report **ERMS**

Environmental Risk Management System

Program participants: - Agip - Conoco Phillips - Exxon Mobil - Hydro - Petrobras - Shell - Statoil - Total

AM-2004/024 Open
Date: 08.11.2004

ERMS Report no. 9B

Literature report on burial: derivation of PNEC as component in the MEMW model tool

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Report AM 2004/024

RF - Akvamiljø

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Report AM – 2004/024

Rev. no. 00 / Date: 08.11.04

Project number:	695401
Project title:	ERMS
Project Leader:	
Client(s):	Sintef Kjemi
Research program:	ERMS
ISBN:	
Distribution restriction:	Open

RF - Akvamiljø

Preface

This report is a contribution to the ERMS task addressing burial of organisms as a stressor due to drilling discharges.

The report addresses the potential drilling discharge- and burial process, as well as tolerance-, escape- and toxicity aspects of such a process. This forms the background for a discussion of burial in relation to other Environmental Impact Factor (EIF) sediment parameters and how to define a Predicted No Effect Threshold (PNET) for the burial stressor in the EIF.

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Thanks to contributors:

Key Words:

Drill cuttings, drilling mud, burial of organisms, stressor, toxicity, tolerance, Environmental Impact Factor (EIF), Predicted No Effect Threshold (PNET)

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1 Introduction

Within the ERMS project, an Environmental Impact Factor for drilling discharges will be developed, taking account of both toxic and non-toxic impacts. The non-toxic impacts consider the settlement of particles that cover the sediment surface, resulting in burial of organisms. In addition, the particle size of the upper sediment layer may change when the discharged particles are mixed with the sediment. Furthermore, organic material that reaches the sediment surface, may breakdown by oxidation, which may result in low oxygen concentrations.

In this report, the impact of settling of particles, initially covering the sediment and resulting in burial of benthic organisms, will be described.

A similar approach as used for other disturbance parameters (such as grain size and oxygen) will be used for burial. However, in order to assess how this parameter can best be implemented, an introduction is given presenting relevant aspects of burial and of cuttings discharge and deposition. A decision on what to focus on in the model tool can then be made based on these grounds.

It was proposed earlier to apply Species Sensitivity Distributions (SSDs) based on No Observed Effect 'Concentrations' (NOECs) in which the concentration was replaced by a threshold sedimentation layer (Holthaus *et al*., 2003). However, after discussion it was decided that the factor 'time' should be included, since the discharges of particulate matter is not a batch-wise, but a more constant process during drilling activities. Therefore, the SSDs should further be based on the settlement rate of 'exotic' particulate matter, i.e. material with different characteristics (size, shape, etc.).

1.1 Cuttings and mud discharge and deposition on the seabed

1.1.1 Composition

Drill cuttings particles (crushed rock produced by the grinding action of the drill bit as it penetrates into the earth) range in size from clay-sized (<2 μm) to course gravel (>30 mm) and often have an angular or tabular configuration (Kjeilen et al., 1999). The size of the cuttings particles, their morphology and their tendency to agglomerate is mainly influenced by the drilling mud used (McFarlane and Nguyen, 1991). Their chemistry and mineralogy reflect that of the geologic strata being penetrated by the drill. Cuttings from wells drilled in the North Sea typically are composed primarily of sandstone and shale (Gerrard et al., 1999). Geologic strata composed of Upper Cretaceous chalks also are abundant in the North Sea. Westerlund et al. (2001) identified quartz and barite as the two most abundant minerals in cuttings from the Beryl A and Ekofisk 2/4A platforms. The quartz probably is from the sandstone in the cuttings and the barite is primarily from the drilling mud solids adhering to the cuttings. Pyrite (iron sulfide) also is abundant. Illite and kaolinite are the dominant clay minerals present in North Sea cuttings and may have come, in part, from the drilling mud solids adhering to the cuttings particles. These also are the dominant clays in continental shelf sediments of the North Atlantic (Griffin et al., 1968). Thus, the solid phase of North Sea cuttings consists primarily of particles of clastic rocks (i.e., derived from accumulation of individual grains of biogenic carbonates (chalks and limestones) or weathered source materials (sandstones, mudstones, and shales) (Hartley et al., 2003). Smaller amounts of drilling mud solids, primarily clays and barite, also may be present in the cuttings.

Sediment grain size in cuttings piles varies widely; most piles contain a mixture of particles ranging in size from clay to gravel (Table 1). The silt/clay fraction (<63 µm) usually is the most abundant (Tables 1 and 2). Average particle density ranges from 1.4 to about 3.0 g/cm^3, reflecting the mixture of light and heavy particles.

Table 1. Grain size, water content, and hydrocarbon concentration in cuttings pile samples from 3 locations in the North Sea. Data from Dredging Research Ltd. (2002).

Parameter	Beryl-S1	Ekofisk-S2	Ekofisk-S3
Grain Size (%)			
Gravel	1	7	5
Sand	29	33	8
Silt	54	37	62
Clay	16	23	25
Finer than 425 µm	86–100	86–90	80–100
Particle Density (mg/m^3)	2.8–3.0	2.7–2.8	2.5
Water Content (%)	25–31	49–71	49–50
THC (mg/kg)	15,600	443	26,900

Table 2. Selected physical and chemical characteristics of cuttings piles near Platforms Beryl A and Ekofisk 2/4A in the North Sea. Data from Appendices to Westerlund et al. (2001).

Depth (cm)	Dry Density (g/cm^3)	Silt/Clay (%)	TOC (%)	Ba (mg/kg)	THC (mg/kg)	PAHs (µg/kg)
Beryl						
0-20	1.4	41.2	1.7	455-1667	82,000-84,000	5,400-12,000
30-40	1.5	58.4	---	1219-1380	66,000-130,000	5,500-27,000
40-48	1.5	47.8	2.2	991	150,000	35,000
50-68	1.7	51.9	---	151-235	83,000	25,000
68-76	1.6	31.0	3.1	278	190,000	33,000
Ekofisk						
0-15	1.3	26.3	4.1	117-146	44,000-79,000	1,500-1,600
15-33	1.6	19.6	1.4	258-992	560-1,300	390-950
33-43	1.6	6.9	1.1	497-1452	340-1,300	280-3,200
43-53	1.5	30.2	---	470	12	200
53-68	1.7	5.9	0.1	4	<2	4
69-90	1.4	---	4.4	4	<2	4

1.1.2 Mode of discharge

The mixture of cuttings and drilling muds produced during drilling usually is pumped up the annulus of the drill pipe to the rig floor. Drilling muds containing cuttings are circulated through several separation devices on the platform to separate the drill cuttings particles from the drilling mud, which is recirculated through the mud pits and then back down the hole The mud/cuttings mixture is treated in various separation devices, such as shale shakers, sand traps, desanders, desilters, centrifuges and mud cleaners, to separate the fine-grained drilling mud solids and liquids from the coarser cuttings. The cuttings are then, depending on the residual contamination (from the mud, additives, or from oil from the reservoir), normally disposed of by dumping them on the seabed, where they may accumulate in a pile underneath and around the platform (McFarlane and Nguyen, 1991). Water based mud cuttings often contain more than 25 percent drilling mud solids (mostly clay), whereas oil based and synthetic based drilling mud cuttings may contain 5 to 20 percent oil or synthetic chemical (Annis, 1997; CAPP, 2001).

The dimensions of a pile will be determined by a range of site-specific parameters including (Kjeilen et al., 1999):

- discharge quantity;
- period of discharge;
- depth of sea-floor in relation to wave height;
- depth to sea-floor from outfall – effecting dispersion;
- nature of the cuttings and associated residual muds;
- bottom currents – effecting dispersion, scouring and natural sedimentation;
- jacket structure.

In the US Gulf of Mexico, where WBM is used most frequently, WBM volumes of about 20 to 30 m^3 per discharge are discharged intermittently at rates of 80 to 300 m^3/hour during drilling. Small discharges usually occur every 1 to 2 days and last less than 1 hour (Neff et al., 1987). There may be a larger discharge of as much as 200 m^3 of used water based drilling mud at the end of drilling, particularly following drilling of an exploratory well. The US EPA does not permit discharge of oil based or synthetic based drilling muds to US waters. Synthetic based mud cuttings may be discharged in some areas.

Drill cuttings are separated from the drilling fluid and discharged continuously to the ocean during actual drilling. Drilling may take place during about one-half the time during drilling of a well. A well may require more than 1 month to drill with WBM. Drill cuttings containing a small amount of adsorbed drilling fluid usually are discharged at a rate of about 0.2 to 2m^3/hour. Thus, drilling mud and cuttings are discharged at a slow rate over a long period of time. Mud/cuttings solids accumulate slowly on the sea floor.

An evaluation of the dispersion of drilling effluents in the receiving waters when drilling a test well in Lower Cook Inlet, Alaska, was conducted by Houghton et al (1980). The maximum *in situ* concentration of drilling mud occurred at the point of the well discharge. The rate of initial deposition of cuttings (larger than 0.85 mm diameter) near the vessel was measured at 1.25g/h/m^2. Strong bottom currents prevented the accumulation of a visible cuttings pile.

1.2 Natural sedimentation

1.2.1 Sedimentation rates in the North Sea and surrounding areas

Whilst there is much information on sediment budgets in the coastal areas of the North Sea, as reviewed by (Carter, 1988), there is far less data describing or mapping actual, measured sedimentation rates in the offshore North Sea. The majority of work in these regions has centred on the measurement of the consequences of natural sedimentation (Kjeilen et al., 1999). However, several authors have measured accumulation rates or natural sedimentation rates in the North Sea including (deHaas, 1997a; deHaas, 1997b; vanWeering, 1987; vanWeering, 1993; Zuo *et al*, 1989). deHaas (1997a) measured the sedimentation rates in 27 box cores within 500,000 km^2 of the North Sea at depths of < 200 m. Rates ranged between 0.5 – 3.5 mm/y.

Natural sediment deposition in the Skagerrak/Norwegian Trench, the major deposition area for the North Sea, is about 1.1 cm/year. In the deep sea, sediment deposition rate may be less than 1 mm per/100 years and the benthic fauna is dominated by a large number of small (<0.5 mm) animals.

Large storms can cause substantial bed transport to a water depth of more than 200 m, resulting in erosion and deposition of the bottom to produce a ridge and swale topography. Thus, it is likely that continental shelf benthos is more tolerant to burial than slope and rise benthos.

1.2.2 Observations from sedimentation of other industrial discharges

Several studies of burial have examined the effects from short-term discharges (batch, discharges within hours) of natural or special sediments (such as dredged material). Such discharge rates are not realistic for the flux of particles from drilling operations, and thus have limited relevance for the derivation of a PNEC for burial. This is however the situation also for other data used to derive PNEC values. For example, the data used to derive PNRC values for toxicity studies are often short-term, “batchwise exposure”, single chemicals in stead of mixtures, etc., while toxicity PNECs are used to assess continuous low-dose discharges of mixed produced water discharges. These limitations are thus present, but in deriving PNEC values, the best information available / best assumptions that can be made have been used.

Some solids discharge studies of higher relevance (in terms of discharge mode) have investigated the effects of mine tailings on benthic communities. Although the discharge mode of mine tailings are more similar to drilling discharges in that they are long-term, they are, on the other side, more continuous than drilling discharges. However, Olsgard & Hasle (1993) reported that a sedimentation rate of 4-5 cm of tailings per year resulted in changes in fauna composition, while at a rate of 1 mm per year no impact was observed. Such studies are considered relevant for the derivation of a PNEC for burial, as the discharge situation is similar to the situation in the sediments receiving discharges from drilling operations.

1.3 Burial of organisms

The potential risk of cuttings contaminated with WBM residues (inert clay, bentonite and barite) settling onto the seabed has been primarily explained by the temporary effects of physical burial of benthic fauna (Daan & Mulder, 1993). The following factors that determine the effect of burial on species are mentioned (Maurer *et al*., 1980, Kranz, 1974 and Baan *et al.*, 1998):

- Depth of burial
- Tolerance of species (life habitats, escape potential, degree of mantle fusion and siphon formation, low oxygen tolerance)
- Burial time
- Nature of material (grain size different from native sediment)
- Temperature (mortality rate by burial higher in summer than winter)

1.3.1 Tolerance to sediment deposition

Tolerance of offshore benthic fauna to sediment deposition and burial probably is dependent primarily on their size, the frequency and magnitude of natural deposition, and location of residence on or in sediments.

In general, the effect of burial mainly depends on the mobility of organisms in the sediment matrix and on the settling rate of particles. Sedentary organisms, which have no or very limited abilities to move, such as attached barnacles or mussels, are very sensitive. Other species with a low capability to move through the sediment, such as certain bivalve species, may eventually suffer from low oxygen concentrations in the sediment (Essink, 1999). Most species present in muddy sediments or in high-energy, dynamic sediments are, however, well adapted to changes in their substrate. Especially species with burying behaviour, experience hardly any effect (Bijkerk, 1988).

For most species, the oxygen consumption rate is lower in winter than in summer. This can cause organisms to survive longer in winter after burial. Movement of the organisms, however, is also lower, so it takes longer for the organism to escape from the layer of burial. The influence of the season on the effect of burial is therefore hard to predict. It depends on the species, location and temperature.

1.3.2 Tolerance to changes in sediment texture

Sediment mineralogy and grain size distribution often is different in cuttings piles and adjacent sediments. In much of the Norwegian Sector of the North Sea, sediments are primarily sands, while most cuttings piles contain a high concentration of silts and clays, as indicated in Tables 1 and 2 above.

Effects of sediment texture on benthic communities are superimposed on effects caused by any direct toxicity of cuttings pile chemicals, and organic enrichment from high concentrations of biodegradable organic matter in the cuttings. WBM cuttings often contain low concentrations of toxic chemicals and biodegradable organic matter. Benthic effects of WBM cuttings accumulations often are caused primarily by physical burial and changes in sediment texture and usually are less severe and persistent than effects of OBM and SBM cuttings accumulations (Olsgard and Gray, 1995, Daan and Mulder, 1996). Differences in sediment texture have the effect of rendering the substrate less suitable for habitation by some species of benthic organisms and more suitable for colonization by other benthic organisms (Neff, 1987).

As discussed later, the life stages of many marine invertebrates will have varying sensitivities, which thus can affect the long-term ‘adaptation’ to the drilling discharge deposition of that species.

1.3.3 Ability to escape burial

The Escape Potential (EPn) of a given species can be identified as the probability that the organism will escape a given depth of burial (Kranz, 1974) The EP10 thus means that 10% of the individuals are able to escape the given (maximum) depth of burial and successfully re-establish themselves in normal feeding position at normal living depth. The EP10 is therefore more comparable to an EC90 than to a NOEC (or EC10). The threshold values in Table 3 for burial with both exotic and native sediment concern the maximum burial depth values that can be escaped. Other information is mainly based on studies by Maurer *et al.* (1980; 1981; 1982) and Bijkerk (1988), see Table 3.

Kranz (1974) studied the effect of burial on bivalve species and showed that the life habitats of the taxa affected the susceptibility of the fauna to mortality. The ability of species to escape burial varies with their habit. For instance, epibenthic fauna are generally unable to escape more than a 1 cm burial depth (Kranz, 1974), whereas infauna taxa, which are adapted to be covered with sediment, may escape from burial to 10 cm or more (Jackson & James, 1979; Bellchambers & Richardson, 1995). In Table 4 the EP10 of groups of bivalve species are shown. Difference is made for burial by exotic and native sediment. Species which suffer most from burial (with a sediment type different from the native one) are the infaunal nonsiphonate suspension feeders, infaunal mucus tube feeders and labial palp deposit feeders. When buried with native sediment, the mucus tube feeders and labial palp deposit feeders seem to be the least affected groups. The group least affected by burial with exotic sediment are infaunal siphon-feeding bivalves. This could be explained by the fact that the members of this group do not demonstrate any significant escape burrowing.

The vertical migration by the buried infauna may be dependent on the depth and the duration of burial, structure and temperature of the sediment (Maurer *et al.*, 1981; 1986). The silt content of the sediment is an important parameter which may change the ability of the fauna to regain the upper sediment after burial. Silty sediments are more compact, and generally contain less oxygen than coarse sediments. Several studies have documented increased mortality rates in silty compared to sandy sediments (Glude, 1954; Jackson & James, 1979; Maurer *et al*., 1986; Chandrasekara & Frid, 1998). This fact makes it more difficult to derive generalized response patterns.

Table 3 Threshold values of burial (depth in cm) for different benthic species (EP_{10}).

Species	Group	Threshold (cm)	Reference
Mercenaria mercenaria	Bivalve	16	Maurer *et al.* (1980)
Mercenaria mercenaria	Bivalve	>15	Kranz (1974)
Ilyanassa obsoleta	Bivalve	16	Maurer *et al.* (1980)
Nucula proxima	Bivalve	8	Maurer *et al.* (1980)
Nucula proxima	Bivalve	10 - >57	Kranz (1974)
Crassostrea virginica *	Bivalve	0	Kranz (1974)
Hinnities multirugosus *	Bivalve	0	Kranz (1974)
Modiolus demissus *	Bivalve	0	Kranz (1974)
Mytilus edulis *	Bivalve	0-4	Kranz (1974)
Mytilus edulis *	Bivalve	<3	Bijkerk (1988)
Anadara notabilis	Bivalve	5	Kranz (1974)
Astarte castanea	Bivalve	2 - >10	Kranz (1974)
Astarte undata	Bivalve	6 – 7	Kranz (1974)
Cardita floridana	Bivalve	1 - >15	Kranz (1974)
Venericardia borealis	Bivalve	1-5	Kranz (1974)
Codakia orbicularis	Bivalve	12 - >52	Kranz (1974)
Divaricella quadrisulcata	Bivalve	11 - >48	Kranz (1974)
Phaciodes nassula	Bivalve	2 – 41	Kranz (1974)
Yoldia limatula	Bivalve	10 – 45	Kranz (1974)
Mya arenaria	Bivalve	>15	Kranz (1974)
Mya arenaria	Bivalve	<3 – 40	Bijkerk (1988)
Clinocardium nuttalli	Bivalve	10 – 16	Kranz (1974)
Clinocardium nuttalli	Bivalve	5	Bijkerk (1988)
Ensis directus	Bivalve	>40	Kranz (1974)
Gemma gemma	Bivalve	>6 - >23	Kranz (1974)
Macoma nasuta	Bivalve	>36 - >40	Kranz (1974)
Cerastoderma edule	Bivalve	5	Bijkerk (1988)
Laevicardium crasum	Bivalve	5	Bijkerk (1988)
Acanthocardia echinata	Bivalve	5	Bijkerk (1988)
P. longimerus	Crustacea	7	Maurer *et al.* (1981)
S. laticauda	Crustacea	1	Maurer *et al.* (1981)
Cancer magister	Crustacea	10	Maurer *et al.* (1981)
N. sayi	Crustacea	32	Maurer *et al.* (1981)
Crangon crangon	Crustacea	20	Pinn & Ansell, 1993
Scoloplos fragilis	Polychaeta	<8	Maurer *et al.* (1982)
Nereis succinea	Polychaeta	<30	Maurer *et al.* (1982)
draadworm	Polychaeta	20	Bijkerk & Dekker, 1990
Hydrobia ulvae	Gastropoda	**	Chandrasekara & Frid (1998)
Littorina littorea	Gastropoda	5	Chandrasekara & Frid (1998)
Mya arenaria	Bivalvia	??	Glude (1954)
Katelysis scalarina	Bivalvia	10	Bellchambers &Richardson (1995)
Clinocardium nuttallii	Bivalvia	20	Chang & Levings (1978)
Cerastoderma edule	Bivalvia	10	Jackson & James (1979)

* These species belong to the group of epifaunal suspension feeders and have almost no ability to escape once buried. Many members of this group are permanently cemented to hard substrate. One of the major factors preventing these bivalves from burrowing out once buried is that they lack a foot modified for digging (Kranz, 1974). Occasionally, they can escape by flapping its valves or pulling up on its byssus. Some species can escape burial by swimming away.

** Dependent on duration of burial and sediment temperature.

Table 4 Depth of burial for different bivalve groups, at which the escape potential is 10 % (EP_{10}) (Kranz, 1974)

Bivalve group	EP10 exotic sediment (cm)	EP10 native sediment (cm)
Epifaunal species		
Suspension feeders (on hard substrate)	0 to 4	-
Infaunal species		
Labial palp deposit feeders	10	>45 to >57
Mucus tube feeders	2 to 12	41 to >52
Nonsiphonate suspension feeders	1 to >10	5 to >15
Siphonate suspension feeders (deep burrowers)	>15	>11
Siphonate suspension feeders (shallow burrowers)	>6 to >40	10 to >45
Siphonate deposit feeders	>40	>36

Horizontal movement, or dispersal, is also of relevance. Dispersal is a key process maintaining spatial and temporal population patterns. For many benthic marine invertebrates dispersal occurs primarily during the planktonic larval stages. Post-larval and juvenile stages of benthic invertebrate species can however also exhibit high rates of dispersal. Experiments carried out with bivalves showed that juvenile bivalves dispersed over scales of metres within one tidal cycle (Norkko et al. 2001). Within about 15 hours a 50% turnover was observed for post-larval, while juvenile stage bivalves did the same within 30 hours. It is thus possible that transportation out of a contaminated/ sedimentation area can be considerable, allowing individuals to escape rather than die.

1.3.4 Type of effects from burial

Effects from burial can be short-term and mainly on an individual level, or they can be more long-term and affecting whole populations. Such effects are; mortality, reduced growth of some species, reduced larval settlement and changed fauna composition.

1.3.4.1 Mortality

The most obvious effect of drilling discharge deposition is smothering of the present fauna by the settling drilling discharge. In the areas just beneath the discharge point, such effects will be quite obvious in many cases, depending on the total amount discharged during drilling of a well (during a period of about one month) and the distance from the discharge point to the receiving area.

Some specimens will die due to the heavy masses hitting them from above, while other specimens will die because they are not able to penetrate through the deposited layer burying them. Mortality as described here is an immediate effect, and is thus a short-term response to the deposition of drilling waste. Close to discharge sites (in the actual piles), all fauna may disappear as a result of the discharges. However, the direct physical smothering of macrobenthic organisms during cuttings pile build-up is clearly restricted locally, and unlikely to have an effect at the community level (Rullkötter, 1997). The experience from the North Sea is that re-colonisation of piles will take place within 1-5 years (depending on types of drilling muds used), and that the re-colonisation starts at the edges of the pile.

1.3.4.2 Reduced growth

The growth of organisms may also be influenced by burial, which particularly may be the case when the discharged particles contain less nutrients than the native sediment. Thus, even when the community composition is not affected, there may be ecological effects.

1.3.4.3 Reduced larval settlement

Settlement and metamorphosis phases are generally the most sensitive stage in the life history of marine invertebrates (e.g. Thorson, 1946; Woodin, 1976; Obreski, 1979; Jablonski and Lutz, 1983; Watzon & Rosgigno, 1997). Thus information on the tolerance towards burial is not necessarily relevant when it is based on the adult stage only. Increased sedimentation of particles renders the sediments unstable, which may inhibit the settlement of larvae (e.g. Hyland et al., 1994). Many species have larvae that are able to actively select their habitat, and if natural sediments are altered physically or chemically, the cues important for settlement of larvae may be eliminated (Menzie, 1984). Altered sediments may also lead to increased mortality rates after settlement. Menzie et al. (1980) and Gillmor et al. (1985) suggested that physical alterations of sediments around an exploratory drilling rig might have resulted in diminishment of recruitment as evidenced by localized reductions in abundance of a number of taxa and shift in the size frequency distribution of brittlestars. Bioassays had revealed that the drilling discharges had little toxicity.

1.3.4.4 Changed fauna composition

Changed fauna composition may be the result of reduced growth and larval settlement and increased mortality rates after settlement. Most observations of effects of cuttings on the benthic fauna are made based on oily cuttings discharges (Bell et al., 1998), and a major effect reported is the effects of organic enrichment. Changed fauna composition (or impacts on biodiversity) has traditionally been examined around North Sea installations for a long period of time, and data are abundant when considering discharges from drilling with oil or synthetic based muds. Data from drilling discharges strictly with WBMs are however scarce.

2 PEC/PNEC and EIF approach for BURIAL

The framework for risk assessment of toxic substances as set by the EU Technical Guidance Document (EC, 2003), is based on the PEC/PNEC approach. Recently, this approach has also been adopted by OSPAR (ref. nrs. 2002-19 and 2003-20). Conform the model for produced water (EIF produced water), the calculation of the risk of drilling discharges will be based on the PEC/PNEC approach, which is developed for risk assessment of toxic substances. Although the risk of burial, as described in this study, does not regard any toxicological effects, a PEC/PNEC approach is suggested to be used for the risk assessment of burial, redefining "PEC/PNEC" to PET/PNET (Predicted effect threshold/predicted no effect threshold).

The PET represents the exposure, in this case the depth of burial, which can be modeled by ParTrack/DREAM on the basis of forecasted discharge scenarios. The PNET represents the sensitivity of the ecosystem, in this case the threshold value (depth) for adverse effects caused by burial. A PNET for burial should then be selected as the "lowest threshold" value (point estimate), or another representative measure. As presented in the draft report by Holthaus et al (2003), PNET values for burial depth can be derived from SSD curves (based on the data in Tables 3 and 4). This is further discussed below.

In addition to the burial depth factor, it has been agreed that the dimension of burial time needs to be integrated. At the moment, an approach to link these two parameters has not been worked out. SSD curves for tolerance of burial time have not been developed. If such data exist and can be transformed into SSD curves, a similar approach can be used for burial time. PNET values of burial depth and burial time will then need to be merged or correlated when such data prevail. Another way to handle the "time" (or burial rate) aspect is to start calculating the risk at the moment the settled material is exceeding the PNET of burial depth. I.e. when the thickness of the layer of settled particles exceeds the PNET of burial depth, there is a risk at that location. This level could be reached after 1 day of releases, after one week, or whatever period of time. Since there will also be some restitution of particles (migration), a maximum risk area will appear after some period of time, after which there will be ' restoration', i.e. the layer will erode to values below the PNET of burial threshold value.

Another important aspect of the EIF approach is to base the PNEC/PNET component on the 'most sensitive species' to ensure the risk assessments are sufficiently conservative. The conceptual framework for the EIF for drilling discharges is discussed in detail by Smit and Jak (2003).

2.1 Most sensitive species

Based on the guidelines for risk assessment (EU Technical Guidance Document: EC, 2003) an assumption should be made that the 'most sensitive species' is always present. PNEC values shall therefore reflect this.

As opposed to PNEC values for toxicity, the PNET approach for burial is more complicated. The most sensitive species of the seabed in a specific area will be highly dependent on the actual characteristics of the seabed, it being a hard-bottom substrate, sand, or fine clay or silt. Variations in sensitivity will also be apparent with seasonal variation and the life stage of a given organism. For instance, larvae may be particularly sensitive towards burial. When the sediment surface is physically disturbed, they may reject the sediment (Woodin et al., 1995), and they may also show increased post-settlement mortality. Another important aspect is that the sensitivity is likely to increase the larger difference there is between a species' 'normal' habitat and the conditions appearing after a drilling discharge. Choosing 'the most sensitive species', then can result in PNET values based on species that were already unable to live in the receiving area before the discharge. The generic PNET may therefore be unrealistic for predicting local actual impacts.

References to specimens being particularly sensitive to sedimentation have been made by several sources. E.g. soft bottom fan worms are expected to be particularly vulnerable towards sedimentation. They are suspension feeders, and a large flux of particles may clog their respiratory and feeding systems. Hyland et al. (1994) found a significant negative correlation between the abundance of two species of sabellides and the flux of drilling mud particles. This polychaete group has also shown decreased abundances in other environments influenced by large particle fluxes (see e.g. Holte, 1998). Also, epibenthic species are expected to be more sensitive than infaunal species (Kranz, 1974; Turk and Risk, 1981; Olsgard and Hasle, 1993). It is reasonable that species that are adapted to a life under the sediment surface will be more tolerant to a e.g. 1 cm "new" layer than species living at the top of the sediment. There are several crustaceans among the epibenthos (amphipodes, cumaceans and others), and representatives of this group should preferable be included in the SSD curves to embrace the more sensitive species.

Most of the benthic fauna in areas of the North Sea where drilling is occurring are vertically and horizontally mobile to some extent. However, there are some hard bottom areas where there is an abundance of attached fauna. There also are corals in some areas of the northern North Sea that are immobile. Hyland et al. (1994) showed that some of the fauna associated with hard substrates off the California coast are sensitive to increased suspended sediment fluxes and burial. Hermatypic corals and probably also solitary corals are quite sensitive to suspended particulate fluxes and burial (Hudson et al., 1982; Powell et al., 1984). Most species have at least a limited ability to clear suspended sediments from their upper surfaces according to Bak and Elgerhuizen (1976).

An approach towards using data for 'the most sensitive species' for burial could therefore be based on deriving PNET values for 'the most sensitive species' of a "typical" receiving environment. This can either be done by defining a typical receiving environment for various (North Sea) regions, or by relating it to the actual seabed type (e.g. grain size) of the relevant discharge site. For this purpose, a different task within the ERMS project will focus on the characterization of sediment types.

2.2 Burial in relation to other EIF sediment parameters

Burial as a stand alone parameter must be seen in context to both rate and thickness of the deposited layer. In addition, burial must be seen in relation to other disturbance parameters, first of all the grain size. The grain size affects the burial tolerance - animals can tolerate more sediment of the same grain size than sediment of a different grain size. Hence, the tolerance value will likely be higher for burial of sediment of the same grain size that exists at a location than of grain size that is very different. The grain size distribution of cuttings and mud discharges (having higher variation in size and particle shape) is different from any natural sediment (either silt/clay or sand). Therefore, the consequences of the grain size distribution can be considerable even in the cases where the average grain size of the drilling discharges are quite similar to the grain sizes of the natural sediments at the receiving locations. The bigger the differences however, presumably a larger effect can be expected.

Oxygen levels are also of importance. Receiving areas with low oxygen levels are probably more vulnerable to other disturbances than more "healthy" areas. If the discharged material contains considerable amounts of organic material, the oxygen impacts can be expected to increase further. With purely WBM discharges the organic content is expected to be low, however, and increased oxygen consumption is thus not expected to be a major concern.

2.3 Ways of decreasing the burial EIF

In case of a drilling discharge, a major goal will be to reduce the impacts as much as possible, i.e. decrease the EIF. In terms of the burial EIF contribution, the following aspects will contribute to such a reduction:

- decrease the volume of mud/cuttings solids discharged,
- increase dispersion of the solids in the water column (this would increase the area of cuttings deposition, presumably to a depth less than 1 cm),
- decrease the depth below the sea surface at which cuttings are discharged, allowing more water depth for cuttings dispersal and dilution,
- or reduce the area impacted by decreasing the distance from the discharge point to the seabed.

The first point is the only one involving reduced discharge volumes, and obviously would be the preferred alternative seen from the point-of-view of the receiving environment.

The next two alternatives imply spreading the material over a larger area, thereby decreasing cuttings pile size. The intention then is that the deposition observed is below the PNET threshold. The most promising strategy for achieving this is to improve the efficiency of separation of mud from cuttings. Getliff et al. (1997) reported that low-viscosity SBMs, such as LAO SBMs, allow better separation of the drilling fluid from the cuttings on the shale shaker screens. Cuttings with lower concentrations of adhering SBMs have a lesser tendency than cuttings containing high concentrations of SBMs to clump, and dispersion is greater as the SBM cuttings settle through the water column. When cuttings containing 5 percent LAO or less (measured by retort analysis) were discharged, they dispersed in the water column and no cuttings pile accumulated on the bottom. Cuttings driers are being developed that can remove nearly 99 % of the oil or synthetic base chemical from oil based or synthetic based drilling mud cuttings.

The last alternative is to reduce the size of the receiving area by reducing the dispersion of the material. This will give high(er) impacts (above PNET), but a much smaller impacted area.

2.4 Deriving a PNET for burial depth based on SSD curves

In the report by Holthaus et al (2003), PNET values for native and exotic sediment is calculated based on SSD curves. The input data used to generate the SSD curves are the threshold levels presented in Table 3. Some important assumptions and adaptations have been made, such as:

- In case the threshold value is described as 'less than' a certain value, half of the value is taken as input for the SSD, assuming that the value at which no effect is observed (NOET) is the lowest observed effect value (LOET) divided by two.
- For some of the species (mainly epifaunal suspension feeders, permanently attached to hard substrate) threshold values of 0 cm are given, since they could not escape burial of 1 cm depth (lowest burial depth tested). Because a threshold of zero cannot be used as an input value, these thresholds values have been set to 0.5 cm, also assuming that the lowest effect level is twice the no observed effect level.
- In case two, or more, threshold values are reported for only one species, the average value for that species is taken as the input for the SSD.

Based on these assumptions, the following PNET values were calculated:

PNET burial - exotic sediment:	0,96 cm
PNET burial - native sediment:	0,65 cm

By using this approach and the current assumptions, one important aspect is missing. By assuming that the threshold value for the species showing effects at all burial depths examined can be put to half the lowest tested value, the conservative approach chosen in developing the DREAM/ERMS model and EIF calculations have not been taken sufficiently into account. Considering also that there should be a special emphasise on the most sensitive species, this substantiates the lack of conservatism. Based on the data available, the PNET value cannot be lower than 0.5 cm, even though several species are reported to have a threshold value of 0. It is on this basis the view of the authors that the PNET values presented in the report by Holthaus et al. (2003) may be too high. We therefore suggest to include one of the following two alterations to give a more conservative estimate of the PNET values:

1. From the calculated PNET for burial value, the assumed "lowest" threshold value of 0.5 cm is subtracted from the calculated PNET values, or
2. A new SSD curve is made, using a lower value than the 0.5 cm as the lowest input value for deriving the curves. Since the reported values in the literature are 0, the numbers should be closer to 0.

It is possible that such changes in PNET values will not affect the overall outcome of the importance of the burial parameter in the risk assessment. It is however important to test the sensitivity of the model using the more conservative estimates before making any final conclusions. This can easiest be done by running the model using the values calculated by Holthaus et al. (2003) and with the PNET value derived when subtracting 0.5 cm.

2.5 Deriving a PNET for burial time

As mentioned, data reporting the importance of burial time has not been examined in the same way as for burial depth. To have a comparative approach for both burial depth and burial time, it is suggested that the SSD approach could be used for both parameters. It is currently not clear whether such data exist, and if possible existing data is sufficient to derive SSD curves of any confidence.

It is possible to model drilling discharge rates with the ERMS tool against which the SSD-derived burial rate PNET can be compared. The implementation of a burial rate PNET can therefore be accomplished, provided natural burial rate data are available. Expert reviewers consider that deposition rate will be very difficult to use due to lack of data, and difficulties in obtaining reliable data. It has thus been suggested to use SSD derived from the offshore monitoring database with Ba as indicator variable. This approach has been discussed, but has not been related to burial depth specifically. If such an approach is to be followed, one should select fields where one has accurate measurements on the discharges, to try to calculate a rate.

Based on discussion within the project team, it has been suggested that a suitable burial rate should be expressed as mm deposition/day, provided that the model can give estimates within this short time frame.

3 Final discussion and conclusions

Based on the available literature data and the discussions in the previous sections, the following aspects must be considered to be the most relevant aspects when considering burial as part of drilling discharge impacts:

- Depth of deposition
- Rate of deposition
    - Most relevant for modelling: Short-term effects such as smothering effects, expressing deposition as e.g. mm/day
    - Also relevant from an ecological perspective: Long-term effects such as changed growth patterns, changed larvae recruitment/ settlement, changed species composition (months to years) etc.

In addition, the relation between burial and other potential stressors need to be emphasised, as it is evident that they are linked to each other. The stressors most relevant in relation to burial are then;

- Change in grain size, which will be important from an ecological perspective, as a different fauna may establish if the sediment environment changes much
- The oxygen content is also of relevance. This is however believed to be most influenced by the deposition of drilling discharges giving a significant contribution of organic material (such as with OBM/SBM discharges)

A challenge in providing a good approach for assessing burial impacts as input for developing a method for calculating EIF for drilling discharges is to correctly attribute benthic effects in mud/cuttings piles to the different parameters in the EIF (toxicity of mud ingredients, burial, sediment texture, sediment dissolved oxygen concentration, suspended particulate matter etc.) All parameters co-vary in a cuttings pile, so field studies do not provide a clear indication of which parameters are contributing most to adverse biological effects in the benthos.

In addition to the larger “picture” of combining the different stressors, deriving suitable PNET value(s) for burial as such are not completely straight forward. A practical approach to provide PNET values to assess the importance of burial as part of a drilling discharge EIF is to use the SSD approach. Two parameters have been identified as being important, namely the burial depth (for which an SSD-curve has already been generated) and the burial rate.

The importance of the burial rate and the best approach to consider it is at the moment not clear. As an example, a deposition of 2 cm in a day may be acceptable, as long as there is no more deposition for a few months. Similarly, a continuous deposition rate of 2 cm/month may be acceptable if it is gradual. The tolerance value of depositions rate for the model may be some combination of a maximum deposition in a day (with a defined period of time in between) and a rate for gradual slower deposition. It is suggested that an SSD curve for burial rate could be developed if relevant data are available. It has however been considered that deposition rate will be very difficult to use due to lack of data, and difficulties in obtaining reliable data. It has thus been suggested to use SSD derived from the offshore monitoring database with Ba as indicator variable. If such an approach is to be followed, fields should be selected for which accurate measurements on the discharges exist, to try to calculate a rate. A suitable burial rate should be expressed as mm deposition/day, provided that the model can give estimates within this short time frame.

An SSD curve for burial depth has been developed (Holthaus et al., 2003), based on a list of selected species. The implementation of a PNET value for burial depth based on this curve can be made, following the same approach used for other stressors. There is however a concern that the data put into the SSD curve do not take sufficiently account of particularly vulnerable species and species’ growth stages. Furthermore, we question whether the approach taken to set a “lower threshold limit” at 0.5 cm when the literature report values of zero, is conservative enough. These considerations should be taken into account in the further assessments and model tests.

In combining deposition depth and deposition rate to become one stressor of burial for EIF calculations, two approaches have been suggested. Either, rate and depth PNET values are calculated separately based on SSD curves, and a suitable weighting between the two are developed, or, the rate PNET value is not considered until the depth PNET value has been exceeded. In the latter case, it is then important that the most conservative measures are used in deriving the burial depth PNET value from the SSD curve.

It has been suggested that it would be a feasible approach to first indicate whether burial is a relevant disturbance factor, by modelling and using available data, before going into further details on how to express the two aspects of burial depth and rate together. The SSD approach is intended to provide an estimate of the "most sensitive species", and the use of SSD curves can therefore be made. However, to reliably exclude or reduce the importance of the burial factor when assessed against the other drilling discharge stressors, it needs to be ensured that the SSD data are derived and used in a sufficiently conservative manner. If, for instance, the first calculations are based on deriving the SSD curves mainly from particularly tolerant taxa, like infaunal species, and not including the larval phase, we may potentially have a situation where we prematurely conclude that burial does not seem to have any impact.

As a fist approach, it is suggested to use the more conservative approach of subtracting the set "lower threshold limit" of 0.5 cm from the derived PNET value for burial depth when making such early assessment of the importance of burial depth in the EIF drilling discharge assessment.

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