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UKOOA Phase II – Task 3 joint report on factors determining future pile characteristics

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Preface

This report presents the outline and conclusions of the work carried out within task 3 of the UKOOA Drill cuttings JIP phase II.

Under the working title “Comparative time series data on factors determining future pile volume”, task 3 embraces several sub-tasks, involving separate experimental work carried out by the project participants. Each of the sub-tasks has been reported separately by the performing participant. The project team includes RF - Rogaland Research, SINTEF, ERT (Scotland) Ltd (ERTSL) and AEA Technology. The project is led by RF.

The task 3 project is part of a larger R & D programme on drill cuttings issues. Liaison between the different projects has been highly focused, and has for task 3 been especially important with respect to task 4 – “Adaptation and evaluation of mathematical models”, and task 1 – “Cuttings pile characterisation”.

Several scientists and engineers have been involved in the task 3 work:

SINTEF: Svein Ramstad (management of mesocosm studies and responsible for experimental setup), Odd Gunnar Brakstad (data processing and reporting of mesocosm studies), Kristin Bonaunet (monitoring, sediment sampling and extraction), Inger Kjersti Almås (THC analysis and calculations), Sylvi Vefsnmo (erosion studies) and Arne Lothe (erosion studies).

AEAT: Sarah Macnaughton (management and reporting, chemical biomarker work) Martin Jones (analysis, University of Newcastle), Richard Swannell.

ERTSL: Annette Woodham (experimental and reporting), David Runciman (management), Iain Dixon and Brian Roddie.

RF: Øyvind Tvedten (re-colonisation and bioturbation), Sigfryd Torgrimsen (experimental set up and various analysis), Kjell-Birger Øysæd (THC-analysis), Veslemøy Eriksen (re-colonisation), Grete Jonsson (validation THC-analysis), Stig Westerlund (sample preparation), Odd Ketil Andersen (quality asssurer), Grethe Kjeilen (project management and co-ordination, reporting and experimental).

The project team has also benefited from constructive dialog with the appointed sponsors responsible, Geir Indrebø (Exxon) and Stuart Anderson (Marathon Oil). Valuable input has also been given by the Task 4 team, led by Andrew Tyler (BMT).

Stavanger, 15. January 2002

Grethe Kjeilen, project manager

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Executive summary

The UKOOA Task 3 focuses on factors that may cause cuttings pile changes (e.g. pile size and composition) with time primarily due to natural processes. Task 3 has been organised in several sub-tasks that separately and combined seek to give input to the main objectives of the study. This report summarises the findings of these sub-tasks, produced jointly by the project participants, RF, SINTEF, ERTSL and AEAT.

The main objective has been to generate time series data on factors that affect cuttings pile characteristics, feeding relevant data into a mathematical model (task 4) that predicts the fate of cuttings piles with time.

More specifically, relevant objectives addressed include:

- To define essential factors to be used as numerical model input data, and define data sets to be handled by the model tool,
- To visualise how cuttings piles are eroded, depending on the conditions in and around the pile,
- To measure rates and impacts of biodegradation, microbial processes, bioturbation and re-colonisation, and to see how these factors are affected by and affect pile characteristics and contaminant concentration.

Basically, two main processes have been addressed in this project, namely erosion, and depletion of THC. Associated processes and their impact on these main processes have further been addressed. The main findings of the task 3 project are summarised, addressing the questions raised in the scope as presented below. It must be kept in mind that the research carried out has addressed two cuttings piles, the oil-based pile Beryl A, and the Ekofisk 2/4 A pile that has part pseudo-oil based (PBM; esters, poly-alphaolefines) and water based cuttings.

Major findings and conclusions from the task 3:

The major findings and conclusions are summarised by addressing the questions raised in the scope-of-work for task 3. The work planning and progression has been a dynamic process, increasingly so as the realisation of the complexity of the issue has become clearer. Hence, not all of the issues have been addressed to the same extent as the need to focus the most relevant ones has been realised.

The main outcome of this task 3 work is the realisation that for the two piles investigated, and with the conditions prevalent in the areas where they are situated, erosion will be the major factor affecting the piles. Degradation processes and other processes that may influence these will in comparison be of limited relevance.

Below, each of the scope-of-work questions are addressed and commented on:

1. *What is the rate of natural degradation in the surface layers of the cuttings piles?*

Degradation processes of the organic fraction of drill cuttings material, both aerobic and anaerobic, have been examined. It has been shown, both through small-scale and meso-

scale experiments that biodegradation processes are slow, that they mainly take place in the oxygenated surface active layer (SAL), and that they probably are little influenced by macrofaunal presence and bioturbation activity. However, bioturbation activity may influence the effective thickness of the SAL.

Degradation rates for hydrocarbons (THC) of cuttings pile material at aerobic conditions are estimated to 3 mg/kg THC per day with Beryl cuttings (OBM) and 11 mg/kg THC per day with Ekofisk cuttings (PBM/WBM). This corresponds to half-lives of 120 days for Beryl (initial concentration about 750 mg/kg THC) and 750 days for Ekofisk (initial concentration 74,000 mg/kg THC). There are considerable inaccuracy in the THC data and hence in the presented rates and half-lives. Presented data must hence be taken only as indications of degradation. This has been discussed in detail by the sub-reports.

There is some evidence of toxic conditions or inhibition that limits degradation of Beryl at concentrations above 2000 mg/kg. Similar degradation patterns and rates observed with the Ekofisk cuttings were also evident with Frøy cuttings (PBM). Only aerobic degradation processes take place to a significant extent.

2 *What is the rate of erosion to the surface layers of the cuttings piles?*

The erosion rate of the Ekofisk cuttings (PBM/WBM) was about 6 kg/m^2 per day at the maximum shear stress tested (12 N/m2). With the Beryl cuttings (OBM) a similar shear stress gave erosion rates 40-100 times higher (up to 600 kg/m^2). The conditions at which these erosion rates were measured represent a combination of a 100-year current speed and a 10-year significant wave height, conditions that are rather extreme.

The current speed at which significant erosion started was around 35 cm/s for both Beryl and Ekofisk (no waves applied). This value represent a 1-year current sped at the bottom of Ekofisk.

At a maximum shear stress of 3 N/m^2, the erosion rate of Beryl material was 12 kg/m^2. No erosion was observed at Ekofisk at the same conditions.

3 *Does degradation influence the rate of erosion?*

This has not been addressed directly, but has been discussed briefly in the report. THC concentrations may influence erosion, and hence degradation processes indirectly may have an impact. Based on the two piles investigated, it seems that at the highest THC concentration in the surface layer (Ekofisk), erosion is lower. However, there may be other parameters responsible for the differences observed (like e.g. protection from the platform itself, localised differences in current and waves etc).

4 *What is the rate of re-colonisation of the OBM contaminated sites?*

The rate of re-colonisation has not been established. Re-colonisation is a long-term process not suited to study during the time-frame of the research programme. Macrofaunal survival, burrowing activity and disturbance effects on drill cuttings material by two contrasting species (*Capitella capitata* and *Abra alba*) has been examined.

Re-colonisation of cuttings piles is of interest for two main reasons. Firstly re-colonisation is a sign of the cuttings pile surface becoming healthier thus allowing macrofaunal species to settle and thrive. Secondly, re-colonisation is a necessary precursor for bioturbation to occur.

Re-colonisation processes are known from other situations to be slow, i.e. considerable time, maybe years, is needed for a macrofaunal community to establish on a "new" surface. In areas with significant and regular erosion, re-colonisation of the pile is therefore expected to be practically absent. Bioturbation as a result of macrofaunal activity is thus assumed to be limited. In cases where a macrofaunal community is established, bioturbation is only expected to affect the top few centimetres of the pile surface.

An estimation of the thickness of the SAL has been provided based on measured redox profiles of the cuttings, apparent burying depths of *Capitella* and *Abra*, and from what layers depletion/degradation apparently has occurred:

- In the mesocosm experiments, the main depletion/degradation processes were restricted to the top 4-5mm.
- In the macrofaunal colonisation mesocosm, burial depths down to about 20-30 mm was observed by *Capitella capitata*. The burrowing depth was dependent on the cuttings concentration (THC), the depth decreasing to only the top 5-10 mm at the 100% cuttings samples of both Beryl and Ekofisk. At the lower concentrations tested (20% cuttings), the burial depth extended to 20-30 mm on both cuttings types.

5 What is the rate of sedimentation?

Rates of sedimentation have not been established directly. Other studies show that in some cases significant sedimentation has occurred, covering the cuttings layer, while at the two piles of the study, no evidence of net sedimentation is seen. From the erosion study it was shown that most of the eroded material was transported on the seabed. However, with the Beryl material, about 10% of the material (smaller particles) were kept in suspension.

6 How would cuttings piles, if left to degrade naturally, be characterised in 50 and 200 years time?

The purpose of the long-term model (task 4) is to address exactly this. No attempt has therefore been made to address this into any detail in this task.

However the main observation made is that in the case of Beryl and Ekofisk, erosion will determine the fate of the pile in the long-term perspective. In the case erosion or other disturbance events would not happen, the pile will become practically inert as only the top few centimetres will be significantly altered.

To give an indication of the long-term fate of a pile in the case degradation was the <u>only</u> process to affect cuttings piles the following apply;

- If a threshold concentration of 1,000 mg/kg THC for biodegradation to take place in the Beryl OBM pile is realistic, no degradation will occur in the main pile. Areas with lower THC concentrations, possibly at the pile edges, may degrade. Assuming the presented degradation half-lives, it will take 2-4 years to reduce concentrations from less than 1,000 mg/kg THC to < 100 mg/kg THC.

- In the Ekofisk PBM pile, degradation is assumed to take place at all THC concentrations. With the presented degradation half-lives, to reduce the THC concentration from 75,000 mg/kg to < 1,000 mg/kg in the aerobic surface zone will require about 15 years.
- The degradation can only be expected to take place in the oxygenated zones, the upper 10-15 mm. Degradation below this zone will be absent once initially available electron acceptors in this layer (e.g. oxygen, sulfate) has been deplenished.

7 Are there any differences between OBM and WBM piles with regard to natural degradation?

The two piles investigated are not typical representatives of oil-based and water-based piles. The oil content of the OBM surface layer is low, and the THC content of the surface layer of the PBM/WBM Ekofisk pile is high.

True water-based piles, defined as piles having NO discharges of non-water-based muds at all do exist. Such piles most likely contain low levels of THC (100-600 mg/kg), the THC in such WBM piles likely being of the same type as the THC in the OBM piles. In that respect, there seem to be little differences between natural degradation in WBM and OBM piles, except the total THC concentration will be the determining factor. There will however be a major difference between WBM and OBM piles in that the concentration of oil will be considerably higher in an oil-based pile.

8 What would be the appropriate monitoring programme for a natural degradation 'solution'?

This is at present difficult to answer. Given that erosion processes are likely to be the main denominator for cuttings pile changes, a monitoring programme should preferably address such processes. However, addressing only erosion as such will probably give a simplified picture of the total processes occurring.

The proper extent and frequency of a monitoring programme can not be estimated with the current knowledge, and should build on emerging experience.

9 How much would natural degradation cost (in terms of monitoring etc.)?

Costs of natural degradation will be related to the extent of monitoring. No attempts have been made to present any cost estimates.

10 What would be the energy consumption for natural degradation?

This issue has not been addressed, as it has limited direct relevance. Energy consumption could again be related to monitoring.

Conclusion:

The following two main conclusions are drawn based on the work carried out in UKOOA phase II Task 3:

- Erosion may be quite significant at both Beryl and Ekofisk at extreme weather conditions. (The effect of the shelter provided by the platform structure at Beryl is however not known.)
- Degradation and depletion of hydrocarbons and related compounds are rather limited and seem to be confined to the top few centimetres surface layers of the piles.

Acronyms

RF	RF- Rogaland Research
SINTEF	SINTEF Applied chemistry and SINTEF
AEAT	AEA Technology Environment
ERTSL	ERT (Scotland) Ltd
CP	Cuttings pile
DNV	Det Norske Veritas
UKKOA	UK Offshore Operators Association
OBM	Oil based mud (i.e. well drilled using a OBM)
PBM	Pseudo oil based mud
WBM	Water based mud
LSE	Large scale experiment
MSE	Mesoscale experiment (mesocosm)
SSE	Small scale experiment (microcosm)
THC	Total Hydrocarbon
TRH	Total Resolvable Hydrocarbons
BEP	Best Environmental Practice
BAT	Best Available Technology

1 The UKOOA Drill cuttings Initiative

Within recent years there has been a growing appreciation that the decommissioning of offshore oil platforms incorporates more than just structures. As a consequence of this appreciation, the attention has been directed also towards drill cuttings piles.

The UKOOA Drill Cuttings Initiative was established in 1998. Following on from a stakeholders' dialogue seminar in London in November 1998, a plan was drawn up for a comprehensive desk-top based, initial research and development programme (http://www.oilandgas.org.uk/issues/). The studies commissioned in phase I are listed in table 1.1.

Table 1.1: *UKOOA Drill Cuttings Initiative - phase 1 studies commissioned.*

	Title	responsible
1.1	Physical characteristics of cuttings piles	Cordah
1.2	Toxicity of cuttings piles	ERT Ltd/RF-Rogaland Research
2.1	Faunal colonisation of cuttings piles	Dames & Moore
2.2	Contaminant leaching from cuttings piles	BMT
2.3	Natural degradation and recovery	RF/ERT Ltd
3.1	Identification and quantification of in situ disturbance	BMT
3.2	Mathematical model of pile dispersal following disturbance	BMT
4.1	Bioremediation solutions	AEAT/RF/ SINTEF
6.1	Identification and effectiveness of removal solutions	CEFAS
6.2	Proposed methods of lifting cuttings	CEFAS
6.3	Environmental effects of removal solutions	CEFAS
7.1	Impact of onshore disposal	DNV

The Phase I desk-top studies raised several issues that were poorly understood. To elaborate on these issues, a phase II was established during spring 2000. The projects commissioned as phase II during summer 2000 are presented in table 1.2. The phase II work was established to fill the gaps identified in phase I that would 'allow sound scientifically-based recommendations for the destiny of cuttings accumulations at the end of a production development's life'. The primary objective of Phase II is, therefore, to collect sufficient data to enable a Best Environmental Practice (BEP) and Best Available Technology (BAT) to be determined for the present time, by method of comparative assessment. Phase II projects are scheduled to be completed during autumn 2001.

Table 1.2: *UKOOA Drill Cuttings Initiative - phase II projects.*

	Title	responsible
1	Characterisation of cuttings pile	RF
2a	Toxicokinetics of WBM drill cuttings contaminants in marine sediment	ERTSL
2b	Assessment of actual environment impact	Cordah/Akvaplan Niva
2c	Water column and food chain impacts	Dames & Moore/TNO
3	Comparative time series data on factors determining future pile volume	RF/SINTEF/ERTSL /AEAT
4	Adaptation and evaluation of mathematical models	BMT
5a	In-situ solution: enhanced bio-remediation	AEAT/SINTEF/RF
5b	In-situ solutions: covering	Dredging Ltd
6	Pilot Lifting operation	BP/Halliburton
7	Evaluation of options for slurry handling	ERM
8	Comparative assessment	?

1.1 Objectives

The objectives of task 3 are several.

The main objective has been***: to generate time series data on factors that affect cuttings pile characteristics, feeding relevant data into a mathematical model (task 4) that predicts the fate of cuttings piles with time.***

More specifically, relevant objectives addressed include:

- To define essential factors to be used as numerical model input data, and define data sets to be handled by the model tool,
- To visualise how cuttings piles are eroded, depending on the conditions in and around the pile,
- To measure rates and impacts of biodegradation, microbial processes, bioturbation and re-colonisation, and to see how these factors are affected by and affect pile characteristics and contaminant concentration.

Having established the relationships between defined processes within a pile, a further step is estimate the changes of a pile on the long-term perspective (50-200 years) if left to degrade naturally. These aspects are addressed by task 4.

In more detail, the scope of this project has been defined by UKOOA as described in table 1.3. Some changes to the outlined scope have been adopted.

Table 1.3: *UKOOA defined scope for task 3 project.*

Title	**Initiate predictive time series data on factors determining future pile characteristics from representative OBM&WBM cuttings piles.**	**Task 3**
Contractor	RF - Rogaland Research (with SINTEF, AEAT and ERTSL)	
Objective	Initiate time series data on factors that determine future pile characteristics of cuttings pile sets.	
Method	Using all current knowledge including that from Tasks 1, 2, 3, 5 & 6, establish predictive time series data on microbial processes, re-colonisation, bio-degradation, settlement, erosion (including natural and operational disturbance) and sedimentation. Laboratory/ In-situ erosion experiments. Operators, in time, will take measurements to validate predictions.	
Timescale	1year for predictive data analysis to meet JIP deliverables with contingency to cover gap analysis and one year for operator validation (improvements in data set will be an ongoing process beyond JIP)	
Inputs/outputs	• Phase I knowledge E&P Forum 1996 studies, information feed from Task 6 lifting trials • Information acquired should be available for other research areas namely Tasks 1, 2, 4 & 5. Determination of rates of microbial processes, re-colonisation, bio-degradation erosion & sedimentation to allow evaluation of effect on range of pile types. Report, should be useable in the comparative assessment. • Data necessary for predictive modelling	
Other issues	• Develop acceptable protocols (see OLF work) to ensure comparability of data from different piles • Develop protocol for time series measurement, i.e. what samples/tests to repeat and how often • Maximise data acquisition from Task 1 • Ensure data format is useable in modelling • Erosion rates could form part of modelling scope • Critical thickness for processes contributing to bio-degradation requires definition. • Outer fringe where natural remediation works – implications for rate limiting steps • Samples required for Task 3 experiments will be collected during Task 1 survey	
Checklist of questions to be answered	1. What is the rate of natural degradation in the surface layers of the cuttings piles? 2. What is the rate of erosion to the surface layers of the cuttings piles? 3. Does degradation influence the rate of erosion? 4. What is the rate of re-colonisation of the OBM contaminated sites? 5. What is the rate of sedimentation? 6. How would cuttings piles, if left to degrade naturally, be characterised in 50 and 200 years time? 7. Is there a difference between OBM and WBM with regard to natural degradation? 8. What would be the appropriate monitoring programme for a natural degradation ‘solution’? 9. How much would natural degradation cost (in terms of monitoring etc)? 10. What would be the energy consumption for natural degradation?	

1.2 Project outline

The project focuses on factors that may cause cuttings pile changes (e.g. pile size and composition) with time; primarily due to natural processes, but also those resulting from operational or accidental disturbances. Task 3 has been organised in several sub-tasks that separately and together seek to give input to the main objectives of this study.

1.2.1 Sub-task organisation

Separate small-scale experimental systems have been interactively combined with more complex meso- and large-scale laboratory systems in this project. This approach is chosen because of the important link such a split experimental approach can give, i.e. to both discern the most important basic mechanisms influencing the piles as well as present an understanding of the complex processes in the long term.

In the simpler, small-scale test systems, a range of variables have been screened separately. In this way, mechanistic processes and impacts are being described singularly, trying to reduce the complex interplay between different processes, intentionally simplifying the interpretation of the results. It has also made it possible to cover a wider range of cuttings material. More complex systems (meso-scale set-ups) have been used to better describe the interplay between factors, and to increase the realism in the experimental output by working on more realistic samples and scales. They are also valuable in giving a better approach to determine the complex aspects that cannot be measured realistically in the small-scale systems. Erosion has been measured in specifically-designed large-scale systems, on realistic real pile material.

1.2.2 Cuttings material

When the UKOOA phase II was planned, the intention was to focus on four distinct types of cuttings piles, representing the ‘limit cases’, to get the best background data for modelling cuttings piles in general. The four pile types were to include a small and a large example of both OBM and WBM piles.

For several reasons, the number of piles was reduced to two. The timing and practicalities associated with choosing piles for sampling resulted in one large OBM pile (Beryl A) with relatively low oil content of the surface layer and one medium sized WBM pile with elements of PBM deposits (Ekofisk 2/4 A) in the surface layer. It can be argued whether these two piles are the best suited to generate model input data, but these are the ones that were made available.

For parts of the small-scale studies, additional cuttings samples available (Frøy (PBM, olefines), Lille-Frigg (WBM) and Ekofisk 2/4C (WBM/PBM)) were also included, to cover a wider range of cuttings types. The Ekofisk 2/4C sample was sampled by RF on a previous survey (1998), as were the Frøy and Lille-Frigg samples (Westerlund, 1999).

1.2.3 Parameters considered

The interplay between factors relevant for cuttings piles establishment and development is, as mentioned, complex. This complexity is expressed through sets of opposing results that all need to be considered. Some examples of such are presented below. The actual findings of the project are discussed against these issues in section 3. Not all aspects have been addressed to the same extent, as i.a. the experiences made during the course of the project has influenced the focus and decisions made.

1. *Extent of erosion*

- What is the rate of erosion of the surface layers of the CP?
- How does the content of oil in the CP pile affect erosion?

Hypotheses/facts that need to be tested are, amongst others, that: 1) Oil in the cuttings pile may act as a "binding" material that reduces the erosion of the pile. 2) Bioturbation by benthic populations may increase erosion processes (see also bullet point four).

2. *Extent of sedimentation*

- How does sedimentation affect cuttings pile characteristics?

Different theories are that: 1) Sedimentation rates that exceed erosion rates may produce a "healthy" surface area of cuttings piles, and helps to confine the contaminants within the pile, allowing the natural processes taking place to continue at their own pace. 2) Covering up the pile surface reduces the natural degradation processes taking place by limiting further the availability of oxygen. 3) A "healthy" surface that stimulate colonisation will cause improved bioturbation, and hence increase natural biodegradation processes in the surface layers.

Sedimentation has not been closely addressed in the experimental design, but it is partly discussed in relation to the other test parameters in the discussion section.

3. *Degradation of pile material contaminants*

- What factors affect the extent and rate of degradation of organic pollutants in the CP?

Considerable evidence suggests that biodegradation processes are favoured at conditions of oxygen availability. The most prominent degradation processes are therefore likely to occur in the surface layer of a pile, the thickness of this layer being determined by the physical/chemical conditions of the pile, and by bioturbative activity as well as changes in the surface layer due to erosion and sedimentation. Nevertheless, sediments with high microbial activities will soon become anoxic below the surface layers, and anaerobic processes may then be responsible for further biodegradation. If water fluxes are poor, anaerobic degradation in the anoxic zones is reduced by consumption of essential nutrients, e.g. the electron acceptor sulphate.

- What are the degradation rates of organic pollutants in the CPs?

Microbial degradation activities at both aerobic and anaerobic conditions have been addressed. These data are coupled to physical/chemical factors to enable prediction of pile degradation on a larger scale.

4. The impact of natural processes on organisms in the water column and sediments

- What effects will erosive processes have on living organisms ingesting soluble or particle-bound suspended material from eroded CPs?
- What impacts will sediment re-settling have on exposed benthic organisms?
- To what extent will biodegradation processes de-toxify CP sediments?

The issues dealing with effects in the water column has not been included in this project. The toxicity of drill cuttings has been dealt with separately in task 2c. Toxic effects to benthic fauna have partly been examined, and have been studies in relation to sediment type, contaminant concentration, biodegradation of material, effects of bioturbation etc.

5. Influences of bioturbation on other cuttings processes

- What effect does the presence of a benthic population have on a cuttings pile?

There are evidence that high concentrations of oil in the cuttings inhibit colonisation of a benthic population, and thereby also reduce bioturbation. Theoretically, reduced bioturbation may produce either a reduction or an enhancement of erosion processes (Kjeilen et al., 1999) mainly due to the effects bioturbation may have on the microbial community of the pile surface layer. It is therefore essential to examine the impact of bioturbation on cuttings characteristics and erosion processes.

Effects of bioturbation are complex, but these issues have been studies, both by relating a fixed stirring activity to sediment conditions and loss/degradation of the organic fraction, and by looking at the prosperity of animals added to different concentrations of cuttings. Specific re-colonisation of cuttings material has not been addressed directly, as these processes are slow, and therefore difficult to assess at the time-scale available in this project.

1.3 Liaison with task 4 modelling

As stated, the collaboration and generation of data to task 4 has been an interactive process. The figure below (1.3.1, courtesy of BMT) shows the relationship between parameters for which most were addressed through the task 3.

To maximise the data output from task 3 to be used for task 4, several project workshops have been held. The discussions at these workshops have provided the basis for changes and adjustments made during the course of the project. In the most recent workshop (17th and 18th September 2001), the input parameters for the model, as presented in the table below, were identified.

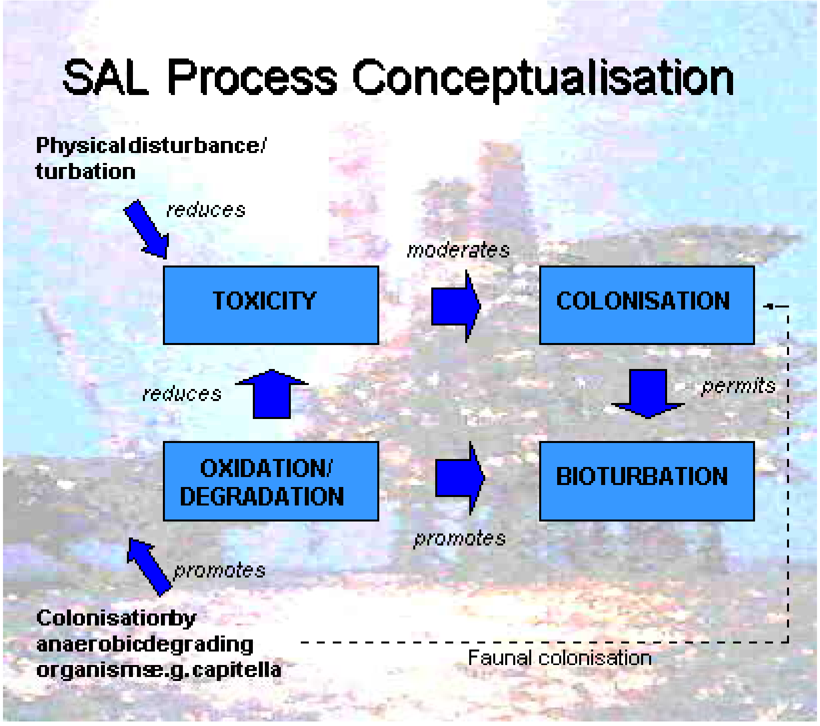


Figure 1.3.1: Relationship of important model input parameters that in general are addressed by task 3

Table 1.3.1: Parameters addressed by task 3 projects, and expected input parameters to long-term model. The SPECIFIC PILES to be addressed include WBM literature data (mainly Frigg area), Beryl pile (OBM pile) and Ekofisk 2/4 A (PBM pile)

Parameter	**Specific pile**			**Notes**
Degradation rates				Rates to be provided for aerobic and anaerobic degradation, or a compound rate. Same rates to be used for WBM and OBM
Degradation end point				Defined as percentage of initial concentration remaining after degradation
Degradation threshold				Threshold oil content above which no degradation can take place
Degradation zone				Vertical extent of degradation. Defined either as a lower depth limit for degradation (in which case a linear fit will be made), or a generic depth profile for degradation (as percentage of surface degradation rate)
Surface loss rate				Rate of physical loss (via leaching, permeation, interstitial water exchange) from surface of pile. Use DML-referenced data for corroboration
Recolonisation rate				To be taken as an exponential relationship with a plateau after 1 year. References to be provided to substantiate.
Surface loss zone depth				Depth of the surface loss zone (provisionally 2 mm) Corroboration with DML data
Bioturbation depth				Bioturbation depth & Relationship to oil content
Max. sust. Pop. density				To be derived from the cuttings pile characterization surveys. Relationship between oil content and max. sustainable population density to be derived if possible

1.4 The role of the project participants

This project has been carried out by a consortium of four institutes, each having clearly defined roles. The project planning, follow up and conclusion has been an interactive process, with regular meetings/workshop and frequent communication. This process also has included the sponsors responsible and task 4 management.

SINTEF has been responsible for erosion studies (large scale) and mesocosm studies focused at biodegradation and processes affecting this.

AEAT has been studying chemical biomarkers within the cuttings material that can relates to the historical biodegradation of the material that has been retrieved and used in the experimental phase of this study.

ERTSL has worked with RF on re-colonisation issues. The laboratory work was performed at RFs premises, with ERTSL responsible for the reporting.

RF has performed small-scale laboratory studies within biodegradation (aerobic and anaerobic), re-colonisation and effects of turbation. RF has also been responsible project manager.

2 Task 3 Experimental work

In this section a condensed summary of each sub-project within task 3 is presented. Detailed reports have been issued for each sub-task by the responsible sub-contractor. The report references are represented in the table below:

Grethe Kjeilen, Sigfryd Torgrimsen, Kjell Birger Øysæd, Grete Jonsson	UKOOA Task 3: Aerobic and anaerobic degradation of drill cuttings – results from small scale laboratory experiments Report RF-2001/217, ISBN: 82-490-0148-6
Annette Woodham, Øyvind Tvedten, Veslemøy Eriksen, Sigfryd Torgrimsen, Juliana Kerr, Grethe Kjeilen	UKOOA Task 3: Re-colonisation and bioturbation of drill cuttings material – results from small scale laboratory experiments Report RF-2001/218, ISBN: 82-490-0149-4
Øyvind Tvedten, Sigfryd Torgrimsen, Grethe Kjeilen	UKKOA Task 3: Bioturbation of drill cuttings – results from a small scale laboratory experiment Report RF-2001/219, ISBN: 82-490-0150-8
Sylvi Vefsnmo, Arne Lothe	UKOOA Phase II - Task 3: Large scale experiment Report STF81A01848, ISBN 82-14-01828-5
Odd-Gunnar Brakstad, Svein Ramstad	UKOOA Phase II - Task 3: Depletion studies of contaminants in drill cuttings mesocosm systems Report STF66A01139, ISBN 82-14-02297-5
Sarah Macnaughton, Martin Jones, Richard Swannell	UKOOA: Phase II - Task 3: Chemical Biomarker Development Report AEAT/ENV/R/0808.

2.1 Erosion (LSE)

2.1.1 Main goal

The purpose of the Large Scale Experiment was to determine the response of Cuttings Piles to wave and current action, and to provide input data to a larger, global model that predicts their long-term behaviour and fate. More specifically, the aims of the erosion study are:

- to define the erosion rate of the surface layers
- to establish threshold level of shear stress for incipient motion
- to establish the fate of material removed by erosion
- to establish whether there is a stage at which no further erosion may occur and the size of the cuttings piles at this stage
- to define essential factors used as numerical model output data and define data sets to be handled by the model tool

2.1.2 Method used

An experimental facility using samples taken from real cuttings piles was built at the laboratory at SINTEF. The experiments were carried out in a closed loop consisting of a 21 m long tunnel connected to a tank with two submerged impeller pumps (see Figure 2.1). The pressure in the loop was maintained by the water level in the tank, while the pumps provide oscillations and transient flow. A PC was used for management of the flow, and for oscillatory flow both the amplitude and the frequency were controlled. The test section covers an area of approximately 35 cm x 150 cm and 3 pile samples were used for each experiment. The samples were exposed to flow regimes that varied in the steady and the oscillating components and combinations of these.

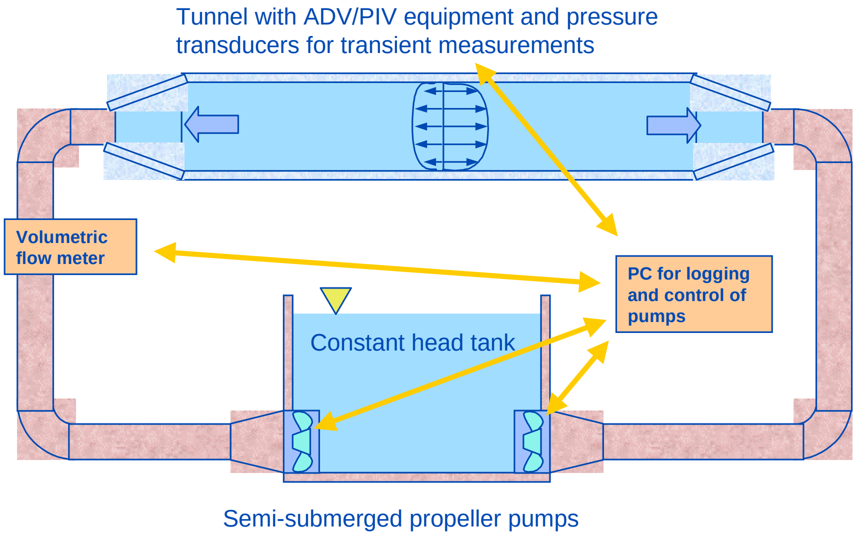


Figure 2.1.1 Sketch of tunnel rig system.

CP sample behaviour was observed visually and instrumentally by collecting material eroded from the samples. Video cameras that capture the motion of individual particles were used to monitor the erosion. A Particle Image Velocimetry (PIV) system was used to monitor the velocity field above the CP samples.

Each sample was tested in the following way:

- increasing the steady current in order to determine the threshold levels of shear stress for incipient motion
- increasing the loading with oscillatory current stepwise up to the maximum performance of the test rig (current amplitude of approximately 120 cm/s)
- duration of each loading is 30 minutes
- measurements of suspended material and bedload
- PIV measurements above the sediments
- Sieve analyses of bedload
- Coulter analyses of suspended sediments

2.1.3 Results and discussion

A total of 5 experiment series were carried out (see Table 2.1.1). The 4th experiment was only partially successful, since air bubbles appeared in the loop, which resulted in problems with controlling the flow. Experiment 2 was conducted to investigate the effect of a possible armour layer or crust on the CP, and to see if the CP would degrade dramatically much faster once this crust was removed. In all runs the salinity was 33 ‰ and the wave period was 14 s.

Table 2.1.1: *Experiment runs*

Experiment	Sample location	Samples	Comments
1	Ekofisk	39,44,45	Hard surface
2	Ekofisk	39,44,45	Upper 5 cm layer removed
3	Beryl	10,18,28	Fine material, some clay lumps
4	Beryl	26,27,31	Fine material
5	Beryl	9,14,15	Fine material, hard surface

Incipient motion

The steady current speed was increased slowly until the grains began to move. The speed was determined by the PIV and the shear stress was calculated by the formula of Soulsby (1997). The current speed for incipient motion was on average 36 cm/s for Ekofisk and 38 cm/s for Beryl. These values represent a 1-year current speed at the bottom at Ekofisk. More details from the measurements are shown in Table 2.1.2.

Table 2.1.2: *Incipient motion threshold speed levels*

Experiment	Sample location	Samples	Current speed (cm/s)	Shear stress (N/m^2)
1	Ekofisk	39,44,45	37	1.08
2	Ekofisk	39,44,45 *	35	0.97
3	Beryl	10,18,28	37	1.08
4	Beryl	26,27,31	36	1.02
5	Beryl	9,14,15	42	1.39

*upper 5 cm layer removed

Erosion rates

For combined waves and currents, the waves provide a stirring mechanism, which keeps the sediment grains mobile, while the current adds to the stirring and also provides a mechanism for net transport. The non-linear interaction of the bed shear-stress is an important factor in determining the bedload transport.

Table 2.1.3 shows the erosion rates as functions of shear-stress. The bed shear-stresses beneath combined waves and currents are calculated using the procedure described by Soulsby (1997). Notice that these values are different from the ones that would arise from a simple linear addition of the wave-alone and current-alone stresses. This occurs because of a non-linear interaction between the wave and current boundary layers.

The crust that has been found on some samples at Ekofisk does not seem to be important for inhibiting erosion of the CP; no dramatic change in behaviour was observed *in the laboratory* when the crust was removed, refer Experiments 1 and 2.

The authors find this somewhat surprising and worthy of some analysis.

One may speculate that the erosion of crust-covered samples may be influenced by the sample collection method in two ways:

1. If a CP is covered by a relatively solid, contiguous crust cover, then this crust may crack as the sampler penetrates the surface, creating more crack lines than would otherwise exist. More sediment is therefore able to escape through the crack lines than would happen in the CP's natural state.

2. If a crust exists as described above, the sampler may cause the newly formed crust plates to stand up near the crack lines, thereby making them more susceptible to attack by the fluid. The surface of the sample will then not be smooth as before, but have the ends of the plates sticking out and into the flow. The fluid may then break of larger chunks of the crust plates.

In both cases, the erosion rate of the crust-covered sample would be greater than in situ. This uncertainty could not be resolved in the experiments. The problem can be addressed by testing a larger sample (say, 1 m^2), or by conducting a video-survey of the CP to determine the in situ amount of natural cracks. It should also be noted, however, that the erosion rates at Ekofisk are very low compared to Beryl, which would not indicate that the erosion rates at Ekofisk have been overestimated.

Generally, the erosion rates at Ekofisk are low compared with Beryl. For low shear-stresses it was difficult to measure the bedload mass for Ekofisk cuttings due to low erosion rates.

For Beryl cuttings the erosion rates varied a lot from one experiment to another, mainly due to variations in the surface characteristics. Some samples had a very hard surface, which influenced the incipient motion threshold and the erosion rates. The rates depend strongly on wave and current loading. A combined shear stress of 12 N/m^2 gave erosion rates 40-100 times greater at Beryl than at Ekofisk. However, this event is rather extreme. At Ekofisk, this event represents a combination of a 100 year current speed and a 10 year significant wave height. A significant wave height of 10 m and a wave period of 11 s will produce a near-bed orbital velocity amplitude of 54 cm/s at Ekofisk. The 100 year significant wave height at the Ekofisk field is 13.5 m and the corresponding period is 15.7 s. These values represent a near-bed orbital velocity amplitude of 130 cm/s, which gives a shear stress of 27 N/m^2.

The sediments removed from the CP by erosion will mainly be moved along the bottom to some downstream location. About 10 % of the eroded mass was found to move as suspended particles during the Beryl experiments. At Ekofisk nearly 100 % of the eroded material was moved as bedload.

Table 2.1.3*: Erosion rates*

Exp.	Location	Stationary flow (cm/s)	Oscillatory flow (cm/s)	Max. shear stress (N/m^2)	Erosion rate (bedload) (kg/m^2 day)
1	Ekofisk	60	52	12.47	6.0
2	Ekofisk	60	52	12.47	6.5
3	Beryl	50 60 65 60	11 21 36 52	3.09 5.69 9.42 12.47	12 101 516 595
4*	Beryl	50	20	4.32	44
5	Beryl	50 60 65 60	10 20 36 51	2.96 5.52 9.42 12.21	36 55 163 247

* uncertain due to a lot of air bubbles

Size distribution of eroded mass

Sieve analyses of bedload mass have been carried out for all the measurements. Figure 2.1.2 shows the distribution of the eroded material at the two sites. The median size at Beryl is 0.4 mm and the corresponding figure for Ekofisk is 1.8 mm.

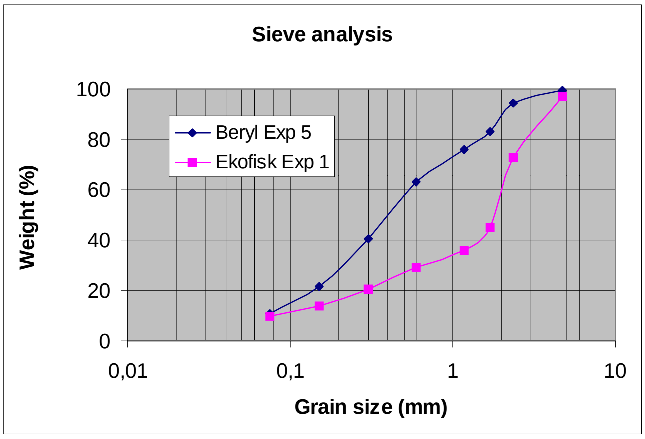


Figure 2.1.2: *Size distribution of bedload mass*

2.1.4 Conclusions

Although only 5 experiments have been conducted, some trends have been observed that lead to the following statements:

- The erosion rates at Beryl are much higher than at Ekofisk. For extreme events the erosion rates at Beryl may be more than 40 times greater than at Ekofisk.
- There was no significant difference between the threshold steady current speed for Beryl and at Ekofisk.
- The sediments removed from the cutting piles by erosion will mainly be moved along the bottom to some downstream location. About 10 % of the eroded mass were characterised as suspended particles during the Beryl experiments. At Ekofisk nearly 100 % of the eroded material was moved as bedload.
- The eroded particles at Beryl were generally smaller than at Ekofisk
- Both for Ekofisk and Beryl, a stage where no further erosion occurs has not been found, presumably because the tests could not be carried out at the velocities required.
- The crust that has been found on some samples at Ekofisk does not seem to be important for inhibiting erosion of the CP; no dramatic change in behaviour was observed when the crust was removed. However, this statement reflects only the laboratory behaviour of the sample, and must be treated with caution, and we recommend further studies before firm conclusions are drawn.

2.2 Depletion of contaminants in CPs (MSE)

2.2.1 Main goal

The objective of the mesocosm studies was to quantify depletion processes within intact and eroded (e.g. due to wave action and trawling incidents) cuttings pile sediments. The mesocosm results provide part of the input data for the fate numerical model (task 4), which includes processes like e.g. physical depletion, biodegradation, bioturbation and recolonisation. Important processes to determine in the mesocosm studies are; depletion/degradation rates in oxic and anoxic sediments, the relations between biodegradation and other processes causing depletion, and the vertical zones of depletion related to degradation and physical depletion processes.

2.2.2 Methods used

The mesocosm studies were performed as two separate experiments with intact or “eroded” Beryl or Ekofisk cuttings. The eroded sediments were generated by carefully removing the top 1 or 5 cm sediment surfaces before experiment start. The cuttings sediments were submerged in a constant laminar current of natural seawater (taken from 90 m depth). The first experiment (E-1) was performed in an open system, and sediment samples were collected as core samples during the experimental period (98 days) for determination of depletion kinetics in the sediments. The cores were split in two layers representing different depths, to separate between the depletion processes in the upper oxygenated surfaces and the deeper strictly anoxic layers. A second experiment (E-2) was conducted in a closed system without contact between water face and air. In this experiment the oxygen consumption of the cuttings sediment was determined to quantify the sediment biodegradation processes. The respiration analyses were complemented with chemical analysis of the upper surface layers of the sediments at the end of the experiment (58 days).

The sediment sampling regimes differed for the two experiments. In E-1 samples were collected as cores (diam. 35mm) with a randomised approach, separated in expected oxic (0-0.5 cm depth) and anoxic (3-5cm depth) layers, where the replicates from similar depths were mixed before extraction and analysis. In E-2, sediment samples were taken as complete top fractions of the expected oxic zones (0-2mm and 2-4mm respectively) at the end of the experimental period.

Chemical analyses were performed as total hydrocarbon (THC) analysis by extraction of drilling fluids from the sediments by a miniature saponification procedure. The extraction was followed by removal of polar compounds by hydrophobic interaction chromatography (BondElut), and analysis in a gas chromatograph with flame ionisation detector (GC-FID) of the HC in the range of C10 to C40. Depletion kinetics was determined mainly by first-order reaction kinetics while the respiration was determined by sediment oxygen consumption (SOC). Supporting analysis included the determination of the temperature in air and water, seawater flow rates, oxygen saturation in the reservoir water, redox analysis, and observations of the changes in the sediment surface characteristics during the experimental periods.

2.2.3 Results and discussions

The cuttings pile material from Beryl A and Ekofisk 2/4 A were originally categorised as oil based cuttings (OBM) and part water-based/pseudo-oil based (WBM/PBM) cuttings, respectively. The GC-FID results showed a typical mineral oil profile of the THC in the Beryl cuttings. The analysis of the Ekofisk cuttings revealed typical pseudo-oil based GC profiles, and average THC-concentrations were approx. 8 times higher than in the Beryl sediments. Many of the Ekofisk sediments had hard crust surfaces colonised by sea anemones (which was removed prior to initiation of the experiments). From some Beryl sediments oil seeping into the water phase was observed after sediment submergence into seawater, indicating pockets of free oil in the cuttings.

The mesocosm studies were performed at average seawater temperatures of approx. 13°C, and with natural seawater (3.3-3.4% salinity) not significantly affected by seasonal variations (90m depth). The two experiments were conducted at different laminar seawater flow-rates (3L/h in E-1 and 0.5L/h in E-2).

The THC analyses showed considerable variations in THC concentrations within each of the cuttings, ranging from 1300-6000mg/kg THC for different Beryl and 300-60000mg/kg THC for different Ekofisk sediments. The time series also revealed considerable variations within individual sediments, with the potential of partly masking for the measurements of any systematic THC depletion profiles during the test periods.

For THC analysis, sub-samples from each cuttings sample, representing the surface and deeper layers, were mixed, and subsequently re-mixed with similar samples from the other cuttings samples with similar content and treatment.

Beryl cuttings:

Visual inspection of the Beryl samples at the end of the experimental period revealed large differences in surface appearances of the sediments, differing from little or no differences to thick black or brown microbial mats with white patches, presumably due to elementary sulphur. The results for the intact Beryl sediments (MS-1) showed a slow depletion rate in the deeper sediments (3.5cm; $t_{1/2}$ of 91 days, 21mg THC kg^{-1} d^{-1}), while no depletion rate was determined in the top layer. When Beryl sediments were "eroded", similar depletion rates could be determined in the upper layers caused by the exposure to the seawater (1cm "eroded": $t_{1/2}$ of 32 days; 5cm "eroded": $t_{1/2}$ of 39 days), corresponding to approx. 150mg THC kg^{-1} d^{-1}. However, no depletion was estimated in the deeper layers. The biodegradation data from the small-scale experiments showed that the THC in the 100% Beryl cuttings was not biodegradable within a time-frame of 230 days, and indicated therefore that the processes determined in the mesocosm studies were more related to physical than to biological activities. The depletion in the Beryl sediments were therefore probably caused by physical processes like leaching, permeation, or pore water exchange. This was further indicated in MS-2, where no sediment oxygen consumption was measured in any of the Beryl samples. In MS-2 significantly higher THC depletion was measured from the upper 0-2mm surface layers (69%; > 500mg THCkg^{-1} d^{-1}) than from the 2-4 mm surface layers (9%; 75mg THC kg^{-1} d^{-1}) in both intact and "eroded" sediments. According to Shimmield et al. (2001) the Beryl sediments were oxygenated only in the upper 0-2mm, indicating the oil depleted in our experiments was removed from the cuttings surface by seawater fluxes.

Ekofisk cuttings:

Visual inspections of the intact Ekofisk sediments revealed moderate surface changes during the experiments, while "eroded" sediments showed significant patches of black to brown microbial mats, with white spots of presumable elementary sulphur. In Ekofisk sediments (MS-1) a slow depletion rate was determined in the deeper sediments, both in cuttings with hard crust surfaces ($t_{1/2}$ of approx. 450 days; 75mg THC kg^{-1} d^{-1}) and with soft surface characteristics ($t_{1/2}$ of approx. 540 days; 60mg THC kg^{-1} d^{-1}). No depletion could be determined in the surface layers of these intact cuttings. In the "eroded" Ekofisk sediments a slow depletion was determined in the surface layers (1cm "eroded": $t_{1/2}$ of approx. 330 days; 5cm "eroded": $t_{1/2}$ of approx. 300 days), corresponding to rates of 120mg THC kg^{-1} d^{-1}. However, depletion in the deeper sediments was insignificant or very slow (5cm "eroded": $t_{1/2}$ approx. 600 days; 40mg THC kg^{-1} d^{-1}). Although the Ekofisk rates were significantly lower that the rates for the Beryl cuttings the daily concentrations of depleted THC in the sediments were comparable because of the higher initial THC concentrations in the Ekofisk cuttings. Based on the rate kinetics of MS-1 18-20% of the THC was depleted within 14 weeks, while 11.5-12.5% was depleted within 8 weeks. Whether depletion was caused by biological or by physical processes was further studied in the MS-2 using comparison of respirometric (SOC) and chemical analysis. SOC was significant in the "eroded" sediments, but was not measured in the intact Ekofisk cuttings. For the eroded sediments the SOC corresponded to mineralisation of 3-10 % (average 8%) of the initial HC in the individual sediments after 8 weeks, assuming that the process took place mainly in the upper 0-5mm layers. Comparison of the results from the THC and SOC analysis thus indicated that biodegradation was the dominating process causing depletion of contaminants in the "eroded" cuttings.

Degradation as a function of sediment depth:

High concentrations of reduced sulphur (H_2S and MeS) were present in the sediments, indicating considerable anaerobic activity. Anoxic conditions appeared a few millimetres below sediment surfaces, both observed visually and indicated by redox measurements. Results from core measurements in Beryl cuttings showed dissolved oxygen, dissolved Fe and Mn, as well as dissolved sulphide (Shimmield et al., 2001), and a stratification of the sediments with respect to the analysts. The top 2mm layer was oxygenated with seawater, followed by a 2-10mm oxygen-depleted layer, indicating gradually reduced seawater fluxes and reductive conditions (reduction of Fe_3O_2 and MnO_2), followed by a 10-15mm zone with sulphide accumulation (requiring reductive conditions of –200mV). Thus, aerobic degradation is probably the only degradation process in the upper 0-2mm, while mixed processes appear in a zone of 2-10mm. Strict anaerobic sulphidogenesis is dominating in the 10-15mm zone and is the only degradation process below 15mm depth. If the electron acceptor for biological sulphide reduction is provided by seawater (2000mg/l sulphate) the potential for biodegradation in sediments with stagnant pore water conditions will be 70mg carbon from 1kg wet sediment (30% pore water), according to Mitchell et al. (2000). This corresponds to approx. 1% of the THC in the Beryl A and 0.15% of the THC in the Ekofisk 2/4 A cuttings. We may thus state that degradation is negligible in the layers where sulphide accumulates (deeper than 1cm).

2.2.4 Conclusions

The results from the mesocosm studies, combined with data from the small scale studies revealed the following:

Depletion

- Depletion was determined from the surface layers of Beryl intact or "eroded" cuttings, corresponding to > 500mg THC m^{-2} d^{-1} from the upper 0-2mm, and about 75mg THC m^{-2} d^{-1} from the 2-4mm layer. Below this layer, practically no depletion was seen.

Beryl A cuttings:

- Depletion was significant in the upper 2mm surface layers (> 500mg m^{-2} d^{-1}; 69% after 58 days), and considerably less in the 2-4mm surface layers (75mg THC m^{-2} d^{-1}; 9 % after 58 days), and presumably negligible below 4-5mm.
- The results indicated enhanced depletion from the 0-5mm surface layers when sediments were "eroded", with (130mg m^{-2} d^{-1}; 50 % depletion reached after 32-39 days) in eroded sediments for the upper 5mm sediments.

- No biodegradation was determined, indicating that the depletion was mainly caused by physical processes like leaching, permeation, pore water exchange
- The results also indicated a slow gravitational movement of oil in the deeper layer in intact cuttings, (20mg THC m^{-2} d^{-1}), but whether this was a result of experimental conditions (artefacts) or can be related to field situation is unknown

Ekofisk 2/4 A cuttings:

- Slow sediment depletion was determined in the cuttings, predominantly in surface layers (0-5mm) of “eroded” cuttings (120mg THC m^{-2} d^{-1}). No specific depletion was related to the upper 0-2mm.
- The results indicated that biodegradation was a major depletion process in “eroded” sediments (appr. 12% THC depletion and 9% SOC mineralisation).
- The results also indicated a slow gravitational movement of oil in the deeper layer, (70mg THC m^{-2} d^{-1}), but as for the Beryl cuttings it impossible to determine whether this was a result of experimental conditions or not.

Degradation processes:

- Aerobic biodegradation probably takes places only in the surface layers (0-2mm), while microaerophilic/anaerobic processes appear in the 2-10mm zone, to be completely replaced by strict anoxic sulphidogenic processes in the 10-15mm zone.

Both available electron acceptors, measured sulphide, and the high carbon levels in piles with organic-based drilling fluids strongly indicate that biodegradation of drilling fluids are low or negligible in the sulphidogenic zone (1% THC or less), thus setting a depth limit for potential biodegradation of 1 cm in the cuttings.

2.3 Aerobic and anaerobic biodegradation (SSE)

2.3.1 Main goal

The main goal of the small scale biodegradation experiment series was to obtain biodegradation rates of THC in drill cuttings material, at conditions partly realistic for *in situ* drill cuttings accumulations. Both aerobic and anaerobic biodegradation was investigated separately from other processes known to affect biodegradation rates in these small scale experiments.

The biodegradation rates obtained will be used as input to a numerical long-term model.

2.3.2 Method used

Series of small-scale degradation experiments were prepared to provide expected degradation rates of total hydrocarbons (THC) from the Ekofisk 2/4A and Beryl drill cuttings material. In addition, available drill cuttings material from other piles was included to expand the range of input data to also embrace other pile characteristics (basically based on oil type and concentration). North Sea reference sediment was also included in the test matrix.

Conditions of test systems:

Degradation experiments were carried out under both aerobic and anaerobic conditions. The set up was designed to focus exclusively at biodegradation (as far as possible), not taking into account parameters like erosion, surface active layers or loss of THC etc. The degradation series were prepared as closed systems. Time-series data was obtained over a period of 100 and 229 days for anaerobic and aerobic series respectively.

The experiments were carried out at 10°C, somewhat higher than expected site conditions (likely range, 3-6°C). It is a general trend that microbial degradation processes become more rapid with increasing temperature, within certain limits. The higher temperature used in this experiments was selected for several reasons:

- possibly higher degradation rates (advantageous since experiments were rather short-term);
- the increase in temperature was not too large, with the rather small deviations, to risk that the same fraction of the microflora would no be active;
- and so that the experiments can be directly comparable with other task 3 experiments that have certain limitations in that the ambient seawater temperature in the lab is about 10°C.

The cuttings material, representing the top 30-40 cm of the piles, was homogenised (mixed) and the same batch was used for both degradation series. Homogenising implied that; the content of the test bottles was similar and thus comparable; the mix did not represent a specific layer, but represented the top section of the pile; existing surface active layers (SAL) was removed.

2.3.3 Results and discussion

Degradation of THC was measured as changes in THC levels in the sediment fraction. Microbial related processes were further examined by including parameters as oxygen, sulfide and pH in the water-phase, and microbial activity in the sediment phase.

The microbial related process parameters reproduced quite similar in the different treatments. The small variations seen basically corresponded to the observed changes in THC. In the anaerobic series, sulfide levels and bacterial activity showed clear correlation to decreasing THC levels for the Frøy cuttings material. In general, these parameters supported the observations of the THC levels, but only in a few cases were they clearly motivating conclusions on the biodegradation.

It should be noted that when preparing the anaerobic test series, no chemically reducing agents were added to completely remove traces of oxygen. Therefore, it might be that the THC degradation reported in these test bottles may be a combination of degradation at microaerophilic and true anoxic conditions. This is difficult to confirm from the oxygen measurements since the method used is not the best suited at very low oxygen levels.

The variability of THC measurements was high, most likely due to heterogeneity of the cuttings material on a micro-scale. Statistically, the variation in the data is in the order of 25-30%, implying that THC reductions far above this is needed to conclude with certainty that THC is degraded. However, other analyses within this sub-task and other tasks have been used to judge the appropriateness of presenting actual degradation rates. Although the inaccuracy of the data must be regarded as high, half-lives of THC and relative changes in concentration from start to end of the experiments have been calculated when possible. These calculations and measured concentrations are presented in Tables 2.3.1 and 2.3.2.

Table 2.3.1*: Aerobic degradation series – reduction in THC and degradation half-lives. For series where no rate constants and half-lives have been presented, there were too little input data.*

Cuttings	C_0 (mg/kg)	C_1 (mg/kg)*	C_1/C_0	K_1 d^{-1} **	$t_{1/2}$ (days)
Beryl A 20 %	553	338	0,61	**0.006**	**120**
Beryl A 100 %	2428	2662	1,10	**ND**	**ND**
Ekofisk 2/4 A 20 %	10600	9110	0,88	**0.0005**	**1300**
Ekofisk 2/4 A 100 %	73990	61793	0,84	**0.0009**	**750**
Frøy 20 %	322	121	0,46	**0.003**	**200**
Frøy 100 %	4971	4574	0,92	**0.0005**	**1250**
Ekofisk 2/4 C 20%	647	614	0,95	**ND**	**ND**
Ekofisk 2/4 C	4763	4178	0,88	**ND**	**ND**

C_1 is the THC concentration measured at the end of the experiment, after 229 days of incubation
** K_1 d^{-1} values are derived from 1st order kinetics. The $t_{1/2}$ has been derived from the same

Table 2.3.2*: Anaerobic degradation series – reduction in THC and degradation half-lives. For series where no rate constants and half-lives have been presented, there were too little input data.*

Cuttings	C_0 (mg/kg)	C_1 (mg/kg)	C_1/C_0	K_1 d^{-1} **	$t_{1/2}$ (days)
Beryl A 20 %	749	343	0,46	**0.01**	**70**
Beryl A 100 %	2981	3972	1,33		
Ekofisk 2/4 A 20 %	10110	10476	1,04		
Ekofisk 2/4 A 100 %	64924	64262	0,99		
Frøy 20 %	1681	997	0,59	**0.01**	**60**
Frøy 100 %	6110	5054	0,83	**0.0007**	**950**
Ekofisk 2/4 C 20%	511	570	1,12		
Ekofisk 2/4 C	4825	4108	0,85		

* C_1 is the THC concentration measured at the end of the experiment, after 100 days of incubation
** K_1 d^{-1} values are derived from 1st order kinetics. The $t_{1/2}$ has been derived from the same

In sum, the tables above indicate that:

- Reduction in THC was seen with the Frøy cuttings both aerobically (mostly for the 20% cuttings series) and anaerobically (both 20 and 100%). The other measurements (sulfide, pH, oxygen removal) supported an presumption that this decrease was of biological origin. Most strongly was this the case in the anaerobic series.
- A decrease in THC was also seen with Ekofisk 2/4A cuttings in the aerobic series, but the decrease in THC was less than the assumed accuracy limits of the THC data.

This decrease is also assumed to be due to biodegradation. No measurable decrease in THC was seen with the anaerobic series. However, there were indications of microbial processes occurring, as seen by microbial activity and sulfide measurements particularly.

- Some evidence of Beryl biodegradation was also seen, mainly in the 20% cuttings series. Lack of degradation of the 100% Beryl series may be indicating toxic THC levels reducing or preventing microbial degradation.

The degradation half-lives reported is based on 1^{st} order kinetics calculated from rather few input numbers. The accuracy is therefore low (only the Frøy 100% of the aerobic series showed a confidence interval above 95%). However, the figures presented may be interpreted as indicative of potential maximum degradation rates at the experimental conditions applied.

2.3.4 Conclusion

The calculated degradation rates can be used as input to the mathematical model, representing maximum rates under optimal conditions.

The constraint in the data, seen isolated from the other experiments of task 3 is:

- The degradation rates represent a process going on in a mixed sample. At least anaerobically, other factors than the presence of a microbial community capable of degrading THC will be limiting.
- With the mixed sample, components of the cuttings may have been redistributed in a manner that increases the likelihood of biodegradation to take place. Also, oil contained within the larger particles may have become more bioavailable due to the mechanical actions.

At the aerobic test conditions, the sediment and water phase was constantly mixed. The whole sample can then be seen as representing a surface-active layer of a “real” cuttings pile.

2.4 Macrofaunal colonisation (SSE)

2.4.1 Main goal

Since bioturbation can influence many of the characteristics of sediments, including their stability, microbial populations and contaminant degradation rates, there is a need to assess both the potential for macrofaunal colonisation of cuttings piles and the influences of bioturbation on degradation rates.

Colonisation of cuttings piles is a long-term and complex process, and the approach taken has therefore been to examine a relatively small range of variables in small-scale experiments, in order to simplify interpretation of the results. The aims were to obtain, for different concentrations and types of cuttings, data on:

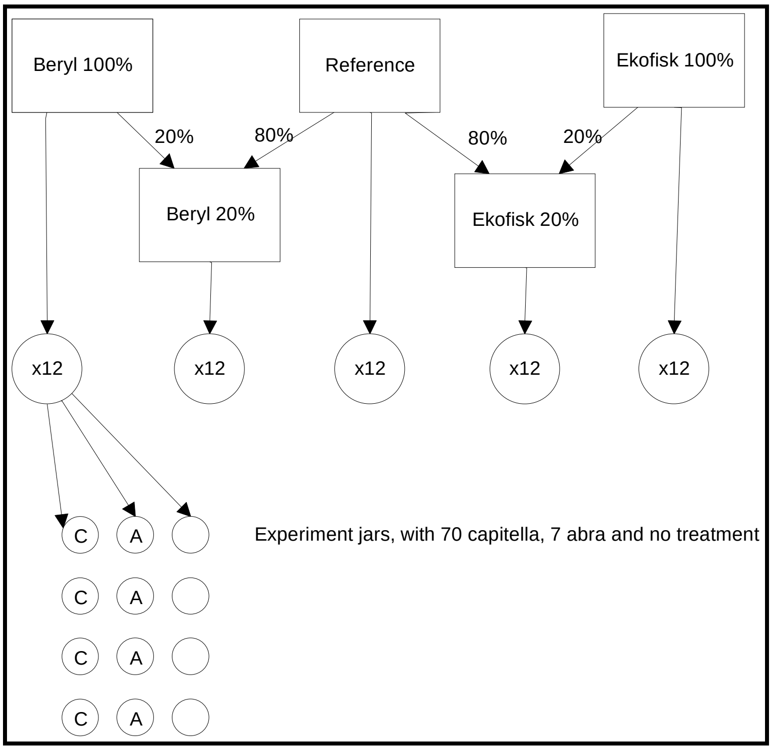
1. survival of invertebrate species, their growth, burrowing behaviour and disturbance of sediment;
2. effects of invertebrate colonisation on aspects of sediment chemistry relating to degradation processes (THC, redox and pH).

2.4.2 Method used

Two invertebrate species were used separately in the experiments: *Capitella* sp 1 and *Abra alba*. *Capitella* sp 1 is a small, fast-growing opportunistic polychaete, tolerant of sediments polluted with mineral oils and typically among the first colonisers of cuttings piles. It has previously been shown to enhance degradation of organic contaminants in sediments, and its response to differing concentrations and types of cuttings is therefore of relevant interest. *Abra alba*, a bivalve molluscs, was used in the study to represent a larger, slower growing species, with a contrasting feeding and burrowing mode and a greater sensitivity to oily substrates than *Capitella*.

Drill cuttings material from Beryl A (OBM) and Ekofisk 2/4 A (PBM/WBM), was compared. The experiments were carried out using five treatment levels (see figure) chosen to be consistent with the degradation experiments. For each treatment level, separate jars were prepared for *Capitella* and *Abra* and controls (four replicates each). The following measurements and observations were made immediately after set-up (T0) and again six weeks (T1) and 14 weeks (T2) after set-up, with some intermediate readings also taken:

- Redox (duplicate) and pH profiles (using microelectrodes)
- Visual observations, including colour of sediment/cuttings and any depth variation, evidence of disturbance of surface, presence and condition of animals on sediment surface, evidence of animal activity and depth of burrows (for *Capitella*);
- *Capitella* abundance and individual lengths, at different depths in the sediment/cuttings;
- *Abra* survival and individual lengths and wet weights;
- THC concentrations



Recolonisation experiment - preparation and set-up. The density of Capitella jars were approximately 8000 ind.m^{-2} (70 per jar), for Abra the density was approximately 1000 ind.m^{-2}. The jars were placed inside aquaria for each treatment level, which were maintained in the dark at 10°C with flow-through seawater. The experiment ran for a total of 14 weeks.

2.4.3 Results and discussion

Survival and growth

Survival of *Capitella* ranged from 37% to 69% for the different treatments after six weeks (T1), and was highest in 20% Ekofisk and lowest in 100% Ekofisk cuttings and in the reference sediment. At the end of the experimental period, survival was only significant in Ekofisk cuttings, especially 100% Ekofisk. Reasons for the death of *Capitella* in the reference sediment and Beryl cuttings could include starvation or toxicity or other unknown factors, but the changes in survival that occurred between T1 and T2 would indicate starvation to be the primary factor. Survival on Beryl cuttings would perhaps be better if an external food source were available. A decision was made not to add food to the experimental chambers, as a build-up of organic matter would affect THC and redox data and confuse the results. The results indicate that the Ekofisk cuttings provided a food source for the *Capitella*, which was probably microbial. Other published studies have demonstrated the tolerance of *Capitella* sp 1 to mineral oils including PAHs. The *Capitella* in the present experiment appeared to thrive and to be reproducing in the 100% Ekofisk cuttings. Average worm length apparently decreased during the experiment. Although this may be an artifact of the measuring process, energy-limited *Capitella* are known to use stored reserves to meet their energy needs.

Abra also showed at least moderately good survival (43% to 71%) in all of the treatments at six weeks and was highest in 20% Ekofisk cuttings and the reference sediment. At 14 weeks, survival was only significant in 20% Ekofisk cuttings (52%)

and the reference sediment (62%). Survival in the reference sediment indicates that the lack of provision of food was not a significant factor; *Abra* are known to survive for some time without feeding. The individuals that survived appeared to have lost biomass. Toxicity of the cuttings material is likely to be the main influencing factor in *Abra* survival.

Burrowing behaviour and disturbance of sediment

The most notable feature at T1 was the depth distribution of *Capitella* in the substrate. For the 100% Beryl and 100% Ekofisk cuttings, almost all of the individuals were found in the top 5mm. For both of the 20% cuttings mixtures, they were distributed mostly within the top 20-30mm, while in the reference sediment they were distributed throughout the substrate depth, with most found in the bottom 25mm of the jar. The surviving animals at T2 showed a similar depth distribution as they had at T1.

Abra showed little or no willingness to burrow into 100% Beryl cuttings. Some burial attempts were seen for 100% Ekofisk cuttings, but no significant disturbance of the sediment was observed. The 20% Ekofisk mixture was more favoured than the 20% Beryl mixture, and the majority of the *Abra* became established in the 20% Ekofisk cuttings.

Factors that could influence burrowing behaviour include redox potential and toxicity of the cuttings material. The depth of burrowing of *Capitella* in 100% Ekofisk coincided with the depth at which reducing conditions commenced, and more individuals were found at the bottom of the jar in the Beryl cuttings, which exhibited higher redox values.

Depths of colonisation observed in the small-scale experiments cannot be reliably extrapolated to the field because of the disturbances associated with sampling and the mixing of the cuttings during experimental set-up. Rather, they should be related to cuttings type, THC concentrations and redox potentials. Cuttings piles are not easily categorised, and they also exhibit heterogeneity over the surface of a single pile. Thorough mixing of the cuttings material was conducted prior to experiment set-up, in order to minimise heterogeneity in the experimental chambers.

Evidence of bioturbation in the jars was manifest as the presence of a pelletised layer at the surface, mixing of the surface layers and unevenness of the surface due to *Abra* burrowing activity. These effects were noted for the Ekofisk and reference sediment jars.

Effects on sediment chemistry/degradation rates

The redox data obtained clearly distinguished the different types and concentrations of cuttings. Even at the start of the experiment, redox values were lower in the Ekofisk cuttings than in the other treatments, and within less than a week the values in the Beryl jars had also fallen to less than those in the reference sediments. After the first week, values stabilised in all of the experimental jars and no further change with time was demonstrated. No clear effects of the presence of *Abra* or *Capitella* on redox potential were demonstrated by the experiment. However, for the Ekofisk cuttings, there was some evidence that the *Capitella* jars had higher redox potential values than the *Abra* jars or the controls, which could be a result of burrowing activity, but further data would be required to demonstrate the significance of the differences.

Although leaching of THC could be expected to occur in the open flow-through system used, only limited leaching was observed in the mesocosm experiments using similar systems, and only from the top few mm of the Beryl cuttings. There were no obvious trends of decreasing THC levels in the current experiment. This was not unexpected, since the degradation tests had already shown a high degree of variability in THC data and consequent difficulty in demonstrating changes in levels over short timeframes. The presence of macrofauna apparently had little impact on THC degradation and/or depletion, as no obvious differences between the *Capitella*, *Abra* and control jars were seen for any of the cuttings types.

2.4.4 Conclusions

- Survival and burrowing behaviour of both *Capitella* and *Abra* showed clear differences on the two types of cuttings examined. The Beryl cuttings material was shown to be less favourable to the animals than the Ekofisk cuttings, despite containing significantly lower THC levels. These differences were also present in diluted (20%) cuttings.

- *Capitella* appeared to thrive in 100% Ekofisk cuttings at THC levels in the region of 70,000mg/kg, although the experiment was not long enough to allow the development of generations. Survival in Beryl cuttings and the reference sediment was initially good but had declined by the end of the experiment, apparently due to lack of food.

- Burrowing depth of *Capitella* in cuttings material was clearly limited compared to clean sediments, and showed distinct variation with both cuttings type and concentration. Burrows were mostly limited to the top 5-10mm in the 100% cuttings and the top 20-30 mm in the 20% cuttings, although for both concentrations penetration was slightly deeper in the Beryl cuttings. Burrowing depth appeared to be related to redox potential, which in turn correlated with THC concentration.

- The more sensitive species, *Abra alba*, only survived in diluted PBM/WBM cuttings, and OBM cuttings were toxic even at THC concentrations in the region of 100 to 200mg/kg. Information is needed for more species, but the results indicate that there is a greater potential for the development of more stable communities on PBM/WBM cuttings piles than on OBM piles, and that THC concentrations for the former type may still be too high at present.

- Evidence of sediment disturbance related to both species was apparent in terms of surface layer mixing and alterations in surface texture, and was greater for the PBM/WBM cuttings than for the OBM cuttings.

- Although no significant effects of *Abra* or *Capitella* activity on redox potentials were demonstrated, for the Ekofisk cuttings there was evidence of enhancement related to *Capitella* presence.

- THC data were not expected to be important in demonstrating combined degradation and depletion over the short timeframe of the experiment, due to a high degree of variability in analytical results. No effects of macrofaunal presence on THC degradation were demonstrated, and detectable effects may only occur in the top few mm of cuttings material.

2.5 Bioturbation (SSE)

2.5.1 Main goal

Bioturbation can influence many of the characteristics of sediments, including their stability, microbial activity and degradation rates of contaminants. This study addresses the effects of mechanical disturbance, resembling bioturbation, on hydrocarbon levels (indicative of degradation and leaching). Drill cuttings from Ekofisk 2/4A, Beryl A and reference sediment were exposed to different amounts of mechanical disturbance. The aim of this disturbance was to mimic variable effects of bioturbation rates on cuttings. Redox profiles in the sediment and levels of THC in the surface sediment were the main investigated parameters.

2.5.2 Method used

A total of 9 chambers were filled with 3-4 cm of sediment/cuttings and placed under flow-trough seawater conditions. Each type of sediment was exposed to three levels of mechanical disturbance, no (none), some (“little”) or much disturbance, at a depth of 1 cm into the cuttings/sediment.

In the chambers exposed to ‘little’ and ‘much’ mechanical bioturbation, a specially designed “rake” was placed approximately 1cm down into the sediment. In the chambers with ‘little’ disturbance the rake was turned 1/10 of a complete turn five days a week. It then took two weeks to complete one turn. In the chambers with ‘much’ disturbance the rake was turned twice five days a week. The frequency of stirring was selected to give relatively large differences between the treatments.

Redox measurements (duplicate for each chamber) were made regularly during the 90 day experiment. At the start and end of the experiment samples for analysis of THC content were taken.

2.5.3 Results and discussion

The most distinct differences observed were between the reference material and the two cuttings materials. While most of the redox (Eh) measurements in the reference sediment gave positive values, the cuttings had a more distinct gradient from surface to the bottom, changing from positive to negative. There was also a slightly larger drop in the Ekofisk sediment compared to the Beryl sediment. These differences might be caused by higher degradation rates combined with less water transport (diffusion) through the denser cuttings material, and a higher organic content than in the reference sediment.

It was not possible to see any clear differences of the Eh in the top cm of the sediment in the chambers in relation to the degree of sediment disturbance. Mechanical disturbance (i.e. bioturbation) did not result in more oxygenated surface sediments. The experiment did not reveal any clear changes over time. The gradients in the samples developed rapidly within less than 14 days (12-25 June) and did not change significantly thereafter. The cuttings reached a stable gradient that was not altered by the rotation of the rake.

With regard to THC, on the other hand, there are clear indications that THC levels declined in chambers with stirring compared to the chambers without. The reduction seemed to be restricted to the top cm of the sediment. This depletion of THC might be due to higher degradation in the cutting caused by the mechanical stirring, or loss to the seawater flow, either as direct leaching or by THC being removed associated to particles.

2.5.4 Conclusions

Loss of THC was observed with both Beryl and Ekofisk cuttings when exposed to mechanical disturbance. There were no clear differences in the rate of disturbance (i.a. “little” or “much”). Similar observations were made with redox-levels and gradients, and differences between the cuttings and the reference material were obvious.

2.6 Chemical biomarker identification

2.6.1 Main goal

The objective of the chemical biomarker identification was to assess whether any change in the total resolved hydrocarbon (TRH) concentration to that of a recalcitrant hydrocarbon (a chemical biomarker) could be used as a tool to look at biodegradation of drill cuttings material in general.

Drill cuttings materials contain a complex mixture of hydrocarbons, some of which are more susceptible to biodegradation than others. The extent to which biodegradation is occurring can be assessed by normalising any change in the total resolved hydrocarbon (TRH) concentration to that of a recalcitrant hydrocarbon (a chemical biomarker). This report details the use of a chemical biomarker based approach to the assessment of the biodegradation in the two drill cuttings materials Beryl A (OBM) and Ekofisk 2/4A (PBM).

2.6.2 Method used

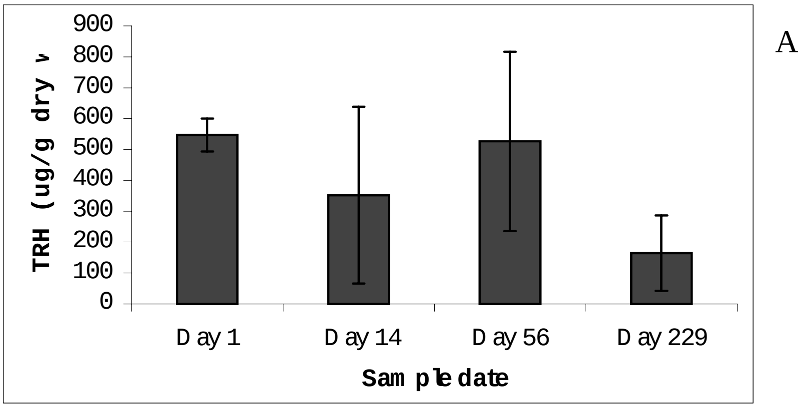
Samples of the Beryl A and Ekofisk material were analysed for the presence of appropriate chemical biomarkers. Total hydrocarbon content of the samples from the Beryl A material was 3154µg/g dry weight. Of this 0.54 µg/g dry weight was identified as the biomarker 17α, 21β hopane. This was deemed to be a sufficient proportion of the TRH to allow its use as a biomarker in these studies. The Ekofisk material contained >52,000 µg/g dry weight total hydrocarbons, however no suitable biomarker was detected in the material. This was not an unusual or unexpected finding in that the hydrocarbons in Ekofisk are primarily synthetic and would have been selected in part because they were easily degradable. It was decided, therefore, to concentrate subsequent efforts on the analysis of biodegradation in the Beryl A microcosms (under aerobic and anaerobic conditions, Forsøk 1 and Forsøk 2) and in a 56 day study of degradation of Beryl A at elevated temperature (20^{o}C) and in nutrient amended and un-amended samples.

Samples from the Beryl A degradation microcosms and the 56 day study of biodegradation under increased temperature and with and without nutrient amendments were analysed. The samples were as follows:

- Aerobic microcosm: (replicate Beryl A samples (at 100% and 20%) from days 1, 14, 56 and 229)
- Anaerobic micrososm: (replicate Beryl A samples (at 100% and 20%) from days 1, 28, 56, 100)
- Beryl A ± N/P at 20^{o}C (single samples from day 56, replicates from day 1)

2.6.3 Results and discussion

TRH and hopane concentrations in the 20% Beryl A samples were below detection limits and therefore are not commented upon herein. For the 100 % Beryl A, there was no significant decrease in the amount of hydrocarbons (either total petroleum hydrocarbons, or TRH) over time in the aerobic and/or anaerobic microcosm studies (Figure 2.6.1a, $P>0.05$). In addition, there was no significant change (Figure 2.6.1b, $P>0.05$) in the ratio of TRH/hopane, indicating that biodegradation did not occur in these microcosms. As such the biodegradation rate for both the aerobic and anaerobic microcosm studies was zero. It should be noted, however, that the variation in the data was less for the normalised biomarker data than for the total hydrocarbon content data. This finding demonstrates the utility of the biomarker approach when analysing data from heterogeneous samples.



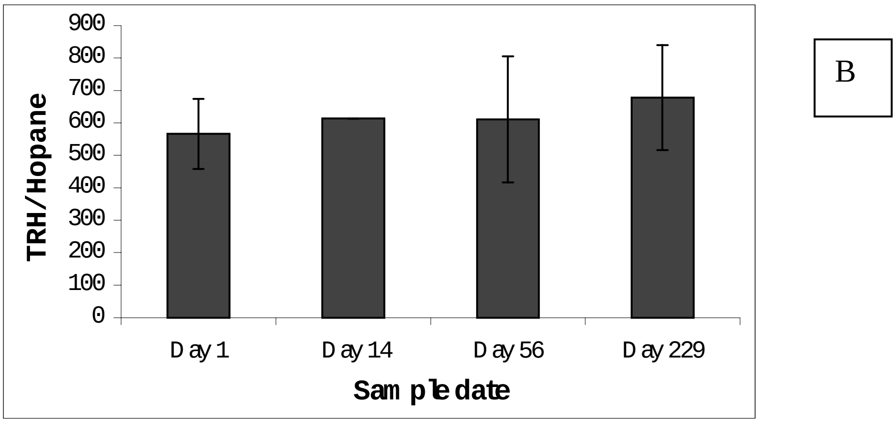


Figure 2.6.1: A) Average amount of Total Resolved Hydrocarbons (TRH) over time in the aerobic degradation microcosms; B) Change in the ratio between TRH/hopane over time in the aerobic degradation microcosms. Error bars are standard deviation

The hydrocarbon content of the samples taken from the 56 day study of OBM degradation at 20°C with or without nutrient amendment, did not change substantially over time. Analysis of the change in the ratio of TRH/hopane indicated an increase over time in comparison to the ratio at day 1 for the sample without nutrient amendment (~30%) with a decrease in the ratio (~15%) occurring with nutrient amendment. This decrease in the ratio of TRH to hopane provides evidence that biodegradation *may* have occurred in the nutrient amended samples. However statistical verification of this finding was impossible given the scope of the study and the fact that only single samples were available for analysis.

2.6.4 conclusion

The conclusions from this study are as follows:

- 17α, 21β hopane was identified as an appropriate biomarker for the quantification of biodegradation in OBMs.
- Although there was a trend towards a decrease in TRH over time in the aerobic and anaerobic microcosms, the TRH/hopane ratio's did not change over time. As such biodegradation was not detected in the either study (Trial 1 and Trial 2). TRH levels in the Beryl A 20% samples were below detection limits. As such, no conclusions could be drawn regarding biodegradation in these samples.
- The analysis of the ratio of TRH to hopane negates the effect of heterogeneity of hydrocarbon content between samples, and is therefore a more statistically robust method for determining biodegradation than is comparison of total amounts.
- Biodegradation was not detected in the nutrient amended and un-amended Beryl A samples that were maintained at elevated temperatures.

3 Discussion

The discussion section has two main foci. The first part deals with the results of the different sub-tasks and how they can be related. An important issue will be to link the results and use them in combination to substantiate the findings. Feeding data into the model task (task 4) has been a main objective, and the findings reported are therefore discussed with this in mind.

The second part addresses directly the questions put forward in the original scope. The road has changed during the course of the project, and therefore different parts of the scope has also changed focus. The changes adopted and foci of experiments have been discussed and approved at regular project Workshops, including both the sponsors responsible and task 4 members.

3.1 Model input from the task 3 experimental work

The outcome of this project has been directed at giving useful model input for the task 4 long-term model. During the project period, as summarised in table 3.1.1, several parameters were identified. The corresponding input data presented by the project team is also presented in Table 3.1.1. These data and other relevant findings of the project are discussed in the following.

Basically, two main processes have been addressed in this project, namely erosion, and depletion of THC. Associated processes and their impact on these main processes have further been addressed.

From the data presented in section 2 of this report, and discussed in more detail below, the main outcome of this task 3 work is the realisation that for the two piles investigated, and with the conditions prevalent in the areas where they are situated, erosion will be the major factor affecting the piles. Degradation processes and other processes that may influence these will in comparison be of limited relevance.

Erosion:

In the erosion studies, all samples were exposed to conditions simulating the effects of the shear stress from waves and current combined. The highest loading applied was a shear stress of 12 N/m^2, corresponding to a 100-year current speed and a 10-year significant wave height.

The current speed (no waves) at which significant erosion started was around 35 cm/s for all samples. This value represents a 1-year current speed at the bottom of Ekofisk. For extreme events the erosion rates at Beryl was more than 40 times greater than at Ekofisk. The highest loading gave a range of erosion rates from 6 to almost 600 kg/m^2 day, corresponding to a height loss of 0.4 to 40 cm/day.

Some samples (Ekofisk) had a well-developed ”crust” on the surface of the sample. One would expect this ”crust” to increase the sample’s resistance to erosion, but it was found, somewhat surprisingly, that the erosion rates increased by only approximately 10 % when the ”crust” was removed. The authors speculate that this effect may be related to the technique applied when retrieving the samples, and that the erosion rate with the ”crust” intact may be overestimated, i. e. the ”crust” was not as intact as previously thought.

Other processes than erosion:

Degradation processes of the organic fraction of drill cuttings material, both aerobic and anaerobic, have been examined. It has been shown, both through small-scale and meso-scale experiments that biodegradation processes are slow, that they mainly take place in the oxygenated surface active layer (SAL), and that they probably are little influenced by macrofaunal presence and bioturbation activity. However, bioturbation activity may influence the effective thickness of the SAL.

An estimation of the thickness of the SAL has been provided based on measured redox profiles of the cuttings, apparent burying depths of *Capitella* and *Abra,* and from what layers depletion/degradation apparently has occurred:

- In the mesocosm experiments, the main depletion/degradation processes were restricted to the top 4-5mm.
- In the macrofaunal colonisation mesocosm, burial depths down to about 20-30mm was observed by *Capitella capitata*. The burowing depth was dependent on the cuttings concentration (THC), the depth decreasing to only the top 5-10mm at the 100% cuttings samples of both Beryl and Ekofisk. *C. capitata* is a species readily colonising organically enriched sediments, and also cuttings piles (Cripps et al., 1999, Kjeilen et al., 1999). Although there are several sub-species of *C. Capitata*, and despite the fact that cuttings samples used were homogenised (mixed) in the experimental set up, the burying depths observed are thought to be indicative of real conditions. It seems therefore to be adequate to suggest that macrofaunal activity of a cuttings pile may extend the surface active layer down to 20-30mm at the most. However, it can not be stated that the whole SAL actually will be oxygenated through these processes.

During significant erosion events, the existing SAL might be removed, and a new has to form. If the “old” SAL has been present for a long time, THC degradation may have ceased as the THC level decreases. Exposing new layers of the cuttings pile will then allow more degradation to occur. Degradation is however slow, and these processes have little impact on reducing the overall contaminant (THC) level of the pile even on a long-term basis. Degradation within the pile interior is assumed to be practically absent. Even though anaerobic and microaerophilic degradation processes are assumed to occur, only small portions of the present THC may be degraded with the nutrients and electron donors available within the pile. The main process for “natural attenuation” of a pile where erosion is very low is therefore almost exclusively the degradation process within the SAL.

Re-colonisation processes are known from other situations to be slow, i.e. it takes considerable time, maybe years, for a macrofaunal community to establish on a “new” surface. In areas with significant and regular erosion, re-colonisation of the pile is therefore expected to be practically absent. Bioturbation as a result of macrofaunal activity is thus assumed to be limited.

The sources of errors in the presented degradation measurements are many:

- The degradation rates are produced at temperatures somewhat higher than expected seabed conditions (expected to increase rates).
- With the small-scale degradation studies, constantly mixing removed the limitations of exchange within the SAL.
- Further, the low statistical accuracy of the THC measurements, likely to be a result of sample heterogeneity despite attempts to overcome this, limits the certainty of the conclusions drawn.

These sources of errors all suggest that the presented rates are more likely to be overestimating degradation rates rather than the opposite. In light of the fate of cuttings piles on the long-term basis this then underlines the overall suggestion that microbial degradation plays a minor role in pile “development”.

The degradation rates produced are quite inaccurate, as discussed in the sub-task reports. However, the main trends of whether degradation actually takes place or not is generally supported by various measurements from the different experimental series. Together, all the measurements are indicative of the fate of the piles, and then substantiate a general conclusion or suggestion that the presented rates can be used as suggested. The authors of this report therefore suggest use the indicated degradation rates as model input, representing potential maximum rates of degradation. When comparing degradation rates to erosion rates, this strongly indicates that degradation is of less importance. To significantly alter the model output, degradation rates will have to be several orders of magnitude higher given the measured erosion rates. Model validation (task 4) will probably confirm this.

More specifically, the following issues have been emphasised to provide the model input parameters as presented in Table 3.1.1. It must be emphasised that the data presented are derived from the specific piles Beryl and Ekofisk. Whether a generalisation to other piles may be made is unclear, and is not being substantiated by the Task 3 project team:

- Degradation rates have been provided by microcosm degradation experiments. Findings of the meso-scale depletion studies showed similar trends and hence support the use of these rates, despite the statistical inaccuracy in the figures. The rates presented as anaerobic are most likely a combination of microaerophilic and anaerobic processes. The observation of i.a. sulfide production in the samples supports that true anaerobic degradation also takes place. This is also supported by the work done at University of Oklahoma (RF 2001/217), where the results indicated the presence of anaerobic degradation products at least with the Beryl cuttings material.

- Degradation end-points have not been measured directly. Given the slow processes and duration of the project period, this has not been achievable. Generally, in an open system, all THC is likely to be degradable with time. Since no specific factors have been identified in the cuttings piles that suggest otherwise, it is suggested that degradation will continue until no THC is left (i.a. background levels are reached). This applies however only to the SAL, where oxygen and nutrients are not limited. Below the SAL (or in the anoxic zone), the degradation processes tend to stop when some essential component is depleted. Based on assumed available sulfate levels, only about 70mg/kg THC can be removed by degradation from this zone.

- Degradation thresholds are presented based on the observations of Beryl and Ekofisk. Since no degradation was indicated at the 100% Beryl conditions (2,000-4,000mg/kg), but degradation was indicated at concentrations less that about 700-800mg/kg (20% Beryl), a threshold level between these points are assumed. For the model input it was then agreed to use 1000mg/kg (or ppm) as this level. Generally, THC present in WBM piles is expected to be of the same type as those found in OBM piles, however it is difficult to postulate that the apparent threshold level of Beryl is generally applicable. No threshold level is therefore suggested for WBM piles. The THC concentrations of such piles are however expected to be below the Beryl threshold limit in any case. Apparently degradation took place also at quite high THC concentration in the Ekofisk pile (74,000mg/kg). Threshold levels are therefore expected to be higher than this, and therefore no specific threshold has been suggested.

- Since biodegradation depend on continuous availability of essential nutrients provided mainly by seawater, the degradation process will appear only in the zones of the piles influenced by seawater fluxes. Oxygen necessary for aerobic degradation and sulphate important for anaerobic degradation, are both supplied by seawater. Considerable biodegradation will therefore occur only in the upper millimetres of an undisturbed pile. Based on field data by Shimmield et al. (2001) this zone is indicated to be 10-15mm. However, when top layers of the pile are removed, as in an erosion event, biodegradation is initiated in the exposed surface layers. In general, natural biodegradation will therefore be a minor process in undisturbed piles, affecting only the upper millimetres of the exposed surface layers.

- Loss of THC may be expected to occur also by other processes than physical removal of the cuttings material and biodegradation. From mesocosm experiments, loss of THC evidently not being caused by biodegradation was indicated with the Beryl cuttings. No such indications were seen with the Ekofisk cuttings. The loss of THC was quite significant (78% was removed from the surface mm-layer within 2 months), but restricted to a very confined layer of only a few mm, and no loss was evident below 4-5mm. A surface loss rate for Beryl cuttings is presented in Table 3.1.1. This rate has been derived from the following: Average THC concentrations of Beryl intact and eroded cuttings from the second mesocosm experiment at 8670mg/kg (ww). Average loss of THC from the upper 2mm layer at 6044mg/kg (ww) during 58 days. The sediment volume of 1m^2, 2mm thick cuttings is 2dm^3, and the corresponding weight is 5 kg given a density of the material of 2,5. The total daily loss/m^2 is thus 5 kg * 6044 mg/kg/ 58 days = 521 mg/day and m^2.

- For the Ekofisk material, the lost THC of the surface layer (second mesocosm experiment) corresponded to apparent degradation as measured by oxygen consumption. No surface loss resulting from other processes than biodegradation could therefore be measured in the Ekofisk material. It is though still likely that some loss at a low rate occurs also with the Ekofisk material. It is however not possible to indicate any rate or loss depth for the Ekofisk pile.

- No specific re-colonisation rates have been provided by task 3. It has been confirmed through Task 1 that macrofauna are present on both the Beryl and Ekofisk piles, although the macrofauna present are not indicative of a stable, mature, benthic community. Further, it has been established through the Task 3 colonisation study that selected species did survive and burrow in the Beryl and Ekofisk drill cuttings material. The suggested 1 year re-colonsiation rate is based on literature findings, and estimates that a period of one year is required for a substantial settling and survival of early colonising species of macrofauna in the cuttings.

- Bioturbation depths have been provided for the selected test species. A similar behaviour of *C. capitata* was seen in both cuttings types. A maximum burrowing depth of 20-30 mm was seen in diluted cuttings, while the burrowing depth was less, 5-10mm, in 100% cuttings samples. The observed burrowing depths (20-30mm) correspond to literature data on the same species. Since *C. capitata* is presently the most abundant species on both the piles, as evident from Task 1, this is suggested to be maximum expected bioturbation depths of the Beryl and Ekofisk cuttings piles while conditions prevent the development of a more mature fauna.

- The maximum sustainable population density has not been directly addressed. Population densities of the most abundant species have been reported, at other conditions, to reach levels of 30,000 individuals/m^2 or more. However, such numbers are several times higher than the ones observed at Ekofisk (about 5,000) and Beryl (about 2,000). It seems from the colonisation studies that available organic load may be limiting the survival of *Capitella*. Sustainable numbers might therefore not be very high. However, there are too little data to give any clear suggestions on this.

Table 3.1.1: *Model input parameters derived from Task 3 experiments. Input data are addressing THC levels of the Beryl A and Ekofisk piles specifically and should not be directly generalised to apply to OBM and PBM piles in general. All THC derived parameters have a high degree of uncertainty as described thoroughly in the text. Numbers must therefore be used with caution to represent possibly maximum rates/values.*

Parameter	**WBM (various input)**	**Beryl A (OBM)**	**EKOFISK 2/4 A (PBM)**	NOTES
Degradation rates	Same as for Beryl (oil-based mud)	Aerobic (20 % Beryl): C_0 = 550 mg/kg, t1/2=**120** days **3 mg/kg** THC per day (0.57 % / day) Anaerobic (20 % Beryl): C_0 = 750 mg/kg , t1/2=**70** days **7 mg/kg** THC per day (1.0 % / day)	Aerobic (100 % Ekofisk): C_0 = 74000 mg/kg, t1/2=**750** days **68 mg/kg** THC per day (0.09 % / day)	Rates to be provided for aerobic and anaerobic degradation, or a compound rate. Same rates to be used for WBM and OBM Rates derived from small scale degradation studies
Degradation end point	0 in oxygenated zone, and max 70 mg/kg degraded in anoxic zone Inhibition/toxicity may be effective, threshold limits not evident	< 1000 ppm: 0 in oxygenated zone, max 70 mg/kg degraded in anoxic zone > 1000 ppm: Toxic (no end point)	Zero in oxic zone, max 70 mg/kg degraded in anoxic zone (e.g. final level = C_0 - 70mg/kg)	Defined as percentage of initial concentration remaining after degradation Derived from small- and mesoscale studies
Degradation threshold	1000 ppm	1000 ppm	None	Threshold oil content above which no degradation can take place
Degradation zone	15 mm (guesstimate)	15 mm	15 mm	Vertical extent of degradation. Either a lower depth limit for degradation, or a generic depth profile for degradation
Surface loss rate		0-2 mm: 78 % THC after 2 months (521 mg/m^2/d from C_0 = 8670 mg/m^2)	Not determined	Rate of physical loss (via leaching, permeation, interstitial water exchange) from surface of pile
Surface loss zone depth		4.5 mm (lower depth limit)	0 mm	Depth of the surface loss zone (provisionally 2 mm) Corroboration with DML data
Recolonisation rate	1 year	1 year	1 year	Exponential relationship, plateau after 1 year. Based on literature data/phase 1
Bioturbation depth	25 mm (guesstimate)	25 mm (20% C, 500-700mg/kg) 5 mm (100% C, 2500-4000 mg/kg)	25 mm (20% C, about 10,000mg/kg) 5 mm (100% C, about 75,000 mg/kg)	Bioturbation depth and relationship to oil content. Based on colonisation study
Max. sust. Pop. Density		Not answered	Not answered	Relationship between oil content and max. sustainable population density

3.2 Discussing the questions initially raised in the scope

The questions below were initially raised in the scope of work (see also table 1.3). The work planning and progression has been a dynamic process, increasingly so as the realisation of the complexity of the issue has become clearer. Hence, not all of the issues have been addressed to the same extent as the need to focus the most relevant ones has been realised.

Below, each of the following questions are addressed and commented on:

1 What is the rate of natural degradation in the surface layers of the cuttings piles?

Degradation rates of cuttings pile material have been presented, as discussed earlier in this report. The presented rates at aerobic conditions are 3 mg/kg THC per day with Beryl cuttings (OBM) and 68 mg/kg THC per day with Ekofisk cuttings (PBM/WBM). This corresponds to half-lives of 120 days for Beryl (initial concentration about 750 mg/kg THC) and 750 days for Ekofisk (initial concentration 74,000 mg/kg THC).

With the Beryl cuttings (OBM), degradation was not indicated at initial THC concentrations of 2,000-4,000 mg/kg. With the PBM cuttings (Ekofisk), degradation took place also at high concentrations. Similar degradation patterns and rates observed with the Ekofisk cuttings were also evident with Frøy cuttings (PBM).

For Beryl and Frøy, degradation at preferentially anaerobic conditions was indicated. Degradation in the layers below SAL will however be limited by parameters not mimicked in the experimental system used. The rates provided will thus only be representative for e.g. the first stage degradation that will occur when a new anoxic zone will stabilise after the pile surface has been formed.

It is **evident** that the degradation rates presented have a large degree of uncertainty, and hence must be taken as **indications of degradation** more than absolute values.

2 What is the rate of erosion to the surface layers of the cuttings piles?

The erosion rate of the Ekofisk cuttings (PBM/WBM) was about 6 kg/m^2 per day at the maximum shear stress tested (12 N/m^2). With the Beryl cuttings (OBM) a similar shear stress gave erosion rates 40-100 times higher (up to 600 kg/m^2). The conditions at which these erosion rates were measured represent a combination of 100 year current speed and a 10 year significant wave height, conditions that are rather extreme.

The current speed at which significant erosion started was around 35cm/s for both Beryl and Ekofisk (no waves applied). This value represents a 1-year current speed at the bottom of Ekofisk.

At a max. shear stress of 3 N/m^2, the erosion rate of Beryl material was 12 kg/m^2.

No erosion was observed at Ekofisk at the same conditions.

3 Does degradation influence the rate of erosion?

Based on the data from the present erosion experiment it is not possible to answer this question.

The erosion rates are lower with the PBM cuttings having the highest THC concentration compared to the OBM Beryl cuttings. It can be speculated that this is a result of the THC levels. If so, it seems that THC concentration, and then indirectly degradation rates, influences erosion rates. From studies on oil/sediment interactions it is clear that the presence of oily contaminants affect the physical characteristics of sediments, which then again will effect erosion rates. It is thus possible that different erosion characteristics can be observed with other cuttings materials having different THC concentrations. Likewise, if the erosion “pressure” is low, and a pile is left undisturbed for some time, degradation/depletion may change the SAL conditions in a way that lowers the threshold for erosion to happen with the next severe weather condition.

The differences observed may also be a result of other parameters. For one, the Beryl pile has more recent discharges than the Ekofisk pile, and also the discharges are accumulated in a rather confined area along the concrete base structure (Westerlund et al., 2001). This may have protected the pile from being eroded to the same degree. Bottom current and wave influence may also vary at the two sites due to localised conditions of the area, especially the water depth.

4 What is the rate of re-colonisation of the OBM contaminated sites?

The rate of re-colonisation has not been established. Colonisation, or macrofaunal activity, of drill cuttings material by relevant species has been examined.

Re-colonisation is a slow process and it may take years to establish a faunal community. Within the scope and time-scale of this project it was not possible to investigate this directly. Survival and behaviour of individuals of *Capitella capitata* (common first coloniser of organically enriched habitats, and also identified as main colonisers of the Beryl and Ekofisk cuttings piles), and more sensitive *Abra alba* (known toxicity test species) were examined and related to THC content of cuttings material etc.

5 What is the rate of sedimentation?

Rates of sedimentation have not been established directly.

From the erosion studies it was shown that most of the eroded material resettled or was transported on the seabed. However, with the Beryl material, about 10% of the material (finest particles) were kept in suspension.

With the two piles investigated, no significant sedimentation of material on top of the cuttings base has been observed (Westerlund et al., 2001). However, other observations (e.g. Westerlund and Olsen, 2000) show that cuttings material become buried in other sediment types. Sedimentation of natural seabed sediments is therefore known to happen at some conditions. No rates are presented as model input.

6 How would cuttings piles, if left to degrade naturally, be characterised in 50 and 200 years time?

The purpose of the long-term model (task 4) is to address exactly this. No attempts have therefore been made to address this into any detail in this task.

However, to give and indication of the long-term fate of a pile in the case that degradation was the only process to affect cuttings piles, the following exercise has been done:

- If a threshold concentration of 1,000 mg/kg THC for biodegradation to take place in the Beryl OBM pile is realistic, no degradation will occur in the main pile. Areas with lower THC concentrations, at the pile edges, may degrade. Assuming the presented degradation half-lives, it will take 2-4 years to reduce concentrations from > 1,000 mg/kg THC to > 100 mg/kg THC.
- In the Ekofisk PBM pile, degradation is assumed to take place at all THC concentrations. With the presented degradation half-lives, to reduce the THC concentration from 75,000 mg/kg to < 1,000 mg/kg in the aerobic surface zone will require about 15 years.
- The degradation can only be expected to take place in the oxygenated zones, the upper 10-15 mm. Degradation below this zone will be absent once initially available electron acceptors in this layer (e.g. oxygen, sulfate) has been deplenished.

In the case of Beryl and Ekofisk, erosion will determine the fate of the pile in the long-term perspective. In the case erosion or other disturbance events would not happen, the pile will become practically inert as only the top few centimetres will be significantly altered.

7 Is there a difference between OBM and WBM with regard to natural degradation?

The two piles investigated are not typical representatives of oil-based and water-based piles. The oil content of the OBM surface layer is low, and the THC content of the surface layer of the PBM/WBM Ekofisk pile is high.

True water-based piles, defined as piles having NO discharges of non-water-based muds at all do exist. However, also such piles most likely contain THC levels in the range 100-600 mg/kg (Westerlund and Olsen, 2000). The type of THC in such WBM piles is likely to be of the same type as the THC in the OBM piles. In that respect, there seem to be little differences between natural degradation in WBM and OBM piles, as the total THC <u>concentration</u> will be the determining factor.

There seem to be a difference between OBM and PBM piles in that the degradation is less concentration dependent. The apparent dependency of concentration is possible linked to toxicity or inhibition that generally are more expressed with OBMs than PBMs.

8 What would be the appropriate monitoring programme for a natural degradation ‘solution’?

This is at present difficult to answer. Given that erosion processes are likely to be the main denominator for cuttings pile changes, a monitoring programme should preferably address such processes. However, addressing only erosion as such will probably give a simplified picture of the total processes occurring.

Erosion and degradation processes will also be inter-related. Erosion and possibly re-sedimentation of cuttings material and other material within the pile area will complicate and mix processes. It can therefore be useful also to address degradation related parameters during monitoring. The chemical biomarker approach examined did not identify a biomarker set that can be used to identify the “current” degradation status of a pile. Alternatively, microbiological markers may be useful tools, like population characterisation (genetic monitoring), quantification and viability of key organisms, specific enzyme expression etc.

The proper extent and frequency of a monitoring programme can not be estimated with the current knowledge.

9 How much would natural degradation cost (in terms of monitoring etc.)?

This question needs to be considered in light of the other questions addressed.

Costs of natural degradation will be related to the extent of monitoring.

Task 4 seeks to identify the processes providing the most prominent changes to a cuttings pile, and at what time-scales such processes may act. A monitoring programme of a “leave in situ” option must be based on such anticipated long-term effects. No cost estimate can be given at present.

10 What would be the energy consumption for natural degradation?

This issue has not been addressed, as it has limited direct relevance. Energy consumption will again be related to monitoring.

4 Conclusions

The following two main conclusions are drawn based on the work carried out in UKOOA phase II Task 3:

- Erosion may be quite significant at both Beryl and Ekofisk at extreme weather conditions.
- Degradation and depletion of hydrocarbons and related compounds are rather limited and seem to be confined to the top few centimetres surface layers of the piles.

5 References

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