on fish, fig 4. Capelin larvae showed a significant effect of oil exposure. The oxygen uptake is reduced with 20% compared to the control larvae, (Serigstad *et al.* 1988). A reduction which place capelin on our sensitivity scale between cod and herring.

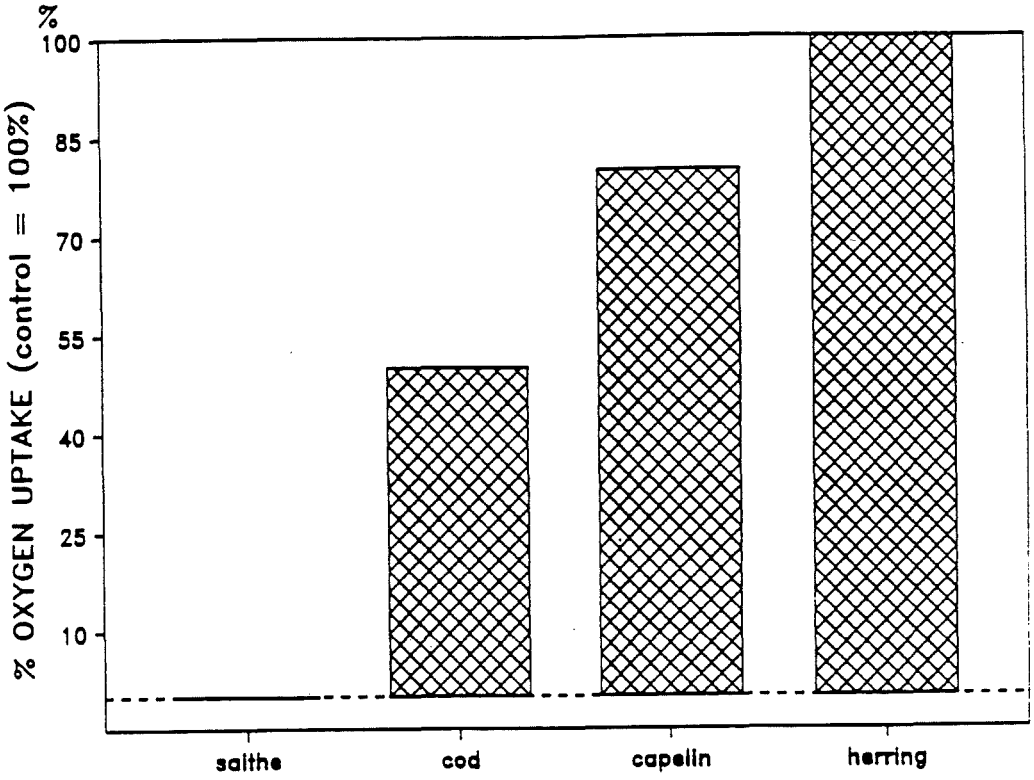

FIGURE 4
The relative sensitivity to oil for saith, cod, capelin and herring, presented as percentage of oxygen uptake under exposure to oil. Control larvae for each specie = 100% oxygen uptake.

Our experiments have identified cod and saith as the most critical species. For the purpose of our assessment, we have chosen cod as the critical species. This choice is based on both the fact that we have more experimental results from cod than saith and, more important, cod is more representative as species in the actual area of concern.

By our experiments we have defined the egg stage and larva <20 mm length to be the critical development stages for cod. The corresponding critical concentrations of oil are found to be 50 ± 20 ppb, WSF. The immediate increased oxygen uptake, fig. 3, of a juvenile cod when exposed to oil contaminated water, allow us to conclude that there is a strong escape reaction in free swimming fish. This may well prevent them from entering watermasses containing oil or any other pollutant with a pronounced "smell/taste", thus reducing the possibility to harm marine species provided they have a certain swimming ability. However, this avoidance reaction may affect recruitment if the spawning area and the watermasses leading to this area are polluted by oil.

The further use of the established critical stages is then to combine this information with observations in the field of the distribution of the critical species and critical stages. Thus the critical area and time may be defined. An assessment of a potential damage from an oil spill, may then be to calculate the percentage of eggs/larvae that may come in contact with the critical concentrations of oil, released from a chosen location and a simulated oil-drift created to give a worst case situation.

Earlier estimates, from our institute, of oil damages have been based in calculations of the overlapping area between a simulated spread of an oil slick and the observed horizontal distribution of fish eggs and larvae. Such calculations did not consider the vertical distribution of eggs and larvae and the oil, nor were the difference in response to oil from species to species and in the various development stages considered. However, these estimates were, at a time, valuable examples of *worst case* situations of potential reductions in a certain fish stock. These examples of calculated reductions of an year class varied from 30 % up to 45% depending on the said fish stock and the area for conflict. For the purpose of making political decisions at the time when norwegian oil exploration was proposed extended northwards from the North Sea, these rough calculations were satisfactory. However, in spite of this anticipated possible losses, oil exploration have been extended northwards.

For a more distinct assessment of defined smaller areas, considered opened for oil exploration, it became obvious that more realistic case calculations had to be done. Thus our effort to expand the research.

The vertical distributions of both eggs and larvae and oil are essential in the calculation of effects on the fish resources. In figure 4, the vertical distribution of cod larvae is constructed for the open sea area, Tromsøflaket, based on visual observations of the surface layer as well as trawl hauls, below and above 18 m depth (Bjørke pers.com.). The vertical distribution of oil on the figure is calculated by using the model for vertical distribution of egg (Westgård, 1988), assuming the oil to be droplets of the same size as fish eggs and having the density of an actual oil. For the purpose of the figure an oil concentration of 300 ppb WSF (Børresen *et al.* 1988) is defined as the surface starting concentration.

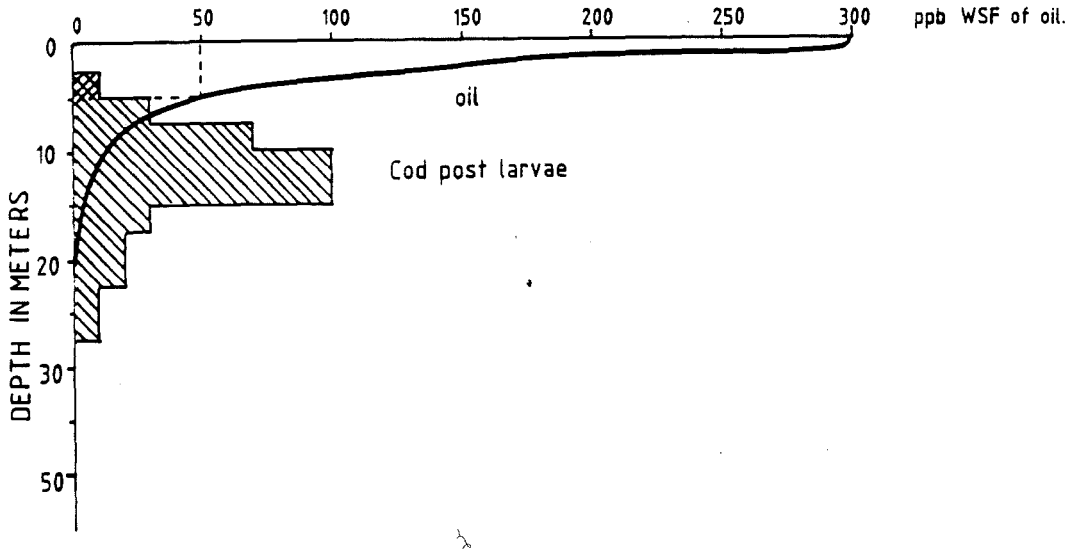

FIGURE 5
The constructed mean vertical distribution of cod post larvae at Tromsøflaket in July, and the calculated vertical concentration profile of the water soluble fraction (WSF) of oil at a wind force of 5 m pr sek.

The validity of our constructed vertical distribution of cod larvae at Tromsøflaket may be justified by the observations by Melle & Skjoldal (1989) of *Calanus finmarchicus*, eggs and nauplii. They concluded that *C.finmarchicus* seems to adjust the spawning

according to the chlorophyll distribution, seeking maximum chlorophyll layers. In july, at Tromsøflaket, the chlorophyll maximum is found at a depth of 20 - 30 m (F. Rey, pers. com.). Cod larvae are feeding on eggs and nauplii of *C.finmarchicus* , and therefor are most likely to be found in the same waterlayers as their food. Melle & Skjoldal (1989), quoting several authors, also conclude that vertical migration of *C. finmarchicus* is of minor importance for the vertical distribution, due to the relatively small variations in light between day and night in summertime.

However, the constructed vertical profile do not have a general validity, as there are observations from other areas differing considerably. Sundby (pers.com.) observed from three Mocness hauls in a fjord in northern Norway a cod larvae abundance much closer to the surface than what is constructed in fig. 5. Observations by Mocness hauls, from an open sea area, Sklinna, of the vertical distributions of herring larvae (Sætre *et al.* ,1988) show a more clearly deeper distribution than the constructed vertical cod larvae profile in figure 6. Although there is likely to be species dependant behavior in the vertical distribution of larvae, the vertical profiles may as well reflect the conditions in the sea, as the same authors observed, in more near shore waters a herring larvae distribution related to the upper 20 meters. Furthermore, Sætre & Bjørke (1988) observed maximum abundance of saith eggs, from an open sea area, at a depth between 60 and 140 m.

The construction of fig. 5 serve both the purpose of establishing means to calculate the vertical coincidence between oil and fishlarvae and to illustrate the fact that oil do not penetrate too far down into the water from an oil slick at the surface. Therefor when using the constructed vertical distribution of cod larvae at Tromsøflaket, figure 5, we may well be within a realistic basis for calculations of damages to cod larvae from an oil spill in these actual waters.

From figure 5 it may be seen that 2,5% of the larvas are found within a water depth containing more than 50 ppb of the WSF of oil. Although, the pry for the larvae is found in the deeper layers our calculations ought to have room for a certain vertical migration of the post larvas. The migration is likely to be age dependant, as the swimming activity of the larvae increases with age. Turbulence may also add to the vertical mixing, and taking consequence of these two vertical mixing processes, and a *worst case* situation, there is reasons to double the percentage, to 5%, of larvae that daily may be contained in water with more than 50 ppb of oil, WSF.

Both the oil distribution and the larval distribution are considered dynamic processes. Calculation of a potential coincidence between critical oil concentrations and the critical larval stages must be based on an anticipated total coverage of the sea area modeled to be within the oil slick.

Figure 6 presents the simulated oil drift pattern for the month of July at Tromsøflaket where post larvae of cod are most abundant in July as the figure expresses. The distribution of cod larvae is for the size < 20 mm, the upper critical size of the larvae for which over experiments show effects from oil. A certain oil spill will only cover a certain amount of the total possibilities for distributions as the figure shows. By choosing an oil slick to cover an area where the abundance of larvae is at the most, we may present, figure 6, a situation describing a *worst case* situation. In figure 6 approximately 25% of the larvas with a size < 20 mm may be covered by the oil slick. Taking the vertical conflict zone, as described above, into considerations, the percentage

of vulnerable cod larvas that will coincide with critical oil concentrations is reduced to between 1% and 2% of the mean total observed cod larvae < 20 mm distribution.

The experiments on cod larvae have demonstrated that there will be no survival for this calculated 1 - 2% of the total larval mass. Following the assumption that a larval damage is equal to a recruit damage, the modeled oil spill at Tromsøflaket will then reduce a mean year class from the years of 1978 - 87, by 1 - 2%.

Further south, on the shelf proposed to be opened for oil exploration outside Troms, the so called Troms II, where there are spawning areas for cod representing from 20 - 40% of the total biomass of the spawning cod (Sundby 1988), the consequences of an oil spill may be one order of magnitude greater than the previous presented for the Tromsøflaket. This 10 - 20 % reduction may be the result provided the oil spill takes place within the short period of time from late March through the first half of April. As the experiments have shown, the effect on cod eggs is very pronounced in that only a short exposure to oil is enough for the eggs to achieve a deleterious effect on the later survival chance. Applying the assumptions connecting larval damage to reduction in recruitment, an oil spill in this area, Troms II, in late March beginning of April, may reduce the recruitment to a said year class of cod by 10 - 20 %.

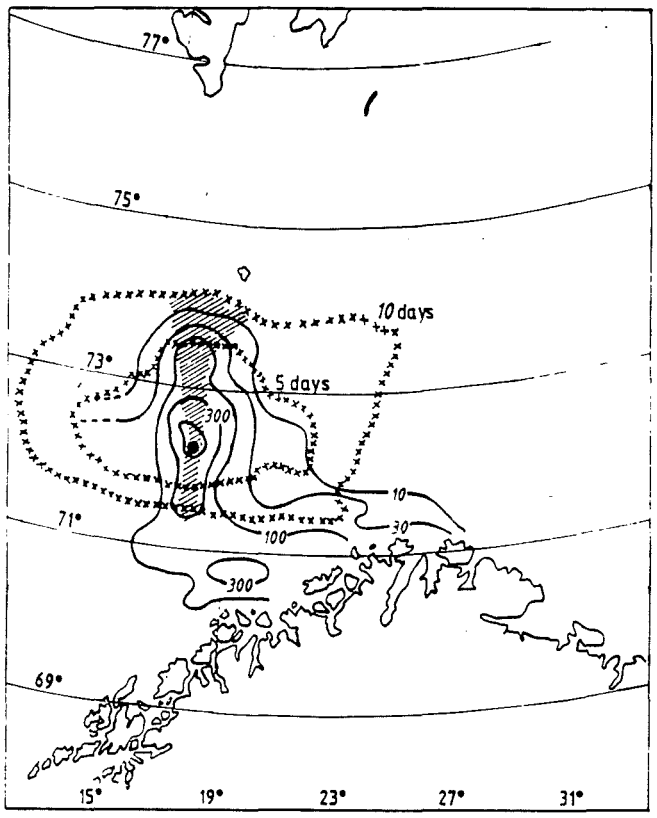

FIGURE 6.
Observed mean distribution of cod larvae < 20 mm (solid line, number per trawl hour), in July. Modelled fastest drift route for an oil slick for the various wind directions in July (crossed line, drift in days). Hatched area marks the maximum probable area of coincidence between an oil slik and the maximum abundance of cod larvae.

Assessments of this kind will always have to be made on some assumptions and with a considerable degree of uncertainty. However, our experiments have shown, by establishing the critical parameters for various marine species and the corresponding critical oil concentration, that it is possible to calculate a potential reduction in the recruitment to fish stocks in a realistic magnitude, provided there exist a good knowledge of the distribution of these critical stages and realistic models for oil drift.

CONCLUSION

Fish stock recruitment may be affected by pollution provided that there is coincidence between the critical stages of the said species and the corresponding critical concentrations of the pollutant.

The recruitment in fish stocks will be reduced with the same percentage as the critical stages are reduced, provided that less density of the critical stages do not benefit the survival-rate in the development from egg to recruit.

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